APPLICATIONS OF SEISMIC REFLECTION IN THE COAL ENVIRONMENT

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ABSTRACT

Seismic reflection has grown to become a valuable geophysical tool for the accurate and cost-effective imaging of coal seams, and is now of significant importance to the economics and safety of coal mining in Australia. This paper provides an essential, up-to-date overview of the advantages and potential pitfalls of using the seismic method in the coal environment based on the experiences of a number of Australian coal mines. The major advantage of using seismic data is its ability to produce a more continuous image of a target coal seam than can be achieved via borehole drilling. Seismic-derived elevation surfaces, and information about faults and other stratigraphic anomalies located via seismic imaging, can be used by mines to target borehole drilling for fault evaluation and grout pattern design, and help predict changing roof, floor and seam conditions. Recent developments in advanced 3D seismic interpretation and converted-wave seismology focus on detecting more subtle stratigraphic features, locating gas, and mapping lithology away from borehole locations. However, the accuracy to which the seismic method can recover structural and stratigraphic information is controlled by the inherent limitations in the technology and the geological environment in which the seismic survey is conducted. Vertical and lateral resolution limits of a seismic dataset restrict the size of a feature that can be imaged using seismic data, and the ability to resolve closely spaced structures. Unfavourable near-surface geology (e.g. thick Tertiary sediments or basalts) will have a negative impact on seismic image quality and reduce the ability of the seismic data to resolve faults and other stratigraphic anomalies. Seismic reconciliation is a calibration process that enables a mine to gain a greater understanding of the uncertainties of the seismic method in characterising faults and stratigraphic anomalies in their particular environment. A proactive approach to using and assessing seismic data throughout the mine planning and development process will maximise the benefits of a seismic survey to a coal mine.

INTRODUCTION

Seismic reflection data have been acquired for coal mining operations in Australian coal basins for over 30 years. Originally used solely as a resource exploration tool, the seismic method now routinely contributes to coal-mine design and development. In the decades since seismic reflection data were first acquired for coal applications, there have been remarkable developments in the acquisition, processing and interpretation of seismic data. Today significant amounts of high-resolution information extracted from seismic datasets contribute to reducing mine downtime and increasing the safety of mine operations. This paper provides a concise summary of the fundamental concepts of seismic reflection, details the type of information that can now be extracted from seismic data and discusses the effective use of seismic data in the coal environment – knowledge that all mine staff using seismic data should have. Traditionally, application of the seismic method in the coal environment has involved delineating structures that have the potential to impact on mining operations. More recently, seismic depth conversion has gained popularity as a tool for deriving detailed coal elevation surfaces, and efforts are being directed towards extracting stratigraphic information from seismic data. This paper also highlights new converted-wave coal-seismic applications, such as imaging very shallow coal seams, detecting zones of fracturing via shear-wave splitting analysis, and mapping lithology away from boreholes using integrated P/PS interpretation.

FUNDAMENTAL CONCEPTS OF SEISMIC REFLECTION

In brief, seismic reflection involves imaging the sub-surface using artificially-generated sound waves. Typically, small dynamite explosions or vibratory sources (e.g. mini-SOSIE or Vibroseis) are used to generate seismic waves at or near the surface. Receiving devices (geophones) are placed on the surface to detect the seismic energy that originates from the seismic source, travels down into the earth and gets partially reflected back to the surface at each geological boundary. 2D seismic exploration involves acquiring seismic data along a single line of receivers. The resultant 2D seismic image can be used to detect features in the subsurface along the particular survey line. 3D seismic exploration involves using a grid of surface receivers to detect the reflected seismic energy generated by each seismic source. 3D seismic data yield a much more extensive and higher-resolution image of the subsurface than 2D seismic data. This makes 3D seismic more attractive in terms of being able to contribute significantly to the structural and stratigraphic understanding of a mine area.

Conventional coal-seismic acquisition assumes that typical coal-seismic sources will result in only compressional (P) waves arriving at the surface. P waves are longitudinal sound waves that have particle motion in the direction of travel. Hence reflected P-wave energy travelling upwards from a geological boundary will have particle motion with a strong vertical component at the surface receiver (Figure 1a). Conventional 2D and 3D seismic acquisition records only the vertical component of seismic energy arriving back at the receivers. This type of seismic recording can also be referred to as single-component (1C) recording, and is by far the most common method of seismic exploration used in the coal environment (e.g. there have been approximately fifty conventional 3D seismic surveys acquired in the Bowen and Sydney Basins since 1997).

In reality, both reflected P and shear (S) waves typically arrive at the surface during a seismic survey. S waves are transverse sound waves that have particle motion perpendicular to the direction of travel. Since coal-seismic sources dominantly produce P-wave energy, most of the S energy arriving at the surface is in fact mode-converted PS energy. That is, energy from a wave that travels down to a geological boundary as a P wave, gets partially converted to S energy at the boundary, and then travels back to the surface as an S wave. Any PS-wave energy arriving at the surface will have a strong horizontal component of particle motion (Figure 1b). Multi-component seismic recording measures both the vertical and horizontal components of ground motion to enable exploitation of both the P and PS energy arriving at the surface. Note that, multi-component recording may also be referred to as three-component (3C) recording since the vertical and two orthogonal horizontal components (inline and crossline components) of ground motion are generally recorded. To date, less than ten 2D-3C seismic reflection surveys have been conducted for coal exploration in Australia – all of them believed to be in the Bowen Basin, Queensland. No 3D-3C seismic reflection surveys have been undertaken for coal exploration.

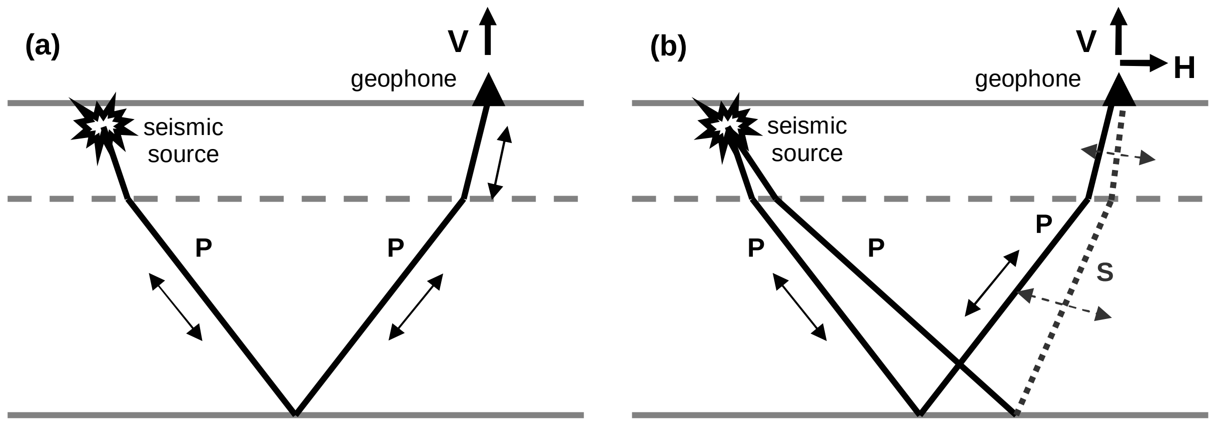

Figure 1. (a) Conventional seismic reflection assumes that only P waves arrive at the surface. Since the particle motion of an upward travelling P wave is largely vertical (indicated by the solid arrows), a vertically-oriented geophone is used for acquisition. (b) Multi-component seismic recording recognises that both P and mode-converted PS waves will arrive at the surface. The particle motion of an upward travelling S wave is largely horizontal (indicated by the dashed arrows). Thus both the vertical (V) and horizontal (H) components of ground motion must be recorded to take advantage of both wave types.

SEISMIC INTERPRETATION

A 2D seismic image or 3D seismic volume is a graphical representation of the geological boundaries in the survey area as a function of two-way reflection time. In simple terms, seismic interpretation is the process of tracking significant geological boundaries (e.g. target coal seams) in the seismic data and producing two-way time (TWT) horizons or surfaces. Whereas the interpretation of 2D seismic data is confined to a single vertical plane, the spatial redundancy of 3D data provides the user with high-density maps of the coal seam topology. In both instances, the major advantage of seismic exploration is the ability to produce a more continuous image of the target coal seam than can be achieved via borehole drilling.

Depth Surfaces

Provided sufficient geological control exists (e.g. borehole data), a reliable time-to-depth conversion can be performed on the interpreted seismic TWT horizons to yield coal-seam elevation surfaces. These surfaces can give a more accurate indication of relative changes in coal-seam elevation that can be extracted from widely-spaced borehole data. Conventional P-wave coal-seismic data can typically map coal seams from depths of approximately 50 m, down to depths of approximately 800 m. Due to differences in the way P and S waves propagate in the subsurface (e.g. Hendrick, 2004), PS seismic data can image much shallower coal seams. Our experience indicates that PS data can map coal seams as shallow as 25 m (Figure 2), making multi-component seismic data particularly useful for opencut coal exploration.

Seismic-derived elevation surfaces can be integrated with borehole information about the mine and used to assist with grout pattern design, flight plan design for longwall cutting profiles, and guiding inseam drilling for the purpose of gas drainage.

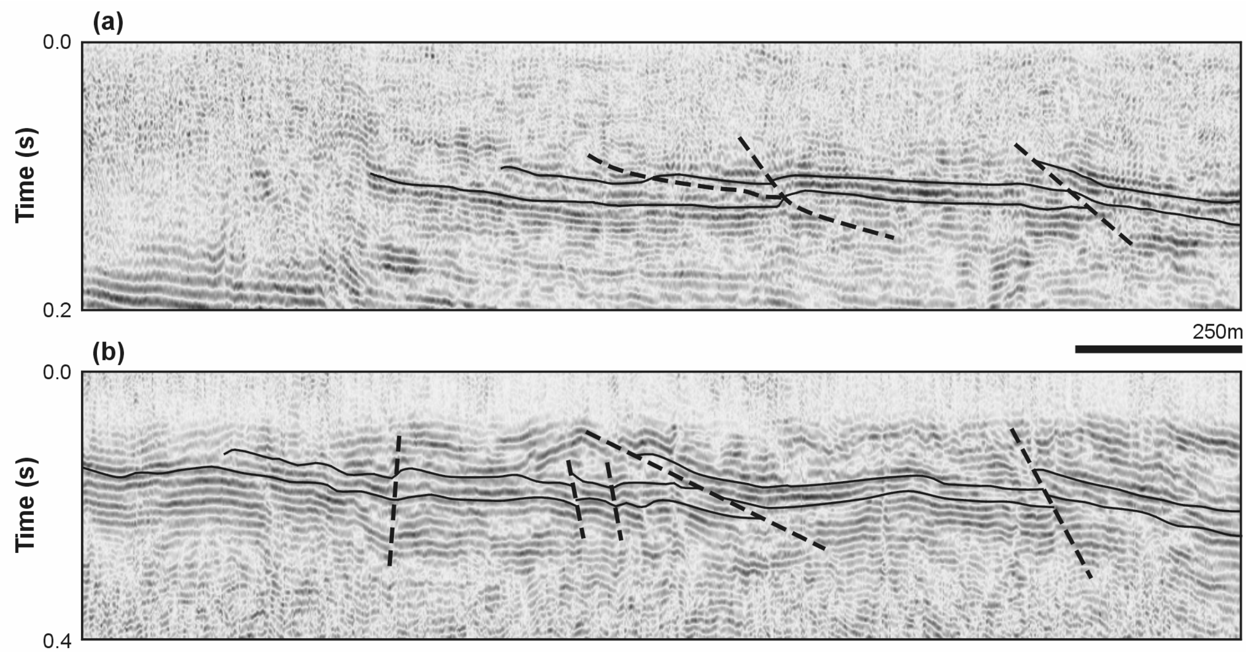

Figure 2. (a) Conventional P-wave image and (b) PS image from a 2D multi-component seismic survey in the Bowen Basin, Queensland. The target coal seams are indicated by the solid lines. Interpreted faults are approximately marked by the dashed lines. For this trial, the PS section is able to image the shallow coal seams to depths of approximately 25 – 30 m (left-hand edge of image).

Structural Information

Typically, accurate delineation of structure is the primary objective of a seismic reflection survey. Seismic TWT horizons, together with the seismic data, can be used to derive a number of seismic attribute maps (e.g. TWT gradient, seismic amplitude, instantaneous frequency, semblance) that can be used to highlight structural features that may impact on mining operations (Figure 3). Seismic data provide a dense sampling of the subsurface and so can detect a greater number of structures than borehole drilling. Estimates of fault throw, fault width and the location of a structure can be computed from the seismic data. Our experience indicates that faults as small as 2-3 m can often be detected using 3D seismic data. Velseis has recently undertaken research (Hendrick, 2006) to utilise the phenomenon of shear-wave splitting (SWS), as a method of detecting fracturing or faulting at a smaller scale than that obtained from conventional P-wave seismic. Shear wave splitting is the process whereby S waves split into two approximately orthogonally-polarised shear waves with different velocities in fractured media. The potential of SWS to contribute useful information about minor, localised faulting is still being evaluated.

Once mine staff have gained a better understanding of local structure from a seismic survey, drilling programs can be targeted for fault evaluation and grout pattern design. If necessary, mine plans can be designed or amended to avoid significant structures. In this way, fault information derived from seismic data can help reduce longwall downtime and increase the safety of mine operations.

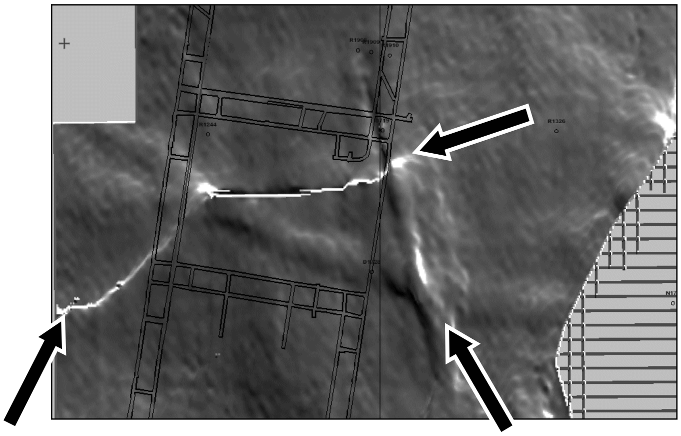

Figure 3. Map view of the semblance attribute derived from a 3D seismic volume acquired in the Bowen Basin, Queensland. Rapid changes in the seismic attribute map (highlighted by the arrows) delineate structures cutting the proposed mining panel.

Stratigraphic Information

Recently there has been an increasing desire to obtain more than just structural information from seismic data. Careful examination of seismic waveform variations, and anomalous features in seismic attribute maps, can contribute to the stratigraphic interpretation of a seismic dataset. Often reconciliation drilling is required to gain an understanding of what a seismic anomaly represents in real physical terms. Nevertheless, highlighting such features can contribute to the greater geological understanding of the mine area. Our experiences indicate that seam splitting and igneous intrusions (sills) are two of the most prevalent stratigraphic anomalies detected via conventional 3D seismic interpretation (often detected in the instantaneous frequency attribute map). There are a number of more complex seismic interpretation procedures being developed and tested that involve full seismic waveform analysis, geological inversion or integrated P and PS interpretation. Such tools attempt to provide additional information on rock type and pore fluids, for example. A recent ACARP research project completed by Velseis (Hendrick, 2006) presents the first attempts to map lithology away from borehole locations using integrated P/PS seismic interpretation. The interpretation results from many of these more advanced seismic tools are still being evaluated in the context of remote imaging in the coal environment.

Stratigraphic anomalies and lineaments derived from seismic data can be used by mines to design targeted drilling programs to help optimise mine plans, avoid intruded coal, prepare for weak roof/floor conditions or accommodate changes in seam thickness during mining.

EFFECTIVE USE OF YOUR SEISMIC DATA

In order to maximise the advantage of conducting a seismic survey, it is imperative to have an understanding of both the inherent limitations of the seismic method, and the impact the local geological environment can have on the seismic data. Armed with this knowledge, and the resources to actively integrate seismic data into mine planning and development, any potential pitfalls associated with using seismic can be minimised, resulting in considerable technical and cost benefits to the mine.

Understanding Seismic Resolution

The ability of a seismic dataset to image a geological feature is largely a function of the frequency content of the seismic data – with higher frequency content leading to greater resolution. The frequency content of a seismic dataset is controlled by the seismic source type (with a dynamite source resulting in a higher-resolution seismic dataset than a mini-SOSIE source), the receiving device and the near-surface and subsurface geological conditions.

The vertical resolution of a seismic dataset is often indicated by two measures – the ‘detectable limit’, which is defined as the minimum layer thickness required to produce an observable seismic reflection (Sheriff, 1991), and the ‘resolvable limit’, which is defined as the minimum separation of two discrete seismic reflectors at which one can determine there is more than one interface present (Sheriff, 1991). Good quality 3D coal-seismic datasets will have a ‘detectable limit’ of the order of 1-2 m and a ‘resolvable limit’ between 2.5-5 m. This implies that the seismic volume won’t be able to detect structures with displacements less than approximately 1-2 m, and seam splits and/or faults are unlikely to be properly imaged in the seismic volume until the interburden and/or displacement becomes greater than approximately 2.5m. Obviously, these resolution limits become larger in the presence of noise. The dangers in not understanding the vertical resolution limits of your seismic dataset are assuming that your seismic data will detect all geological features that could impact mine operations and placing too much significance on the computed physical dimension of seismic anomalies with very small displacements.

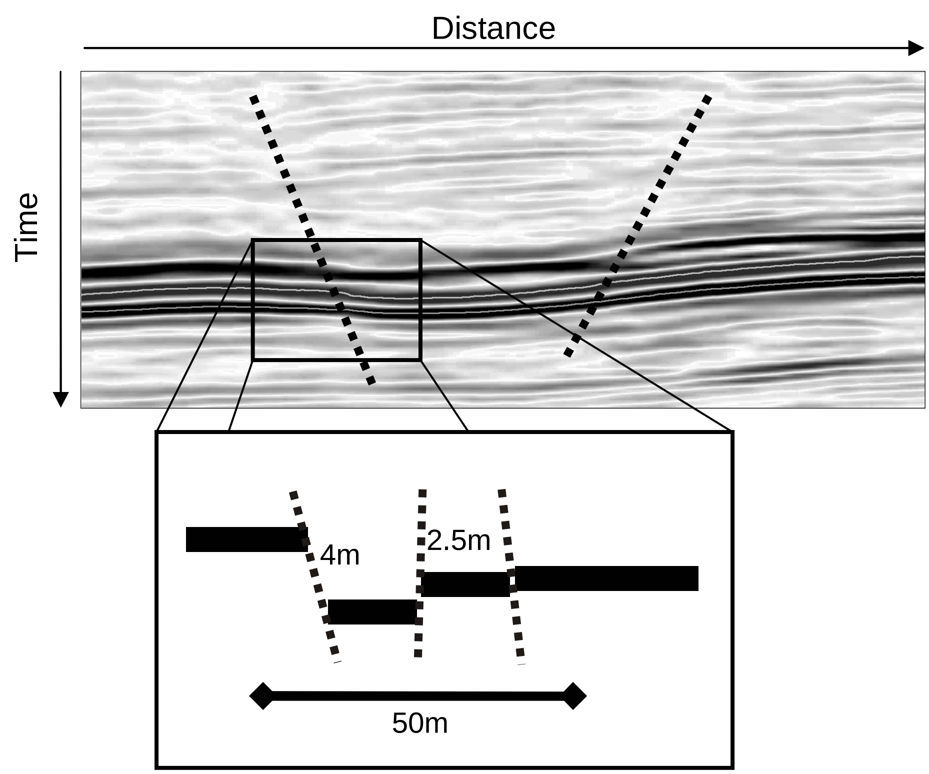

Figure 4. Interpretation of these seismic data acquired in the Bowen Basin, Queensland indicates there are two faults present. Subsequent mapping during underground mining reveals that the left-hand seismic structure is in fact three closely-spaced faults. The lateral resolution limits of the seismic data prevent the three faults from being imaged clearly.

The lateral resolution limit of a seismic dataset is generally indicated by the ‘Fresnel zone’ – the zone over which any two or more reflecting points are considered indistinguishable from the Earth’s surface (Sheriff, 1991). In practical terms, this means a disruption in a target coal seam can influence the recorded seismic reflection event across a broad area. The implication of this for imaging structures with seismic data is two-fold – first, we can expect errors of up to ± 15 m in the interpreted locations of geological features and structures. The potential pitfall in this instance is to not accommodate this magnitude of error in seismic fault locations when including seismic data on mine maps or determining detailed cutting profiles. Secondly, seismic data will generally not be able to detect multiple faults that occur within close proximity (e.g. within a zone of 40-50 m). Rather, the seismic image will likely show a single, broad displacement with a throw equivalent to the net throw of the fault zone (Figure 4). Mine staff must avoid the trap of always interpreting a single line on a seismic fault map as a single structure. Referencing fault widths supplied by the interpreter will help highlight locations where multiple faults may exist.

The Influence of Coal-Mine Geology

As noted above, coal-mine geology can have a negative impact on the frequency content of a seismic dataset. Unconsolidated, thick surface layers will cause significant attenuation of high-frequency seismic energy, which in turn reduces the resolution of the seismic dataset (Peters and Hearn, 2001). In addition, near-surface geology can affect the ability of energy from the seismic source to penetrate downwards to the target coal seam/s. For example, thick near-surface basalts and other high-velocity layers will result in a very poor signal-to-noise ratio in the resultant seismic image (Figure 5). In these situations, the above-defined resolution limits become less relevant, and the ability of seismic data to detect faults and other geological features can be dramatically reduced. Obviously, if near-surface geology is understood prior to a seismic survey being undertaken, steps can be taken to minimise any negative effect (e.g. the seismic source may be able to be positioned below thick Tertiary or interbedded basalt layers). Nevertheless, care must be taken to avoid the assumption that all faults and stratigraphic anomalies on a seismic interpretation map are equally reliable. Referencing fault confidence levels supplied by the seismic interpreter will indicate the significance that should be given to a fault interpretation. Mines should also be careful about assuming no structures exist when a seismic dataset does not detect any structures, particularly through areas flagged as poor-quality data areas by the seismic interpreter.

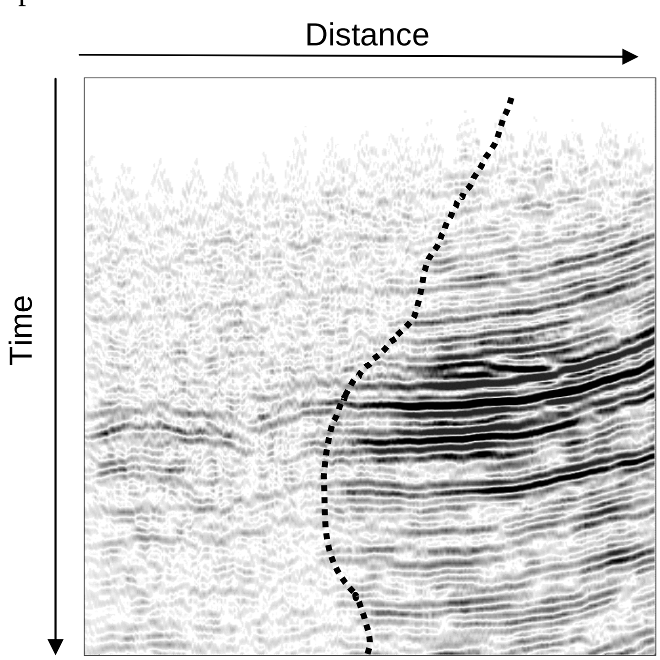

Figure 5. Clearly the seismic data on the left-hand side of this image suffers from a poorer signal-to-noise ratio than the data on the right-hand side. The seismic data on the left have been acquired beneath a thick, near-surface basalt layer. The high-velocity layer attenuates the seismic energy as it propagates down to the target coal layers, and again on its return to the seismic receivers. Seismic structures and other anomalies are more difficult to detect in the data on the left.

Perhaps surprisingly, the stratigraphy of the coal seams can also influence a seismic dataset. For a single-seam environment, the depth of the coal seam will only marginally alter the seismic response (with deeper reflection events suffering only a minor reduction in high-frequency energy compared to shallow reflection events). However, in a multi-seam environment, it becomes progressively more difficult to extract a clean, high-resolution image of coal seams at depth. Seismic energy will suffer severe transmission loss as it passes through multiple coal seams in a geological sequence. Thus, seismic reflection events for deeper seams in a multi-seam environment can be affected by a poor signal-to-noise ratio. This can lead to false structures in the data or the potential for real structures to be inaccurately imaged. Mine staff must have a good understanding of their local geology to assess the relative robustness of any seismic interpretation results and take this, as well as observations from the seismic interpreter and lessons learnt from the seismic reconciliation process, into consideration when utilising their seismic data.

Time-to-Depth Conversion

Initially, all seismic interpretation is conducted with reference to two-way reflection time. However, in order to integrate seismic information into mine-planning packages, often seismic surfaces, and sometimes the seismic trace volume itself, are converted to depth. Time-to-depth conversion relies on borehole information to compute conversion velocities (since the depth of a geological boundary at a certain point is equal to the average seismic velocity multiplied by half the TWT of the interpreted horizon at that point). Away from borehole locations, the conversion velocities are extrapolated via sophisticated gridding algorithms. Nevertheless, these velocities are not necessarily accurate away from the borehole locations and the seismic depth horizons should not be assumed to be absolutely correct. Our experience is that while absolute seismic-derived depths can be erroneous away from boreholes, the *relative* changes in coal seam elevation are quite reliable.

Integrating Seismic Data into the Mining Process

The interpretation of a coal-seismic dataset results in a significant quantity of additional information that needs to be incorporated into traditional mine-planning packages. Such information will include, but not be limited to, coal-seam elevations (ASCII format), fault characterisation files (DXF format) and interpreted seismic images (TIFF images). Effective integration of seismic data into the mine planning and development process not only requires that these data be included in maps and software used daily at the mine site, but also requires that mine staff gain an understanding of the uncertainties inherent in their local seismic data.

The process of gaining a better understanding of the uncertainties of the seismic method in characterising faults and stratigraphic anomalies in a particular environment is commonly referred to as seismic reconciliation. Reconciliation involves comparing seismic interpretation results with hard geological data available from either validation drilling or underground mine mapping. Mines that most effectively integrate seismic into their mine planning and development are those who are proactive about reconciliation (Peters, 2005). Clearly, seismic data cannot be considered in isolation from all other geological and geophysical information available at a mine site – the more information that is fed into the seismic interpretation process, the better the outcomes. The reconciliation process enables mine staff and the seismic interpreter to develop realistic expectations about what seismic data can deliver to a particular mine. This process of reconciliation should continue throughout the working life of a mine.

CONCLUSIONS

Seismic reflection data can produce a more continuous image of a target coal seam than can be achieved via borehole drilling. Seismic-derived elevation surfaces, and locations of faults and other stratigraphic anomalies can be used by mines to target drilling programs, assist with grout pattern design, guide inseam drilling for gas drainage, contribute to flight plan design for longwall cutting profiles, and help mines prepare for changing roof, floor or seam conditions. Recent developments in advanced 3D seismic interpretation techniques and converted-wave seismology are tackling the more difficult problems of detecting fracturing, zones of gas, and seam intrusions, and mapping coal quality and lithology away from borehole locations. To optimise technical and cost benefits to the mine, staff using seismic data must understand the inherent limitations of the seismic method. Care must be taken to not assume that seismic data will detect all geological features that can impact mine operations. When faults are closely spaced, or seismic data suffer from significant noise contamination or frequency attenuation, structures and other geological features can be missed by the seismic data. An active seismic reconciliation program will enable mine staff to develop a greater understanding of the uncertainties of the seismic method in characterising faults and stratigraphic anomalies in their particular environment. In this way, mine staff can develop realistic expectations about what seismic data can deliver to their mine.

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