An in-depth look at ultra-high-density 3D seismic acquisition for mining

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Summary

The use of 3D seismic for mining exploration is increasing but its application for active open-cut mines remains rare. In this paper we describe how recent improvements in acquisition technology have allowed the acquisition of ultra-high-density 3D seismic surveys that enable the identification of structures that are estimated to cost the Australian coal mining industry alone $6 Billion/year.

Introduction

3D seismic has long since established itself as the most important tool for oil and gas exploration. Its use for mining applications is increasing, although it continues to be uncommon. Part of the methods increased popularity for mining targets is the depth at which exploration is possible, an important consideration giving the increasingly deeper targets being sought. A less frequent application is for defining shallow mining targets, a subject we discuss here.

There are two major types of mining: underground and open-cut. Underground mining, as the name suggests, requires tunneling into the earth, whereas open-cut mining involves extracting the resource from the surface. Targets for underground mining tend to be deeper and are thus more analogous with oil & gas targets, although they do tend to be more steeply dipping and thus require larger offsets. The shallower targets of open-cut mining however, such as coal and iron-ore, require much higher resolution surveys than deeper targets as we are interested in identifying shallow small-scale structures and this presents a challenge to acquisition, processing, and interpretation. In this paper we describe the desired outputs from a seismic survey acquired over an open-cut target. We then detail how such a dataset is designed, acquired, processed, and interpreted. In the example presented here, the resource is a coal deposit in the Bowen Basin, Queensland, Australia. The depth of the targets range from 50 to 200m.

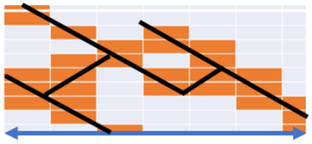
Survey Outcomes

The primary objective of an open-cut seismic survey is to identify and characterize subsurface structures that could significantly influence mine planning and safety. Faults represent zones of structural weakness within the rock mass, posing potential hazards to mine wall stability. By accurately mapping faults, mining operations can anticipate and mitigate associated risks more effectively.

The relative geometry between mine walls and fault planes is a critical consideration in assessing the potential impact on mine wall stability. Early identification of faults allows for strategic planning and implementation of measures to address stability concerns. Delayed detection of faults may necessitate reactive measures such as reducing the angle of mine walls, typically from approximately 70° degrees to 35-45°. While this approach reinforces the integrity of mine walls by buttressing walls with blasted material, it often leads to reduced mining efficiency and complicates highwall mapping, hampering hazard identification in subsequent strips.

In cases where the full fault network can be comprehensively mapped, strategic adjustments to mining operations may offer more efficient long-term solutions. Reorienting strip directions to intersect main faults at oblique angles can mitigate potential hazards associated with fault activity while optimizing mining efficiency (Figure 1).

(a) Original Mine Plan



(b) Updated Mine Plan

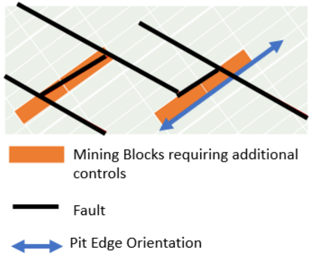


Figure 1: (a) original mine plan developed without knowledge of the local faults resulting in numerous mining blocks requiring additional controls. (b) updated mine plan developed with knowledge of the local faults resulting in far fewer blocks requiring additional controls.

Survey Design

It is no surprise that the success of an open-cut seismic survey will depend on the resolution that it can achieve. As shown by the wedge models in Figure 2, the vertical resolution of the survey is heavily dependent on the maximum frequency of the sweep (due to the source density required vibroseis tends to be the only viable source). Of course, the generation of increasingly high frequencies is ultimately pointless as they will be absorbed by the earth but we have found that the maximum sweep frequency tends to be a result of the vibrators limitations rather than a choice we are forced to make.

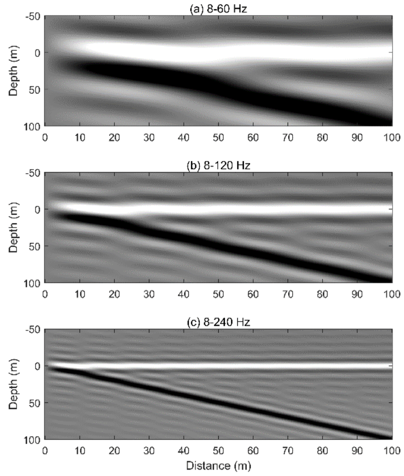


Figure 2: Three wedge models calculated for an average velocity of 2,500 m/s. The bandwidth increases by one octave for each model.

In terms of lateral resolution, we do not tend to be interested in the target size as the resources are generally continuous. Nor is the maximum unaliased frequency an issue as the resources tend to have very small dips. Instead, we need to focus on the requirement of lateral resolution. The bin size B can be calculated using (Cordsen et al., 2000)

$$B = V_{int}/4f_{dom}$$

were V_{int} is the interval velocity and f_{dom} is the dominant frequency (the mid-frequency of the sweep). The resulting bin size for a range of velocity and frequency values are shown in Figure 3. Note that the bin size remains small (between 2 and 5 m) for high dominant-frequency values even when the velocity varies significantly. It should be noted that we have found superior resolution even for bin sizes smaller than the theoretical limits (Dean et al., 2021a) and thus we typically employ bin sizes of between 2 and 3 m.

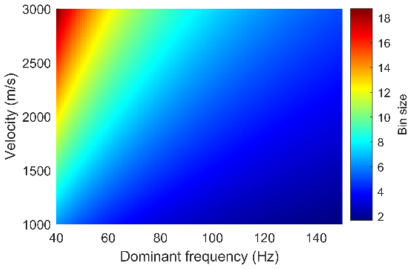


Figure 3: The relationship between bin size, velocity and dominant frequency.

This small bin size, and the requirement for relatively high fold at shallow depths, results in the receiver spacing and line spacing being much smaller than in more conventional surveys, as low as 12 m, although 20-30 m is more typical. For example, Figure 4 shows the fold at three different depths for a survey employing 4 m point spacing and 20/24 m source/receiver line spacing. Even with this very dense geometry the fold at typical target depths is still quite low.

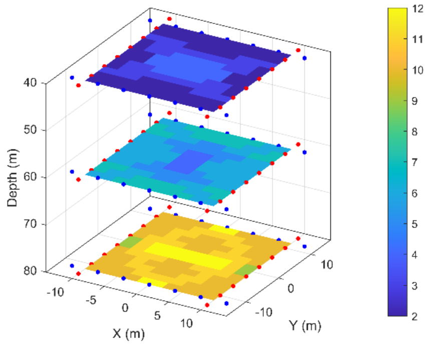


Figure 4: The fold calculated at three different depths (we assume that the maximum useable offset is equal to the target depth) for 4 m point spacing and 20/24 m source/receiver line spacing.

Acquisition

The requirement for a large bandwidth sweep necessitates the use of small vibrators, which are better at transmitting high frequencies. Unfortunately, even small vibrators struggle to transmit the sweep at full force at frequencies above ~120 Hz. It is therefore necessary to design a custom sweep that allows for the performance of the vibrator by reducing the sweep amplitude at higher frequencies (Dean et al., 2016). We have found that the performance of even ostensibly identical vibrators does vary, with the maximum frequency they are capable of emitting being somewhere between 220 and 250 Hz. We are therefore limited to the limit of the worst performing vibrator (usually ~220 Hz).

Even with their relatively small size, the high point density of such surveys (>10,000 points/km^2) means that acquiring them using conventional methods would be prohibitively expensive. To keep the costs as low as possible we employ a variety of techniques such as:

- Fielding enough receivers so that the lines span the width of the block, this avoids having to acquire zippers. Channel counts of between 10 and 20 thousand are common.
- Employing designs that have a high source-receiver ratio by having a smaller source line interval, without exceeding the recommended limit of 1.3 (Vermeer, 2012).
- Incrementally increasing the line spacing as the target gets deeper.
- Using modern lightweight nodal systems (Dean et al., 2021b; Dean et al., 2018) to enable the efficient movement of large (10,000-20,000) channel count

crews. Side-by-side tests of the latest lightweight acquisition systems have shown minimal differences in quality (Figure 10) (Dean, 2024).

- Using high-productivity acquisition methods based on time-distance rules (Quigley et al., 2013). Although unconstrained acquisition is tempting, given the low fold of our surveys the slight decrease in productivity from constraining the acquisition using rules is worthwhile to avoid the worst interference (Dean et al., 2021a).
- Using short sweeps: Shallow targets do not require high levels of source energy, even with relatively low fold. For example, Figure 9 shows a 2D line acquired with 4 and 12 s sweeps. There is no discernible difference between them. If faced with a choice, it is better to increase fold than force (Bianchi et al., 2009).

Results

Figure 5 shows a small section through a volume acquired with the geometry shown in Figure 4. It clearly shows a fault-bend fold with an offset of ~9 m at the coal seams. Figure 6 shows a high-angle normal fault with ~3 m offset.

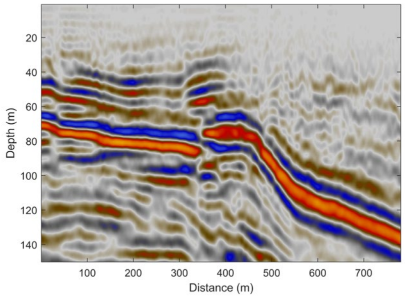


Figure 5: Seismic section showing a fault-bend fold with ~9 m offset at the coal seams.

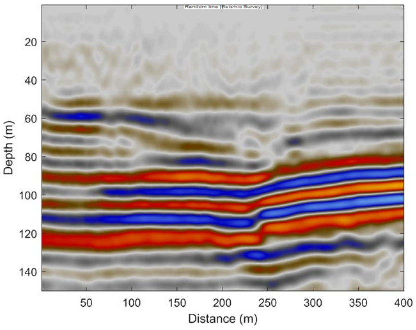


Figure 6: Seismic section showing a high-angle normal fault with ~3 m offset at the coal seam.

Figure 7 shows depth slices through the same volume, even at the shallowest depth of 40 m coherent events are clearly visible. At the deeper sections, below the depth of weathering, the coal seams become clearly visible.

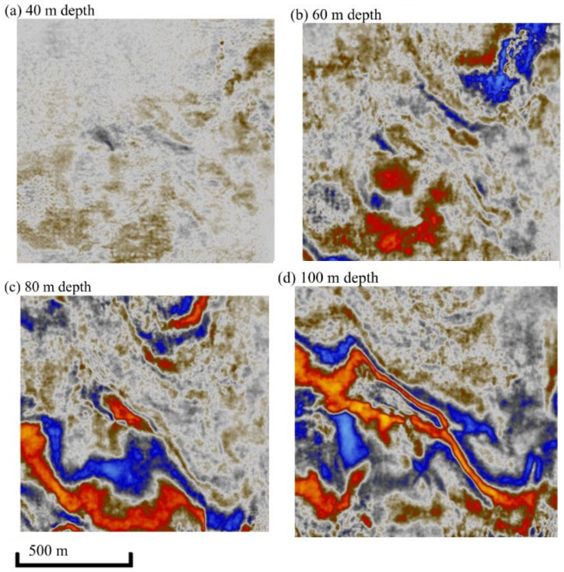


Figure 7: Depth slices through an ultra-high-density volume.

Figure 8 shows the importance of acquiring 3D vs. 2D data. The original 2D lines are shown in green with the associated fault observations and their resulting connections in magenta. The faults interpreted from the 3D survey are shown in black. Note how nearly all the faults interpreted from the 2D data are incorrect, in particular their predominant orientation was identified as north-south whereas it is actually east-west.

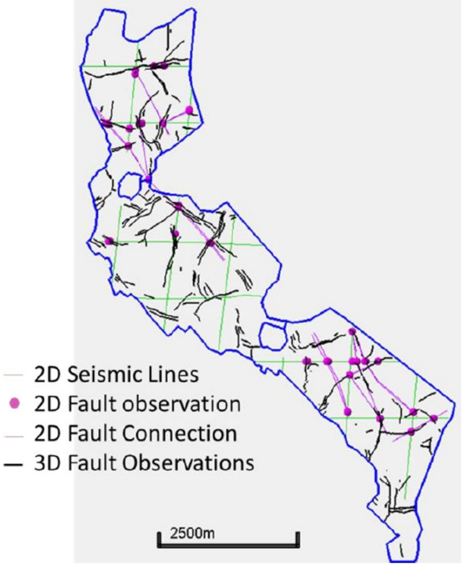


Figure 8: Fault maps resulting from the interpretation of 2D and 3D datasets (Pranoto et al., 2022).

Discussion and Conclusions

Ultra-high resolution seismic surveys are becoming increasingly popular in the open-cut coal mining industry in Australia. These surveys have been primarily enabled by improvements in both source and receiver technology. The high quality data they provide is suitable for advanced QI workflows (Pavlova et al., 2021) and along with the reflection volumes, the surface-wave and refraction data can also be used to further characterize the near-surface (Dean et al., 2021c; Strobbia et al., 2021a; Strobbia et al., 2021b). Overall, the structures they are capable of identifying are estimated to cost the Australian coal mining industry $6 Billion/year (Dean et al., 2021c) and thus we expect 3D surveys to become increasingly common across the open-cut mining industry.

Acknowledgements

We thank our acquisition and processing partners, and our colleagues within Anglo American.

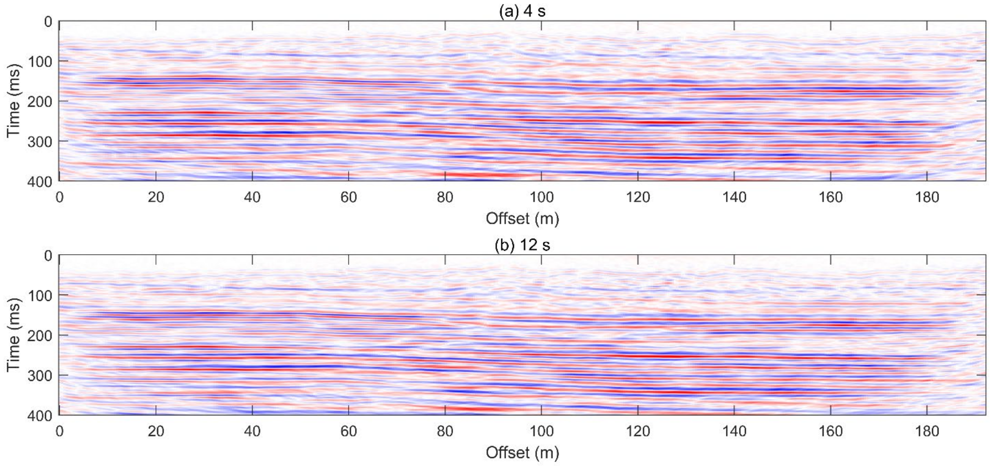


Figure 9. The same 2D line acquired with (a) 4 s and (b) 12 s sweeps.

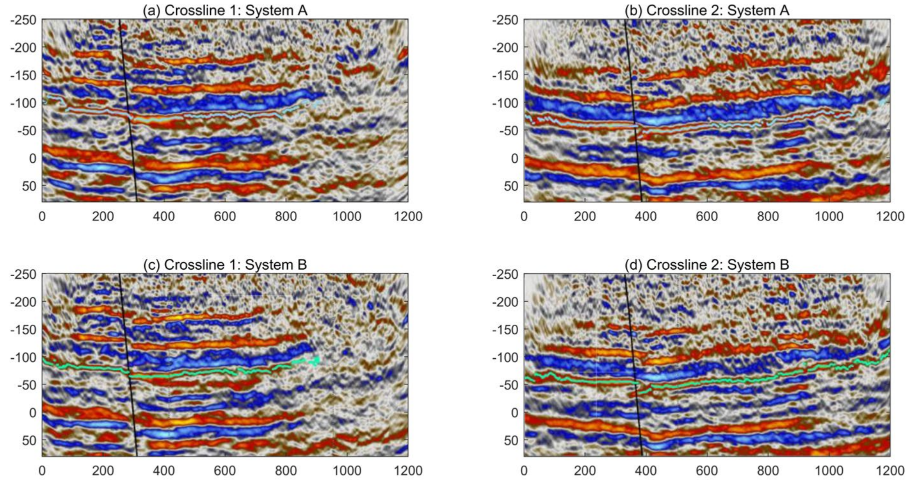


Figure 10. Crosslines extracted from a 3D volume acquired simultaneously using two different acquisition systems. System A is the latest lightweight system, whilst system B is a more established system. On line 1 the fault (black line) is better defined on the System B data but on line 2 the shallow reflector is better defined on the system A data.