4 SUMMARY OF COAL PROBLEMS AND POSSIBLE GEOPHYSICS SOLUTIONS

Michael van Schoor

CHAPTER OUTLINE

▶ **Cavity/old workings detection**

▶ **Dykes, sills and other seam disruptions**

▶ **Coal thickness mapping**

▶ **Depth of weathering detection**

▶ **Pinnacle mapping (dolomitic basement)**

▶ **Pollution plume mapping (discard dump drainage)**

▶ **Mapping coal underneath pans**

▶ **SPONCOM and underground fires**

▶ **Variations in seam topography**

▶ **Coal seam identification/ correlation/characterisation**

▶ **Application summary**

This chapter provides a brief overview of some of the most commonly encountered coal mining and exploration problems, where geophysics has either been called upon in the past to provide solutions, or it may be able to play a role in the future. Each problem description concludes with a list of geophysical methods that may be applicable. The application summary table at the end of the chapter aims to integrate all of this information into a single, one-page reference guide.

▶ Cavity/old workings detection

This is arguably the most challenging problem encountered when coal mining occurs over, or in close proximity to, previously mined areas. The problem can take one of three forms:

I. Sometimes the only information required is the position of the boundary between the previously mined area and the virgin (to-be-mined) area;

II. In other cases, there is a need to detect and accurately delineate individual bords and pillars;

III. Finally, one may need to detect near-surface cavities in old workings.

These scenarios will be discussed in more detail below.

The size of a typical pillar is approximately 6 m x 6 m and the mining height may vary between 2 m and 4 m (**Figure 4.1**). The depth to the mined-out seam can range from as little as a few metres to more than 60 m, but is typically between 15 m and 40 m in the Witbank area. Old workings may be partially or completely water-filled; another challenge, associated with problems I and II above, is to discriminate between flooded and void workings.

Figure 4.1 Schematic plan and sectional views of typical 'old workings'

Plan view of old working

Cross section (A–B)
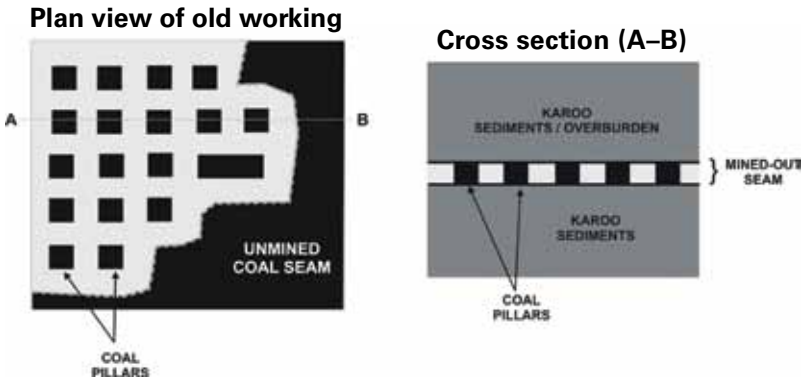
Delineating previously mined areas

This problem typically occurs where active mining encroaches on a previously mined area. Historic mine plans sometimes do not provide accurate information regarding the extent of former mining activities. Mining into such old workings is usually undesirable as this may lead to catastrophic flooding. The development of mining infrastructure over old workings may also be undesirable, for example, where the mined-out area is susceptible to surface subsidence.

Delineating individual pillars

This problem is often encountered in open-cast areas, where effective drilling and blasting requires an accurate knowledge of the position of buried pillars: boreholes drilled for blasting should ideally be located in the centre of a pillar instead of near the edge. The safest placement of infrastructure and roadways can also be derived from such knowledge.

Detection of near-surface cavities

The deterioration of old workings may cause pillar or beam failure, leading to subsidence or caving above the workings. This caving, which is sometimes referred to as rat-holing, may either break through to surface, or form undetected subsurface cavities; either way, unpredictable disasters may result.

Possible geophysical solutions – The delineation of previously mined areas is the easiest to address of the three challenges listed above. Mined-out cavities have a density and resistivity contrast with the surrounding Earth. Methods such as micro-gravity, EM and electrical methods may therefore be applicable. Gravity works well when the density contrast is greatest; that is, in the case of air-filled voids. EM works well when the cavities are filled with (conductive) mine water. Electrical resistivity imaging may be used as an alternative, especially in cases where the density and resistivity contrasts are more subtle.

MASW may also be a good choice where the target zone lies in the upper 30 m or where gravity/EM/electrical methods are logistically difficult to apply.

It is currently almost impossible to delineate individual pillars from surface, unless the workings are very shallow; that is, less than 10–15 m. ground penetrating radar (GPR) may be applicable in such cases, provided sufficient penetration can be achieved, Airborne thermal imaging may also be applied, but it is only expected to be effective for ultra-shallow workings. This problem can usually only be effectively solved by exploiting boreholes drilled into the old workings; for example, by using laser and sonar imaging technologies.

Detection of near-surface cavities, which generally represent small, isolated and scattered targets, requires a higher-resolution method that can cover large areas efficiently. Safety is also an issue: on some mines, the areas affected by near-surface cavities are dangerous for ground crews. Airborne thermal imaging has been tested in parts of the Witbank coalfield, but with limited success, probably due to the small thermal contrast of anomalies associated with isolated subsurface cavities. The only tools that have a realistic chance of success are high-resolution shallow electromagnetic or GPR scanners, perhaps deployed on a remote-controlled aerial platform. In cases where ground crews can be deployed, but where EM/GPR is ineffective, the MASW method may be considered.

GPR should perhaps also be reconsidered: past GPR trial surveys in the Witbank-Highveld areas have generally been disappointing because of limited penetration, which is partly due to the relatively conductive Karoo overburden, but also because most of these surveys were conducted using GPR operating frequencies between 200 MHz and 500 MHz. GPR technology has improved significantly in the last decade or two; low-frequency (e.g., 20–100 MHz) surveys with modern GPR equipment may address some of the problems associated with mining over old workings.

▶ Dykes, sills and other seam disruptions

Many coal mining areas in South Africa are affected by intrusive dykes and sills that inhibit the cost-effective extraction of reserves. These dykes and sills often disrupt the lateral continuity of coal seams and may also change the properties of seams that occur close to the intrusion[65]. A major challenge with these intrusive geological bodies is that their occurrence, geometry and area of influence are not always known or easy to predict ahead of mining; consequently, when mines unexpectedly encounter intrusive bodies it may have a severe negative impact on their reserve and target estimates. To make matters worse, the intrusive bodies are typically constituted of a tough geological material, such as dolerite, which presents a great challenge for mining machines and equipment.

Dykes and sills occur in a variety of shapes and sizes. In some cases, these intrusive bodies may affect only a narrow linear band or localised area measuring a few metres across; however in other cases, their presence may render significant areas of a mine property uneconomical to mine.

Another type of seam disruption is caused by localised in-seam inclusions such as smaller dolerite intrusions and sandstone lenses. These geological features present an even greater challenge to geophysical detection efforts because of their geometry. Such features may only be a few metres in diameter and they also typically do not have a linear trend or extend up towards the surface. Consequently, their size-to-depth ratio is usually very small, which makes them difficult to detect using conventional surface geophysical methods.

Two distinct scales of geophysical investigation will be considered here. During primary or first-phase exploration activities, one typically relies on remote sensing and airborne data sets to map the larger intrusive structures. **Figure 4.2**, for example, shows a major lineament interpretation for a broad regional area including the Witbank coalfield, which was derived from satellite (Landsat Thematic Mapper (TM)) imagery. During second-phase exploration or active mining – which is also the focus of this book – one may need to resort to higher-resolution airborne or ground geophysical methods to map the small-scale intrusive bodies.

Figure 4.2 Interpretation of major lineaments, on a regional scale, using Landsat TM information[65]
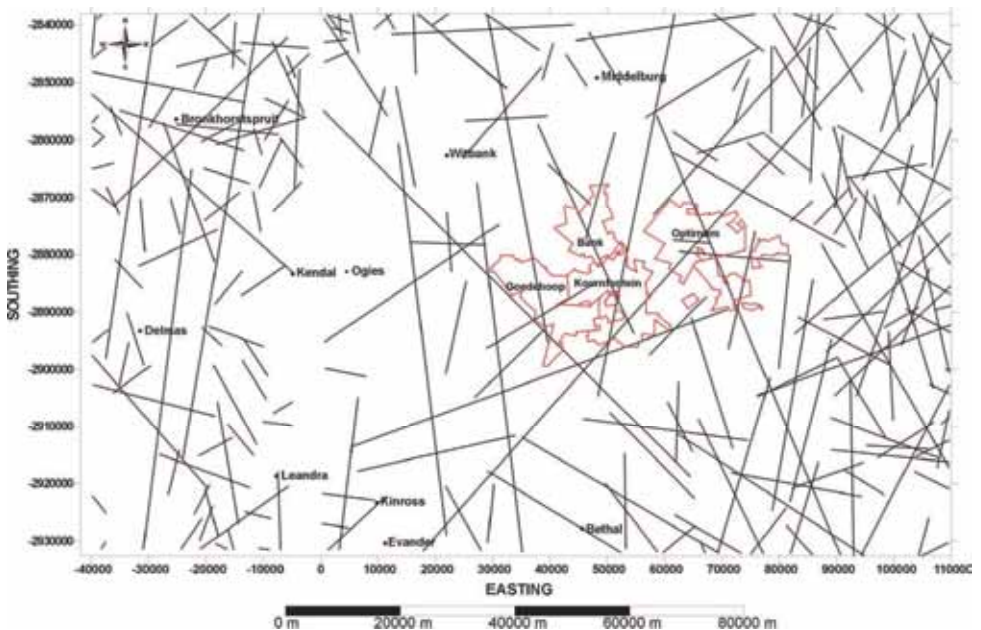
A key aspect of dyke and sill detection is that of selecting the appropriate physical property to be exploited. Many intrusive bodies have a distinct magnetic property contrast with the surrounding host rock types and coal seams and therefore constitute good magnetic targets. Others, however, do not. In such cases, an electromagnetic method may give the best chance of success.

Cost is unfortunately a major limiting factor when mining companies decide on exploration strategies. Airborne electromagnetic surveys are particularly expensive. For

example, in 2009 it was possible to conduct an airborne magnetic survey at a cost of around 20 USD per line kilometre, while the same survey using an electromagnetic method would have cost approximately 140 USD/km. Even if the appropriate method for a given area is selected, sub-optimum survey parameters (e.g., line spacing, flight direction, altitude, or sampling rate) are sometimes used, in an effort to maximise areal coverage and to reduce costs. This results in unsatisfactory survey interpretations. Where historic airborne data is used, this problem may also result from technological shortcomings at the time of the survey.

In coal mining, it is often difficult to justify spending millions of dollars on a detailed airborne electromagnetic survey that is not guaranteed to produce any significant structural anomalies over and above those that manifest on a typical airborne magnetic image of the area. What needs to be considered, on a case-by-case basis, is whether the possible cost of unexpectedly encountering intrusive bodies during future mining justifies the upfront detection efforts and associated costs.

Possible geophysical solutions – The benefit of well-planned and executed airborne magnetic surveying has already been demonstrated to the coal mining industry. The industry is also well aware that airborne EM (preferably in tandem with magnetics) may offer the best chance of mapping most intrusive features. The key is always to aim for the highest possible spatial resolution – implying closer line spacings – and there is a trade-off between mapping accuracy and cost. Some airborne geophysical companies have in recent years introduced emerging technologies that enable much better data quality and higher resolution, in part through low altitude airborne surveys. The SkyTEM TDEM system is one such example[66].

As previously mentioned, one often needs to detect and delineate smaller scale intrusive structures ahead of mining during second-phase exploration or active mining. This may, for example, occur when it is discovered that existing data sets – perhaps a combination of geological (borehole) and geophysical (airborne) data – do not provide enough mapping detail to give advance warning of these structures. In such cases, high-resolution ground reconnaissance methods can provide the required information. Most airborne data sets will only provide a mapping accuracy of 5–10 m at best, while ground surveys can achieve a resolution of 1–2 m, if required. For the detailed mapping of dykes and sills from surface, that is, where metre-scale resolution is required, the integrated use of the magnetic and electromagnetic methods is recommended. Other geophysical methods, such as electrical imaging and gravity, may also be able to detect intrusive bodies, but these methods are generally more time-consuming and costly to apply. In cases where the intrusions occur at depths of several tens of metres and traditional electrical or EM methods may be of limited applicability, the controlled-source audiomagnetotellurics (CSAMT) method may be considered.

In-mine intrusions

For deep underground workings, the problem of detecting intrusive features ahead of mining is a challenging one. Geophysical surveying tends to interfere with production, and will not be embraced unless this can be avoided. Airborne and surface surveys may fail to detect localised intrusive features that occur in the seam ahead of the face. Seismic, electromagnetic or radar technologies that scan into the advancing face do not typically provide the required range to make their routine application an attractive option. The most viable technique appears to be the use of boreholes drilled ahead of mining. Developments that extend into mining territory can also be exploited for this purpose. Perhaps the biggest obstacle to in-mine geophysical solutions is the intrinsic safety requirements. Most commercially available geophysical tools are not intrinsically safe and cannot simply be tested in underground mines. The effort and cost involved in making equipment intrinsically safe and obtaining the required certification is only justified if one is reasonably certain that the technology will be successful. This 'chicken-and-egg' situation often hampers the search for the ideal solution to in-mine problems.

In-seam borehole radar appears to be a promising application. Although most major dykes and faults are picked up simply by drilling such boreholes, it is quite possible to miss smaller, localised structures that affect the continuity of the coal seam. Through the strategic placement of multiple boreholes, one may even obtain information about possible intrusions in the unmined blocks between adjacent boreholes, through a tomographic approach. However, the unavoidable range-resolution trade-off associated with methods such as cross-hole radar imaging may require many more boreholes than are economically justified. Furthermore, the presence of conductive mine-water may render radar methods ineffective. If the mine layout and planning allows for it, tunnel-to-tunnel tomographic methods such as RIM or seismic tomography can be considered.

Even though the routine, day-to-day use of a method such as GPR at the coal face may seem impractical for the reasons cited earlier, its performance should perhaps be assessed on a site-by-site basis; if radar proves capable of providing useful tactical information, then the effort of integrating the technology safely with mining activities is worthwhile.

▶ Coal thickness mapping

Recently, the industry has regularly highlighted the need for a geophysical tool that can quantify the thickness of the coal layer – whether left in the roof and floor in old workings, or ahead of mining in virgin seams. In some cases, this need is driven by the economics of mining in new areas, or of re-mining old workings. In other cases, it is purely related to safety – for example, where a minimum layer of coal needs to be left in the roof for rock engineering purposes. Due to these varying requirements there is a need for real-time monitoring tools that can be mounted on mining machines; for hand-held, portable tools that can be used as needed by mining crews; and for tools that can map virgin seam thickness

ahead of mining. In this section, we will focus on the latter problem, as any solution to this can probably be adapted to handheld devices or for mounting on mining machines.

Possible geophysical solutions – There is currently no technology available that can accurately map coal seam thickness from surface measurements. The 'target' is effectively variations in thickness of a 2–4 m coal seam that is located at a depth of say 15–40 m, or deeper in some cases. Such small target-size-to-depth ratios rule out established high-resolution surface methods like seismic reflection as possible solutions. In-seam geophysical tools offer the only realistic hope of addressing this problem, but until recently there has been no proven technology commercially available that is suitable. However, recent experimental work on in-seam acoustic sounding tools has been very promising, and once the optimum system/survey parameters are determined, in-seam coal thickness mapping with commercially available equipment may become a routine application.

▶ Depth of weathering detection

Open-cast mining operations typically 'strip' the mining areas by removing the unconsolidated overburden or weathered zone prior to drilling and then blasting the deeper hard rock horizons. Upfront knowledge of the depth of weathering is, therefore, valuable for mine planning and costing purposes. Depth of weathering may range from as little as a few metres to several tens of metres. In some cases, the weathering profile may vary significantly so that 200m-spaced borehole data is just not good enough for accurate estimates and mine planning. Knowledge of the weathering profile also has some safety implications; for example, deep weathering may adversely impact on coal quality and may ultimately lead to poor ground conditions, hazardous pit floor or high-wall conditions, etc.

Possible geophysical solutions – The resistivity method may be the best choice for mapping the boundary between the weathered overburden and the underlying geological layers. Seismic refraction (provided good coupling can be achieved) may also be applicable. In cases where resistivity or refraction methods are logistically difficult to apply due to interfering infrastructure, the MASW method may be a good alternative. All three methods can be applied where the depth of weathering is up to a few tens of metres below surface. GPR may be considered where the weathering profile is relatively shallow at, say, less than 10 m below surface; alternatively, a low-frequency radar system may be a viable solution. The optimal survey method and survey parameter selection will have to be determined on a site-by-site basis.

▶ Pinnacle mapping (dolomitic basement)

The problem of dolomitic pinnacles occurs where open-cast mining activities are conducted in an area with a dolomitic basement. The topography of the basement may include finger-like structures or pinnacles that protrude upward and disrupt the lateral continuity of the overlying coal seams. The dolomitic basement may also contain potholes. These pinnacles and potholes present great challenges to mining activities due to the uneven floor conditions. For example, at New Vaal Colliery, the dolomitic footwall may rise and fall by several tens of metres over a 100 m span. The upward protruding dolomite pinnacles present a problem for mining machinery, as they are generally much harder than the coal[67].

Possible geophysical solutions – If there is a significant contrast in electrical properties between the dolomite and the overlying coal/sedimentary rocks, GPR or microgravity is an ideal mapping tool if the basement is very shallow. However, at collieries such as New Vaal that are affected by dolomitic structures, the basement occurs at a depth of several tens of metres and even low-frequency GPR is unlikely to succeed. The alternatives are to use two- or three-dimensional resistivity imaging or MASW. If it is known that the dolomitic basement represents a relatively conductive lithological unit, then TDEM may also be considered; for large survey areas, the high-resolution, low-altitude airborne TDEM approach mentioned on page 104 may be suitable.

▶ Pollution plume mapping (discard dump drainage)

Discard dumps, slimes dams and old workings are potential sources of unwanted subsurface pollution. In particular, the oxidation of pyrite leads to the formation of sulphuric acid and a lowering of the pH of water. This process is also referred to as acid mine drainage or AMD. Pollution plumes can easily find their way into the local ground- and surface water systems and migrate towards surrounding areas, leading to the contamination of valuable and scarce water resources. There are two approaches to dealing with pollution problems through the use of geophysical technologies. The first is a reactive approach, where areas that are known or suspected to have a pollution problem are surveyed. The second is a preventative approach in which sources of potential pollution and surrounding areas are continuously monitored for developing problems. The latter approach is of course strongly recommended. However the same geophysical technologies are likely to be applicable in either case. As usual, the choice of geophysical solution is site-specific. Factors such as the type of pollutant, depth below surface, local groundwater conditions and geological environment will determine whether the pollution plume is a good geophysical target and whether it can be mapped by surface or borehole measurements, or through the use of an airborne approach.

Possible geophysical solutions – Of all the problems described in this chapter (except perhaps for SPONCOM fires), pollution is arguably the one that has the greatest potential of changing over time, and the rate of change may vary greatly. Thus, methods that can be applied continuously or repeatedly at discrete intervals are preferred. Satellite-based imagery may offer the ideal monitoring solution in many cases, provided that the known or anticipated pollution plume is detectable by this means, and that regular repeat surveys are possible. Hyperspectral or thermal imaging, for example, could be ideal solutions, but the spatial resolution of these technologies is no better than approximately 10–15 m; it is thus only applicable to the mapping of fairly extensive contamination. Furthermore, satellite-based imaging typically only senses variations in the very near surface (upper few metres). For deeper plumes – for example those originating from old workings – other airborne, ground- or borehole-based imaging technologies must be used. Pollution associated with acid mine water can be expected to have a high electrical conductivity. For this reason, methods such as TDEM and electrical resistance tomography (ERT) may be suitable. In groundwater and pollution studies, integrated ERT and induced polarisation (IP) measurements often provide better discrimination than the resistivity method on its own.

▶ Mapping coal underneath pans

Perhaps a less common coal geophysics problem is that of trying to obtain subsurface information from below existing water bodies such as pans and dams. For example when mining is planned underneath a dam, the amount of sludge in the dam needs to be determined as this could pose a hazard to the mining. The depth to the dam bottom is also of interest in such surveys[68]. Apart from characterising the water body, the quality of the coal or coal thickness may also be important. The presence of the water body makes exploration drilling almost impossible and greatly inhibits the application of conventional ground geophysics.

Possible geophysical solutions – In cases where the water body is deep enough to accommodate a water-borne vessel (for example a small boat) one could consider the use of technologies such acoustic sounding devices, towed-array seismics or ERT. A simple acoustic device such as those employed by ships may be able to map the bottom profile effectively, but will not provide significant information about deeper geology. If deeper information is required the seismic or ERT methods must be used. The quality and properties of the water and near-surface layers may have an adverse effect on the application of methods like ERT or seismics.

High-resolution airborne methods such as magnetics or TDEM may also play a role, provided the intended target in the layers below the water body has a measurable anomalous response.

▶ SPONCOM and underground fires

When coal is exposed to oxygen it can ignite spontaneously – both *in situ* coal (for example, in existing or old workings) and stockpiled coal are susceptible to SPONCOM. There is a need to detect and delineate subsurface 'hotspots' – that is, areas that are heating up and which may ignite without intervention, or areas that are already burning. In the Witbank coalfield there are several existing and historic mining areas that are known to be affected by SPONCOM, but the distribution and extent of existing fires are not accurately known. A complication related to SPONCOM is that affected zones are often located close to or beneath built-up areas, including industrial and residential areas. Though SPONCOM and uncontrolled underground fires may result in significant financial losses through lost reserves, the safety hazard that these fires pose is arguably a much greater concern to coal mining companies. In some cases, the uncontrolled burning of old workings may also lead to their collapse – evidence of this can, for example, be seen at the old abandoned Transvaal and Delagoa Bay Colliery near Witbank[69]. The result of another local subsidence is shown in **Figure 4.3**. A further problem of uncontrolled coal fires is their environmental impact and, in particular, the uncontrolled emission of carbon dioxide into the atmosphere.

Figure 4.3 Collapses associated with subsurface fires in old abandoned coal workings *(photo provided by CJS Fourie)*

Possible geophysical solutions – For underground fire detection the obvious solution is to employ a heat-sensing technology such a thermal imaging. These types of technologies have been tested on the local mining scene – both on satellite platforms as well as on fixed wing aircraft. These approaches traditionally have a few challenges associated with them. The first is the limited spatial resolution, especially for satellite-based systems. Secondly, the very small temperature gradients that manifest on the surface of the Earth often make the responses from subsurface fires very difficult to detect. Thirdly, in order to enhance the anomalous responses from subsurface fires, such surveys are usually limited to specific times – for example night-time and non-summer flights – which makes effective, ongoing monitoring difficult.

Some non-thermal technologies have been reported as possibly applicable to mapping deeper underground fires. In particular, the controlled-source audiomagnetotelluric (CSAMT) and self-potential (SP) methods may hold some promise, but cannot yet be considered as proven technologies in this regard. Some reports have also shown that the magnetic and electromagnetic methods, especially when used as dynamic monitoring tools, are capable of identifying burning and burnt areas[70, 71].

▶ Variations in seam topography

The economic coal seams of the Witbank area appear well-behaved in terms of topographic variations. The seams are generally flat-lying, and the cross-cutting of intrusions is generally a greater issue than the undulation of the seams. There are some mining areas, however, where undulations present a significant challenge to mining. Significant seam topography variations over short distances can complicate mine planning and day-to-day extraction and may also present hazardous ground conditions in both surface and underground mines.

Possible geophysical solutions – Since metre-scale vertical resolution is critical for this type of application, a method offering high resolution must be used. Methods like LF GPR, seismic refraction or reflection and resistivity imaging are all possible choices, but the depth of the target horizon and the properties of the overlying strata will dictate which method is the most suitable. Seismic reflection would be the logical choice for deep layers, for example, deeper than 40 m; the other three methods listed above are better suited to shallower targets. Note that with LF GPR one might struggle to effectively optimise the range-resolution trade-off for targets deeper than about 20 m.

▶ Coal seam identification/correlation/characterisation

During primary or ongoing exploration there may be a need to identify specific geological layers or coal seams and to correlate the geological log of one hole with those of other boreholes in the same area. There may also be a need to characterise coal seams in terms of certain quality parameters, for example, the estimation of calorific values or ash content. It is not standard practice on all South African coal mines to run downhole geophysical surveys on exploration boreholes. Consequently, the mines do not extract the maximum possible information from boreholes.

Possible geophysical solutions – For verifying the top and bottom seam contacts, borehole logging may be the most applicable method. In cases where specific layers or seams need to be correlated between boreholes, the results of borehole logging may provide some useful clues. If, however, correlation is not straightforward – as may be the case in structurally complex areas – then some other high-resolution geophysical method, such as seismic reflection or GPR, may be needed to 'fill in the gaps'.

As was discussed in Chapter 3, the suite of borehole logging tools is used to derive quality-related parameters such as calorific value and ash content. Borehole logging can also be used to assess certain parameters that may be relevant from a rock engineering perspective such as fracture characteristics, elastic modulus, Poisson's ratio, etc.

▶ Application Summary

Table 4.1 (overleaf) provides a quick reference guide to the application of geophysics to the mining and exploration problems described in this chapter. For more details refer back to the relevant sections in the chapter.

Table 4.1 Coal geophysics application summary

	PROBLEM SCENARIO	PROBLEM PARAMETERS
1.1	**Delineation of old workings**	Flooded workings
		Air-filled workings
1.2	**Detailed old pillar location**	Ultra-shallow workings (< 10 m)
		Workings deeper than ~ 10 m
1.3	**Near-surface cavity detection**	Cavity dimension of same order as depth, or larger
		Cavity dimension small compared to depth
2.1	**Dyke and sill detection**	Magnetic intrusions
		Non-magnetic intrusions
2.2	**In-seam disruptions (lenses, etc.)**	Detection from within seam developments/boreholes
		Detection from surface or short range at the face
3	**Coal thickness mapping**	From surface
		From within seam/old workings
4	**Depth of weathering**	Shallow weathering profile expected (< 5 m)
		Deeper weathering profile expected (> 5 m)
5	**Dolomitic pinnacles/uneven floor**	Shallow dolomitic basement (< 20 m)
		Deeper dolomitic basement (> 20 m)
6	**Pollution plume mapping**	Discard dump drainage, unwanted plumes from old workings
7	**Mapping coal underneath pans**	Any of the other problems (e.g. depth of weathering, dyke detection, structural mapping) complicated by water body
8	**SPONCOM/underground fires**	In situ (e.g., old workings) and stockpile hot spots/fires
9	**Variations in seam topography (structure)**	Shallow seam(s) < 15 m
		Deeper seam(s) > 15 m
10	**Coal seam identification/ correlation/characterisation**	Determining top and bottom of seam(s) in boreholes
		Corellate seams between exploration boreholes

POTENTIALLY APPLICABLE TECHNIQUES

TDEM

Resistivity, microgravity

GPR, airborne thermal imaging

Customised borehole ranging/imaging tools (LASER and/or SONAR technology)

Airborne thermal imaging, AEM, GPR, MASW

GPR

Airborne or ground magnetics (CSAMT for deeper structures)

Airborne or ground TDEM

RIM, BHR (reflection or tomography), seismic tomography

GPR?

Currently not possible for thin seams

(In-seam) acoustic or EM tool or in-seam radar

GPR, resistivity

Resistivity, seismic refraction, MASW

2D/3D resistivity imaging, TDEM, microgravity, LF GPR, MASW

TDEM, MASW, 2D/3D resistivity imaging

Hyperspectral/thermal imaging, TDEM, ERT

Towed sensors, e.g. SONAR for bottom mapping, seimics or ERT for deeper targets, also consider airborne magnetics or TDEM

Thermal imaging, CSAMT; possibly also SP, magnetics and EM

LF GPR, seismic refraction, resistivity

Seismic refraction for upper ~ 40 m, reflection for > 40 m

Borehole logging

Seismic reflection (target seam deeper than ~ 40 m), LF GPR or seismic refraction