Safety in Mines Research Advisory Committee

Project Report

The occurrence, emission and ignition of combustible strata gases in Witwatersrand gold mines and Bushveld platinum mines, and means of ameliorating related ignition and explosion hazards.

Part 1 : Literature and technical review

A P Cook

Research agency : Itasca Africa (Pty) Ltd.
Project number : GAP 504
Date : October 1998

Executive Summary

The review output of the project comprised three main sections, literature, gas incidents and accidents, and technical interviews with mine personnel.

Literature covered combustible gas emissions in mining operations in South Africa and other countries, as well as the geological origins of methane. All gas emissions reported at the DME from 1987 to 1997 were reviewed, a total of 1914, as well as 32 accident reports. Technical interviews were conducted on 33 individual mines, to evaluate the approach taken by the mines and ventilation practitioners to combustible gas emissions.

Combustible gases are reported from hard rock and other non-coal mining operations all around the world, and occur in numerous strata and ores. Methane is the predominant gas, although often associated with other hydrocarbons and hydrogen. The geological origins of methane can be determined by isotopic analysis of the carbon and hydrogen in the methane, with the carbon isotope ^{13}C the main indicator. This classifies the methane as being of biogenic or abiogenic origin, from either an original bacterial type origin or not. Biogenic methane is further classified into recent, such as landfill and coal origins, or more ancient, such as thermogenic gas. Abiogenic methane is classified as hydrothermal, from volcanic intrusions through carbon bearing strata, or from the earth's mantle.

South African gold mine methane could be bacterial, hydrothermal, abiogenic or a mixture of all of these. Platinum mine methane is almost certainly abiogenic.

The number of flammable gas reports and accidents are increasing steadily for both gold and platinum mines, with the highest number of occurrences being in development, and commonly from diamond drill or cover drill holes. There are both regional and mine by mine variations in occurrences, but this is influenced by different reporting priorities on different mines.

Gold mines have more ignition related accidents, whereas the platinum mines have face outbursts during drilling, usually without ignition. The most common causes leading to gas accidents are changes to the ventilation, lack of testing for gas, and contraband, and of those of gas ignitions are contraband and illegal tampering with caplamps.

There is a general lack of awareness of the hazards of methane on mines, with only four mines considering combustible gases to be a problem. It is likely that methane is regularly emitted from strata but the normal ventilation is sufficient to control it. Very few reports have methane above five per cent in the general body. These factors, and the number of accidents involving ventilation and gas testing, shows this lack of awareness.

Acknowledgements

Mr. A Leach and Mr. K Balt of Itasca Africa, and Mr. C Meyer, of Varicon, made significant contributions to this report.

Tony Leach reviewed geological sources of methane and reported on these in Chapter 1; Karel Balt spent many hours at the DME offices and collated all the incident and accident reports reviewed in Chapter 2, and Cor Meyer carried out and reported on the technical interviews in Chapter 3.

Contents

Page

Figures

Tables

Terminology and abbreviations

The terms combustible, flammable and inflammable, to describe gases encountered in mining, are all used commonly in literature and within the South African mining industry. The Concise Oxford English dictionary defines them as:

combustible: capable of burning
inflammable: easily set on fire
flammable: rarely used except in “nonflammable”.

In this report combustible and flammable are used to describe gas or gases that will burn or explode in air, with no difference in definition or meaning.

Methane is generally used to define the gas or gases being emitted from strata. Other gases are sometimes present so fin this report the terms, methane, gas mixtures, gas and gases are used interchangeably, and unless so stated as meaning the flammable gas emitted from the strata.

For the technical review the mines are divided into three groupings, Witwatersrand, Bushveld and Free State. Although the Free State mines are within the Witwatersrand basin, the close proximity of overlying coal seams differentiates them from most of the other high occurrence reporting gold mines. For report purposes the Witwatersrand gold mines are those between Evander and Klerksdorp.

The individual gases are referred to by name or by chemical formula.

Abbreviations used are:
LEL: lower explosive limit of gas in air
UEL: upper explosive limit of gas in air

1 Introduction

Methane ignitions have long been acknowledged as a hazard in South African gold and platinum mines, but the origins and transport mechanisms of the gas have not been well understood. This lack of understanding has contributed to the hazard, making gas emissions difficult to predict and prepare for.

Furthermore, the name methane continues to be applied to the gases emitted, even though the presence of other gases has been acknowledged and documented.

The primary output of this SIMRAC project is to improve the understanding of the gas emissions in general, particularly the factors contributing to gas emissions, and the measures that can be taken to reduce the risk of explosions and injuries.

This initial review output has comprised of three main sections, literature, technical and reported gas incidents. The literature to get a more complete understanding of the occurrences and origins of strata and mine gases; the technical mine review to learn from the personal experiences and knowledge within the industry; and the incident review to indicate the main problem areas, mines or activities that contribute to gas problems.

Hard rock gas emissions are generally remembered as spectacular or injurious events. Emitting from fissures, the gas burns in rings around shafts during sinking operations (Viljoen, 1998), and along the length of stope faces (Du Plessis, 1998). It accumulates in raises and other high areas, layering in poor ventilation (Rowe, 1998), and this can lead to long tailing layers extending along the hangingwall. The pressure of gas pockets causes the face to break out (Marais, 1998), resulting in injuries or ignitions. Gas blowers last for many years at high pressure (Van Greunen, 1998), emitting large volumes of gas into the ventilation.

What is generally not remembered are all the other times methane or other gases are emitted, in small and insignificant, or undetectable, volumes. The diamond drill or pilot holes that have “”no gas”, and the fissures that have only water coming out.

The review output indicated that gas emissions may be a more common occurrence than generally considered, but that it usually goes undetected. Gas occurs in many strata types throughout the earth, being continually emitted as both biogenic and abiogenic gases, and often associated with other gases. Hydrocarbons and hydrogen are the most common, and are all combustible in their own right, as well as in mixtures.

Geological evaluation of the strata has indicated the likely areas to concentrate the research on for output 2, identifying the possible sources and transport mechanisms of the gas.

2 Literature review

Gas is the simplest state of matter, and is essentially a swarm of atoms and/or molecules moving randomly and chaotically (Crowcon, 1996). Gases are widespread throughout the earth, in their free state, adsorbed and absorbed into other substances, and dissolved in liquids, but at normal mining atmospheric conditions they usually occur in their free gaseous state.

Gas particles have a minute volume compared to the total space that they occupy, so continually move around and collide with each other. This constant movement and collision is what causes gases to disperse rapidly throughout the space they are occupying, and is the reason that they do not easily separate into layers. Gases do not behave like liquids.

2.1 Gases associated with mining

Numerous hazardous gases are associated with mining, divided generally into combustible and toxic. The emphasis of the review has been on all the combustible gases, and the combinations of these. This included some toxic gases that are also combustible, however their toxic limits or control measures have not been considered.

Table 2.1 shows the most common gases associated with underground emissions, and the upper and lower explosive limits for mixtures of each with air (LEL, UEL). The explosive limits of gases and some gas mixtures in air are all well documented (various sources including Holding, 1981).

Table 2.1 Common gases emitted in mines

GAS	SYMBOL	LEL (%)	UEL (%)
Methane	CH_4	5	15
Ethane	C_2H_6	3	12.4
Propane	C_3H_8	2.1	9.5
Butane	C_4H_{10}	1.8	8.4
Carbon monoxide	CO	12.5	74
Helium	He	-	-
Hydrogen	H_2	4	75
Hydrogen sulphide	H_2S	4	44

(from various sources)

2.1.1 Relevant properties of combustible gases

The properties of gases are all well documented in literature (Le Roux, 1990; Tennent, 1971) and are not for detailed discussion within the scope of this output. However, a brief review is given of the pertinent properties of each, in relation to mining emissions.

2.1.1.1 Hydrocarbons

The most common combustible gases emitted from strata in mines are hydrocarbons, with methane being by far the most abundant of these. Hydrocarbons are simple organic compounds comprising carbon and hydrogen, and are combustible in air and oxygen. They are alkanes, the first four of which are normally gases, and the higher ones are liquids (Crowcon, 1996).

The combustion and ignition properties for the four gaseous hydrocarbons, such as temperatures, energies, explosive limits, and the effects of pressure, are well documented elsewhere, (various sources including Coward and Jones, 1952). The explosive limits are different for each, with methane having the widest range at 5 per cent to 15 per cent, but butane having the lowest LEL at 1,8 per cent.

They are soluble in water to varying degrees, so can be transported in dissolved states in fissure water.

Their relative densities to air are the most significant points generally considered. Methane, the most common, is lighter than air, and therefore considered to separate upwards and layer against the hangingwall. Butane on the other hand, is slightly heavier than air, and considered to separate downwards and layer against the footwall.

Apart from being combustible, a point generally overlooked is that they are also fast acting narcotics (Drummond, 1993). With the exception of methane, gaseous hydrocarbons in concentrations approaching the LEL, will begin to induce dizziness and confusion.

2.1.1.2 Other combustible gases

Of the other gases, hydrogen poses the greatest combustion threat because of its large explosive range, between 4 per cent and 75 per cent, and relatively low ignition energy.

Although combustible, both hydrogen sulphide and carbon monoxide present a much greater, fast acting, toxic hazard well below their respective LELs.

2.2 Mining Emissions, Non-Coal Mines

Gas emissions are reported from around the world in non-coal mining and tunneling operations (Edwards and Durucan, 1991), including Europe, the previous USSR region, USA, Canada and Australia.

The USSR has occurrences of methane and hydrogen in apatite, gold and diamond ores where solid or liquid bitumen occurs in the rock.

Scandinavian iron ore deposits have methane and other hydrocarbons in boreholes that intersect pitch and asphalt within the deposits, and methane and nitrogen in boreholes and fissures in arsenic and sulphide ores.

In eastern Europe, petroleum and gas has been observed in igneous and metamorphic rocks in Yugoslavia, as well as in some copper mines in Hungary, and in mica schists containing limestone intrusions in Romania.

Granites in Cornwall and Aberdeen in the UK, and iron ore deposits at Cleveland all report hydrocarbon gases, associated with overlying bituminous shales. Also Derbyshire lead mines have reported methane along with bitumen.

Canadian Shield mines have methane, other hydrocarbons, and sometimes hydrogen and helium (Fritz et al, 1987, Andrews, 1987). These are widespread and occur in almost all the mines, particularly where carbonaceous materials are found in the rocks. Although widespread, the emissions are usually associated with boreholes (Sherwood et al, 1988) and relatively short lived and easily dissipated (Bord, 1998). Kidd Creek mines have methane pockets associated with sulphide deposits, (Jurenovskis, 1998), but consider SO_2 to be a much more significant problem, and the heating of sulphide ores.

At some Canadian Shield mines the occurrences of methane and hydrogen increase with depth (Sherwood, 1996), and the resulting gas mixtures reduce the LEL to as low as 4,5 per cent.

The Ontario Ministry of Labor (OML), including the Sudbury mines, has approximately eight reports per year of combustible gas in an underground working place (OML, 1996). These are almost always from boreholes, with concentrations of 0,1 per cent - 10 per cent. Gas is only very seldom detected in the general body. Ignitions have been reported to the OML due to cigarette smoking and to frictional ignitions.

The USA has methane emissions associated with oil shales, salt, trona, potash, limestone, copper and uranium ores.

In Australia hydrocarbon gases are reported from copper mines, and from Precambrian rocks at Kalgoorlie. In general however, methane or other combustible gases are not considered to be a significant problem in Australian mines (Whitely, 1998). The usual type of intersection is a diamond drill blower and readily dispersed. One explosion in an unventilated stope in Western Australia was suspected to be due to a mixture of methane and carbon monoxide, although details are not available.

South Africa has combustible gases in almost all gold and platinum mines, as well as kimberlite pipes. Along with the methane there can be hydrogen and helium. The usual assumption is that the methane is associated with overlying Karoo strata, which is coal bearing (Searra, 1990, Eschenburg, 1980, Jackson, 1957). The gas is then transported downward through the rock dissolved in water.

2.2.1 Emissions in South African non-coal mines

Emissions of combustible gases are widespread, and although gas mixtures are reported, this is often on a more general level, rather than specific. The origins and transport mechanisms are not well understood.

2.2.1.1 Gas mixtures

Methane is the predominant gas, but other higher hydrocarbons, as well as hydrogen, have been detected. Table 2.2 shows some reported ranges of mixtures, compiled from several sources (Searra 1990; Eschenburg, 1980; Greig, 1989; AAC, 1997a).

Table 2.2 Combustible gases in South African mines

GAS	SYMBOL	PROPORTION, Air Free (%)
Methane	CH_4	80 – 100
Ethane	C_2H_6	0 – 1
Propane	C_3H_8	0 – 1
Butane	C_4H_{10}	0 – 5
Hydrogen	H_2	0 - 20
Hydrogen sulphide	H_2S	Trace

The other main components are non-combustible, or inert, and comprise nitrogen, helium and argon, with helium being the most common. The nitrogen may be a product of the coalification process (Searra, 1990) and the argon and helium are usually assumed to be radiogenic in origin (Hugo, 1963).

The possibility of extracting the helium on a commercial basis has been investigated several times (Hugo, 1964; Greig, 1971).

Table 2.3 Non-combustible gases in South African mines

GAS	**SYMBOL**	**PROPORTION, Air Free (%)**
Argon	A	trace
Helium	He	0 - 15
Nitrogen	N_2	0 - 27

2.2.1.2 Origins and transport

The origins of the methane in gold mines is normally reported as coal seams, or carbon within the reefs, and that it moves through the strata in association with fissures and water (Jackson, 1957). The gas either moves along with, or dissolved in, the water.

In the Bushveld platinum mines magmatic fluids, not coal, have been postulated as the original source of the gas (Visser, 1995), but also with fissures as transport mechanisms (Hartley, 1992).

The gas sources and transport are covered in detail in the geological evaluation later.

Barometric pressure has also been proposed as a factor controlling the movement of methane. A drop in barometric pressure allows methane to flow more easily from the fissures (Eschenburg, 1980) and some correlation has been obtained between changes in pressure and combustible gas explosions (Fauconnier, 1989).

Within the strata different gases may diffuse at different rates (Rogers, 1998). This can produce samples of predominantly one gas over another, depending on the time of sampling. Helium is the most noticeable example of this, as it has a high diffusion rate due to small molecular size. However, the molecular size of the hydrocarbons also varies, and could result in separation. This may have occurred for reported high butane readings during some analyses.

Transport within the ventilation after emission is often considered to have layering and separation (various sources including Greig, 1971; Rowe 1998, Phillips, 1998). However, the physics of gas behaviour do not support this (Crowcon 1996, Van Heerden, 1995), and although a common belief within the mining industry, the separation of mixed gases is very unlikely.

2.3 Detection and measurement

Standard methanometers are the usual means of combustible gas detection, although the shortcomings for additional gases and gas mixtures have sometimes been identified (CPUG, 1995). The effect of mixtures combining the readouts of the individual gases to increase the true reading has also been reported (COM, 1990).

Gas detection systems and detection methods are well documented elsewhere, and are not for detailing in this output, but some relevant points are discussed. The monitors used on the individual mines are discussed in the technical review, and output three of the project will research the suitability of present detection systems and instrumentation in detail.

2.3.1 Pellistor sensors

Catalytic pellistors are used for the detection of most flammable gases, and one detector can therefore monitor a wide range of gases. However, the detector must be calibrated for each specific gas, or gas mixture.

In the normal mining situation the detectors are calibrated for methane using standard methane calibration gas mixtures of 1,4 per cent or 2,5 per cent. When other gases, such as hydrogen or higher hydrocarbons are present the readout should be adjusted by a correction factor.

Suppliers and manufactures of detectors have a range of correction factors for individual gases, and some examples of these are given in Table 2.4.

Table 2.4 Example correction factors for pellistors calibrated in methane

Gas	Correction Factor (LEL) (calibrated in methane)
Ethane	1.4
Propane	1.3
Butane	1.6
Hydrogen	1.2
Carbon monoxide	1.2

(adapted from Schauenburg, 1998)

These correction factors are for individual gases. The gas emissions in underground mines are normally a gas mixture containing some or all of the gases listed. For a mixture of gases the LEL of the mixture must first be calculated, and the correction factor is then assumed to be the same as an equivalent gas with a similar LEL to the mixture (Lewis, 1998). This requires obtaining a complete list of correction factors for a range of gases from the manufacturer or supplier for specific detectors.

2.3.1.1 LEL for gas mixtures

A relatively simple method to calculate the lower and upper explosive limits for gas mixtures is Le Chatelier's Rule (Hughes and Reybould, 1960). This has been proven for mixtures containing methane, other hydrocarbons, hydrogen and carbon monoxide (Coward and Jones, 1952) so is acceptable for the most likely mixtures obtained.

However, it does not hold for all gases or gas mixtures, so should not be applied indiscriminately.

The rule can be applied to both lower and upper explosive limits.

$L_{mix} = 100 / (P_1/L_1 + P_2/L_2 + P_3/L_3 + \ldots)$

Where : L = explosive limits of the individual gases
P = percentage of each gas in the mixture by volume

An example of the application if this is to a combustible mixture determined by Elandsrand Gold Mine (AAC, 1997b). The combustible gases on an air-free basis were:

Methane: 45,8 %
Ethane: 6,8 %
Propane: 1,0 %
Butane: 13,5 %
Hydrogen: 32,8 %

Applying Le Chatelier's Rule gives an LEL of 4,2 per cent and UEL of 19,2 per cent for the mixture, considerably different from that of methane alone.

2.3.2 Gas chromatography

Gas chromatography is a technique that accurately identifies the individual gases comprising a mixture, but it must be carried out in controlled laboratory conditions. Gas samples for detailed gas chromatography analysis are collected in glass pipettes or Tedlar bags.

The gas sampling and collection process must be correctly implemented, as some contaminants can give false gas readings.

A common error in hydrocarbon testing is due to water vapour, which can be misread as butane during chromatography (Rogers, 1998). This is very significant in terms of the gas mixtures emitted in South African mines, and a gas sample should be chemically dried over anhydrous calcium chloride during the sampling. This type of error may account for some unexpectedly high butane results previously recorded (AAC, 1997b).

Helium quantities in a sample can be under estimated due to its very high diffusion rate through materials. Helium samples must be collected in glass pipettes or stainless steel canisters (Pieters, 1998), and analysed as quickly as possible afterwards. It can leak through Tedlar bags much more readily than from properly sealed pipettes.

2.3.2.1 Reporting of gas concentrations

Analysis results from gas chromatography tests must be reported on an air free basis. During sampling, air contamination can occur, and this does not reflect the true readings of the emission gas.

The gas results from chromatography indicate the amount of a gas as a percentage of the total sample, which can be relatively small. A result of 0,6 per cent ethane at Elandsrand Gold Mine (Elandsrand, 1997), was interpreted as insignificant, whereas air free it actually represented approximately 7 per cent of the combustible gases.

Air free volumes are required to apply Le Chatelier's rule, for calculating the explosive limits, and the gas mixture referred to from Elandsrand in fact produced an LEL reduced to 4,7 per cent.

2.4 Control of combustible gases

Mine standards for ventilation are covered in Chapter 4, the technical review, and all procedures and practices, including legislation and guidelines will be fully evaluated during output three of the project.

2.4.1 Standard practices

The normal means of dealing with accumulations and emissions are well documented (various including Greig, 1989; Eschenburg, 1980), although a part of this is based on the assumptions that gases separate depending on relative densities. The methods include ventilation, cementing or plastering fissures, water infusion of fissures, drainage and compressed air.

Cementing, plastering and water filling of fissures are only partly successful, with drainage seen as a good advantage due to the collection and removal of the gas from the workings.

Additional clearing of accumulations has required drainage or flushing boreholes (Walters, 1992)

It is generally considered that the relatively small methane volumes can be controlled by good ventilation practice and proper detection procedures (Jackson, 1957; Kidd ,1997), and that other procedures are additional for particular circumstances.

2.4.2 Legislation and guidelines

Legislation tends to use the term flammable for gases that will burn or explode.

South African legislation limits the permissible quantity of flammable gas to 1,4 per cent in air (Reg. 10.6.6) but does not define flammable gas. The assumption is that the gas is methane, and that the LEL is 5 per cent in air. This is 28 per cent of the LEL of methane, which is relatively high compared to the levels in other countries with similar gas mixtures. Kidd Mining Division (Kidd, 1997) have low level alarms at 5 per cent of LEL.

In the USA hard rock mines are classified as Category IV if they have not had methane above 5 per cent, and require no special electrical or diesel equipment. If methane is above 1 per cent, the mine is classified as Category III, and must use intrinsically safe and flameproof equipment (US CFR). In Quebec, intrinsically safe, and flameproof equipment is required in the presence of any concentration of methane.

The OML in Canada defines a flammable or combustible gas as any gas that will burn in normal concentrations of oxygen, and acknowledges that this is usually methane, but that mercaptans (sulphurs) or natural gas may also be present (OML, 1996). It is recommended that after an emission work only resumes at concentrations below 0,5 per cent, or equivalent 10 per cent LEL of methane.

A guideline for flammable gases in Australian underground metalliferous mines is presently being drafted (Whitely, 1998). It is intended as a general document, and may not provide specific information.

2.5 Terrestrial methane sources

To consider the sources and origins of strata gases, it is necessary to look at which gases are present and the possible origins of each. Methane normally comprises 80 per cent - 100 per cent, of the gas emitted, although this can be as low as 45 per cent. This makes it the most significant constituent of the gas mixtures and the most likely to be encountered. It is therefore considered the best indicator of the likely origin of the gases.

Sources of terrestrial methane can be subdivided into two classes (Schoell, 1988). Where organic matter is the ultimate source of methane, it can be termed biogenic or biogenetic. Where the source does not directly include organic matter, the methane is abiogenic or abiogenetic. These categories can be subdivided into bacterial or thermogenic for biogenic gas, and hydrothermal or mantle for abiogenic (Gold, 1979, Schoell, 1988, Welhan, 1987). These are indicated schematically, in Figure 2.1.

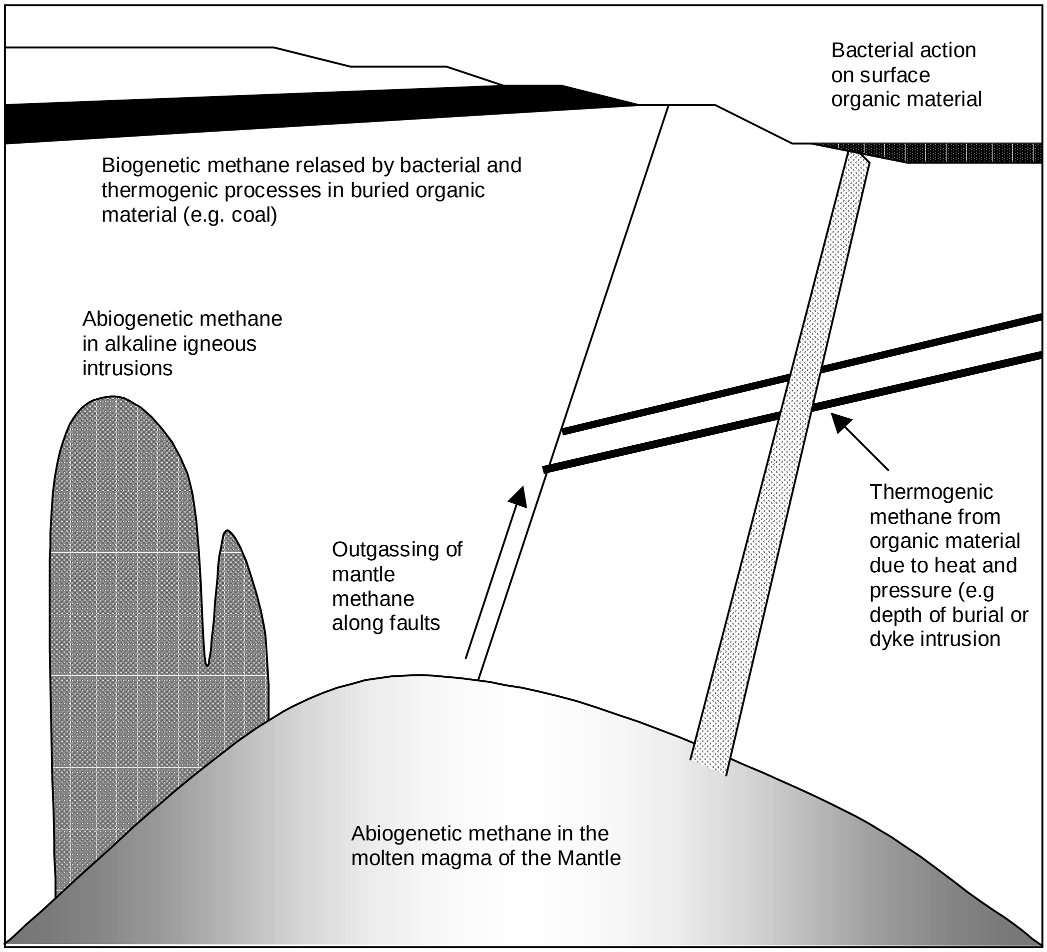


Figure 2.1 Sources of methane in the earth

2.5.1 Biogenetic methane

In young or recent sediments methane is produced and consumed by bacterial processes involving CO_2 reduction or fermentation. This is termed bacterial or microbial methane. This methane is typically that from landfill sites or coal seams, or released during the coalification process.

In deeper sections of the crust, methane is a product of the conversion of organic matter under the influence of elevated temperatures. This is termed thermogenic methane. It occurs where, for example, dykes are intruded into sedimentary rocks containing organic material. Cracking processes of high molecular weight organic matter is the probable source, releasing methane. Depth of burial to several kilometres for several thousand million years can, in theory, also produce this form of methane.

2.5.2 Abiogenetic methane

Methane and other hydrocarbons are present in large quantities in the molten mantle material beneath the Earth's Crust, where methane is stable under high temperatures and pressures (Gold, 1979; Gold and Soter, 1982). This has been determined from outgassing methane, the presence of hydrocarbons in meteorites, and their occurrence in igneous rocks.

This gas is released from the mantle in many ways, including volcanic gases, earthquakes and geothermal fluids.

Methane is found in fluid inclusions (or vesicles) of metamorphic and alkaline igneous rocks (Konnerup-Madsen et al., 1981). In a 300 million year old agpaitic alkaline intrusive complex on the Kola peninsula concentric hydrocarbon zoning and association with pegmatite mineralogy indicates that methane and other hydrocarbons originate within the cooling magma (Welhan, 1987). Hydrocarbon gas content of 200 cc per kg of rock are recorded. Bituminous substances in addition to hydrocarbon gases are also found in certain alkaline igneous rocks, e.g. the Ilimaussaq intrusion, South Greenland. Methane has also been found in inclusions in diamonds and in very small quantities in inclusions in Mid Ocean Ridge basalts (Welhan, 1988).

Methane emanates in very minor quantities in recent volcanic gases (Symonds et al., 1994, Cadle, 1980, Gold, 1979), with geothermal waters on continents and with hot water vents at mid-ocean ridge volcanic spreading centres (Welhan, 1987, 1988), where up to 2.5 cc of gas per kg of vent fluid have been measured. These are generally areas where intrusion of magma and creation of new igneous rock is actively occurring, and these geothermal or hydrothermal gases probably originate in the mantle (Welhan, 1987). They may also be the result of the thermogenic action of hot fluids on organic-rich host rocks which is then biogenetic.

Combustible gases are released at ground surface over the outcrops of major structures when earthquakes occur (outgassing). Methane is one of the major components of these gases (Gold 1979) and originates in the mantle. If methane can move rapidly along active structures during earthquake activity it is likely to also slowly move upwards along any other permeable of porous structures, including major faults, pervasive joints and porous stratigraphic horizons. Waters of lakes along the East African rift system are enriched with methane (Gerlach,1979, Gold, 1982), possibly through this type of mechanism.

The likelihood of encountering methane in igneous rocks is a function of the magma geochemistry and the temperature-pressure regime during cooling and solidification (Gerlach, 1979, Gold, 1982). This is indicated in Soviet literature on alkaline intrusions which generally reports methane in secondary fluid inclusions with homogenisation temperatures of 200-500 ^{o}C, indicating creation during the later stages of the cooling process, while primary inclusions (800-1050 ^{o}C and 1-1.5 kbar pressure) contain carbon dioxide and no methane. At temperatures below 600 ^{o}C these gases are estimated to become supersaturated with carbon, i.e. graphite.

Note that it is only igneous intrusions of alkaline composition (where feldspar is predominantly sodic or potassic) which are reported to have associated hydrocarbons, especially methane. Feldspathoid crystals of nepheline and sodalite in particular have been noted to contain methane in inclusions. Non-alkaline rocks (with calcium-rich feldspars) show inclusions with carbon-dioxide, carbon monoxide and hydrogen (Konnerup-Madsen et al., 1981). The presence of hydrocarbon-rich fluids during the later stages of solidification of alkaline intrusives could well influence the distribution of certain rare earth elements, including platinum.

In general, when considering the emission of methane from the mantle, if temperature is high, pressure reduced and oxygen donors are present, the equilibrium between methane and carbon dioxide favours the release of carbon dioxide (Gold, 1982). These conditions would occur in magma intrusions in relatively narrow feeders (dykes), where very hot magma is in close contact with pre-existing rocks, or where magma extrudes in surface volcanics and lavas. Hence methane is not expected to be widely found trapped in pores in lava flows or narrow dykes but is more likely in massive plutonic igneous rocks, where pressure is maintained during cooling. Outgassing through fractures where magma is not present, both under lower pressure and temperature, would favour the release of hydrocarbon gases, assuming these were present at the source of the gas in the Mantle (Gold 1979). The hydrostatic pressure of mantle gases is considered sufficient to open pathways from the mantle to crustal faults or fractures where gas can rapidly move to the surface without injection of magma.

It is expected that methane of mantle origin is released at a slow rate via fractures in most areas and it is not unreasonable to expect that its concentration might increase with depth, particularly in ancient rocks. However, methane of a biogenic origin has also been identified at great depth in Europe (Faber et al., 1995), and in volcanic gases associated with sea floor spreading areas in the Gulf of California (Welhan, 1987).

Methane has been observed in hydrothermal fluids, which is a term applied to any hot fluids circulating in the Earth's crust. These are frequently, but not necessarily, the residual fluids from igneous intrusions, which may leach material from any rocks they pass through. These fluids act as a transport mechanism for dissolved hydrocarbon gases, whose original source may be biogenic or abiogenic (Sherwood, 1988, Welhan, 1987, 1988). Such fluids, possibly bearing methane, are responsible for mineral infilling in many faults.

2.6 Identification of methane sources

Isotopic compositions of materials can provide a unique signature, indicating their origin or history.

For methane or other hydrocarbons the relative proportions of the different isotopes of carbon and hydrogen in methane samples, plus the percentage of C_{2+} hydrocarbons (ethane, butane, etc.) in the full gas sample mix have been used as an indicator of source (Schoell, 1983, 1988, Gold, 1977). Where the C_{2+} percentage is low, the mix is termed "dry". Documented research work is targeted largely at the petroleum industry, where gas is associated with or derived from crude oils, which are almost exclusively biogenetic in origin. However, these genetic models can be applied to mine gas intersections particularly through comparison of gas isotope ratios in methane samples to those in potential sources in the Witwatersrand and Bushveld areas.

For carbon, the isotopes ^{12}C and the heavier ^{13}C are generally used. Relative content is expressed using the PDB scale as $\delta^{13}C$, the deviation in parts per thousand from the adopted standard $^{13}C/^{12}C$ ratio of 1123.72×10^{-5}. The PDB reference is a sample from CO_2 prepared from a cretaceous fossil from the upper cretaceous peedee formation in South Carolina (PeeDee Belemnite, PDB) (Edwards and Durucan 1981).

For hydrogen in methane the relative content of deuterium to hydrogen (δD) is examined.

Typical identification of methane types are summarised in Table 2.5 (from various sources, including Gold, 1977, Schoell, 1983, 1988, Welhan, 1987), and shown in Figure 2.2 with the increasing ages of the methane sources.

Although generally classified by these groupings, there can be overlapping and mixing. Gases from different sources can move through the strata and mix before the sampling position. This can give a combined isotope mix that hides the different original sources.

Also the isotope ranges as shown in Figure 2.2 have a degree of overlap, and have been derived from many sources around the word. There is as yet no defined isotope grouping for the South African mines.

Table 2.5 Identification of methane types

Methane origin	**$\delta^{13}C$ ($^{0}/_{00}$)**	**δD ($^{0}/_{00}$)**	**Higher hydrocarbons, C_{2+}**
Bacterial biogenic methane	-55 to –90	-150 to –400	Low (i.e. dry)
Thermogenic biogenic methane	-20 to –60	-100 to –300	1-60% (dry to wet)
Geothermal/hydrothermal methane (general, i.e. biogenic and abiogenic)	-20 to –30		Moderate
Abiogenic geothermal methane (mid ocean ridges)	-15 to –18	-350 to -400	Low
Abiogenic methane in inclusions in igneous plutons	-3.2 to –14		
Mantle methane (general)	> -30		low, very dry

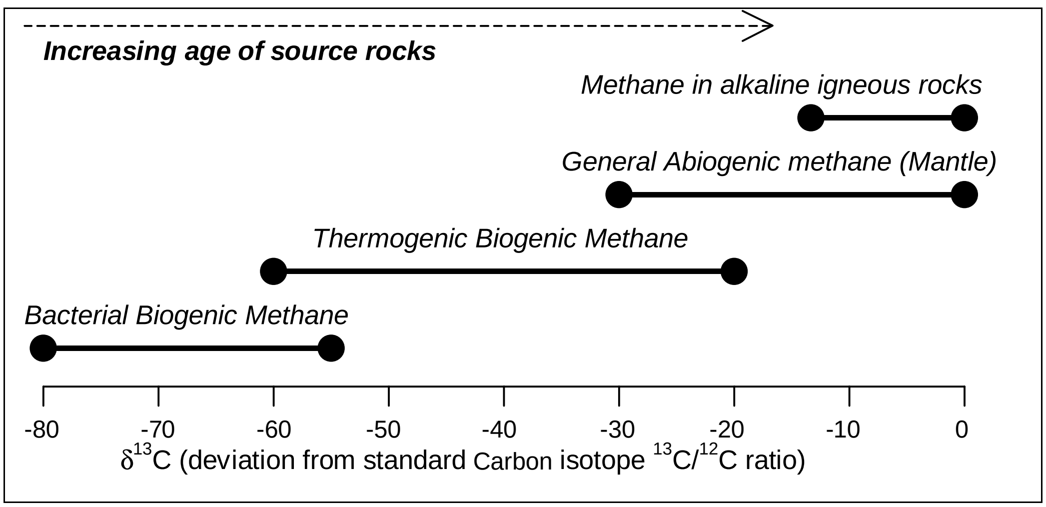


Figure 2.2 Methane carbon isotope signatures

For comparison, the characteristic of the carbon content generally occurring in rocks and other sources are given in Table 2.6 (from Gold, 1979).

Table 2.6 Identification of other sources

Location	**$\delta^{13}C$ ($^{0}/_{00}$)**
Average for terrestrial carbon	-10
Carbonaceous chondrites (meteorites)	+60 to –30 (mean –10)
Igneous rocks	-25 to –28

In general, biological processes result in substances that are depleted in the heavier ^{13}C isotope. Abiogenic processes give rise to ^{13}C enrichment not only in methane, but CO_2 or carbonate bearing igneous rock. The similar isotopic carbon in inorganic hydrocarbons in meteorites is assumed to be typical of that present in the early solar system (Gold 1979, 1982), to which carbon in the earth's mantle should also be similar.

The $\delta^{13}C$ value for methane samples can also be an indicator of geologic age (Schoell, 1983). Recent gas samples tend to be isotopically light, as bacterially produced methane. Samples from older strata are isotopically heavier which probably reflects a greater likelihood of having been subjected to temperature and pressure (thermogenic events), or infiltration by mantle methane, with age. The δD value also indicates increasing deuterium atomic content relative to hydrogen with increasing age.

In the petroleum industry, and in the Canadian Shield mines, it is generally concluded that, while trends can be observed, the exact signatures of isotope compositions of gas in a particular area will be the result of the specific geological and thermal history of the area (Schoell, 1983, 1988). The Witwatersrand basin and Bushveld complex rocks have some 2000 million years of history, ten times most of the commercial oil or gas fields. Globally, the only similar sized area of comparable age with significant mining activity is the Canadian Shield.

2.6.1 Other isotopes

The other isotopes that may give an indication of the origin are the deuterium (hydrogen) and helium. The presence of helium-3 (^{3}He) in gas samples is frequently assumed to indicate a mantle origin.

Deuterium is included in Table 2.5, and should be considered if the methane sources prove inconclusive.

Helium isotope analysis cannot be carried out in South Africa (Talma, 1998), and there is considerable difficulty in transporting samples to suitable testing facilities due to the high diffusion losses from canisters. Helium should be considered if carbon isotope analysis proves inconclusive for mantle origin gas.

2.7 Geological features of the Witwatersrand and the Bushveld Complex, with relevance to methane sourcing and transport

To gain a general understanding of the source of methane encountered underground a review and comparison of the relevant geological features of different areas of the Witwatersrand basin and Bushveld complex is required.

Relevant topics are potential methane sources, possible conduits for methane to migrate towards mining areas, and possible reservoir areas into which methane could migrate and become trapped. Gas sources may include the occurrence of carbonaceous matter, plus the nature of any igneous rocks which would have had associated gas phases at the time of intrusion, plus extensive faults or other pervasive structures which may provide a channel for transport of methane or other gases and fluids.

Although the Canadian Shield mines report similar gas mixtures to the South African mines, the geology is sufficiently different to not merit a full inclusion in respect of South African mines. For reference a brief overview of the geology of the Canadian Shield is in Appendix I.

Methane is generally reported as emitting from fissures and dykes, and originating in carbon sources within the strata. The connection between the two, if any, has to be established. Output two of the project researches the possible sources, and transport mechanisms of gas, so an initial direction has to be established from the geological evaluation. Where are the most likely sources, and what mechanisms allow for the release of gas from these into the workings?

A generalised North-South section illustrating the relative geological settings of the gold and platinum mines in the Witwatersrand and Bushveld strata is shown in Figure 2.3. The origins of the former are sedimentary, while the latter is igneous, although overlying sediments are similar to the Witwatersrand strata, with common basement rocks beneath.

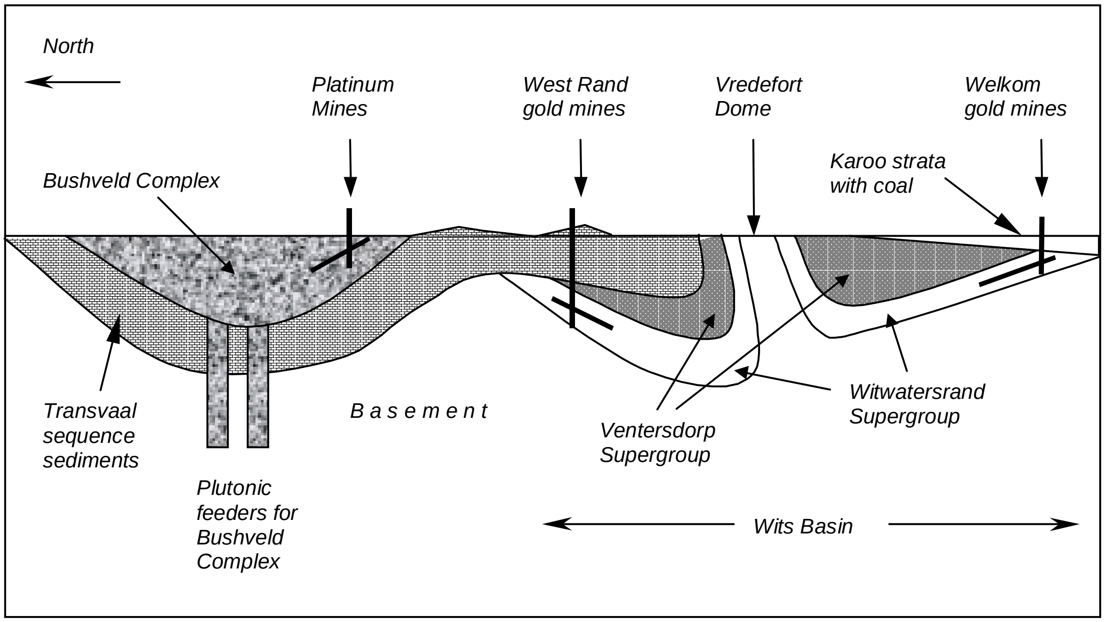


Figure 2.3 North-south section showing the relative locations of the Witwatersrand basin and Bushveld complex igneous intrusions (from Lurie, 1977).

Popular opinion is that coal seams are the main source of methane occurrences in many gold mines (Searra, 1990, Eschenburg, 1980, Jackson, 1957), although conclusive proof is not given. Impermeable shales in the Karoo strata provide a cap that prevents upward leakage of gas and fluid. Beneath this, the theory is that gas is dissolved in the groundwater in the Transvaal dolomite and Ventersdorp group aquifer which is drawn into underlying mine workings through channels along major fault systems. While under pressure, the gas remains in solution, however pressure drop (e.g. on entrance to mine workings) allows release of methane. There are some limitations to this coal origin theory, the first being that methane is found in mines where Karoo age strata bearing coal seams are not present. This includes much of the Witwatersrand basin and Bushveld complex (although prior to erosion coal seams would have been more extensively present). Further, the methane is required to migrate downwards through the strata for several thousand metres, i.e. driving a gas, which is lighter than air, against gravity and the lithostatic stress gradient. A further point against this theory is the reports that methane occurrence increases with depth, i.e. with increasing distance from coal strata.

Frequently, methane in the gold mines is reported to be associated with water-bearing or open, dry, fissures (Jackson, 1957). This is also observed in the Bushveld platinum mines (Hartley, 1992), however in this case magmatic fluids, not coal, have been postulated as the original source of the gas (Visser, 1995).

2.7.1 Witwatersrand basin

The strata containing the gold and uranium bearing reefs are sedimentary in origin, deposited around the margins of a subsiding, water filled, basin some 2700 to 3100 million years ago during the Precambrian Era (Robb, 1998). Reefs are generally obvious conglomerate bands with thicknesses ranging from a few centimetres to several metres, one metre is a typical mining average. Strata dips also vary, with 20 degrees being a typical average.

The generalised stratigraphy in different parts of the basin is shown in Figure 2.4. Note that the Karoo sediments are of Carboniferous age, and hence some 2000 million years younger than the Witwatersrand Supergroup, Ventersdorp and Transvaal Group strata. The Precambrian strata have all been subjected to mild metamorphism due to pressure and temperature resulting from moderate depth of burial over millions of years. As a result, original sand and siltstones are now quartzites with no negligible porosity or permeability or storage capacity for gas, except for that resulting from fractures such as faults, joints and bedding. Temperatures of 120 to 350 ^{o}C and pressure of 2.5 kb were thought to be reached during metamorphism of the strata (Hallbauer, 1986, Phillips, 1994).

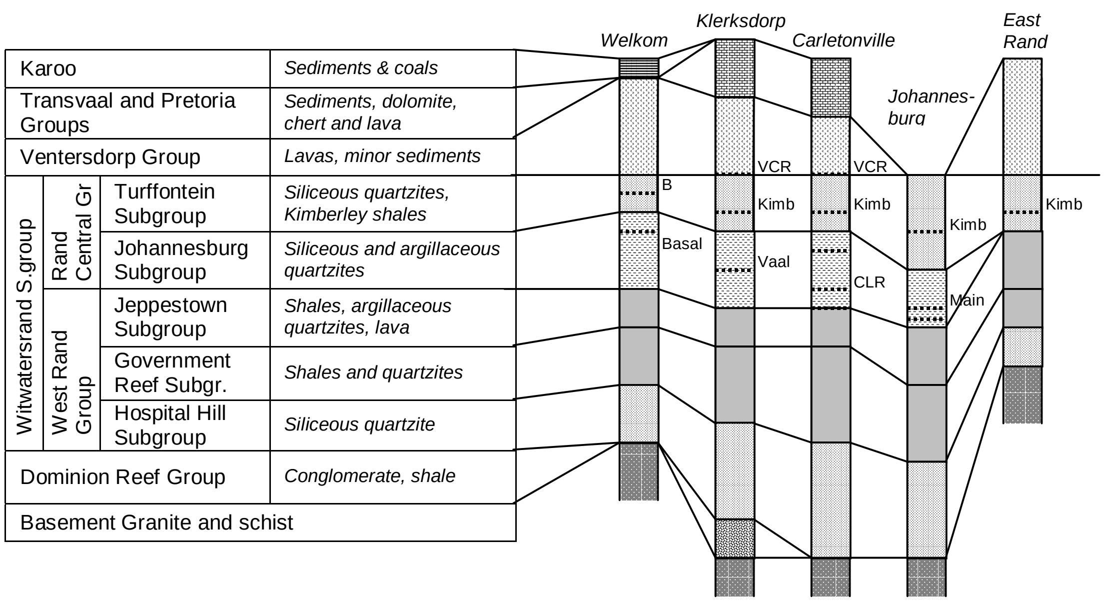


Figure 2.4. Generalised stratigraphy of the Witwatersrand Basin showing important reefs

(from various sources)

2.7.1.1 Sources of methane

Carbon, thermogenic

It is frequently stated that the Precambrian atmosphere was probably deficient in oxygen. To account for the oxidised state of Precambrian deposited, plus the source of surface carbon it can be argued that a substantial methane supply (possibly via mantle outgassing) would have been available during deposition (Gold, 1979). Note that certain of the granites around the Witwatersrand basin are not older basement rocks but were intruded during Witwatersrand deposition (Robb 1998) and as such would have possibly transported mantle methane. Such granites are included in the Johannesburg dome and the Westerdam and Hartbeesfontein domes near Klerksdorp.

Thucholitised hydrocarbon material occurs in the Witwatersrand sediments and strictly should be called kerogen or bitumen (Robb, 1998). This is found on depositional unconformities or other areas where low-energy sedimentation would have occurred during deposition (Snyman, 1965, Hallbauer, 1975, 1986, Minter, 1976). kerogen is found in most reefs and is associated with high gold, uraninite, and pyrite concentration. In all occurrences, it is similar in chemical composition and classification with medium and low volatile semi-bituminous Karoo coals (Coetzee, 1986, Haughton, 1964). As such, the kerogen may be expected to have similar capacity for absorbed gas, which would have been produced during diagenesis.

Several origins of the carbon present in the Witwatersrand sediments are considered possible. The kerogen represents the fossilised remains of algal mats attached to underlying sediment in shallow, 2 to 3 feet, water areas or where depressions occurred in the ground surface (Hallbauer, 1975). After sediment compaction, circulating fluid hydrocarbons from thermal degradation of organic material were polymerised, or hardened, and precipitated around and by radiation-emitting uraninite. i.e. detrital uranium trapped the hydrocarbons rather than vice versa (Robb, 1998). This is supported by U-Pb dating which places kerogen age at 2300 million years ago. It is also thought that hydrocarbon bearing fluids are necessary to account for gold mobilisation and concentration in the reefs. The presence of such fluids is supported by the existance of vein-quartz hosted fluid inclusions.

The kerogen occurs as 0.2 mm to 2 mm granules or in lustrous black carbon seams up to 10 cm thick. The main carbonaceous reefs are the Carbon Leader, Vaal, Kimberley, Basal, B and Bird reefs, and the Steyn Reef at St Helena, although present to some extent in all reefs. The carbon atom isotope ($\delta^{13}C$) composition of the kerogen from the Basal and B reefs shows values between –22.4 and –32.8, averaging -28.1 (Hoefs, 1967).

Outside the payable reef horizons, details of carbon content in sediments are scarce. In the Vaal reef clasts of carbonaceous clay (25 mm to 100 mm in diameter) with graphitic material on fracture surfaces are not uncommon (Minter, 1976). Carbonaceous, Precambrian, black shales are encountered in the Transvaal Group, overlying the Ventersdorp lavas, where structures in the dolomites have been identified as stromatolites, or algal colonies. Bituminous nodules are found in certain of the alkaline granites surrounding the Witwatersrand basin, and may provide evidence of circulating hydrocarbon-bearing hydrothermal fluids (Robb, 1998).

Coal seams, biogenic
Karoo age sediments containing coal seams are encountered across the Welkom and Springs-Evander parts of the Witwatersrand basin. However, small Karoo outliers, also with coal, occur in the Klerksdorp and West Rand areas, indicating that originally these areas, too, were covered by Karoo coal-bearing strata which has subsequently been eroded away.

Mantle and igneous intrusions, abiogenic
Methane coming from the mantle seems a more likely source than from igneous intrusions. Only dykes of Pilanesberg age are considered to be a realistic source, because they are sufficiently alkaline. However, all dykes are sources in that they are probable transport mechanisms, or reservoir areas.

2.7.1.2 Transport mechanisms
Dykes are more likely to be transport mechanisms than true sources of gas. As emissions are often associated with fissures, or dykes and with water, a possible means of movement through the strata is along the joint and intrusion planes.

During the millennia subsequent to deposition, under the temperatures and pressures resulting from depth of burial, the Witwatersrand strata have undergone low grade metamorphism, turning sand and mudstones to quartzites. Consequently the strata have almost no porosity, and any permeability is confined to joints (almost zero) or certain uncemented major faults where the roughness of the fault walls permits the presence of a network of small cavities which can be water bearing.

The Witwatersrand sediments are overlain, generally unconformably, by the andesitic or tholeiitic basalt composition Ventersdorp lavas in many areas, with the Ventersdorp Contact Reef often payable at the base of the lavas. These lavas were eroded away completely in certain areas prior to subsequent deposition of the Transvaal sequence. Various minor lava bands are found within the Witwatersrand strata, such as the Crown lavas.

Both during and after deposition the strata have been subjected to extensive tilting and faulting with throws from centimetres to kilometres. Creation of the Vredefort dome, generally concluded to be a meteorite impact approximately 2025 million years ago (Robb, 1998), is probably the last event that had a major tectonic effect on the Witwatersrand strata (although there are some later dyke intrusions) and *in situ* horizontal stresses around the basin appear higher in a direction towards the Vredefort dome.

Various ages and composition of igneous intrusion have cut through the Witwatersrand sediments since deposition (Haughton, 1964, Coetzee, 1986, Robb, 1998). These include:

1. Ventersdorp age near-vertical, variable width (2 to 20 m), North-south striking, diabase or epidiorite dykes, many of which would have been feeders to surface for the Ventersdorp lavas. These dykes are often associated with faults and may be water bearing.
2. Bushveld age, North or North-east striking, wide (10-15 m), extensively altered diabases. Contacts are sheared, often water bearing, and adjacent quartzites are blackened due to thermal metamorphism.
3. Pilanesberg age, wide (15 to 60 m) alkaline dykes (alkali dolerites, syenites), radiating from the Pilanesberg complex and in some cases showing several phases of intrusion of different compositions. Carbonatite dykes of this age also occur.
4. Karoo age, North-South or East-west striking, sometimes amygdaloidal, narrow porphyritic dolerites and associated non-porphyritic dolerites which often form sills in Karoo sediments.
5. Post-Karoo age kimberlite, lamprophyre and dolerite dykes. Some lamprophyres show a high olivine content, are highly altered and rapidly erode on exposure ("running dykes"). These dykes are all generally thin.

Many dykes have major fault planes associated with them. Some define groundwater compartments. A full list of dyke types is provided here as certain types may be more prone to gas intersections than others, due either to width, mineralogy, age, or prevalence of associated faulting and jointing. For example, if gas originates in Karoo coal then structures of Karoo or post-Karoo age would be most likely to provide paths for transport of gas to mine workings. In the Virginia area East-West striking faults associated with Karoo dykes were noted, in particular, to be water and gas bearing, while North-south structures are not. These fissures showed widths of 1 mm to 10 cm (Bekker, 1986)

At least four joint sets are present as discontinuities in the Witwatersrand strata in addition to bedding (e.g. Cambitzi, 1987, Lightfoot et al., 1994) . While joints are generally tightly closed or infilled with calcite and quartz when undisturbed by mining, major fault planes may be water bearing, even at the greatest mining depths, indicating that interlinked voids, or channels, exist along these structures. Northwest-Southeast trending, steep dipping, tension faults of post-Transvaal age cut the strata from surface downwards, providing conduits for water ingress from surface to mine workings. Strata storage capacities for water, and hence also gas have been estimated on the basis of expected voids (after Haughton, ed., 1964) to be less than 1per cent below the water table in the Transvaal dolomites and 0.018 per cent from measured fractures in Witwatersrand quartzites. Individual open fractures measured at West Driefontein generally had widths of 1/32 to 1/64 inch (4 to 8 mm), with a maximum of 1 inch (25 mm).

2.7.1.3 Reservoirs

The land surface prior to Karoo strata deposition was not flat. It has been noted for the Welkom and Evander mining areas (Brand, 1986), that where hills or domes existed in this pre-Karoo land surface, greater flows of gas are observed in the underlying gold mine workings in areas where the water table is drawn down in the Transvaal sequence dolomites. If impermeable Karoo age Ecca shales form cap rocks, methane would tend to be trapped beneath them in dome areas, however surface boreholes in such areas do not necessarily confirm this (Searra, 1990).

2.7.2 Bushveld complex

Tabular platinum and chromite reefs are hosted in igneous rocks of the Bushveld complex, and hence have a different origin to the gold reefs of the Witwatersrand basin, although its age, at approximately 2000 million years, also places it in the Precambrian Era. Consequently it is probable that sources of methane will be different.

The platinum ore bodies lie within the Rustenburg Layered Suite, a massive igneous sill-like intrusion (Coetzee, 1986) up to 8 km thick. This was created during a plutonic phase of the Bushveld igneous activity, when basic and ultrabasic magmas were intruded into the earlier Transvaal sequence sediments. Other phases of activity included acid plutonic intrusion and both acid and basic volcanic activity. The reef-bearing Bushveld igneous rocks show layering, which occurred as developing crystals settled out of the liquid magma during cooling. Successive surges of magma intrusion resulted in repeated layered units. A generalised stratigraphic column, showing the zones and main economic horizons, is given in Figure 2.5 (Viljoen and Schurman, 1998).

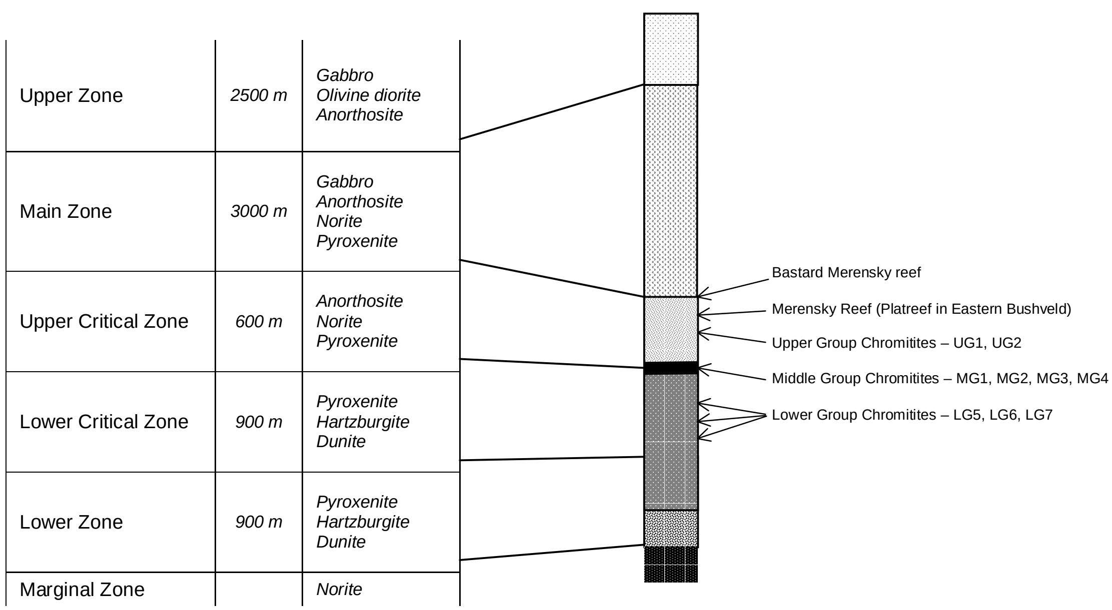


Figure 2.5 Generalised stratigraphy of the Rustenburg Layered Suite of the Bushveld Complex, showing important reefs (based on Robb, 1998)

A mantle plume is a favoured origin which has been proposed for the Bushveld (Hatton, 1995), in which case it would be similar to the current Yellowstone plume in North America.

The Bushveld Complex covers some 66 000 km^2. Mining occurs principally along the outcrop in the Western Bushveld Complex, near Rustenburg, North and South of the Pilanesberg volcanic intrusion. Other outcropping mining areas are 200 km to the East near Burgersfort and North-East near Potgietersrus. The principal mining horizons, the Merensky (Platreef in Eastern Bushveld), UG2 and LG6 reefs, lie within the central Critical Zone, and are pyroxenite bands with norites and anorthosites in hangingwall and footwall. The Merensky reef is generally thin, pegmatoidal (i.e. with large pyroxene crystals) bounded with narrow, weak chromitite stringers. However, along strike in the Western Bushveld, the character changes, becoming wider and more evenly crystalline. Trace quantities of graphite are frequently observed in association with platinum group metals (Viljoen, 1998): no other indication of carbon or hydrocarbon is reported. On average reefs have a mining width of 1 m and dip of 15 degrees.

2.7.2.1 Sources

The Bushveld complex methane is almost certainly abiogenic. The massive igneous intrusion makes any biogenic source unlikely.

Various structures developed in the layered complex as cooling, crystalisation and settlement of crystals in the magma took place. These include near-circular potholes in the reefs, and local areas with larger sized phenocrysts such as pegmatite veins and replacement pegmatoid bodies. Potholes represent a slump in the developing crystal lattice during formation and range in diameter from a few metres to several hundred metres (Viljoen and Schurman, 1998), with depths possibly exceeding 100 metres. These structures appear to have an association with methane occurrence (Hartley, 1992).

Dykes of Pilanesberg (alkaline), Karoo (dolerite and syenite) and post-Karoo age (lamprophyres), as listed above, are also present (de Maar, 1993, Lougher 1993). The alkaline Pilanesberg intrusion lies centrally in the Western Bushveld mining area.

2.7.2.2 Transport mechanisms

As with the Witwatersrand strata, the Bushveld rocks are generally impermeable, with fracturing again providing the only permeability. Layering in the igneous rocks gives an appearance similar to sedimentary strata, with occasional weak reef-parallel partings similar to bedding but actually thought to be thrust faults, such as at the Bastard reef and Merensky reef footwall, which form regional discontinuities (Viljoen, 1998). Three sets of orthogonal joints (De Maar, 1993) are present, however structurally, the Bushveld igneous strata are less disturbed than the Witwatersrand Basin. Small throw, steep dipping, faults and shear zones are present, with partings showing a high degree of shearing and alteration (serpentinisation). Serpentinisation of joints and faults appears to increase with depth and indicates the passage of fluids at some stage, although many joints are now infilled with calcite, chlorite and serpentinite. Joint spacings in the overall rock mass average 5 to 10 m (Godden, 1993), although considerable variation occurs, with density increasing (less than 1 m spacing) close to faults and dykes. Increased joint density occurs, in particular, close to certain thrust faults such as in the bastard Merensky which may mark the sheared interface between two magma intrusion phases. There is also generally a marked increase in jointing and minor faulting around potholes.

The stress regime in the Western Bushveld area, where horizontal stresses are frequently higher than vertical stresses, would favour the opening and development of flow paths for water or gas along reef parallel weaknesses, such as in the Merensky and Bastard reef zones.

Methane has been noted in association with lamprophyre and dolerite dykes, faults and fractures (Hartley, 1992), where fractures are seen only as transportation paths for methane.

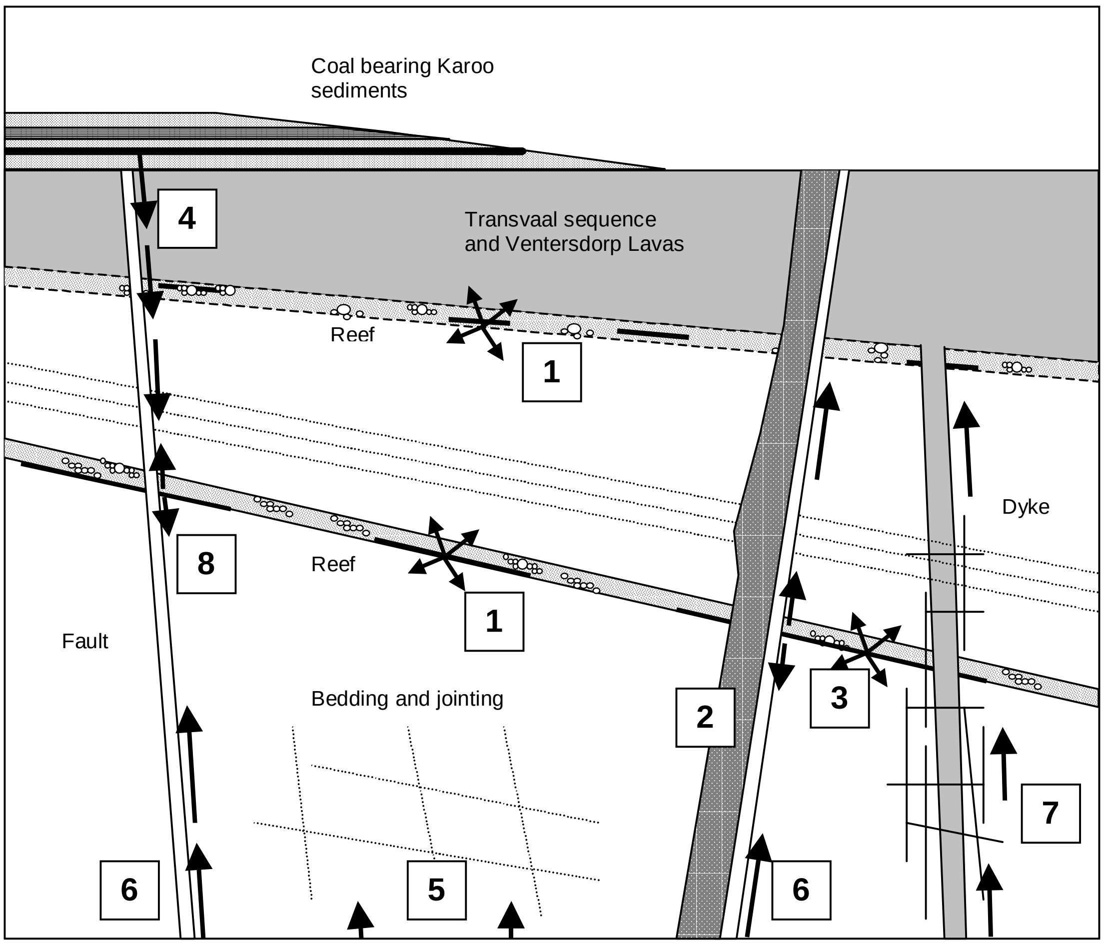
2.8 Evaluation of geological conditions to determine methane sources

On the basis of the broad outlines of the geology of the Witwatersrand and Bushveld, an estimate can be made of where methane is most likely to be located in gold and platinum mines, and what its origins, and hence isotopic composition, should be.

These areas will be investigated in detail in output two of the project, obtaining and quantifying gas samples, and geological evaluation of sources and modeling transport mechanisms.

2.8.1 Gold mines

The expected sources of methane for Witwatersrand gold mines are summarised in Figure 2.6.

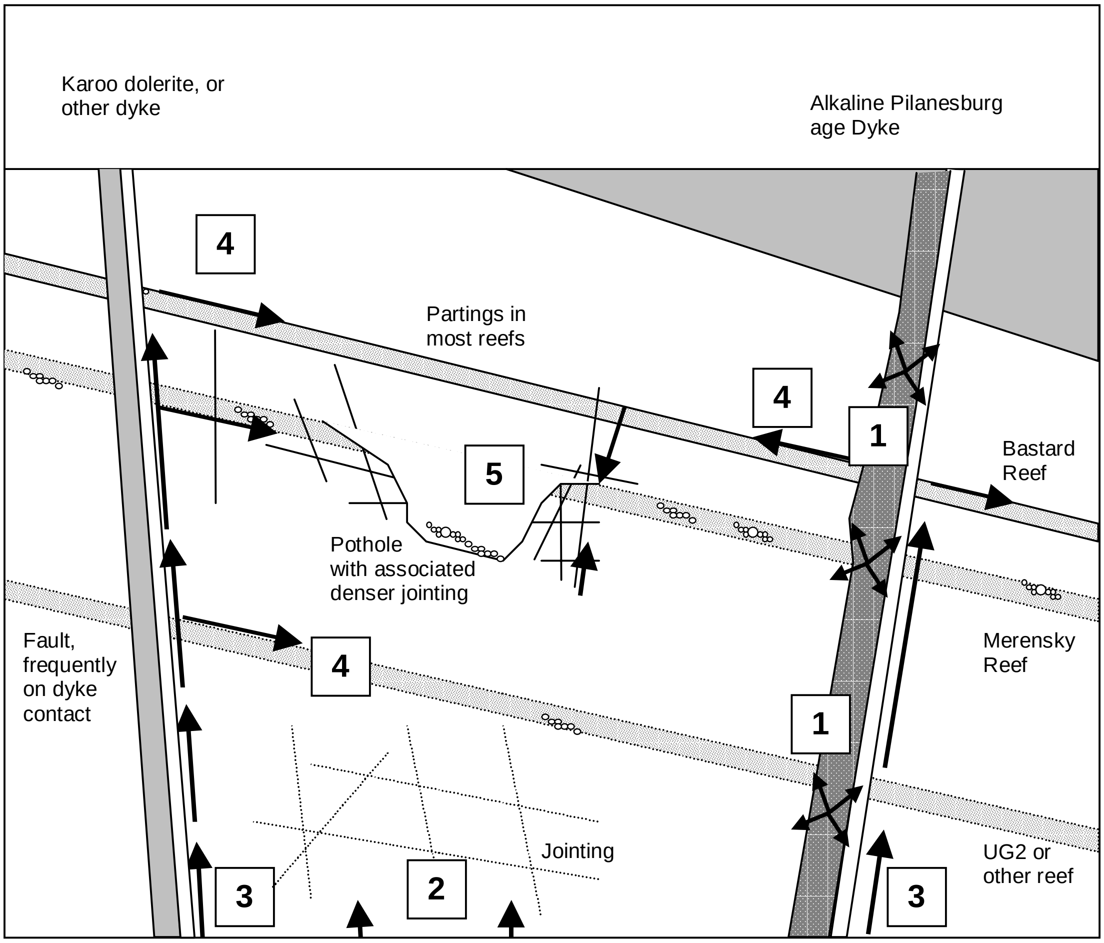


1 Associated with carbonaceous material in reefs
2 In inclusions in alkaline dykes (although unlikely in dykes generally)
3 Thermogenic methane where dykes have heated carbon in reefs.
4 Coal seams in overlying Karoo sediments, with transportation to Witwatersrand strata in solution in water via fault planes
5 General seepage of Mantle methane via joints and bedding
6 Strong seepage of methane along major faults, which are often along dyke contacts
7 Collection of methane in highly jointed areas, e.g. adjacent to dykes
8 Seepage of methane from reef carbonaceous material into fault systems

Figure 2.6 Potential sources, or occurrences, of methane in Witwatersrand gold mine strata

2.8.2 Platinum and chromitite mines

The expected sources of methane for the Bushveld complex mines are summarised in Figure 2.7.



1 In inclusions in alkaline dykes (although unlikely in dykes generally)
2 General upwards seepage of Mantle methane via joints
3 Strong seepage of methane along major faults, which are often along dyke contacts
4 Flow along partings associated with orebodies
5 Collection of methane in highly jointed areas, e.g. around potholes

Figure 2.7 Potential sources or occurrences of methane in Bushveld platinum and chromitite mines

2.9 Discussion, literature review

Emissions of combustible gases are widespread, and although gas mixtures are reported, this is often on a more general level, rather than specific. The origins and transport mechanisms are not well documented for mining.

Many countries report combustible gas emissions, with Canada and South Africa having the most widely documented gas contents and results. There are about eight gas reports per year for the Sudbury mines, with most of the other intersections being from drill holes. Deeper holes and deeper levels do intersect more gas, and the mixtures reported are similar to South Africa.

South African mines report methane, or mixtures of methane with ethane, butane, propane and hydrogen. There is sometimes helium and nitrogen present as well. Methane is the predominant gas, normally constituting more than 80 per cent of the gas mixture. Any toxic gases also present are a much more significant toxic hazard well below their LEL.

The mixture of gases affects the readings of pellister type methanometers, which do have correction factors for different gases. Suppliers should be contacted to obtain the factors. However, the gas mixtures must still be obtained on an air free basis by gas chromatography and the LEL calculated before correction.

Strata methane is of two main types, biogenic origin and abiogenic. The biogenic origin gas derived from an original carbon source, and the abiogenic most probably from the mantle. Isotope analysis to determine the ratio of the ^{13}C isotope in the carbon identifies the type and origin of methane.

The most probable sources for methane for the gold and platinum mines have been identified from geological evaluation of the Witwatersrand and Bushveld complex with specific reference to gas sources and transport. A total of thirteen possible target areas for methane in mines have been identified, eight for gold mines and five for platinum, and these will form the basis of the test procedures in output two.

3 Incidents and accidents review

3.1 Introduction

All available information was reviewed for flammable gas incidents and accidents reported to the DME for the 10 year period from 1987 to 1997. All regional DME offices were contacted by telephone and letter, and then visited to review the reports.

Only reports for gold and platinum mines were considered and reviewed, However, there are a considerable number of reports for other types of non-coal mines, particularly diamond mines. Other mines fall outside scope of this project, and have not been investigated.

A total of 1914 incident reports and 32 accident reports were located, although details could be recovered for only 25 of the 32 accidents. The accidents accounted for 25 fatalities and a further 36 reported injuries, including 6 fatalities and 21 injuries from platinum mines.

The incidents were evaluated in respect of the numbers, time, area, working place, as well as the percentage of gas if reported.

Information, statistics and data regarding all other accidents and injuries are from the Department of Minerals and Energy (DME, 1997)

3.2 Reported combustible gas incidents

The reporting of combustible gas incidents varies considerably, and not evenly distributed between mines or regions. This is partly due to the reporting requirement of Regulation 10.6.8, which stipulates that flammable gas must be reported if not detected for three months, partly to individual preferences of mine environmental personnel and management, the regional DME, and to the variable distribution of gas throughout the mines and regions.

Some mines reported every occurrence of gas, such as within cover holes, where others only report gas detected in the general body.

This presented difficulty in trying to normalise the data to e.g. production rates, as so many other factors can influence the data. Therefore, most of the information is reported as simple total of incidents, rather than normalised.

The incident data was collated on spreadsheets and evaluated for distribution with time, region, mines, working place and the percentage of gas detected.

3.2.1 Time distribution

The number of reports per year for all mines is shown in Figure 3.1, a plot of incidents against years. It is clearly seen that following a reasonably steady rate of reports from 1987 to 1991, there has been an increase from 1992 onwards. The trend line through the curve is clearly upwards.

The two peaks in incidents, in 1992 and 1995, coincide with, or follow shortly after accidents involving multiple fatalities (see Figure 3.11). These two years follow immediately after either steady or declining report numbers.

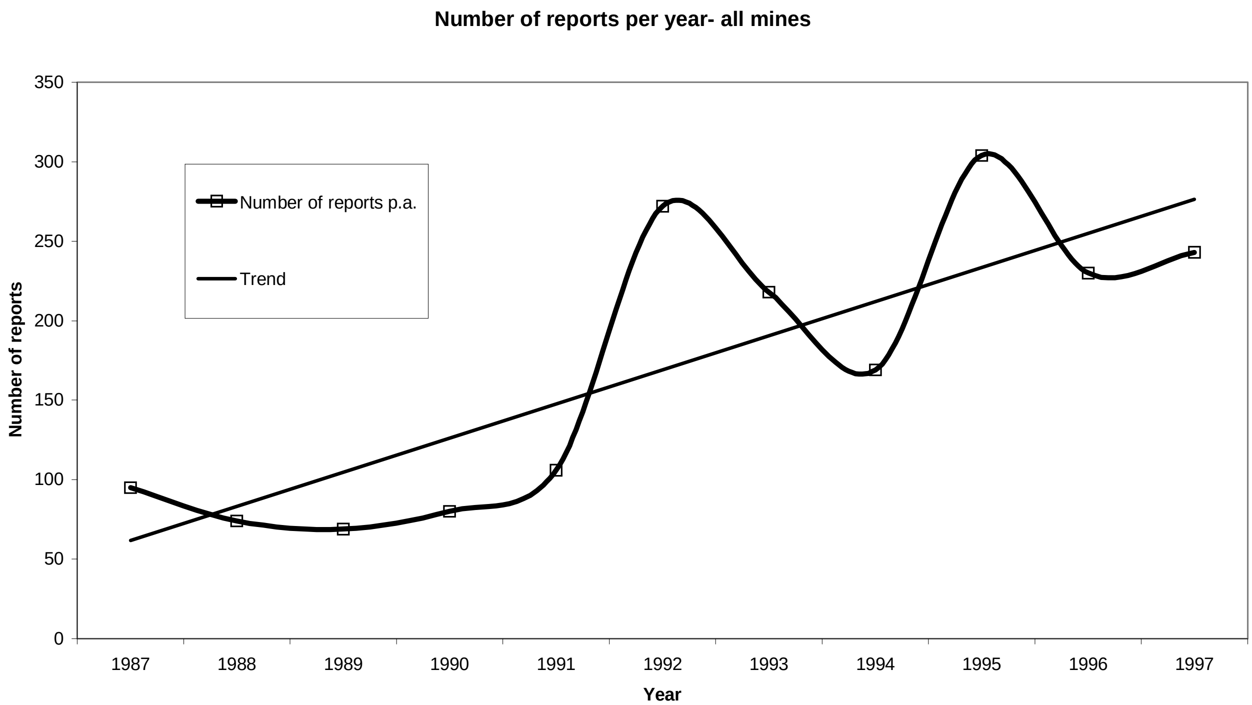


Figure 3.1 Total number of reported combustible gas accidents

The total incident data is shown separately for gold and platinum mines in Figure 3.2. The gold mine data, with the highest number of reports is very similar to the curve for total data, but the declining reports are more obvious from 1987 to 1991. Platinum mines show a steady increase in incidents throughout the period, from almost nil in 1987 to 100 in 1997.

The present number of reports is in decline, the same situation that has preceded the last two multiple fatality accidents.

This work did not consider any further distribution of the reports between months or days, however a previous review of gas explosions in gold and coal mines covered a period of twenty years prior to the scope of this work (Fauconnier, 1989). It concluded that there was an even distribution of gas explosions per months of the year, but that an explosion is most likely to occur on a Wednesday, and during the morning. This is attributed to production rates, and the number of men underground.

3.2.2 Commodity distribution

The proportion of occurrences in platinum mines to those in gold mines is shown in Figure 3.3. In this case the data has been normalised to number of incidents per number of mines. There is an approximate 1:2 split between the commodities, with gold mine incidents accounting for 69 per cent and platinum for 31 per cent.

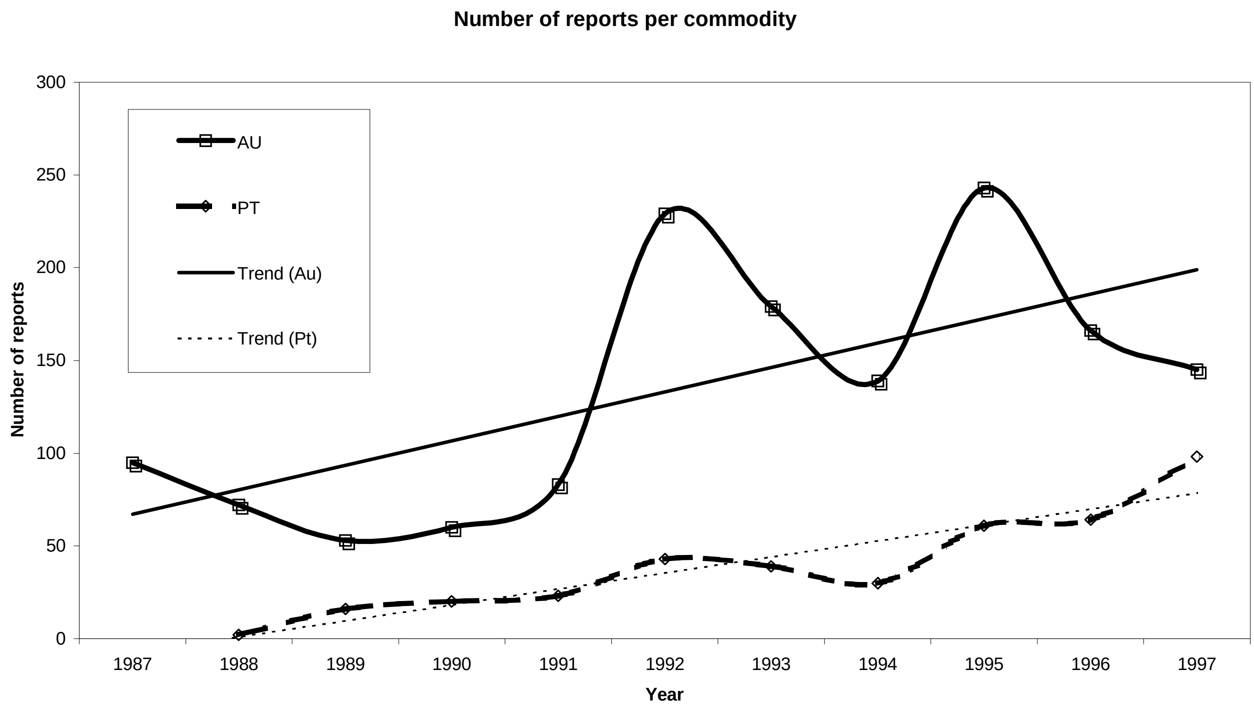


__Figure 3.2 Reported combustible gas incidents, gold and platinum mines__

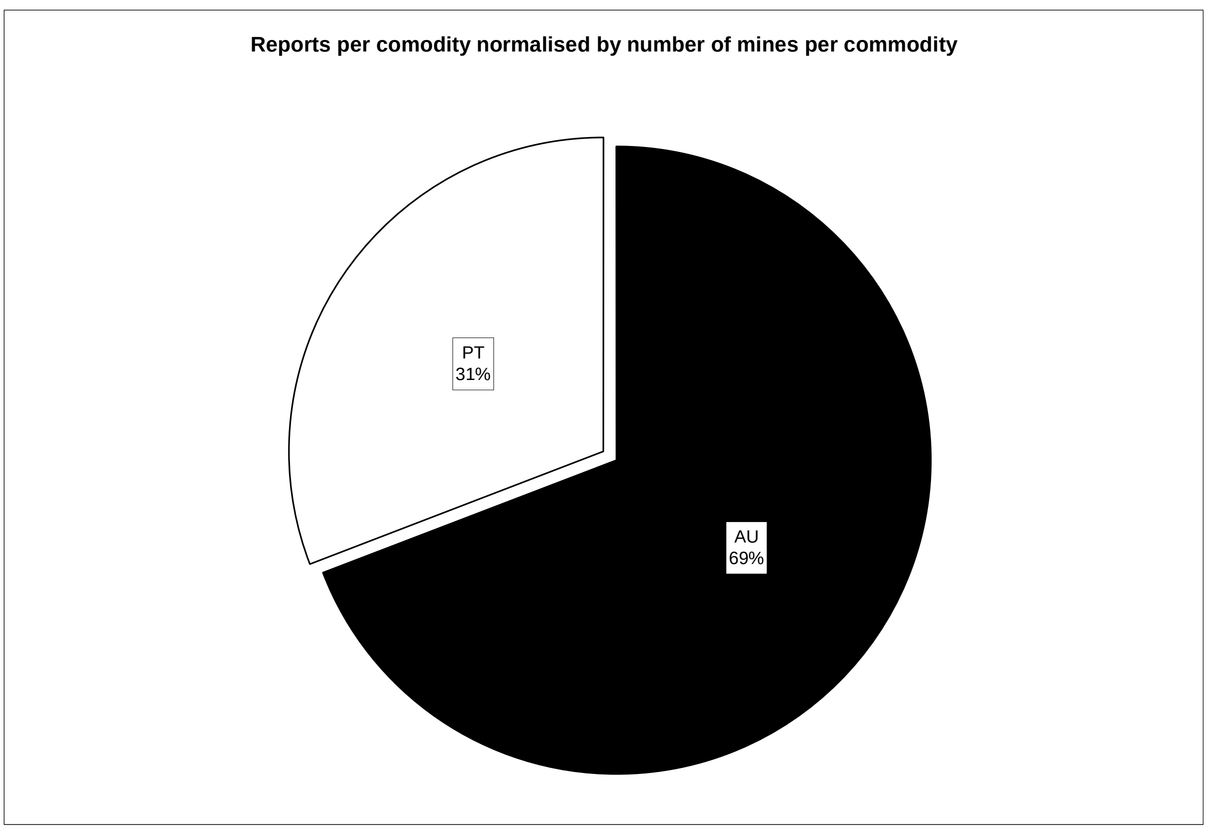


__FIGURE 3.3 Distribution of flammable gas incidents, gold and platinum mines__

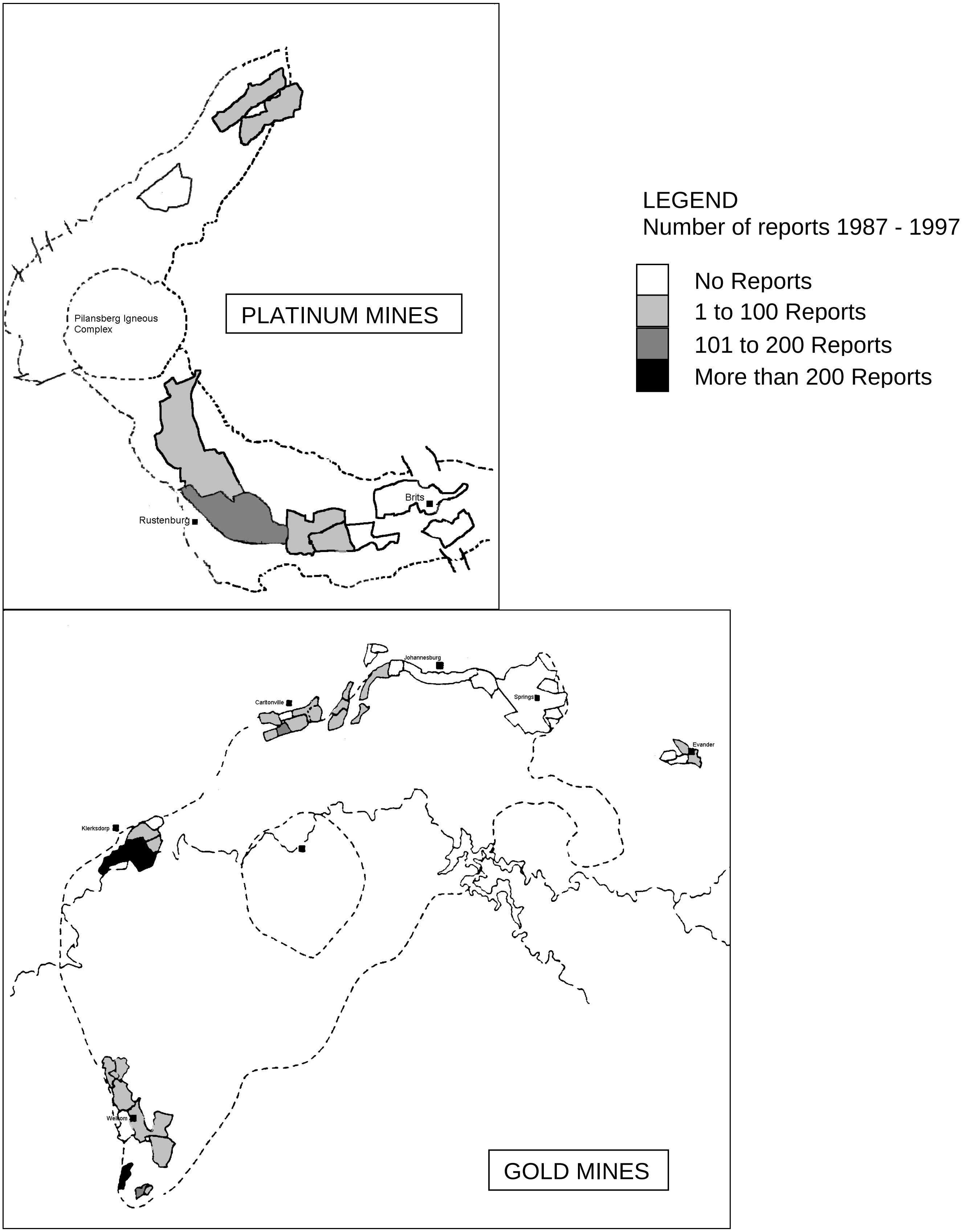


Figure 3.4 Geographical distribution of reported combustible gas incidents

3.2.3 Geographical distribution

Combustible gas in the last 10 years was reported from most mining areas across the Witwatersrand and Bushveld. Figure 3.4 (adapted from Spearing, 1995; Wilson and Anhaeusser, 1998) shows maps of the gold and platinum mining areas, indicating the numbers of reports from each region during the period, divided into categories of 100 reports.

Most are in the 0 – 100 category, with only two above 200.

There are few reports of incidents for the East Rand, Central Rand and West Rand goldfields from Springs to Randfontein, due possibly to less production in these areas, and different individual approaches to reporting.

3.2.4 Regional distribution

Reports from the regional DME offices are shown in Figure 3.5, which plots the total number of reported incidents against region. For ease of identification, these are presented as per the mining region covered, rather than by the name of the DME regional office.

Flammable gas incidents increase towards the Far West Rand, Klerksdorp and Free State, with relatively high occurrence in the Rustenburg area, which comprises platinum mines exclusively.

The Near West Rand, West Rand and Evander regions have very few incident reports.

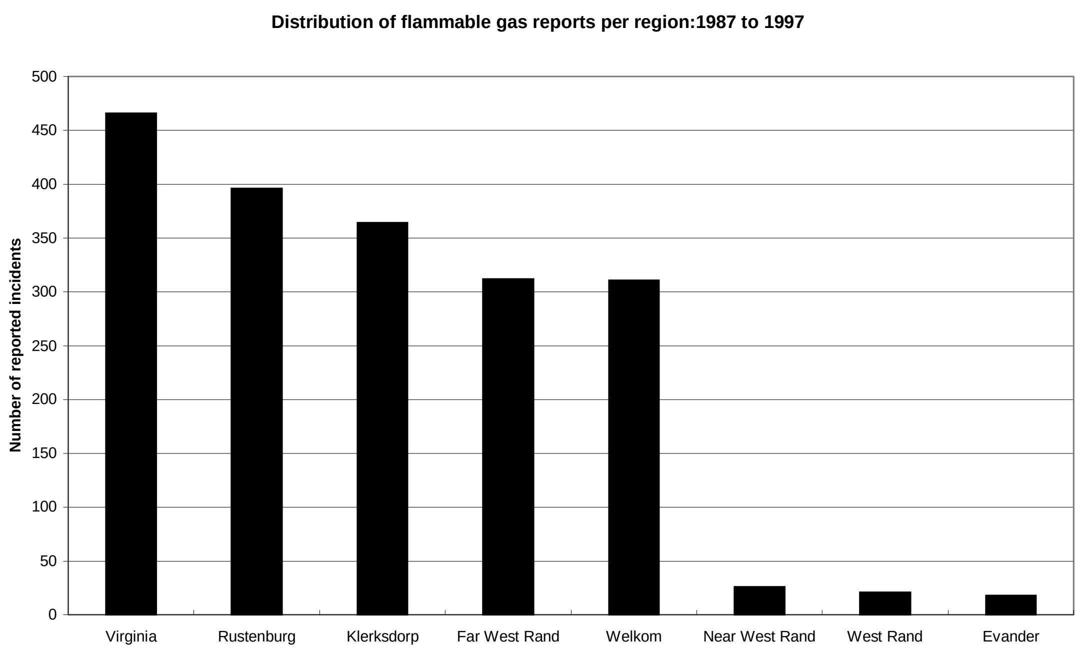


FIGURE 3.5 Reported flammable gas incidents, DME regional offices

3.2.5 Mine distribution

The distribution of incidents on a mine by mine basis is shown in Figures 3.6 and 3.7, plots of each individual mine against the total number of reports. Figure 3.6 shows the mines ranked from lowest to highest by number of reports. The extent of the variation between mines is clearly seen, although approximately two thirds of the mines have below 50 reports.

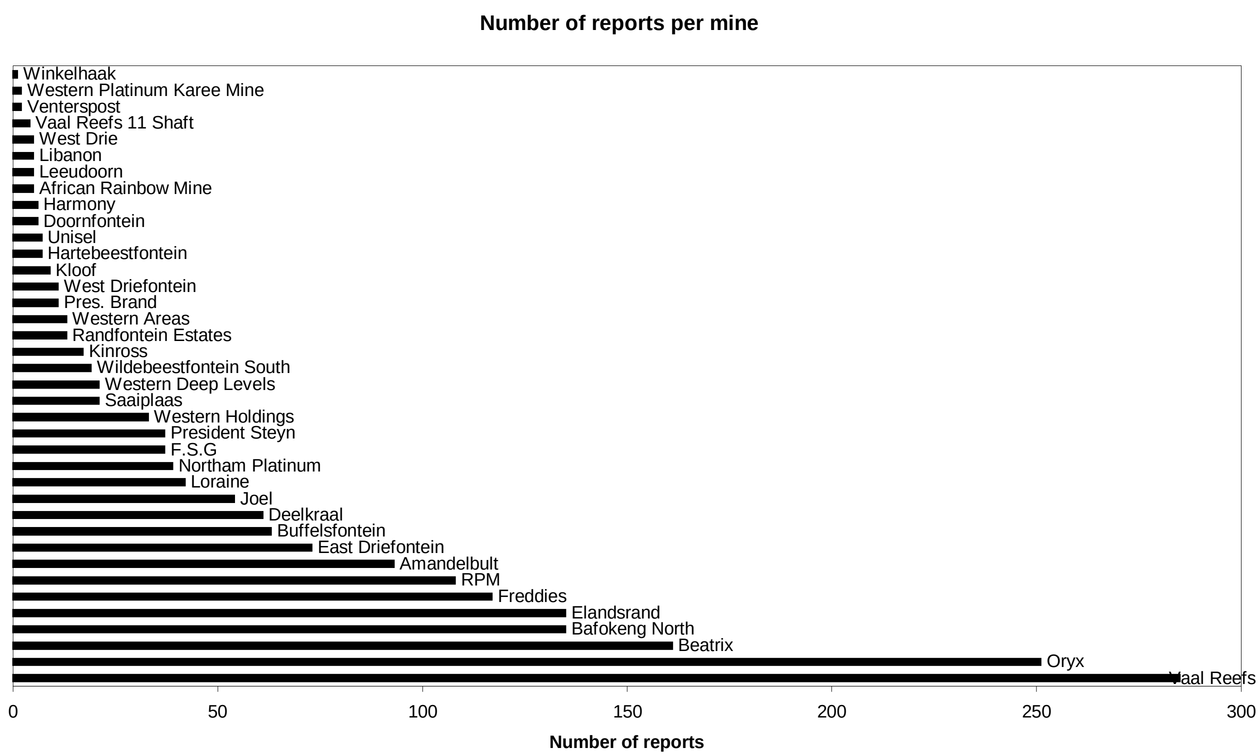


FIGURE 3.6 Reported flammable gas incidents, individual mines

The highest number of reports is from Vaal Reefs, at almost 300, with the lowest at Winkelhaak with almost nil. However, a straight comparison is difficult to make, as so many factors influence the total numbers, from personal preferences to production rate and even whether the mine is still operating.

The same information is again given in Figure 3.7, but this plot also divides the mines regionally.

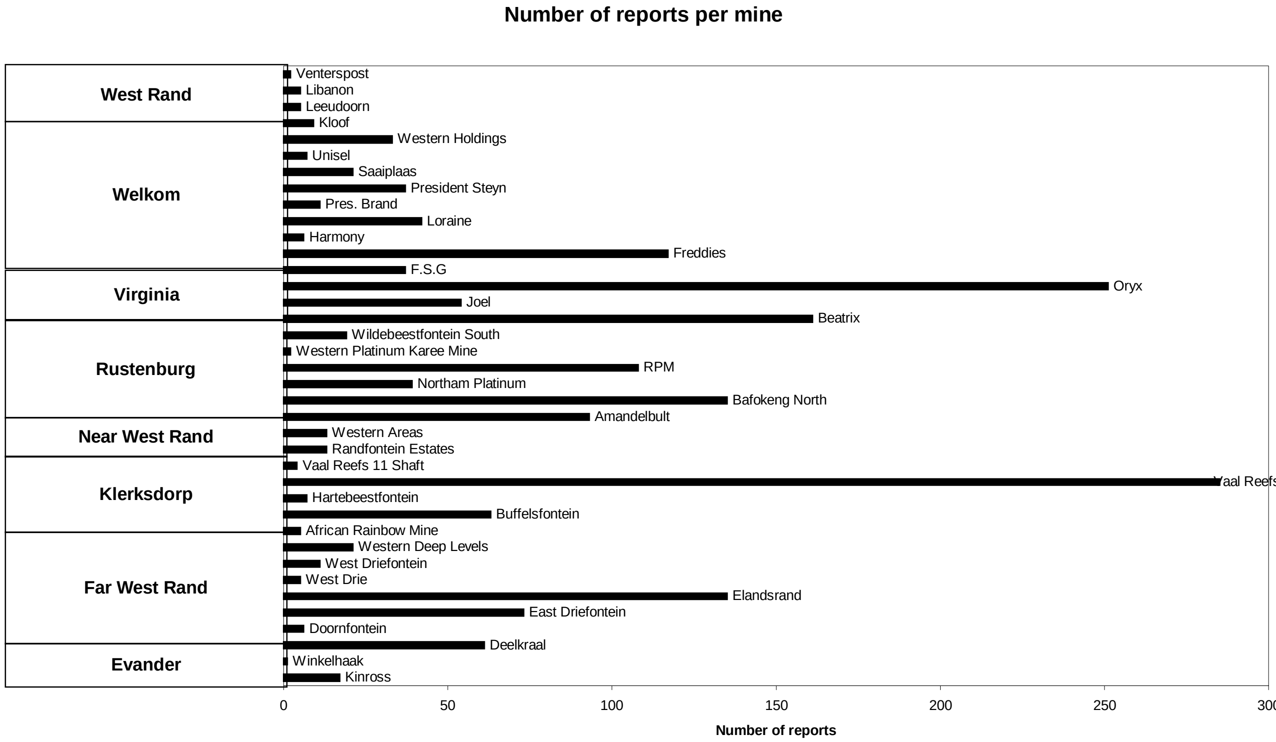


FIGURE 3.7 Reported flammable gas incidents, per mine per region

3.2.6 Working place distribution

The distribution of reports for different classification of working places is shown in Figures 3.8 and 3.9. Figure 3.8 shows the number of reports for each classification, and Figure 3.9 the percentage distribution.

Crosscuts and haulages report the most occurrences of gas with a combined total of 69 per cent, followed by stopes and raises with a further 11 per cent each. The remaining six classes of working place, and those ‘unknown’, all combined account for only 9 per cent of the total.

Almost all the reports are in off-reef development. This is not entirely unexpected as a lot of intersections are from cover drilling, but the number of stope interceptions is low at only 12 per cent. As the carbon associated with reefs is a commonly referenced methane source, the number of stope emissions may have been expected to be greater.

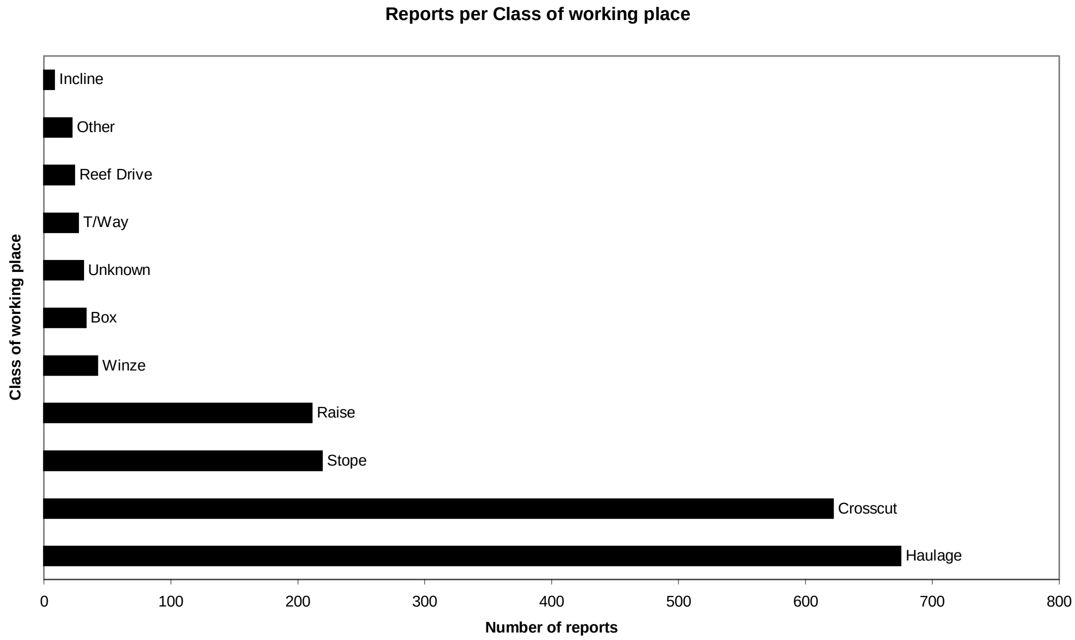


FIGURE 3.8 Reported flammable gas incidents, per working place

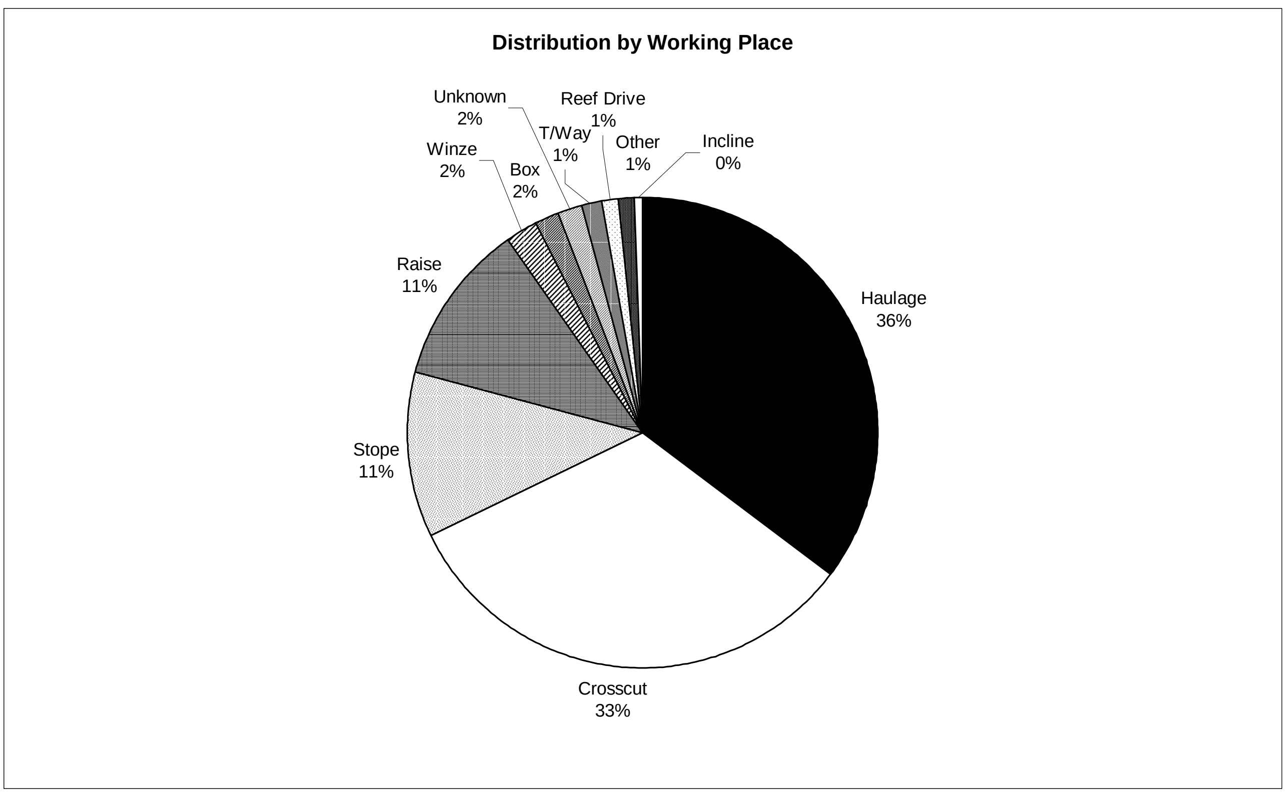


FIGURE 3.9 Reported flammable gas incidents, per working place

3.2.7 Percentage of gas reported

The percentage of gas concentration measured or reported for the incidents is shown in Figure 3.10, which plots the number of reports for each percentage at the source, the collar and in the general body beyond 0,5 m.

It is seen that although the vast majority of occurrences reported above 5 per cent at the source, very few of these maintain this level into the atmosphere. Almost all the reports show below 1 per cent beyond the collar.

Most readings are taken with methanometers with a maximum scale of 5 per cent, or 100 per cent of LEL, so no more accurate evaluation can be made of the reports above 5 per cent.

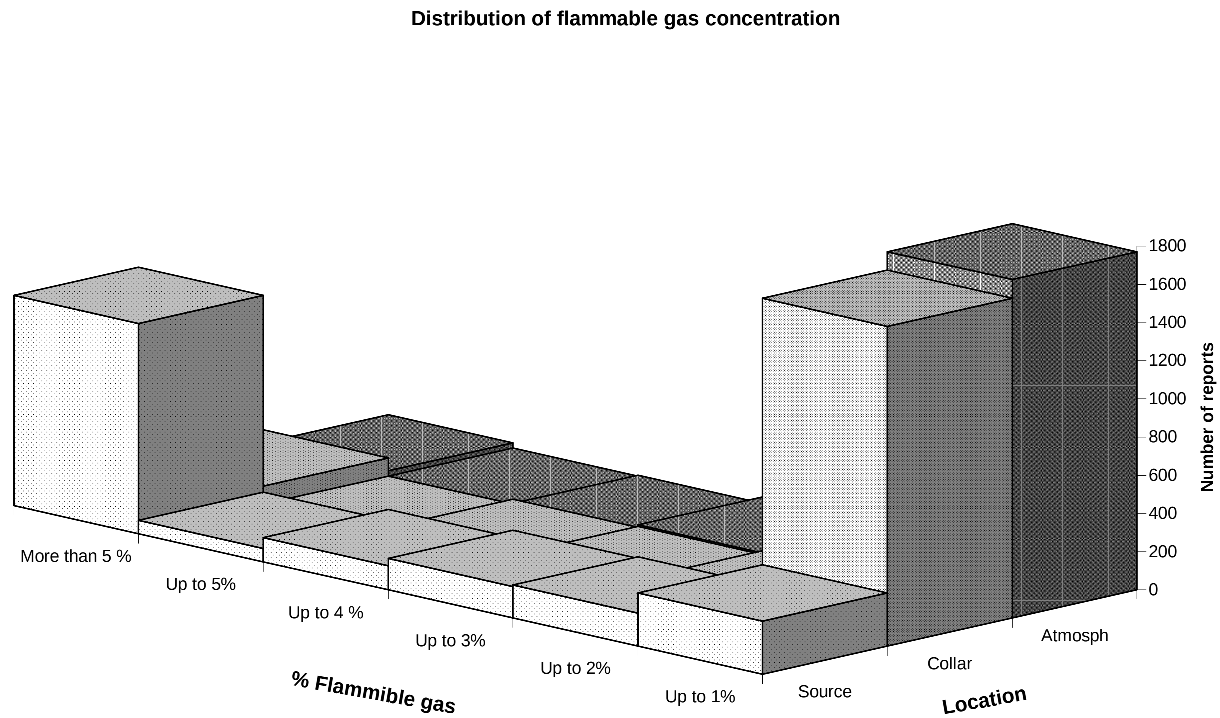


FIGURE 3.10 Reported flammable gas percentages

3.3 Flammable gas accidents: reportable injuries and fatalities

The number of accidents during the survey period totaled 32, of which details were obtained for 25. As the total in this case was much less than the number of incidents, the evaluation of the accidents took a different approach. Each report was studied for the cause or probable cause of the ignition or accident, as well as where it occurred. Usually not much information was given as to the geological conditions, or depth of mining.

The relatively small number of accidents made reporting of the accident totals impractical, so the results are reported as fatalities and injuries. Data was collated on spreadsheets and evaluated for distributions with time, working place, significant factors contributing to the accident, and the source of ignition.

The field notes, briefly reviewing all the accidents, are given in Appendix II, listing the file number, the appropriate DME office, and some details. It is seen from these reports that a great deal of information is overlooked or disregarded or just not available for the follow up inquiries in many cases.

3.3.1 Time distribution

The distribution of fatalities and injuries due to flammable gas over the period 1987 to 1997 is given in Figure 3.11. The plot shows the numbers for each year, and also includes the reported number of incidents for comparison.

It is clearly seen that both gas related fatalities and injuries have upward trends, similar to the results seen for the number of reported incidents. The peaks in 1990 and 1995 both include accidents involving multiple fatalities. This type of accident seems to temporarily increase general awareness, as shown by the increased number of reported incidents which follow for two to three years afterwards.

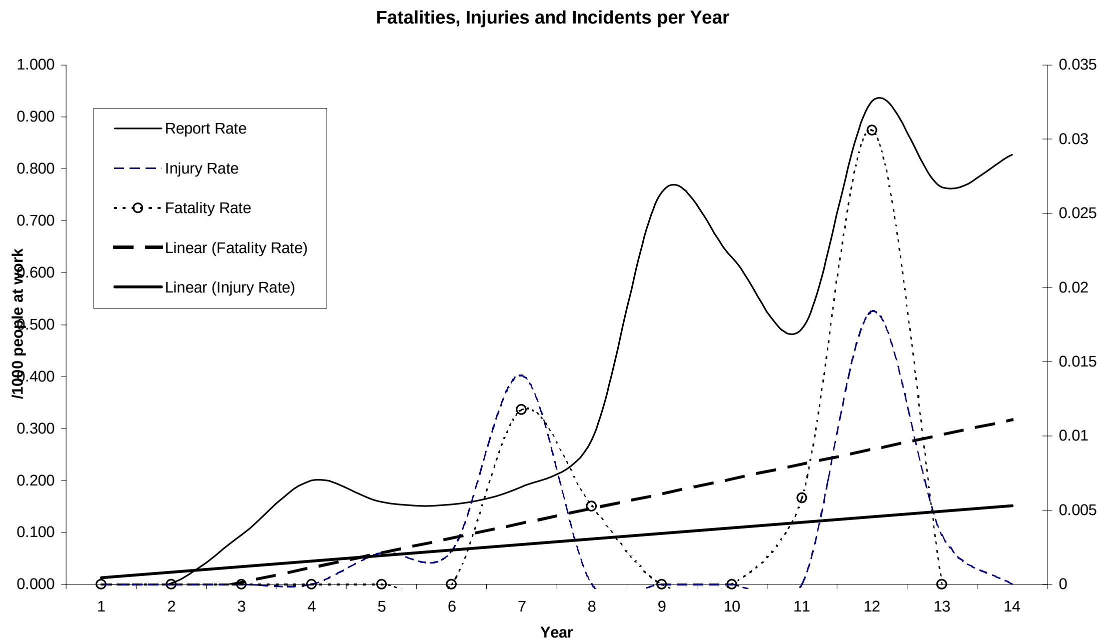


FIGURE 3.11 Flammable gas fatalities and injuries per year

3.3.2 Injury distribution

The number of injuries per year is shown in Figure 3.12 for gold mines and 3.13 for platinum mines. The flammable gas injuries are compared with the total number of injuries reported for each industry.

Figure 3.12 shows an upward trend on gold mines for flammable gas injuries. This goes against the downward trend for injuries in general. Results over the same period for platinum mines are in Figure 3.13, and show the same upward trend for flammable gas injuries, but with a similar upward trend for injuries in general.

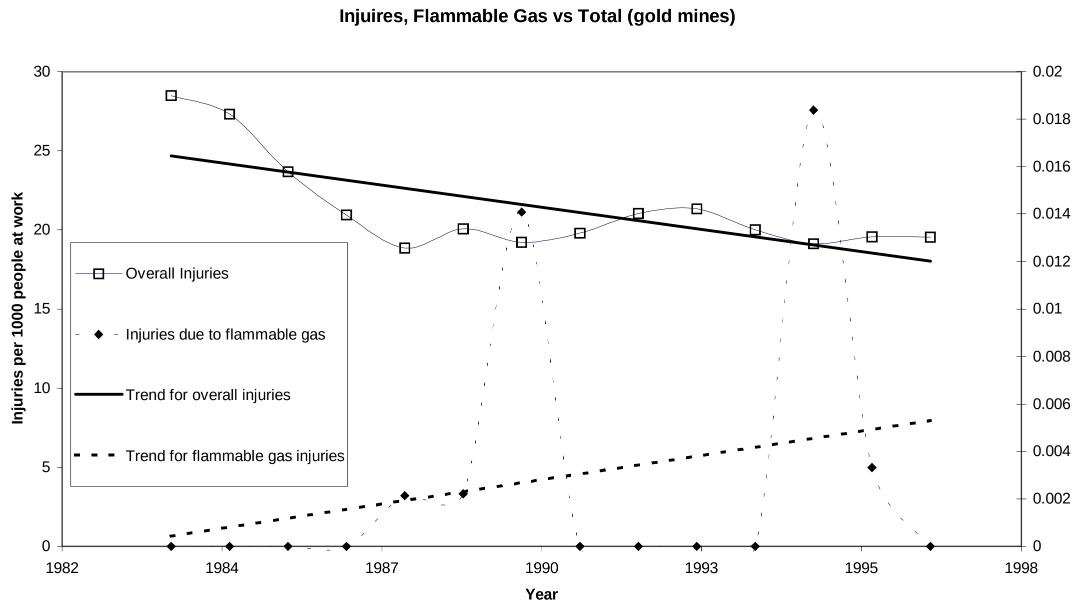


FIGURE 3.12 Flammable gas and total injuries, gold mines, per year

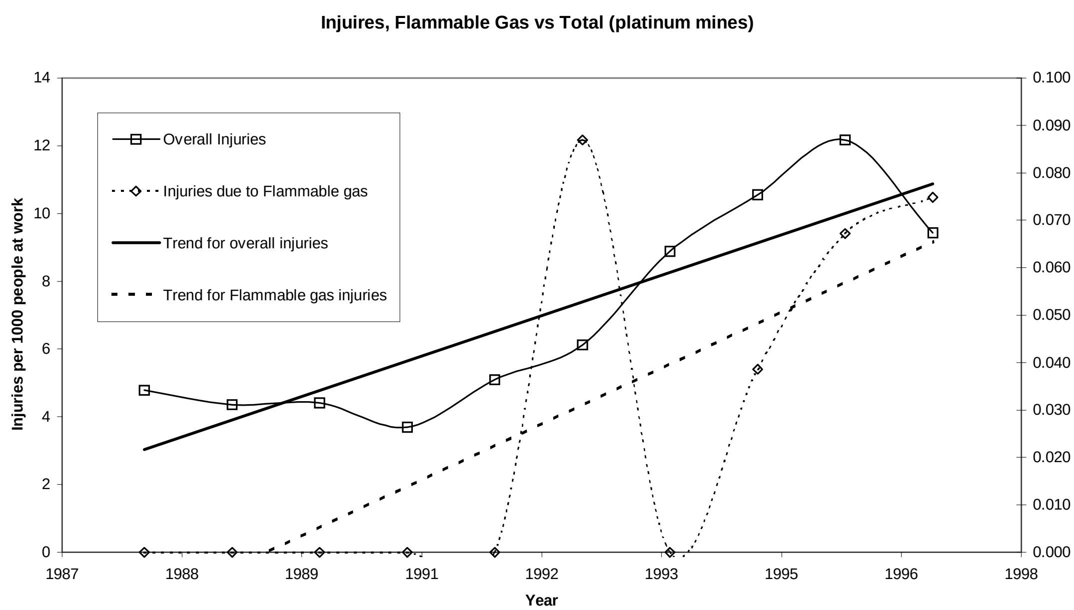


FIGURE 3.13 Flammable gas and total injuries, platinum mines, per year

3.3.3 Fatality distribution

Fatality rates are given for the period in Figures 3.14 and 3.15. Gold mine results, in Figure 3.14 show a similar upward trend for flammable gas fatalities as was seen for injuries, and again this is in contrast to a general downward trend in gold mine fatalities.

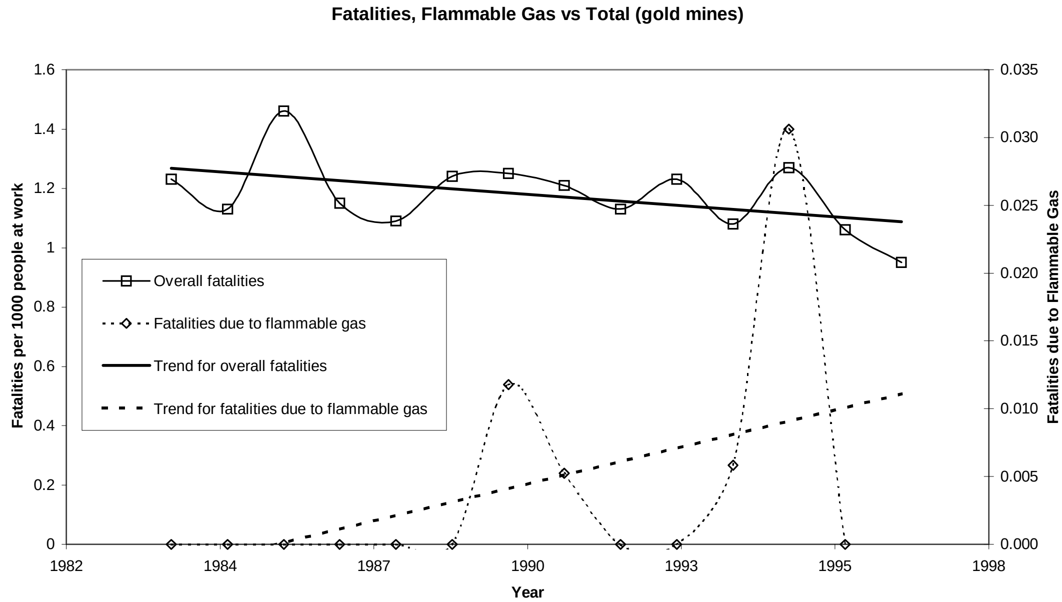


FIGURE 3.14 Flammable gas and total fatalities, gold mines, per year

The totals shown in Figure 3.15, for platinum mines also show an upward trend for flammable gas fatalities, but with a similar upward trend for fatalities in general.

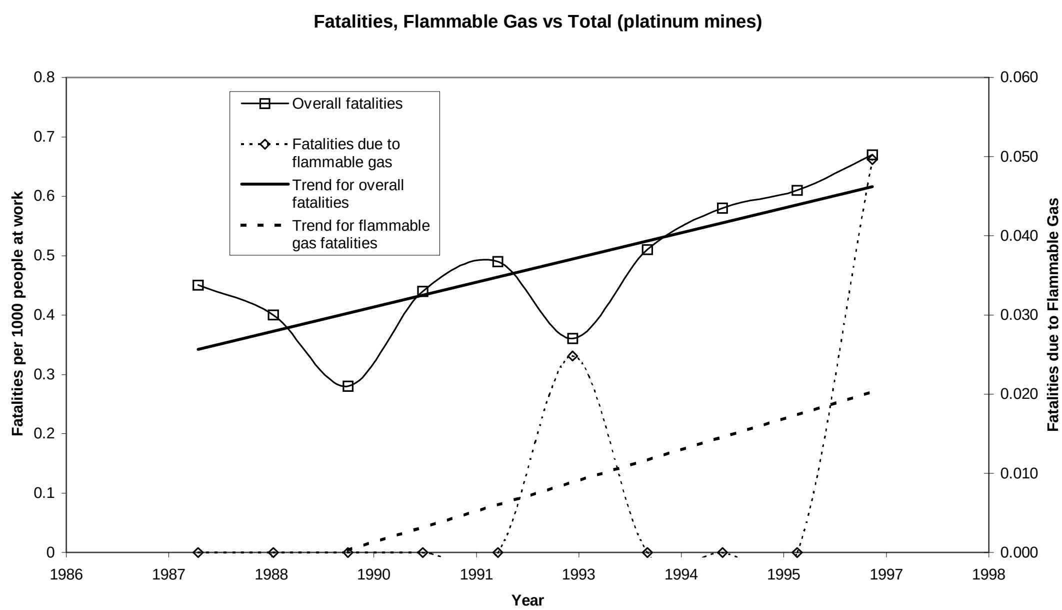


FIGURE 3.15 Flammable gas and total fatalities, platinum mines, per year

3.3.4 Commodity distribution

The distributions of fatalities and injuries per mining commodity are given in Figures 3.16 for injuries, and 3.17 for fatalities. Both figures show results normalised for the number of mines of each type.

The injury and fatality distributions show almost exactly opposite results. Injuries are much more prominent in platinum mines, at 65 per cent of the total, as shown in Figure 3.16 The fatalities however show only 24 per cent for the platinum mines, and 76 per cent for gold, shown in Figure 3.17.

These figures are very much influenced by a type of accident and injury exclusive to the platinum mines. This is a stope face blow-out during drilling, which is generally not ignited, but causes eye and head injuries from either the drill or particles of rock and dust being ejected from the hole or face due to gas pressure. The gas is almost always immediately dispersed.

This type of blow-out incident is invariably reported as flammable gas, however, there is usually no measurable percentages or volumes to support this, so the gas type cannot always be proven as flammable.

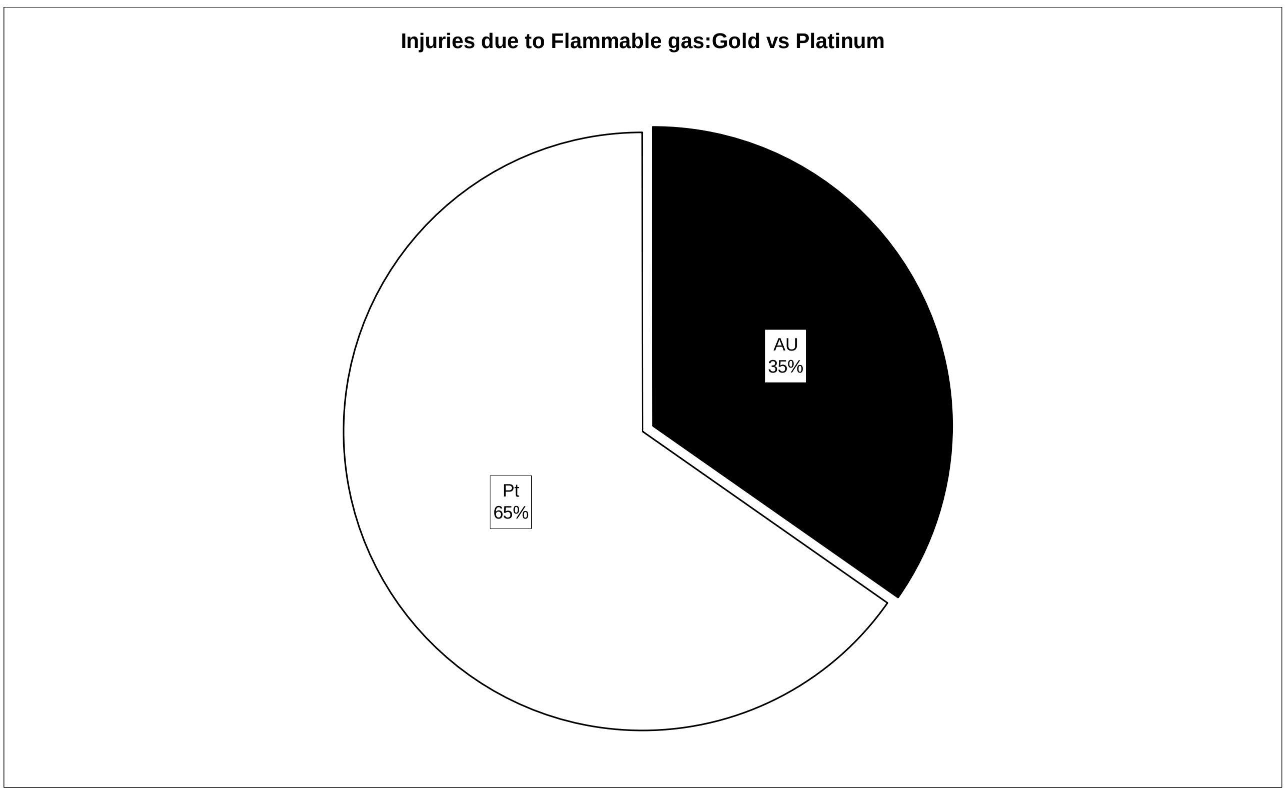


FIGURE 3.16 Distribution of flammable gas injuries, per commodity

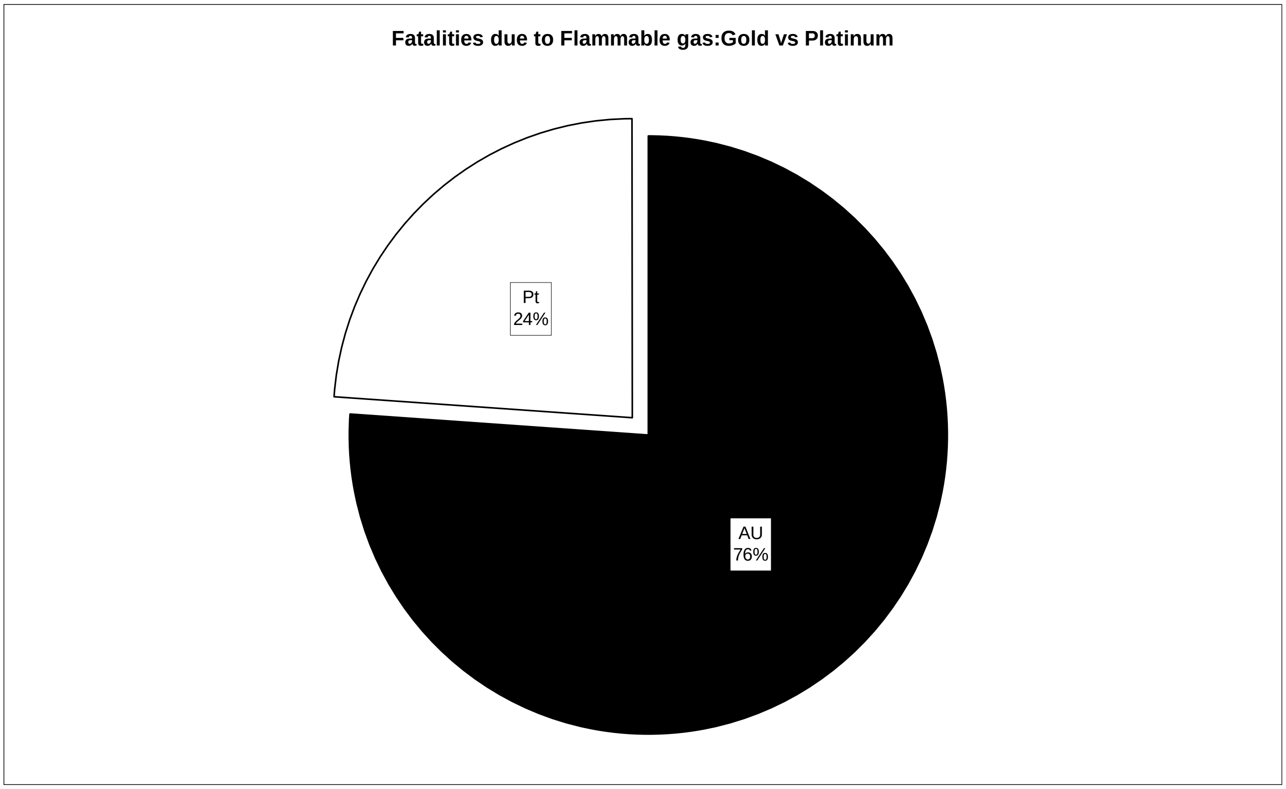


FIGURE 3.17 Distribution of flammable gas fatalities, per commodity

3.3.5 Working place distribution

The total number of accidents reported for stoping or development is shown in Figure 3.18. Development accounts for 72 per cent of all the accidents, and stoping only 23 per cent. However, the distributions for injuries and fatalities are shown in Figure 3.19, where it is seen that stoping accounts for 35 per cent of fatalities and 40 per cent of injuries. So an accident in a stope results in a higher number of injuries.

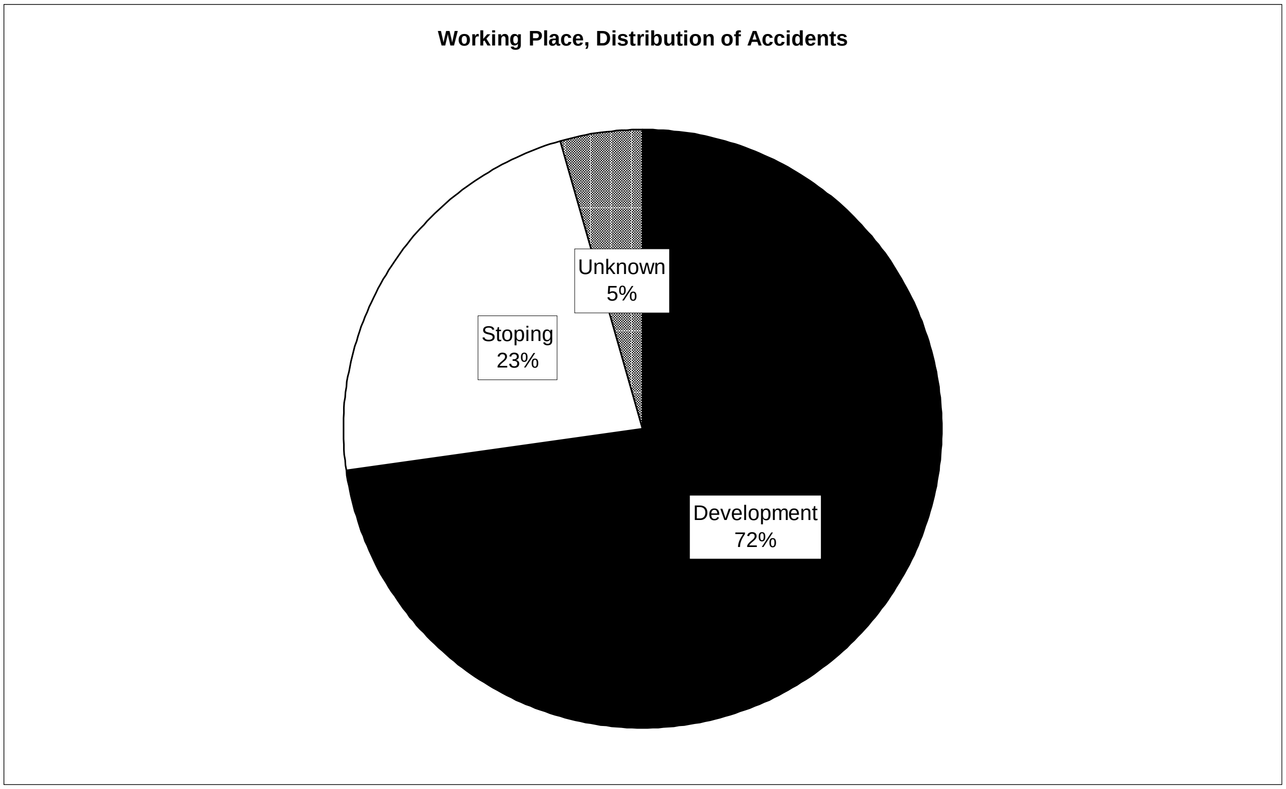


FIGURE 3.18 Distribution of flammable gas accidents, per working place

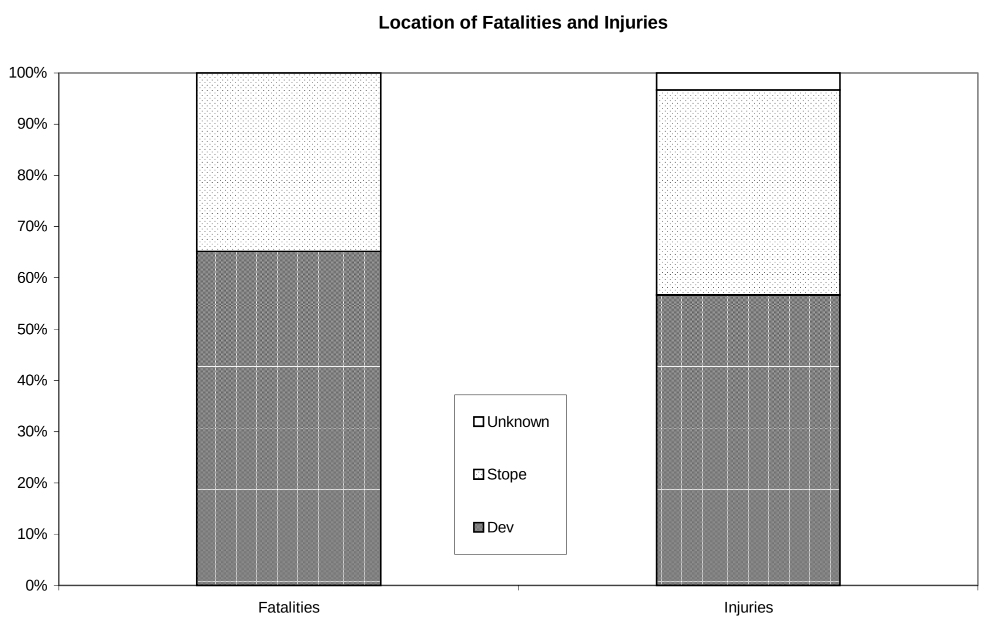


FIGURE 3.19 Distribution of fatalities and injuries, per working place

3.4 Activities contributing to flammable gas accidents

The most common mining activities associated with accidents are shown in Figure 3.20, and the significant factors associated with them shown in Figure 3.21. These exclude accidents such as blowouts and face breaks, in which no ignitions took place.

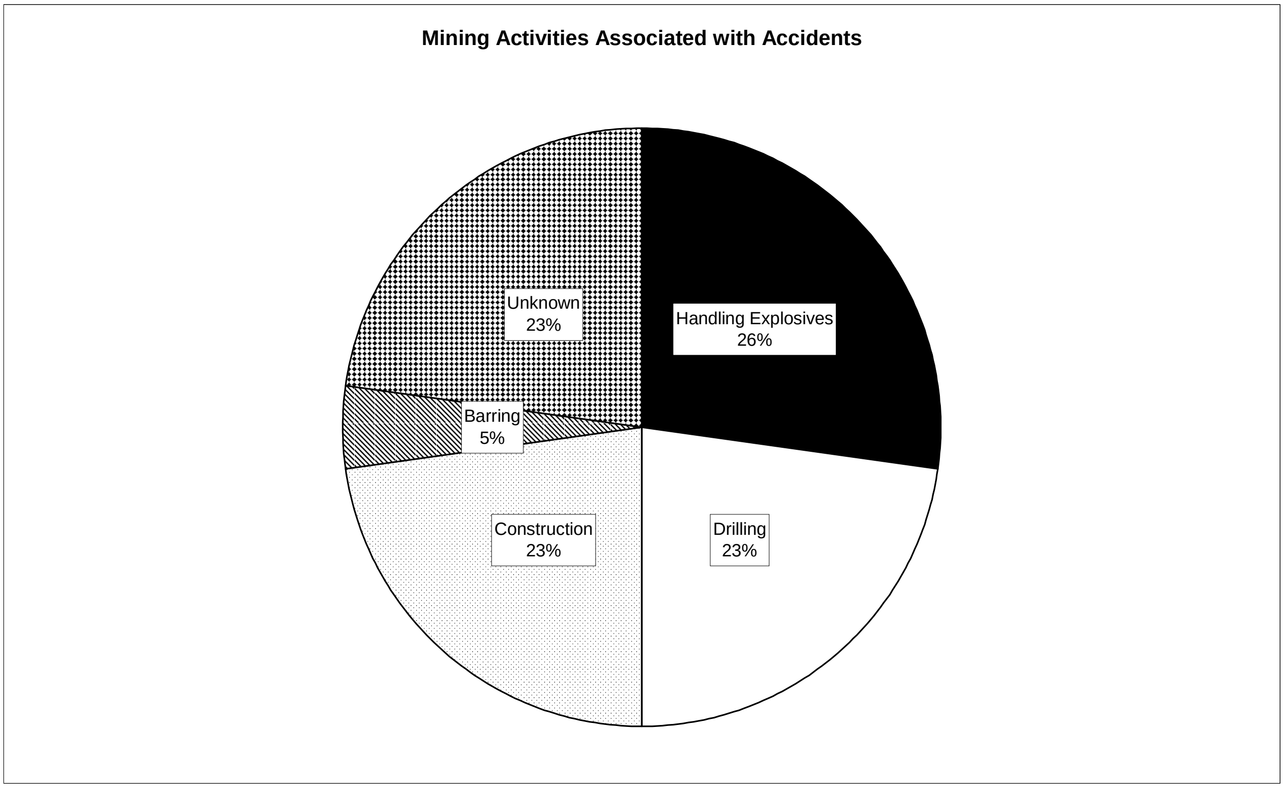


FIGURE 3.20 Mining activities associated with flammable gas accidents

Figure 3.20 clearly shows three main activities associated with ignition of flammable gases, with almost equal distribution between handling explosives, drilling and construction. There is also an equal amount of unknown situations, with the remaining 5 per cent being attributed to barring.

The three significant factors associated with the accidents are shown in Figure 3.21. Changes to, or non-standard, ventilation and no-testing for gas are both contributing factors to more than 60 per cent of all accidents, with almost 40 per cent being attributed to contraband or tampering with cap lamps to make an ignition.

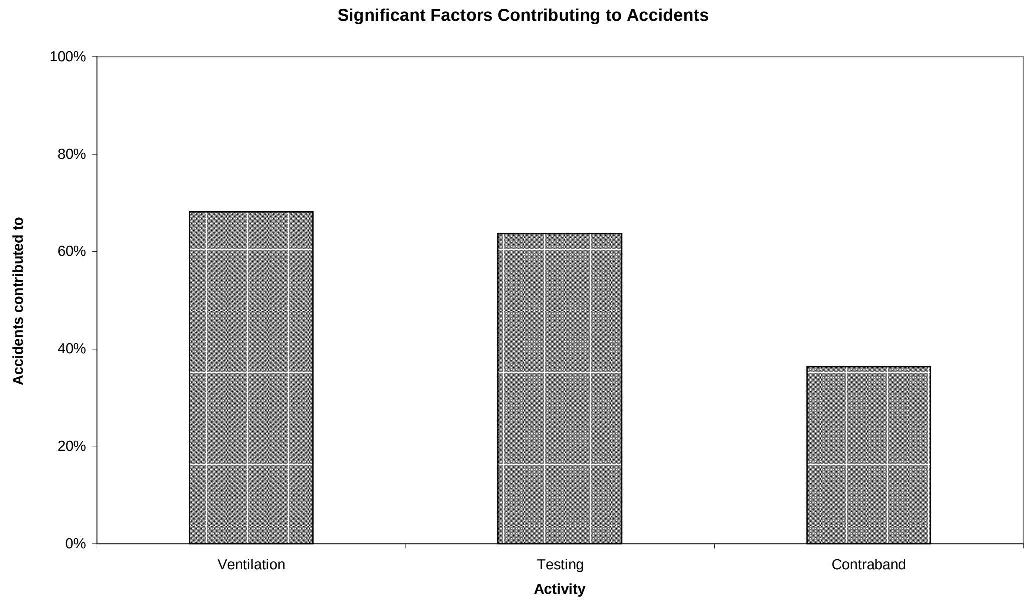


FIGURE 3.21 Significant factors associated with flammable gas accidents

3.5 Sources of ignition

The reported sources of ignition are shown in Figure 3.22. Contraband is the single biggest known cause of ignition at 22 per cent, followed by tampered cap lamps at 14 per cent.

No ignitions took place in 23 per cent of the accidents, which are those on the platinum mines consisting of blow-outs or breaks from the face. These are attributed to methane, however, they are always quick releases of gas, and not measured, so there is no proof that the gas is in fact flammable.

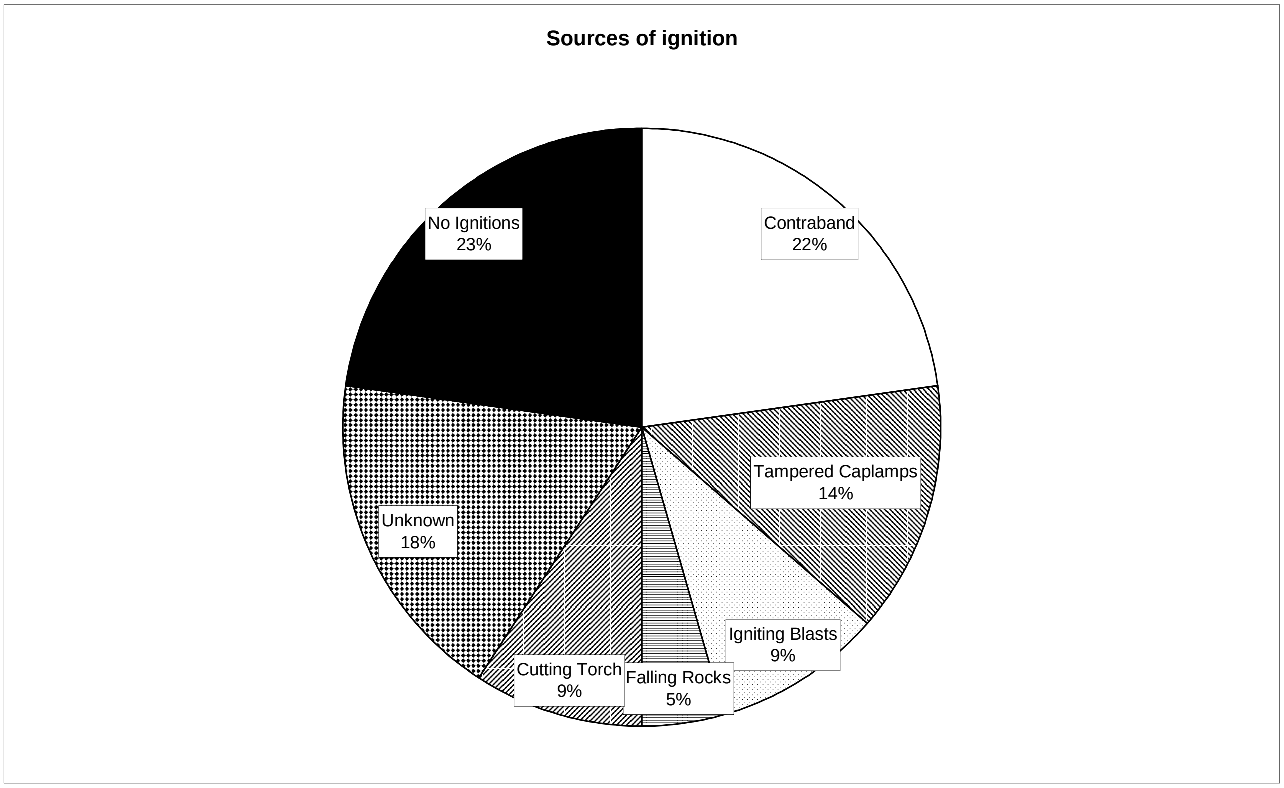


FIGURE 3.22 Sources of ignition

3.6 Examples of flammable gas accidents

All the field notes for the accidents that were reviewed are given in Appendix II, but it is worth to consider three for further discussion. These accidents are well known within the industry and have been selected to show the attitudes and beliefs that can lead to accidents.

3.6.1 (LM0229) Harmony no. 5 shaft

A worker was injured when an explosion occurred in the shaft. Preparations were under way to remove the sinking stage from the shaft when the explosion happened, lifting the stage right out of the shaft and damaging the headgear.

Gas had been detected in the shaft and during shaft sinking, so the workers were aware of its presence and had the shift foreman had a methanometer to warn them. A flame safety lamp was suspended below the stage, and it was believed that methane from deeper in the shaft would float up and collect as a layer below the stage and would be detected.

This did not happen. After the accident methane was still being released into the shaft, and was detected in high concentrations well below the cage position. The methane did not separate and layer, and did not float up the shaft. Being a gas, it diffused around its area of release, and would eventually have diffused throughout the entire shaft, displacing the air.

The actual ignition was probably caused by hot or burning material from an acetylene torch falling down the shaft. However, the cause was the belief that methane would separate from the air, and float up the shaft.

3.6.2 (94H265K) Doornfontein

A team leader and winch operator were in a raise, placing a bomb to remove a restriction from an orepass, when a methane explosion apparently killed them. The actual cause of this explosion was not determined, but both cigarettes and an ignitor cord were found in the vicinity.

Further tragedy in this accident, was the subsequent deaths of three more men who went to investigate the noise heard in the raise. These men were all overcome by carbon monoxide.

All five men were experienced workers, and not one of them tested for gas, either methane or carbon monoxide.

In the investigation it was stated that no flammable gas had been detected for ten years prior to the accident. A lack of gas awareness had apparently developed over time, if no gas is ever detected why bother to look for it?

The fatalities due to flammable gas are reported as two, although five men actually died.

3.6.3 (95H2268K) Elandsrand

The most recent multifatality accident, in which eight men were killed. Butane was detected in gas samples taken afterwards, and may have contributed to the gas mixture that ignited in a stope. The suggested source of gas is a dyke at the bottom of the panel.

Shortly before the accident an change to the ventilation had taken place. A single fan had been replaced with two fans in preparation for an extension of the working faces. On the day of the accident one of the fans was not working, and this was apparently causing some recirculation.

Gas had been detected over a two week period before the accident with concentrations up to 2,5 per cent., and with an unusual smell. Continuous gas monitors had been recommended, but were never installed.

Changes to ventilation, combined with inadequate gas detection, and an apathetic approach to the gas all contributed to this accident.

3.7 Discussion, incidents and accidents

Flammable gas is widely reported from both gold and platinum mines, and has resulted in a total of 25 fatalities and 36 injuries in the last 10 years. An increasing trend in reported incidents of flammable gas is reflected in increasing fatality and injury rates, in contrast to a generally reducing trend in other fatalities and injuries.

The vast majority of incidents are reported from development, and most of these are from cover, or exploration drilling. This does however indicate a variation in reporting, as not all mines or personnel consider this to be an emission worth reporting.

There are three main reasons leading to methane accidents: changes to ventilation, not testing for gas, and contraband including tampering with caplamps to make ignitors. The ventilation conditions are not necessarily non-standard or poor ventilation, but are also cases where, for example, the ventilation had recently been changed, or a fan had not been operating. This has allowed a build up of gas, which is then moved by the ventilation being restored.

Lack of gas testing in some respects is associated with the ventilation problem, but is also a problem on its own. Inadequate gas testing shows a general lack of awareness of the hazards and occurrences of combustible gas.

Three main mining activities associated with gas ignitions are handling of explosives, drilling and construction, in almost equal proportions of one quarter each, although an equal number are also “unknown”.

Caplamps and contraband were the two biggest sources of ignition. The practice of tampering with the caplamp barrel to make an ignitor has been included as contraband as it amounts to an illegal procedure.

In platinum mines the most common accident is a non-ignition stope face blowout during drilling.

4 Technical Review

This is the report from the individual mines. It is formed from the opinions and answers of the persons interviewed, and is intended to reflect these opinions. This gives rise to a somewhat subjective style, with statements that cannot be directly referenced or further substantiated.

4.1 Introduction

The technical review was held on individual mines, with the objectives of determining the approach taken by the mines and ventilation practitioners to combustible gas emissions. In addition it was intended to outline the opinions within the industry as to the importance, or significance of combustible gas emissions.

General Managers of the mines were informed by letter of the SIMRAC project, and that the safety and health, and geology departments would be contacted for information and assistance. Subsequent interviews were held with senior safety and health personnel at gold mines in the Free State, Witwatersrand, and East Rand, and the Bushveld Platinum Complex.

A total of 28 mines was visited and this chapter reports the results from these interviews, covering several aspects including ventilation practices, and instrumentation. The mines, and the individual representatives interviewed are listed in Appendix III.

4.1.1 Technical interviews

The basic format of each interview was similar, covering the technical aspects of ventilation practices on each mine, with notes on any particular memories, anecdotes, or theories of the individual.

The format was based around the following questions:

- The frequency of flammable gas intersections, if any.
- The gas or mixtures of gases detected.
- Types of instrumentation used to monitor and detect combustible gases.
- Any special precautions taken to prevent and/or to remove the gas.
- Standard ventilation systems for development ends and stope faces, with relevant air quantities.
- The reef or reefs mined and mining depths below surface.
- Personal opinions and theories as to gas emissions, gas sources, gas hazards etc.

4.2 Witwatersrand gold mines

A total of 13 Witwatersrand gold mines was visited covering the East Rand to the Far West Rand areas, and a further two had to be rescheduled for visits at a later stage. These are reported collectively in this section, with specific references made to individual mines where applicable, such as specific occurrences or precautions on that particular mine.

4.2.1 Technical reviews

4.2.1.1 Frequency of intersections

In general most of the mines consider that there are no serious flammable gas problems. A gas problem is defined as a continuous source that is detected in the atmosphere in and around the working place. In general the flammable gases are found only in the pilot holes drilled and not in the general body. Only two of the mines interviewed (Elandsrand and Leeudoorn), reported gas more frequently than the others, and only one of these considers that there is a history of flammable gas problems.

Elandsrand reports flammable gas problems of more than 5 per cent in development ends on a continuous basis and air samples were also drawn for analysis, which showed the presence of other hydrocarbons such as butane and ethane. All the incidents are reported into a register for reference use.

On Leeudoorn Gold Mine the number of intersections are less frequent, but are treated with care and special safety precautions are in place. Flammable gases are reported apparently at random within the mine at approximately two to three week intervals. Although the number of intersections is considerable, the ventilation system used prevents the gases from accumulating in the general body of air and is restricted to the drill holes.

4.2.1.2 Gases detected

Methane was considered to be the main gas present, although it was known that other gases, specifically hydrogen can be present. Some mines are also aware of the presence of other hydrocarbons, such as butane.

4.2.1.3 Instrumentation and measuring procedures

There is no set industry standard regarding to the use of gas monitoring or detection instruments. In general, instrumentation is issued to the personnel in supervisory positions such as gangers, team leaders, shiftbosses, etc. The instruments are issued with the cap lamps and are calibrated with either the standard 1,4 per cent or 1,2 per cent methane in air calibration gas mixtures, as supplied by Afrox or the manufacturers.

The instrumentation used for detecting flammable gases is given in Table 4.1.

No telemetry system is used for methane detection purposes. In most cases the Anglo American system is used for monitoring CO/CO_2 levels for fire patrol purpose.

Some of the mines also issue continuous CO monitors to workers in the development ends and stopes. In certain mines, the problem of fires in abandoned areas is considered to present a bigger danger than flammable gases, and these are therefore better equipped to monitor CO/CO_2 levels than CH_4 levels.

4.2.1.4 Special Precautions

In general it is considered that the normal ventilation practices currently used are more than adequate to prevent any accumulation or sudden outburst of flammable gases in a working place.

Throughout the industry, the same basic principles are applied when a dangerous situation is detected inside a workplace. Whenever flammable gases are detected in the general atmosphere, the people are withdrawn and the ventilation department is notified. In most cases, compressed air blowers are used on the source to efficiently dilute the gas mixtures.

Frequent air samples are taken from the affected workplace and no work is allowed until the working place is cleared of gas by the ventilation department.

If needed, additional fresh air will be introduced into the workplace by means of auxiliary fans and ducting. If a problem occurs in a stope face area, additional control measures are be taken to increase the air velocity on the face.

To accommodate the monitoring of other hydrocarbon gases present in the atmosphere, Elandsrand has lowered the alarm levels on instrumentation to 0,5 per cent. Whenever more than 0,5 per cent is detected, the workplace is treated as a methane filled end with the normal safety precautions being applied.

Where the presence of other hydrocarbons is known or suspected, some mines have altered the testing procedures for flammable gases. Monitoring and testing is now carried out on the footwall as well, as some of the other hydrocarbons are heavier than air.

Table 4.1 Gas detection instrumentation on Witwatersrand gold mines

NAME	TYPE / COMMENTS
G F G 2000 Methanometers	Spot Measurements
M S A D6 Methanometers	Spot Measurements
G 614 Methanometers	Continuous Monitor
Gastech Tri-Tector, CH_4, CO, and O_2 Monitor	Used on Cap Lamps
Sperosense Multi 21, CH_4, CO, and CO_2 Monitor	Instrument on Trial
G F G G3111	Continuous Monitor
Pump Action G F G BP 614	Spot + Continuous Monitor
Draëger Pumps with Hydrocarbon Tubes (Vent. Dept.)	Spot Measurements
Brogas S006 Methanometers	Spot Measurements
Gasmo Major CH_4 Monitors	Used with Cap Lamps
Oldham Multi-Gas Detectors	(Used by Vent. Dept.)
G D I Methanometers	Spot Measurements
M S A Methanometers	Continuous Monitors

4.2.1.5 Ventilation system used

Throughout the gold and platinum mining industry, the means of ventilating development ends, stope faces boxholes and raises are generally the same. The differences are small and site specific to deal with special conditions.

Development ends

Normal development ends are ventilated with 570 mm diameter fans and ducting. The ducts are not more than 12 m from the face.

The air quantities differ from 0,15 $m^3/s/m^2$ of face area to 0,3 $m^3/s/m^2$ depending on face conditions and personal preferences reflected in the mine standards.

The law requires a minimum air quantity of 0,15 $m^3/s/m^2$ of face area to be delivered into a development end.

Multiblast ends
In the event of multiblast ends the force/exhaust overlap system is used and the re-entry period determines the size of ducts to be used as well as the air quantities delivered.

Some mines adhere to the prescribed four hour re-entry time, but some mines have permission for ten minutes re-entry time.

In the event of the force/exhaust overlap system being used, the length of the overlap system is between 9 m and 12 m.

The exhaust air quantity is always more than the force air quantity to ensure that fresh air is always flowing in this overlap section.

Exhaust quantities vary from 1,1 times the force quantity used to 1,5 times the force quantity used. Another criterion is to use 6 times the clearing quantity to determine the exhaust quantity.

The size of the exhaust ventilation ducts used vary from 960 mm diameter to 1016 mm diameter.

Stopes
Apart from Elandsrand Gold Mine, no other mine has indicated a specific problem with flammable gases in the stope areas. The result is that no special emphasis is placed on the ventilation of stope face areas for combustible gases.

In the stope areas normal strike control brattices and in some cases small airjet fans are used to maintain strong airflow on the face. Standards of airflow velocities vary from 0,25 m/s to 1,5 m/s.

Boxholes
With regard to boxholes and orepasses the type of ventilation varies from using conventional waterblasts, compressed air or 406 mm diameter boxhole fans, which is normally a centrifugal fan.

4.2.1.6 Reefs mined
The reefs being mined are shown in Table 4.2, along with the approximate mining depth below surface for each.

4.2.1.7 Opinions
There is no real understanding of where the gas comes from, how it is transported, or when it is likely to be encountered. In particular why certain mines have more frequent gas encounters than others when mining in the same areas and mining on the same reefs.

However, there are some general opinions, and some specific ones on particular mines, the most significant of these being:
- Development ends are more likely to intersect combustible gas than stopes.
- Gas is encountered when the “Booysens Shale” is intersected
- (Leeudoorn Gold Mines).
- The deeper the reef that is mined, the more frequent the intersections.
- The higher the grade of the reef, the higher the carbon content and the higher the rate of flammable gas intersections.
- Water tables separate the methane sources between the shallow reefs and deeper reefs.
- Dykes and fissures are the usual transport mechanism.

- Water is often associated with the gas.
- Hydrogen is associated with fissures and dykes.
- No specific areas are associated with other gases, or other hydrocarbons

Table 4.2 Reefs mined on the Witwatersrand Gold Mines

MINE	REEFS MINED	MINING DEPTH
EAST DRIEFONTEIN	CARBON LEADER V C R MAIN REEF*	2000m
ERPM	MAIN REEF	3500m
KLOOF	V C R	3500m
WEST DRIEFONTEIN	NORTH LEADER* V C R MAIN REEF CARBON LEADER	2950m
BLYVOORUITZICHT	CARBON LEADER MIDDLEVLEI*	4000m
RANDFONTEIN ESTATES (NORTH SECTION)	N/A E8 VE 1 A'S	N/A 700m 800m
LEEUDOORN	V C R	3100m
ELANDSRAND	V C R	3700m
DEELKRAAL	V C R	3200m
ARM (OLD VAAL REEFS)	VAAL REEF	2400m
WAGM	V C R MIDDEL ELSBURG	3400m

*Prominent reef being mined by the particular mine.

4.2.2 Discussion, Witwatersrand gold mines

Only a few mines regard methane, or any other flammable gases, as a safety and health problem.

Flammable gases are encountered at random and no set patterns can be established or pinpointed at specific areas to identify a specific origin for the gases.

Ventilation control overall is efficient and the effective use of instrumentation to monitor the appearance of flammable gases tend to keep the methane incidents under control.

Methane blowers are not often encountered and every methane intersection is cleared rather quickly and effectively which might be the reason why flammable gases are not envisaged as a safety and health problem in most of the mines.

Methane is always expected to be present in the workings and ventilation systems are designed to deal with any unexpected incident.

Some gas encounters are found in virgin areas during the development stages but as soon as stoping commences, the gas is drained and very little incidents are reported.

At Elandsrand where the frequency of methane intersections is above normal, the manager identifies restricted areas. In these areas only flameproof fans are used and are fitted with a 0,5 per cent trip switch mechanism. When the fan trips out, the workforce withdraw and switch on compressed air, which is normally pre-installed. These restricted areas are normally identified as a result of a higher than normal incidence of emissions, or geological forecasts that high flammable gas is expected.

As no known coal seam is in close proximity of the reefs that are mined, it is difficult to identify the origin of the flammable gases but as is usual, gas is often associated with geological disturbances such as faults, dykes and fissures.

4.3 Bushveld platinum mines

A total of 13 Bushveld platinum mines were visited. These are reported collectively in this section, with specific references made to individual mines where applicable, such as specific occurrences or precautions on that particular mine.

4.3.1 Technical reviews

4.3.1.1 Frequency of intersections

Only two mines (Frank Shaft + Northam Plats) reported frequent gas intersections.

Frank Shaft mine forms part of Rustenburg Platinum Mines and reported a continuous blower in the belt incline at No. 2 shaft, at approximately 1200 m from surface.

Northam Platinum mine reports high gas pressures when a pocket is intersected but the gas clears very fast and does not present a problem in the general atmosphere.

The appearance of gas at Northam Plats is more frequently closer to the so-called potholes, caused by iron rich replacements, and it occurs specifically in stope areas.

The remainder of the mines visited, reported low gas intersections which only appear when drilling. The gas does not bleed out into the general body of the atmosphere and therefore does not present a problem.

4.3.1.2 Gases detected

It is considered that only methane is present as the flammable gas emitted from the strata.

4.3.1.3 Instrumentation and measuring procedures

No effort is made on these mines to monitor for gases other than methane and carbon monoxide, with the perception is that only methane is present. No air samples are taken to test for other hydrocarbons.

There is no set standard with regard to the type of instrumentation in use across the different mines.

In general instrumentation is issued to personnel in supervisory positions. On an ad-hoc basis, methanometers are also issued to surveyors and diamond drill teams.

All instruments are calibrated with standard 1,4 per cent methane in air calibration gas, except on Karee mine, where a mixture of 2,6 per cent methane in air is used.

The different types of instrumentation used for detecting flammable gases are given in Table 4.3.

Table 4.3 Gas detection instrumentation on Bushveld platinum mines

NAME	TYPE / COMMENTS
Gastech S006 Methanometers	Spot Measurements
HC 002 Methanometers	Continuous Monitor
Gastech, Tri-Tector, CH_4 CO and O_2 Monitor	Used on Cap Lams
Gastech CO Monitor	Fire Patrol
Logica CO + CH_4 Monitors	Continuous Monitors
G D I Duel CO + CH_4 Monitors	Continuous Monitors
Brogas S006 Methanometers	Spot Measurements
G F G Protectors	Vent. Department
Flamalarm	Cap Lamps
Gaswatch	Cap Lamps
Tox Alarm CO Monitors	Fire Patrol
Board MSA Methanometers	Spot Measurements

No telemetry system is used for monitoring methane, but the Anglo American system for monitoring CO/CO_2 levels is used for fire patrol purposes.

4.3.1.4 Special precautions

In general the workplaces are considered adequately ventilated to handle any sudden outburst of flammable gases.

At Frank Shaft mine, a Sperosense continuous methane monitoring system is installed in the belt incline at No. 2 shaft to monitor the area around a methane blower. This is connected to an alarm system on surface.

Karee Mine pre-drill boxholes for methane drainage.

When methane is detected in the general atmosphere, the workforce is withdrawn and additional ventilation is introduced into the source by means of compressed air or additional auxiliary fans. Northam Platinum mine is the only exception to the rule. Instead of compressed air or waterblasts, this mine uses high pressure venturi water air-movers to ventilate the work face and to dilute the methane. As is the case with the gold mining industry, an accepted ventilation method of dealing with methane outbursts is applied throughout.

Air samples are drawn and analysed by the ventilation department until the end is cleared and work can be continued.

4.3.1.5 Ventilation system used

In general the platinum mines are ventilated similarly to the gold mines, with only small differences that are site specific and determined by unique individual conditions.

Development:

Footwall 1015 mm diameter exhaust duct
570 mm diameter force duct ends

All mines, with the exception of Northam Plats, ventilate development ends by means of 570 mm diameter force ventilation. The air quantities start from 0,15 $m^3/s/m^2$ depending on prevailing conditions.

At Northam Platinum mine, different standards are applied. Development ends are ventilated by means of the force/exhaust overlap:

Exhaust air quantity = 6-8 m^3/s
Force air quantity = 5 m^3/s

crosscuts = 760 mm diameter exhaust duct
570 mm diameter force duct
Exhaust air quantity = 6-8 m^3/s
Force air quantity = 5 m^3/s

Stopes

More emphasis is placed on the ventilation of the stope faces than was apparent from the gold mines, as methane intersections are considered much more frequent in the stopes.

Normal practice is to use the strike control and centre gully brattices to force air onto the face.

Air velocities in excess of 0,4 m/s are measured on the face and in certain situations use is made of 1,5 kw jet fans of high pressure venturi air-movers (Northam Plats) to assist in creating sufficient air velocities on the face.

Average air velocities range between 0,68 m/s and 0,8 m/s.

Boxholes

Karee Mine ventilates boxholes by using normal compressed air blowers.

In general the boxholes are ventilated by using 305 mm diameter boxhole fans and the high pressure venturi air-movers (Northam Plats).

Boxhole fans are normally a 0,75 kW centrifugal type fan.

4.3.1.6 Reefs mined

The reefs being mined, the corresponding approximate mining depths below surface, and grade of reef where available, are given in Table 4.4.

Table 4.4 Reefs mined on Bushveld platinum mines

MINE	REEFS MINED	MINING DEPTH
EASTERN PLATINUM	U G 2 (UPPER GROUP) (5,5g/t)	250 m
WESTERN PLATINUM ROLAND SHAFT NO. 1 SHAFT	 MERENSKY REEF U G 2 REEF U G 2 REEF	 1000 m 1000 m 300 m
UNION PLATINUM	MERENSKY REEF (6,8g/t) U G 2 REEF (4,6g/t)	1500 m 750 m
KAREE MINE NO. 4 SHAFT NO. 3 SHAFT	 MERENSKY REEF (2,8g/t) U G 2 (3,6g/t) MERENSKY REEF (4,2g/t) U G 2 (4,6g/t)	 250 m 800 m 400-800 m 650-800 m
RUSTENBURG PLATINUM FRANK SHAFT	 MERENSKY REEF (7,2g/t)	 1200 m
NORTHAM PLATINUM	MERENSKY REEF (6,9g/t) N P 2 (non payable) P 2 (8g/t) FOOTWALL P 2 (small pay zone)	2000 m “ “ “

4.3.1.7 Opinions

Impala Platinum Mines carried out a five year survey (Hartley, 1992; Visser, 1995) to try and establish a pattern of methane intersections and also the type of rock that can be associated with these intersections. No definite conclusions were drawn from this, and the only solution was to say that methane is always present.

In general there is no real understanding of the sources, transport or particular emissions of methane. It is considered to be more of a stope hazard than in the gold mines, and the stope emissions are frequently associated with outbursts.

However, there are some general opinions, and some specific ones on particular mines, the most significant of these being:

- Although the gas clears fast once intersected, the gas pressures inside the holes are extremely high and cases where the drilling machines have been pushed back a number of metres have been reported.
- Water zones east and west of Northam Plats cause high gas pressures at 2000 m depth.
- High frequency of faults and dykes are associated with the water zones.
- Depth below surface influences the grade of reef and also the frequency of gas intersections.

- Some of the mines reported high pH values and sulphates in the water from the fissures associated with gas.
- The higher the grades of reef the higher the frequency of gas intersections.
- At Frank Shaft the gas is found in the footwall markers, approximately 12 m below the reef.
- At Karee mine, a large intrusion is separating the reef and causes the difference in the mining depth between No. 3 and No. 4 shafts. This intrusion is approximately 2 km wide and no reef is found in between.
- The UG 2 reef that is mined has a high chrome content and with a grade of 4,6 g/t more intersections is associated with this reef.
- At Union Plats, methane is always encountered at a distance of approximately 100 m after passing though a dyke, but never in front of the disturbance.
- At Union Plats more methane is reported when drilled into quartzite and Leoco Norite rock strata.

4.3.2 Discussion, Bushveld platinum mines

Methane intersections are more frequent in the vicinity of potholes and other geological disturbances. As the reef goes deeper and the value of the reef increases, the higher the number of incidents. As in the Witwatersrand gold mines it is difficult to establish where the flammable gases originate.

Apart from one or two mines, no big emission hazard exists that is considered a major danger to the health and safety of the underground workers.

Methane is considered to be the only gas present. No history of other hydrocarbons or other flammable gases could be found in any of these mines and no great interest has been expressed in the possibility of the presence of these substances.

Ventilation is considered to be adequate to handle most gas situations. Only in areas where ventilation is poor does a build-up of methane occur. This was considered to be the cause of an explosion at Paardekraal Mine.

4.4 Free State gold mines

Three Free State gold mines were visited as part of the technical review. The lesser number was because of the information already available from this area, and the more accepted general opinions that methane is frequently detected in the Free State mines because of the presence of overlying coal seams.

4.4.1 Technical review

4.4.1.1 Frequency of intersections

Free State Gold mines experience large numbers of methane intersections, but it is not perceived to be a problem. The emissions are considered generally as pockets with relatively small volumes that are diluted and removed from the workplace quickly and effectively by the ventilation systems.

4.4.1.2 Gases detected

In general the gas is considered to be methane, but Beatrix mine reports the presence of other hydrocarbons. It was also noted that hydrogen could be present.

Hydrogen sulphide was reported from some fissures, but only in very low concentrations, detected by odour.

4.4.1.3 Instrumentation and monitoring procedures

Gas samples are collected at some sites for laboratory analysis.
The instrumentation used for monitoring the methane in the mines is given in Table 4.5.

Table 4.5 Gas detection instrumentation on Free State gold mines

NAME	TYPE / COMMENTS
GFG 2000	Continuous CH_4 Monitors
Schaunburg	Continuous CH_4 Monitors
Logica CH_4	Continuous CH_4 Monitors
Brogas CH_4	Continuous CH_4 Monitors
G D S CROCON CH_4 + CO	Continuous CH_4 Monitors
G D I 007 CH_4 + CO	Continuous CH_4 Monitors

4.4.1.4 Special precautions

No specific extra precautions were reported, however there is a more general awareness of the presence of methane than in the other areas surveyed, and ventilation standards are strictly enforced and the workforce are reminded constantly of the presence and dangers of methane and other flammable gases.

4.4.1.5 Ventilation system used

The ventilation practices are as previously described for the Witwatersrand gold mines.

Development ends are ventilated with force auxiliary fans varying between 570 mm diameter ducting to 760 mm diameter ducting.

Stope faces have air velocities that range from 0,5 m/s to 0,9 m/s. These are normally caused by using centre gully brattices and strike control brattices. Where needed small air-movers are used to enhance airflow on the faces.

Raises and boxholes are normally ventilated using either centrifugal boxhole fans or 406 mm diameter axial flow force fans.

4.4.1.6 Reefs mined

The individual reefs that are mined and the relevant mining depths are shown in Table 4.6.

Table 4.6 Reefs mined on Free State gold mines

MINE	REEFS MINED	MINING DEPTHS
ST. HELENA	BASAL REEF LEADER REEF } 6g/t	4 SHAFT 433m-844m 2 SHAFT 1013m-1630m 8 SHAFT 1081m-1817m 10 SAHFT 1075m-1215m
ORYX MINE	KALKOENKRANS REEF 6g/t BISA REEF	1800m-2200m 462m-900m
BEATRIX MINE	BEATRIX REEF 6g/t	800m-860m

4.4.1.7 Opinions

The general opinion for the Free State mines is that the methane originates from the overlying coal seams, which can be as much as 3 m thick. This may also account for the reports that the deeper the reef mined, the fewer gas intersection, which is the opposite of the Witwatersrand and Bushveld mines.

As well as the general opinions, and some specific ones on particular mines, the most significant of these being:

- The workings close to the coal seam showed more methane intersections than some of the other workings.
- Mines that are working south of the Zandriver showed more frequent intersections than the mines that work north of the river.
- Workings close to the old Bisa mine (Oryx mine) detected more methane than workings more remote from this old mine.
- Gas is associated with reefs that show higher uranium values than gold values.
- Also a large number of geological disturbances that show high quantities of methane associated with small amounts of water and H_2S gas.

4.4.2 Discussion, Free State gold mines

Fewer mines were covered in this region, than in the other two, however there is a more general awareness of the presence of methane, attributed to the presence of the coal seams.

The number of occurrences is high, but the ventilation is considered to be adequate to cope with emissions, which are considered to be short term pockets of gas.

4.5 Discussion, technical review

The majority of the mines believe that they do not have a problem with flammable gas. Out of all the interviews, only four mines considered that there is methane or other flammable gases that could present a health and safety problem.

Good ventilation is considered to be the reason why methane intersections are kept under control. Ventilation volumes are said to be above standard and any methane appearances are dealt with effectively.

Only what many mines consider to be an extreme case is reported. Some mines that indicated no gas problems do detect the methane inside drill holes but in very small quantities and do not report it. In most cases methane only present in holes is not seen as a problem, because does not progress to the atmosphere due to the adequate ventilation.

Shown in table 4 .7 is an indication of the difference between the number of incidents perceived on mines, and those reported to the DME. It indicates the variation in how different mines considered a methane occurrence and how they report.

Impala Platinum reported 64 occurrences, and perceived 60 to 70 per year. Its is likely that each and every gas intersection is reported to the DME. In contrast the perception at Leeudoorn is for 20 to 30 intersection per year, but with no reports in the records.

This indicates a possible over cautious reporting system for some mines, compared to the requirement of the regulations (Reg. 10.6.8). This will also have influenced the geographical distribution of incidents in Chapter 3.

Table 4.7 Methane incidents reported 1997 and perceived on the mines

MINE	NUMBER OR REPORTS IN 1997 PER DME RECORDS	PERCEIVED NUMBER OF INCIDENTS FROM INTERVIEWS
Western Deep Levels	4	No gas problem
Western Areas	2	± 3 Year
Kloof	-	Maybe 1 per year
African Rainbow Minerals	-	No gas
Elandsrand	19	± 50-60 per year
Buffelsfontein	-	No gas
Leeudoorn	-	± 20-30 per year
Randfontein Estates	-	No gas
Blyvooruitzicht	-	No gas
ERPM	-	No gas
East Driefontein	5	
West Driefontein	-	
Rustenburg Platinum (Rustenburg Section)	18	± 30-40 per year
Amandelbult	10	± 20-30 per year
Karee Mine	1	10 per year
Impala Platinum	64	± 60-70 per year
Eastern Platinum	-	No gas
Western Platinum	1	No gas
Union Platinum	1	± 12 per year
Northam Platinum	-	± 12 per year
Oryx	23	± 40 per year
Beatrix	19	± 50 per year
St. Helena	-	± 3 per year

All the perceived number of reports by the mine personnel include cases where methane is detected inside pilot holes during drillings operations even if it was a small amount. In most cases methane is only detected inside drill holes and is quickly cleared.

Deeper mines did consider that they have more gas problems Mines that are working at depths of 200 m to 500 m below surface do not have any experience of methane incidents and they do not expect to have methane in the near future unless mining proceeds to deeper levels.

5 Conclusions

Increasing trends in combustible gas incidents and accidents are in contrast to the industry wide perception that combustible gases do not present a significant problem. Uncertainty as to the origins and transport mechanisms of gas within the strata make emissions difficult to predict, so although the ventilation is adequate to control the normal situation, sudden emissions do create problems.

Adjustments to ventilation arrangements, inadequate testing for gas and contraband contribute to almost every accident in South African mines. All of these are avoidable and manageable causes.

5.1 Combustible gases

Combustible gases are reported from non-coal mining in many countries, with the most occurrences in the hard rock mines of South Africa and Canada. Methane is the main constituent of the gases, but often present are other hydrocarbons, hydrogen, hydrogen sulphide and carbon monoxide. The gas or gas mixture is commonly referred to as methane, even when the presence of other gases is known.

In South African gold and platinum mines, methane normally constitutes 80 per cent - 100 per cent of the combustible gas, with 0 per cent - 10 per cent of other hydrocarbons, and 0 per cent - 20 per cent hydrogen. However, all of these are variable, and methane can be as low as 45 per cent of the total and hydrogen as high as 40 per cent.

In addition to the combustible gases, inert strata gases are usually nitrogen, helium and argon. These are low in concentration and not always reported. This makes any inertising effect on the gas mixture difficult to predict.

The gases may separate out in the strata, as well as in the atmosphere. If different size molecules can move through the strata at different rates, then different gases can be emitted in preference to others. This accounts for the high butane readings for example, on some occasions, and on the variable helium contents. Separation of mixed gases after being emitted into the ventilation is commonly assumed to take place, but an unlikely actual occurrence.

Each gas and gas mixture has specific explosive limits, and these can be calculated using Le Chatelier’s rule. Physical gas samples must be collected and analysed by gas chromatography to identify the gases present, and the calculations for the strata gas mixture carried out on an air-free basis.

South African legislation does not take into account the variation in explosive limits for the different gas mixtures, with the present limit of 1,4 per cent limit in air. This is 28 per cent of the lower explosive limit of methane, but is 78 per cent of the limit for butane. In the Canadian Shield mines, where the gas mixtures are similar to South Africa, the limit for flammable gas is 10 per cent of the LEL.

The range and mixtures of gases affect the readouts on methanometers. All instruments in use are calibrated with methane, so wherever other gases are present these give incorrect readings. Correction factors are available from manufactures and suppliers for the instruments, and the appropriate ones should be obtained and applied by each mine.

Most gas occurrences are from drill holes with very few reports above 1 per cent in the general body of the air.

The distribution of gas is across almost all mines, but to variable degrees. There is no distinct correlation between reefs, mines, depths or regions, making prediction difficult to generalise. Many individual mines and people have their own opinions where the chances of gas emissions are greater. These are usually in deeper area, associated with dykes and faults, or where the reef is a higher grade.

5.2 Geological sources and transport of methane

Methane is classified broadly into being of biogenic or abiogenic origin. Biogenic gas is derived from an original bacterial origin, and abiogenic is not. These are further subdivided depending on their age and the geological conditions they have been exposed to.

The sources can be identified by the carbon isotope ratio of the carbon content in CH_4, which differentiates between the different classifications of methane. Geological evaluation of the Witwatersrand basin and Bushveld complex has identified several probable sources and transport mechanisms of methane for the gold and platinum mines, which will be researched in output two. The carbon isotope ratios will then identify the most probable source.

5.2.1 Gold mines

The main expected sources and corresponding carbon isotope ratios for gold mines are:

- Coal in overlying Karoo sediments
  (Bacterial or thermogenic biogenic methane, with $\delta^{13}C$ less than –50).
- Carbon matter in reefs, in particular where subjected to heat by adjacent dyke intrusion (Thermogenic methane with $\delta^{13}C$ of –20 to –60).
- Fluid inclusions in dykes, but only possibly in those of alkaline composition of Pilanesberg age (Abiogenic methane with $\delta^{13}C$ greater than –30).
- Seepage of methane from the mantle along joints, bedding and faults.
  (abiogenic methane with $\delta^{13}C$ greater than –30)
- Areas where methane would most probably be encountered in drilling, stoping and development are expected to be close to areas of high concentrations of carbonaceous matter in reefs.
- In fractures where voids exist, e.g. major faults, faulted dyke contacts, and areas of dense jointing, e.g. adjacent to dykes. These fractures may form channels for flow of gas, or, where capped by later strata, reservoirs for accumulation of gas.

Due to composition, and conditions during emplacement, it is unlikely that methane is generally trapped in most dykes and lavas in the stratigraphic sequence. Association of gas with dykes is most likely due to associated faults or increased levels of jointing, or heating of adjacent sediments bearing carbonaceous matter.

In general, it is unlikely that methane encountered in the gold mines originates from a single source. Different sources may predominate in different mining areas and resulting $\delta^{13}C$ isotope ratios are likely to reflect mixing of gases of different origins.

5.2.2 Platinum mines

In the Bushveld mines, all methane sources are most probably abiogenetic, hence the carbon isotope ratio would expect to give $\delta^{13}C$ values greater than –30.

The main expected sources of methane for the Bushveld complex mines are:

- Fluid inclusions in dykes, but only possibly in those of alkaline composition of Pilanesberg age.

- Seepage of methane from the mantle or from deeper alkaline intrusives along joints, bedding and faults.
- Fractures where voids exist, e.g. major faults, faulted dyke contacts, partings parallel to the reefs and in areas of dense jointing, e.g. adjacent to dykes or around potholes. These fractures may form channels for flow of gas, or, where discontinuous, act as reservoirs for accumulation of gas.

5.3 Gas related accidents

There is an increasing trend in flammable gas related fatalities and injuries. This is in contrast to general downward trends in fatalities and injuries in the industry.

Three main factors contribute to the accidents: adjustments to ventilation arrangements, inadequate testing for gas, and contraband. Changes to the ventilation and inadequate or no gas testing are both reported in over 60 per cent of all accidents, with contraband in more than 40 per cent.

The two main identified causes of gas ignitions are contraband and tampering with caplamps to make ignitors, although the second biggest cause of all ignitions is “unknown”. The mining activities when most ignitions occur are handling explosives, drilling and construction.

An accident is three times more likely to occur in development than in stopes.

Platinum mines have a high proportion of non-ignition accidents, when blowouts occur during drilling. These normally involve face and head injuries caused by either the drill, or rock and gas, being ejected form the drillhole. The gas quickly disperses, and is not measurable, but it is assumed to be methane.

Accident reports do not always include full details of the ventilation, gas occurrence, and other procedures and factors contributing to an accident. This makes a complete evaluation of accidents difficult.

The present number of gas incident reports is in decline, the same situation that has preceded the last two multiple fatality accidents.

5.4 Reporting and awareness

The requirements of Reg. 10.8.6 are interpreted differently by different mines and regional DME offices. There is an apparently over-cautious approach from many, which report every occurrence. This in itself does no harm, and did seem to make these mines more aware of gas, but makes the incident reports biased toward some mines.

Only what many mines consider to be an extreme case of gas is reported. Some mines that indicated no gas problems do detect the methane inside drill holes but in very small quantities and do not report it. In most cases methane only present in holes is not seen as a problem, because does not progress to the atmosphere due to the adequate ventilation.

This reporting problem is added to by the lack of detail as to the type of gas incident that should be reported. Almost all occurrences are in drill holes, with very little gas detected in the general body. This is considered by many to be an insignificant gas occurrence, but drill holes are specifically stated in Canadian legislation.

A standard needs to be considered for the industry of what type of occurrence needs to be reported.

Methane is generally considered to be present in the strata, but because of sufficient ventilation it is not always detected. This apparently leads to apathy regarding combustible gas and the poor and often inadequate testing or monitoring of gas in the workplace.

6 Interim recommendations

Gas samples should be taken for analysis by gas chromatography to determine the gas mixtures on individual mines. This must be done at regular intervals, and with the correct sampling procedures.

Methanometers calibrated in methane must be read with correction factors for the appropriate gas mixtures present.

Increase the awareness of all workers as to the hazards of flammable gas, highlighting the three main factors contributing to accidents, changes to ventilation, inadequate testing for gas and contraband.

Initiate research into the separation of gases in air and in strata, with practical large scale and laboratory testwork appropriate to South African gold and platinum mines, and evaluate the applicability of previous work regarding methane layering.

Initiate research into the occurrence and control of combustible gases in other types of South African non-coal mines.

Alarm levels should be reduced to 1 per cent wherever hydrogen or other hydrocarbons are known, or suspected to be, present.

7 References

Andrews J N 1987. Noble gases in groundwaters from crystalline rocks. Saline water and gases in crystalline rocks. Geological association of Canada special paper 33, p 234-244.

AAC (Anglo American Corporation of SA Ltd) 1997a. SIMRAC research proposal, draft. Internal company communication, Johannesburg.

AAC (Anglo American Corporation of SA Ltd) 1997b. Internal company communication, Environmental Engineering Department, Johannesburg.

Bekker E H 1986. Fossil water and the associated gas mixture within and below the Ventersdorp Supergroup in the Harmony mine area, Welkom goldfield. Mineral deposits of Southern Africa, Anhaeusser C R and Maske S (Eds.) Vol.I & II, Geol. Soc. S. Afr., Johannesburg, pp 731-752.

Bord M 1998. Itasca Consulting Group. Personal communication, e-mail, Minneapolis.

Brand E.L 1986. Water and gas occurrences in the Evander goldfield. Mineral deposits of Southern Africa, Anhaeusser C R and Maske S (Eds.) Vol.I, Geol. Soc. S. Afr., Johannesburg, pp 731-752.

Cadle R D 1980. A comparison of volcanic with other fluxes of atmospheric trace gas constituents. Reviews of Geophysics and Space Physics, Vol. 18, pp. 746-752.

Cambitzi C 1987. Support design of large winder chambers at depth on No. 1 shaft Western Deep Levels Gold Mine. SANCOT seminar, 1987.

COM (Chamber of Mines of South Africa) 1990 Flammable gas in metal mines : a guide to managers. Johannesburg.

CPUG (Cleveland Potash Underground Engineering) 1995. Detection of inflammable gases composed of methane and higher hydrocarbons. Internal company communication. UK.

Coetzee C B editor 1986. Mineral resources of the Republic of South Africa. Fifth edition. Department of Mines Geological Survey.

Coward H F and Jones G W 1952. Limits of flammability of gases and vapours. USBM Bulletin 503.

Crowcon Detection Instruments Ltd. 1996. Talking gas. Issue 1.

De Maar W J, Holder G 1993. An overview of rock engineering problems at Rustenburg Platinum Mines Limited. Proceedings of the SANGORM symposium “Rock Engineering Problems Related to Hard Rock Mining at Shallow to Intermediate Depth”. Rustenburg.

Department of Minerals and Energy (DME) 1997. Statistical summary of accidents reported to the chief inspector of mines for the period 1 January 1984 to Decenber 1997. Pretoria.

Du Plessis M 1998. DME, Personal communication, Johannesburg.

Edwards J S and Durucan S 1991. The origins of methane. Mining Science and Technology, 12 p193-204. Elsevier Science Publishers, Amsterdam

Elandsrand Gold Mining Company Ltd. 1997. Internal company communication. Environmental safety and health.

Eschenburg H M W 1980. Sources and control of methane in gold mines. Journal of the Mine Ventilation Society of South Africa, August 1980.

Faber E P, Gerling U Berner and Weise S 1995. Abiogenic or mantle methane in the KTB – German continental deep well? Extended abstract, 17th International meeting on organic chemistry, San Sebastian, Spain.

Fauconnier C 1989. Barometric pressure fluctuations as a factor contributing to gas explosions in South African mines.

Fritz P, Frape S K and Miles M 1987. Methane in the crystalline rocks of the Canadian Shield. Saline water and gases in crystalline rocks. Geological association of canada special paper 33, p 211-223.

Gerlach T M 1979. Chemical characteristics of the volcanic gases from Nyiragongo lava lake and the generation of CH4-rich fluid inclusions in alkaline rocks. Journal of volcanology and geothermal research, 8 (1980), p 177-189.

Grieg J D 1989 Gases encountered in mines. Environmental engineering in South African mines, p 713-740.

Grieg J D 1971. Report on helium emissions on gold mines. Chamber of Mines Research Organisation, 31/71, Johanneburg.

Godden S 1993. Notes on internal stope support design in the western Bushveld. Proceedings of the SANGORM symposium “Rock Engineering Problems Related to Hard Rock Mining at Shallow to Intermediate Depth”. Rustenburg.

Gold T 1979. Terrestrial sources of carbon and earthquake outgassing. Journal of petroleum geology, 1, 3, pp. 3-19.

Gold T and Soter S 1982. Abiogenic methane and the origin of petroleum. Energy Exploration & Exploitation. Vol. 1, No. 2, pp 89-104.

Hallbauer D K 1975. The plant origin of the Witwatersrand “carbon”. Minerals Sci. Engng, Vol 7, No. 2, pp 111-132.

Hallbauer D K 1986. The mineralogy and geochemistry of Witwatersrand pyrite, gold, uranium, and carbonaceous matter. Mineral deposits of Southern Africa, Anhaeusser C R and Maske S (Eds.) Vol.I & II, Geol. Soc. S. Afr., Johannesburg, pp 731-752.

Hartley D M R 1992. A follow-up investigation into the relationship between geological structures and methane occurrences on Bafokeng North mine. Bulletin 224, Addendum No. 1. Geology Department, Impala Platinum Limited.

Hatton C J 1995. Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. Journal of African Earth sciences.

Haughton S H editor 1964. The geology of some ore deposits in Southern Africa. The Geological Society of South Africa.

Hoefs J, Schidlowski M 1967. Carbon isotope composition of carbonaceous matter from the Precambrian of the Witwatersrand System. Science, Vol. 155, pp 1096-1097.

Holding W 1981. Acute hazards of explosive gases, their detection and control. Journal of the Mine Ventilation Society of South Africa, vol. 34 No.1.

Hughes A J and Raybould W E 1960. The rapid determination of the explosibility of mine fire gases. The Mining Engineer.

Hugo P J 1963 Helium in the Orange Free State gold field. Bulletin of the Geological Society of South Africa, Vol 39.

Hugo P J 1964 The Evader gasfield. Bulletin of the Geological Society of South Africa, Vol 41
.

Jackson K A B 1957. Methane on St Helena Gold Mined Limited. Assoc. Mine Managers of S. Afr.

Jurenovskis P 1998. Safety Supervisor, Kidd Mining Division, Falconbridge Ltd. Personal communication, letter, Ontario.

Kidd Mining Division 1997. Combustible gas procedure. Falconbridge Limited, Canada.

Konnerup-Madsen J, Rose-Hansen J, Larsen E 1981. Hydrocarbon gases associated with alkaline igneous activity: evidence from compositions of fluid inclusions. Rapp. Grønlands geologiske undersogelse, Vol. 103, pp 99-108.

Le Roux W L 1990. Le Roux's notes on mine environmental control. The Mine Ventilation Society of South Africa.

Lewis A 1998. Gas Detection Systems, Personal communication. Boksburg.

Lightfoot N, Kullman D H, Leach A R 1994. A conceptual model of a hard rock, deep level, tabular ore body that incorporates the potential for face bursting as a natural product of mining. Proceedings of the First North American Rock Mechanics Symposium, Austin, Texas. A A Balkema publishers.

Lougher D R, Mellowship P 1993. Strata control problems associated with geological structures on Impala Platinum Mines. Proceedings of the SANGORM symposium "Rock Engineering Problems Related to Hard Rock Mining at Shallow to Intermediate Depth". Rustenburg.

Lurie J 1977. South African geology for mining, metallurgical, hydrological and civil engineers. McGraw-Hill Book Company.

Marais, D 1998. GAPEEAG, Personal communication, Johannesburg.

Minter W E L 1976. Detrital gold, uranium and pyrite concentrations related to sedimentology in the Precambrian Vaal reef placer, Witwatersrand, South Africa. Economic Geology. Vol. 71, pp 157-176.

OML (Ontario Ministry of Labour) 1996. Health and Safety Guidelines, Draft #4,Sudbury Ontario,

Pieters C 1998. CSIR Materials Science and Technology. Personal communication, Pretoria.

Phillips G N, Law J D M 1994. Metamorphism of the Witwatersrand gold fields: a review. Ore Geology Reviews. No. 9, pp 1-31.

Phillips H R 1998. University of the Witwatersrand. Personal communication, Johannesburg.

Robb L J and Robb V M 1998. Gold in the Witwatersrand Basin. In: Wilson M G C and Anhaeusser C R (editors) The mineral resources of South Africa. Sixth edition. Council for Geoscience.

Rogers D E C 1998. CSIR Materials Science and Technology. Personal communication, Pretoria.

Rowe, D 1998. DME, Personal communication, Johannesburg.

Schauenburg Flexadux (Pty) Ltd. 1998. Personal communication, fax, Johannesburg

Schoell M 1988. Multiple origins of methane in the Earth. Chemical Geology, 71, pp 1-10. Elsevier Publishers B.V.

Schoell M 1983. Genetic characterisation of natural gases. The American Association of Petroleum geologists Bulletin. Vol 67, No. 12, pp 2225-2238.

Searra J A 1990. Gas related problems in the Witwatersrand Supergroup. Unpublished MSc thesis, University of the Witwatersrand, Johannesburg.

Sherwood B, Fritz P, Frape S K, Macko S A, Weise S M and Welhan J A 1988. Methane occurrences in the Canadian Shield. Chemical Geology, Vol. 71, pp 223-236.

Sherwood B 1996. Communication to Falconbridge Ltd., University of Toronto.

Snyman C P 1965. Possible biogenetic structures in Witwatersrand Thucholite. Geol. Soc. South Africa Trans., vol. 68, pp 225-235.

Spearing A J S 1995. Handbook on hard-rock strata control. The South African Institute for Mining and Metallurgy, Johannesburg.

Symonds, Rose, Bluth, Gerlach 1994. Volcanic gas studies: methods, results and applications. In Carroll M R, & Holloway J R (eds.) Volatiles in Magmas: Mineralogical Society of America, Reviews in Mineralogy, Vol. 30.

Talma A S 1998. CSIR Mattek, Personal communication, e-mail, Pretoria.

Tennent, R M 1971. Science data book, Oliver and Boyd, Edinburgh.

US CFR (US Code of Federal Regulations). Title 30, part 57. Safety and health standards – underground metal and non-metal mines, subpart T,.

Van Heerden J 1995. Atomic Energy Corporation of South Africa Ltd. Personal communication. Pelindaba.

Van Greunen D 1998. Orxy Mine. Personal communication, Welkom.

Viljoen, PLJ 1998. Sasol Mining, personal communication, Secunda.

Viljoen M J and Schurmann L W 1998. Platinum group metals. In: Wilson M G C and Anhaeusser C R (editors) The mineral resources of South Africa. Sixth edition. Council for Geoscience.

Visser L 1995. A follow-up investigation into the relationship between geological structures and methane occurrences on Bafokeng North mine. Bulletin 224. Addendum No. 2. Geology Department, Impala Platinum Limited.

Walters D M 1992. Clearing a methane filled interlevel. Journal of the Mine Ventilation society of SA.

Welhan J A 1987. Characteristics of Abiotic Methane in Rocks. In: Saline water and gases in crystalline rocks, edited by Fritz P and Frape S K. Geological association of Canada special paper 33, 1987, pp 225-233.

Welhan J A 1988. Origins of methane in hydrothermal systems. Chemical Geology, 71, pp 183-198. Elsevier Publishers B.V.

Whitely M 1998 DME Western Australia, Personal communication, e-mail, Western Australia.

Wilson M G C and Anhaeusser C R (editors) 1998. The mineral resources of South Africa: handbook, Council for geoscience, 16, 740pp.

APPENDIX I Geology of the Canadian Shield

The Canadian Shield is a large craton of Precambrian age of predominantly igneous and metamorphic rocks, including greenstone belts, covering much of the Eastern half of Canada and is host to a number of mineral deposits, which are igneous or volcanic in origin. It has formed a largely stable continental section of the Earth's crust for the past 2000 million years, and hence is similar to the South African Kaap-Vaal craton, which contains the Witwatersrand Basin and Bushveld complex.

Gold-quartz veins occur from Western Quebec to the Northwest Territories, for example the Hollinger, McIntyre and Dome mines in the Porcupine district of Ontario, which reached depths of almost 2000 m. Veins were formed from hydrothermal ore solutions considered to be derived from underlying magmas. Further important gold veins occur in the Kirkland lake district of Ontario.

Massive sulphide desposits, sandwiched between felsic volcanics below and andesites above, feature in the Noranda, Quebec, area (Quemont, Horne, Waite-Amulet, Normetal, Aldermac), with copper, zinc, silver and gold mineralisation. These deposits are thought to be of a submarine volcanic exhalative fluid type. In the Timmins area (e.g. Kidd Creek) massive sulphides are hosted entirely in volcanics. Other volcanic exhalative massive sulphides are found in the Churchill district of Manitoba and in New Brunswick.

The Sudbury area hosts numerous massive copper-nickel sulphide deposits in granite-gneiss plutonic igneous rocks and breccias immediately beneath norites, quartz-dorites and micropegmatites of the layered complex which crops out as an elliptical ring 11 km long by 5 km wide, forming a basin. The layers represent various phases of magma intrusion and the ores are probably magmatic, not hydrothermal, in origin. It has been suggested that the intrusion occurred in response to a meteorite impact. Mines such as Creighton reach several kilometres depth.

APPENDIX II Brief review of reported accidents

File:93 G Platinum Amandelbult section
Working 0072 I
Held at D.M.E. Rustenburg
Mine: Rustenburg Place:9/32 W boxhole
Injuries: 1
Fatalities: 0
Date of Accident:17/2/93
A short description of the accident:
No details
Geology:
No details
Ventilation:
The fan serving the boxhole was not in operation.
Testing for the presence of gas:
No tests for flammable gas were carried out.
Source of gas:
No details
History:
No details
Mixture
No details
Ignition
The injured person lit up a cigarette and ignited the flammable gas.

File: JM 0276/95
Held at D.M.E.Rustenburg
Mine: Western Platinum Karee Mine
Working Place:21C3 Raise
Injuries: 2
Fatalities: 0
Date of Accident:14/1/95
A short description of the accident:
Whilst connecting an already lit delay starter to igniter chord, methane was ignited and burnt the hands of the team leader and the face of a co-worker.
Geology:
No details
Ventilation:
A compressed air blower was used to ventilate the box hole. The haulage from which the raise was broken away was not ventilated. The ventilation column was 35m away.
Testing for the presence of gas:
Several witnesses state that after water was intersected in one of the holes, the team leader tested for flammable gas with a methanometer but found none.
After the accident, 1.3 per cent methane was registered on a methanometer approximately 2m from the face. A hissing sound emanated from a hole in the top right corner where 5per cent methane was recorded.
Source of gas:
Gas issued from a borehole in the top right corner of the face.
History:
No details
Mixture
No details

Ignition
The methane was ignited while a lit stay-a-lite was being connected to igniter chord..

File:95k0202
Held at D.M.E. Klerksdorp(Rustenburg)
Mine: Impala Platinum/; Wildebeestfontein North Mine.
Working Place:1266 Stope
Injuries: 1
Fatalities:
Date of Accident: 7/11/95
A short description of the accident:
A machine drill operator was injured when the machine was forced back from the hole and struck him on the mouth. The pressure inside the hole was presumed to be caused by Flammable gas.
Geology:
No details
Ventilation:
No Details
Testing for the presence of gas:
No Details
Source of gas:
No Details
History:
No Details
Mixture
No Details
Ignition
No Details

File:96/k0521m
Held at D.M.E. Rustenburg
Mine: Western Platinum Mine South
Working Place:11 E 12 SPD West
Injuries: 1
Fatalities: 0
Date of Accident: 17/5/96
A short description of the accident:
Whilst drilling the face of the working place, a methane pocket was intersected. Objects that were ejected from the drill hole penetrated the operator's eyes and ears.
Geology:
No Details
Ventilation:
No Details
Testing for the presence of gas:
No Details
Source of gas:
No Details
History:
No Details
Mixture
No Details
Ignition
No Details

File:96k0541m
Held at D.M.E.Rustenburg
Mine: Rustenburg Platinum Mine East
Working Place:13 level 3E x/c S vent raise.
Injuries: 2
Fatalities: 0
Date of Accident:29/5/96
A short description of the accident:
During early examination, a fall of ground occurred during barring operations and an explosion ensued. It is suspected that the explosion was due to the prescience of flammable gas.
Geology:
No details available
Ventilation:
The ventilation column was 20.2m from the face of the raise and 12.2m from the raise break away. The raise inclines at approximately thirty degrees. Instructions were given to bring the ventilation columns up to date on the day prior to the accident, but these instructions were not carried out. The mine procedures require that Methane tests should be completed before barring commences. The team supervisor stated that he started to test for gas, but then felt that hanging wall was too dangerous and needed to be barred first.
Testing for the prescience of gas:
The team supervisor claimed to have tested for flammable gas with a tritector equipped with a probe on the morning before the accident occurred. However he interrupted the test to bar down bad hangingwall.
After the accident, 0.6per cent Methane was measured in the general body of the air, and 0.7per cent issued from a drill hole in the centre of the face.
Source of gas:
A socket near the centre of the face.
History:
No details available
Mixture
No details available
Ignition
Falling rock caused a spark.

File:96/k0601
Held at D.M.E. Rustenburg
Mine: RPM Union Section
Working Place:26.16 Belt Incline
Injuries: 1
Fatalities: 0
Date of Accident: 10/6/96
A short description of the accident:
A methane pocket exploded and injured the operator.
Geology:
No Details
Ventilation:
No Details
Testing for the presence of gas:
No Details
Source of gas:
No Details
History:
No Details

Mixture
No Details
Ignition
No Details
File:96/k0965I
Held at D.M.E. Rustenburg
Mine: Western Platinum North Mine
Working Place:20 W no.2 Boxhole
Injuries: 1
Fatalities: 0
Date of Accident:10/10/96
A short description of the accident:
Whilst igniting a charge a methane explosion occurred and the person sustained burns to his face and forearms. The boxhole was blasted later than the normal blasting time as the drilling took longer because a dyke had been intersected. The injured consequently ignited the blast manually.
Geology:
No details
Ventilation:
A compressed air blower was used to ventilate the box hole. The haulage from which the raise was broken away was not ventilated. The ventilation column was 35m away.
Testing for the presence of gas:
The developer was not supplied with a methanometer on the day of the accident but one was available in the section. The developer claimed to have tested for methane before lighting up but the team leader stated that the methanometer was in his possession all the time, yet he saw the miner using it to test for methane.?
After the accident up to 49per cent methane was measured.
Source of gas:
No details
History:
No details
Mixture
No details
Ignition
The ignition of a stay-a-lite by means of an open flame caused ignition of the gas.

File:97/k0190k
Held at D.M.E. Rustenburg
Mine:RPM West
Working Place:PK 39/22 Rse 2E
Injuries:2
Fatalities:4
Date of Accident:6/3/97
A short description of the accident:
4 Workers were killed and two severely burnt when a methane explosion occurred while they were installing a ventilation fan in a raise.
Geology:
No details
Ventilation:
The fan supposed to ventilate the end, had been out of order for seven days prior to the accident. A 25mm air hose was blowing from a distance of 3.0m from the face.
Testing for the presence of gas:
The miner did not test for the presence of gas in the end . He did not take a methanometer underground with him.

The development team supervisor allegedly tested for flammable gas with a methanometer during the early shift examinations.
After the accident methane readings of up to 74per cent were measured in boreholes
The working place was defined as a working place in which flammable gas is likely to occur.
Source of gas:
No details
History:
No prior intersections of methane in this working place were reported
Mixture
No details
Ignition
Explosives and contraband was found at the scene of the accident.

File:97 KO293M
Held at D.M.E.Rustenburg
Mine:RPM East
Working Place:TF 3E-29 x/c North
Injuries: 2
Fatalities:
Date of Accident:16/4/97
A short description of the accident:
Whilst drilling a hole, a machine operator sustained injuries to his face when objects from the hole were ejected under pressure thought to be caused by methane.
Geology:
No details
Ventilation:
No details
Testing for the presence of gas:
No methane was found before or after the accident.
Witnesses reported a loud sound like an explosion and one witness reported a green flame.
Source of gas:
No details
History:
No details
Mixture
No details
Ignition
No details

File:97 KO745N
Held at D.M.E. Rustenburg
Mine: Impala Platinum, South Mine
Working Place:5c45 Stope raise
Injuries: 1
Fatalities:
Date of Accident:30/9/97
A short description of the accident:
During early examination, a team leader’s co alarm sounded. He watered down the area and the alarm stopped. He instructed a winch driver to rig the scraper while he commenced to install a blower. When he turned around, the winch driver lay on the blasted rock.
Geology:
No details

Ventilation:
No details
Testing for the presence of gas:
No details
Source of gas:
No details
History:
No details
Mixture
No details
Ignition
No details

File:97/KO803I
Held at D.M.E.Rustenburg
Mine: Western Platinum Karee Mine
Working Place: Injuries:1
Fatalities:
Date of Accident: 21/10/97
A short description of the accident:
Whilst drilling a hole, the machine operator was injured by loose face rock ejected from the face by an explosion.
Geology:
No details
Ventilation:
No details
Testing for the presence of gas:
No details
Source of gas:
No details
History:
No details
Mixture
No details
Ignition
No details

File:LM0229
Date: 1/3/1988
Working Place: Harmony no. 5 Shaft
People Killed: 0
People Injured: 1
Short description of accident:
A worker was injured when an explosion took place in the number 5 shaft after it had been stripped and whilst preparations were being carried out to remove the sinking stage. An acetylene torch was used. Suction into the shaft was felt before the stage was lifted by the concussion of the explosion, out of the shaft. This caused damage to the shaft headgear and the stage. A heavy thunderstorm occurred in the vicinity prior to the accident.
Geology
The shaft intersected two faults, one below the 1000 dam level and one halfway between eight level and ten level. The exhibit also shows that the shaft intersected a dyke just above 8 level, however no mention of this was made during the inquiry. No significant coal seems were

encountered. Whilst developing the dam level at 516m , a fault was exposed and 2per cent flammable gas was detected.
Just above 8 level, cover holes intersected 1 to 2 per cent flammable gas.

Ventilation

During sinking and stripping operations, the shaft was ventilated with between 17 and 26 cubic meters of air. However at the time of the accident the shaft barrel below the stage was not ventilated.

Method of gas detection

A continuous methane monitor was mounted on the bottom deck of the stage. A flame safety lamp was suspended under the canopy of the top deck. The shift foreman carried a methanometer. About two hours before the accident, the bank doors were opened and testing for flammable gas was carried out. Before the boilermaker started to cut the plate he was working on, the foreman again tested for flammable gas.

History

During pre sinking exploration drilling, 87per cent flammable gas was detected in the hole, but none in the general atmosphere.

Mixture

No details.

Ignition

It is implied, but nowhere stated, that burning material from the acetylene torch fell down the shaft and ignited a body of flammable gas further down the shaft.

File: II 0685/89
Held at D.M.E. Braamfontein
Mine: Kloof
Working Place:30-30 vcr stope
Injuries: 1
Fatalities: 0
Date of Accident: 10/7/89

A short description of the accident:

A worker was seriously burnt when flammable gas ignited.

Geology:

No evidence was given pertaining to geology

Ventilation:

Compressed air pipes were installed to ventilate the stope whilst establishing a holing after falls of ground restricted normal airflow.

Testing for the presence of gas:

This area was not a development end, and not declared as a methane area. For that reason regulations pertaining to this mine at the time did not require testing for flammable gas in the stope.

Source of gas:

The source of the gas was not established.

History:

No prior intersections of flammable gas were reported.

Mixture:

The gas was not analyzed.

Ignition:

Cigarettes and matches were found on the scene, and although no witnesses saw anyone smoking, the investigating officer found that smoking caused the ignition.

File: m 0316/90
Held at D.M.E. Braamfontein
Mine: Kloof
Working Place:29-82 cross cut East

Injuries: 2
Fatalities: 0
Date of Accident: 6/4/90
A short description of the accident:
A flammable gas explosion occurred when a team leader was igniting the blasting round of a development end.
Geology:
A slip was present near a roof bolt hole in the northern sidewall 4.4m from the face. A small amount of water issued from the hole.
Ventilation:
The end was ventilated by means of a force-exhaust overlap system. The exhaust column end was 24.4m from the face. The end of the force column was 20.4m from the face. It was required to be not further than 12m from the face. The water blast was 18m from the face.
The force fan was not working.
Two 90mm flexible hoses supplied compressed air to the end.
Testing for the presence of gas:
The miner attempted to test for gas with a flame safety lamp when it was reported to him that one of the bore holes intersected water. He found that the lamp was inoperative. No testing was done before the round was ignited.
After the accident, the manager tested for gas and read 5per cent methane from his methanometer 1.5 m from the hole from which water issued.
Source of gas:
The source of gas was not established. Evidence indicates that it might have come from the roof bolt hole. The investigating officer and manager both seem to have implied this.
History:
There was no evidence of prior gas intersections.
Mixture:
The flammable gas mixture was not determined
Ignition:
No evidence concerning the method of ignition was presented.

File: IK0959/90
Held at D.M.E. Braamfontein
Mine: East Driefontein
Working Place: 32-19 Carbon Leader Following Footwall drive West at no.4 Boxhole
Injuries: 0
Fatalities: 5
Date of Accident: 17/10/90
A short description of the accident:
Burning gas overcame a construction team leader and four construction workers while they were in the process of installing pipes.
They later succumbed to their injuries.
An acetylene torch was used, but the torch flame had been extinguished before the flammable gas was ignited.
Geology:
No evidence was given pertaining to geology
Ventilation:
The boxhole was not ventilated at the time of the accident.
The construction crew was on top of a temporary boxfront at the opening of the boxhole. The accident scene was not situated in fresh intake air.
Testing for the presence of gas:
A special team leader tested for flammable gas, about 10m into the 18m boxhole with a methanometer at the beginning of the shift. He reported no gas detected.

At about 7:30 the developer tested for gas about 10m into the boxhole but found none.
The construction team leader did not test for flammable gas prior to working with the cutting torch. He was not issued with a methanometer. There was an arrangement for him to borrow a methanometer from the developer.
The Ventilation Engineer tested the atmosphere in the boxhole the day after the accident occurred. He found the air contained 17.5 per cent oxygen and more than 5per cent methane.
The methanometer issued to the special team leader proved to read 3.5per cent flammable gas when tested against a 2.5per cent methane/air mixture.
Source of gas:
The source could not be identified.
History:
The intersection of gas in the 32-19 Carbon Leader following footwall drive west, east of number 4 boxhole was reported to the ventilation engineer on 27 June 1990 and to the inspector of mines on 29 June 1990.
On 3 July 1990 the area was declared clear of methane.
Mixture:
This was not determined
Ignition:
A cutting torch was used to heat a pipe. It is thought that the heat of the pipe, or a spark or the hot tip of the torch ignited the gas. The torch flame had been extinguished before the accident occurred.

File: BM1430/90
Held at D.M.E. Braamfontein
Mine: West Driefontein
Working Place: 18/41 2E Panel
Injuries: 4
Fatalities: 0
Date of Accident: 23/10/90

Short description of accident:
A drilling machine operator prepared to drill and three other workers prepared to move a blasting barricade forward when gas was ignited. Four people sustained injuries.
Geology:
At the top of the 2E panel a fault throws approximately 2m down on the north side and strikes almost parallel to the reef. It had been exposed for considerable time.
Ventilation:
As the result of damage to one of the two ventilation doors of an airlock, the other door was forced to stay open by spragging it. This caused ventilation air to short circuit a booster fan, which normally exhausts the air out of the workings via 18 level.
Method of gas detection:
The stope was not declared a hazardous area and no tests for flammable gas were carried out. Routine inspections are conducted periodically by environmental staff equipped with continuous monitors.
The last survey done before the accident occurred was on 3/8/90.
Source of gas:
No source could be identified.
History:
No history of flammable gas exists for this area prior to the accident. The last three surveys before the accident did not encounter flammable gas. The fault does not have a history of flammable gas associated with it.
Mixture:
Gas samples were not analysed

Ignition:
Circumstantial evidence suggests that one of the workers lit up a cigarette.

File: 94H2657K
Held at D.M.E. Braamfontein
Mine: Doornfontein
Working Place: 35-39 C L Raise
Number of people injured: 0
Number of people killed: 2
Date of Accident: 24/10/94
Short description of accident:
A team leader and winch operator were placing a bomb to remove a restriction from an orepass when a methane explosion apparently killed them. In the subsequent rescue operation a mine overseer, his assistant and a shift boss died carbon monoxide poisoning.
Geology:
A dyke or dykes intersected the raise near the face not far from where the victims were found.
Ventilation:
The open end of a ventilation column was directed towards the bottom of the boxhole that was restricted
There was no ventilation where the two methane victims were found.
Method of gas detection:
No measurements or tests were carried out to detect gas, neither by the team leader and winch driver, nor by the subsequent rescue party. A party that included the mine manager and production manager inspected the raise earlier the day. They also did not test for gas.
Source of gas:
The source of the gas was not determined.
History:
One witness stated that someone had mentioned to him that methane had been detected prior to the accident. He could not say where or how much gas had been recorded, and he could not identify the person who had mentioned this to him.
There were no records of reports of flammable gas.
The subordinate manager could not recall any incident of flammable gas during the ten years prior to the accident.
Mixture:
The proto rescue team measured gas in the raise as follows:

Position	Carbon monoxide	Methane
5m into the raise	700 ppm	1.7%
15m above the first ore pass		8.9%
41.3m into the raise	11 000 ppm	5.8%
4 paces forward		6.9%
2 paces forward		7.8%

Ignition:
Matches and an empty cigarette packet was found near one of the methane victims.
Two rolls of spent igniter chord were found towards the bottom of the raise.
The actual cause of ignition was not established.

File: 95H2268K
Held at D.M.E. Braamfontein
Mine: Elandsrand
Working Place:88-26 Stope
Number of people injured: 5
Number of people killed: 8
Date of Accident: 26/9/95
Short description of accident:
Flammable gas was ignited in a stope. Reports of methane detected prior to the accident, a strange smell, a broken fan ignorance and apathy were some of the factors leading to this tragedy.
Geology:
The stope is situated in the Ventersdorp Contact Reef, which dips 25º to the South.
The Roque dyke is between 15m and 20m wide and strikes NE-SW. It was exposed in the bottom of no. 2 E panel.
Ventilation:
The stope was placed under negative pressure by means of two fans situated at the bottom of a ventilation boxhole in 88/26 crosscut.
Rubber brattices in the gullies and backfill in the back areas contained the ventilation air in the face area.
Venturi blowers supplemented the airflow in north sidings.
A ventilation change over took place shortly before the accident. A single fan arrangement was substituted for the two fans, apparently in preparation for extension of the working faces in the stope. A ventilation survey had not been carried out during the period after the change over and before the accident.
On the day of the accident, one fan was not working. This led to a certain amount of re-circulation of air.
Method of gas detection:
Methanometers were used to test for the presence of flammable gas.
After the accident, readings as high as 20per cent were recorded.
The ventilation department recommended a continuous monitor to be installed in the stope. The section manager and mine overseer decided against that, as the alarm signals when 1per cent flammable gas is detected while regulations called for 1.4per cent.
Source of gas:
The source was thought to be somewhere in the 2 E panel, with the Roque dyke as the prime suspect.
Evidence of a continuous source extending from a crack in the top of the panel to the dyke at the bottom was submitted.
History:
Various people detected flammable gas on several occasions in the stope since 13 September 1995. Readings of up to 2.5per cent were recorded. A number of witnesses detected a strange smell for considerable time before the accident.
Mixture:
Samples of gas were analysed after the accident and contained carbon monoxide, carbon dioxide and methane. Traces of ethane and butane were also recorded.
Ignition:
The source of ignition was not identified.

File: : LK 1031/9
Held at D.M.E. Welkom
Mine: Merriespruit No. 3 Shaft
Working Place: 4-24 Slusher drive North
Number of people injured: 0
Number of people killed: 2

Date of Accident: : 22 December 1991

A short description of the accident:

Two people were killed when an explosion took place in a slusher drive.

Geology:

A dyke cuts through the end.

Ventilation:

The ventilation fan serving this area was electrically linked to a winch. The cable to the winch was damaged. The fan was not working when the accident occurred.

Testing for the presence of gas:

Methane patrols inspected the area on a regular basis.

The team leader (deceased) did not take a flame safety lamp underground with him on the night of the accident.

Source of gas:

Unknown

History:

Methane was often detected in the area in cracks, fissures, dykes and drill holes.

The night shift miner detected 0.1per cent flammable gas on the face in a socket on 19 December.

On 21 December, methane was detected at cracks in the dyke.

Mixture:

Not determined

Ignition:

The source of ignition could not be established.

File:95C 0703K

Held at D.M.E Welkom

Mine: Beatrix gold Mine

Working Place:15E80 Raise, no.1 Shaft

Date of Accident:19/4/95

Number of people injured: 0

Number of people killed 2

A short description of the accident:

Two people died in an explosion in a development raise close to a diagonal.

Geology

The raise was stopped on a fault.

Ventilation

The diagonal was broken away approximately 160m from the face of the raise. The ventilation column was broken at the point of the break away and the rest of the raise was left unventilated. Workers were in the process of repairing the column when the explosion occurred.

The volume of air at the face, according to the last ventilation survey was only 0.14 cubic meters per second. The force column leaked excessively. The force column was further than 12m from the face.

Method of gas detection

A surveyor wanted to install pegs when he noticed a that his methanometer alarm had been activated.

At least 5 instruments had been activated during this time, but the miner thought them to be unreliable due to the extreme heat.

History

There was no previous history of flammable gas in the vicinity of the raise.

On 9/2/95 3per cent methane was detected in the raise.

An entry in the methane book indicated 5per cent methane was detected on 19/4/95.

Ignition

One of the cap lamps found had the charging barrel lock in a position so that current could be drawn from it. (A means of producing heat to light cigarettes or delay starters.)

APPENDIX III Mine representatives visited for technical interviews

NAME OF MINE	CONTACT PERSON
Blyvooruitzicht Gold Mine	Doug Genner
East Driefontein	Brian Bunt
West Driefontein	G.J. Beukes
Elandsrand	Johan du Plessis
Kloof Gold Mine	Boet v/d Vyver
ERPM	Daug McClaghlan
Randfontein Estates	Tinus Haywood
Leeudoorn	Stoffel Ahlers
Buffelsfontein	Lemmer Visser
Western Deep Levels	Lourens Smith
Western Areas Gold Mines	Tienie De Jager
African Rainbow Mineral	Willie Retief
Durban Deep	George Niewoudt
Western Platinum Mines	Thys Knoetzer
Eastern Platinum Mines	Dave Mallett
Union Platinum	Arnoldt Erasmus
Karee Mine	Smiley Roux
Frank Shaft Mine	Tienie Roux
Paardekraal Shaft	Roger Barett
Brakspruit Shaft	Joseph Logadima
Turffontein Shaft	Org Haywood
Townlands Shaft	Hein van Loggenberg
Amandelbult Mine	Jaques Van Yssen
Northam Platinum	Braam Minnaar
Impala Platinum	Nick Skophouse
Oryx Gold Mine	Dirk van Greünen
Beatrix Gold Mine	Jan Van Der walt
St. Helena Gold Mine	Chris Castle