Detecting adverse coal-seam geology ahead of mining using advanced radiowave geophysics, and recent longwall applications

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This paper describes the current state-of-the-art in the field of radio imaging method (RIM) for applications in the geotechnical and geological evaluation of coal-producing areas and future coal reserves. Advanced RIM-6 instrumentation possesses higher signal-to-noise ratio capability than any previous RIM system in the 50-year history of the technique. When mapping anomalous structural geology in a coal seam, this RIM-6 improvement provides greater signal range distances, allows the use of higher imaging frequency for improved sensitivity, and generates image reconstructions of greater spatial resolution than any previous RIM technology or technique. Improved survey procedures associated with the improved system allow RIM-6 to be utilized at mine sites without significant impact on or disruption to mining practices. This paper describes current RIM-6 processes and presents several recent case studies involving radio tomography for longwall mapping. These studies confirm the importance of applied radio geophysics in the coal mining process and the critical need to detect and scale in-seam structure well ahead of mining, providing greater intelligence to the mine’s geologists and engineers.

Introduction to radio imaging method

Underground mining of coal is a critical factor in low-cost power generation and the heat production needed in developing and sustaining world economies. Policy-makers believe that mineable world coal reserves are sufficient to provide low-cost fuels well into the future. Forecasts of coal reserves using current mining technology may be optimistic when considering coalfield sterilization rates and the near exhaustion of ‘easy-to-mine’ reserves. Future mining will take place in coal seams that are deeper, thinner, more geologically complex, and closer to abandoned mines. Better exploration methods must now be adopted in the geotechnical and geological evaluation of coal seams ahead of mining.

Geological anomalies and ground control problems are prevalent in nearly all of the world’s coal deposits. Coal production can come to an abrupt halt when a longwall machine becomes trapped or ‘iron-bound’ in bad geology such as along the margins of a channel, intersecting a fault or a dyke. Tomographic radiowave mapping around these areas can assist in geotechnical planning and operation. Imaging of palaeochannels ahead of mining locates where ground control should be intensified by roofbolting and installing screening or trusses. Frequently, the roof rock fails when entries are driven under margins of palaeochannels. Roof-fall injuries could be reduced significantly when images of margins are mapped and ground control measures are intensified.

Medium-frequency mine-wide radio communications demonstrated in the late 1970s discovered that the coal seam waveguide supports the transmission of electromagnetic waves in the low-frequency range of the AM broadcast band. Radio communication through the seam showed that signals travelling through faults in the coal bed created reflections and amplitude loss in the radio signal. Early experimentation proved that radiowave science could be a powerful tool for evaluating anomalous geological structures in the coal seam. Within a decade, radio imaging method (RIM) instrumentation and survey practices had validated radio geophysics’ capabilities in mapping palaeochannels, faults, fracture zones, intrusions, and seam thinning. These coal seam anomalies were easily detected by rapid reconnaissance scanning through the coal seam with borehole or handheld RIM instrumentation.

The primary function of RIM equipment is to send radio waves from a transmitter across the area of interest to a receiver, the waves reacting to the geology and structure between the two. RIM leverages the natural waveguide effect of signal propagation in layered strata to produce wavefront absorption, refraction, and scattering within the coal bed. Signal analyses allows for the detection of conductivity changes and material boundaries, while the geometric distribution of signal vectors, or ray paths, allows for the generation of reconstructed images through tomographic
inversion. RIM applications go beyond coal mining, and have proven to be powerful tools in metalliferous mining, environmental research, civil engineering, and security applications.

The current state-of-the-art RIM system (termed RIM-6) has been in use throughout 2011 and has demonstrated an improved transmission range and enhanced image resolution. RIM-6 is both man-portable and borehole-capable, and provides a tool/service to reduce risk and adds value to continuous and efficient mining production. This paper describes several recently conducted surveys involving radio tomography for longwall mapping, and confirms the added value of RIM imaging.

Advanced RIM instrumentation

Radio geophysics applies methods in computerized axial tomography (CAT) to the processing of RIM data to effectively reconstruct geological images. Advanced algorithms include corrections for complex refraction and reflections in the coal seam waveguide. The development of practical RIM technology has had to evolve to keep pace with processing algorithms and the ever-growing scale of mining. Longwall panels in particular have increased in width to more than 1500 feet in the last decade, nearly three times wider than those first mapped with RIM in the 1980s.

Given the need for longer range and better resolution, borehole and in-mine RIM system design has required significant technical innovation to improve performance, primarily by reducing receiver noise levels, combating mine-site electrical noise generated by underground power and communication systems, and enabling signal detection at the theoretical limits of possibility. Therefore, RIM receivers are unlike any commercial radio receiver available to the public. RIM-6 is not quite at the theoretical limit, but does provide a 20–40 dB improvement in signal-to-noise ratio (SNR) over RIM-4, and allows for the use of much higher imaging frequencies for similar applications. The system was introduced in February 2011 and has been trialled at six Australian coal mines and three American coal mines with extremely high performance gains. By way of example, a recent RIM-6 survey at a Colorado coal mine in the USA provided a 70 dB signal-to-noise ratio at 700 kHz, while a previous RIM-4 survey in the same mine provided a 40 dB ratio at only 300 kHz. These improvements have the potential to increase resolution by an order of magnitude.

The in-mine RIM-6 survey equipment is man-portable and consists of a transmitter and one or more receiver units. During operation along a longwall block, the transmitter is used in the headgate entry (beltway, intake) and the receivers must be used in the tailgate entry (return). The transmitter broadcasts a continuous-wave signal to the receivers at a fixed radiated power. The units are not connected by cable or wire and the signal passes entirely through the coal seam. Signal processing and an extremely narrow bandwidth help to filter out mine-site noise and the effects of conductors and pipes in the return entry. The conveyor belt has no impact on the transmitter. In addition to longwall mapping with hand-held instruments, the RIM-6 system is also built as a borehole package for mapping from drill-hole to drill-hole, maximizing the information garnered from drilling efforts. Using widely spaced boreholes to detect and image in-seam structure can provide a large cost saving and better direct exploration efforts. Figure 1 shows current RIM-6 systems in both the in-mine and the borehole configurations.

Figure 1. RIM instrumentation is packaged for either hand-held or borehole deployment. The hand-held-system (right) is lightweight and man-portable, and is typically carried through underground entries during data collection. The borehole system (left) is deployed from specialized fibre optic hoists on the surface or from underground
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**Longwall mapping with in-mine radio imaging**

The process for surveying a longwall panel includes five steps:

- Plan the survey; timing, proper instruments, budget, and mine-site preparations
- Collect the field data; includes equipment calibration to the specific seam, a reconnaissance scan, and tomographic scans as needed
- Analysis of the data, which includes construction of 2D or 3D tomographic images
- Confirmation as required (in some cases, drilling or mining into anomalies to confirm target is prudent)
- Integration of geologic intelligence into mine planning and correlation with ground truth after mining.

Figure 2 illustrates the process and results of a RIM longwall mapping operation in a sample tomographic image (tomogram). The tomogram is a 2D plan view representation of signal loss within the coal seam block. The blue areas are normal signal quality representing ‘clean coal’ while the red areas are excess signal loss indicative of ‘hazardous’ structures or severely disturbed coal. The image uses hundreds of ray paths to create a general size, shape, trend, and severity for the in-seam anomalies. Therefore, the tomogram provides detection and scaling.

![Figure 2. In-mine RIM-6 units are shown during a typical underground survey for longwall panel mapping. The tomogram is a 2D plan-view representation of signal loss within the coal seam block. The blue areas are clean coal while the red areas are spatially reckoned in-seam anomalies (non-coal structures or severely disturbed coal)](image)

Each coal seam is unique and thus the RIM system should be calibrated to establish baseline attenuation rates (rate of signal decay per lateral distance unit). Once established, it is fairly efficient to send a signal directly across the panel every 20 to 40 feet along the panel’s length. This is known as a RECON scan (for reconnaissance) and if no anomalies are present, the attenuation rates of the signals should be fairly consistent. However, if an anomaly is encountered, there will be a general loss of energy in the signal with an increase in the attenuation rate. Once encountered, a more in-depth evaluation can take place around this anomaly whereby diagonal scans across the panel are made to increase the density and orientation of the signal’s ray paths, generating greater resolution. This detailed survey is termed a TOMO scan (for tomography). Tomograms provide mine planners and geologists with important intelligence about the location and severity of thinning seams, faults, sandstone channels, etc., that can impede longwall advancement. Factoring this information into production forecasts provides management with another tool to better assess financial, production, maintenance, and safety issues; the goal is elimination of ‘surprises’ during production, or ahead of development, reducing risk and enabling greater productivity.
Recent longwall mapping case studies

A major Australian coal producer has recently utilized several types of RIM techniques for borehole exploration and longwall mapping. This mine encountered a number of geological anomalies that caused great difficulty during the mining process. In some cases, large coal seam structures were intersected without prior knowledge or warning, causing temporary production stoppages, and production was resumed only at a substantial cost. Some of the structures typically intersected were igneous plugs, dykes, or diatremes. Using both the in-mine and borehole versions of RIM-6, this mine can detect hazards early in development and image the anomaly before production passes through the hazardous zone, enabling supplemental ground control methods such as surface-deployed long strata bolts and grouting to improve stability.

The mine uses traditional exploration processes such as aeromagnetic or ground magnetic surveys, and then further investigates through drilling. However, the mine has found that this process has a number of limitations insofar as these techniques can only identify large anomalies with strong magnetic signatures at the surface. Since this is frequently not the case, exploration drilling is often guided by more direct and mundane technique.

Longwall mapping with older versions of in-mine RIM was able to identify large anomalies within longwall blocks prior to mining, but due to some technical requirements, conducting the RIM survey was disruptive. Power had to be cut to the panel, and infrastructure such as metal pipes had to be broken. This created downtime not only for the shifts RIM was utilized, but over several shifts during preparation and remediation. Additionally, the width of the longwall blocks continued to increase and the older systems were not providing adequate results over the required distances. The poor performance, combined with the disruption to production, led the mine to look for advanced RIM technology to fill the void.

With RIM-6 the mine realized it did not need to disrupt the mining process, and the better performance created more opportunities to discover a broader range of geological anomalies that could impact both development and production. Recently a number of RIM-6 surveys were conducted over an area initially identified from a reconnaissance survey of the block. Progressive exploration was undertaken further utilizing RIM-6 at each stage, which included borehole-to-borehole, borehole-to-gateroad, and gateroad-to-gateroad. The result was detection and scaling of an anomalous area well before interaction with the mining process. This permitted timely communication to the mine site, preparation of geological information plans encompassing the RIM-6 images, and preparation for additional support of the anomalous area prior to mining through it.

The project began with a rapid RECON scan along the longwall block. The 1-D results indicated that an unknown anomaly existed at the centre of the longwall block. A focused 2-D tomography survey was performed in the anomalous area and further refined the size, shape, and location of the structure. A drill-hole was then developed from the surface into the anomaly to explore the source of the disturbance. Unfortunately, the drill-hole missed the anomaly due to severe deviation. However, the drill-hole provided an opportunity to image from the borehole to the in-mine entries to further refine the image from within the block. Using the drill-hole at mid-block, the required signal propagation distances are 50% less than normal, allowing for the use of higher frequencies with better resolution. This initial series of RIM imaging efforts shown diagramatically in Figure 3.
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Figure 3. A recent RIM longwall mapping project used both the in-mine and borehole versions of RIM-6 in conjunction to detect a mining hazard early in panel development, and later, to image and scale the anomaly before production passed through the hazardous zone. The project began with a rapid 1D RECON scan along the longwall panel (upper) and then a full 2-D TOMO survey (lower left). The results indicated that an unknown anomaly existed at the centre of the longwall block. A drill-hole was then developed from the surface into the anomaly to explore the source of the anomaly via borehole RIM (lower right).

The results of this borehole-to-gateroad method provided a 2-D shape for the unknown anomaly and it was decided that the anomaly would be surrounded by a small grid of boreholes for additional mapping. A significant borehole-to-borehole mapping survey commenced and led to the creation of dozens of vertical image planes criss-crossing the anomalous area. The survey predicted severe fracture zones in the roof strata and upper sequences of the multi-bench coal seam. The resulting image was used to plan a dense drill-hole pattern for the purposes of supplemental strata control, including long cable, anchors, and grouting from the surface holes. In the end, the longwall passed beneath the fracture zone with no disruption to longwall mining. Had the RIM survey not been conducted, the mine could have encountered severe ground control issues for more than 300 feet of longwall advance. The final series of imaging efforts leading to geotechnical intervention, and subsequent longwall mining, are shown in Figure 4.

During the mining process through the anomalous zone, geologists mapped the longwall face 24 hours a day to reconcile the RIM anomaly with actual longwall face conditions. What was determined and visually mapped on the longwall face was a seam roll of significant undulation (up to 2 m). Related to the fold was a clear increase in jointing directions and frequency. The start, finish, and trending direction of this seam roll and associated jointing coincided with the RIM-6 tomogram. Consequently, information was provided to production crews regarding the likely distance of the anomaly, and therefore when mining conditions were likely to improve.

RIM-6 clearly has the ability to identify a wide variety of geological anomalies. In addition to being able to identify large igneous plugs or diatremes that have low magnetic signatures within limited sized longwall blocks, RIM-6 enables detection of finer-scale structure within larger longwall blocks (such as the roll and jointing encountered), and without disruption to the mining process.
A second major Australian coal producer has been able to utilize and document the benefit of progressive advancements in RIM, using imaging on successive longwall panels for several years. As improvements in the technology are brought into the district, mine engineers have been able to document the improved detection sensitivity and image resolution of RIM advancement over 5 years (RIM-4, RIM-5, and RIM-6) by tracking significant in-seam anomalies across entire mining districts, including faults, igneous intrusions, sills, and palaeochannels. Each new longwall panel shows increased RIM performance from frequency gains and better signal-to-noise ratios. The series of graphics in Figure 5 shows several recent multi-panel case studies. In general, the use of improved RIM platforms has increased sensitivity to in-seam structure, increased signal range (maximum distance), and improved image resolution.
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Figure 5. Several recent multi-panel case studies with longwall operators have shown RIM-6 to have increased sensitivity to in-seam structure, increased signal range (maximum distance), and improved image resolution. The sequence of tomograms from this mine show several intrusions, washouts, and boggy zones tracked across three longwall blocks.

This coal producer chose RIM technology when a volcanic plug was encountered in the middle of a longwall block, which had a massive effect on business, from which the operation took 6 months to recover. The decision was made to use RIM as a predictive tool to better understand any significant geological features and prevent a similar outcome to operations. This decision has led to the routine use of RIM for longwall mapping as a standard practice to assist in the location and definition of geological structures. The three consecutive longwall tomograms shown from this mine have been verified through mining history to correlate with actual structures encountered during production. To date the majority of anomalies in the tomograms have been explained and confirmed. There have been a few small tomogram anomalies that did not correlate to severe structure, but no structures have been encountered that were not identified by RIM.

This coal producer has also utilized high-resolution RIM around pillars to locate historical surface boreholes, providing invaluable information to assist with locating potential water in-rush hazards. The mine does a significant amount of in-seam drilling to de-gas and de-water; however, the mine is quick to point out that they no longer depend on existing drilling to fully map the longwall. Other mines have argued that their existing in-seam drilling efforts for degassing should typically locate these structures. However, this producer has documented two significant events where numerous in-seam drill-holes did locate a small number of dykes but missed their source plug entirely. In fact, the mine actually drilled two holes beneath the silled section, but the zone was misinterpreted by the drillers as simply being ‘hard coal’ while it was actually the base of a massive plug that increased in width, thickness, and hardness moving away from the drill-holes. These events proved to the coal producer that in-seam drilling was not reliable for the detection and scaling of these structures. Since adopting RIM-6 as standard practice, this mine site has been able to document intrusions and avoid unknown pitfalls.

A third major Australian coal producer has also tracked progressive advancements in RIM through successive longwall imaging. With focus on intrusions, faults, and seam splits, this producer has utilized RIM to better understand mining challenges and mitigate production delays, maintenance planning, and potential ground control risk on the longwall. As with many sites in Australia, this coal producer has used RIM surveys to track significant in-seam anomalies across three or more consecutive blocks, including faults, igneous intrusions, seam splits, and washout zones. Each new longwall block shows increased RIM performance and adaptation of results to mine planning. The graphics in Figure 6 show three recent longwall blocks surveyed with in-mine RIM. Additionally, the most recent block used horizontal borehole-to-borehole RIM to better resolve a particularly severe section of a complex intrusion. The borehole results illustrate individual intrusion planes within the anomaly, including the core of the intrusion and its flanking extremities. Regions of heat-affected coal are also easily detected along the boundaries of intrusions, even if the intrusion is out-of-seam.
Figure 6. This coal producer has used RIM for several longwall blocks to track severe intrusions across the mining district. Recent efforts have included the use of borehole RIM in horizontal in-seam holes along the intrusion. The use of borehole RIM in conjunction with hand-held RIM can improve the resulting resolution and scaling of the in-seam structures.

Future considerations

For the past decade the underground coal mining industry has been moving toward a reality of ‘super panels’ – wider faces and greater lengths. An obvious economy of scale exists and super panels have certainly enabled the industry to keep pushing the limits of productivity. However, panel size, now and especially in the future, will be driven in large part by geological factors. While larger panels capture economies of scale, containing several times the coal volume of a conventional panel, the probability of encountering serious anomalies is several times greater. Given the increased probability of encountering anomalies, improved assessment of geology is important for future longwall panels. Also, the quality of coal reserves is declining, so in the future mining will be in deeper and most likely thinner seams – and these seams appear to contain greater anomalies that threaten efficient operations. To counter the impact of reserve deterioration, the industry must move towards greater use of geophysical tools and services.

The results of the case studies described in this paper confirm that the RIM-6 system provides additional intelligence about the coal geology of large and geologically complex longwall panels. Only by integrating this intelligence into geotechnical models and advanced mine planning can radio-geophysics build a strong partnership with mining engineering. A geotechnical vision is created to identify risk and improve the chances of positive outcome.
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