

**Safety in Mines Research Advisory Committee**

**Literature survey on the advance  
detection of dykes in underground coal  
mine workings**

**Prof. G A Fourie**

**Laboratory for Advanced Engineering**

**University of Pretoria**

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## Executive Summary

To minimise risk, a more effective system of mine planning and operation is required which calls for advance knowledge of structural and geological conditions ahead of the coal working face. This research project attempts to identify, by means of a literature survey, different exploration and geophysical methods that could be used to detect dykes ahead of underground coal mine workings.

In this study a range of geophysical and exploration methods have been identified which are generally used in the mining industry. Each different method exploits a different physical property of the earth's crust, e.g. seismic and acoustic methods measure the velocities of sound waves, while magnetic methods distinguish the variance in magnetic susceptibility of different rock types. Gravitational survey methods detect and measure lateral variations in the earth's gravitational pull that are associated with near surface changes in density.

Dykes generally display a high level of magnetic susceptibility and magnetic survey methods are therefore commonly used by most coal mining companies to identify the presence of this geological feature. The sophistication of aeromagnetic survey techniques has increased significantly over the past decade and is now routinely used by local and overseas coal mining companies to explore relatively large target areas fairly successfully.

Horizontal, in-seam drilling was first tested in the United States during the late 1950's. This technique was initially developed to degasify the coal seam ahead of mining operations. Similar trials were conducted in Australia during 1980 and by mid-1981 the Australian Coal Industries Research Laboratories Limited (ACIRL) reported that "600 m longholes can be achieved on a regular basis". In-seam drilling is now practiced on a number of South African collieries and hole lengths of up to 1200 m are standard. During the early 1990's Amcoal introduced incline-directional drilling from surface as a means to detect dykes and other geological features ahead of mining. Average borehole lengths achieved with this method are now in

the order of 1200 metres, however, development work is in progress to increase the effective reach to 2000 metres. Similar work is currently in progress at Sasol Coal.

The use of ground penetrating radar as a means to detect dykes has been tested on various South African gold mines. Initial reports indicate that the presence of dykes and faults could be detected successfully up to a distance of 40 metres ahead of the mining face. The same level of success could, however, not be achieved on coal mines.

At present most South African coal operations use a combination of vertical drilling, aeromagnetic surveying and in-seam drilling techniques to detect and identify the presence of dykes ahead of the mining face with a relative high degree of accuracy

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## 1. Introduction

This review examines the various techniques of applied geophysics used by the coal industry at large to delineate the boundaries of geological and man-made structures in coal deposits, with special reference to the detection of dykes ahead of underground workings.

Applied geophysical techniques exploit the physical properties of the earth to investigate relatively small-scale and shallow features in the earth's crust. They have been used for several decades in the exploration for metallic minerals and since the beginning of this century in the exploration for oil and gas and were first applied to coal deposits in the 1920s and 1930s

Although geophysical techniques continued to be used to some extent, examination of coal deposits in many areas continued until the early 1970s to be performed mainly by a combination of geological mapping and the drilling of boreholes. The coal industries in many countries have become aware of the potential economic and safety benefits which may be gained from the use of applied geophysical techniques to examine coal deposits for features of importance to mine planning and operations.

Geophysical techniques are capable not only of delineating the edges of the coal seam more accurately than by using surface mapping, but also of locating and characterising geologic and man-made structures in the deposit. The commonest geologic structures are faults, folds, dykes and clay layers which may cause the coal seam being mined to decrease in thickness or even to disappear altogether. In addition, they may cause roof falls, accumulations of gases and water, all of which contribute to the risk associated with mining. Features such as these can rarely be detected by only drilling conventional vertical exploration boreholes. Clearly if the coal industry could plan its operations to avoid such structures then it might be able to reduce losses of coal, disruptions to production and most important, the reduction of safety hazards. A number of geophysical techniques originally developed in the search for metallic minerals, oil or gas have been tested in coal deposits. Each technique responds to a certain physical property of

the rocks. The objective of this project is to determine, through a literature survey, various

geophysical and other techniques used in the coal industry to detect the presence of dykes ahead of underground mining.

There are a number of reasons why geophysical techniques are not used more widely in the coal industry. One which may be the cost involved or otherwise the prejudice against geophysical techniques due to earlier poor results in surveys.

Often, the poor results have been due to communication problems between mining companies and the geophysical companies in terms of the needs of the one and the capabilities of the other. Clarke (1976 a,b) and Ziolkowski (1981) discuss some of the difficulties encountered in the United Kingdom in the early 1960s when surface seismic surveys were first performed. Price (1978) surveys the geophysical techniques employed in the Australian coal industry and the confidence placed in them by the mining companies. The clash of attitudes between the enthusiastic geophysicists and the sceptical mining companies which is noted is certainly not unique to Australia.

However, confidence in the techniques has steadily grown as more and more successes are recorded. Many of these may be attributed to the redesign of field procedures and instrumentation specifically for coal rather than their adoption from oil and gas exploration techniques.

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## 2. Investigation Objectives

A major component of mining risk is the risk of encountering unexpected geological disturbances ahead of the working face. Of particular concern to the

coal mining industry is the presence of dykes in underground workings and the general safety risks associated there with.

The objectives of this study are to determine through a literature search, various methods that can be used to determine the presence of dykes ahead of mining and to identify further research work (if any) that needs to be performed.

### **3. Seismic and acoustic methods**

#### **3.1. Background**

Seismic surveying techniques from the surface of the earth were originally developed by the oil and gas industry in the search for large geological structures containing hydrocarbons at depths of 600 to 10 000 metres (Bredewout and Gouly, 1986). Recent developments associated with the use of the seismic and acoustic methods to evaluate environmental sites have enhanced the potential of this technique for cost-effective application in the mining industry (Miller and Steeples 1990, 1995). Shallow, high-resolution seismic reflection profiles can be useful in characterising shallow structures or anomalies and extending features identifiable in outcrop and surface excavation into the upper several hundred metres of the subsurface (Miller and Steeples 1995). The high-resolution seismic reflection method has only recently developed into a practical and effective tool for identifying shallow (<100 metres) structures (Miller and Steeples, 1995; Hunter et al., 1985; Jongerius and Helbig, 1988 ; Treadway et al., 1988; Miller et al., 1989; Miller and Steeples, 1991; Goforth and Hayward, 1992).

### **3.2. Basic principles and concepts of shallow seismic reflection profiling**

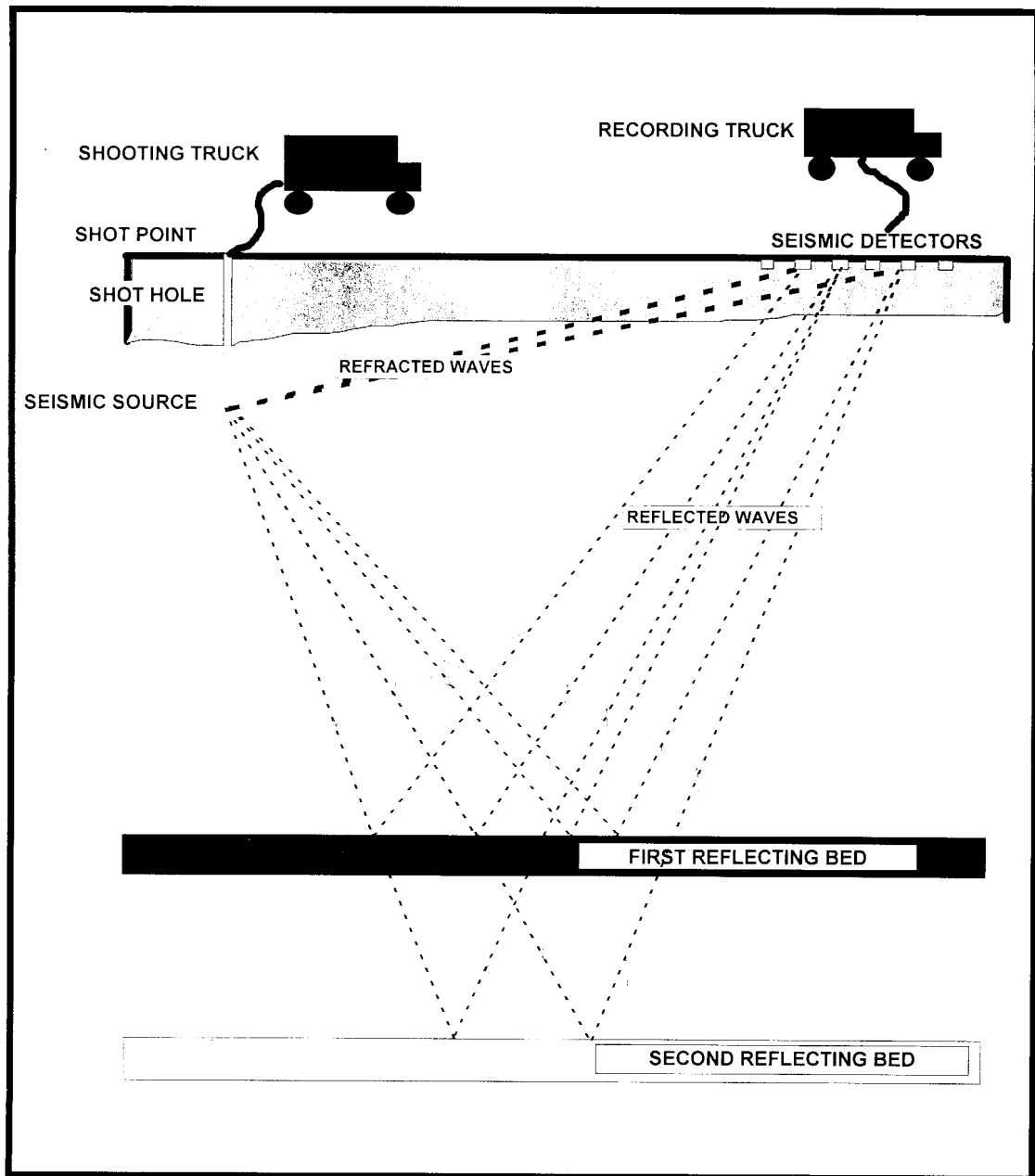
Seismic methods make use of the fact that elastic waves travel at different velocities in different rocks and behave in certain ways when encountering interfaces between different rock types. Steeples and Miller (1993) refer to these velocity differences as “acoustic impedance contrasts”. Acoustic impedance contrasts occur at natural boundaries between geologic layers, although manmade boundaries, such as tunnels and other underground excavations, also represent contrasts. The classic use of seismic reflection is to identify the boundaries of layered geologic units. However, the technique can also be used to search for localised anomalies such as sand/clay lenses and cavities.

Compression waves (P-waves) propagating through the earth behave similarly to sound waves propagating in air. When sound waves (voices, explosions, horns, etc.) come in contact with a wall, cliff or building (all acoustic contrasts), it is common to hear an echo. When a P-wave comes in contact with an acoustical contrast underground, echoes (reflections) are also generated. P-wave

reflections can be thought of as sound echoes from underground acoustic impedance contrasts. In the underground environment the situation is more complex because some P-wave energy impinging on a solid acoustical interface can also be transmitted across the interface, refracted at the interface and/or converted to other types of seismic waves at the interface.

Seismic methods are sensitive to the physical properties of earth materials and relatively insensitive to the chemical make-up of contained fluids in earth materials. The work of Hunter and Pullan and their colleagues at the Geological Survey of Canada (Hunter, et al 1984; Pullan and Hunter, 1985) and Helbig (Doornenbal and Helbig, 1988 Jongerius and Helbig, 1988) and his students at the University of Utrecht in The Netherlands has been instrumental in developing shallow seismic reflection techniques. In particular, the simple data manipulation and display of Hunter's optimum window-common offset makes it a cost-effective method of imaging the shallow subsurface in areas conducive to seismic reflection.

The simplest case of seismic reflection is a single layer over an infinitely thick medium (**Figure 1**). Seismic energy induced into the ground from a point is radiated spherical away from that point in much the same fashion in three dimensions as waves from a pebble tossed into a still pond radiate outward in two dimensions (Steeple and Miller, 1993). One particular ray path will direct energy to a subsurface layer and return as an echo to the ground surface first.



**Figure 1**

**BASIC PRINCIPLES OF SEISMIC SURVEY METHOD**

(After Steeples and Miller, 1993)

Seismic reflection surveys routinely involve three basic parts : acquisition, processing and interpretation. A variety of selectable parameters and methods are possible at each of these three distinct stages. Pronounced differences exist between shallow and conventional seismic reflection techniques during the acquisition and processing stages. The basic principle of interpretation for shallow and conventional seismic reflection is consistent, except for scale differences. The underlying theoretical method is consistent for conventional and shallow applications.

### **i) Data Acquisition**

The most site-dependent part of the acquisition system is the acoustic energy source. A variety of sources have been developed and are in routine use on shallow seismic reflection projects. As a human voice is a source of acoustic energy, so is an explosion, a car horn or an electric razor. The method of generating and transmitting acoustic energy into the ground is what determines the quality of a source at any particular site.

There are two types of sources : impulsive and vibratory. Impulsive sources are the predominant type of shallow seismic source while vibratory sources are the predominant conventional seismic source. The frequency-limited nature of vibratory sources is what has held them to very limited use on shallow reflection surveys. Most shallow reflection surveys employ weight drop (accelerated) or explosives as the source of acoustic energy. Other types of sources which may be used are weights, hydraulic hammers, vibrators, air guns, gas exploders and piezoelectric stacks (Lepper and Ruskey, 1976; Zoilkowski 1978; Zoilkowski and Lerwill, 1979).

The second part of the acquisition system consists of seismic detectors. The main requirement of the seismic wave detectors is that their frequency response should match the frequencies transmitted through the rocks by the seismic source. The commonest detectors in use are geophones and hydrophones with natural frequencies of 28Hz and 100Hz (Farr and Peace 1979).

## ii) Data Processing

All data, generated by the geophones, are processed using special developed computer programmes. In general, the aim of the computer processing of raw seismic data is to enhance the signals from features of interest and to reduce unwanted noise to a minimum. "Noise" in this case does not only mean the effects of ground roll and man-made phenomena but also the distortion of the seismic data by velocity variations in the rocks and differences in elevation over the survey area. The results of processing the digital data is normally a seismic record or seismogram (Ziolkowski and Lerwill, 1979; Steeples and Miller, 1993).

## iii) Data Interpretation

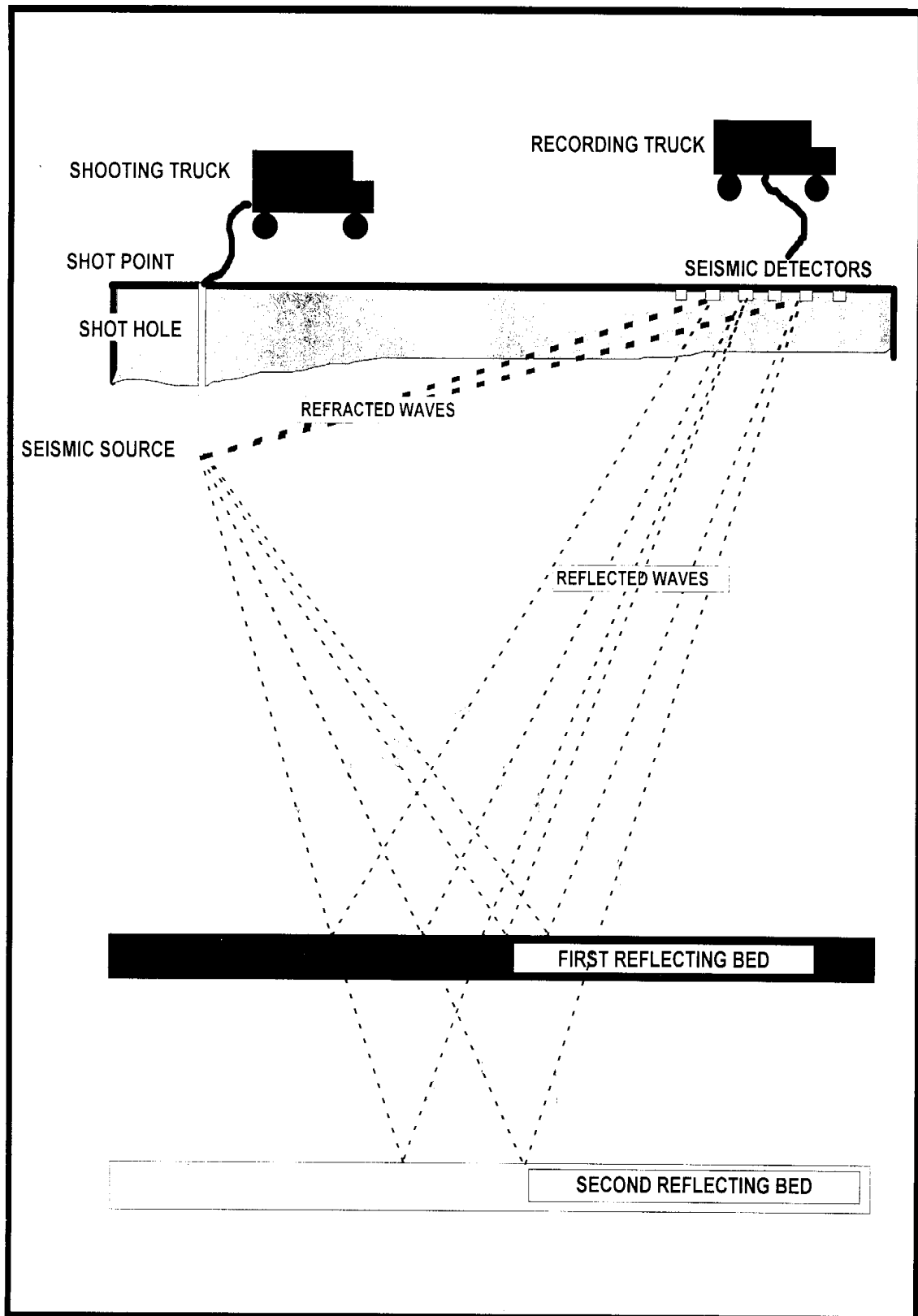
Interpretation of the collected seismic data needs a thorough understanding of the geology of the project, seismic methods used and other relevant information.

### 3.3. In- seam seismic methods

A variation to normal seismic surveying techniques is underground - or in-seam seismic surveys.

Most of the surveys currently being conducted underground involve the use of channel waves propagating in the coal seam to detect discontinuities in advance of mining although some more conventional seismic surveys have been done from mine roadways downwards into the underlying rocks.

In the in-seam seismology work two techniques are used in the detection of discontinuities in the coal seam: transmission in which the distortion of the channel waves as they pass a disturbance is recorded and reflection in which the reflected waves are recorded. Suhler and others (1978) present sketches illustrating the conceptual behaviour of channel waves reflected from or transmitted through certain geological discontinuities and anomalies (Refer to **Figure 2**)



**Figure 2**

Conceptual behaviour of channel waves in : (a) a coal seam pinchout, (b) a channel sand cutout and (c and d) faults with throws less than and greater than seam thickness (from Suhler and others, 1978).



The equipment used for this in-seam seismic surveys is similar to that used in surface seismic work. Rüter and Schepers (1979) describe equipment used in the Federal Republic of Germany : the United Kingdom equipment is described by Dawson et al (1994) and Jackson (1985)

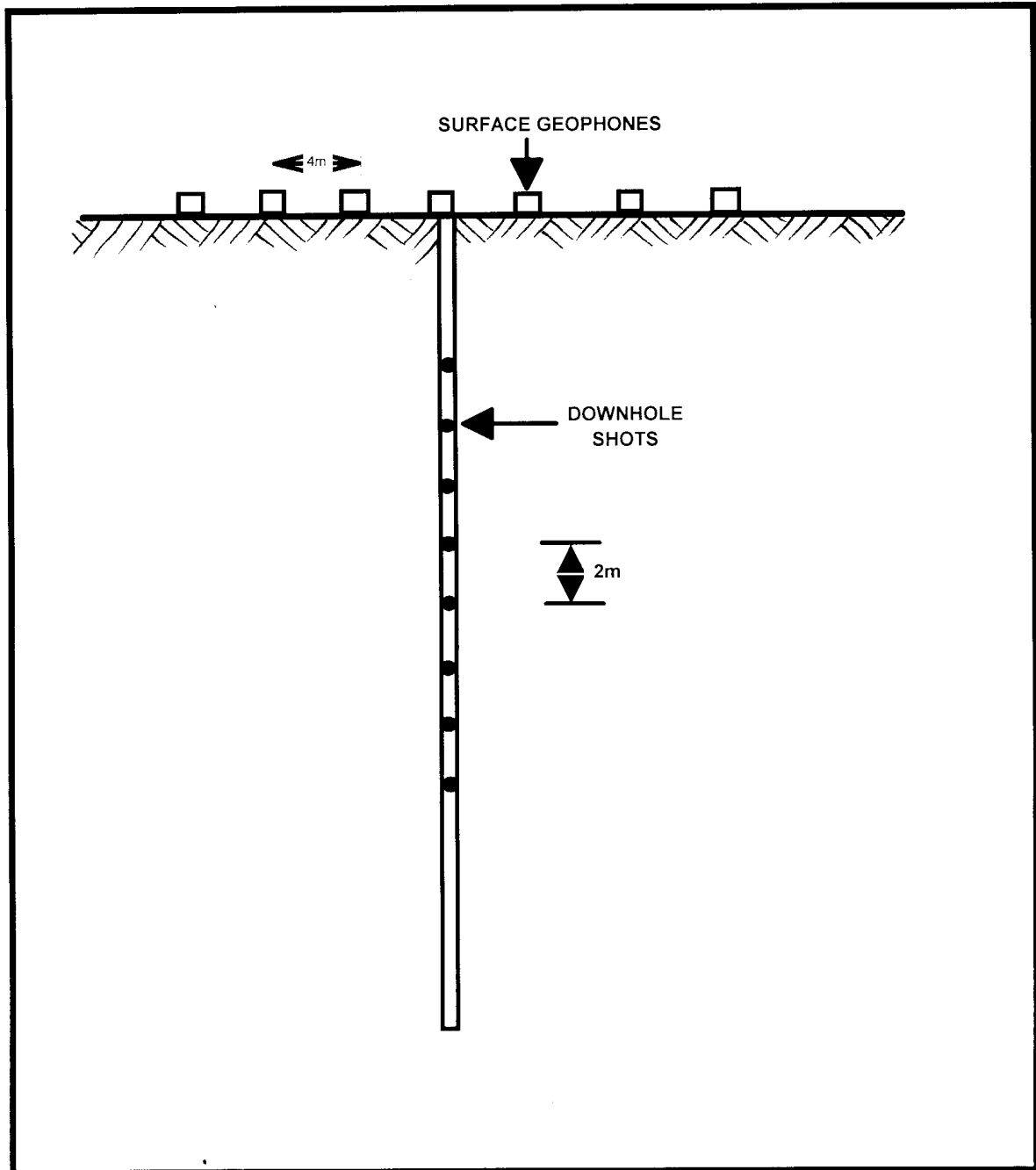
The seismic sources used underground are usually small quantities of approved commercial explosives placed in drill holes 2-3 metres deep in the centre of the coal seam. An exploder with a coupling to the seismic recorder is used to record the time when the explosion is initiated. The seismic waves are recorded by an array of at least 12 geophones of natural frequency, usually about 28 Hz, mounted singly or in pairs in the centre of the coal seam and orientated in such a way that they record certain components of motion and hence may discriminate between different wave types.

There are two important difficulties in doing underground or in-seam seismic work. Firstly the restricted environment of the working face means that a smaller array of geophones than in surface seismic work must be used. Secondly, there are stringent safety requirements governing the use of electrical equipment underground. In the UK no flameproof recording equipment is available commercially and special permission was obtained from the authorities concerned (Buchanan 1979). In the Federal Republic of Germany, however, a flameproof digital recording unit was developed by Prakla-Seismos GmbH in 1977 and certified by the German mining authorities in 1978. The instrument is described in Prakla - Seismos GmbH (1980) and also by Klar and Arnetzl (1978), Rüter and Schepers (1979), Brentrup (1979) and Klinge et al (1979).

#### **3.4. Hole - to - surface seismic methods**

Kragh et al (1992) and Goultly et al (1984) argue that conventional shallow seismic reflection surveys have limited value for opencast mines in the United Kingdom mainly because the nature of the near-surface geology causes the reflection records to be swamped by reverberant refracted arrivals, and commonly groundroll also. As an alternative they suggested the use of hole-to-surface

seismic methods. For this method, boreholes drilled routinely for ongoing opencast exploration were used to locate the acoustic source, while geophones were installed on surface as illustrated in **Figure 3**.



**Figure 3**

**Hole - to - surface field geometry**

(after Kragh et al 1992)

Small charges of 25g of special explosives were used as shots and single geophones as receivers. Shots were fired at intervals of 2 or 3 metres below the surface in the borehole and the geophones were spaced 4m apart in a line intersecting the top of the borehole. A 24-channel seismograph was used to record the data. Kragh concludes that the hole-to-surface data have produced high-resolution seismic sections with strong reflections originating from coal seams “only tens of centimetres” thick and a major fault has been located to an accuracy of  $\pm 4$  metres laterally.

### **3.5. Typical Applications in Mining.**

According to Miller and Steeples (1995) the application of shallow, seismic reflection to problems associated with mineral exploration, mine planning, abandoned-mine detection and environmental evaluation has been successful in many geological settings. The increased dynamic range of recording equipment and the decreased cost of processing hardware and software have made shallow, seismic reflection a cost-effective means of imaging geological targets significant to mining operations.

A large number of publications have been found on the use of seismic surveys to locate faults, subsurface voids (eg. abandoned underground workings) and variations in stratigraphic horizons (Miller and Steeples, 1995; Branham and Steeples, 1968; Ziolkowski, 1981; Miller and Steeples, 1991; Goultly and Branham, 1984; Goultly and Ziolkowski, 1979; Al-Rawahy and Goultly, 1995; Buchanan et al, 1981; Jackson, 1997, Clarke, 1976) however nothing could be found on the use of this specific geotechnical method to detect dykes ahead of mining faces.

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## 4. Tomography

### 4.1. Introduction

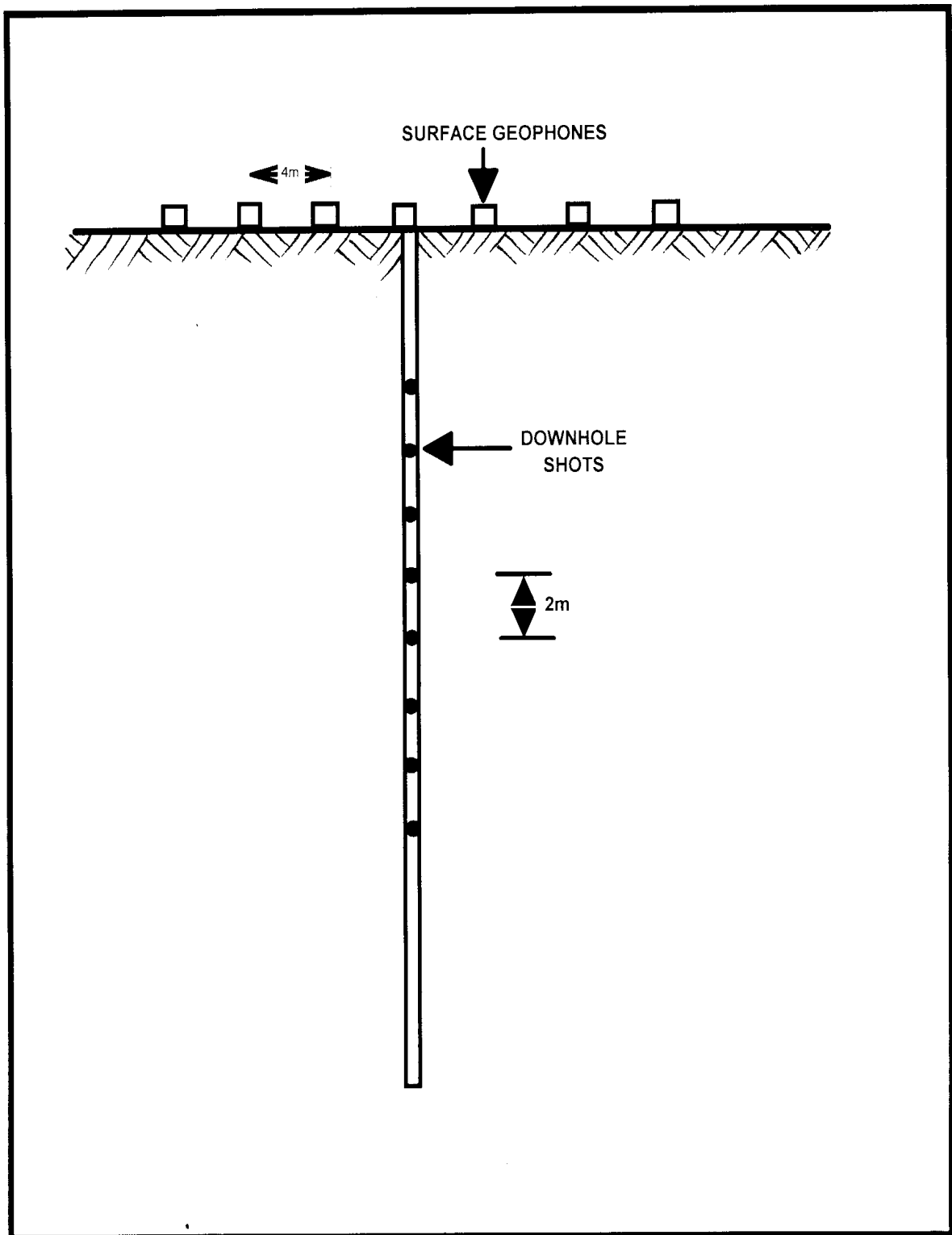
Seismic and radiowave tomography are two of several additions to the suite of geotechnical engineering tools for use in various underground rock and mineral geological structures (Neil and Associate, 1996; Campbell, 1994).

Tomography was developed for the medical field as a means of imaging the interior of the human body and within the last 15 years the technology has been transferred to the earth sciences to image geological structures. The principle behind tomography is that the interior of a region can be imaged by measuring the energy that has passed through it (Jackson and Tweeton, 1994).

In the case of seismic tomography a seismic wave is transmitted through a rock mass and the travel time of that wave through the rock mass is determined at several points. As large an area as desired can be surveyed although with corresponding levels of field effort. Knowing the travel time and the distance between source and receiver locations, a velocity along the ray path can be calculated by incorporating many unique ray paths into the study and subdividing the region into discrete areas, called pixels, a velocity distribution throughout the rock mass can be calculated. Because the velocity of the seismic wave is a function of the physical properties, an image of the distribution of the physical properties within the rock mass can be inferred. Time-dependent changes in the image of the area studied can be attributed to mining-induced temporal stress redistribution within the rock mass, whereas time independent features are attributable to geologic anomalies (Westman and Haramy 1996).

Tomography is essentially a transmission technique and therefore requires borehole and/or tunnel access across the area of investigation. Seismic or radiowave signals are generated at closely spaced intervals (2-6m) down a "shot" hole, and travel along various angled raypaths to receiver arrays in the detector hole. Each of the single raypaths contains information about the various rock units encountered along its path. A tomographic image is then constructed by dividing the area between the boreholes into a number of rectangular elements (or pixels), and combining the information from all the raypaths via software inversion techniques. A schematic flow sheet of a topographic survey and its interpretation is presented in **Figure 4** (Campbell, 1994).





Campbell (1994) states that placing of the geophysical sensors in pairs of boreholes, or within the underground tunnels themselves, permits the use of

higher frequency seismic and electromagnetic systems which have mapping resolutions down to 2m. In the main these higher frequencies are possible because of the shorter probing distances involved (compared to surface surveys), and the better signal transmission properties of the virgin rock (in the absence of a weathered zone). These techniques offer penetration ranges of 40 meters (for radar) to 200 metres (seismic and radiowave tomography), and allow for the advance delineation of reef geometry via the generation of 2-D, pseudo-geological cross-sections from acoustic or electrically imaged data.

#### **4.2. Applications in Mining**

The potential of seismic tomography in exploration for ore pods of metallic minerals and for evaluating the geological structure in coal fields has been examined in various test surveys (Goultly 1993). A different type of application is in giving advanced warning of mining hazards, such as weak zones, water filled old workings from abandoned mines, and stress concentrations indicative of rock burst hazard (Rogers et al 1987, Watanabe and Sassa, 1996; Sassa et al 1989, Podolski et al 1990; Westman and Haramy 1996, Campbell, 1994).

Secunda Collieries in the Highveld coalfields have locally initiated the use of seismic cross-hole tomography to map variations in coal-seam elevation and faults or dykes ahead of the working face (Jordaan 1986 ; Campbell 1994).

CSIR Miningtek has pioneered the use of cross-hole radiowave tomography in South Africa and developed local survey instrumentation and software (Wedepohl, 1994 : Campbell, 1994). Wedepohl indicates that "radio wave tomography performs best when used in appropriate environments, specifically where there is a reasonable contrast between the electrical conductivity of the feature and the host rock" (Nixon, 1994).

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## 5. Ground-penetrating Radar

### 5.1. Electromagnetic Methods

Electromagnetic radiation may be used in a number of ways in the examination of coal deposits. One important method which has been tested in underground coal mines in the United States of America, the United Kingdom, the Federal Republic of Germany and Australia is pulse radar, in which reflections from small disturbances are detected (Church and Webb, Friedel et al; Momayez et al, 1996; Dennen and Stroud, 1991).

Under good conditions, the radar may have a range of about 45 metres in coal and is particularly effective at detecting small features such as water-filled tunnels (Friedel et al), abandoned oil and gas wells (Church and Webb), clay veins and sand lenses in the coal deposit (Dennen and Stroud, 1991).

Momayez et al (1996) describes the general basic principle of Ground Probing Radar (GPR) as follows : "The radar antenna transmits a short electromagnetic pulse of radio frequency into the medium. When the transmitted wave reaches an electric interface, some of the energy is reflected back while the rest continues its course beyond the interface. The radar system will then measure the time elapsed between wave transmission and reflection. In modern systems, this is repeated at short intervals while the antenna is in motion and the output signal (or scans) are displayed consecutively in order to produce a continuous profile of the electric interfaces in the medium. In general, the propagation speed of the wave and its reflection are affected by the dielectric constant and the magnetic susceptibility of the medium. The electrical conductivity of the medium contributes to the attenuation of the wave and to some extent its reflection. The antenna wavelength affects the ability of the system to identify objects of different sizes. For example, high frequency antennas have better resolution, but shallow penetration depth, while low frequency antennas have a coarser resolution, but penetrate deeper into the medium. Water content in a medium has a great influence on the penetration and reflection of electromagnetic waves. The electrical conductivity of a medium influences the degree of attenuation in the

amplitude of the electromagnetic waves. Significant attenuation takes place when electrical conductivities become greater than 10 mS/m.

If the conductivity is low and the number of electrical interfaces are high, multiple reflections will reduce penetration depth, while poor conductivity combined with a small number of interfaces will cause the wave to be attenuated as a function of the distance between the antenna and the reflecting interface”.

Campbell (1994) suggests that “ground probing radar (GPR) is a reflection technique and the electromagnetic equivalent of seismics”. Campbell further indicates that water- or air-filled voids, such as disused underground workings, pipes or boreholes, generally represent good radar targets.

Radar equipment consists of an antenna, a pulse generator, a receiver/recorder and a power supply. There are many problems associated with using radar equipment underground : the mine roadways are often narrow, cluttered, dusty and wet and so the equipment must be protected. In addition, most equipment are not specifically designed for use underground and in order to conform with electrical safety requirements it must therefore be used in intake airways only. Research programmes are in progress to design portable, intrinsically safe mine radar systems (Coon and others, 1979).

Pulse radar has been tried from the surface, from boreholes penetrating the coal seam (Cook, 1977) and also from underground mine roadways (Cook, 1972, 1973, 1974) whereas the continuous wave method has only been successful below the surface (Ellerbrich and Adams, 1974 , Ellerbrich and Belsher 1976, 1978).

## **5.2. Application in Mining**

Ground penetrating radar is now a well established geophysical tool for shallow engineering investigations. It has had spectacular successes in locating underground pipes, cables and cavities and mapping shallow geological structures. It is an attractive method because it can rapidly produce high resolution images of the subsurface. The speed is due to the ability of the

equipment to work from the ground surface without the need for holes or trenches.

One area in which ground radar has yet to establish itself as a production tool but in which great potential is seen, is in coal mining. There is a strong contrast in electromagnetic properties between coal and its host rocks and therefore boundaries between the two have strong reflection coefficients. In addition to this the low conductivity of coal enables good propagation distances.

Early investigations into coal mining applications were conducted by John Cook in the 1970's (Cook, 1975). Cook also conducted trials in the Hunter Valley in New South Wales in 1976. Subsequent published work has been carried out by ENSCO Inc. (later Xadar Corporation) (Fowler et al, 1977, Coon et al 1981), the US National Bureau of Standards (Ellerbruch and Belsher, 1978) and the US Bureau of Mines (Church et al., 1985), (Foss and Leckenby, 1986).

Various test programmes with ground penetrating radar were conducted by the Australian Coal Industry Research Laboratories (ACIRL) and Georadar Research in both opencast and underground coal mines in Australia and the following results were reported :

a) Geological mapping

Ground penetrating radar was successfully used at the Ashford opencast mine (New South Wales) to map the locality of dipping coal seams.

b) Horizon control

In March 1989 ACIRL and Georadar Research conducted surveys at the Howick mine in the Hunter Valley to assess the potential of GPR as a means of tracking coal seams and parting layers in order to improve coal recovery and qualities. Relatively good results were achieved.

c) Locating old workings

Another application for which ground radar has been used successfully in opencast mining is for the location of old workings beneath the mine floor.

d) Roof inspection

The use of ground penetrating radar for roof inspection has been investigated at Tahmoor Colliery in the southern coalfields of New South Wales. The inspection was carried out to identify local areas of bad roof expected to be characterised by separations within the roof or delaminations. Delaminations provide a good target for ground penetrating radar because of the strong difference in electro-magnetic properties between air and coal. The presence, however, of roof bolts and straps made this trial extremely difficult as ground radar has a high sensitivity to metal objects and the straps and bolts alter the antenna's impedance and therefore the signal propagated into the roof.

e) Pillar structures and the detection of structures ahead of the mining face

Cook (1975) claims that ground radar has the potential to rapidly produce high resolution images of structures ahead of the mining face.

Ground penetrating radar also has the potential to be used in transmission mode for assessing fracturing in pillars to aid in pillar design studies.

f) Detection of dykes in underground coal mines

Although no reference could be found in the literature where ground penetrating radar has been used specifically to detect dykes ahead of the coal mining face, Nami (1990) reports that this method has been used successfully on South African gold mines to delineate dykes and faults up to 40m ahead of the mining face. Bell (1998) reports that five different experiments were conducted at one of the Amcoal Collieries, primarily to establish the presence of old underground workings. These experiments were terminated because of the poor and unreliable results achieved.

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## 6. Radio Imaging Method

### **6.1. Principles**

The Radio Imaging Method (RIM) is an electromagnetic (EM) wave survey procedure used to detect geological abnormalities ahead of mining. RIM utilises medium frequency radio waves (100-500 kHz) (Thompson, Hatherly and Liv, 1990, Stolarczyk et al, 1988).

There are two basic types of RIM surveys e.g. :

- in-mine RIM and
- Borehole RIM

In-mine RIM is conducted entirely within the mine, with a transmit and receive antenna to either side of the coal pillar under investigation. Currently all RIM in-mine work is done using 300 kHz equipment. The in-mine RIM equipment is light and portable and certified intrinsically safe.

The RIM borehole to in-mine or borehole to borehole survey utilises transmit or receive antennae from surface boreholes (Thomson et al, 1990).

The RIM method is based upon the propagation of electromagnetic radio waves through the coal seam which acts as a waveguide.

As the radio wave propagates, it interacts with the bulk seam material and surrounding rock. This interaction causes the signal to lose energy thereby decreasing its strength. The amount of energy lost per unit path length (attenuation rate) depends on the local coal seam height and the conductivity of the coal and surrounding rock. The attenuation rate will increase as the coal seam thickness decreases.

Higher than normal attenuation rates also indicate a geologically disturbed zone which could be a fault, igneous body, sandstone washout or water filled tunnel in an abandoned coal mine.

RIM surveys are based on the determination of the attenuation along various ray paths. At each measuring station a voltage is induced in the receiving antenna and then measured by the calibrated receiver.

The measured signal level can be expressed as :

$$L(r) = 20 \log c' - \alpha r$$

where  $c'$  = a calibration constant

$\alpha$  = the average attenuation rate along the ray path

$r$  = the radial distance from the radiating antenna.

(Thomson et al, 1990)

The right hand side of this equation is a straight line with intercept  $20 \log c'$  and a slope  $\alpha$ . The intercept is the RIM system coupling factor (c factor), and the slope is the attenuation rate.

Mine entries can be used to conduct calibration surveys to obtain values of  $c'$  and  $\alpha$  in both disturbed and undisturbed zones of a coal seam. Calibration surveys are an essential part of every RIM survey. Once these have been undertaken, unmined panels can be investigated.

## **6.2 RIM Operations**

The licence to operate the Radio Imaging Method in Australia, New Zealand and Papua New Guinea is held by METS Pty Ltd (Mine Exploration and Technical Services), a joint venture between Australia Coal Industry Research Laboratories Ltd (ACIRL) and MECO Australia Pty Ltd. Stolar Inc. of the USA hold the patents on the method and also holds an exclusive licence to operate in North America and South America. MECO International (UK) operates under a non-exclusive licence in Europe.

METS has been offering RIM survey services on a commercial basis since 1989 (Thompson et al 1990). All RIM surveys to date have utilised RIM 1 in-mine equipment. The majority of applications have concerned hazard detection in longwall panels.

## **6.3. RIM Survey Results**

Thompson et al (1990) states that the best way to test the RIM response to a known structure is to run a 'calibration' survey along a mine roadway. This involves leaving the receiver (Rx) stationary and moving the transmitter (Tx)

progressively further away (usually at 10 or 15 metre intervals) until around 300 metres antenna separation is achieved. In this way the drop in signal strength through a structure can be observed by the operator of the receiver unit when the transmitter operator passes to the far side of the structure.

To further clarify the effect of the structure a “step-out” survey may be performed. This requires the receiver and transmitter being located immediately either side of the structure of interest and progressively moving away from each other (usually by 15m intervals) until the signal can not longer be recorded. This enables an assessment of the attenuation rate through the structure at various Rx and Tx separations.

#### **6.4. Application in detecting dykes ahead of mining**

No evidence could be traced in the literature where the RIM survey technique has been used conclusively to detect dykes ahead of mining operations

#### **6.5. References : Radio Imaging Method**

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## **7. Drilling**

### **7.1. Vertical or near vertical drilling**

One of the most widely used methods of examining geological deposits involves the drilling of holes from surface and recording and analysing the drill chippings or drill core.

The development of geophysical borehole logging techniques were initially promoted by the oil and gas industry motivated both by the high cost of cutting continuous drill cores and the inadequate results from analysis of the rock chips carried to the surface from the rotary drill head by the drilling mud. Strangely enough, one of the earliest borehole logs to be performed by geophysical methods was in a coal deposit (Allaud and Martin, 1977, pp. 130)

Campbell (1994) (1984); and Heidstra and Jones (1990) claim that geophysical wireline logging of boreholes is a well-established technique in South African coal and uranium mines.

The drilling of a single vertical hole rarely provides adequate information about the coal deposit on its own, but when used in combination with other boreholes and borehole logs will allow the various lithologies present to be identified and strata thicknesses to be measured.

Vertical boreholes can be used to detect dolerite sills, but its ability to detect vertical or near vertical dykes is negligible, merely because the probability of intersecting a dyke is relatively small. No reference could be found in the literature where only vertical surface boreholes were used to detect dykes in coal deposits.

### **7.2. Horizontal or in-seam drilling**

Horizontal or in-seam drilling was introduced during 1958 at the Humphrey Mine of Consolidation Coal Company in the United States of America (Thakur and Poundstone, 1980) mainly for degasification of the coal seams. Spindler and Poundstone (1960) experimented for years with vertical and horizontal holes and concluded that horizontal drilling in advance of underground mining appears to

offer the most promising prospect for degasification, but effective and extensive application would be dependent upon the ability to drill long holes, possibly 300 to 600m, with reasonably precise directional control and within practical cost limits. Mining Research Division of Conoco Inc., the parent company of Consolidation Coal Company began a research program in the early 1970's to achieve the above objective. The technology needed to drill nearly 300 metres in advance of working faces was developed by 1975 and experiments on advance degasification with such deep holes began in 1976 (Thakur and Davis 1977). Encouraged by the results, Consolidation Coal decided to design a horizontal drilling system that would be mobile and comparable with other face equipment. Thakur and Poundstone (1980) stated that, if successful, this mobile horizontal drilling machine will be able to detect faults, clay veins, sand channels and the thickness of the coal seam in advance of mining.

During March 1982 Thakur reported on the successful commissioning of a horizontal drilling machine, capable of drilling 600 metres in advance of mining. (Thakur and Dahl, 1982).

Although this machine was designed mainly to degasify the coal seam, it was also used at a mine in northern West Virginia to delineate a sand channel ahead of the advancing mining face (see **Figure 5**).

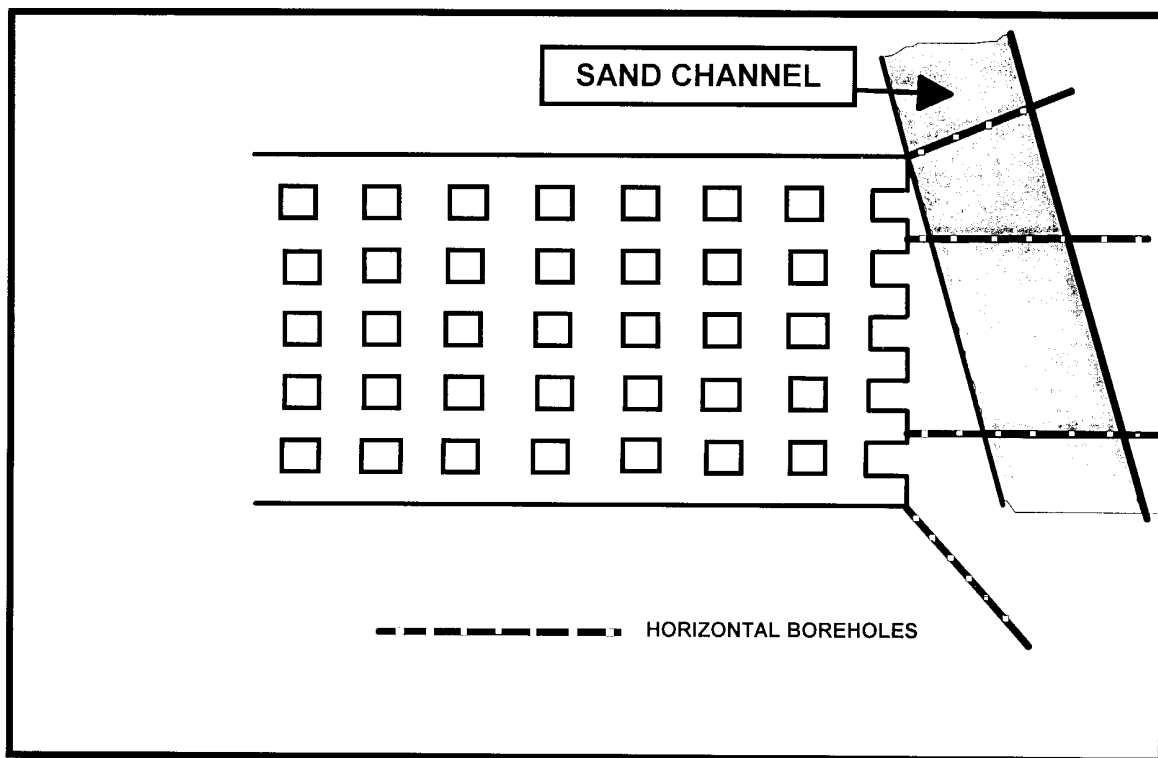
Similar to the method used to detect the sand channel, this method can also be used to detect dykes.

At basically the same time as developments were progressing in the United States, the National Coal Board's Mining Research and Development Establishment (MRDE) undertook a new project to develop a "Guided Longhole Drilling Machine" (Morris and Wykes, 1984). The objectives of this project were :

- a) the development of equipment and techniques for drilling long holes in coal for distances up to 1000 metres, with certified instrument packages to permit surveying of the hole, in order to determine the angle and attitude of the drill string, and the position at any time of the drill head relative to a coal/stone interface.



b) the development of techniques and acquisition of information and general “know-how” to be available at the appropriate time for application to the underground gasification project



**Figure 5 :** Detecting a sand channel ahead of mining face by means of horizontal boreholes (Thakur and Dahl, 1982)

c) the ability to drill ahead of a proposed tunnel line and to establish the nature of the rock along that line, so as to assist in selection of machines for tunnelling operations.

Initial trials were conducted at a disused opencast coal mine in close proximity of the MRDE offices. These trials were most encouraging in the sense that it indicated that it would be possible to steer and keep a horizontal drill string within the seam for distances up to 1000 metres. During these trials the position of a fault was determined with a high degree of accuracy.

The Australian Coal Industries Research Laboratories Limited (ACIRL) introduced the use of longhole in-seam drilling techniques to the Australian Coal Industry during 1981. This method was specifically developed for seam gas drainage ahead of mining. (Richmond et al, 1985). The objective of this research program was to develop and demonstrate drilling and borehole survey technology which could achieve 600 metre longholes on a regular basis. To this effect, ACIRL acquired an Acker Big John drill rig which at the time was considered the most applicable to the work requirement. Numerous ancillary items were also obtained including 1000m BQ drill rods, a variety of 80mm drill bits, drill rod stabilisers and borehole survey instrumentation. In the initial two years of the work program a total of approximately 10 000m of in-seam rotary drilling was undertaken at West Cliff and Tahmoor Collieries. The techniques employed basically consisted of controlling the vertical deviation of the drill bit, by altering the thrust and speed applied to the bit via the rotating chuck. Stabilisers were also used to achieve specific vertical deviation, by locating them at various points away from the drill head. The holes were incrementally surveyed as the hole progressed, so that decisions could be made as to any changes required in drilling parameters.

On completion of the research program Richmond and his team (1985) concluded that :

- a) the longest borehole that could be drilled was 732 metres and
- b) horizontal deviation was virtually impossible to control

With regard to horizontal deviation, numerous techniques of drill string stabilisation were tested. However, it was finally concluded that the combination of inherent

directional weakness in the coal seam, aligned to the right handed torque of the rotating drill string, produced uncontrollable lateral wander.

### **7.3. Developments in South Africa**

Bell and Dingemans (1998) indicated that until the early 1980's Amcoal primarily used information derived from vertical holes, drilled from surface, to determine geological conditions of its coal deposits. To augment this information, horizontal holes were drilled underground from specially developed cubbies. During the initial years, borehole lengths rarely exceeded 250 metres, however, through in-house research and development lengths of 1200 metres are now achieved on a regular basis. At the Goedehoop and Bank Collieries, drilling of 300 metre long horizontal in-seam holes is standard procedure. Drill chippings derived from these holes are sampled on a regular basis to determine any changes in volatile content of the coal seam. A change in volatile content signifies the possible presence of dykes ahead of the mining face.

A major breakthrough was made by Amcoal during the early 1990's with the introduction of inclined, directional holes from surface (Bell and Dingemans, 1998). Inclined holes are generally drilled at an angle of 45-60° through the overburden strata. At the overburden/coal interface the drill bit is directed along a horizon directly above the coal seam. Specially designed sensors, positioned behind the drill bit, emit information in digital format to surface on the actual position of the bit. The bit can then be steered along the required path. Bell and Dingemans reported that borehole lengths of 1200 metres are possible with current technology but development work is in progress to increase this number to 2000 metres.

Visser and Van Dam (1998) indicate that Ingwe Coal Corporation primarily use aeromagnetic techniques to delineate dykes on a regional basis. This is followed by in-seam horizontal drilling. To date the maximum drilling length that could be achieved with this method is 1200 metres.

In addition to the standard aeromagnetic and electromagnetic methods used by Sasol Coal, this company is at present also testing the use of directional holes from surface into the coal seam as a means to detect dykes and other geological features ahead of mining (Potgieter, 1998). Potgieter indicated that the concept of down-the-hole motors is used to drive the drill bit. Lengths of 600 metres are achieved on a regular basis, and the record distance drilled to date stands at 1500 metres.

#### **7.4. Reference list - Drilling**

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## 8. Magnetic methods

### 8.1. Magnetic susceptibility

The magnetic susceptibility is a measure of the degree to which a rock can be magnetised. Rock-forming minerals (quartz, feldspar etc.) are virtually non-magnetic, so the magnetic susceptibility is related to the amount of minor accessory minerals in rock which contain iron such as magnetite, pyrrhotite and haematite.

Magnetite is the most important magnetic mineral, because it is not only very common, but also has a magnetic susceptibility up to 10 times that of pyrrhotite (Mc Mullan, 1998). Laboratory measurements report a range of susceptibility for magnetite between 7,957 to 127,323  $\mu\text{cgs}$  and an average for pyrrhotite of 9,947  $\mu\text{cgs}$ .

Campbell (1994) indicates that most basic intrusions such as dolerite dykes or dunite pipes carry accessory magnetite and thus can be mapped from airborne or ground magnetic surveys.

Analyses of magnetic susceptibility measurement from exploration projects in Botswana indicates that basement gneissic rocks tend to have a low but variable susceptibility from 10 to 100  $\mu\text{cgs}$ . Karoo sediments are virtually non-magnetic, with an average of 5,5  $\mu\text{cgs}$ . Coal beds in the Karoo are slightly diamagnetic, but have no inherent magnetic susceptibility unless there are impurities, such as maghaemite or pyrrhotite, present.

The most magnetic units are quartz-magnetite horizons, dolerite intrusives and the Stormberg basalt, with a range of susceptibility from approximately 50 to 1500  $\mu\text{cgs}$ , depending on the degree of weathering.

The Kalahari beds are virtually non-magnetic, but may have a small remnant component due to ferricrete duricrust.

Volcanic and sedimentary rocks may have been deposited at a time when the earth's magnetic field was in a different direction than present day. The frozen or remnant magnetism may modify dipole anomalies into a complex shape, possibly exhibiting reversed polarity. In some cases, particularly in iron-rich sediments,

the remnant magnetic component may be more important than the induced magnetisation.

## **8.2. Magnetic Method Theory**

The earth's magnetic field resembles that of a large bar magnet which is created by electrical currents flowing in the core. The magnetic field is constantly changing at different time scales. Long term or secular variations are a result of changes in the current flow in the core. Shorter period variations (diurnal or micropulsations) are caused by the interaction of the earth's field with the solar ionic wind. Occasionally the earth's magnetic field is affected by strong solar flux caused by sunspots, which creates a magnetic storm.

The interaction of the earth's field with rocks induces a magnetic field proportional to the magnetic susceptibility. Time variations in the magnetic field must be removed to map the spatial distribution of the field, which is useful for mapping the subsurface geology.

## **8.3. Magnetic survey techniques**

Magnetic measurements can either be done on surface or from the air (aeromagnetic). The interpretation of the magnetic measurements is concentrated on the identification of geologic units with distinctive magnetic signature, and structures inferred from magnetic lineaments.

Lineaments in magnetic contours are identified by linear contour patterns, terminations or offsets in high or low trends, or changes in slope. Lineaments may represent faults, geological contacts, or artefacts introduced in the data acquisition or processing.

Geologic units are identified by areas with distinctive magnetic signature, i.e. magnitude, shape, texture and trend. The textural characteristics (e.g. flat, stippled) are difficult to reproduce in hard copy colour images, and can only be truly visualised on the computer image processor. It is not strictly valid to assign

rock names to pseudo-geologic units unless direct measurements of the physical properties have been made on representative rock types from the area.

Magnetic surveys map the distribution of magnetic minerals, primarily magnetite, in crustal rocks. The distribution of magnetite is mostly controlled by the original rock composition, but this may be altered by metamorphic and weathering processes. The observed magnetic pattern therefore reflects both the rock type and subsequent metamorphic and weathering history (Grant, 1985 a,b).

#### **8.4. Instrumentation and survey methods**

The most common types of magnetometers in use today are fluxgate proton precession and nuclear resonance (alkali vapour). Fluxgate magnetometers operate by sensing the difference in the magnetisation of two highly permeable iron alloy cores oriented in opposite directions, which is proportional to the inducing magnetic field. Fluxgate magnetometers measure the strength of the magnetic field in one direction only, and are often used in gradient applications. Fluxgate magnetometers can measure the magnetic field to 0,2 nT sensitivity.

Proton precession magnetometers measure the precession frequency of the magnetic moment of spinning protons, which is proportional to the total magnetic field. These measurements can be made to 0,1 nT sensitivity. Proton precession instruments are the most common type used on ground magnetometer surveys.

Alkali vapour magnetometers are based on the excitation of electrons to different energy levels by irradiating an alkali gas (e.g. sodium or caesium vapour) with light of a specific energy. The electrons of the gas are optically raised (pumped) to a higher energy level which is a function of the magnetic spin moment and the ambient magnetic field. The amount of light which is absorbed by the gas in exciting electrons to a higher energy level is proportional to the total magnetic field. The sensitivity of alkali vapour magnetometers is 0,001 nT and is most commonly used in airborne applications.

Magnetometers can be used to measure the total magnetic field, or several sensors can be configured to measure the gradients of the entire magnetic field



under investigation. The main advantages of gradient measurements is the removal of diurnal variations of the earth's magnetic field, magnetic noise can be cancelled, and the resolution is greatly increased.

Magnetic surveys can be undertaken from aircraft, ground surveys or in boreholes depending on the scale of exploration.

### **8.5. Application in mining**

As early as 1928 iron-ore deposits, rich in magnetite, ilmenite, pyrrhotite or some other strongly magnetic mineral, have been located by magnetic methods. (Brough et al, 1928). In 1935 the course of the Acklington Dyke in Northumberland was plotted by means of a Watts Magnetic Variometer (Poole et al, 1935) and during 1959 D.A. Robson resurveyed this dyke using a Proton Magnetometer. This instrument was claimed to be of "high sensitivity" (Robson, 1964). In addition to confirming the position of the dyke, more accurate information on various geological aspects of this dyke were obtained due to the more sophisticated equipment being used.

Campbell (1994) reported that earlier ground magnetic work in the Ermelo district of the (previously) eastern Transvaal had shown the dolerite intrusions to be only weakly magnetic and of variable strike orientation. To map this large target area ( $\pm 200\text{km}^2$ ) cost effectively the first aeromagnetic survey to do "detailed dyke mapping" was introduced during 1983. Since this early start the sophistication of aeromagnetic surveys has increased significantly and this technique is now routinely used by the South African coal mining industry (Bell and Dingemans, Visser and Van Dam, Cochran, 1998). As most of the magnetic surveys completed in Southern Africa (and elsewhere in the world) are undertaken for private sector clients, all data remain proprietary and no publications could be traced on actual results obtained. (Mc Mullan, 1998).

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## 9. Gravitational method

### 9.1. Fundamental principles of gravity prospecting

The gravity method detects and measures lateral variations in the earth's gravitational pull that are associated with near surface changes in density. Many geological structures of interest in oil and coal exploration give rise to disturbances in the normal density distribution within the earth which cause diagnostic anomalies in the earth's gravitational field. Such anomalies will be very small compared to the earth's over-all attraction, in some cases being less than one ten-millionth as great. Extremely sensitive instruments are required to resolve such small differences in gravitational force.

The theory behind gravitational prospecting depends directly upon Newton's law expressing the force of mutual attraction between two particles in terms of their masses and separation. This law states that two particles of mass  $m_1$  and  $m_2$  respectively, each with dimensions very small compared to the separation  $r$  of their centres of mass, will be attracted to one another with the force

$$F = \gamma (m_1 m_2)/r^2$$

where  $\gamma$ , known as the universal gravitational constant, depends on the system of dimensions employed (Dobrin, 1960).

Coal has a very low density relative to the rocks commonly found in coal deposits. Density variations in the ground may be examined by measuring the difference between the earth's gravitational field at an observation point and at a reference point, and then plotting the values of these differences on a map of the survey area. Areas of lower or higher density will appear as gravitational anomalies.

In the examination of coal deposits, gravity surveys have been found to offer a quick and cheap method of delineating the boundaries of the coal at depths suitable for surface mining. The survey results may be used in the selection of suitable sites for drilling to verify the geophysical interpretation and these drillholes may subsequently be logged using a tool which measures density.

Gravity surveys have not been very successful in revealing structures such as faults in coal deposits, except in those cases where there is a large contrast in density between the rocks likely to be thrown by the fault and where the superficial deposits are reasonably uniform (Rees,1975).

### **9.2. Equipment**

Relative gravity measurements must be made with an accuracy approaching 1 to 5 parts in 10 (Parasnis, 1972). Before modern gravimeters were developed, an instrument known as the Eötvös torsion balance was widely used to detect anomalies in the earth's gravitational field. However, each observation usually took several hours to make and various elaborate corrections for topographic irregularities in the vicinity of the measuring station had to be applied to the data. This instrument has now been completely replaced by the modern gravimeters, on which readings may be taken in a matter of minutes.

### **9.3. Application in coal mining**

Gravity surveys of coal deposits have been performed for many years. Hasbrouck and Hadsell (1979) present a survey performed by Miller in 1931 in the Onakawana lignites of Ontario, Canada, using a torsion balance. Miller's results showed the expected inverse correlation between gravitational attraction and lignite thickness - the thicker the lignite, the smaller the gravity anomaly.

A number of more recent gravity surveys are reported in the literature - for example, Verma and others (1976) who present the results of a survey of the Raniganj coalfield in north-west India, Grosse and others (1976) who report good detection of glacial erosion channels in brown coal deposits in the German Democratic Republic and Hasbrouck and Hadsell (1976,1978) who describe in detail three gravity surveys performed in Wyoming, North Dakota and Colorado to detect the presence and extent of a known sand intrusion. Hasbrouck and Hadsell conclude that gravitational methods appear capable of delineating the

edge of a cut-out in a thick seam and that this would have been detectable even if the seam was considerably thinner.

Gravitational methods are also used to detect subsurface cavities such as abandoned mine shafts and tunnels. Hellewell and Cox (1975) describe theoretical studies and Dresen (1977) reports successful location of abandoned shafts in longwall mining areas in the Federal Republic of Germany.

This method, however has not been used specifically for the purpose of detecting dykes ahead of underground mining operations.

#### **9.4. Reference list : Gravitational Prospecting**

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## 10. Conclusions



In addition to conventional drilling a number of geophysical methods have been developed to delineate the boundaries of geological and man-made structures in coal deposits. In this report, which is based on a literature survey, various techniques are described that could possibly be considered as a means to detect dykes ahead of underground coal mine workings. Each geophysical method responds to a particular and unique physical property associated with the rock types concerned. Depending on the method used, data acquisition may take place from surface, or from within boreholes drilled, or from a position within the underground workings. The applicability (or suitability) and efficiency with which different geophysical methods can be used to detect dykes under typical South African coal mining conditions are primarily dependent on the following two factors :

- a) the total range or distance that can be covered from a single observation point
- b) the degree of accuracy to which dykes can be distinguished as a unique geological feature within the coal horizon.

In the following table a qualitative assessment of the applicability and efficiency of the various methods to detect dykes under the following scenarios is presented :

### *Scenario 1 : Large target area*

Target areas to be covered under this heading will extend over several kilometers and will typically include selected coal regions or the total mining area required over the entire life of a mine.

### *Scenario 2 : Medium size target area*

This category will include target areas of limited dimensions (say 5 km<sup>2</sup>) that will generally be required for medium term planning purposes of a typical coal mining operation.

### Scenario 3 : Limited target area

This category includes coal reserves in close proximity of the working face or the short term planning of a particular production section.

TARGET AREA TO BE COVERED			
METHOD	LARGE	MEDIUM	SMALL
<b>Surface Seismics</b>	<ul style="list-style-type: none"> <li>• Applicability limited</li> <li>• Efficiency low</li> <li>• Interference from near surface noises affects data</li> </ul>	<ul style="list-style-type: none"> <li>• Applicability limited</li> <li>• Efficiency low</li> <li>• Interference from near surface noises affects data</li> </ul>	<ul style="list-style-type: none"> <li>• Applicability limited</li> <li>• Efficiency low</li> <li>• Interference from near surface and underground noises</li> </ul>
<b>In-seam seismics</b>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Tunnel access required</li> </ul>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Tunnel access required</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate applicability</li> <li>• Moderate efficiency</li> <li>• Interference from background noises could effect data</li> </ul>
<b>Hole-to- surface seismics</b>	<ul style="list-style-type: none"> <li>• Applicability limited</li> <li>• Efficiency moderate to low</li> <li>• Near surface noise interference</li> </ul>	<ul style="list-style-type: none"> <li>• Applicability limited</li> <li>• Efficiency moderate to low</li> <li>• Near surface noise interference</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate applicability</li> <li>• Moderate efficiency</li> <li>• Noise interference</li> </ul>
<b>Tomography</b>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Limited range</li> <li>• Tunnel and/or borehole access required</li> </ul>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Limited range</li> <li>• Tunnel and/or borehole access required</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> <li>• Further research and development required</li> </ul>
<b>Ground penetrating radar</b>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Limited range</li> </ul>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Limited range</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> <li>• Further research and development required</li> </ul>
<b>Radio imaging</b>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Limited range</li> <li>• Tunnel and/or borehole access required</li> </ul>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Limited range</li> <li>• Tunnel and/or borehole access required</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> </ul>
<b>Vertical drilling</b>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> <li>• Low probability to intersect dykes</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> <li>• Low probability to intersect dykes</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> <li>• Low probability to intersect dykes</li> </ul>
<b>Horizontal or in-seam drilling</b>	<ul style="list-style-type: none"> <li>• Not applicable</li> <li>• Limited range</li> <li>• Tunnel access required</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Limited range</li> <li>• Tunnel access required</li> </ul>	<ul style="list-style-type: none"> <li>• Highly suitable and applicable</li> <li>• High efficiency</li> </ul>
<b>Directional drilling from surface</b>	<ul style="list-style-type: none"> <li>• Moderately applicable</li> <li>• Limited range</li> <li>• High efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Highly suitable and applicable</li> <li>• Range restriction</li> <li>• High efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• High efficiency</li> </ul>
<b>Magnetic methods</b>	<ul style="list-style-type: none"> <li>• Highly suitable and applicable</li> <li>• Moderate efficiency (not possible to detect non-magnetic and shielded dykes)</li> </ul>	<ul style="list-style-type: none"> <li>• Highly suitable and applicable</li> <li>• Moderate efficiency (not possible to detect non-magnetic and shielded dykes)</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Moderate efficiency</li> </ul>
<b>Gravitational methods</b>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> </ul>	<ul style="list-style-type: none"> <li>• Limited application</li> <li>• Low efficiency</li> </ul>

From this table it can therefore be concluded that magnetic methods offer the best solution to establish the presence of dykes over very large areas. Since its introduction during the early 1980's the sophistication of aeromagnetic surveys has increased significantly and this technique is now routinely used by the South African coal mining industry. A major limitation of this survey technique is its ability to detect non-magnetic dykes or dykes shielded by overlying strata with high magnetic characteristics. Magnetic survey techniques can be used effectively for long term conceptual planning purposes.

To obtain more accurate information over smaller target areas, directional drilling techniques offer the best solution. Major progress in the development of this survey method has been made in South Africa over the last 10 years and it is envisaged that this system will be more widely used in future.

Despite attempts to develop alternative techniques, in-seam drilling remains the most reliable and robust method to detect dykes immediately ahead of the mining face.