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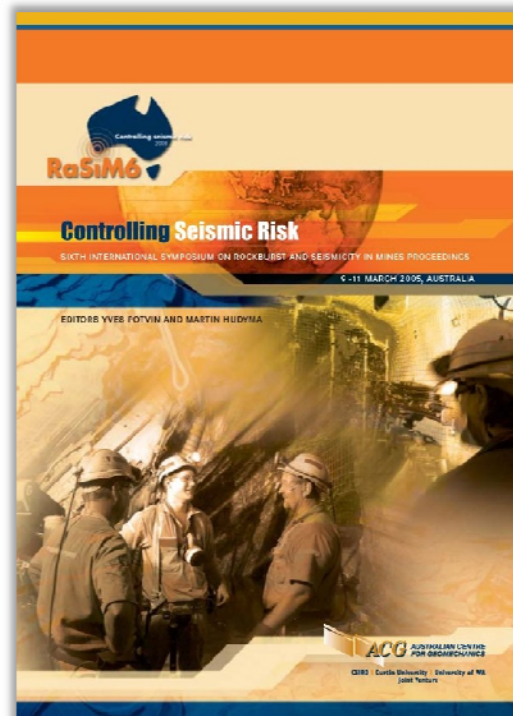
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# RaSiM Comes of Age—A Review of the Contribution to the Understanding and Control of Mine Rockbursts

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*It is the intention of this study to give a broad overview of the contribution that RaSiM has made to progress in combating the hazard of mine rockbursts during the almost one quarter of a century of its existence. In attempting to appraise the present understanding of the fundamental mechanisms involved in the occurrence of a rockburst, a phenomenological rather than a theoretical or analytical approach has been adopted. The extent to which the problem can be said to be managed or controlled is assessed from a practical rock engineering point of view.*

*The proceedings of the previous five RaSiM symposia form the main basis of the review, with only brief excursions into other reference sources for completeness of explanation or as background where necessary.*

*A view of the more important gaps in present understanding and the more obvious deficiencies in applied technology is given. Finally, some suggestions are offered on possible directions for future endeavour.*

## 1 INTRODUCTION

Underground mining has been one of mankind's most dangerous pursuits. Since the early days of coal mining when methane explosions were by far the major killer and mining's most profound mystery, it is probably true that rockbursts have been the mining hazard that is the least understood and the most feared.

It has to be emphasised that to understand the phenomenon does not imply that the danger necessarily disappears and that the problem is solved. It is also true that some problems can be ameliorated or controlled by applying empirical solutions without the mechanics or physics of underlying processes being adequately understood.

However, much of civilisations' technological progress has developed from knowledge based on real understanding of natural phenomena. Such understanding has generally derived from application of the laws of physics and from recognition of the fundamental requirements of mechanics. It seems reasonable to ask why the underlying nature of the problem of rockbursts should not also have been discovered by the same process by now. Is it simply because the earth's crust is totally opaque?

I propose to start this review by posing some questions that follow from these thoughts.

- To what degree do we really understand the physical nature of rockbursts?
- Are rockbursts still a major threat to underground mining?
- Can the phenomena that create the hazard be resolved by the process of proper scientific enquiry?
- Will mine owners consider it worthwhile to pursue the search for solutions if the cost of sustained research erodes shareholders profits significantly?

Posing the questions does not impose on the reviewer the responsibility of providing the answers. The questions are simply to indicate something of the motivation behind this bid to appraise the present status of the global mining community's need to understand, manage, control or mitigate the rockburst hazard.

In any such attempt to review progress, it is necessary to first appraise the background to the current situation, then

try to assess present shortcomings in practicable knowledge and finally give an indication of future needs. After more than a half-century of formal research and more than twenty-one years of RaSiM efforts to facilitate and stimulate a global search for solutions, the problem still exists! The sixth forum of RaSiM symposia seems an appropriate opportunity at which to attempt an overview of the state of knowledge in this challenging field of rockburst causes and their control.

From the start in 1982, RaSiM has attempted to provide a platform for discussion of rockbursts and seismicity-related problems in mining that would bring a broader, international perspective to the search for understanding. One main reason for hosting successive sessions of the symposium at venues in different parts of the mining world is the hope that sharing of experiences will allow areas of common approach to be discovered, for the mutual benefit of all participants.

It follows that there is a corresponding responsibility incumbent on any reviewer of the status quo, to make a serious attempt to avoid parochialism. This is very difficult to achieve, given the fact that the problem of rockbursts is not confined by geographic boundaries and that the problem affects mining communities of different language groups and cultures, in different ways.

In preparing this review some attempt has been made to avoid these difficulties. For reasons that may become apparent later, it is particularly difficult (in the case of a reviewer with such long and intimate involvement in the South African rockburst research effort) to avoid provincialism, prejudice and even self interest.

I trust that the reader will make due allowance for these factors. Hopefully, close involvement and long experience with the realities of the underground aspects of the problem may be beneficial. It enables me to bring into the review process insights and practical understanding that someone of greater academic ability may not possess because he is perhaps too remote from the realities of the problem.

## 2 BACKGROUND

### 2.1 History of Rockbursting

The earliest disastrous event that might now be classified as a major rockburst was probably that which occurred at

Altenberg tin mine in 1640. The tremor was felt in Dresden 45 km away and the collapse was so catastrophic that the mine was not re-opened until 1860\*. The Erzgebirge mountains and the nearby Ostrava-Karvina and Upper-Silesian coalfields were the 'birth places' where underground hard-rock and coal mining first developed intensively and extensively to become substantial industrial activities of Renaissance Europe. Considering the now-established tectonic complexity of the region, it is not surprising that problems of a geotechnical nature would have become apparent early on.

According to Rudajev (1993, p 157), 237 coal bumps were documented to have occurred in the Kladno black coal mines during the period 1880-1894. The first mechanical seismograph was installed at the ore mine Příbram in 1903. In 1929 a local seismic station was constructed to observe rockbursts in the Polish Upper-Silesian coal basin. This was expanded by a further four stations in 1950.

In North America, the first rockburst was believed to have occurred at the Atlantic copper mine in Michigan in 1904 – Bolstad (1990) and as early as 1928 in Canada. By the late 1930's in the Coeur d'Alene silver mining district in Idaho, and in the early 1940's in the Sudbury and Kirkland Lake areas of Ontario the rockburst problem was regarded as a serious safety hazard.

Severe rockbursting accompanied the deepening of the steep-vein gold mines of the Kolar field in Mysore, India from the beginning of the 20<sup>th</sup> century. As mining became deeper and more extensive, 'area' rockbursts caused widespread damage to main infrastructure e.g. shafts and deep footwall haulages as well as to the producing stopes. Many fatalities have resulted and costly damage experienced, even on surface – Krishnamurthy and Shringarputale (1990). Since the mines closed some years ago the problem no longer exists.

In Australia, rockbursting was first experienced as a significant but relatively infrequent problem in the Kalgoorlie district in the early part of the last century. During the last decade of the century, as the extraction of the deepest massive orebodies of the Mount Charlotte mine peaked, several very large mining-induced tremors were experienced. Six seismic events between  $M_L$  2.5 and  $M_L$  4.3 (Richter scale) were recorded – Hudyma and Mikula (2001).

As will be described more fully later in this review, the very deep and very extensive tabular mining of the South African gold fields has led to a far more severe and prolonged manifestation of the rockburst hazard than has occurred anywhere else in the world. Although the situation has improved very considerably in recent years, it cannot be claimed that the problem has been solved. It is felt by many that, to some extent at least, the position in recent years has improved because of the decrease in the total size of the mining industry and in the resultant intensity of total underground activity.

In the other major mining countries of the former USSR and the Peoples Republic of China, the extent of seismicity-related problems, including large area

collapses, has not been well documented in the past. Recently, through the activities of RaSiM, more information has begun to emerge.

In South America, rockbursts have been evident as a serious problem only during the last 15 years or so and mostly in the very large Chilean copper mine of El Teniente, as major production shifted from softer secondary ore to the harder primary zones of the massive orebody.

Elsewhere in South America, the only mine to have experienced significant problems was the Morro Velho gold mine which was one of the deepest mines in the world for some decades during the first part of the last century. The mine has recently ceased to operate and the rockburst problem has disappeared.

## 2.2 Official Recognition and Formal Research

With its history of close association with the earliest documentation of technological developments in mining (e.g. Agricola's *de re Metallica*), and as the birthplace of universities, it is very likely that Central Europe exposed its rockburst problem to academic scrutiny earlier than anywhere else.

It is not clear from RaSiM references however, just when the problem was officially recognised by state mining authorities or whether formal research structures or institutes were created. The first seismic network was established in the Upper-Silesian Coal Basin in the late 1920's. By 1988 there were 30 underground seismic networks, supervised by professional seismologists. Gibowicz (1990) has observed that Poland has more seismologists per capita than any other country!

Presently research is carried out by the Central Mining Institute in Katowice, at the Polish Academy of Sciences, the Academy of Sciences in Prague, Czech Republic and at universities in Kraków and Warsaw.

Bolstad (1990) noted that the earliest research in North America was started by the US Bureau of Mines in the late 1930's, has been in progress for 50 years and that the problem has not yet been solved. Swanson (2001) reports that the USBM was relieved of the responsibility of federal rockburst research in 1996 and the function of health and safety research in mining was assumed by the National Institute for Occupational Safety and Health (NIOSH).

According to Brady (2004) the Australian Centre for Geomechanics based at the University of Western Australia is the leading research group. The University of Queensland, the West Australian School of Mines in Kalgoorlie and other universities have also been involved in rock engineering and rockburst research.

In Canada, the first Canadian Rockburst Research committee was formed in 1939 under the direction of R.G.K. Morrison to enquire into the occurrence of rockburst problems in the Kirkland Lake area of Ontario. In 1942 an underground array of 100 short-range geophones was installed at the Lake Shore mine by Obert and Duvall of the US Bureau of Mines – Potvin and Hudyma (2001). A serious episode of large seismic events including a major fatal rockburst at Falconbridge Mine in June 1984 was followed about one month later, on the nearby Creighton mine, by the largest mine-induced event (Richter  $M_L=4.0$ ) recorded in Canada. This series of events led to the appointment of a commission of enquiry whose report eventually resulted in the creation of a collaborative rockburst research programme (CRRP) involving 6 mining companies and the universities of Queens in Kingston and Laurentian in Sudbury. Additionally, research into rockbursts is carried out by CANMET of the Department of Energy, Mines and Resources, Canada.

The problem of mine tremors was first recognised in South Africa with the appointment of the Ophirton Earth Tremors Committee in 1908 whose brief was to enquire into damage to houses on surface. Enquiry was broadened by further committees headed by the Government Mining Engineer in 1915 and 1924. Formal research, funded and coordinated by the entire gold mining industry, commenced in 1953 with a structured program of research carried out by the National Mechanical Research Institute of the CSIR.

\* Information imparted directly by a mine official to visitors to the mine (including the reviewer) after their participation in a conference of the Internationale Büro für Gebirgsmechanik, Leipzig, GDR, 1964

Currently, all research into rockbursts and other geotechnical matters affecting mine safety is coordinated by SIMRAC (Safety in Mines Research Advisory Committee), a tri-partite structure representing the mining industry, the state and the labour body.

### 3 DEFINITION AND CLASSIFICATION

It is readily apparent after even a brief scrutiny of the proceedings of the five RaSiM symposia that there is a very wide range of rock failure phenomena that is embraced by the umbrella term 'rockburst'. The range of magnitude, in energy terms, involved in the spectrum of events from superficial strain-bursting to the collapse of an extensive shallow tabular mine, can extend across 9 orders of magnitude – see Table 1. There are also a few different names or terms that may be used in various countries to describe what is essentially the same phenomenon, and sometimes the same word describes different phenomena.

**TABLE 1** Indicators of size range of seismic events

Richter Magnitude $M_L$	Kinetic Energy MJ	Explosive Equivalent <sup>1</sup> kg	Radius of Source Rupture <sup>2</sup> m
-1	0.002	0.04	0.8
0	0.06	1.2	2.6
1	2.0	40	8.5
2	60	1 200	26
3	2 000	40 000	84
4	60 000	1 200 000	270

Notes: 1 At 1% 'seismic' efficiency  
2 Brune model at 10 MPa stress drop

#### 3.1 Definition

That there is some degree of commonality in the broader perception of the essential nature of the phenomena collectively known as 'rockbursts' is evident in the etymology of the names commonly used in the western languages.

In English, the word 'burst' suggests a more violent process than 'rock fall' or even 'collapse'. The German term 'gebirgslage' (the strike of the mountain) and the French phrase 'coup de terrain' (the blow of the earth) similarly denote power and force. The Spanish name *estallido de roca* literally translates as 'explosion of rock'. All these derive from the obvious suddenness and destructiveness of a violent blow wielded by an unexpected force or an explosive disruption of a portion of the rockmass.

Probably rockburst researchers in most countries have developed their own definitions and classification systems for describing severity and type of damage. Most of these terms would have been descriptive and, in all likelihood, not based on any formalised system. Classification systems tend to categorise the phenomena into ranked intensity of damage, different area of location with respect to the mining geometry, or perhaps into phrases illustrative of modes of failure of the rock, e.g. splintering, spalling, crush-bursting, strain-bursting etc. Devising and formalising a descriptive terminology in this way is useful and necessary within a local area or a country or even a community concerned with a particular type of mining operation or the exploitation of a particular mineral. However such systems are probably not sufficiently precise in terms of fundamental physics or mechanics to be of much use as a basis for structuring and guiding formal research.

Most persons involved with the problem would agree that it would be desirable to have a common terminology and an accepted, standard definition. One of the benefits that might

be expected from even a loose association of minds meeting across national borders such as RaSiM affords, could be the development of a common understanding of terminology and a proper definition of the term *rockbursts*.

Regrettably, the international community of engineering researchers or more formal scientific researchers who have been involved with the problem of understanding and controlling rockbursts, have not been able to achieve this initial step of agreeing on an acceptable definition or a common terminology. Surely such a lack of a shared 'language' must have hindered the proper communication of ideas.

There has been at least one such attempt made (as far as this reviewer is aware) to create a working commission under the auspices of the International Society of Rock Mechanics (ISRM). The initiative was launched by the South African National Group on Rock Mechanics (SANGORM) in 1994 a short while before the ISRM International Conference in Tokyo in that year. Certain proposals were put forward and an interim working group was formed but, sadly, unanimity was not reached and the initiative foundered.

Some of the definitions that have appeared in contributions to the five symposia are repeated here to illustrate the extent of the common understanding that does exist:

Scott (1997 p311): "...a rockburst is defined as the sudden and sometimes violent release of accumulated energy when a volume of rock is strained beyond its elastic limit. Rockbursts can be classified as strain, crush or slip. Strain bursts are small and localised, while crush and slip bursts can cause extensive damage to drifts and stopes".

Working with a completely different objective, namely to find discriminating criteria to distinguish between underground nuclear test blasts and large rockbursts, Bennett et al. (1997) define a rockburst more broadly as "... any type of stress-release phenomenon which has been induced by mining activity and which results in emission of seismic signals".

Gibowicz has, on occasion, simply referred to rockbursts as "... violent failure of rock that results in damage to excavations".

In South Africa it has been thought helpful for the understanding of the problem, to define two terms to, essentially, distinguish the 'cause' and the 'effect'. A seismic event is considered to be the "... transient energy released by a sudden fracture or failure in the rockmass which results in the emission of a seismic vibration transmitted through the rock". A rockburst "... is the significant damage caused to underground excavations by a seismic event".

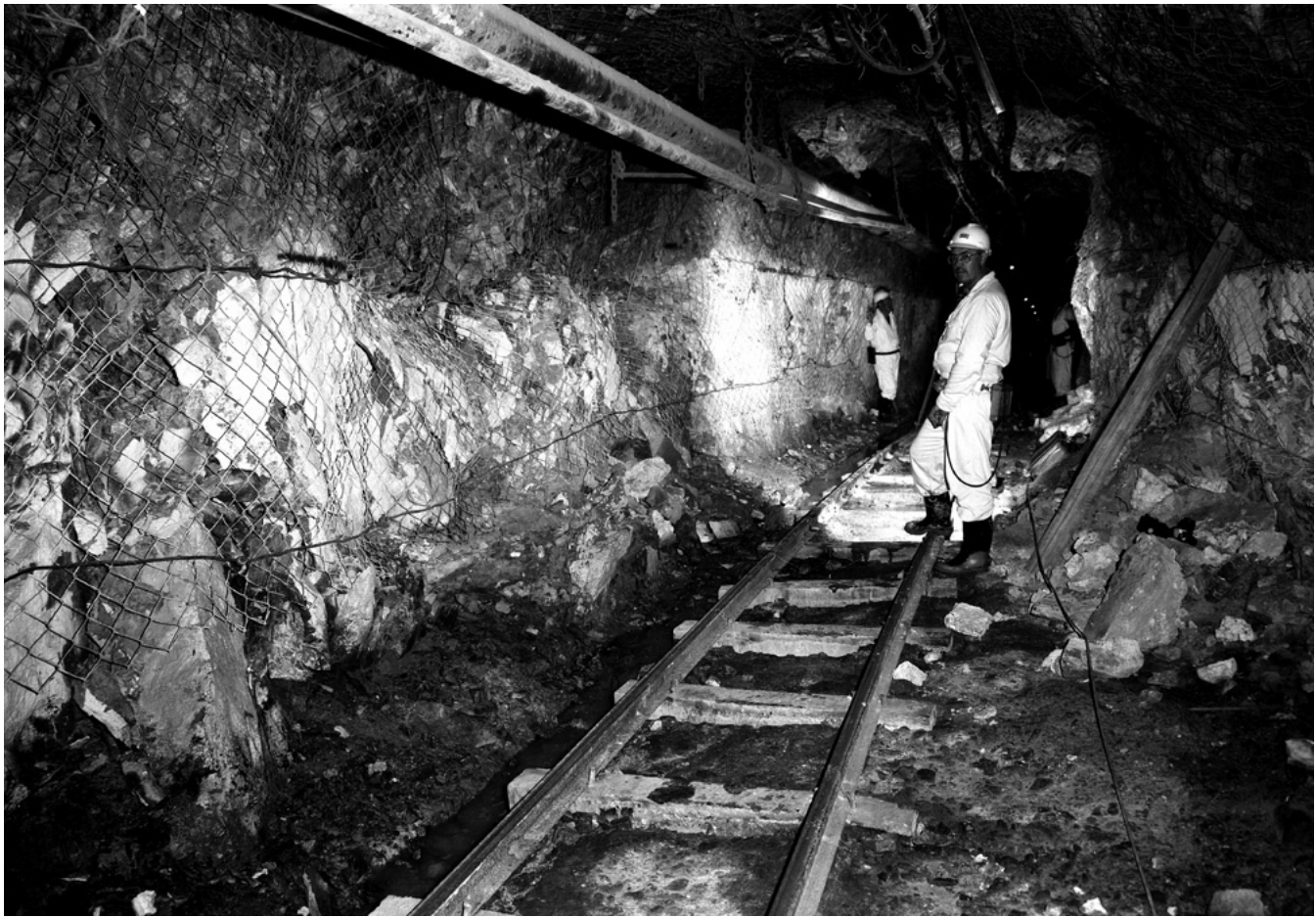
This definition is considered useful because it is not constrained by the magnitude of the seismic event or by whether it is natural or induced. The use of the adjective "... significant ..." allows attention to be focused on whatever level of damage is considered to be importantly disruptive to the successful operation of the mine (or facility).

Since the reader of this review needs to understand what meaning and scope the reviewer has in mind when dealing with his topic, it is necessary for the reviewer to adopt a definition and use a particular terminology even if it is one which does not have universal acceptance. For the purpose of this review then, the sense of the meaning outlined above will be intended unless mentioned otherwise.

#### 3.2 Classification

The very large energy range (9 orders of magnitude) presently embraced in the word *rockburst* suggests that it might be desirable to circumscribe, to some extent, the full scope of where and when it is appropriate use the term. The reviewer feels that the lower end of the scale may perhaps be limited by classifying damage that is essentially confined to the immediate surface of the wall rock involving splintering or spalling of only a few centimetres in thickness, into a separate





**FIG. 1** View along tunnel at trace of intersection with the Brand fault, where the maximum observed slip of almost 400 mm occurred in January 1989. Lesser amounts of slip were observed where the fault was intersected by other tunnels at intervals along a total of 2 km of strike distance. The single 'step' displacement (downward toward the camera) is delineated by the off-set of the painted grade-line bounding the white-painted lower portion of the side wall. Most note-worthy is the lack of significant damage to the sparsely-supported tunnel walls after an event of Richter  $M_L = 4.8$

category. The term 'strain-bursting' is often used in South Africa to denote such minor, superficial effects. Table 2 gives a frame-work of names, mechanisms and magnitudes that has been suggested by Ortlepp (1997) as a useful classification for the South African situation.

There is another distinct class of violent events, confined largely to certain coal mines and tabular mining of evaporate deposits, which are generally not regarded as rockbursts and which, it is suggested here, merit a quite separate classification. These are phenomena where considerable volumes of the coal or ore mineral (and sometimes country rock) are ejected violently in the form of dust or fine particles, leaving behind a conspicuous cavity. The important distinguishing feature of these *outbursts* is that they are invariably accompanied by large volumes of high pressure gas – Paterson (1990).

Proper rockbursts in coal mines are usually largely free from accompanied emission of gas. In gas outbursts fine coal is ejected, often from a conical depression, but the major part of the energy released is liberated as kinetic energy as gas changes from an absorbed state to a free gaseous state.

Gas outbursts have also been observed in salt, potash and other evaporates. Rock outbursts are similar phenomena which occur in porous sandstone strata close to coal seams. These have caused major problems in coal mines in France, Nova Scotia and Japan – Sato and Itakura (1990). Ortlepp (2001) has described an isolated instance of a similar nature

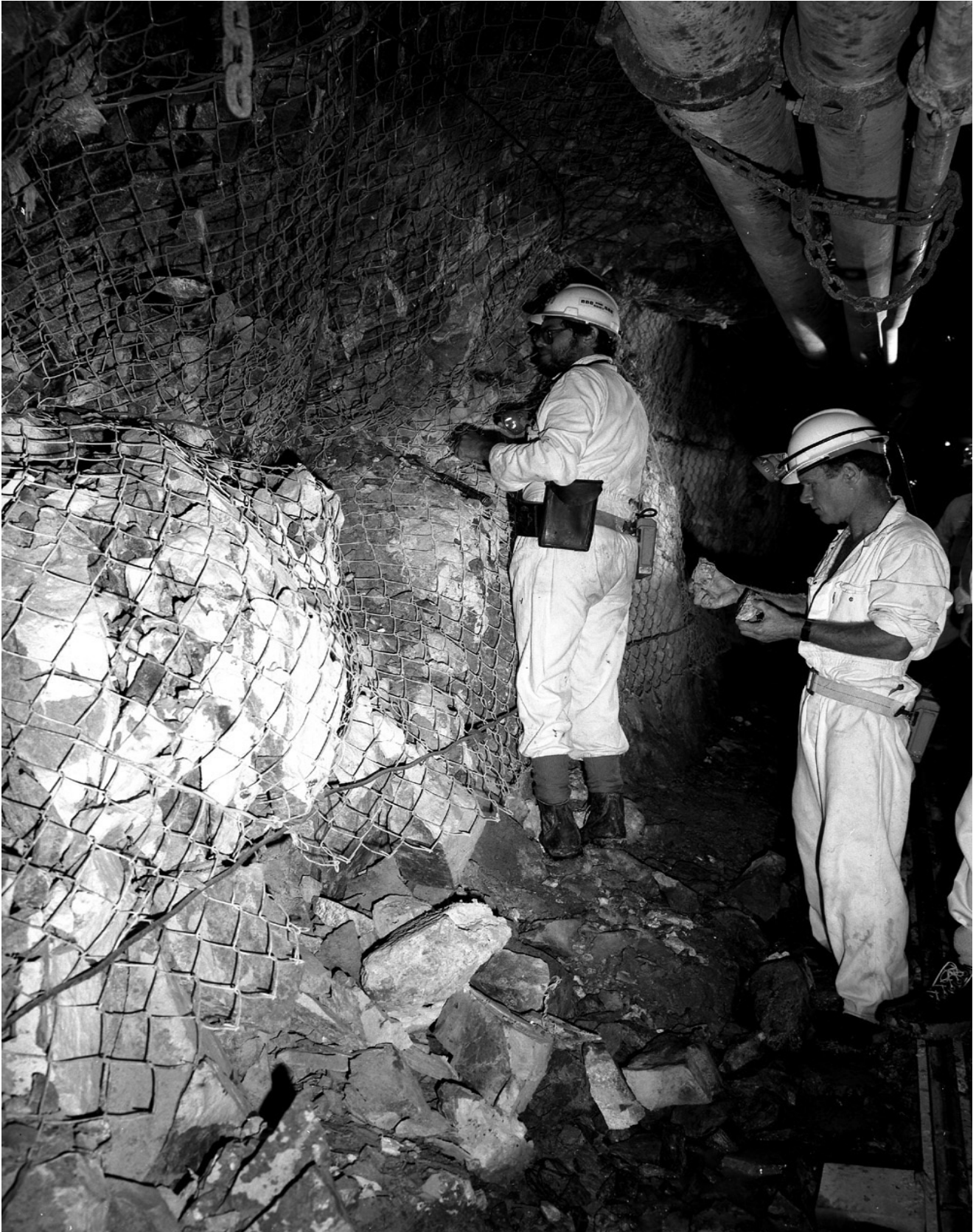
in a South African gold mine. Importantly, very little seismic energy was emitted into the rockmass and the incident was not considered to be a rockburst in the normal sense.

At the upper end of the spectrum of damage, is the catastrophic collapse of a large section of a mine or a complete mine. A special descriptive term is certainly warranted for disasters of such magnitude. Several of these have been referenced in papers of the five RaSiM proceedings, and some of them are described below. The term *mine-quake* which has been used by Fernandez and van der Heever (1984), gives an appropriate sense of the extreme magnitude and the possibility of substantial damage on surface which is often experienced with these events.

The most dramatic of recent occurrences of this kind was the collapse at the 'Ernst Thälman' potash mine at Volkershausen, GDR on March 13, 1989 which resulted in a seismic event of  $m_b = 5.4$  – Bennett (1997). The largest rockburst in North America resulted from the collapse of the Solvay trona mine in Wyoming on February 3, 1995. According to Bennett, both of these incidents were accompanied by subsidence of the surface by amounts averaging between 0.5 m and 1.0 m spread over extensive areas of two to several km<sup>2</sup>.

Russia has also experienced large 'rockbursts' of this kind. The largest of these occurred on January 5, 1995 at the Solikamsk-2 potash mine in the Western Urals – Malovichko (2001). The resulting earthquake had a magnitude of  $m_b = 4.7$  and was accompanied by subsidence of the surface of up to 4.5 m over a 600 m x 600 m area.





**FIG. 2** Up close and contemplative! Gerrie van Aswegen and Art McGarr are shown engrossed in the examination of the source region of a 'gentle' mine-induced earthquake. The dark mark level with Gerrie's left shoulder is the original red paint of the tunnel grade-line. The continuation of the paint line on the down-thrown block (about level with the top of his note-book pouch) is obliterated by the damage to the rock surface. Photographs are by Dave Ortlepp

**TABLE 2** Suggested classification of seismic event source

Rockburst Type	Postulated Source Mechanism	First Motion from Seismic Records	Richter Magnitude $M_L$
Strain-bursting	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	-0.2 to 0
Buckling	Outward expulsion of larger slabs pre-existing parallel to surface of opening	Probably implosive	0 to 1.5
Pillar or face crush	Sudden collapse of stope pillar, or violent expulsion of large volume of rock from tabular stope face or tunnel face	Possibly complex, implosive and shear	1.0 to 2.5
Shear rupture	Violent propagation of shear fracture through intact rockmass	Double – couple shear	2.0 to 3.5
Fault-slip	Sudden movement along existing fault	Double – couple shear	2.5 to 5.0

There is little difficulty in forming a broad understanding of this type of ‘rockburst’ and, conceptually at least, in finding the solution – the initial design must ensure a regular layout of large barrier or regional pillars of adequate size, spaced at sufficiently close intervals.

For the purpose of this review the three types of phenomena discussed above will not be classified as rockbursts.

#### 4 SEVERITY OF THE ROCKBURST PROBLEM – THE GLOBAL PERSPECTIVE

The existence of RaSiM is essentially an expression of the belief that communication between the different mining communities that are threatened by the hazard of rockburst, may assist in understanding the problem. Obviously the severity of the problem varies from country to country and it may be useful to view it in broader perspective. This can be done in two ways. Firstly, by scanning the proceedings of the five RaSiMs held so far, some idea can be formed of the perceptions of the problem as projected by the authors from the various countries, and the number of papers submitted gives an indication of how serious the problem is thought to be. The second approach was to make direct contact with individuals who were believed to be in a position to provide special insight. In a few cases this was successful but generally it was not, probably because the process used did not allow sufficient time for proper communication. The perspectives that follow are influenced, to some extent at least, by the reviewer’s interpretation of incomplete information.

##### 4.1 Central Europe

One solid indication of the seriousness with which the rockburst problem has been viewed in Poland is provided by the support they have given to RaSiM. Polish contributions to the last five symposia have included 42 papers of which 2 have been keynote addresses.

From an unpublished note prepared by Professor Stanislaw Lasocki (private communication 2004), the following statistical picture emerges. Of 42 active coal mines which produced 100 million tons in 2003, 28 are endangered by rockbursts. In the last 20 years, 190 rockbursts caused 122 fatalities. Although production had declined considerably from 190 million tons in the late 1980’s, the reduction in the incidence of rockbursts was less than proportional.

Nevertheless a drop to less than 5 per annum is considered to reflect the success of more recently introduced preventative strategies. More than 1,000 ‘strong’ seismic events (greater than  $10^5$  J or  $m \leq 2$ ) are recorded annually.

Mutke and Stec (1997) provide further detail from records maintained by the Central Mining Institute since 1950, revealing that the largest events have energy magnitudes of up to  $10^{10}$  J. Between May 1992 and January 1996, 15 events

between  $M_L$  2.2 to 4.0 ( $3 \times 10^9$  J) occurred of which 9 caused damage underground and 3 caused widespread but slight damage on surface.

All three copper mines in Poland are seismically active with between 400 and 700 strong events ( $\geq 10^5$  J) occurring each year. The number of rockbursts which resulted from this level of activity is 61 over the last 20 years. According to Butra et al. (2001) “... bumps have become the major hazard facing the LGOM basin deep copper mines”.

In the Czech Republic coal mining started in the Ostrava-Karvina Coal Basin more than 200 years ago. The first reports of rockbursts were dated from 1912, and more than 450 rockbursts have occurred since then. Regular communication and cooperation is maintained between people and organisations concerned with rockburst research and control in Poland and the Czech Republic.

##### 4.2 Russia

Two papers from Russian contributors first appeared in the proceedings of RaSiM4 in 1997 and 6 more in RaSiM5 in 2001. Because of difficulties in language and differences in definition, it is difficult to form any kind of picture of the situation in that vast country. Lasocki, in his note referred to above, mentions that rockbursting mines in Russia are often located in areas of natural seismicity. This has led to recognition of two types of incidents referred to as *tectonic rockbursts* and *mining-induced earthquakes*. The event most frequently referred to was a *tectonic rockburst* of magnitude 4.7 which caused extensive surface collapse over a potash mine in the Upper Kama district in the Western Urals.

Mining-induced earthquakes in Khibiny Massif apatite area in the Kola peninsula had magnitudes up to 4.3 – Kozyrev et al. (2001). Kozyrev expressed the opinion that “... to control rock pressure at depth is one of the most acute and complicated problems of modern mining science and practice”. He regarded the “... hazardous events as ... fraught with great material and human losses”.

The formal structure responsible for coordination of research in mining safety is the State Mining Technical Watch (Gosgortekhnadzor). Any rockburst causing casualties is investigated by a commission appointed by this body. Research is conducted by institutions such as the Russian Academy of Science, VNIMI and the Mechanical Engineering Institute – Linkov (2004). Rockbursts are now not regarded as a significant problem because of efficient measures developed previously and now being applied. In Linkov’s view there are still some shortcomings in present knowledge stemming from inadequate understanding of truly dynamic rockmass behaviour and dynamic damage. More effort is necessary to bring together computational rock mechanics and quantitative seismology.



### 4.3 South Africa

In no other mining country has the rockbursting problem been anywhere near as severe as in the South African gold mines. In few other countries has a formal industry-wide research endeavour been in place for as long as half a century.

Whether the research has been sufficiently well-funded and well-motivated is open to debate. Certainly some of the effort has been unwavering and all of it has been earnestly intended. Probably more specific and fundamental understanding of the problem has been gained than elsewhere in the mining world. Improvements are discernable, but in no way can it be claimed that the problem has been solved.

Amongst South African researchers there was an early perception of how difficult the rockburst problem can be when mining is deep and very extensive laterally. Because of this, it was decided to determine to what extent there was a commonality of interest in tackling the problem.

A symposium on rockbursts and seismicity in mining was accordingly organised and held in Johannesburg in 1982. Sufficient interest was shown by engineers and scientists from other countries who attended, in some cases despite political difficulties, that it was deemed to be worth repeating as an international meeting every four years. Thus was RaSiM born.

The exceptional severity of the rockburst problem in South Africa is better understood when viewed in the light of the great size of the gold mining industry. At peak production in 1970, one thousand metric tonnes of gold was produced by a total labour force of 416 000 people. A total area of 28 km<sup>2</sup> of tabular orebody was mined from an average depth of 2000 m below surface during the year.

Twenty years ago, because of reduced ore grade, total output had fallen to some 620 tonnes of gold. This required the efforts of 477 000 people. During that year, a total of 129 lives were lost in rockburst accidents - an annual rate of 0.27 fatalities per 1000 employed.

Comparable data for year 2003 are 311 tonnes of gold from a labour force of 183 000 that suffered 37 fatalities as a result of rockbursts - a rate of 0.20 per 1000 per annum. From these figures it can be seen that there has been some improvement despite the unavoidable trend of mining difficulties inherently increasing with increasing depth.

Another aspect of the problem is experienced uniquely by the South African gold mining industry where it often happens that one continuous orebody is exploited by several contiguous mines. Consequently a very large area of the earth's crust is affected. Large faults with lengths of tens of kilometres are sometimes re-activated to slip by amounts of a few hundred millimetres, to create seismic events of up to Richter magnitude 5.1- Fernandez and v d Heever (1984). Very occasionally, significant damage to surface buildings has resulted.

The frequency of smaller, but nevertheless significantly large, induced 'earthquakes' and the relative accessibility of the source faulting, has led to a suggestion that South African gold mines could be used as an earthquake research 'laboratory'. Sophisticated research by a Japanese institution has been in progress for some years - Ogasawara et al. (2001). A larger coordinated endeavour is presently being planned by a USA-led group of world-based crustal seismologists.

Applied research into the problems of rockburst causation and their damaging effects has been in progress in South Africa in a formal, organised way for more than 50 years. Impressive developments in sophisticated seismological monitoring have been made in the past two decades, and most present deep-level mining is carried out under close seismic surveillance. Arising out of these efforts, relatively effective layout strategies have been devised and implemented to

reduce the incidence of large seismic events and a certain amount of success has been achieved in controlling rockburst damage by improved support design.

The Kaap-Vaal craton is a very stable area and natural earthquakes are virtually unknown. Based on a study of the national records of the SA Council for Geosciences, Ortlepp (2003) showed that only 8 earth tremors of  $M_L$  3.5 to 4.0 which were more than 30 km from the nearest mining activity, had occurred during the previous 50 years. In all probability these could be regarded as neotectonic or natural in origin. During the same period 370 events in the same size range were located within the mining areas.

### 4.4 Canada

The eastern part of Canada is characterised as a low to moderately active earthquake region. In the period 1984 to 1987, Geological Survey Canada (GSC) reported 46 small earthquakes up to magnitude 3.6 in north-eastern Ontario - Wetmiller et al. (1990). In the same period GSC analysed more than 250 rockbursts ( $M_L$  1.5 - 4.0) of which 6 were between 3.5 and 4.0. It would appear that the possibility of a tectonic influence in rockburst causation cannot be dismissed entirely.

Historically, the problem of rockbursting has always been regarded as a severe one with potentially calamitous consequences. On more than one occasion a complete mine has been lost - the most notable being the Cumberland No. 2 mine in Springhill, Nova Scotia in 1958 when 75 workers died - Notley (1983). The event of June 1984, which caused 4 fatalities, led to the closure of the Falconbridge mine in Sudbury and to the re-structuring of rockburst research in Ontario province. Outside of Ontario, mine-induced seismic activity has been a concern in the potash mines of Saskatchewan and in the copper mines of New Brunswick.

### 4.5 USA

Large seismic events have caused ground control problems in at least two coal-mining regions in the USA. In the Wasatch Basin in Utah 30 events between  $M_L$  3.0 to 3.8 were recorded in 35 years. Bennett (1997) recorded 19 bumps of magnitude  $M_L$  2.3 to 4.3 in 2 years at a single mine in Kentucky. He also analysed seismic data from the largest rockburst to have occurred in North America - the collapse of the Solvay trona mine in Wyoming in February 1995.

In hard rock mining, most activity appears to have been experienced in the Coeur d'Alene district of Idaho where rockbursts were first reported in 1930, according to Bolstad (1990). In the period 1986 to 1990 rockbursts caused 23 injuries to workers and 6 fatalities. The estimated cost of rockbursts ranged from \$7 to \$15 per ton of ore or between 8% to 18% of total mining costs.

### 4.6 Australia

Rockbursting had been experienced in the Kalgoorlie district since early in the 20<sup>th</sup> century with a fatality and several injuries attributed directly to a 'severe earth tremor' in 1917 - Potvin and Hudyma (2001). Since 1970 the Australian regional seismic network had shown Mount Charlotte mine to be the source of some 20 seismic events between Richter magnitude  $M_L$ =2.0 and  $M_L$ =4.0. However, until the mid-1990's the problem associated with rockbursts and seismicity was not perceived to be severe enough to warrant seismic monitoring. Since that time sophisticated monitoring systems have been installed on several mines in the Yilgarn block in Western Australia and at Mount Isa, Broken Hill and Northparkes in the eastern half of Australia.



**TABLE 3** Summary of symposia

RaSiM	Year	Venue, Host Country	No. of Countries Contributing	No. of Papers	Theoretical, Analytic, Laboratory	Practical Applied, Descriptive	Relevant to Rockburst Mechanism
1	1982	Johannesburg South Africa	9	36	17	19	6
2	1988	Minneapolis USA	9	60	40	20	8
3	1993	Kingston Canada	12	71	37	34	15
4	1997	Krakow Poland	13	69	37	32	6
5	2001	Johannesburg South Africa	15	79	36	43	16
Totals				315	167	148	49

Damaging rockbursts have caused serious disruption of production and some fatal accidents in Western Australia and the problem is viewed in a serious light by state authorities and mine owners.

#### 4.7 Japan

The dangerous phenomenon of coal outbursts is closely linked to rockbursts in coal-mine long-walling. These problems have been studied in Japan by Kaneko et al. (1990) and Fuji and Sato (1990). The related problem of rock outbursts, which may be seen as high-volume, low-energy 'aseismic' events (see Ortlepp 2001) has been studied by Sato and Itabura (1990).

From a national perspective rockbursting cannot be perceived as a significant problem but there is another reason why scientists from Japan have maintained an interest in the study of rockbursts. Ogasawara (2001), in a project funded by the Ministry of Education, has made sophisticated strain measurements in the vicinity of 'active' faults in South African gold mines in the belief that *"...our attempt will contribute not only to the study of rockbursts or mine tremors but also to the study of natural earthquakes"*.

#### 4.8 India

The Kolar Gold Fields in Mysore state has long been known as a region subject to very severe rockbursting since the beginning of the last century – Krishnamurthy (2001). In the last few years underground mining has ceased and hard-rock rockbursts are no longer a problem anywhere in India.

#### 4.9 Chile

The only country in South America where rockbursts are known to have been a problem of any consequence, is Chile. Only one mine, the very large cave-mining operation of El Teniente, has experienced severe instances of damage. Seismically-related problems first became apparent in the early 1980's when mining of 'primary' ore commenced. Several large and seriously damaging rockbursts (with some of which the reviewer became professionally involved) occurred in the early 1990's. Very valuable insights into source mechanism were derived from studying details of the associated damage.

Based largely on understanding gained from a sophisticated underground seismic monitoring system, effective management controls have been instituted – Dunlop and Gaete (2001) but significant rockbursts still occur from time to time.

#### 4.10 China

In China it is recognised that the problem of rockbursts has been recorded little serious recognition to date but there is now a growing awareness of the problem in hard rock mines – Li and Guo (2001). There are some 33 coal mines where the hazard of rockbursts is significant: more than 2 000 damaging events have occurred since 1949 – Wu and Zhang (1997).

#### 4.11 Western Europe

With the decline in mining activity over the past decade or so in many countries of western Europe, rockbursting is no longer a problem in Britain, Germany and most parts of France. Somewhat surprisingly, considering the prevalence of strong, brittle rock and high horizontal stresses in the Scandinavian Shield, rockbursting does not seem to be a significant problem in mining in Sweden or Finland although Båth (1984) gives details of a  $M_L=3.2$  event at the Grängesberg iron ore mines in 1974.

### 5 RASIM SYMPOSIA

#### 5.1 Initial Purpose and Onward Development

At the outset the intention was to review progress that had been made in combating the hazard of rockbursts during RaSiM's 23 year life span. It is now clear that such an ambitious undertaking was not possible. One reason is that the published proceedings of the RaSiM symposia are not the only medium through which rockburst and related research results and developments are communicated; most serious work and significant 'break through' development is described in a number of technical journals. At best, the RaSiM proceedings can hope to give 'snapshot' glimpses every four years or so, of a complex road map of approaches to hoped-for solutions that have been adopted by particular individuals in different countries. In parts, these various approaches will run in the same direction, perhaps even converge towards a common recognised goal with, occasionally, a milestone of partial success achieved. Seen realistically, the reviewer will be fortunate, after scanning over 300 of these 'snapshots', to be adjudged to have picked out the most important main roads and to have illuminated some of the milestones.

Table 3, which summarises the growth of the five symposia that have been held so far, indicates the increasing participation of countries in them and, very broadly, attempts to give a sense of how the theoretical and practical approaches are balanced. In tables 4 to 8, the development of different themes is examined more closely.

It is perhaps important to compare actual achievement against the expectations of a quarter of a century ago. To

**TABLE 4 RaSiM1 – Johannesburg 1982**

	Theme Contributing countries	No. of Papers	Relevance to Rockburst Mechanism	Theory, Analytic, Laboratory	Practical, Applied, Descriptive
1	<b>Mechanics of Seismic Events and Rockbursts</b> RSA (3); USA (3); Poland, Sweden	8	4	5	3
2	<b>Monitoring of Seismicity and Seismic Networks</b> RSA (4); USA (3); Canada, France, Germany	10	-	6	4
3	<b>Coal Mining Bumps</b> Australia, RSA, UK, USA	4	1	-	4
4	<b>Rockburst Hazard Mitigation/Ground Control</b> RSA (3); Germany, UK	5	-	-	5
5	<b>Case Studies – Hard Rock</b> RSA (2)	2	1	-	2
6	<b>Strategies to Manage Seismicity and Damage</b> RSA (2); Poland, USA	4	-	4	-
7	<b>Geology, Laboratory Studies</b> RSA (2); USA	3	-	2	1
	Totals	36	6	17	19

Contributing Countries RSA (17); USA (9); Germany (2); UK (2); Poland (2); Australia, Canada, France, Sweden

**TABLE 5 RaSiM2 – Minneapolis USA 1988**

	Theme Contributing countries	No. of Papers	Relevance to Rockburst Mechanism	Theory, Analytic, Laboratory	Practical, Applied, Descriptive
1	<b>Mechanics of Seismic Events and Rockbursts</b> USA (7); RSA (3); Canada (2); France (2); Australia (2); Germany, Japan, Poland	19		14	5
2	<b>Monitoring of Seismicity and Seismic Networks</b> Canada (9); RSA (5); USA (4); Japan	19	-	16	3
3	<b>Coal Mining Bumps</b> France (2); Australia, Germany, USA	5	1	4	1
4	<b>Rock Stress, Structure and Mine Design</b> RSA (3); Australia (2); Canada (2); USA	8	3	2	6
5	<b>Rockburst Hazard Mitigation/Ground Control</b> RSA (4); USA (4); India	9	-	4	5
	Totals	60	8	40	20

Contributing Countries USA (17); RSA (15); Canada (13); Australia (5); France (4); Germany (2); Japan (2); India, Poland

aid the reader in making this evaluation, the reviewer offers some quotations from some of the key thinkers of the last two or three decades of the last century, as an indication of what the expectations might have been.

It is of some interest to see how the prescient thoughts of some of these individuals were expressed in forewords, prefaces and postscripts in the several proceedings.

In his foreword to the first RaSiM proceedings, Nick Gay, the editor, tells the story of how the idea of an international forum of rockbursts was conceived on Western Deep Levels gold mine in November 1980. *Luis Fernandez, the head of seismology at the SA Geological Survey, was reporting to an informal rockburst discussion group of rock mechanics engineers and mine seismologists on his recent trip to South America. Luis had attended the International Seminar on Prediction and Seismic Risk Evaluation in Lima, Peru. A bold prediction had been made that a large earthquake of  $M_L = 8.0$  would occur close to Lima within 6 months. This caused something of a furore at the time which even rippled out into diplomatic circles. The discussion*

*group, knowing that we were nowhere near able to even think of predicting rockbursts despite the recent acquisition of sophisticated underground monitoring capability, were sceptical, but, at the same time impressed and intrigued. We were suddenly aware of our lack of understanding of the physical processes involved. This awareness made Paul van der Heever suggest that there was much we could learn from seismologists working in the field of natural earthquakes and that we needed to meet with them.*

Twenty-two months later in September 1982, we saw the birth of the first RaSiM symposium

In his opening address to RaSiM1 in 1982 W W Malan, then president of the Chamber of Mines, rather optimistically suggested

“...that it will be possible to extend stoping operations to depths of more than 4 000 m – as is planned at mines like Western Deep Levels – without undue risk....”

With the gold price not having increased above levels of the early 1980's and with the reversal of the previous sustained



**TABLE 6 RaSiM3 – Kingston, Canada 1993**

	Theme Contributing countries	No. of Papers	Relevance to Rockburst Mechanism	Theory, Analytic, Laboratory	Practical, Applied, Descriptive
1	<b>Strong Ground Motion and Rockburst Hazard</b> RSA (9); Canada (6); USA (3); Poland (2); Australia, Germany	22	6	10	12
2	<b>Mechanics of Seismic Events and Stochastic Methods</b> Canada (6); USA (4); Poland (3); India (2); RSA (2); Australia, China, Czech Rep., France, Japan, UK.	23	6	13	10
3	<b>Monitoring of Seismicity and Geomechanical Modelling</b> Canada (10); RSA (7); Japan (2); UK (2); Australia, Chile, China, France, Sweden	26	3	14	12
	Totals	71	15	37	34
Contributing Countries		Canada (22); RSA (18); USA (7); Poland (5); Australia (3); Japan (3); UK (3); China (2); France (2); India (2); Chile, Czech Rep., Germany, Sweden			

**TABLE 7 RaSiM4 – Krakow, Poland 1997**

	Theme Contributing countries	No. of Papers	Relevance to Rockburst Mechanism	Theory, Analytic, Laboratory	Practical, Applied, Descriptive
1	<b>Mechanism of Seismic Events and Rockbursts</b> Poland (4); USA (2); Czech Rep, Germany, Italy, UK	10	4	7	3
2	<b>Monitoring of Seismicity</b> Poland (4); RSA (4); Australia, Canada, Czech Rep, Germany, Japan, USA	14	-	6	8
3	<b>Geology, Mining and Seismicity</b> RSA (5); Poland (3); Canada (2); Chile, Germany Ireland, UK, Russia	15	-	7	8
4	<b>Rockburst Hazard and Ground Control</b> Poland (9); RSA (5); Canada (3); China (2); Belgium, Russia, UK	22	2	9	13
5	<b>Induced Seismicity and Laboratory Experiments</b> Japan (4); Germany, Mexico, Poland, USA	8	-	8	-
	Totals	69	6	37	32
Contributing Countries		Poland (21); RSA (14); Canada (6); Japan (5); Germany (4); USA (4); UK (3); China (2); Czech Rep. (2); Russia (2); Australia, Belgium, Chile, Italy, Ireland, Mexico			

trend of a weakening of the local currency offsetting the low dollar gold price, the incentive for mining ever deeper in South Africa has, to a large extent, disappeared during the past two years. Unless there is a dramatic change in global economics in the next few years it is the regretful prognosis of this reviewer that mining will never be extended to below 4 000 m depth.

Horst Wagner, *Chairman*, SA National Group on Rock Mechanics, in his foreword to RaSiM1 said:

*“Rockbursts are the most serious and least understood problems facing deep mining operations all around the world. .... The time has come, therefore, to take stock of what has been achieved, to separate the promising from the less promising areas of research ... and to promote an international exchange of ideas and information”.*

In a preface published in the proceedings of the 1988 RaSiM2 in Minneapolis, Barry Brady (1990) observed that *“....The first major international symposium on mine seismicity and rockbursts was convened by the SAIMM in 1982 .... providing substantial benefits for the rock mechanics and mining communities .... a comprehensive review of the prevailing knowledge of rockburst mechanics and the relationship of rockbursts to natural earthquake mechanics”.* Brady noted advances in numerical analysis methods, seismological instrumentation and analysis of

seismic data. He expressed the opinion that it remained necessary.... *“to clarify the fundamental mechanics and to support subsequent development of reliable, routine mitigation measures in mining conditions identified to be burst prone. These include the mechanics of evolution of shear bands in rockmasses subject to brittle failure, the relative roles of velocity-dependent friction and displacement-controlled friction in unstable fault slip, and the demonstration of field techniques that may create unconditionally stable stope sites which would otherwise be burst prone”.*

In the same volume Paul Young (1990) stated that *“.... Future work should concentrate on a great utilisation of seismic data for rock mechanics design and numerical model validation and calibration. Seismic moment tensor methods could be used to provide a more rigorous analysis of source mechanisms. Research into tomographic imaging and attenuation methods should continue in order to provide suitable methods to fully characterise and model the medium in which seismic waves are generated and propagated as a result of a mining-induced seismic event. A significant emphasis should be placed on near-field propagation/ attenuation and the relationship between near-field amplitude and damage”.*

**TABLE 8 RaSiM5 – Johannesburg 2001**

	Theme Contributing countries	No. of Papers	Relevance to Rockburst Mechanism	Theory, Analytic, Laboratory	Practical, Applied, Descriptive
1	<b>Seismic Instrumentation and data analysis</b> RSA (2); France, Japan, Poland, USA	6	-	1	5
2	<b>Source and Damage Mechanisms</b> RSA (4); Poland (2); Australia, Canada, Israel, USA	10	9	6	4
3	<b>Induced and Tectonic Seismicity</b> RSA (2); Mexico, UK, USA	5	-	4	1
4	<b>Laboratory Studies</b> Germany (2); Czech Rep.; Poland, RSA	5	-	4	1
5	<b>Strategies to Manage Seismicity and Damage</b> RSA (6); China (2); Canada	9	-	5	4
6	<b>Case Studies – Hard Rock</b> Australia (2); Chile (2); India, Japan, RSA, Russia	8	2	1	7
7	<b>Case Studies – Soft Rock</b> Poland (4); Australia, Czech Rep., Russia, Slovenia	8	2	-	8
8	<b>Integration of Modelling and Monitoring</b> RSA (7); Australia (2); Poland (2); Russia (2); Canada, France, Israel	16	3	11	5
9	<b>Prediction Hazard and Risk Assessment</b> RSA (5); Poland (3); Russia (2); Australia, France	12	-	4	8
	<b>Totals</b>	<b>79</b>	<b>16</b>	<b>36</b>	<b>43</b>
Contributing Countries		RSA (28); Poland (13); Australia (7); Russia (6); Canada (3); France (3); USA (3); Chile (2); China (2); Czech Rep. (2); Germany (2); Israel (2); Japan (2); India, Mexico, Slovenia, UK			

## 5.2 Expectation and Achievement

A simple study of the bare statistics summarized in the above tables will reveal a strong and fairly steady growth in overall interest in the activities of RaSiM over the past 23 years. While this is reassuring in some ways, it does not necessarily reflect that commensurate progress in understanding has been achieved. There can be no doubt that spectacular advances have been made particularly in seismic monitoring and analytical modelling capability as part of the explosion in computer and electronic data acquisition and processing. But the nagging questions persist –are we that much closer to understanding the underlying physical phenomena? Have we achieved sufficient improvement in mine design and management strategy to be able to claim that the rockbursting problem is being controlled, contained or is close to complete solution?

In his preface to RaSiM4, Paul Young (1997) observed that “.....it is clear that the computer revolution has dominated the development of new instrumentation, allowing us to monitor mining-induced seismicity from the largest rockbursts to micro-cracking at the centimetre scale, with ever increasing resolution. However our progress towards understanding the cause and the fundamental mechanics of the process lags far behind our ability to monitor the symptoms of the rockburst hazard. Mining has overcome many of the technological challenges of excavating and extracting ore economically at great depth, but rockbursts remain one of the single most hazardous problems of deep mining in brittle rocks”.

In order to ensure progress in the future, Prof Charles Fairhurst in his preface to RaSiM3 (1993) stressed the need “.... to pursue vigorously.... the benefits of rendering the solid opaque earth more transparent with respect to the distribution of in

sity stresses and regions of potential instabilities due to mining.....” It is clear that Fairhurst perceived that significant progress would be the reward for sustained effort.

The quotes included in the previous paragraphs give some indication of the hopes and expectations of some of the pioneers of the time, most of whom are even now still actively searching for the ‘holy grail’ of adequate understanding of the rockburst mechanism.

## 6 APPRAISAL OF RASIM'S CONTRIBUTION TO KNOWLEDGE

In order to attempt an appraisal of the extent to which RaSiM has met those early expectations or, at least, managed to keep hopes and aspirations alive, the reviewer feels that it will be valuable to identify the main topics which define the thematic structure of the five symposia. Certain trends are clearly evident and are reflected by the repetition of the theme titles and by the number of papers devoted to each particular topic. The three themes most clearly discernable in all five symposia are identified below, with the average percentage of total papers devoted to each of them, indicated in parentheses:

- Mechanism of seismic events and rockbursts – (23%),
- Monitoring of seismicity and seismic networks – (25%),
- Rockburst hazard mitigation/ground control – (16%).

These themes maintain continuity of focussed attention to the greatest extent during the period of review. They are consequently endorsed as being the most important threads of logic and structure woven into the complex fabric of RaSiM's picture of the whole rockburst problem.

It is interesting to note that symposia 2 to 5 each identified these three themes as principal topics around which to



structure their sessions. They often used the same phrase or similar wording to describe their themes. RaSiM1 did not arrange their plenary sessions into identified themes but the papers appear, nevertheless, to be grouped into similar topics. The reader can easily discern groups that deal with source mechanisms, with seismic monitoring, with control measures, with case studies and with laboratory work.

If the reader were to scan through the names of the authors and the titles of the papers grouped in the three most important themes and the other topics such as physical/mathematical/analytical understanding, numerical modelling, mitigation and ground control he would see the same names appearing again and again. It is suggested that it is through the works of these familiar recurrent names that one could find a progression of knowledge and, hopefully, would be able to form an idea of the state-of-the-art in that particular aspect of the total problem.

The reviewer has been involved with RaSiM from the very beginning and has been fortunate enough to attend four of the five gatherings. He has been privileged to meet, at least, if not to know quite well, most of the individuals who have played important roles in the development of rockburst understanding. For these reasons it is hoped that the following selection of names may be a useful guide to others who have not been so fortunate. The choice of these names has been difficult and is unavoidably subjective. It is hoped therefore that other worthy individuals who have not been mentioned simply because they were not known, will be understanding and forgiving.

### 6.1 Mechanisms of Seismic Events

S.J. Gibowicz of the Polish Academy of Sciences is a name that recurs continually, right from the beginning, in the annals of the RaSiM community. He reflects the long history of involvement of Polish seismologists and scientists in rockburst research, applied and theoretical. Gibowicz together with his compatriot Lasocki of the Krakow University of Mining and Metallurgy, has ensured that Poland is one of the pillars of strength of the RaSiM movement.

In his keynote address at RaSiM2 (1990) he stated that *"...mine tremors were associated with movement on major geological discontinuities"*.

Art McGarr of the U.S Geological Survey in Menlo Park, California has been involved with the study of rockbursts in South African gold mines since early in his professional life, about 35 years ago. Amongst other accomplishments, he demonstrated in several ways the high degree of similarity between mining-induced seismic events and earthquakes. Based on this, he fostered an interest in mining-induced seismicity as a way of understanding earthquakes, amongst members of the world's earthquake research community. This interest is evidenced by work done by Japanese and Israeli scientists during the past few years – see Ogasawara et al. (2001) and Dor et al. (2001) – and is increasing with work planned by USA, Germany and continued studies by Japan. McGarr's contributions have been so significant and so sustained that he could deservedly be regarded as the 'father' of mine seismology in South Africa.

Another prominent name in the area of using seismology to understand rockburst mechanisms is that of Spottiswoode e.g. (1984), and with Andersen (2001). Gendzwil, Scott and Wong also figure amongst many others who have made contributions in this important activity.

Analyses by Bennett and McLaughlin (1997) of two of the largest mine-induced earthquakes, the  $m_b$  5.4 Völkershausen event and the  $m_b$  5.3 Wyoming trona mine collapse, showed that the gravitational potential energy released by the co-seismic subsidence of the undermined rockmass was

sufficient to account for all the seismic energy liberated. Thus no involvement of tectonic influences is suspected, or necessary. The mechanisms in both instances were strongly implosional.

On the other hand, the authors confirm that the large rockbursts associated with shear failure on faults traversing South African gold mines *"...have double-couple mechanisms similar to those found in (natural) earthquakes and may draw some of their energy from the ambient regional tectonic stress field"*.

The recognition of rejuvenated slip on an existing fault of great geological age as the source mechanism for large rockbursts first appeared much earlier than

the instances studied by Bennett and McLaughlin. Their paper was quoted because it neatly underlines the very important difference in mechanism (and in the nature of the hazard) between pillar-supported shallow tabular mines and deep mines – see again the reviewers comments in section 3.

In their RaSiM1 paper Fernandez and v d Heever tentatively associated a large (SAGS  $M_L = 5.2$ ; USGS  $m_b = 5.5$ ) 'mine-quake' that occurred in 1977, with a major fault in the Klerksdorp district.

Over the years and in many countries, early tentative belief turned into conviction. There would almost certainly be general agreement amongst all those names above, and including most other serious workers involved with the study of source mechanism, that fault-slip is the major component of deep-mine seismic events and that residual tectonic forces play an important role in some cases.

In several instances recently, studies have been made after major mine quakes in South Africa, of the amounts of movement visible on the main slip surfaces where the source fault is exposed in a mine tunnel – e.g. Dor et al. (2001). Figure 1 and 2 show details of the 1989 Brand fault which is listed in Dor's Table 1.

Detailed studies have also been made of the slip surfaces and overall structure of another type of 'fault-shear' event which is less common but in some ways more dramatic and revealing than those where existing geological faults have slipped – Ortlepp (2000), (2001). The reviewer believes this to be the only instance anywhere in the world where the source of a recent 'earthquake' has been exposed and explored.

### 6.2 Monitoring of Seismicity

As indicated by Potvin and Hudyma (2001), the use of electronic signal detection in underground mining to detect initial stages of fracture dates to 1942. However it was probably only when an extensive array of geophones was installed on East Rand Proprietary Mines (ERPM) in South Africa in the early 1960's by N G W Cook (1964), that the potential of seismic monitoring as a tool for understanding rockbursts was first realised.

The improvements in the technology since then have been dramatic and are well documented in the RaSiM proceedings. The various mining applications of the latest innovations of recording and analysis, can be found in the sections on monitoring of seismicity and seismic networks, in the last four symposia proceedings.

With only a superficial understanding of the underlying principles, the reviewer finds it difficult to make independent evaluations of the merits of the various systems which are available.

In the field of development and refinement of systems for monitoring seismicity in mines and in innovation in data processing, the name Aleksander Mendecki is pre-eminent. He acquired his education and early skills in his country of origin, viz Poland, but has since developed his career in South Africa, where many mines have benefitted from the installation of the ISSI system.

The other principal player in this arena has been Paul Young who was the editor of the RaSiM3 Proceedings, and also contributed to 7 co-authored papers in the same year. His major roles have been played out in Canada, separated by a significant return period in his home country, England. Important contributions have also been made in the fields of monitoring and data analysis by Lasocki, Kijko, Trifu and Swanson. Important contributions have no doubt been made by many others, whose names are not known to the reviewer.

As an initiator of important developments in processing and analysing seismic data, e.g. Andersen and Spottiswoode (2001, p.81), Steve Spottiswoode has been prominent since the very beginning. As an indication of the depth of his insight the following perceptive remarks (2001, pp. 371) are worth repeating.

*“After decades of limited interaction between the disciplines of numerical modelling of the behaviour of the rockmass around mines and the recording and analysis of seismicity, we are now faced with the realisation that both disciplines provide an incomplete and limited view on the likely response of the rock to future mining. In the case of modelling, uncertainties about the geological conditions and virgin stress are compounded by questions about the constitutive laws that are supposed to describe rock failure. Further technical and computational difficulties arise from the application of existing constitutive laws. Calibration of any modelling requires careful back-analysis using seismicity and other measures of stress or deformation. The rate of seismicity is generally proportional to the rate of mining, but cannot directly account for any changes in mining geometry or geology. There is a need for each of these disciplines, modelling and seismology, to adapt to one another in order to develop an integrated approach to mine design to control seismicity and rock bursting....”*

### 6.3 Strong Ground Motion and Rockburst Hazard

In this third theme the ‘cause-and-effect’ link between the powerful pulse of energy at the source of a large event and the possible devastation in the mine workings, becomes the centre of attention. The somewhat remote perspective of seismological science needs to find common cause with the urgent requirements of the rock mechanics engineer contemplating the damage. The challenge is to be able to visualise what actually happens at the origin and how the resulting liberated kinetic energy transmutes itself into tangible, sometimes catastrophic, damage of the wall rock of the excavation.

Perhaps the problem leaves the realms of the specialist and becomes more the province of general understanding and engineering intuition. Of course the laws of physics and the rigors of logic must still prevail to constrain extreme speculation. The software skills of the numerical modelling analyst will be even more in demand but must always meet the test of appropriateness. Perhaps it is here that the earthquake physicist is challenged to confront reality, and the insight of the experienced structural geologist becomes the crutch to keep the balance of all the specialists, and the creative spur to stretch the inherent conservatism of the ground control engineer. These roles have been played in exemplary fashion by Gerrie van Aswegen for nearly two decades.

Exploring the theoretical limits of strong ground motion is a challenge that has repeatedly been accepted by Art McGarr (2001) and he has presented strong arguments to back his estimates. Attempts have been made to record damaging wall rock velocities and accelerations, particularly in South Africa, but, by their very nature, these phenomena are extremely difficult to measure.

In the study of this unknown and almost completely ‘opaque’ region close to the source of large events, the

boundaries between specialist disciplines become blurred and perceptive contributions have been made by persons who may appear slightly out of place. Names like Charles Fairhurst, Alex Linkov, Barry Brady, J A Dubinski, and David Ortlepp may be seen to fall into this category.

Dubinski and Lipowczan (1997) have reported vividly on forensic-type medical analyses of victims who suffered fatal injuries in uncollapsed, well supported roadways that showed little signs of damage after major rockbursts. It was clear that the deaths were the consequence of severe accelerations resulting from excessively strong, near-source ground motions.

Photographs 3 and 4 show incontrovertible evidence of extremely high-velocity rockmass displacements accompanying a catastrophic rockburst in a South African gold mine – Ortlepp (1984), (1993).

### 6.4 Other Themes

There are obviously many other important topics where understanding is not yet adequate and without which the holistic treatment of the total rockburst problem is not possible.

In the more clearly distinct categories of rockburst mitigation/ground control where a broader understanding of rockburst mechanism coupled with experience of practical mining reality is required, the names of Peter Kaiser, Doug Morrison, David Ortlepp, Dave Hedley, Ted Williams occur repeatedly.

Geological structure has a critical influence in determining the location, magnitude and nature of induced seismicity, particularly in South Africa where important contributions have been made by Nick Gay, Chris Roering, Paul vd Heever and, particularly, by Gerrie van Aswegen.

The enormous advance made in computer hardware and software during the past two decades has resulted in substantial progress in numerical modelling used as an analytical tool to help determine the rockmass response to mining-induced stress changes. Noteworthy achievements in this area are due to the efforts of Steve Crouch and Peter Cundall in the early days and, lately, Terry Wiles who has possibly now taken over the role of pioneer.

In his seminal paper with Lachenicht and van Aswegen (2001), Terry Wiles makes the visionary but, at the same time, perceptive and cautionary remarks:

*“Deterministic models can be used to make consistent reliable predictions. Many rockburst mechanisms are understood and can be simulated. Deterministic modelling can be used to determine the circumstances required for a rockburst to occur. Certainly no one would deny that ultimately, a rockburst is a deterministic event. Nevertheless, deterministic models do not seem to be able to predict when a rockburst will occur. There can be little doubt that, as in every other science and in virtually every human activity, the advent of everyday computers followed closely by an entirely new culture of numerical modelling has brought great advances in the understanding and control of rockbursts. However the deterministic solution of brittle rock failure remains elusive.*

*The difference between reality and what one believes one knows about the exact physical nature of the rockmass, makes the prediction of when failure will occur currently impossible.*

*It remains true that, as in most other fields of geosciences, the use of numerical modelling in the area of rockburst problems must be cautiously evaluated. The model must be appropriate, particularly in terms of the mode of failure that actually occurs being recognised by the criterion of failure used in the model. Also the choice of values for the parameters describing the response of the materials and the structures must be honest and realistic”.*



**TABLE 9** Less popular, but still important, topics

Topic	RaSiM No	Page no. of first page of referred paper					Total papers in topic	Percentage of total symposia papers
		1	2	3	4	5		
		1982	1988	1993	1997	2001		
<b>Mine design</b> Including stope layout and sequencing		235 245 251	335 337 349	327	167	337	9	2.8%
<b>Ground Control</b> e.g. Support design, backfill		209	363 406 421	13 75 117	337 355	197 229 263 443	13	4.1%
<b>Prevention</b> e.g. Pre-conditioning, water-infusion etc.		229	377	29 35	267		5	1.6%
<b>Prognosis and Prediction</b>		297 317	304		317 325		5	1.6%
<b>Phenomenological Studies</b> Including case studies, observation of damage and inference of source		165	323 401	101 111 129 267	223 377	43 53 59 109 237	14	4.4%
<b>Totals</b>		<b>8</b>	<b>10</b>	<b>10</b>	<b>8</b>	<b>13</b>	<b>46</b>	<b>14.5%</b>

## 6.5 Summary Assessment

This review has been an honest attempt to give some kind of overview of how the RaSiM forums have reflected global progress in understanding of rockbursts during the last two decades. There is little doubt that it is a somewhat fragmented and discontinuous image and perhaps lacks balance. On the other hand, it is hardly possible to form a balanced picture from such a large number of disparate ‘lenses’ and ‘prisms’ assembled in the 315 papers of the five symposium proceedings. If the reader were to attempt to assemble his own cameo sketch from only those authors whose names are mentioned in the preceding section, it would still not be an easy task because some 114 papers are included. Hopefully however, at the end of the effort, the determined reader would have gained a reasonably comprehensive and soundly-based overall appreciation of RaSiM’s value, more easily than if he had to tackle the entire offering, unaided.

## 7 PRÉCIS OF THE PRESENT STATE OF KNOWLEDGE

From the appraisal of the preceding section it seems that the three main themes have received at least a fair share of the contributors’ efforts in terms of the number of papers devoted to each. Before assessing the overall state of present knowledge as reflected by the five symposia it is perhaps useful to show how much attention the other topics have received. This is displayed in Table 9.

It is clear that some topics appear to have received considerably less attention than the three principal themes discussed at some length above. Particularly conspicuous by their absence are what might be termed ‘phenomenological studies’, i.e. those that try to understand rockbursts by making careful observations of the damage and all the attendant circumstances, and then try to deduce useful inferences regarding mechanism and cause-and-effect.

Perhaps these other topics are perceived to be less important, or more difficult, or perhaps there is still insufficient proven understanding of the fundamental physics of the source mechanism and the mechanisms of damage to encourage

speculation. It is likely that all three reasons play a role, to some degree, in inhibiting progress. Moreover there is little doubt that some of the important links that are missing in an otherwise coherent chain of cause-and-effect, still need to be identified.

Whatever the reasons may be, the reviewer feels that it is disappointing that relatively little effort has been made in the direction of direct observation and in the practical application of new technology. To some extent, the lack of overall progress must be due to this lack of balance.

There is a fairly widely-held view that earthquakes and rockbursts share so many similarities that they may be seen as two parts of the same broad spectrum of phenomena. Most, if not all, of the main-stream luminaries mentioned earlier would support this view. In mine-induced seismicity, the double-couple shear-slip mechanism dominates. Implosive events have been carefully studied – Wong and McGarr (1990) – and there is still some ambiguity about the interpretation. It is the opinion of this reviewer that, apart from the case of total mine collapse as discussed in section 4, the implosive-type rockbursts represent a relatively less important rockburst threat to underground mines.

It is necessary to emphasise that both the small ‘superficial’ rockbursts such as ‘strain bursting’ or buckling of thin slabs – Bardet (1990) and Dyskin and Germanowich (1993) – and the largest mine collapse-type earthquakes are, simultaneously, both *the cause and the effect* of the event. Both are almost certainly *implosive* in character and the source mechanism is, at the same time, the damage mechanism. In each case there is one phenomenon and, in a sense, there is no mystery. The event is always accompanied by damage – in the large events it is often catastrophic.

On the other hand, all slip-type events are more complicated and the indirect cause-and-effect relationship of large rockbursts is usually clouded by a great deal of mystery. The magnitude of a fault-slip event can be very large, of the same order as the mine-collapse event. But the fault-slip event does not necessarily cause damage or, more often, the damage

is trivial compared with the enormous amount of kinetic energy released into the rockmass. Figures 1 and 2 illustrate this paradox.

The distinction between the two sets of phenomena is not trivial, and neither is it pedantic. It underlines the fact that, as with crustal earthquakes, recognising that the inelastic deformation is essentially defined by slip on a mostly flat, planar surface does not mean that understanding of the phenomenon is correspondingly simple.

Thus a fault-slip type mechanism lies at the origin of most significantly large, damaging mine rockbursts. This fact was already known to some of the leading thinkers twenty-five years ago but, importantly, has since been repeatedly confirmed, refined and its implications examined in detail. Mine layout design, particularly in tabular mining, now recognises that the presence and location of major faults and dykes is all-important in determining stoping layout and sequencing. Attempting to avoid these features or leaving strategic pillars to control their movement are strategies often employed, usually with success. More imaginative approaches aimed at mobilising and relaxing faults by fluid injection or explosion have been suggested. Greater understanding of the mechanism of slip is clearly required before the effectiveness of such measures can be judged or the possibilities of identifying precursory activity that might make prediction feasible, can be contemplated. More profound insight is required in the following aspects:

- Slip velocity – is frictional resistance constant or does displacement -, or velocity-weakening occur ?
- Strong ground motions – how do near-source values, particularly PPV, relate to fault inhomogeneities?
- ‘Site-effect’ – how does the transient stress wave interact with the stress state and the fracture state of the excavation surface?
- Damage mechanism – how do the above interactions manifest themselves as ejection velocity or convergence velocity of the wall rock?

The answers to the above questions will obviously have crucial implications for the design of support particularly in determining the strength/resiliency of surface cladding and the need for ‘compliance’ or ‘dynamic capability’ in the rockbolts or cable anchors.

It is very apparent that tremendous progress has been made, in the western mining communities particularly, in seismic monitoring technology. This advanced capability, together with the ability to integrate the numerically-modelled stress/displacement response to changing mining geometry, with the actual rockmass response determined by ‘complete’ seismic monitoring, re-kindles hope of predicting rockbursts in the sense that useful warnings can be provided to management.

The proceedings have reflected that there have been improvements in ground control developments, particularly in regard to back-fill technology, and in rockbolt/tunnel cladding design. The use of prevention/ control techniques involving stress-relief drilling and relaxation-blasting in deep coal-longwalling has continued to be routinely applied. ‘Pre-conditioning’ by blasting appears to have been successfully employed in some hard-rock, high stress situations but perhaps not with the same assurance as in coal mining.

It is likely that these control measures will also be improved and more confidently applied when the details of rockburst mechanism at source and the damage response of the excavations, become better understood.

Space and time constraints have prevented this review from fulfilling its original hopes of providing a comprehensive and balanced overview of the state of knowledge in rockbursting. It does not do justice to the content of the many good papers

amongst the 315 submissions to the five symposia, and it does not even identify the authors of many of them. However it is hoped that the names that have been high-lighted will allow the reader who is seriously searching for knowledge and understanding, to more easily explore the main developments and deficiencies in RaSiM’s reflection of progress towards a solution of the problem of rockbursting.

Others who may simply wish to know whether all the research effort has been worthwhile, will want to know what the ‘bottom line’ is. Has there been significant increase in knowledge and, more importantly has there been demonstrable success in reducing the hazard of rockbursting in mines?

It is not possible to obtain any kind of definitive or quantitative answers to this question from the symposia proceedings. However it is possible to confirm that substantial and steady increase in knowledge has been made although perhaps without any major breakthroughs.

In the Western mining communities, most mining companies would probably claim substantial, significant, or, at least partial, success in the form of reduced incidence of large rockbursts and reduced casualty rates, over the past several years. All governmental safety authorities would say that accident and incident statistics are still too high and continued improvement is necessary. In their mission statements, most mine owners would also subscribe to this objective.

## 8 FUTURE NEEDS AND CHALLENGES

While the above perceptions of success are not to be denied, it is likely that most scientists, seismologists and those ground control engineers with imagination and insight, would not be complacent about the present state of knowledge or the present level of funding. The synergy between research into crustal earthquakes and the drive to understand and control mining-induced rockbursts, has been recognised and has already brought benefits. However, the fact that vastly greater funding and brainpower has been brought to bear on the phenomenon of earthquakes for decades now, without any success in prediction or control, has to have a sobering effect on even the most optimistic view.

Prediction of rockbursts, although it may often not be listed as an explicit research goal\*, is obviously still a hope which implicitly underlies much of the more academic research effort. From a positive view point, it can be argued that there are several reasons why the prediction goal is less elusive in the mining situation than it is in the earths crust. Although the surrounding rock ‘space’ is very large, it is finite and its response to mining changes can be ‘sensed’ by seismic monitoring. There is already commercial software available to do ‘interactive’ modelling of this response – G Hofman et al. (2001). This may make the promise of prognosis, if not real-time prediction, realisable in the foreseeable future.

The minimum requirement for a mine to make this happen is that their sophisticated monitoring/ analytical capability must be adequately staffed and operated by a dedicated, experienced professional. The other most important requirement is that there should be good understanding and constant communication between the seismologist and the mine operators.

There are other instances, also, where the limitations of present understanding of the rockburst source mechanism and the mechanics of damage become sharply defined. Spottiswoode (2001) has warned “....*Interpretation of mine seismic events is still largely based on the approach developed for earthquakes with their slip mechanisms described in terms of simplified source processes....estimation of the shape and size of a*

\* Papers on prediction and prognosis make up 1.6% of the proceedings.





**FIG. 3** View up-dip into severely-converged tabular stope, at depth of 2 200 m, after a rockburst of  $M_L = 4.0$  in September 1977. The working height of the stope was originally about 900 mm, and it was supported by rapid-yield, hydraulic props supplemented with timber/concrete 'sandwich' packs. Undulating 'heave' of the footwall left openings of 270 mm to 340 mm high (as estimated at the positions of the two props), in places. Probably 60% or more of the 170 m x 20 m total affected area was completely converged, with the floor impacted into the roof

*seismic source region is still most often based on a circular crack with radius provided by the theory of Brune centered at the event hyper centre...."*

The validity of this simple model needs to be critically assessed. Other aspects of source mechanism which determine strong ground motions near-source, and which urgently require further study include:

- The constancy, or otherwise, of *dynamic frictional resistance* – is displacement- weakening or velocity- weakening a reality?
- How homogeneous is the slip velocity along the fault surface? Is it possible that velocities that are much higher than the average, occur locally in places? (The reader's attention is drawn to a paper by Ortlepp et al., elsewhere in these RaSiM 6 proceedings, which infers from studies of the gouge on a mine-induced fault that extreme phenomena do occur during the faulting process).

For the management and mitigation of the effects of rockbursts, deeper understanding of the mechanism of damage is perhaps even more important than understanding of the source mechanism. The uncertainties discussed by Hildyard et al. (2001) need to be resolved. Extreme damage in tunnels, where the rock between the rockbolts shatters into small fragments leaving the naked tendon tenuously anchored at its end, defies simple explanation – Ortlepp et al. (2004). Solving the question of proper tunnel support design

would surely have universal application. It is also an area where observational and experimental work can be carried out most easily.

In the context of determining just how high ejection/convergence velocities can be near to the source of a major rockburst, the reviewer thinks that it is now permissible to confront the scientists with a challenge. The challenge is for some-one to explain the phenomenon depicted in Figures 3 and 4. These photographs have appeared before, in Ortlepp (1984 p.172) and again in the proceedings of RaSiM3 (1993 p.103). No explanation was offered then, but now the question is seen to be of wider significance and more urgent than it was before.

It is becoming apparent from so much of the good seismological data that is being accumulated now, particularly in South Africa, that there is a wide range of different responses possible in the ground motions generated by fault-slip. Clearly much more needs to be known about the ambient conditions surrounding each fault as well as the physical characteristics of its slip surfaces. There is thus a distinct need for mines to employ geologists whose abilities include the understanding of all aspects of structural geology as well as the economics of ore distribution and grade, in addition to seismologists and rock engineers.

After a long career of close involvement with the rockburst problem, it is gratifying to feel that the veil of mystery is finally lifting a little and the opaque rock space, in some ways





**FIG. 4** Zoomed-in detail shows prop has penetrated deeply into argillaceous quartzite footwall (UCS  $\approx$  180 MPa). It is particularly noteworthy that the wall of the shallow trench blasted for access into the converged area, is undamaged despite the presence of a 125 mm diameter steel 'indenter' only a few centimeters away. There is no indentation rim or bulge in the smooth floor immediately surrounding the outer cylinder of the prop! About 50 m away, another prop had completely punched into the footwall of a completely-converged area, appearing as a solid steel inclusion – see photograph on 104 of Ortlepp (1993). What impact velocity is necessary to convert steel props with designed yielding capability, into rock-piercing 'projectiles'?! Until this question can be answered, our understanding of the damage mechanism of severe rockbursts is sadly incomplete!

at least, is becoming more transparent. It is to be hoped that large mining corporations and mine owners will also see the light and realise that it is ultimately in the best interests of all the stakeholders that the spectre of the rockburst hazard must be further exposed and eventually eliminated. For this to happen, adequate funding for both fundamental and applied research must be available and, importantly, geotechnical engineering must be seen as a vital part of the operational structure on the mine. Let it be hoped that RaSiMs of the future will benignly preside over this evolution as it becomes a wide-spread reality rather than a fervent wish!

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