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OVERVIEW OF GAS OUTBURSTS AND UNUSUAL EMISSIONS

Ripu Lama[1] and A Saghafi[2]

Abstract: Gas and rock outbursts are unwanted complications of underground coal mining, which have occurred over the last 150 years of underground coal mining worldwide and are still occurring. 'Outburst' is a dynamic phenomenon that causes the sudden concurrent release of gas and strata energy. The released energy causes pulverization of large amounts of coal and rocks, which are then ejected into the working areas during mining of the outburst prone zone. This paper discusses some of the 30,000 outburst events recorded worldwide and suggests indices to identify the outburst zones as well as methods of management of outbursts. The conclusions are based on overseas and Australian experiences particularly research carried out by the authors in the early 1990s in coalfields of the Illawara area.

INTRODUCTION

Outbursts and abnormal gas emissions in mines are a manifestation of conditions associated with high gas contents of the coal seam mined and the seams surrounding it. An outburst is an event where coal and/or other rocks are ejected from an advancing face together with the emission of large amounts of gas. The phenomenon manifests itself over a time, ranging from a fraction of a second to a few minutes. It consists of a series of events occurring in succession. The amount of coal and rock material ejected can vary from a fraction of a tonne to several thousand tonnes. The largest outburst in the world occurred at a Gagarin Colliery in the Donetsk coalfield (Russia) where 14,500 tonnes of coal was ejected together with 60,000 m^3 of methane (Stepanovich et al, 1976). There is a long history of outbursts of gas and coal in underground coal mining and they have occurred in most coal producing countries of the world (Table 1). In the last 150 years, almost 30,000 outbursts have been recorded, with the largest number, almost one half, occurring in the People's Republic of China.

High gas emissions occur without the ejection of coal or rock when the coal is permeable and when stress levels are low and strength is high. Coal seams, that at lower stress levels show high gas emissions, invariably experience outbursts when the strength of coal is low or stress levels are high.

Gas outbursts are associated not only with methane gas, but also with carbon dioxide. Outbursts associated with carbon dioxide are more violent, more difficult to control and more dangerous because of the greater sorption capacity for carbon dioxide. Most outbursts in the world, however, are associated with methane, which is formed during coalification process. Outbursts occur more in seams of high rank (bituminous, anthracites and semi-anthracites), because high rank coals have, greater capacity to adsorb gas at a given pressure, higher internal surface areas, lower porosities and lower permeabilities. A few outbursts have occurred in some lignite mines such as the Valenia mine in Slovenia.

Whilst methane present in a coal seam is either generated during coalification or by microbial processes or both, carbon dioxide is usually derived from an outside source such as magmatic activity. Carbon dioxide permeates into the coal seams, together with the circulating fluids through faults, intrusions dykes and major joint systems. At places, this may completely displace the inherent methane. Gas compositions in the vicinity of these structures can thus vary from almost 100% methane to almost 100% carbon dioxide if a coal field has been affected by igneous intrusions. So far outbursts of carbon dioxide have been experienced only in Australia, Poland, Canada, Czech Republic and France.

[1] This paper was prepared during the last months of 1996. Ripu passed away in January 1997.
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Table 1 - Occurrence of outbursts in various countries (Bodziony and Lama,1996)

Country	Mine field/s	Coal/ Rock burst	Gas type	No. of outbursts experienced
Australia	Sydney basin	Coal	$CH_4 + CO_2$	> 669
Belgium	Southern coalfield	Coal	CH_4	487
Bulgaria	Balkan	Coal	CH_4	250
Canada	Crows Nest Canmore Sydney	Coal + rock	$CH_4 + CO_2$	411
China	Large number of coal fields	Coal + rock	CH_4	> 14,297
Czech Republic	Ostrava Slany Oslavany	Coal + rock	$CH_4 + CO_2$	482
France	Various	Coal and other rocks	$CH_4 + CO_2$	> 6,814
Germany	Ruhr Ibbenbüren	Coal and other rocks	CH_4	359
Hungary	Mecsek	Coal	CH_4	~600
Japan	Hokkaido + Kyushu	Coal	CH_4	920
Kazakhstan	Karaganda	Coal	CH_4	45
Poland	Upper Silesia	Coal	$CH_4 + CO_2$	1,738
Rumania	Anima-Resica	Coal	CH_4	20
South Africa	Main Karoo	Coal	CH_4	5
Russia *	Various	Coal and other rocks	CH_4	521
Taiwan	Taiwan	Coal	CH_4	60
Turkey	Zonguldak	Coal	CH_4	58
Ukraine	Donetsk	Coal and other rocks	CH_4	4,689
UK	Various	Coal	CH_4	>219

There is no clear relationship between the frequency and size of an outburst and various parameters that influence outbursts (Cyrul, 1992). The size of an outburst however is related to the size of a geological structure on which it occurs. All other factors remaining constant, depth (and stress) increases the size of an outburst but at a relatively low rate (Bodziony and Lama, 1996). The minimum depth at which an outburst occurs depends on specific local conditions (Table 2). At Ibbenburen Colliery which is the deepest anthracite coal mine of Germany, located in the Ruhr coalfield outbursts were recorded from depths of 1150 m and more.

Table 2 - Outburst depth in various countries (Bodzinoy and Lama,1996)

Country	Largest quantity of material ejected		Minimum depth at which outburst started, m
	Rock + coal, t	Gas, m^3	
Australia	1,000	14,000	95
Belgium	1,600	34,000	250
Bulgaria	350	12,000 - 19,000	130
Canada	3,500	60 - 140,000	200
China	12,780	3.5×10^6	<100
Czech Republic	4,310	96,000	80
France	330	400,000	270
Germany	2,500	66,000	1,150
Hungary	1,800	27,000	140
Japan	5,200	600,000	-
Kazakhstan	-	-	400
Poland	5,000	750,000	80
Rumania	500		300
South Africa	200	-	-
Russia *	-	-	200
Taiwan			
Turkey	700	11,000	300
Ukraine	14,500	600,000	200
UK	400	60,000	183

While a large fall or a fracturing of a pillar or a part of the coal face may give rise to large emissions of gas, together with displacement of coal, it must be distinguished from an outburst. A typical outburst is associated with a violent ejection of coal and emission of gas. The cavity formed from which the coal is ejected has a typical shape of a cone or follows the contours of a structure with which the outburst is associated.

A vast majority of outbursts occur in development roadways when driven in virgin ground in coal or when opening a seam from a cross-cut driven in rock. In mines which operate at depth, outbursts have occurred on longwall faces, particularly where these faces pass below remnants where high stresses result in decreases in permeability and crushing of the coal. Outbursts rarely occur in coal seams which have been destressed and degassed as a result of mining of neighbouring seams. The three most important parameters that characterise a coal seam liable to outbursts are high gas contents, low permeabilities of the coal seam and high rates of gas emission when the coal is crushed. Seams with the following characteristics can be classified as outburst prone:

- gas content (methane) >8 m^3/t,
- permeability < 2 mD, and
- mechanical strength < the lowest principal stress.

In mines with carbon dioxide as the main seam gas, lower gas contents than required for methane can give rise to outbursts.

The presence of a geological structure or discontinuity in the coal seam is very commonly associated with outbursts. Structures such as strike-slip faults, reverse faults and shear zones reduce the strength of coal within and in the vicinity of the structure and cause changes in the stress gradient and gas pressure gradients thus facilitating conditions that favour an outburst if sufficient gas is available. Gas itself does not necessarily initiate an outburst, though some investigations show that the presence of gas reduces strength (Josien et al, 1983; Lama, 1995) and causes high stresses to develop (Ettinger, 1977). It also results in body forces, which can initiate an outburst.

Added to the factors described above, advances in mining technology and the consequent high rate of roadway development and face advances in longwall mining, contribute to the occurrence of gas outbursts as a result of significant reduction in minimal time for the strata and the coal seam to reach a new state of equilibrium.

MECHANISM OF OUTBURSTS

Because of the wide variety of conditions under which outbursts occur, there is no single theory that can explain the phenomenon.

Some of the earliest concepts on the nature of gas emissions, gas pressure and properties of coal was presented by Halbaum (1989-1900) who outlined the basic theory of gas pressure to describe sudden emissions of gas and outbursts. Later researchers such as Telfer (1911-12), Rowan (1911-12), Ruff (1930) developed theories of outburst followed by Caufield (1931), Jarlier (1936), Belov (1931) and Pechuk (1933) who introduced the role of stress and mechanical energy in outburst theory. Since the early 1950's the most extensive work in this area is reported by Russian investigators (Khodot, 1951, Ettinger, 1952, Khristianovich, 1953 a, 1953b) who have considered mechanisms of sorption/desorption of gas and stress, in the generation of outbursts. Skochinski (1954 a, 1954b) synthesised the concepts, his analysis being based upon experiences in the former USSR and results of investigations of a team of about 300 researchers during 1952-54. According to him, outbursts occur as a result of mutual interaction of numerous factors including the followings:

1. Rock pressure, which is associated with,
   - Development of cracking and crushing of coal at the edges of the excavation, its destressing and decrease in strength.
   - Changes in permeability of coal seams, re-distribution of gas pressure and emission of large gas volumes.
   - Transfer of rock pressure from the static phase into a dynamic phase as a result of destruction of the coal seam close to the face or due to loss of the resistance offered to the roof. This results in development of further cracking and crushing and as a consequence, creation of fresh surfaces which increases desorption. This leads to formation of gas transportation paths resulting in a drop in gas pressure and release of its potential energy. Releasing of the elastic energy of the coal together with the gravitational energy, which converts to the dynamic energy of coal in movement and increasing the intensity of sudden outbursts.

2. Gas present in coal:
   - Static and dynamic gas pressure in coal under normal gas pressure gradients cannot initiate an outburst unless the following three conditions are fulfilled:
     (a) Sufficiently high gas contents of coal.
     (b) Fast rate of crack development and disintegration of coal as a consequence of mining, with the formation of a large number of new surfaces that can ensure intensification of desorption and filtration of gas.
     (c) Formation of cracks of sufficient length and volume in fractured or crushed coal that will ensure distressing, flow of gas into the excavation and decrease in gas pressure between the excavation and the coal where gas is desorbing.
   - A sudden drop of gas pressure, of the order of 2 MPa or more over a distance of 1 mm alone is enough to crush the coal, throw it and ensure propagation of the crushing wave to a certain distance into the rock mass.
   - In an outburst, the gas present in coal particles disintegrates the particles into fine dust and intensifies the flow of gas and coal particles into the excavation.
   - The gas liberated from the fractured and crushed coal is sufficient to cause an outburst if the gas pressure is at least in the range of 0.3 - 0.6 MPa.

3. The physical and mechanical properties of coal and micro and macrostructure of the coal seam. The structure of coal defines the following:
   - the strength of coal and its resistance to stress,
   - the rate of emission of gas and work exerted by gas during its emission, and
   - the amount of gas in coal and total potential energy that may be available in an outburst.

4. Gravitational force becomes effective in steeply dipping seams and excavations after an outburst is initiated. The kinetic energy increases under the effect of gravity and approaches an amount equal to that of gas, in the case of outburst caverns formed in line with the rise of the seam (Nekrasovski, 1951).

According to Skochinski (1954 a, 1954b), rock pressure is not the basic factor causing an outburst, rather it is gas that is responsible for its development and sustenance. Skochinski does not consider the role of tectonic forces in the process of an outburst because of the following:

- There are no methods that can define residual tectonic stresses.
- Very often two coal seams lying 20 - 30 m from each other differ in their susceptibility to outbursts in spite of the use of the same method of mining.
- Coal seams and the surrounding rocks are intersected by a number of micro and macro cracks.
- Rock pressure alone is insufficient to cause an outburst.

Since the work of Skochinski (1954 a, 1954b) and his colleagues the concepts have been extended and mathematical theories have been developed. Khristianovich (1953a,1953b) developed the crushing wave theory and has treated the outburst process as a complex function of natural tectonic and induced stress which causes initiation of an outburst; and free gas present in the pore space transports the broken materials. The crushing wave travels from the face into the solid, destroying successive layers of coal in the direction opposite to the direction of movement of the broken mass. These disturbances are destressing waves and receive their energy from the compressed gas in the pore space. According to Khristianovich, differential gas pressure, at the face of the crushing wave is, equal to or greater than the tensile strength of coal. This results in splitting the coal into small layers (discs). His theory is supported by a number of investigators who have reproduced outbursts in the laboratory (Yartsev, 1958, Ujihira et al., 1989, Ujihira and Nakajima, 1991, Gawor et al., 1991).

More recently, coal under high gas pressure has been treated as a retrograde material (Litwiniszyn, 1983) with gas as a solid solution in the coal matrix. The gas undergoes a phase change as a result of changes in thermodynamic conditions. The model presented by Lihvinisyn has been validated in the laboratory (Bodziony & Kraj, 1995).

A number of authors have associated outbursts and rockbursts as one single phenomenon with the difference that gas may be absent or that gas is a secondary factor for rockbursts (Josse, 1957, Budryk, 1951, 65, Coeuillet ,1959, Szirtes, 1966, Lama, 1995). Numerical models which use tensile strength as a criteria of failure, have been used to predict outbursts (Paterson, 1986, Barron & Kullmann, 1990; Chen et al., 1995).

In general, there is convergence of views that the following factors play a dominant role in outbursts:

- Geological structures particularly faults, contact zones of coal with volcanics and deformation of coal.
- Static and dynamic stresses in the neighbourhood of other excavations.
- Lower strength of the coal seam in relation to the stress levels.
- Gas pressure and gas content of the coal seam.
- Rate of gas desorption.
- Sudden exposure of the coal seam.
- Part of the excavation that forms steep faces.

PREDICTION OF OUTBURSTS

The necessary conditions for an outburst to occur vary from mine to mine, but the four most important and widely accepted conditions are:

- gas content,
- geological structures,
- stress regime, and
- material properties.

All the four factors work together in producing an outburst. Geological structures determine the location of the outbursts. Stress plays a role in initiating an outburst. Gas content determines the amount of energy that is available for an outburst and transfer the material.

When predicting outbursts, the important thing is consideration should be given to the factor that plays a major role in a particular situation. Gas content is always an important factor. Without the presence of a certain critical gas content value, outbursts of gas, coal and rocks will not manifest themselves at all.

Geological conditions such as faults, dykes and shear zones, play a very dominant role in shallow mines and even in deeper mines where the size of the outburst increases where a geological structures are present. In the absence of a geological structure, outbursts depths down to 1,000 m depth are small.

Stress plays an important role in deep mines. The role of stress must be judged in association with the strength of the coal/rock. Stress levels that are sufficient to fracture rock to almost a state of pulverisation cause intense outbursts. While gas content can be measured or estimated fairly reliably and geological structures may be predicted or are evident at the places where outbursts have occurred, measurement of stress is not easy and is almost impossible on a regular basis under operating conditions in mines. The effects of stress however can be measured indirectly.

The methods that have been developed to predict outburst conditions can be divided into groups based upon various factors influencing the method (Figure 1). It is difficult to categorise each method precisely. For example, gas content which is a function of gas pressure influences the properties of coal and rock. Discing is a phenomenon which describes the status of stress but it is also influenced by gas pressure and rate of drilling. Radio imaging is based upon the dielectric resistance of coal, but its value is highly dependent upon the moisture levels and in mines with low moisture coal, its use in prediction of structure is dependent upon moisture level anomalies.

The type of method used depends upon local conditions. Some mines may use more than one method for continuous prediction. For local and regional prediction invariably more than one method is used.

CONTROL OF OUTBURSTS

Control of outbursts of gas and coal and rock is based upon two broad concepts. The first approach is to develop and use methods so that outbursts do not occur at all. The second approach, is to develop systems so that the miners and equipment can be protected from outburst effects. The nature of such methods or systems will depend upon the dominant factors that can be changed or controlled most easily. Accordingly, classification is based upon control factors such as gas or stress or locational factors. Two examples of the classification system are given in Figures 2 and 3 (Bodziony and Lama, 1996)

In stress control methods, short holes (40 to 80 m long) of large diameter (up to 300 mm) are drilled ahead of the face (Yu-Bufan, 1985; Anon, 1964). The number and length of holes drilled depends upon local conditions and the technology available. Large diameter drilling presents dangers of an outburst initiation during the drilling process and many times requires either remotely operated equipment (not yet available) or drilling behind specially constructed barriers. Destressing of a coal seam is possible by extracting a neighbouring seam above or below. This lowers the stress as well as gas content levels.

The important point to consider is complete extraction without leaving any barrier pillars. When this is not possible, camouflet blasting, hydraulic washing of the coal face or slitting of the roof/floor rock is adopted. Camouflet blasting was the first and most commonly used method in Europe the first half of the 1900s. Although this method reduces the danger of unexpected outbursts, the frequency increases. Hydraulic washing has been used mainly in Hungary when the seam is very weak and drill holes cannot be maintained even for camouflet blasting. Slitting has been tried in Russia and Ukraine successfully, but the method is highly labour intensive and there are no machines available that can produce deep slits efficiently. Blasting using relief holes has been suggested but has not been clearly demonstrated at this stage.

Gas drainage prior to mining is the most common method presently being used in Australia, Poland, China and Russia. Holes of up to 300 m have been drilled ahead of the face for degassing, to bring the gas levels down to safe threshold values. Technology exists for drilling holes within coal seams to depths of up to 1,000 m. Developments in seam gas drainage from the surface, using surface boreholes and hydraulic fracturing has been successful in the USA, but its applicability to drain gas economically from seams suceptible to outbursts is yet to be demonstrated. Directional drilling from the surface presents a distinct possibility (Oyler and Diamond, 1982). Underground hydraulic fracturing has been successful in Russia (Lidin, 1987).

Chemical treatment of coal seams by injecting water with 2% hydrochloric acid has been tried in Russia successfully to increase permeability of the coal seams where a high percentage of calcite is present (Airuni, 1981).
Modern underground longwall technology requires high rates of advance of development headings. Longhole advance drainage seems to be the only technology at this stage that is capable of meeting the demand.

Remote machine mining is a distinct possibility for outburst control in the near future (Wynne and Case, 1995). Face cutting machines such as continuous miners have been successfully equipped for the protection of the drivers.

Prediction of structures which are the loci of the vast majority of outbursts is the key element in control of outbursts. A number of methods have been tried. Unfortunately, no method has been proven completely successful. Geophysical techniques such as micro-seismic and seismic wave analysis have been reported to be successful in the Donetsk basin of Ukraine, China, Japan and Australia (Hatherly et al, 1995; Styles, 1995; Zhang et al, 1987; Kolesov et al, 1995) and geophysical techniques such as radar imaging are being tried in Australia (Murray, 1995).

Sonic probes (Hatherly et al, 1995) have been developed and are being tested. In-seam seismic techniques are successful in predicting small faults and high moisture zones underground (Thomson et al, 1995). Filtration properties of coal are shown to help in locating zones prone to outbursts (Lama, 1983). Fracture density changes show that the shear zones may be detected up 100 m away (Shepherd, Rixon and Creasey, 1980). More effort is required to ensure that all structures can be delineated prior to their intersection.

MANAGEMENT SYSTEMS FOR CONTROL OF OUTBURSTS

Mining of seams liable to outbursts requires the development of special procedures to ensure that the risk to miners and equipment is eliminated or reduced. Most mines have laid out basic mining conditions which, when achieved, can make mining of outburst-prone seams safer. These conditions may be based upon defining critical threshold values for gas content or gas desorption rate. The methods to reach the threshold values depend upon local conditions. The purpose of the management systems is to ensure that the procedures are in place and are precisely followed and to ensure that under no circumstances can mining proceed if it it endangers operations.

A management system thus relies on checks and balances to achieve the desired result. It also ensures that the system operates independent of the people who developed it. The desired results can be efficiently achieved by defining the methodologies and when the desired results are not achieved, the procedures need to be varied without sacrificing safety. Most countries around the world have developed guidelines for mining under outburst conditions. The basic outline of a management plan is given in Fig. 4.

The key features of a good management system are:

- Definition of the problem which clearly states what is the most important parameter (e.g. gas, structure, desorption index).
- Management plan that outlines the standard to be achieved pertaining to all technical parameters.
- A clear outline of the standard operating procedures.
- A decision making process that clearly allows the direction to be taken when the results of the operating procedures applied become available.
- Organisation, responsibility and authority of each person collecting information and those responsible for decision making.
- Flexibility so that in case of failure of the procedure, new methodologies can be introduced reasonably and quickly.
- Participation of all involved in the data collection, operation and decision making at various levels.
- Training of each member and updating the skills so that the "best practice" is always followed.
- Auditing of the system so that it conforms to the standard set in the plan.
- Information and control documentation is kept and available to all involved.
- Procedures available for corrective action if shortcomings are found in the management plan.
- Outburst mining procedures if normal mining is not possible.

Quite independent of the method used, the management system is the key to safe mining.

UNUSUAL EMISSIONS OF GAS

Very high emissions of gas are commonly noticed in mines particularly on longwall operations and in development headings. Penetration of old workings has been very common in the first half of 1900s. With better

knowledge of the old mine geometry records and development of advance boring, these events have been largely eliminated.

High gas emissions in development workings occur in seams of shalower depth, high permeability and in areas with open jointing. These emissions are basically due to intersection of high conductivity zones which allow very high flow into the mine workings. In mines with low in-situ gas contents (4 to 5 m^3/t), large gas emissions, with ignition at the face have been encountered. Sudden emissions also occur when highly gassy seams lying close to the seam under development, results in the fracture envelope penetrating the adjacent seam or bursting of the floor/roof under high gas pressures.

On the longwall face, sudden emissions of gas occur from the floor when strong sandstone beds separate the seam under extraction and the underlying seam. The adsorbed gas present in the lower seam accumulates below the strong beds in a free state. Strong beds break at intervals and high conductivity cracks allow flow of gas from the floor into the mine workings. The higher the delay in the fracturing of the inter-lying strata, the greater the volume of flow into the workings. Figure 5, which gives methane emissions into a longwall face as a function of time, shows the cyclic nature of the phenomenon as observed in the Bulli seam on the South Coast of New South Wales, Australia. In one example the gas is released from the lower seam lying about 10 m below the seam under extraction. A sandstone bed approximately 1 m to 1.5 m thick lies between the seams almost immediately above the lower seam. Gas emission rates up to 1.5 m^3/s have been recorded. The largest floor outburst delivered 330,000 m^3 of gas. These are more frequent in the first longwall and decrease when the neighbouring longwall has been mined. The phenomenon has been termed by some investigators as floor bursts.

Hinderfeld (1994) reports the occurrence of a similar phenomenon in the Ruhr coalfield. During the period 1969-84, 18 large floor bursts occurred in the Ruhr district with an average flow of 15.6 m^3/min. Large flow rates on the longwalls released between 4,240 to 200,000 m^3 of gas. In the roadways, it released 25,000 - 85,000 m^3 of gas and in the drill holes 2,000 - 16,350 m^3.

Studies have indicated that the factors which influence sudden large emissions are:

- Small tectonic zones of high gas content and high permeability,
- High gas content of coal seams / unit area,
- Strata sequence with thick strong beds, between the seam mined and surrounding seams,
- Coal face geometry where the extracted longwall panels form more or less a square shape.

Control of such events is possible only by pre-drainage of the source of gas emission and gas accumulation.

CONCLUSIONS

Outbursts of gas, coal and rock have increased in frequency as mines become deeper. To avoid the cost of running mines prone to outburst, older coal mining countries have closed their mines where the mining needs to go to deeper seams. In Australia however the gas drainage experiences over the last two decades have shown that the sudden emission of gas and outbursts can be controlled by pre-drainage of the gassy and outburst prone areas. Definition of gas content thresholds and draining seams to levels below the threshold have been effective in reducing the number of outbursts. The main initiative in outburst control is therefore pre-drainage of the coal seams and detection of geological structures.

Modern fast mining increases the risk of outbursts, management systems have been developed to allow safe and outburst free application of rapid mining technology. Remote operation of equipment is needed so that unexpected outbursts do not cause any physical damage to the operators by applying various safety measures in areas where there is a danger of outbursts and where safe threshold levels cannot be achieved can be mined safely.

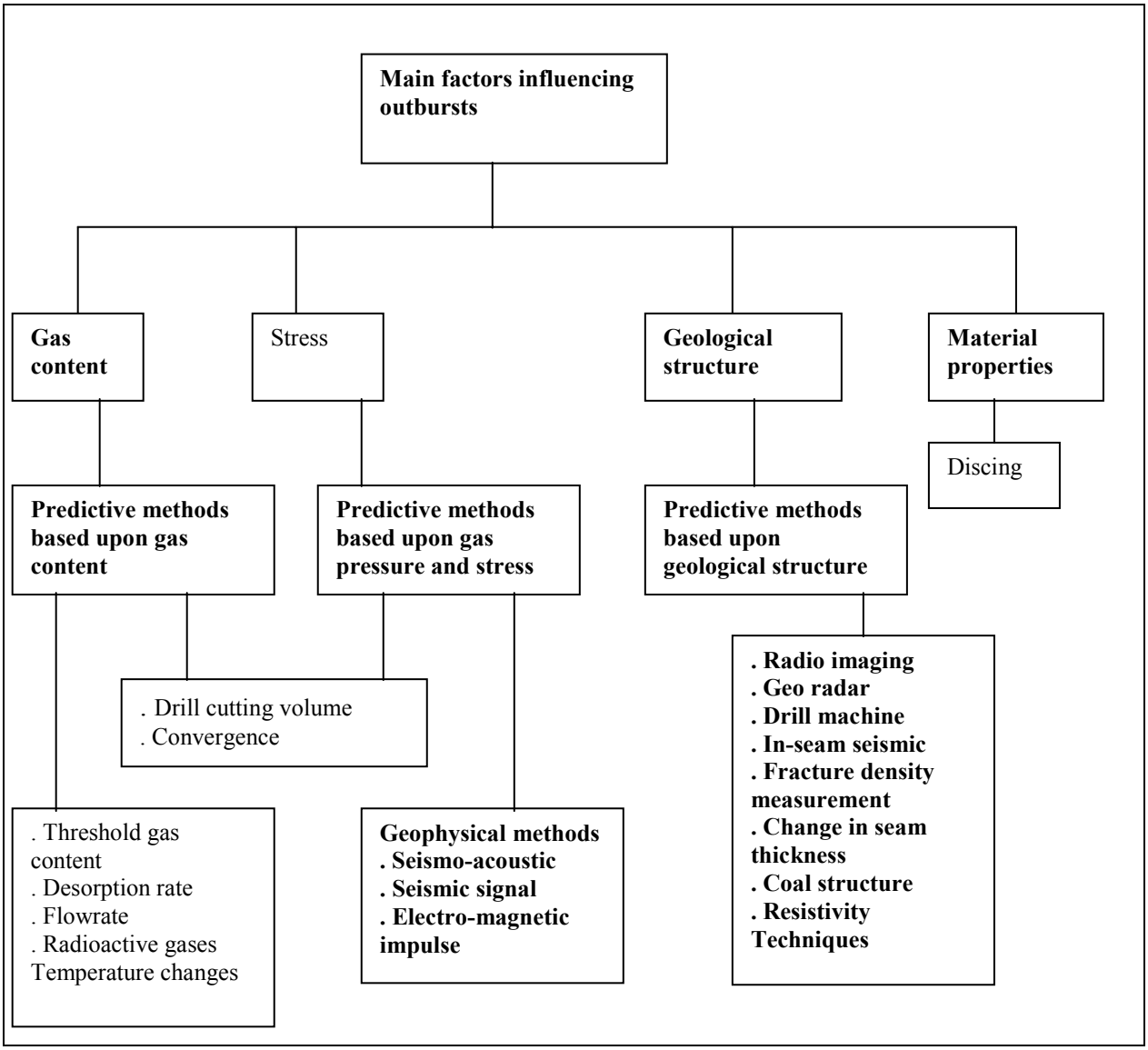

Fig. 1 Classification of outburst prediction method (Bodziony and Lama, 1996)

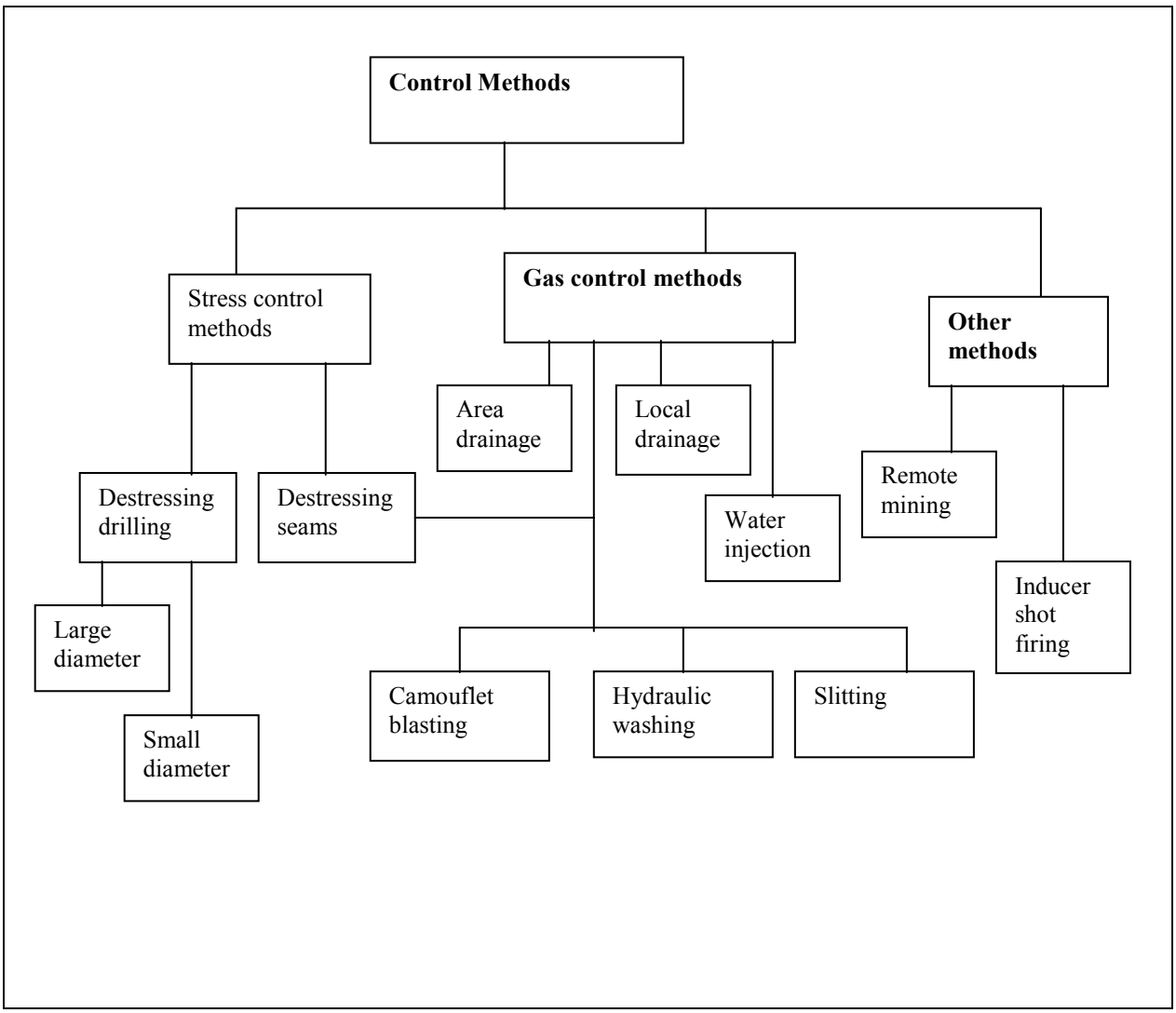

Fig. 2 Classification of outburst control methods based upon most important factors (Bodziony and Lama, 1996)

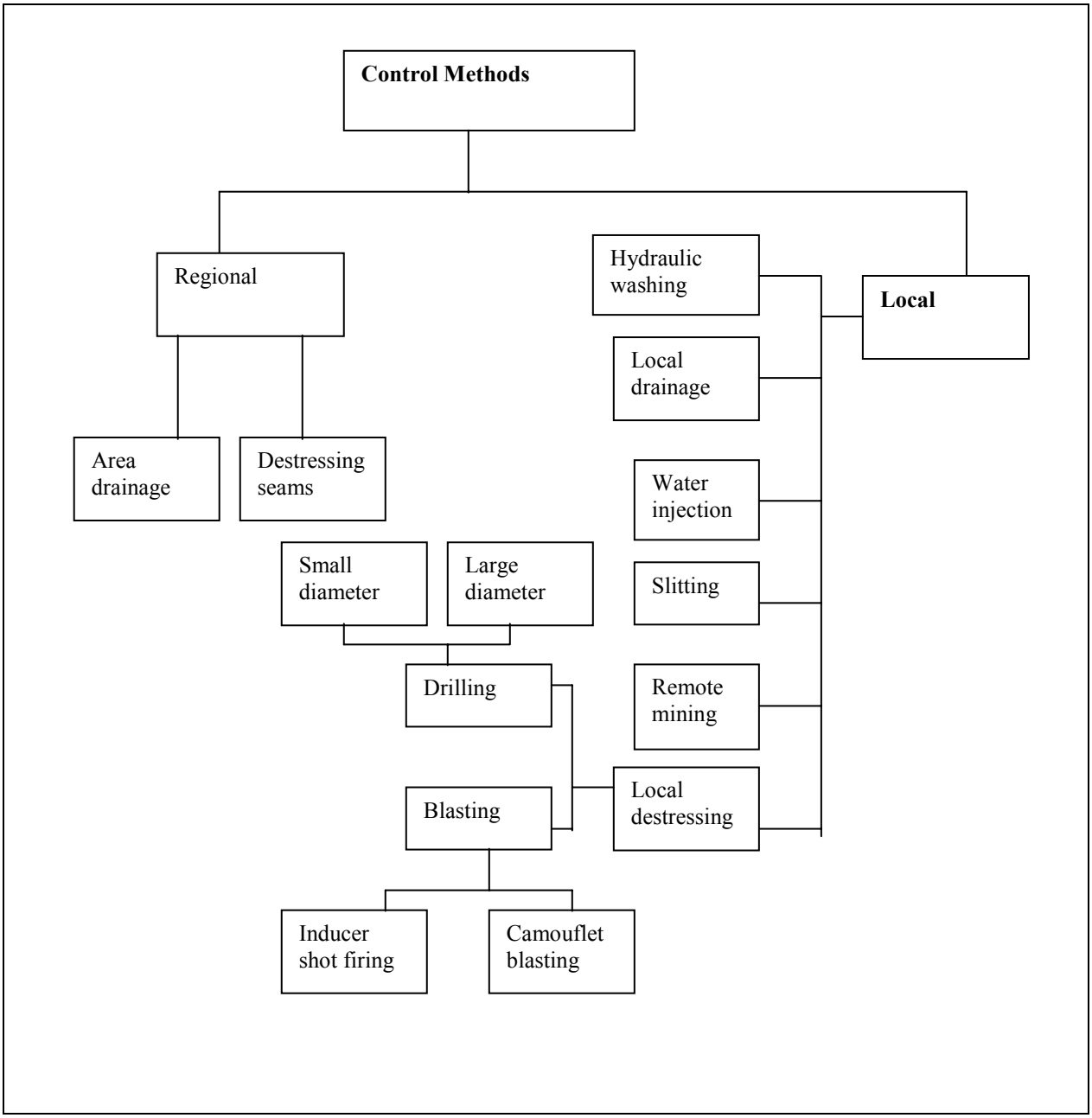

Fig. 3 Classification of outburst control methods based upon locational factors (Bodziony and Lama, 1996)

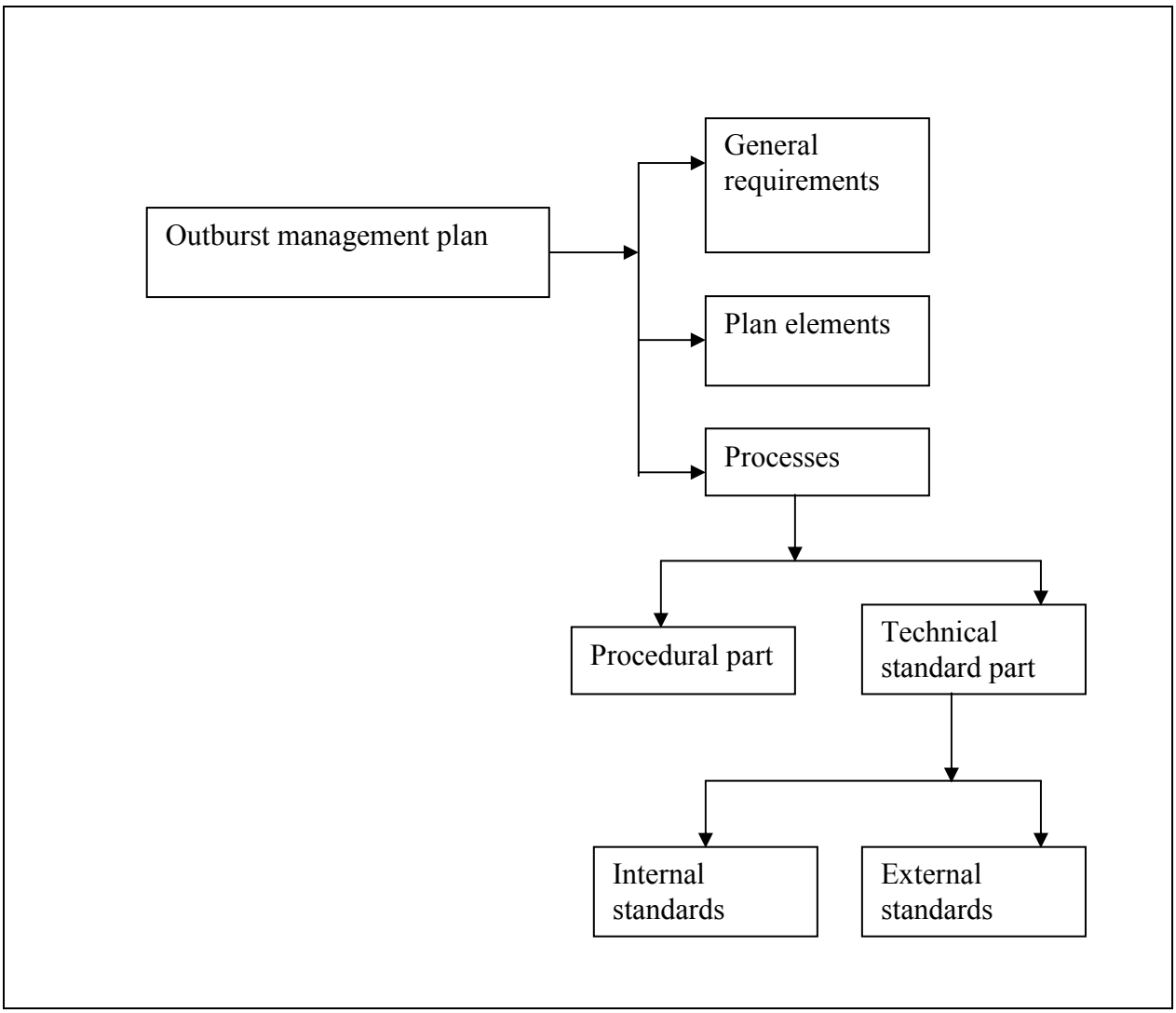

Fig. 4 Basic outline of management plan

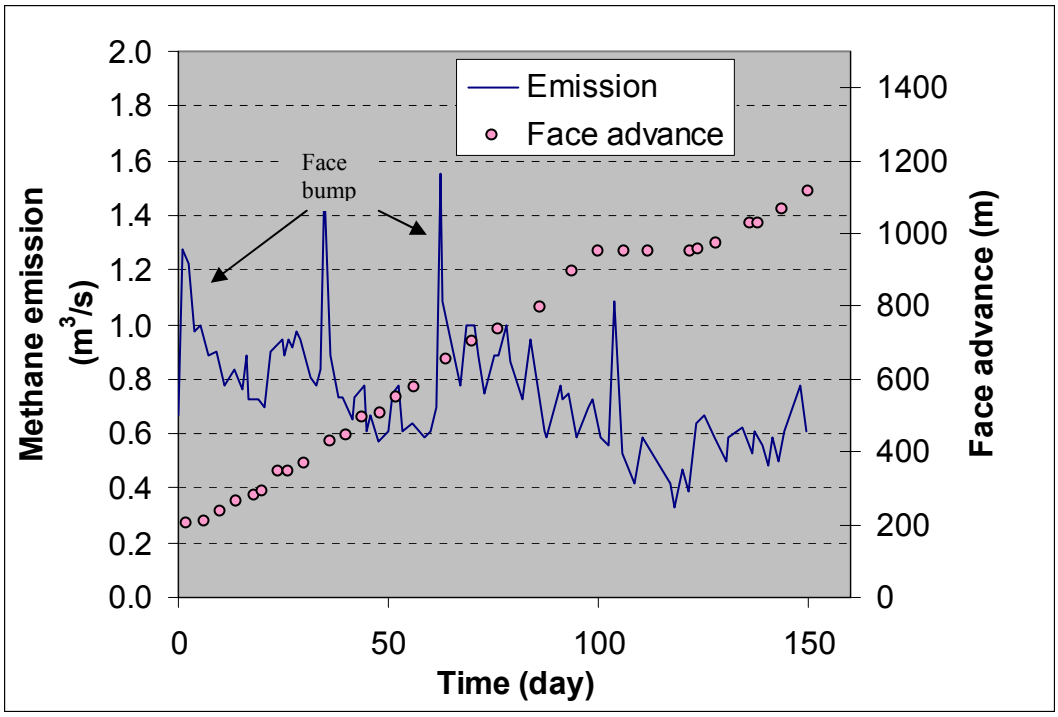

Fig. 5 - Occurrence of high gas emission due to floor bumps on longwall

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