# 3D SEISMIC APPLICATION FOR MAE MOH COAL MINE DEVELOPMENT

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**ABSTRACT:**

*The Electricity Generating Authority of Thailand (EGAT) requested CGG Services SAS to make a high resolution integrated acquisition-processing-interpretation seismic 3D survey over the Mae Moh lignite mine in northern Thailand. The target was two coal seamsat a depth of 100m to 600m below ground surface.*
*The objective of the seismic survey was to image the coal seams and associated fault networks, and from this to better plan future mining operations, in particularhow to avoid potential landslides during further excavations. The resultant well imaged geological structures are very useful in future development of the open pit mine.*

**KEYWORDS:** *Mining/Geology/Geophysics/ Seismic / Coal/*

Exploration in the coal industry is commonly based on geological field cartography followed by intense drilling or trenching campaigns. These boreholes are mainly designed to give a geological description of the terrain, and cores are extracted for mineralogical and chemical analysis to map the coal quality.

Traditionally there is very little use of geophysics in open pits or shallow coal mines. In other mining industries, for base metals for example, some geophysical potential methods are used.

For mine geologists and mining engineers, geophysics is far from being a commonly used and understood tool.

Geophysics allows obtaining an indirect characterization of the rock physics properties. The physical attributes achievable with geophysics are resistivity, density, magnetic susceptibility and seismic velocity. According to the method selected, at least one of these rock properties will be mapped.

The issues linked to near-surface mine or open pit development is to identify the volume of coal in place, the structural map of the play and to de-risk any kind of geo-mechanical hazard that may affect the development and planning of the mine.

## 1 THE CHOICE OF THE GEOPHYSICAL TOOL

Among the geophysical methods available, most of them are potential methods used to make regional studies. For example airborne surveys as magneto-metric, gravimetric, electromagnetism, can be used to identify basins, estimate their shape and the thickness of the sediments. In no case they can be used to directly find coal seams.

The only method able to map in detail the geological layers in basins is the seismic method.

### 1.1 Principle of reflection seismic

The aim of reflection seismic is to provide cross sections or volumes of geological structures located at varying depths. The reflection seismic method which is commonly employed for deep targets (oil and gas) is applied here for shallow-depth exploration using more lightweight acquisition equipment adapted to improving resolution at a reasonable cost.

Reflection seismic can be compared to an ultra-sound scan of the subsurface and the characteristics of the reflections provide information about the nature of the rocks. It is the only geophysical method which can supply a continuous image of the layers of strata and their structures.

In its simplest form the seismic survey yields a two-dimensional image of the subsurface (2D seismic survey). For greater accuracy three-dimensional images are obtained from 3D seismic surveys. These 3D images increase the consistency of the interpretation. High resolution seismic is particularly suitable for civil engineering studies, and has numerous applications in mining exploration for potassium, salt, coal, platinum, gold etc.

The principle of reflection seismic is to measure any kind of contrast in the geological layers due to changes ineitherrock density or seismic velocity. The ability to record reflected waves is linked to the existence of a "reflector" which is a lithological interface that enables the reflection phenomenon to occur. Seismic reflections occur when there is a change in acoustic impedance, meaning the product of the seismic velocity and the rock density, between the two strata in contact with one another. The reflectivity of an interface increases as the difference in the impedance of the layers increases (Figure 1). In case of lignite, its impedance is rather low, having a

velocity of 2200m/s and a density of 1.4, to be compared to surrounding claystone rocks at 2400m/s and a density of 2.0.

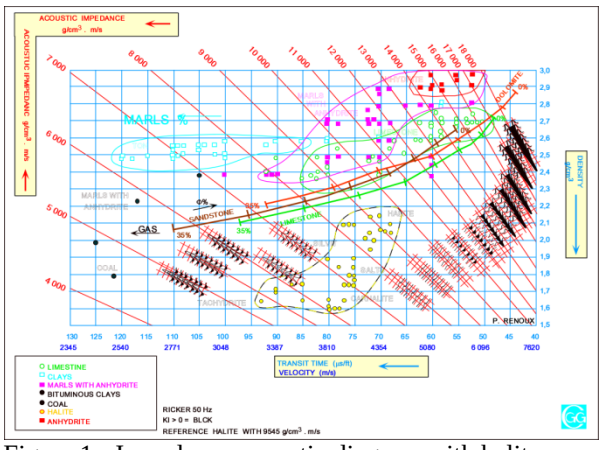

Figure 1 - Impedance acoustic diagram with halite as reference.

### 1.2 What is a seismic survey?

Acquiring a seismic survey means two things: first generate and send seismic sound waves into the ground, then record them when they get reflected backup to the surface.

There are different ways to generate seismic waves, such as using dynamite explosions, heavy weight drops or specifically designed trucks called vibrators that emit a controlled seismic signal into the ground. The benefit of this last method is its flexibility, power and environmental-friendly use as compared to dynamite explosions.

On the other side, the recovery of the signal coming back to the surface is made through a multitude of sensors laid on the ground called geophones. Thousands of these geophones are commonly used in seismic surveys.

The position and number of these energy source points and geophone receiver stations are carefully designed according to surface conditions and the geological objective.

## 2 OBJECTIVES OF THE SURVEY

### 2.1 Geological objective

The geological targets of the Mae Moh seismic survey are the K and Q coal seams (Figure 2). These are part of the Na Khaem formation from the Upper Miocene. The whole NK formation consists of inter-bedded coals and clay stones, however only the K and Q seams are considered economical.

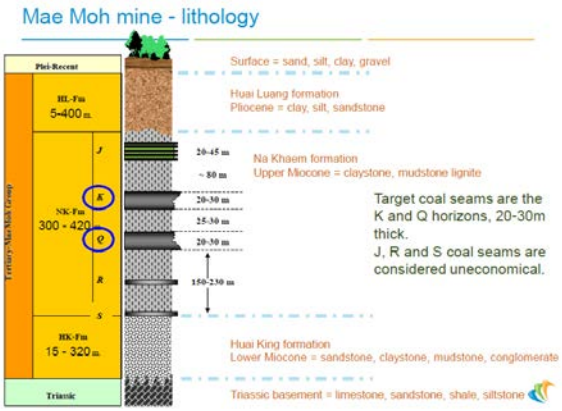

Figure 2 - Geological section at Mae Moh mine.

The stratigraphic sequence of the basin is:

- Superficial gravels and alluvium, this can be thought of as the weathering layer.
- The Huai Luang formation consisting of red claystone. These are up to 400m thick. This is the main overburden layer.
- The Na Khaem formation consisting of grey claystones. This is 300-420m thick and contains several lignite beds including the targeted K and Q seams. (Figure 3).

Figure 3 - K (top) and Q (lower) coal seams at outcrops.

### 2.2 Structural objective

To accurately image faults in the Q and K coals seams from a depth of 100m to 600m below ground surface.

The a priori assumptions in the survey design were:

- Max dip of coal seam is 30-35 degrees, max dip of faults is 60 degrees.
- The targeted coal seams are 20-30m thick. They are separated by 25-30m thickness of inter-burden claystone.
- Legacy boreholes revealed areas where there were no coals, this being due to fault block slippage and rotation along major fault planes.
- The boreholes also revealed that the targeted coal seams get thinner to only a few meters thick towards the heavily faulted no-coal area.

### 2.3 Two fold geotechnical objective

What EGAT are primarily worried about are slope stability problems.

Plotted in Figure 4 are:

- The two coals seams: K (blue) and Q (purple);
- Bedding planes in claystone rock (red);
- Major faults that have previously moved the coal seams relative to the claystone rock.

The two coal seams are currently stopping the claystone slipping downhill along the bedding planes.

The issue is that digging up the coal would create a hole and in case of high water table and monsoonal rains it is possible that the whole claystone rock mass can slip and cause a landslide. This depends on the angle of slope of the faults and bedding planes and the friction properties. Geometrical and structural information brought from the seismic enabled modelling and therefore de-risking the geotechnical planning.

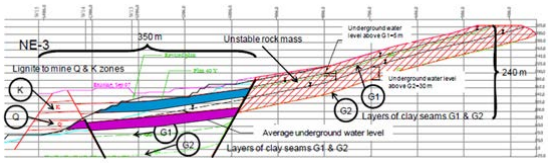


Figure 4 - Representation of the slope stability problem at Mae Moh mine.

Figure 5 is a section across the pit. EGAT want also to better define the characteristic of two main coal seams and their structural geology in the survey area.

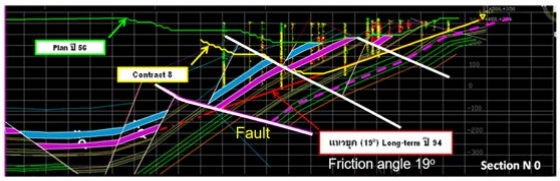


Figure 5 - Section of the pit - green curve is the current elevation profile - yellow curve is the future shape of the pit.

In summary the objectives of the 3D seismic survey is to see if high resolution3D seismic can:

- Accurately image and locate in depth the faults in the coal seams;
- Accurately image and locate in depth the coal seams themselves (top and bottom);
- Improve the safetyof the mining operations through better understanding of the slope stability issues;
- Can we better plan for the future mining operations.

Can we do this better using 3D seismic compared to the existing model using only boreholes?

## 3 CHALLENGES AT MAE MOH LIGNITE MINE / SEISMIC PARAMETERS CHOICE

The design of the 3D campaign started with analysing legacy 2D seismic surveys recorded before the present pits were opened. Three 2D seismic surveys had been previously recorded between 1980 and 1994.

### 3.1 Feasibility study

In order to better understand the challenges facing the seismic survey a feasibility study was first conducted.This took the form of acquiring two 2D seismic lines across the mine open working area.It took place in July 2014.

The feasibility study gave insight into:

- Noise levels due to mine activity;
- The 3D survey geometry design;
- Parameters for seismic energy source effort;
- Operational planning on how to conduct a 3D seismic survey.

### 3.2 Noise due to mine activity

The main challenge to the acquisition of seismic data at Mae Moh mine was the high level of noise associated with the daily mining operations.The main sources of noise identified during the feasibility study were from conveyor belts (Figure 6), excavators and moving dump trucks.The feasibility study showed that good quality seismic data could be recorded, but that the noise levels generated by mining activity were too high and would swamp the reflections being recorded (Figure 7). The best solution was to wait for a period of conveyor belt maintenance when mining activities would temporarily cease in the survey area.

Figure 6 - Conveyor belt source of noise during the seismic campaign.

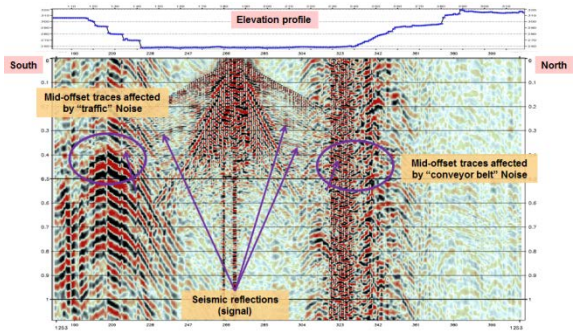


Figure 7 - Noises sources identified: traffic and conveyor belts. The quality of the seismic record is good; however it is dominated by noise coming from the mining activities.

### 3.3 3D survey geometry design

A high resolution seismic survey has to follow these recommendations:

- Short interval distances between energy source points (SPs) and receiver points (RPs). These distances determine the sub-surface spatial resolution.
- Wide azimuth, i.e. a large range of SP-RP azimuth vectors, to ensure proper 3D imaging of the fault network.
- High frequencies in the seismic signal determine the temporal resolution and the ability to delineate thin coal seams.

The area identified by EGAT to focus on covered an area of 0.55km². This demanded an actual surface acquisition area of 3km².

The following geometry was used:

- Distance between energy SPs 10m;
- Distance between RPs 10m;
- SPs and RPs organized in a grid pattern with SP lines being perpendicular to RP lines;
- Distance between parallel SP lines 80m;
- Distance between parallel RP lines 80m.

A total of 4216 SPs and 3704 RPs were used. Note that due to natural obstacles the actual positions of the SPs and RPs had to frequently be moved a few meters from their intended pre-planned locations (Figure 8).

Simulations of the geometry attributes resulting from the moving of the SPs and RPs were performed before the acquisition to make sure that the result agreed with the survey objectives.

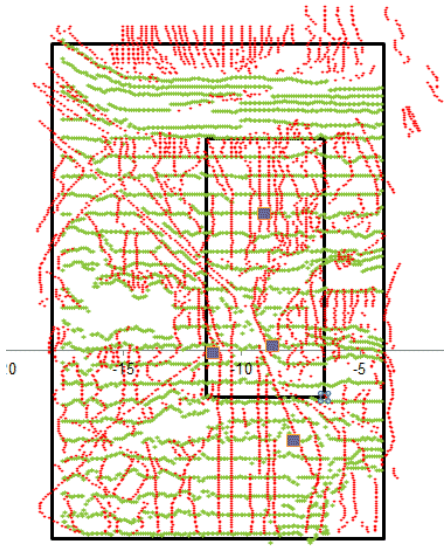


Figure 8 - Location map. SP positions are in red, RP positions are in green.

### 3.4 The seismic energy source

The seismic source selected was a small vibrator mini-buggy (Figure 9). Its light weight (8.4 tons) and small width (2.4m) allows it to access difficult places. Its energy output (15000 lb peak force) is sufficient for the target depth at Mae Moh mine. Unlike dynamite which is a high-impact energy source, vibroseis is a low-impact energy source. The energy was transmitted into the ground over a period of 40s duration in the form of a single vibrator sweep between 8 and 180 Hz. There was a 6dB/oct increase between 60 and 120 Hz to emphasize the high frequencies.

Figure 9 - Vibrator truck operating at Mae Moh mine.

The receiver point (RP) consisted of 6 geophones arranged in a small circle (Figure 10).

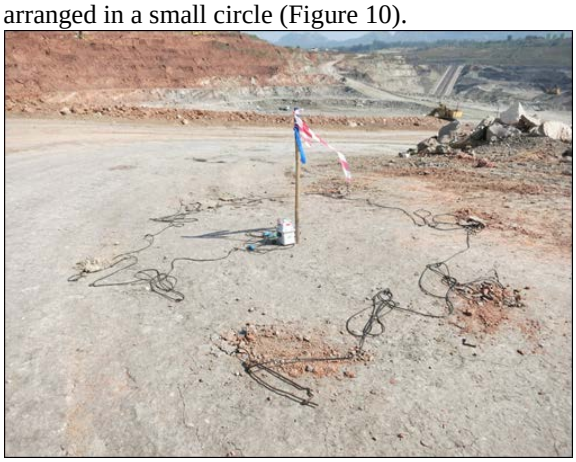

Figure 10 - Receiver point (RP)made of 6 geophones. Each individual geophone is buried to attenuate wind noise.

Acquisition of the 3D survey took place in December 2014. The seismic data recording took place from December 15th, to December 20th, during which period of time the conveyor belt was under maintenance.The whole operation, including mobilization, surveying, laying out of the ground equipment, and demobilization took 5 weeks.

### 3.5 Using the latest acquisition technology

CGG's latest acquisition technology, Independent simultaneous sweeping (ISS), was used to ensure rapid acquisition. This uses a set of 5 autonomousvibrator trucks, each with a different random sweep (seismic waves frequencies are swept randomly between the low and high ends), . This enabled the overlappingin time of the 40 second sweeps between different vibrators. The start time of each sweep is random and controlled by each vibrator. Recording is continuous throughout the day.

Extraction of the individual vibroseis records is done in 2 parts:

- Cross-correlation to extract each vibrator's source record as we have a unique pseudo-random sweep for each vibrator and GPS stamp start time for each sweep;
- Deblending: removing the cross-talk interference from the other vibrators.

### 3.6 Processing challenges

Once the data has been acquired a second challenge is in the processing of the information collected. Main challenges were:

- Noise attenuation (industrial, ground-roll);
- Maintaining sufficient resolution (spatial and temporal) to image the faults and coal seams;
- Sufficient impedance contrast between the lignite and claystone layers to identify the top and bottom of the K and Q coal seams;
- Correct imaging resulting from migration of the coal seams and faults;
- Accurate velocity field for subsequent depth conversion.

The deliverable from the processing stage is a 3D seismic volume in time (two-way reflection time).

Data processing was performed in CGG's Bangkok processing center between January and May 2015.

## 4 INTERPRETATION

Data interpretation took place at GGG's Robertson office in UK between June and August 2015.

### 4.1 Interpretation in time

Figure 11shows a 2D section extracted from the 3D seismic volume. The vertical axis is two-way reflection time. The horizontal axis is either in the x direction or the y direction.

Both the top and base of the K and Q coal seams can be delineated. This is based on the seismic reflections from the top and base having opposite polarities. The section also shows some reflections from the shallower thinner J coal seams.

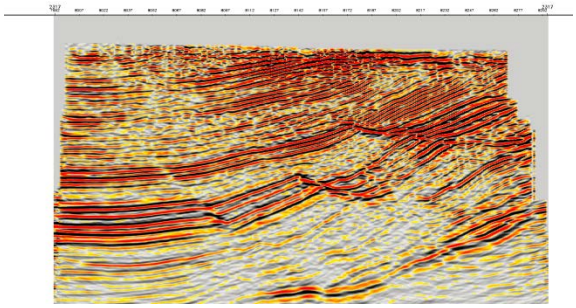

Figure 11– Seismicsection extracted from the 3D volume.

The top of the lignite bed appears as a negative reflection coefficient (red colour) as there is a decrease in acoustic impedance on the claystone-coal interface. The bottom of lignite bed appears as a positive reflection coefficient (black colour) as there is an increase of impedance on the coal-claystone interface (Figure 12).

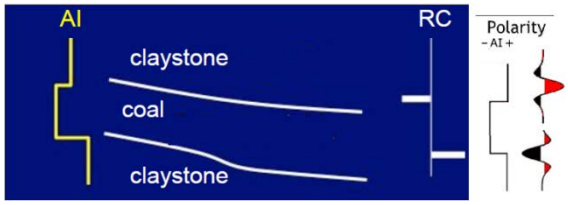


Figure 12 - Seismic polarity and acoustic impedance (AI) value – negative reflection coefficient (RC) gives a positive reflection polarity coded in red – positive RC give a negative reflection polarity coded in black.

The basic steps of an integrated interpretation consist of:

- Study 3D seismic data volume and overview structural trends to generate work map;
- Identify top and base of the K and Q coal seam horizons for structural interpretation;
- Identify and interpret any faults in the coal seams, inter-burden and overburden.

Initial interpretation is done by manual picking the four target horizons along a coarse square grid. This ensures that the horizons tie. Note that picking at this stage is done in the two-way time (TWT) domain.Infill is then done using a horizon fill function that tracks the correct polarity.

Horizons are not interpreted across sections where there are discontinuities due to intersecting faults. These results in gaps in the TWT maps.These discontinuities can also be identified on time slices (Figure 13 lower left). Every horizon is represented on aTWT map with gaps where the horizon is missing (faults, discontinuities) as in Figure 14. These gaps are used to identify three-dimensional fault polygons.

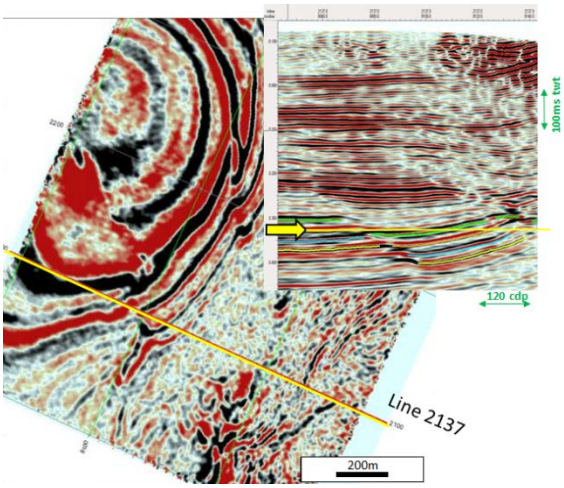


Figure 13 - Discontinuity of a horizon view on time slice at 336ms TWT. Line 2137, marked on the time slice, is displayed as a seismic section in upper right.

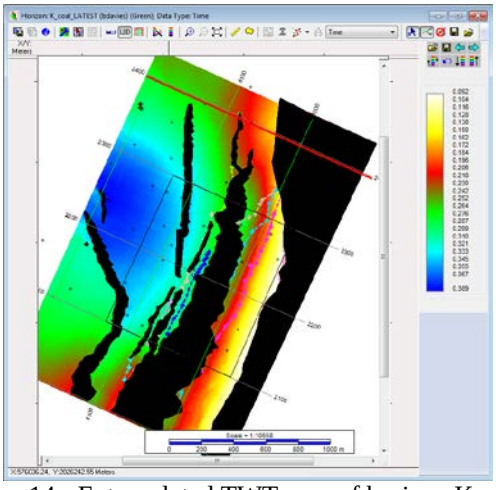

Figure 14 - Extrapolated TWT map of horizon K with fault polygons. The colour scale is horizon depth (in milliseconds of TWT).

## 4.2 Quality control process

There are 3 key points of QC:

- Borehole data – the presence, or absence of coal in the borehole logs is accurately represented on the TWT horizon maps;
- Depth tie –At each calibration borehole the calculated depth of each horizon is checked against the depth in the borehole to make sure that they match;
- Ensure that the interpreted fault planes make geological sense. This is done using 3D visualization tools and attribute maps.

## 4.3 How thin can we see the coal seams?

The limit of vertical resolution depends on:

- Velocity of the seismic waves through the rocks – velocity is dependent on lithology;
- Dominant frequency of the seismic waves, dependent on the seismic parameters and natural ground attenuation. The higher the frequency the better the resolution;
- Quality of the seismic data (signal to noise ratio);
- Acquisition geometry. The denser the grid the better the resolution.

For coals seams thinnerthan the vertical seismic resolution the hanging wall and footwall reflectors appear to merge (Figure 15 –top K and base K east of borehole LM4522C). They tune and these reflectors appear to brighten in amplitude due to constructive interference of the thinning beds. It is hard to resolve the individual horizons and to determine coal seam thickness when the thickness is below the seismic resolution of 7-8m. However, a denser seismic grid (translating into smaller points and lines intervals) would have improved the resolution.

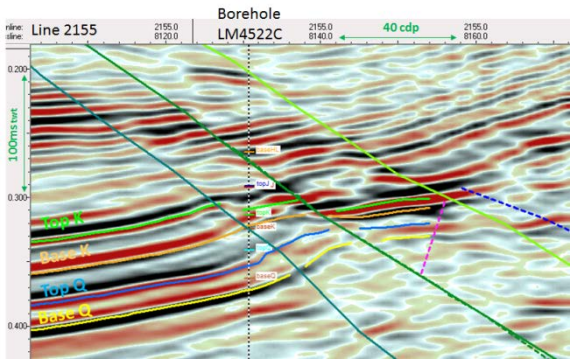


Figure 15 - Line 2155 at intersection with borehole LM4522C - K coal is 12m and Q coal is 24m thick.

The dominant frequency at the Q Coal HW horizon displays variability across the area (Figure 16), with an apparent increase in variability towards the faulted areas. This variation in dominant frequency affects the vertical resolution within these areas.

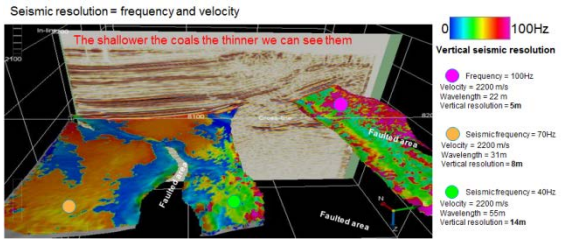


Figure 16 - Q Coal HW: example vertical resolution.

Where the coals are shallow at 100-200m depth the resolution is 5 m; where they are deeper at 600m depth the resolution is 8 m.

### 4.4 Horizon correlation across faults

Horizons can be correlated across faults with some certainty. Correlation becomes challenging when:

- Coal seams thin below the seismic resolution;
- Closely spacing faults dipping in varying directions;
- Deformation of the coals due to drag folding along fault planes.

The seismic in-lines and cross-lines are used in conjunction with the time-slices to assist in determining the dip direction of the faults, in addition to aiding the accurate positioning of fault planes (Figure 17).

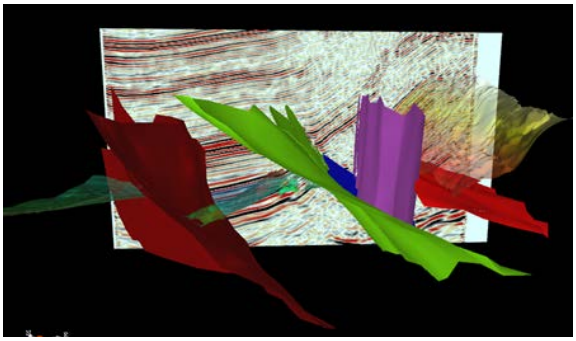

Figure 17 - Eastward dipping faults along inline 2217.

More complex fault geometries involving drag folding and thickness changes are also imaged in the seismic data (Figure 18).

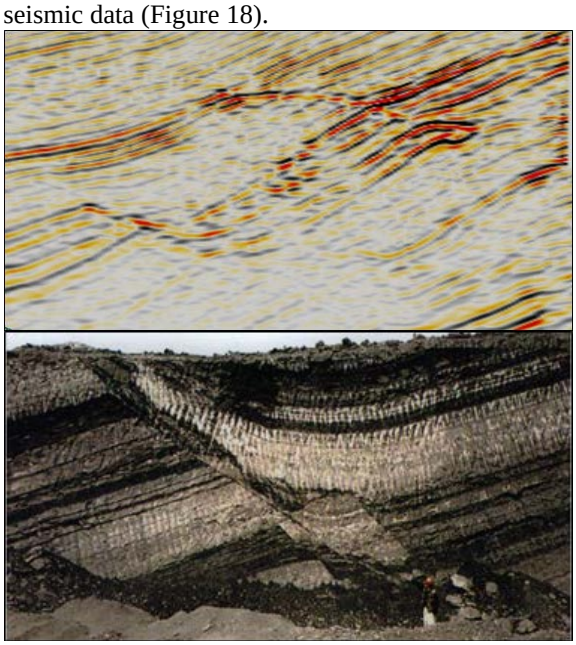

Figure 18 - complex fault geometries seen on seismic section with its analogy on outcrops.

### 4.5 Conversion into depth

Seismic interpretation produces structure maps in two-way time (TWT), which must be converted to depth to be used by geologists and mining engineers.

The fundamental relationship on which the whole process is based is:

(time to travel to horizon) * (velocity) = depth

Required inputs for depth conversion are:

- Two way time maps (the quality/accuracy of the final depth maps depends on the quality of these maps);
- Velocity model that can be created in a wide variety of formats from borehole information (more accurate but are more sparsely sampled) or seismic stack velocities (having the advantage of showing the lateral variations between boreholes);
- Well picks for calibration (and/or well velocities if available).

Different depth maps were made using different velocity models including: uniform velocity, seismic stacking velocity, and seismic stacking velocities scaled in various ways. The velocity model chosen was the one that gave maps with least differences from borehole depths.

Two series of depth maps were calculated, either using all the boreholes or using just the more recent LM-series of boreholes. The LM-series boreholes are exploration boreholes that were drilled between 2012 and 2014. They are deemed more reliable but only cover the western part of the study area. Aversion calibrated to include the older boreholes was also calculated to illustrate possible alternative depths in eastern part of study area.

### 4.6 Example of isobaths map for Top K coal layer.

Top K coal horizon seismic velocity range is 1990 m/s to 2400 m/s, typical values for coal, shales and sands. If the velocity model was correct, the final depth maps should intersect the boreholes at the measured depth for the Top K coal horizon. When it is not the case, a correction factor is applied to the seismic velocity model. Reasonable corrections range from 5-10% but may be higher depending on local geology. Final differences between boreholes and depth map for Top K Coal range from 0.38 m to -0.35 m (Figure 19).

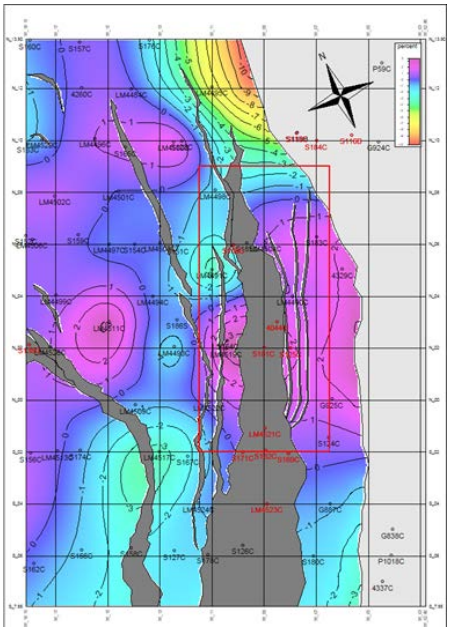

Figure 19 -Top K coal layer - difference in % between borehole depth and calibrated isobaths map.

There are no major bullseyes or other artefacts from the calibration process, suggesting that the underlying interpretation and velocity models are satisfactory for the Top K coal isobaths map (Figure 20).

This conversion to depth has been done for the top and base of both the K and Q coal horizons.

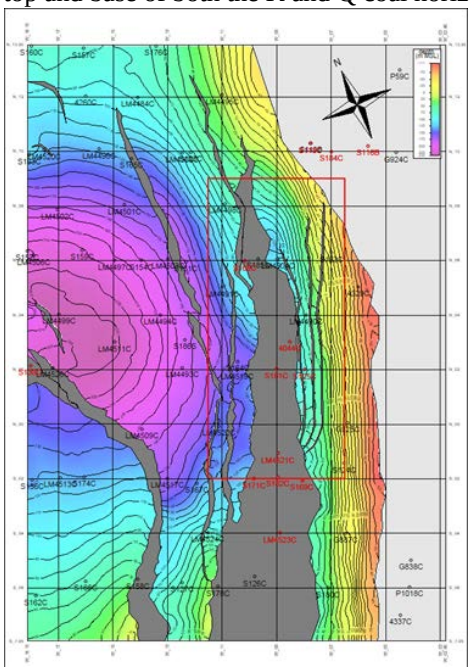

Figure 20 - Top K coal layer - isobaths map.

### 4.7 Mapping the thickness of the coal seams

Subtracting the top isobath map from the base isobath map yields the thickness of the coal seams. From this the volume of the coal seams can be determined. Note that the thickness of the coal seams is not guaranteed where it drops below the seismic resolution limit.

### 4.8 Synergy between boreholes and seismic

The absence of reliable boreholes where the coals rise up shallow in the east of the survey area makes the accuracy of their isobath depth determinations uncertain. The seismic data set will also help on deciding additional bore-holes location, which will be used to strengthen the depth model.

### 4.9 Interpretation deliverables

For each of the 4 interpreted horizons the following were produced:

- TWT map
- Seismic velocity map
- Depth map (isobath)
- Amplitude map

Isopach maps (thickness maps) were also produced for the K and Q coal seams.

## 5 CONCLUSION

The coal seams and a large number of structural features have been successfully imaged by the high-resolution 3D seismic survey.

In the majority of the study area, both the top and base horizons of the K and Q coals are resolvable.

Within the westerly area the coals are easily correlated and the structures present are clearly resolvable. Located within this area are some of the best borehole to seismic correlations within the study area.

Towards the densely faulted central area the coals appear to thin below the resolvable limit and their presence is therefore difficult to correlate and interpret.

The interaction of the three eastward dipping faults and a westward dipping fault are the key controls on the no coal area. Their interaction creates the structurally most complex and most difficult to interpret area within the survey.

## 6 VALUE OF THE SEISMIC

The geologist and geotechnical staff of Mae Moh mine are using indirectly the seismic dataset as a guide for checking, by drillholes, the location accuracy in depth of the coal seams and the characteristics of fault orientation. The information from these drillholes can be used to update and improve the current seismic model.

EGAT's plan now is to develop the open pit on the down-dip side in the central part of the basin. The seismic survey has resulted in better images of the shallow geological structures and coal seams. EGAT has had to re-design the slope angle for pit slope stability

The seismic dataset has provided cost optimization especially in terms of the greenfield area. For Mae Moh coal mine, this survey was sufficiently reliable in its accuracy to help manage decision making for the mine development.