SUBSIDENCE PREDICTION REPORT FOR THE MEADOWBROOK UNDERGROUND PROJECT

Prepared for Lake Vermont Resources Pty Ltd

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TABLE OF CONTENTS

List of Figures

List of Abbreviations

ALPS - Analysis of Longwall Pillar Stability
ASL - Above Sea Level
EIS - Environmental Impact Statement
FLAC - Fast Lagrangian Analysis of Continua
GGPL - Gordon Geotechniques Pty Ltd
GSI - Geological Strength Index
LOMS - Limit of Measurable Subsidence
SDPS - Surface Deformation Prediction System
S_{max} - Maximum Subsidence

Glossary

Angle of Draw	The angle of inclination from the vertical of the line connecting the goaf edge of the underground workings and the limit of measurable subsidence.
Aquifer	A saturated, permeable, geologic unit that can transmit significant quantities of ground water under ordinary hydraulic gradients and is permeable enough to yield economic quantities of water to wells.
Chain Pillar	The block of coal left unmined between the longwall extraction panels.
Compensation Width	Distance from the rib edge to the inflexion point or point of half the maximum subsidence.
Empirical	Based or acting on observation and experiment, not on theory.
Floor	Strata immediately below the extracted seam.
Goaf	That part of a mine from which the coal has been partially or wholly removed.
Groundwater	The supply of fresh water found beneath the ground surface, usually in aquifers, which supply wells and springs.
Hydrogeology	The branch of geology dealing with the waters below the earth's surface and with the geological aspects of surface waters.
Influence Function	A type of function used to solve inhomogeneous differential equations subject to specific initial conditions or boundary conditions.
Longwall Mining	A form of underground coal mining where a face of coal is mined in a single slice.
Maingate	The gateroad in which the longwall panel conveyor is installed.
Modulus	The ratio between applied stress and resultant strain.
Overburden	Sequence of strata above the extracted seam.
Pillar	Coal that is not extracted within the underground workings.
Roof	Strata immediately above the extracted seam.
Stratigraphy	A branch of geology that studies rock layers and layering. It is primarily used in the study of sedimentary and layered volcanic rocks.
Subsidence	Sinking or settlement of the land surface, due to any of several processes. As commonly used, the term relates to the vertical downward movement of natural surfaces although small-scale horizontal components may be present. The term does not include landslides, which have large-scale horizontal displacements, or settlements of artificial fills.

Strain	Relative change in the volume, area or length of a body as a result of stress. The change is expressed in terms of the amount of displacement measured in the body divided by its original volume, area, or length, and referred to as either a volume strain, areal strain, or one dimensional strain, respectively. The unit measure of strain is dimensionless, as its value represents the fractional change from the former size.
Tailgate	Roadway on the other side of the longwall panel to the Maingate.
Tilt	The rate of change in vertical subsidence between two points divided by the horizontal distance between those two points.
Voussoir Beam	A single beam with vertical joints.

1 INTRODUCTION

Gordon Geotechniques Pty Ltd (GGPL) was commissioned to complete a subsidence assessment as part of the Environmental Impact Statement (EIS) being prepared for the Meadowbrook underground project.

1.1 Project Description

The Meadowbrook underground area is located north of the operating Lake Vermont open cut, in the northern part of the Bowen Basin in Central Queensland (**Figure 1**). The project involves the extraction of both the Leichhardt Lower and Vermont Lower seams using longwall mining methods.

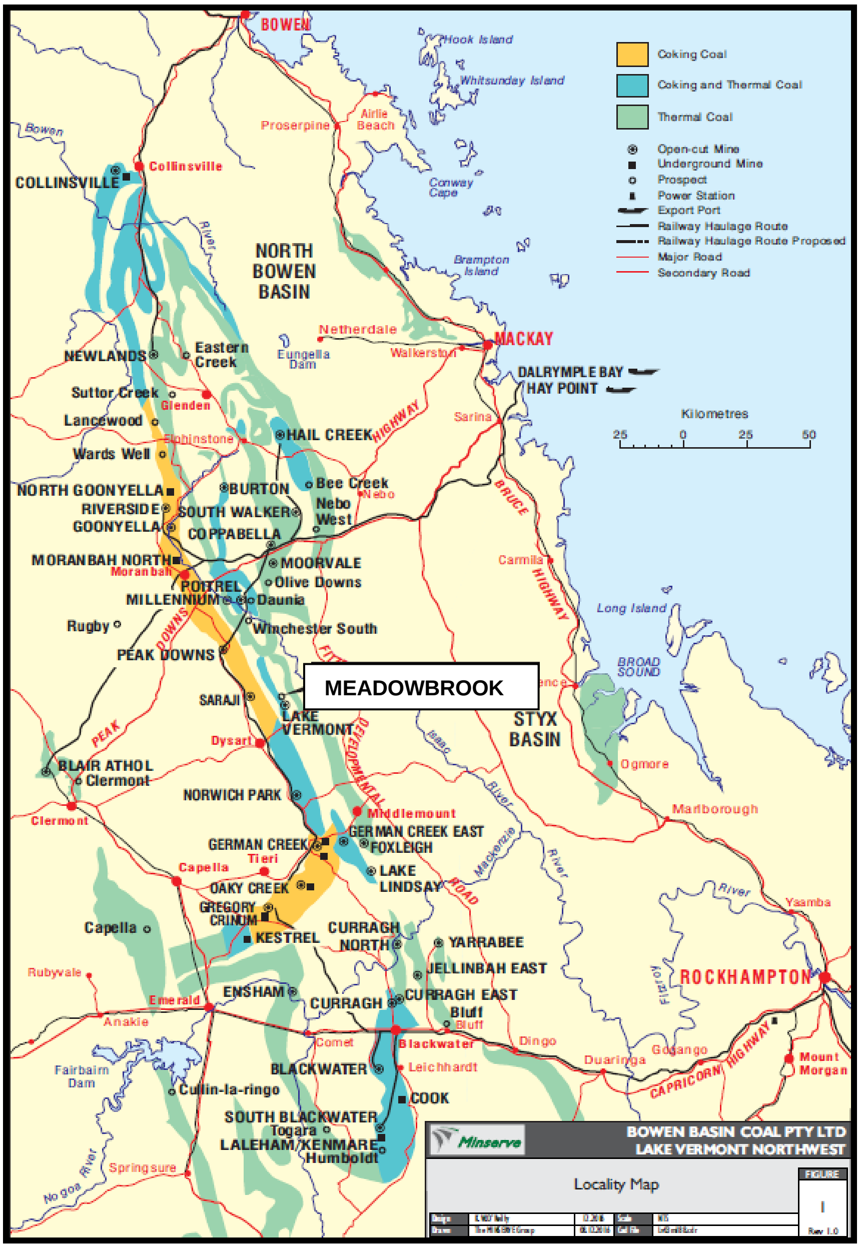


Figure 1. Location Plan (Minserve, 2017).

1.2 Scope of Work

This assessment includes the development of subsidence predictions and an assessment of subsidence effects for the Meadowbrook longwall mining operations, in both the Leichhardt Lower and underlying Vermont Lower seams (**Figure 2**).

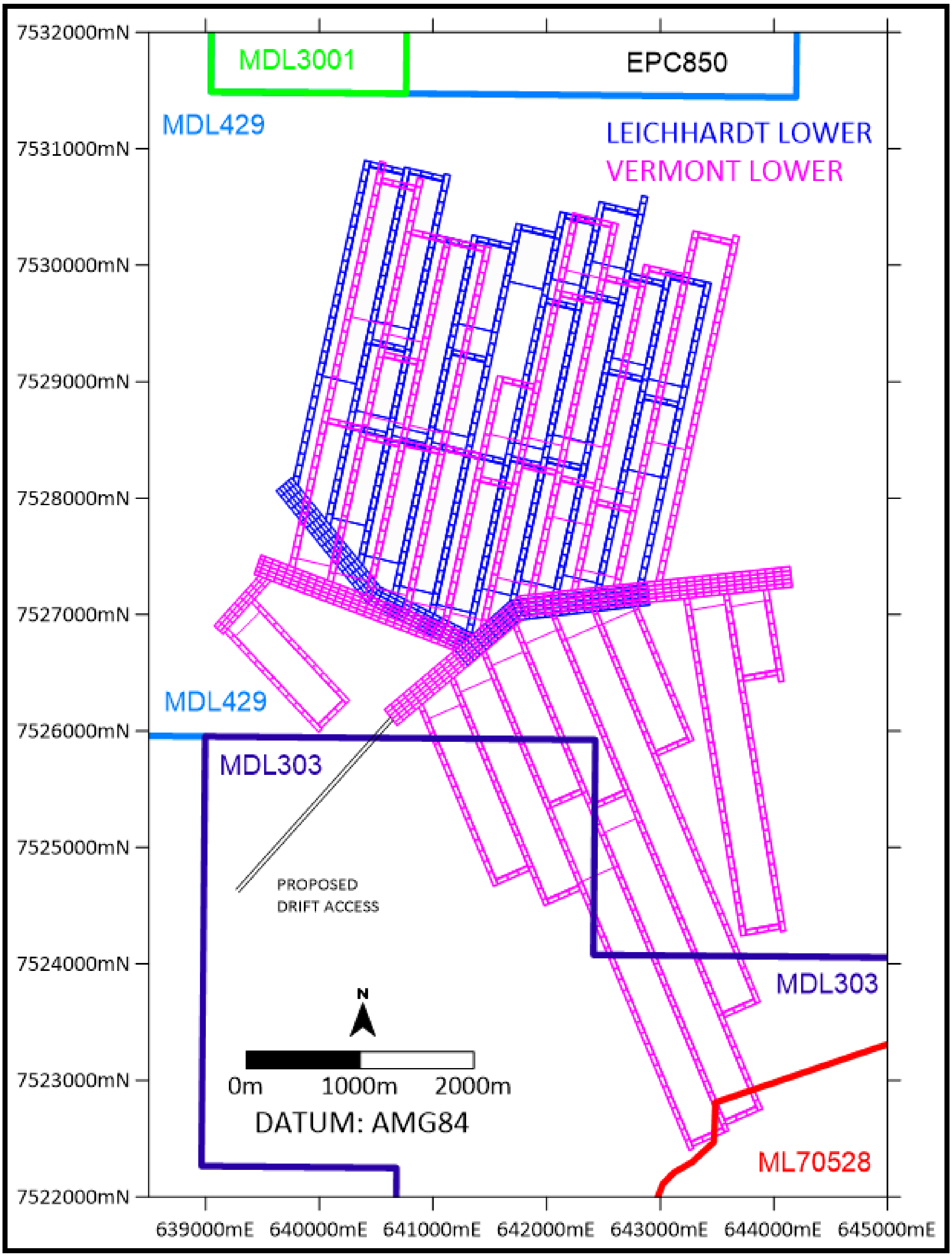


Figure 2. Longwall Panel Layout.

The specific scope of work includes:

- Description of the local geology and mine plan as they relate to the subsidence predictions.
- Detailed description and justification of the subsidence prediction methodology and any associated limitations.
- Subsidence modelling using the influence function methods, as implemented in the SDPS subsidence program, to visualise the resulting subsidence bowl of the longwall extraction and produce surface subsidence contours.
- Description of the predicted subsidence effects including:
    - The magnitude and nature of the subsidence predictions including vertical subsidence, horizontal movement, strains and tilts.
    - The nature and extent of predicted surface cracking.
    - The nature and extent of subsurface strata cracking, including comparisons with experience from other longwall mines.
    - Potential for hydraulic connectivity to the surface due to subsurface cracking.

1.3 Mine Layout

Longwall extraction is planned in both the Leichhardt Lower Seam and underlying Vermont Lower Seam (**Figure 2**). The majority of longwall panels in the Leichhardt Lower Seam are 310 m wide (solid dimension of coal). Three panels have been narrowed to 270 m wide (solid dimension) to maximise recovery between the faults. The chain pillars in the Leichhardt Lower Seam are 45 m wide (solid).

In the Vermont Lower Seam, the panel width is also 310 m (solid), except in the two narrower 290 m wide (solid) panels in the northern part of the area. In the deeper area north of the Mains, the solid dimension of the chain pillars is 45 m (**Figure 2**). In the shallower southern part of the area, 35-40 m (solid) chain pillars have been used.

1.4 Topography

The surface topography in the Meadowbrook underground area is flat to gently undulating grazing country, with seasonal watercourses of various sizes (Minserve, 2017). The northeast flowing ephemeral Phillips Creek is the most prominent creek in the area (**Figure 3**).

Other ephemeral watercourses include the northeast flowing One Mile Creek and the east flowing Boomerang Creek (**Figure 3**). These creeks are tributaries of the Isaac River, which runs north-south to the east of the Meadowbrook underground area.

The surface between Phillips Creek and Boomerang Creek, is a broad, flat floodplain that slopes gently to the east from approximately 180 m ASL in the western part of the area, to around 170 m ASL in the eastern part of the area (**Figure 3**).

Boomerang Creek runs to the south of an east-west to northwest-southeast trending ridge, which is up to 20 m high (**Figure 3**).

The proposed longwall layout will subside both Boomerang and One Mile Creeks (**Figure 3**). An industry accepted standard 26.5º angle of draw has been applied to the southern Vermont Lower Seam longwall panels to ensure that longwall extraction does not affect Phillips Creek (**Figure 3**).

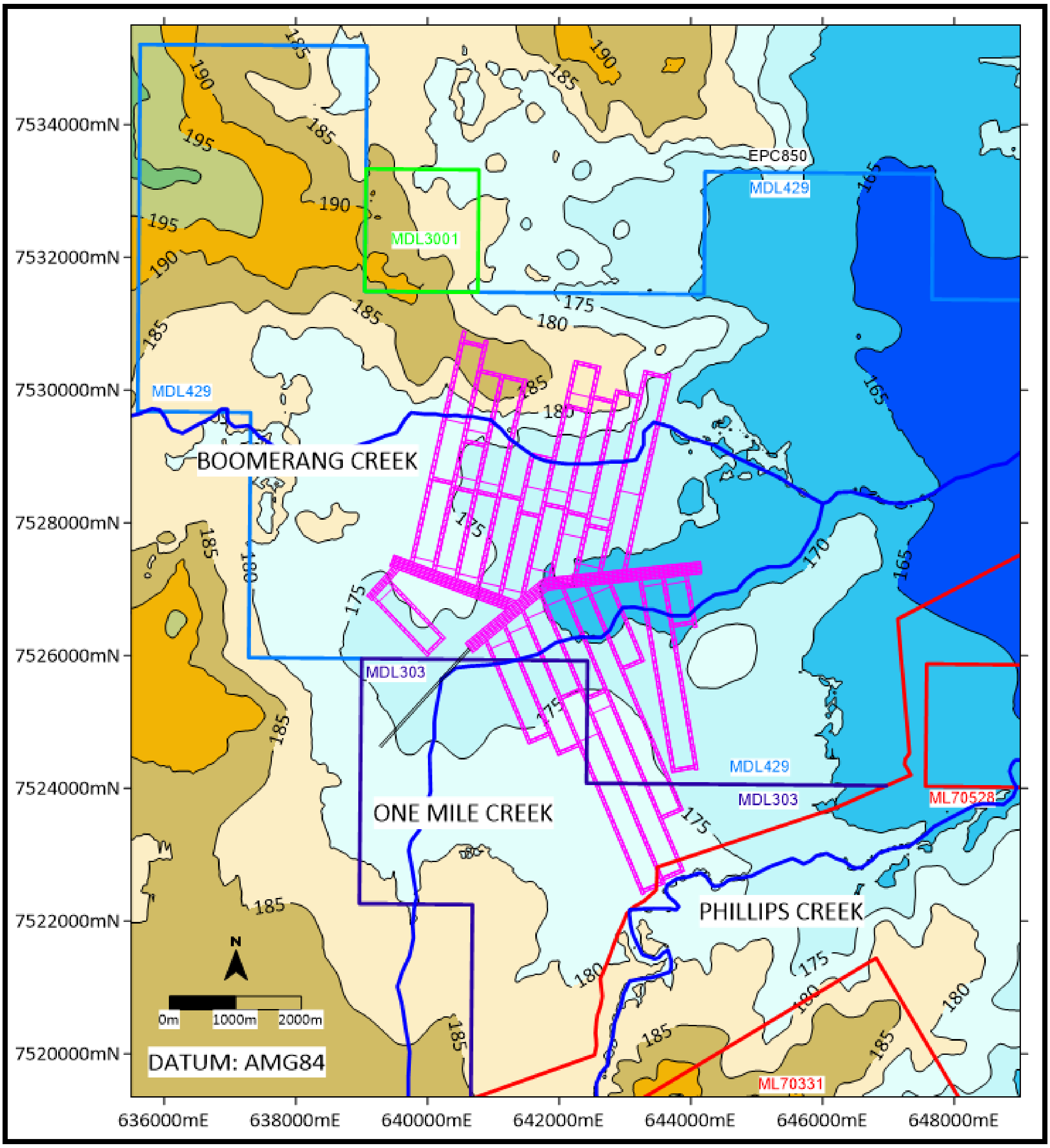


Figure 3. Surface Topography (m ASL).

1.5 Report Structure

Section 1 of this report introduces the project, including the Meadowbrook longwall layout, and the project setting.

Section 2 details the engineering geology, stratigraphy, depth of cover and coal seam thickness.

Sections 3, 4 and 5 describe the subsidence assessment methodology, subsidence predictions and potential subsidence effects of the project, respectively.

Section 6 provides the key conclusions of the subsidence assessment.

The draft version of this subsidence assessment has been peer reviewed by Dr Ross Seedsman of Byrnes Geotechnical Pty Ltd (2022). Where applicable, additional comments from this peer review have been appended to the finalised version of this subsidence report.

2 ENGINEERING GEOLOGY

2.1 Geological Data

The Meadowbrook longwall mining area is covered by closely spaced drill holes undertaken as part of successive exploration drilling programs, as shown in **Figure 4**. The most recent 2020 and 2021 exploration holes are coloured blue and purple respectively to distinguish them from the previous drilling coloured red (**Figure 4**).

These drill holes record the geological sequence of the overburden and coal seams, as well as the sediments immediately below the target seams.

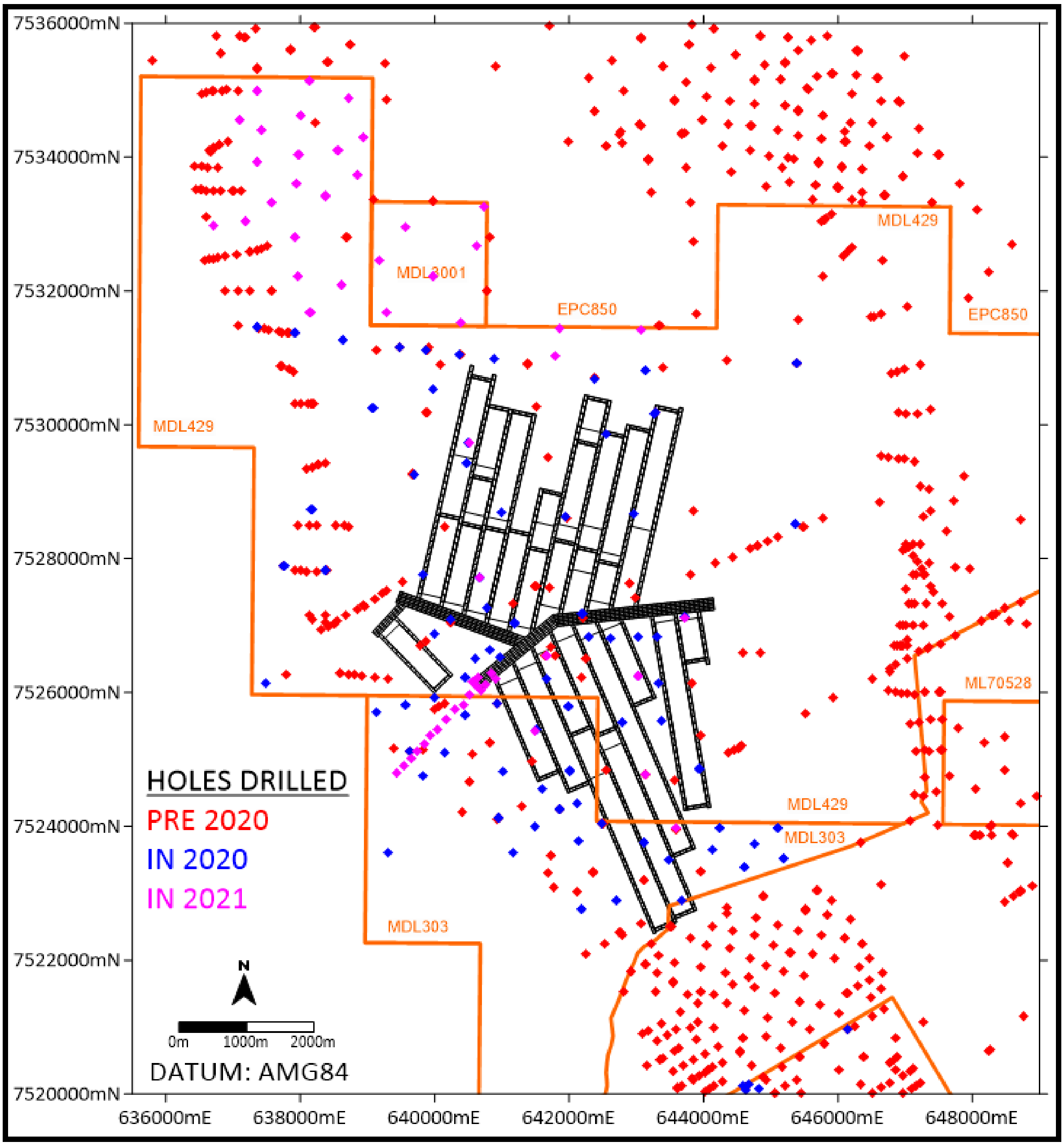


Figure 4. Location of Exploration Boreholes.

Geophysical logs are also available in the majority of the boreholes and provide additional data on the rock and coal seam properties. This density of data provides a high level of confidence in the geological variables used as inputs into the subsidence models for the Meadowbrook longwall mining area.

The exploration borehole drilling is supplemented with both 2D and 3D seismic surveys that have been carried out across the Meadowbrook area over the years (**Figure 5**). The 3D seismic surveying of almost the entire proposed longwall mining area was completed in 2020 (**Figure 5**).

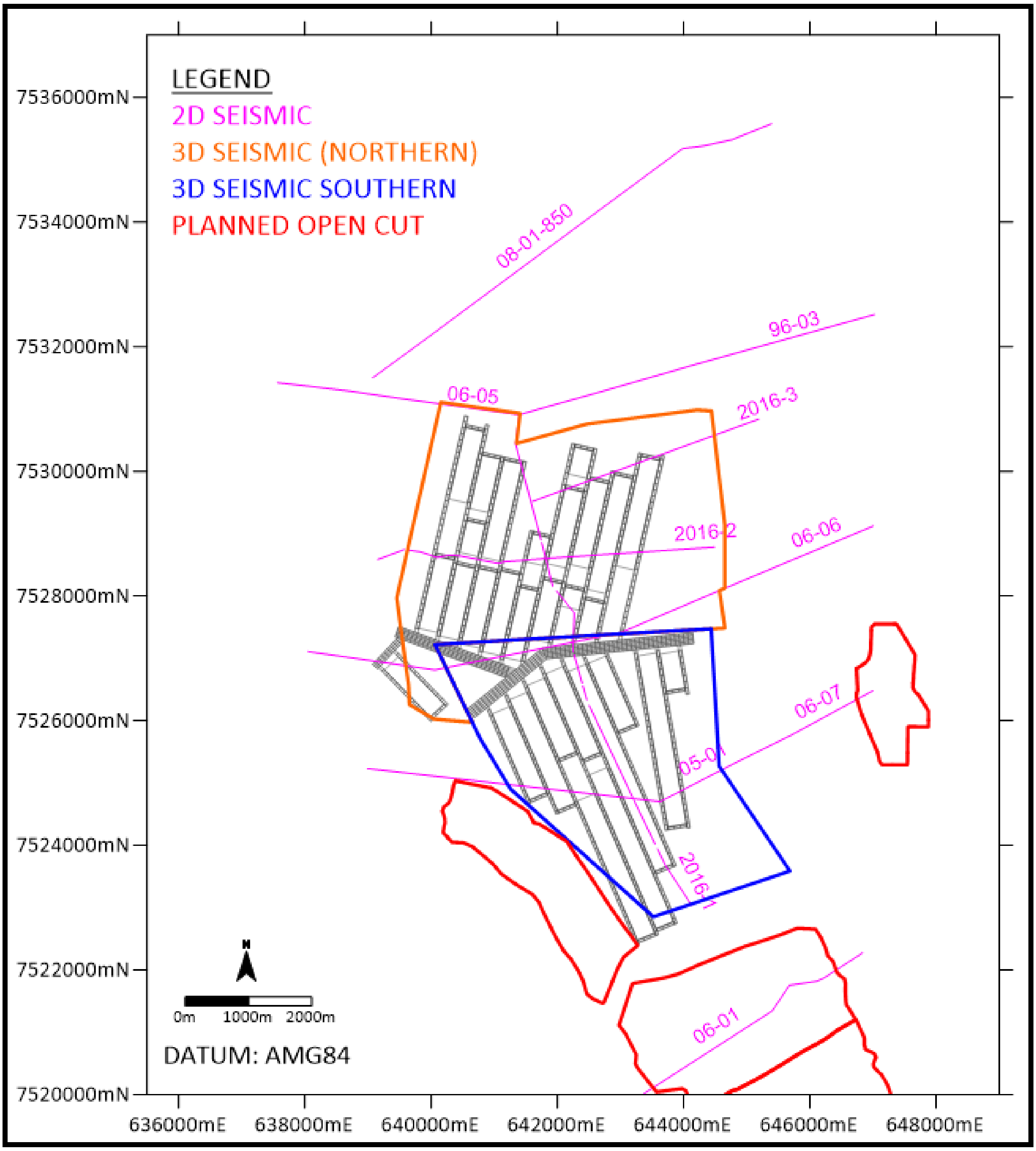


Figure 5. Seismic Coverage.

2.2 Geology Overview

2.2.1 Stratigraphy

The Meadowbrook underground area is located on the western limb of the Bowen Basin adjacent to the boundary between the Collinsville Shelf and the Nebo Synclinorium (**Figure 6**).

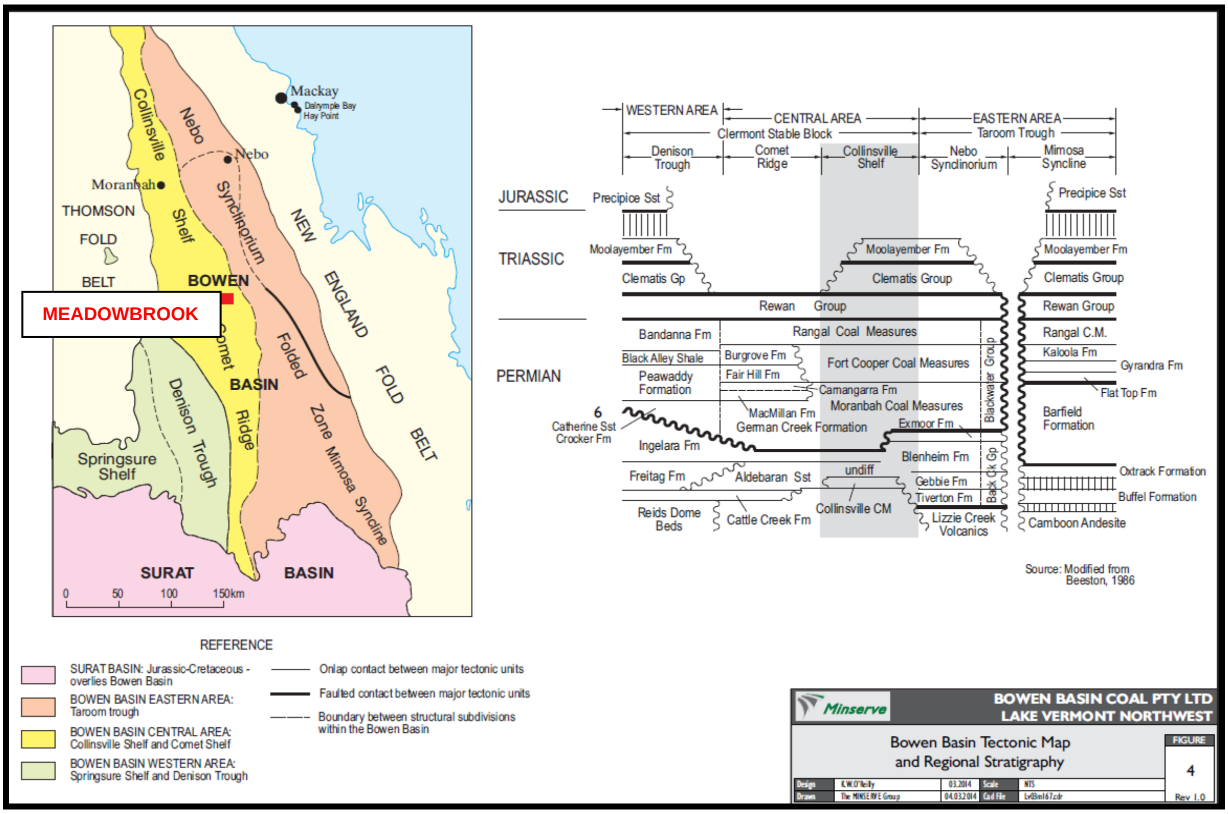


Figure 6. Regional Stratigraphy (Minserve, 2017).

The stratigraphic sequence in descending order is (**Figure 7**):

- the Tertiary sands and clays,
- the non-coal bearing Rewan Formation,
- the Rangal Coal Measures and
- the Fort Cooper Coal Measures.

The target seams in the Rangal Coal Measures are the Leichhardt Lower Seam in the northern part of the underground area and the Vermont Lower Seam in both the northern and southern part of the area (**Figure 2**).

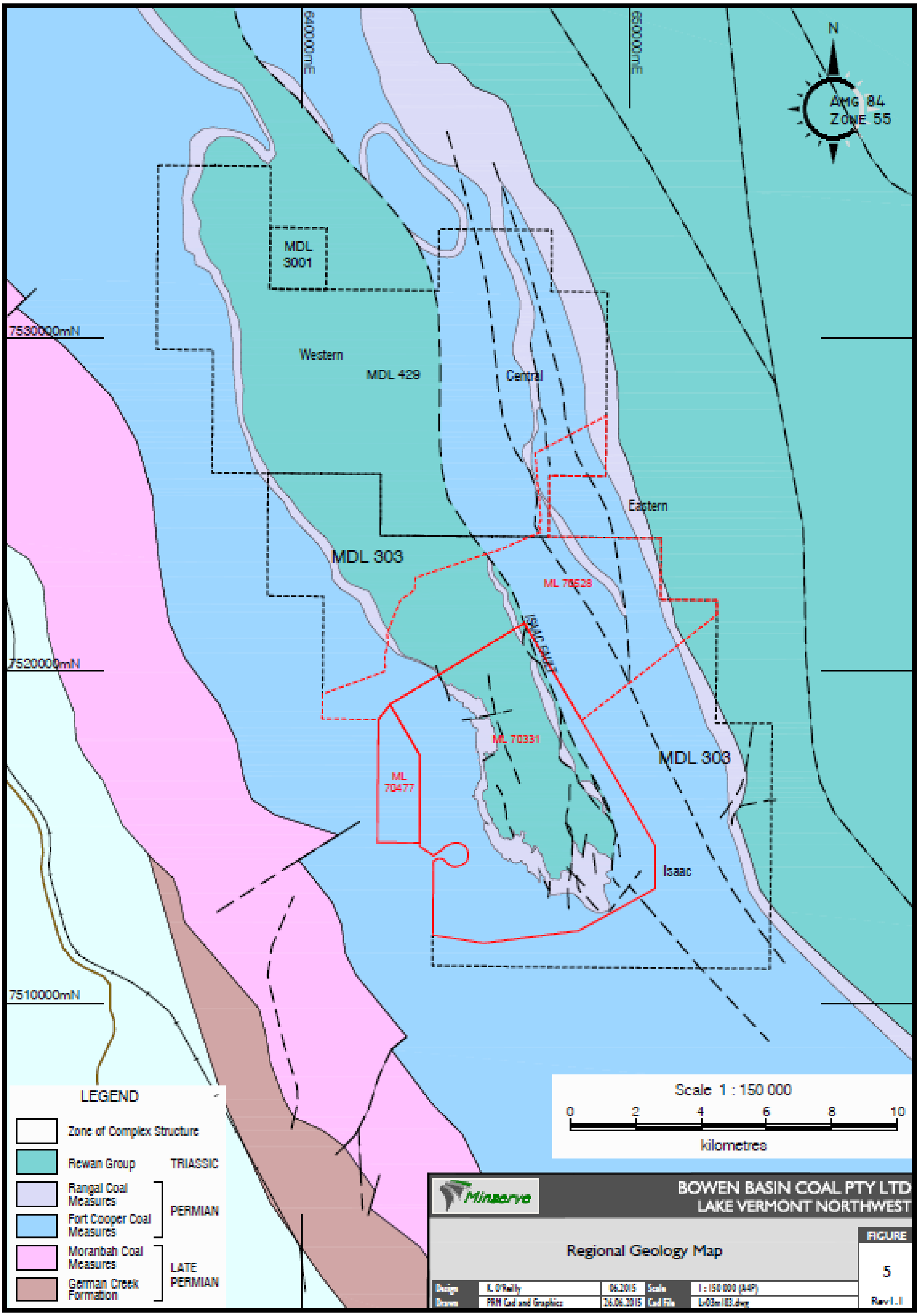


Figure 7. Regional Geology Map (Minserve, 2017).

2.2.2 Depth to Weathering

The weathering profile includes the Tertiary sands and clays, as well as weathered Permian strata. The depth of weathering is typically between 50 to 70 m above the northern Vermont Lower Seam longwall panels, decreasing to <50 m over the southern panels (**Figure 8**).

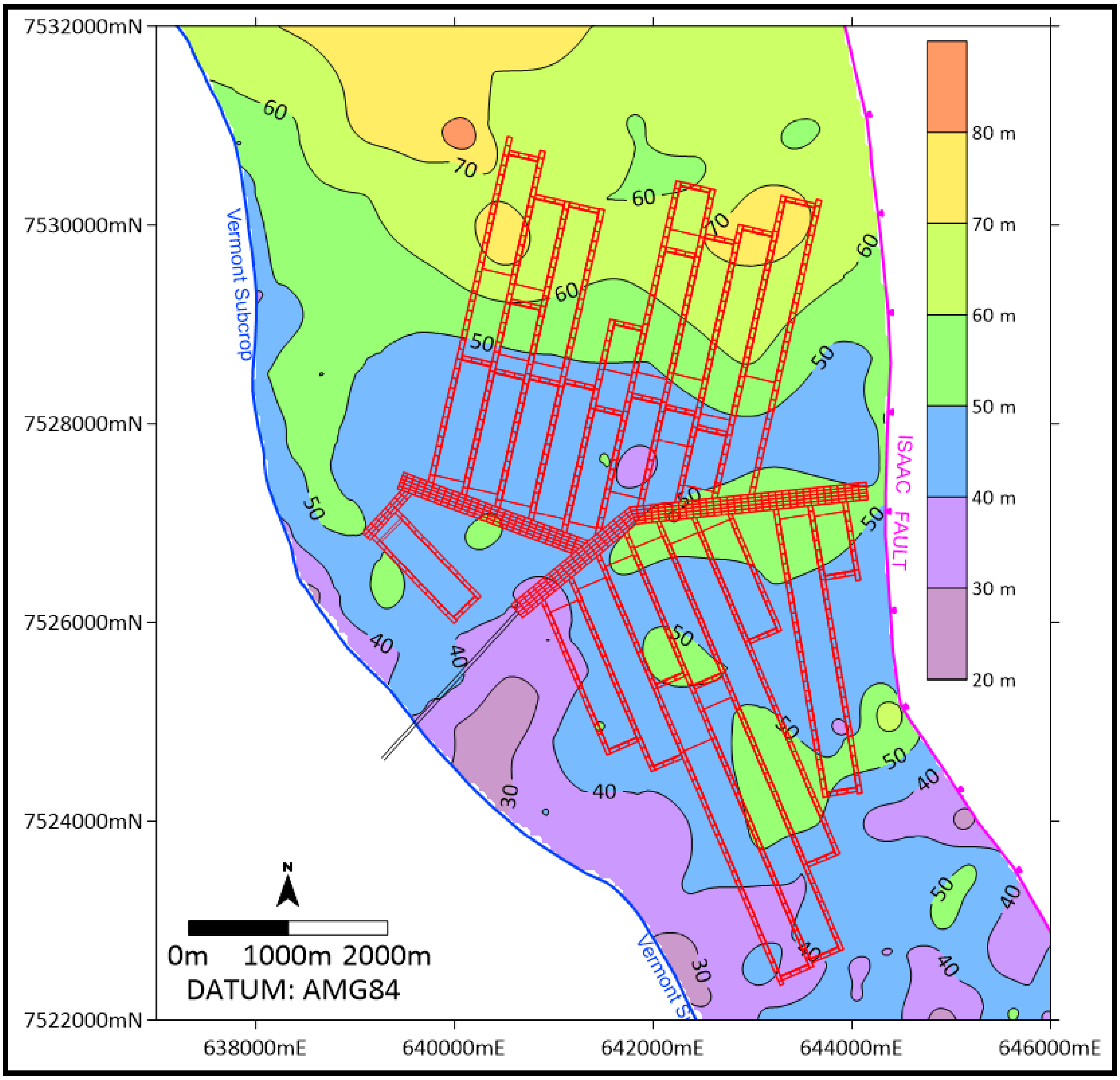


Figure 8. Depth of Weathering (m).

2.2.3 Tertiary

The Tertiary sediments are up to 70 m thick in the northern part of the Meadowbrook underground area and thin towards the south (**Figure 9**). Over the southern part of the area, the Tertiary thins to 10-20 m.

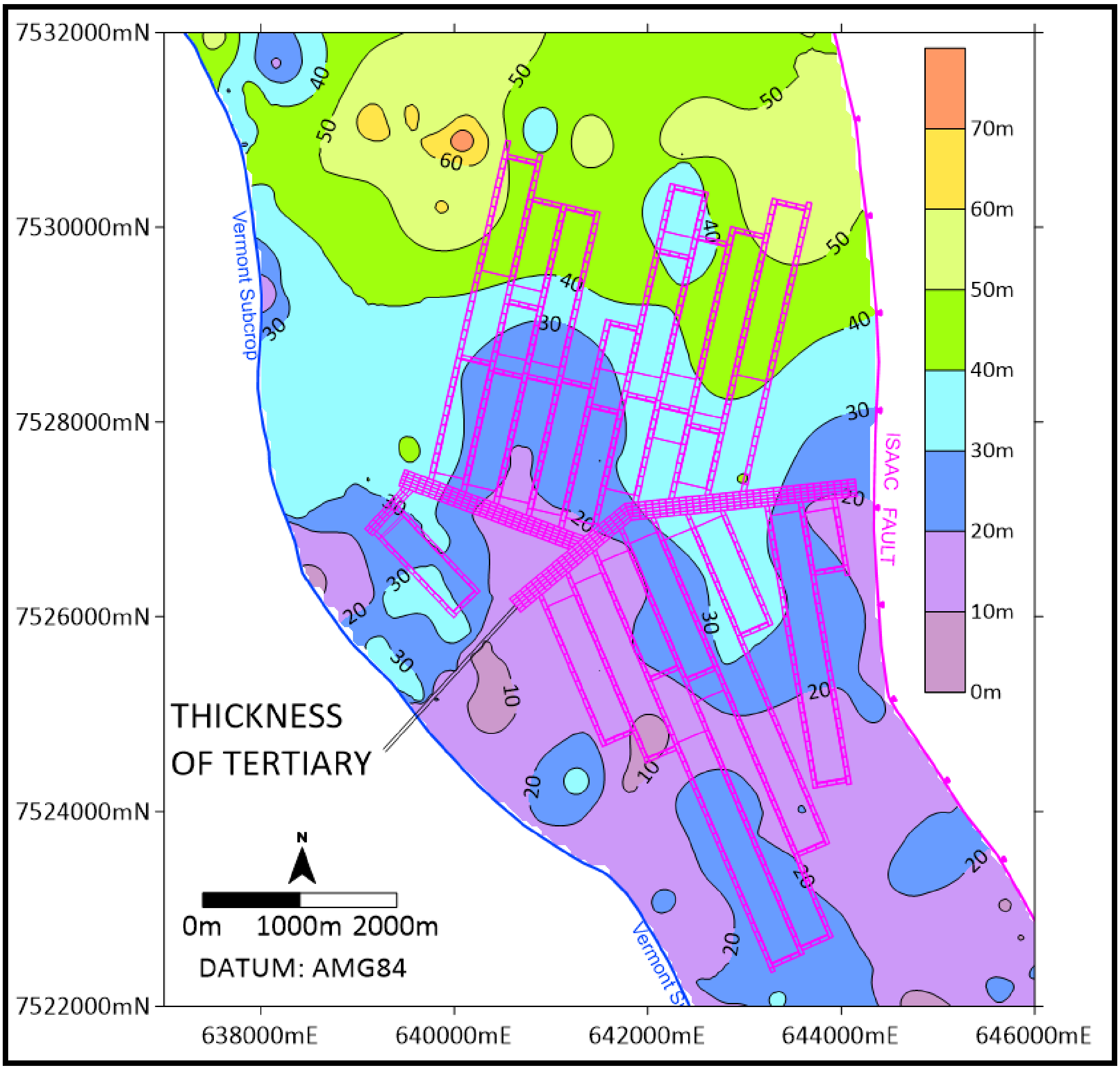


Figure 9. Thickness of Tertiary Sediments (m).

2.2.4 Rewan

The sandstone/siltstone sequence of the Rewan Group thickens to more than 320 m in the deeper northern part of the proposed Vermont Lower Seam longwalll area (**Figure 10**).

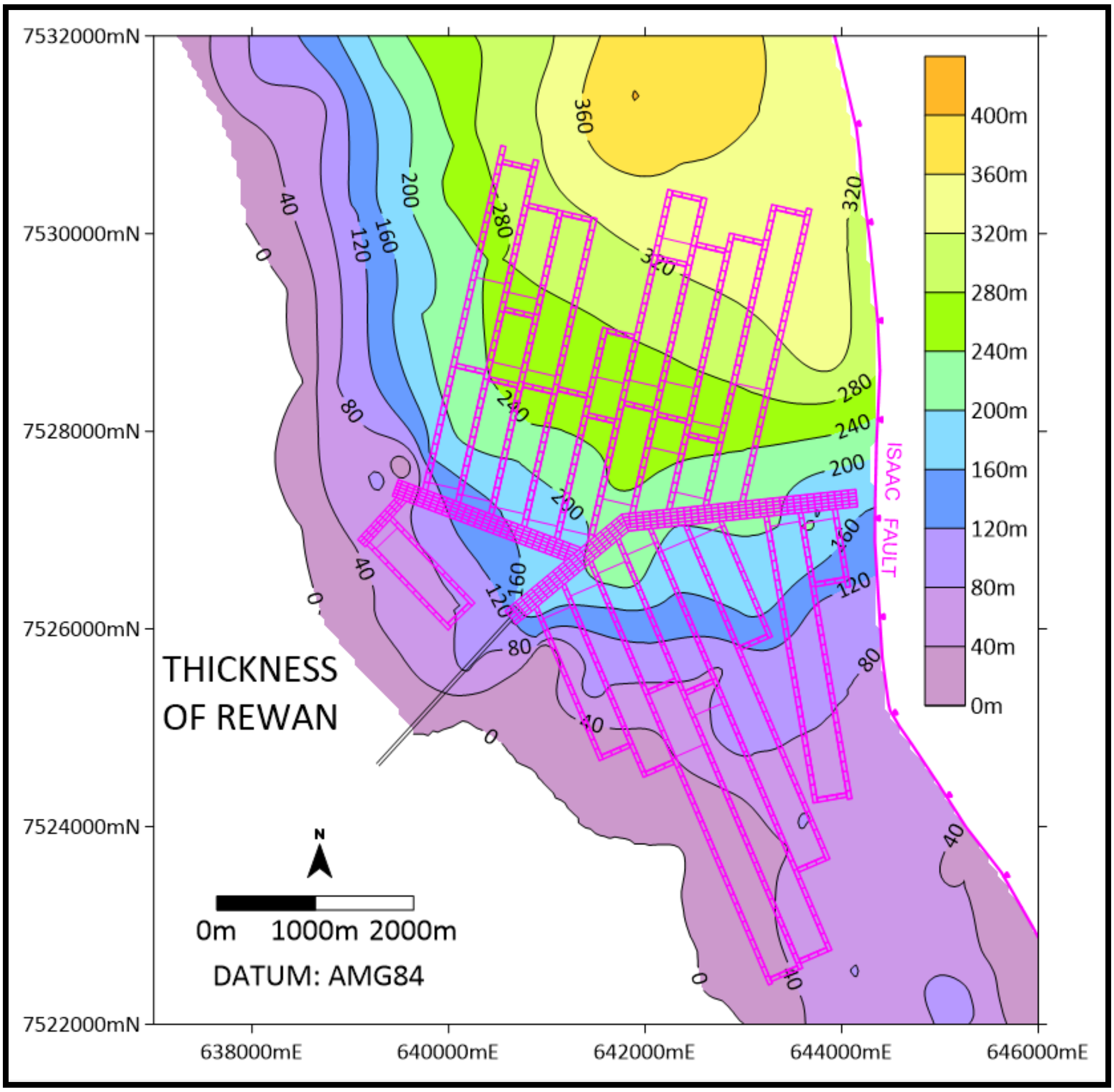


Figure 10. Thickness of Rewan Sediments (m).

2.2.5 Permian Coal Measures

2.2.5.1 Seam Thickness

In the Meadowbrook underground area, the Leichhardt Lower Seam is typically 3.5-5 m thick (**Figure 11**). This seam thickens quite quickly northwards from where it first occurs in the central part of the area.

In the Vermont Lower Seam longwall area, the thickness is typically 3-4.5 m and shows an increasing thickening trend from west to east (**Figure 12**).

In the western part of the area near the subcrop, the Vermont Lower Seam splits into the VL1 and VL2 plies (**Figure 12**). In the north and north-western part of the area, the Vermont Lower Seam thins due to the upper Vermont Rider ply splitting away (**Figure 12**).

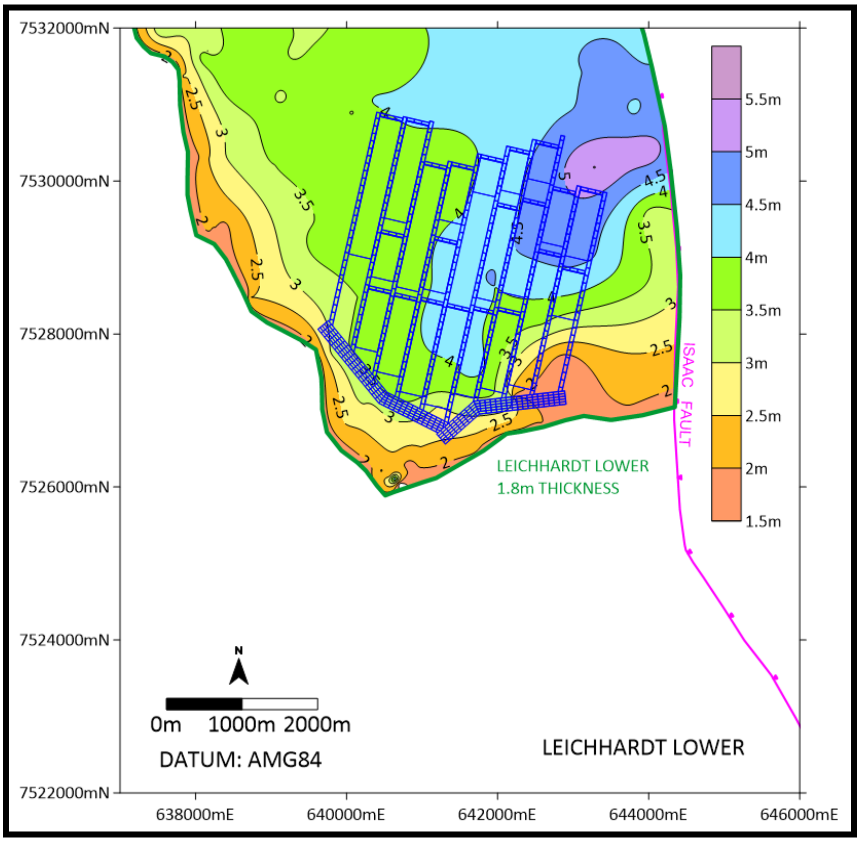


Figure 11. Leichhardt Lower Seam Thickness (m).

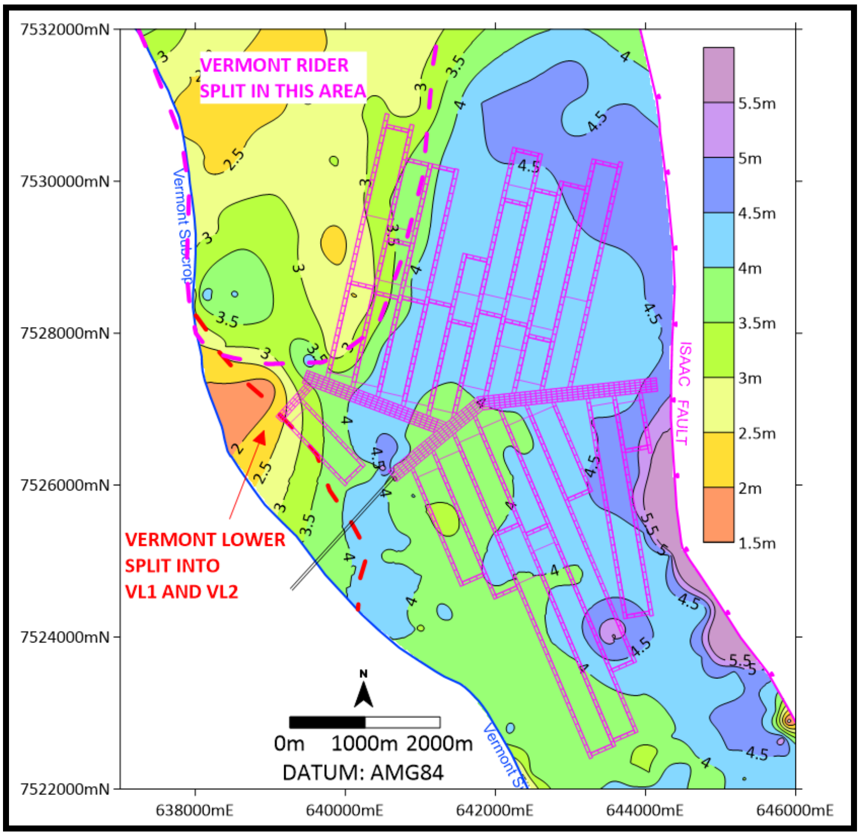


Figure 12. Vermont Lower Seam Thickness (m).

2.2.5.2 Depth of Cover

The Leichhardt Lower Seam occurs at depths from 250 m in the western part of the area and approaching 500 m in the north-eastern corner of the Meadowbrook underground area (**Figure 13**).

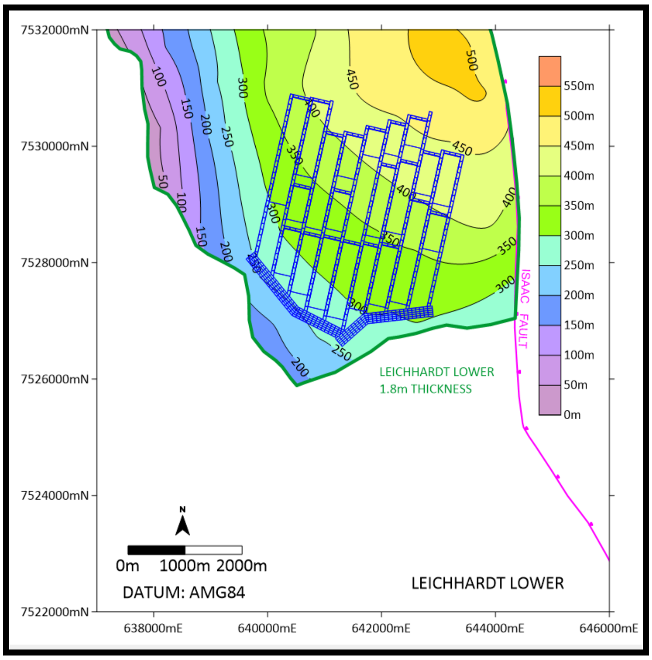


Figure 13. Leichhardt Lower Seam Depth of Cover (m).

The Vermont Lower Seam occurs at depths greater than 500 m in the north-eastern corner of the longwall area (**Figure 14**). In the southern part of the proposed longwall area, the depths decrease to <150 m (**Figure 14**).

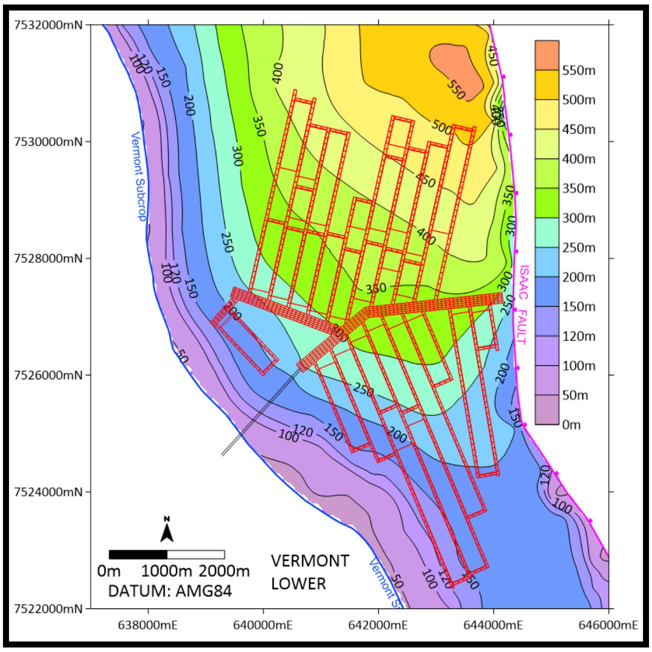


Figure 14. Vermont Lower Seam Depth of Cover (m).

2.2.5.3 Interburden Thickness

The interburden between the Leichhardt Lower and the Vermont Lower seams is typically 20-30 m in the proposed mining area (**Figure 15**). To the northwest, the interburden thins locally to <20 m (**Figure 15**).

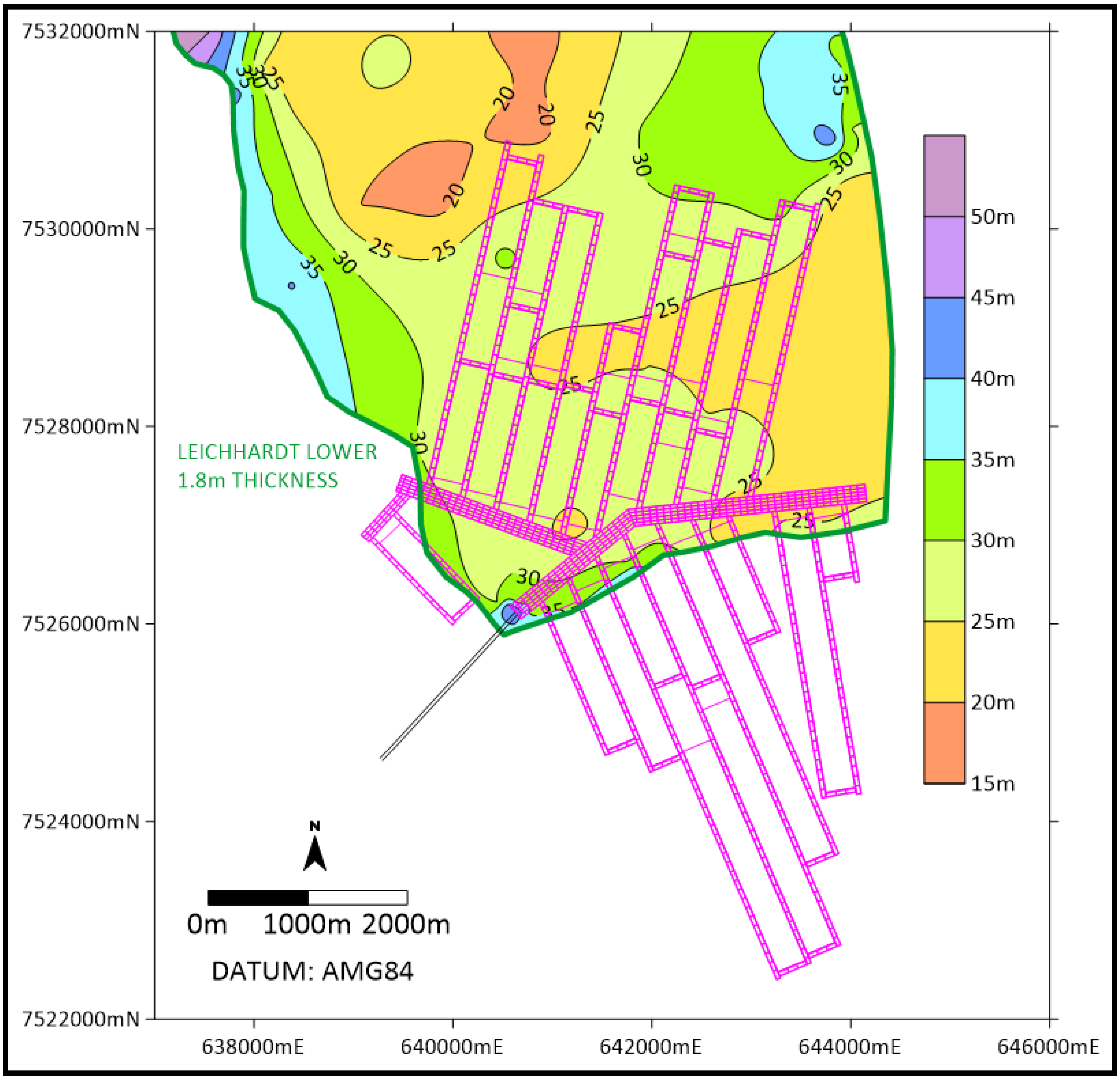


Figure 15. Interburden Thickness between Leichhardt Lower and Vermont Lower Seams (m).

2.2.5.4 Seam Levels

Both target seams dip more steeply near the subcrop in the western part of the area, at around 1 in 6 (**Figure 16 and Figure 17**). The dip progressively flattens in the proposed underground area towards the east, to typical grades of 1 in 20 (**Figure 16 and Figure 17**).

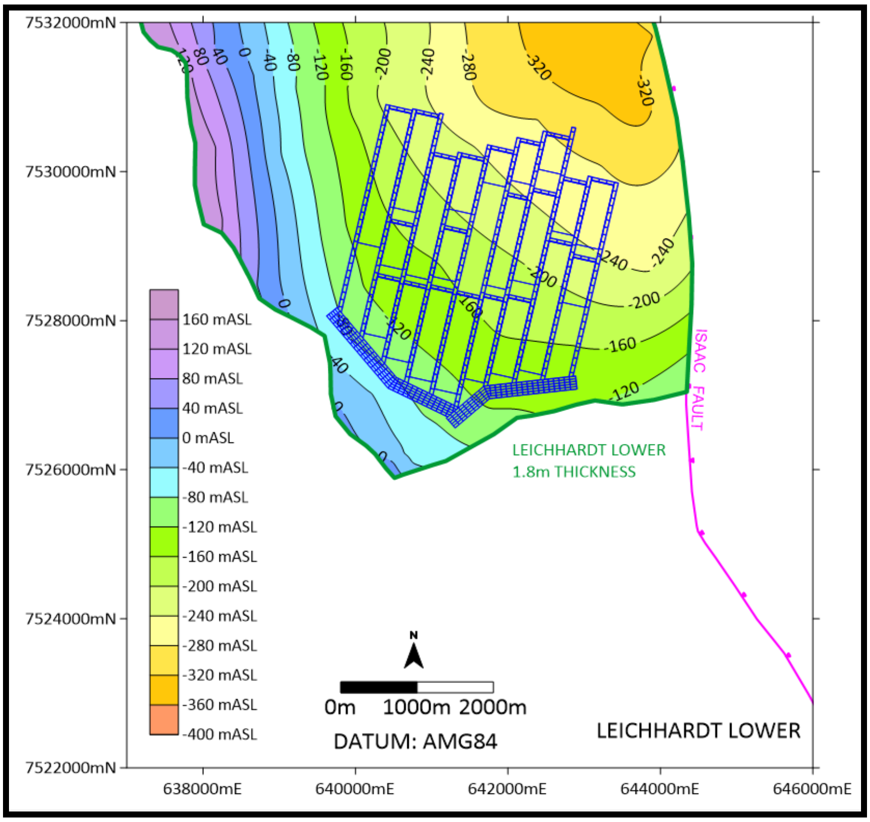


Figure 16. Leichhardt Lower Seam Floor Levels (m ASL).

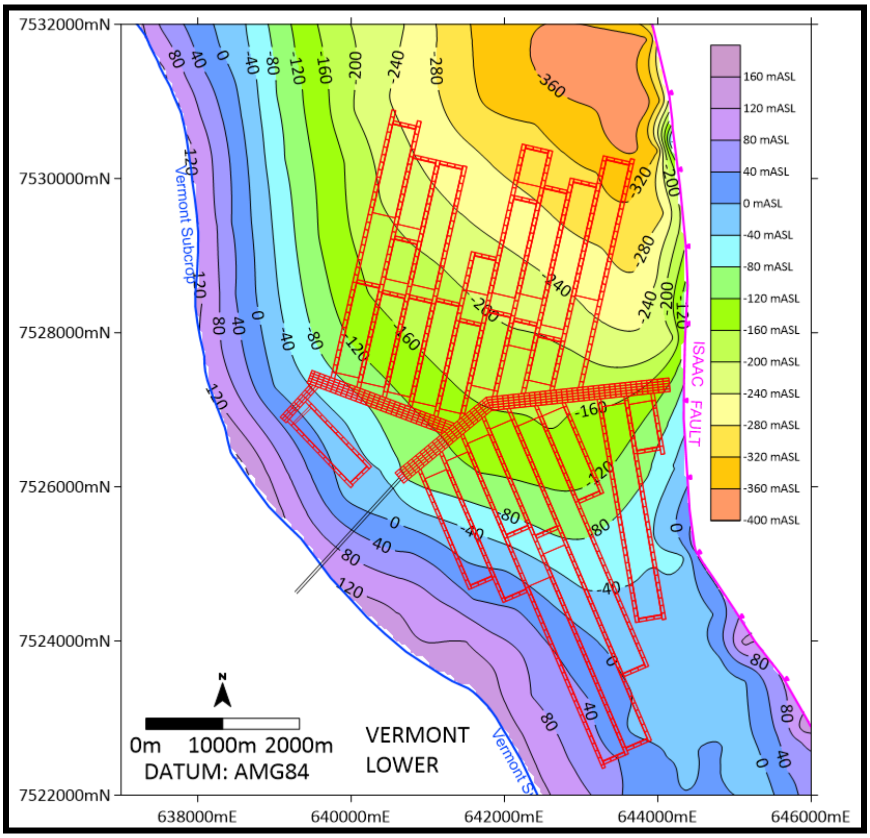


Figure 17. Vermont Lower Seam Floor Levels (m ASL).

On the western boundary of the proposed Vermont Lower Seam longwall area, grades of 1 in 8 could be encountered (**Figure 17**). These characteristics are also evident in the 3D surface plot of the Vermont Lower Seam (**Figure 18**).

This flattening of the seam with depth away from the subcrop is characteristic of other deposits in the Rangal Coal Measures.

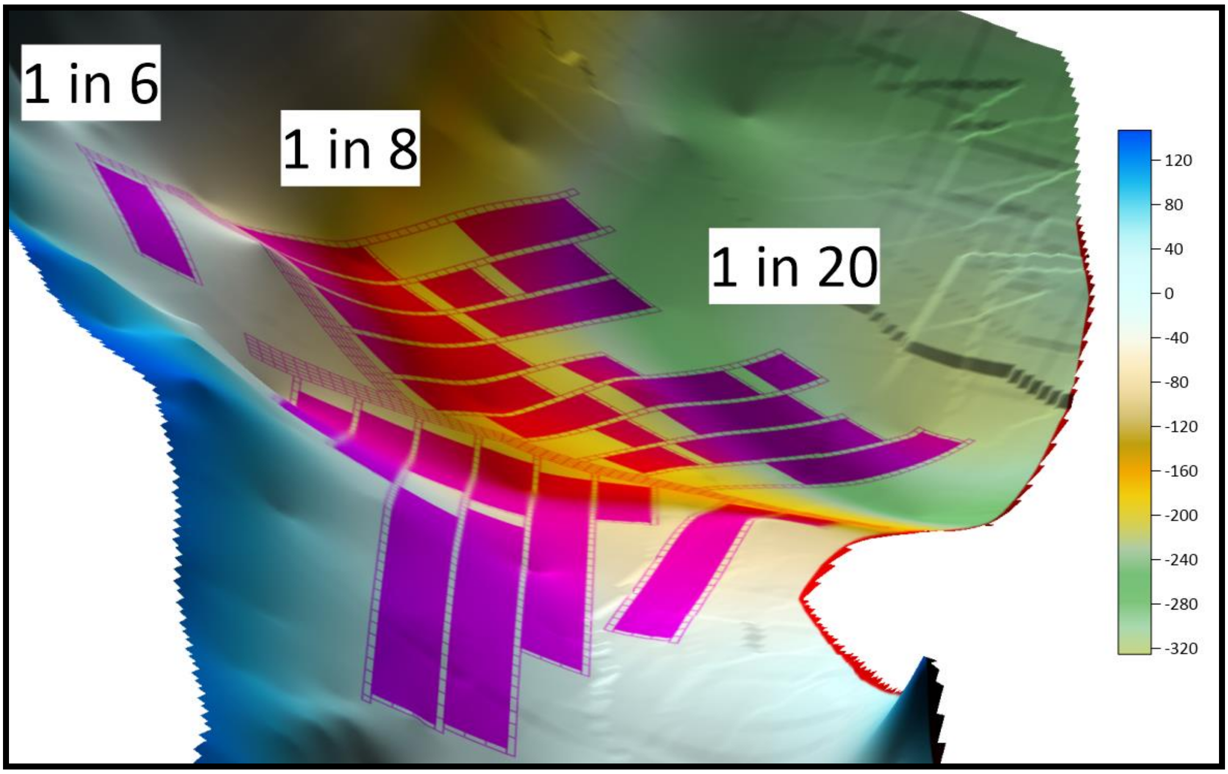


Figure 18. 3D Surface Plot of Vermont Lower Seam Floor Levels (m ASL).

2.2.5.5 Immediate Roof and Floor Lithologies

The immediate stone roof of both target seams is typically made up of interbedded mudstones, siltstones and sandstones, with average strengths up to 40 MPa (GGPL, 2022).

Similarly, the immediate stone floor below the target seams consists of mudstone, grading down into coarser siltstone and sandstone strata, with average strengths up to 20 MPa. This sequence of coarsening downwards sediments is a common feature in the floor strata at other Bowen Basin coal mines.

In other parts of the Bowen Basin, the Yarrabee Tuff is located at the base of the Vermont Seam. Fortunately, this soft tuff layer is typically >20 m below the Vermont Lower Seam in the Meadowbrook underground area and not considered to be close enough to control coal pillar stability and hence deformation (GGPL, 2022).

2.2.5.6 Faults

Both normal and reverse faults were identified by the 3D seismic in the Meadowbrook underground area (**Figure 19**). This faulting style is consistent with neighbouring mining areas in the Rangal Coal Measures. A greater density of reverse style structures is evident closer to the regional Isaac Fault to the east of the underground area (**Figure 19**).

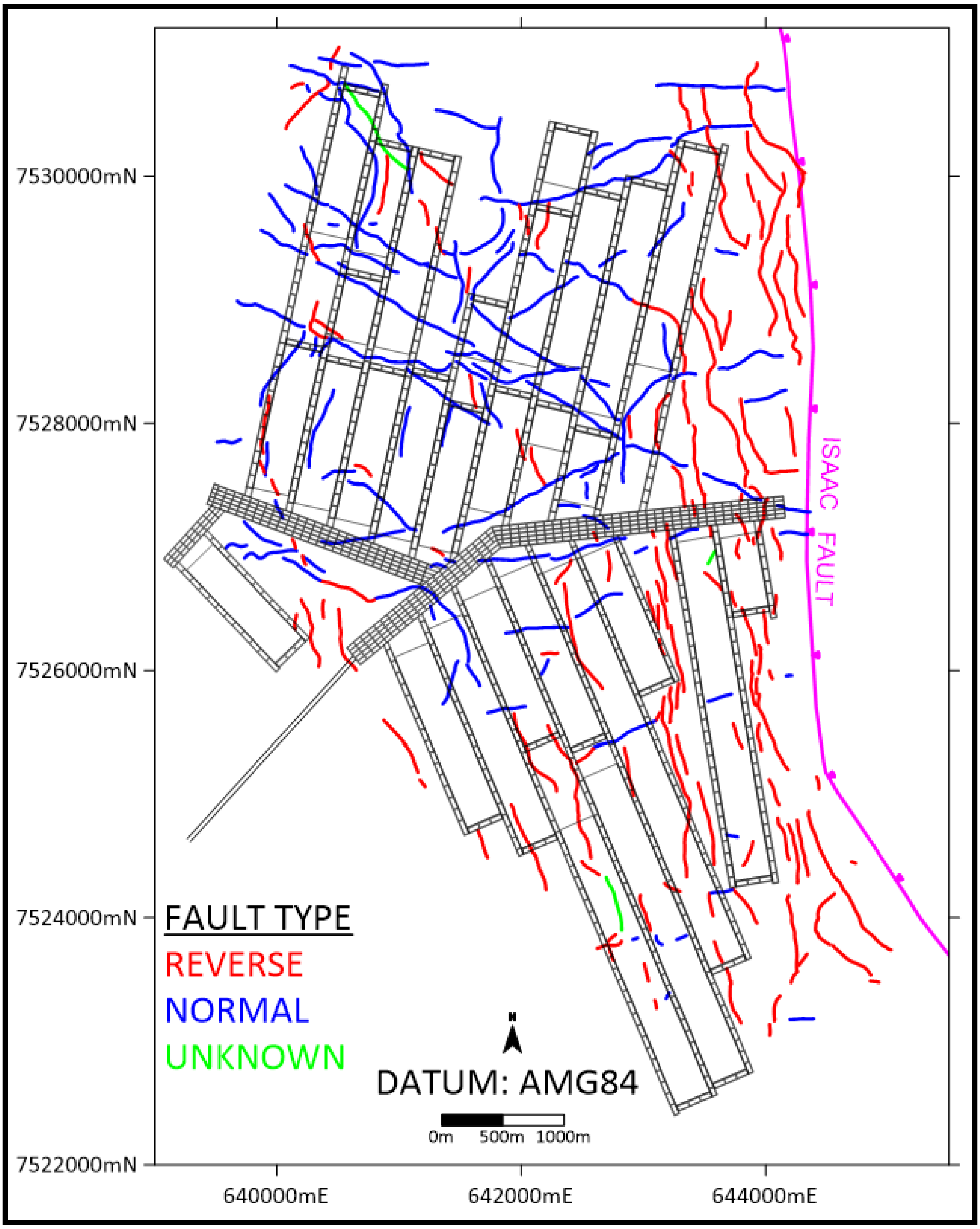


Figure 19. Fault Types from 3D Seismic Survey – Vermont Lower Seam.

3 SUBSIDENCE PREDICTION METHODOLOGY

The majority of longwall panels in the Meadowbrook longwall mining area will create an extraction void approximately 320 m wide. As detailed earlier, to avoid geological features, three panels in the Leichhardt Lower Seam are 270 m wide (solid) and two panels in the Vermont Lower Seam are 290 m wide (solid).

The longwall panels will be developed with two heading gateroads located along the panel length. Chain pillar widths will vary from 45 m (solid) in the Leichhardt Lower Seam and the deeper northern Vermont Lower Seam panels. In the shallower southern Vermont Lower Seam area, the solid chain pillar width has been reduced to 35-40 m.

3.1 SDPS Subsidence Modelling Method

GGPL has used the Surface Deformation Prediction System (SDPS) program (Carlson Software Inc), to predict the subsidence that will occur due to extraction of the Leichhardt Lower and Vermont Lower seams in the Meadowbrook underground mining area.

The SDPS program uses an influence function method that assumes the shape of a subsided surface can be modelled with a Gaussian (bell shaped) curve. This technique is a proven and reliable prediction methodology. This methodology is widely used throughout QLD and NSW to generate predictions of longwall mining subsidence effects and inform environmental impact and engineering assessments (Byrnes, 2003). **Figure 20** illustrates how well SDPS can visualise the subsidence profile.

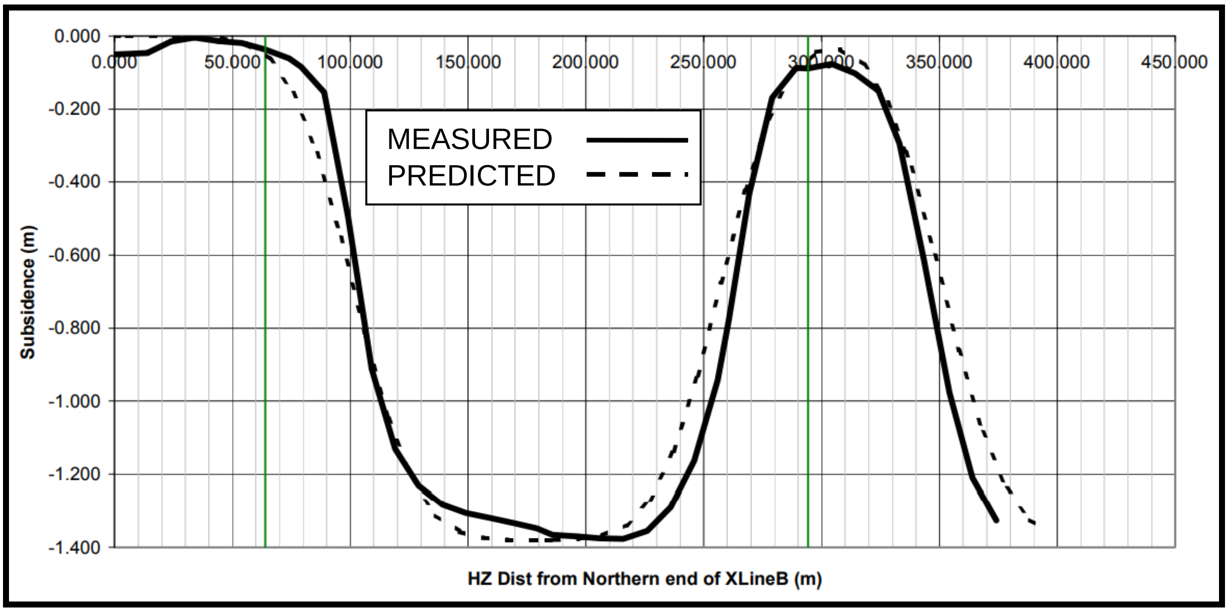


Figure 20. Comparison of Measured versus Predicted Subsidence (Byrnes, 2003).

The method requires calibration to existing survey data and mine geometry. The following inputs are required:

- Panel Layouts (corrected by the Panel Adjustment Factor as detailed in Section 3.2.4).
- Seam Thickness.
- Depth of Cover.
- Influence Angle.
- Subsidence Factor (maximum subsidence (Smax)/extracted thickness ratio).
- Strain Coefficient.

It should be highlighted that the SDPS methodology can only predict the overall or systematic deformations. All subsidence surveys reveal small scale variations from the smooth profile predicted by this method. These deformations can be related to localised movements of blocky rock that is a feature of all coal mine overburdens.

Published dual seam longwall experience has also been referenced from elsewhere in the Australian and overseas mining industry.

Based on subsidence data from the Bowen Basin presented in the South Galilee EIS (SGPL, 2012) and also subsidence studies by GGPL, the following parameters were used for modelling in the proposed Meadowbrook longwall mining area. Discussion on how these calibrated inputs were developed is provided in Sections 3.2 to 3.4 and the subsidence prediction results are presented in Section 4:

- Panel Adjustment Factor of 0.2.
- Influence Angle of 70^{o}.
- Maximum Subsidence Factor of 65% for extraction in virgin ground and 95% for Vermont Lower Seam extraction below Leichhardt Lower Seam goaf areas.
- Strain Coefficient of 0.35.

3.2 Subsidence Modelling

3.2.1 Subsidence Behaviour

The subsidence above longwall panels is comprised of two main components namely sag and strata compression. Depending on the depth of cover and width of extraction these components combine in various proportions (**Figure 21**).

In the deeper part of the Meadowbrook longwall mining area, where the panel width: depth of cover ratios are <1.2 (critical), the total subsidence is anticipated to be a combination of both sag and a component of strata compression, as shown in **Figure 21**.

In the shallower areas where the panel width: depth of cover ratios are >1.2 (supercritical), the majority of the subsidence is anticipated to be due to sag (**Figure 21**).

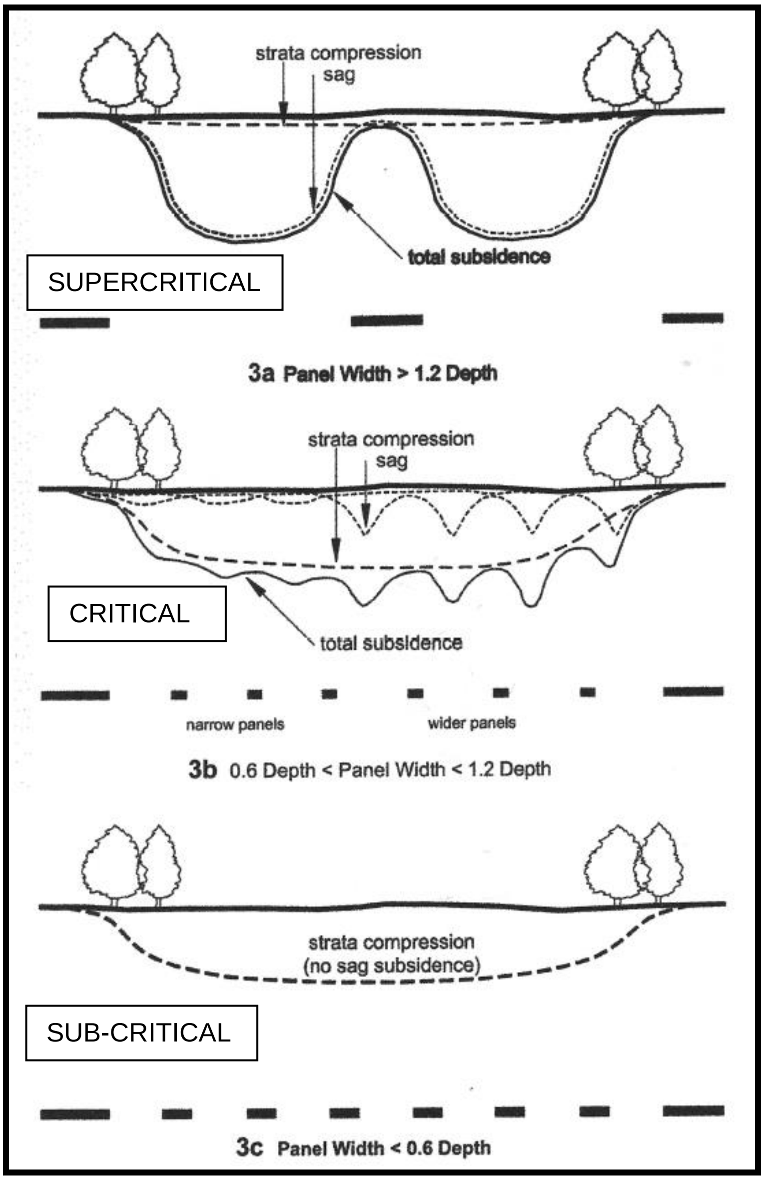


Figure 21. Effect of Panel Width (AUSIMM, 2009).

The general shape of a cross section through a subsidence bowl (**Figure 22**) reveals a number of key features that can be used as a frame of reference:

- The areal extent of subsidence is defined by the angle of draw. The angle of draw is measured from the edge of the extraction void to the limit of measurable subsidence (LOMS). Conventionally, the LOMS is the point of 20 mm of vertical subsidence (not zero). Subsidence less than 20 mm will have a negligible effect, as it cannot be differentiated from natural ground surface variations due to soil moisture changes.

- Maximum tilt should correspond with zero strain.
- The subsidence at the point of maximum tilt and zero strain should be half the maximum vertical movement.
- The maximum tilts or strains do not necessarily correspond with the edge of the extraction.
- The typical subsidence profile is smooth over the cross section.

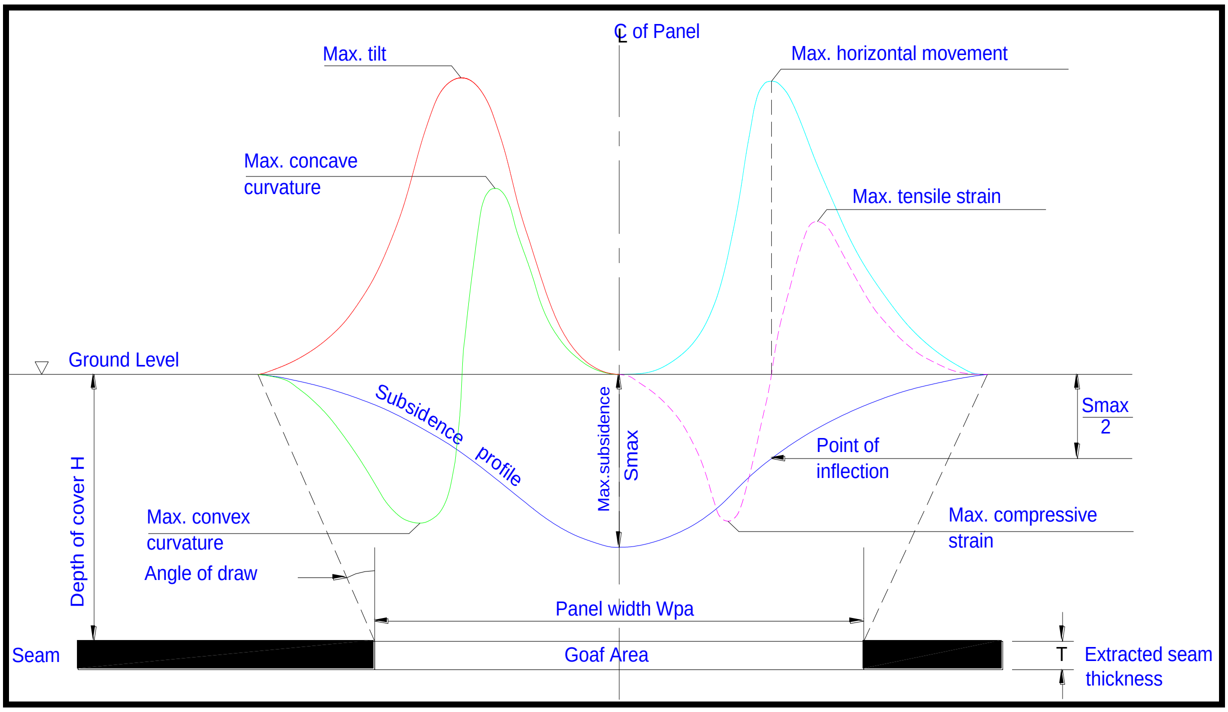


Figure 22. General Characterisation of a Subsidence Cross Line.

These parameters characterise the surface deformations above the extracted longwall panels and provide context to the resulting impacts.

3.2.2 Subsidence Factor

3.2.2.1 Single Seam

The subsidence factor is the ratio of maximum subsidence (S_{max}) to extracted coal seam thickness (T). This ratio is the percentage of the extracted thickness underground, measured as subsidence on the surface. As the panel width to depth of cover ratio decreases, the maximum subsidence correspondingly decreases (**Figure 23**). This decrease occurs as the subsidence behaviour transitions from supercritical to subcritical and finally to bridging behaviour (**Figure 23**).

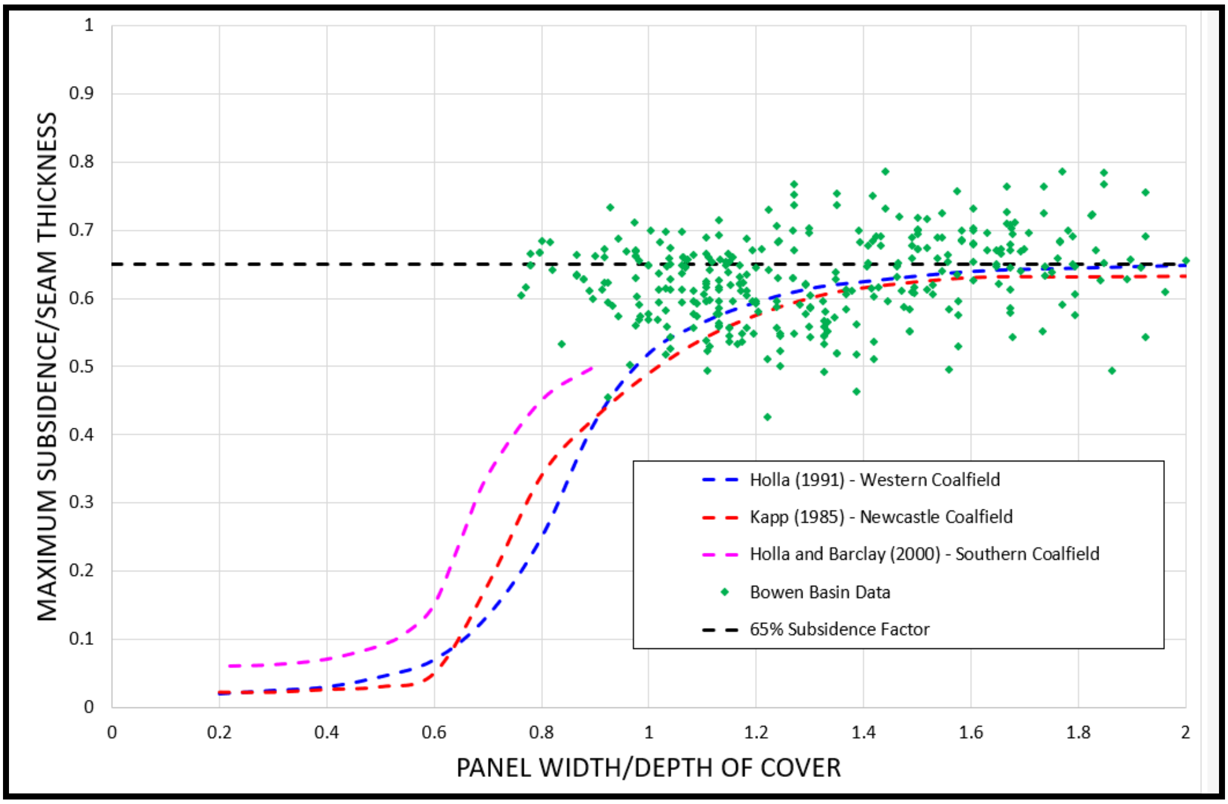


Figure 23. Sag Subsidence over Single Longwall Panels in Virgin Ground.

In the Meadowbrook longwall mining area, the panel width to depth ratio is typically >0.7. Based on the Bowen Basin data set, supercritical behaviour characterised by sag subsidence is therefore anticipated in the majority of the Meadowbrook area (**Figure 23**). It should be highlighted that an empirical curve has not been developed for the Bowen Basin due to fact that the majority of the extraction has been carried out at panel width:depth of cover ratios >0.8 (**Figure 23**).

The available Bowen Basin data validates the application of a 65% subsidence factor to the Meadowbrook longwall area for extraction in virgin ground (**Figure 23**). Furthermore, recognising that the tilt and strain values in SDPS are a linear function of the subsidence factor, **Figure 23** can be used to indicate confidence levels in the prediction. In this case ±23% or 0.15/0.65, based on a subsidence factor range of 0.5-0.8 (50-80% of the extracted thickness).

It is also highlighted that care is required when comparing the Bowen Basin data with the NSW lines in **Figure 23**, as these were drawn as upper bounds, which would be 80% for the Bowen Basin data.

3.2.2.2 Dual Seam

Dual seam longwall extraction subsidence data has been reported by Li et al (2010) and Mills and Wilson (2021). The subsidence factor for the extraction of the underlying seam ranges from 70-110% (**Figure 24**). The interburden thickness in the data set ranges from 13-85 m, which is comparable with the 20-30 m between the Leichhardt Lower and Vermont Lower seams in the Meadowbrook area (**Figure 24**).

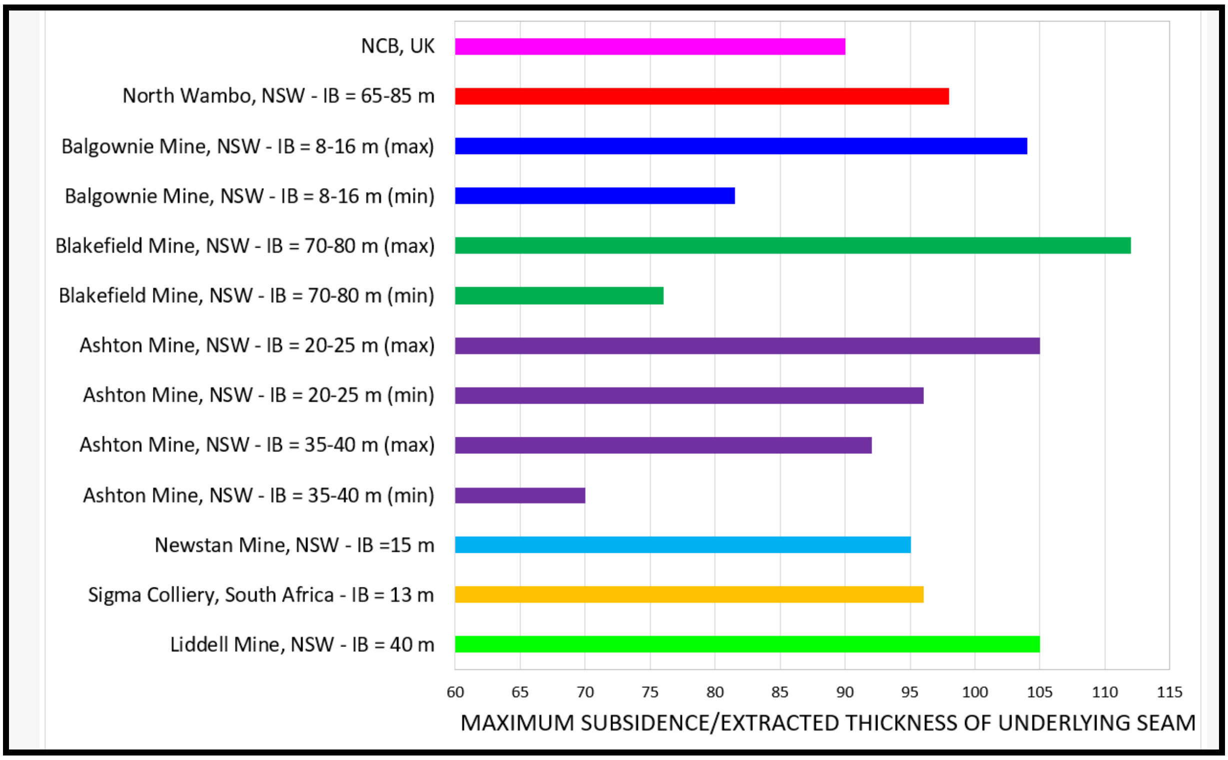


Figure 24. Subsidence Factor for the Extraction of the Underlying Seam.

Based on this published dual seam data, a conservative maximum 95% subsidence factor has been applied to the Vermont Lower Seam extraction below extracted Leichhardt Lower Seam longwall panels (**Figure 24**).

MSEC (2012) also proposed that the additional ground movement in a dual seam mining environment is dependent upon the thickness of the interburden between the seams, as well as the thickness of the seams to be extracted.

In the case of the combined Leichhardt Lower and Vermont Lower seam extraction, the total subsidence at any point is a simple addition of individual values for each seam. The same is not true of the strain and tilts. SDPS has the facility to allow models to be run with both seam layouts simultaneously, to provide outputs of these parameters.

3.2.3 Influence Angle

The influence angle (β) is defined as:

$$\tan \beta = \text{Depth/Radius of Influence}$$

The influence angle is approximately 90º minus the angle of draw and is therefore a key parameter in the prediction of the shape of the subsidence profile above longwall panels (Agioutantis and Karmis, 2002). Based on data from the Bowen Basin, an influence angle of 70º has been adopted for the Meadowbrook area (**Figure 25**).

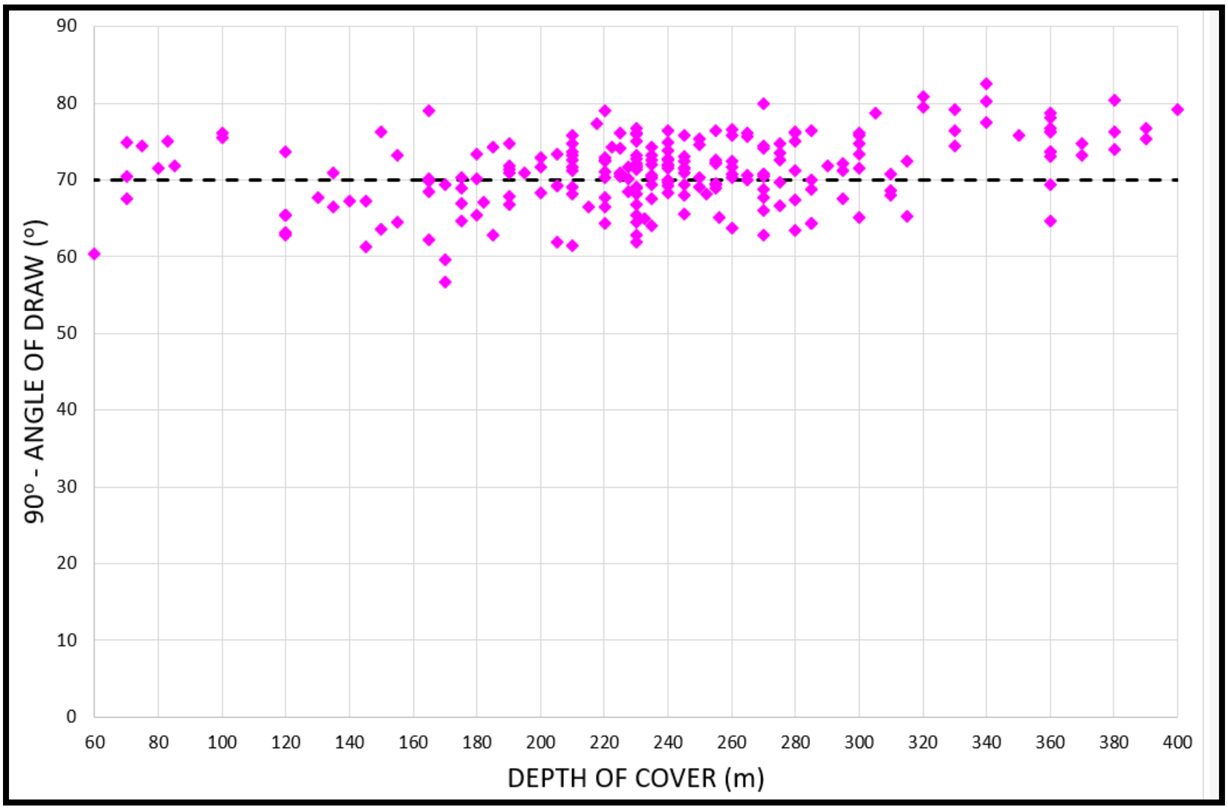


Figure 25. Influence Angle Data – Bowen Basin.

3.2.4 Panel Adjustment Factor

The panel adjustment factor is the compensation width divided by the depth of cover, where the compensation width is the distance measured from the rib edge to the inflexion point or point of half maximum subsidence (**Figure 22**).

Based on data from the Bowen Basin, a panel adjustment factor of 0.2 has been adopted for the Meadowbrook area (**Figure 26**).

SDPS models the extraction of each longwall panel using the projection of the points of inflexion, rather than the panel width (**Figure 22**). For wide extraction panels, the position of the inflexion points is a linear proportion of the depth of cover. The modelled and proposed extents of each Vermont Lower Seam longwall panel are shown in **Figure 27**.

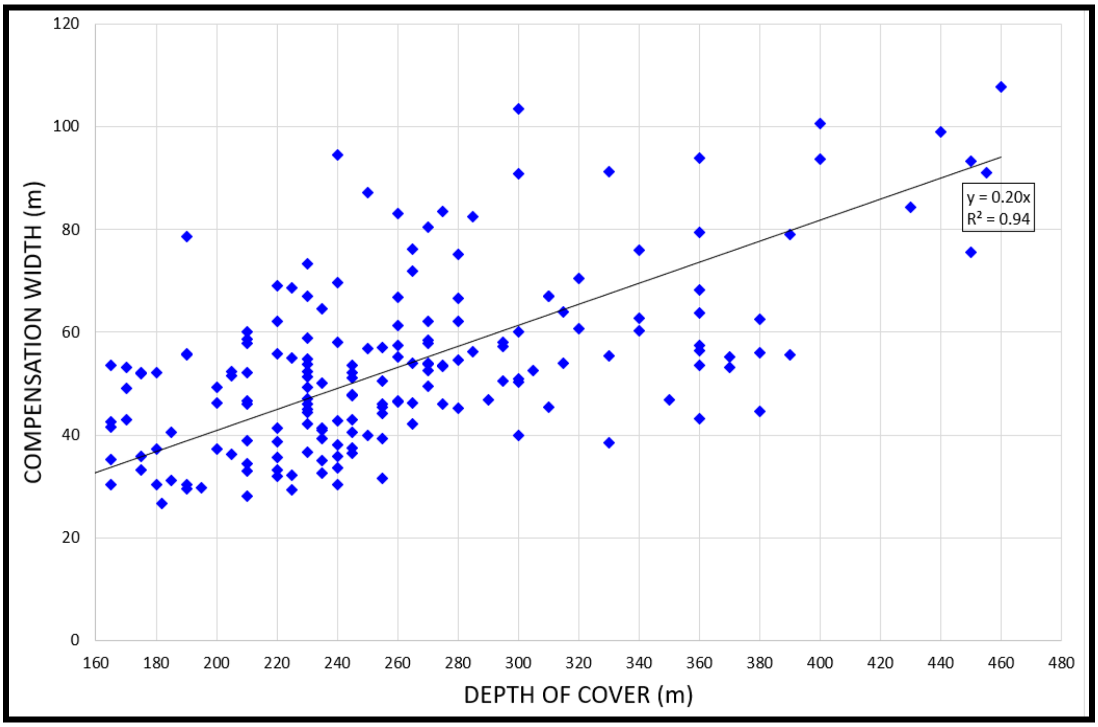


Figure 26. Panel Adjustment Factor Data – Bowen Basin.

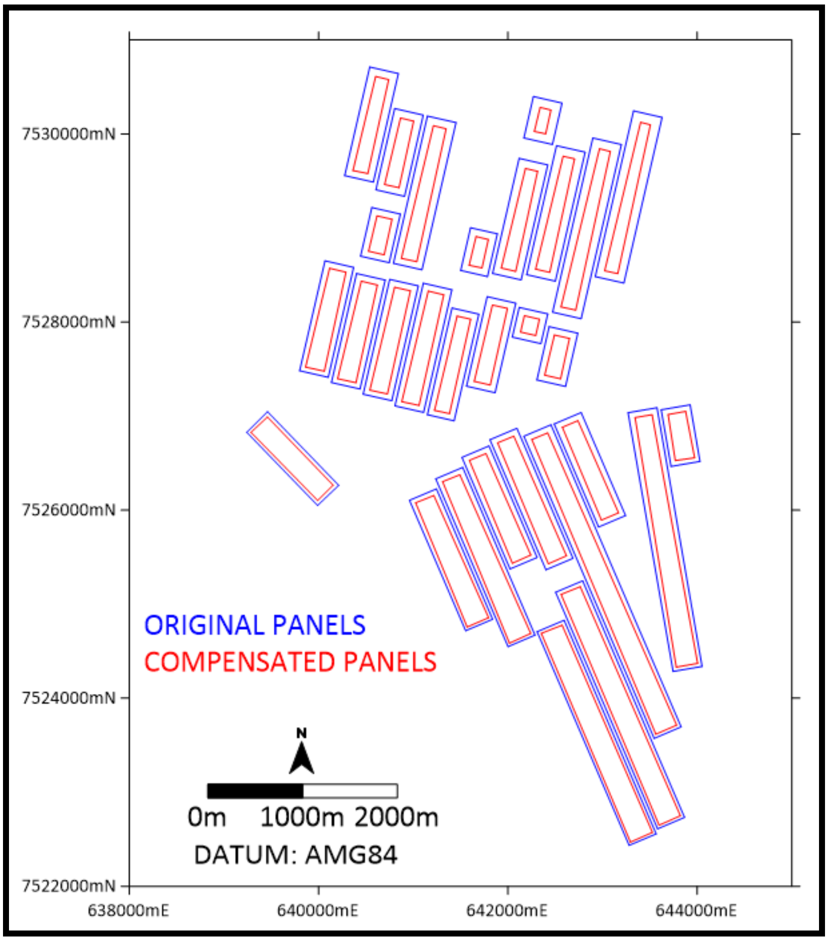


Figure 27. Original Longwall Panels and Compensated Panels – VL Seam.

3.2.5 Strain Coefficient

The strain coefficient influences the strain predicted by the model. Increasing the strain coefficient increases the predicted strain, while reducing the strain coefficient decreases the predicted strain.

A strain coefficient of 0.35 has been adopted for the SDPS modelling and is at the high end of the range of values used at other Bowen Basin mines (Seedsman Geotechnics, 2012). This value is therefore expected to result in conservative predictions of strain and associated cracking in the Meadowbrook longwall mining area.

3.2.6 Mining Height

The subsidence modelling has assumed the full seam thickness is extracted by the longwall.

3.3 Chain Pillar Deformation

The chain pillars between the longwall panels will act to reduce the magnitude of subsidence deformation between each individual longwall panel and therefore the total subsidence over each series of panels.

The depth of cover increases along the length of the panels and the associated chain pillars. In these circumstances, the chain pillars may deform differently along their lengths and this will influence the total subsidence associated with each series of longwall panels.

The key considerations in modelling the effects of chain pillar deformation on the total subsidence are discussed in Sections 3.3.1 and 3.3.2.

3.3.1 Negative Pillar Subsidence Factor

In order to model the influence of chain pillars, SDPS provides the ability to model each series of panels (also termed a super panel). In this mode, SDPS models the negative subsidence (upsidence) of the chain pillars instead of the panels. The adopted SDPS model arrangement for the Vermont Lower Seam layout is shown in **Figure 28**, where the super panel boundaries are shown in purple and the chain pillars in green.

Additional super panels were defined to allow modelling of the Vermont Lower Seam longwall extraction in virgin mining areas not located below Leichhardt Lower Seam workings (**Figure 28**).

The width of these active chain pillars is equal to the distance between the compensated panel boundaries. The feature of this method is that the chain pillars can be given their own negative subsidence factor in the prediction, allowing greater control over subsidence due to compression of the pillar system.

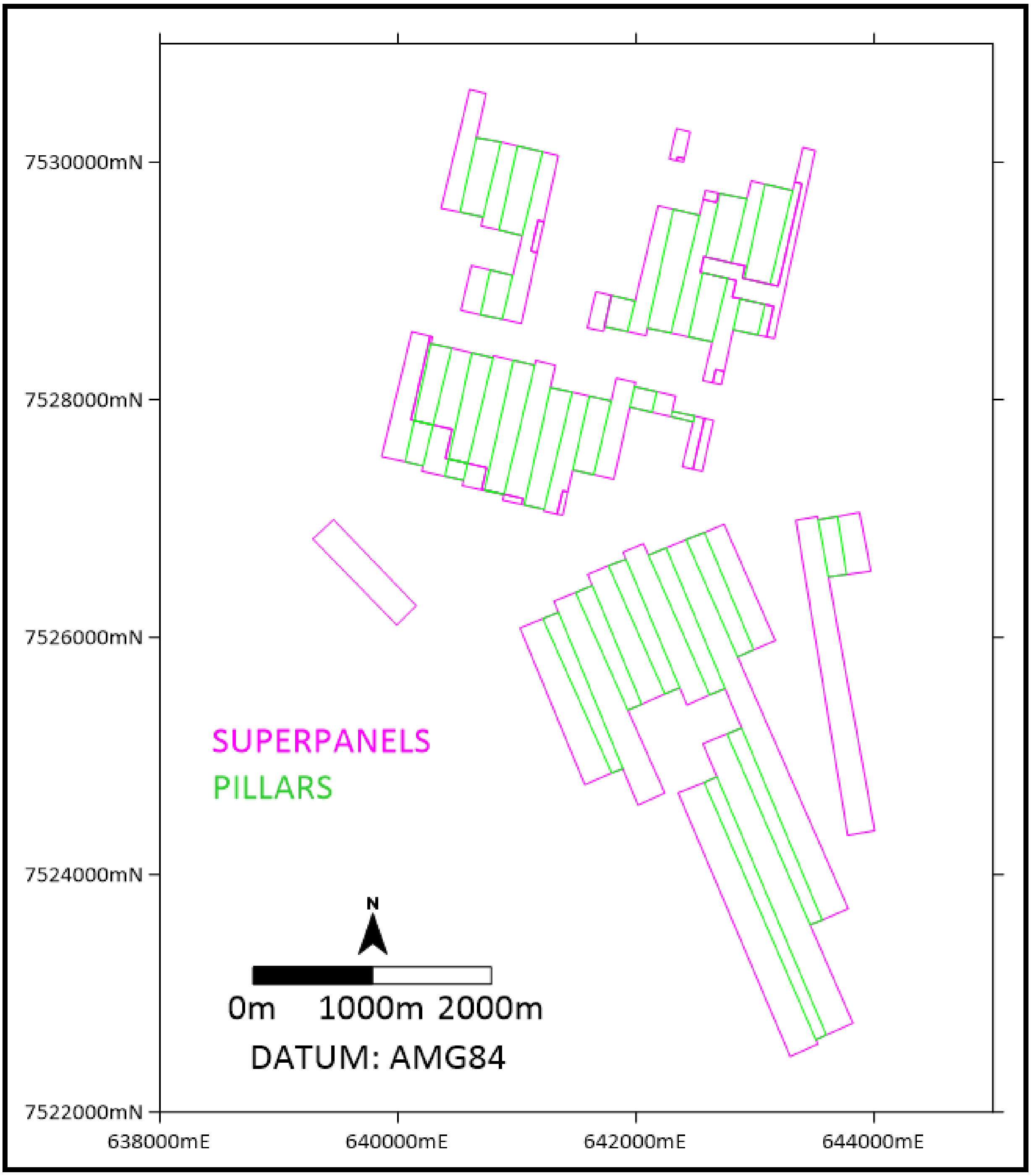


Figure 28. Super Panels and Active Pillars with Compensated Geometries – VL Seam.

3.3.2 Stable Pillars to Yielding Pillars

When a longwall panel extracts the coal, the overburden load that was carried by coal is redistributed onto the chain pillars on either side of the longwall panel. With this increase in overburden load, the coal that forms the chain pillars in the Meadowbrook longwall mining area is expected to experience compression.

Analysis of the pillar stability indicates that the 35 m, 40 m and 45 m chain pillars in the Meadowbrook longwall mining area yield in a full goaf loading situation at depths of 290 m, 330 m and 370 m respectively (**Figure 29**). At the planned range of mining depths, the 40 m chain pillars are not expected to yield and only a small extent of the 35 m chain pillars are anticipated to yield.

Larger areas of yield are expected in the 45 m chain pillar areas in virgin ground. Where these chain pillars in the Vermont Lower Seam are located below overlying goaf, yield is not anticipated due to the reduction in loading conditions, consistent with data presented by Mills and Wilson (2021) at Ashton Mine in NSW.

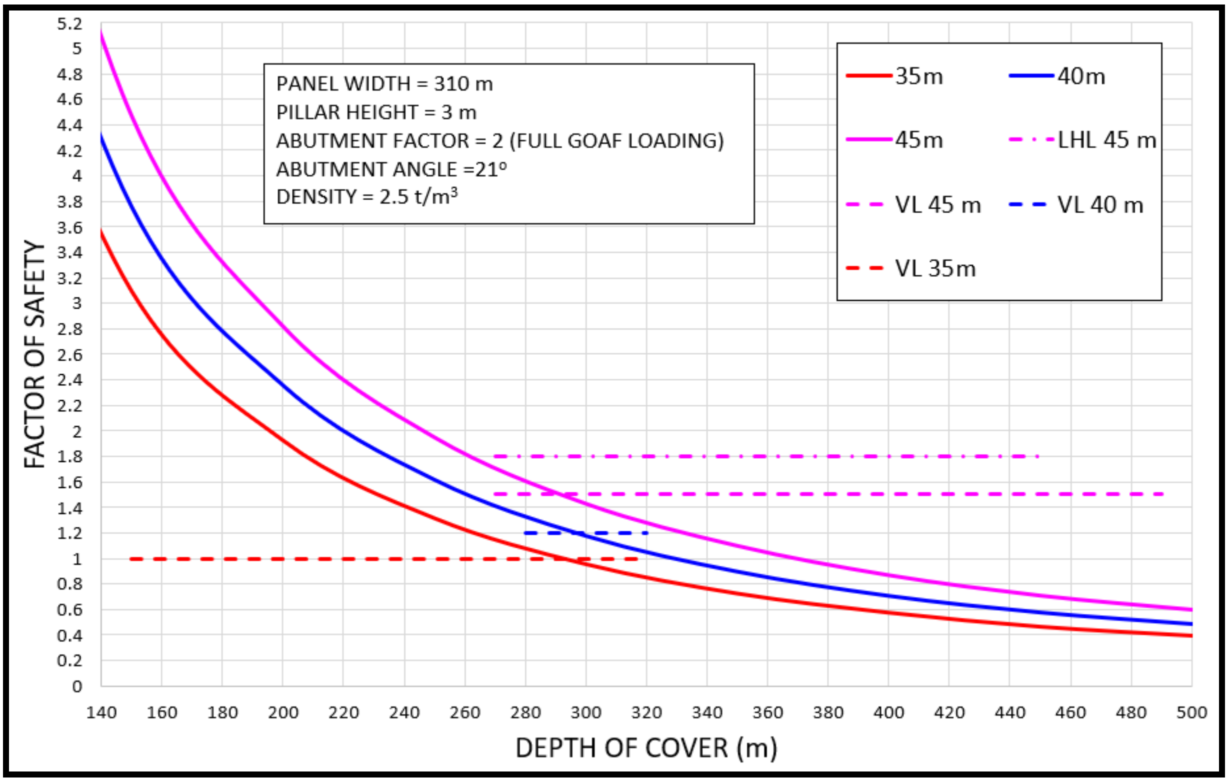


Figure 29. Analysis of Chain Pillars using the ALPS Pillar Design Methodology.

The yielding of chain pillars will result in additional subsidence. This has therefore been considered in the SDPS inputs and predictions in the Meadowbrook longwall mining area.

3.4 Massive Spanning Units

Voussoir or jointed rock beam concepts can be used to determine the required thickness of an overburden unit that can span a longwall (Sofianos and Kapensis, 1998). For the Meadowbrook longwall mining area, a voussoir beam analysis has conservatively assumed a 20° caving angle at the edge of the longwall extraction void, and conservative overburden strength and modulus properties of 60 MPa and 12 GPa, respectively.

A voussoir beam analysis using these parameters indicates that a 53 m thick massive unit, located 50 m above the seam, is required to span a 310 m wide longwall panel at 450 m depth of cover in the Meadowbrook longwall mining area.

To assess the potential for the presence of massive units in the Permian overburden the geophysical gamma log measured in the exploration boreholes can be used. The variability in the gamma response of the overburden in selected holes across the Meadowbrook longwall mining area indicates that the massive units are typically less than 15 m thick (**Figure 30 and Figure 31**).

This is significantly less than the 53 m required to span a longwall panel and as such, spanning of the Permian overburden is not anticipated in the Meadowbrook longwall mining area.

A similar assessment of the overlying Rewan Formation indicates that any massive sandstone units in this stratigraphic unit are typically <10 m thick and are not anticipated to significantly modify the subsidence profile.

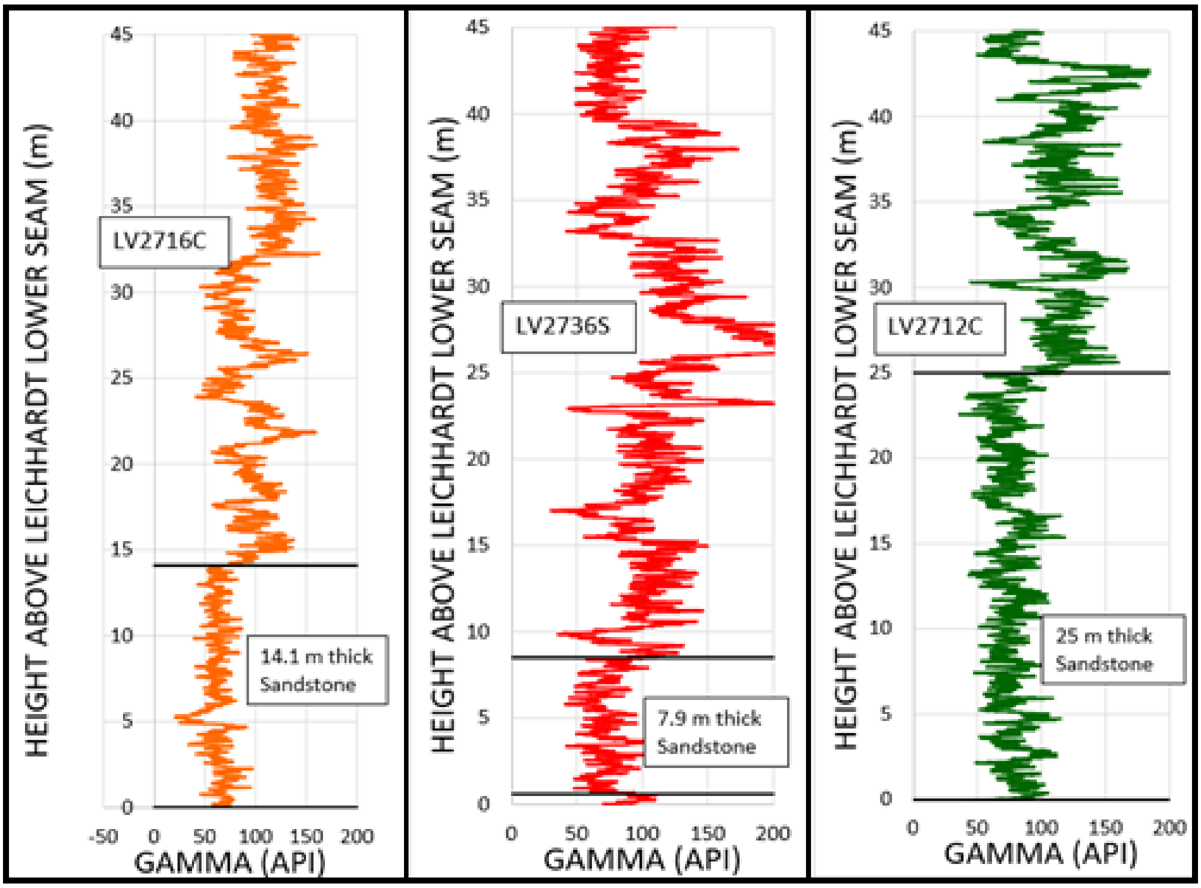


Figure 30. Sandstone Units in the Permian above the Leichhardt Lower Seam.

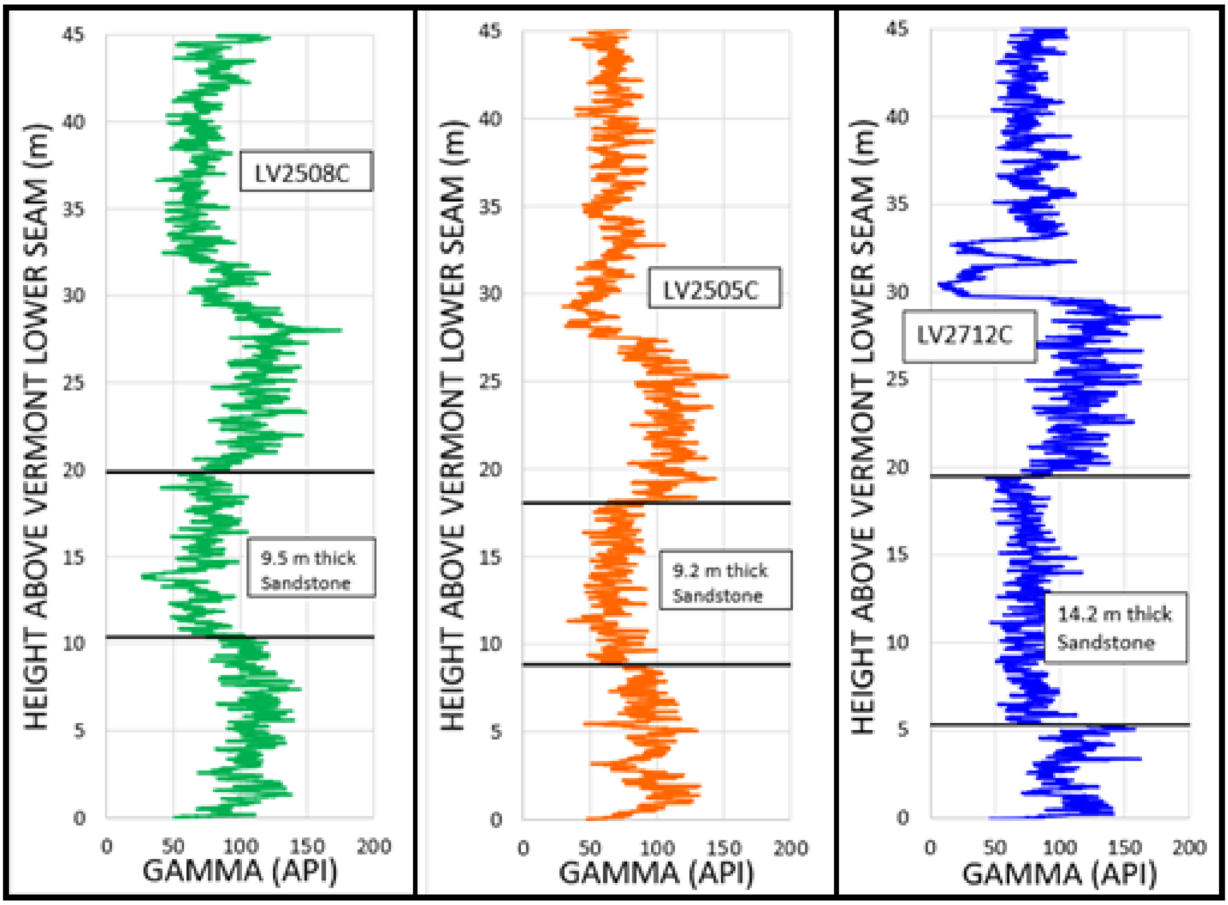


Figure 31. Sandstone Units in the Permian above the Vermont Lower Seam.

4 SUBSIDENCE PREDICTIONS

4.1 Subsidence

4.1.1 Over Longwall Panels

The predicted total subsidence from mining of both the Leichhardt Lower and Vermont Lower seam longwall panels is shown in **Figure 32**.

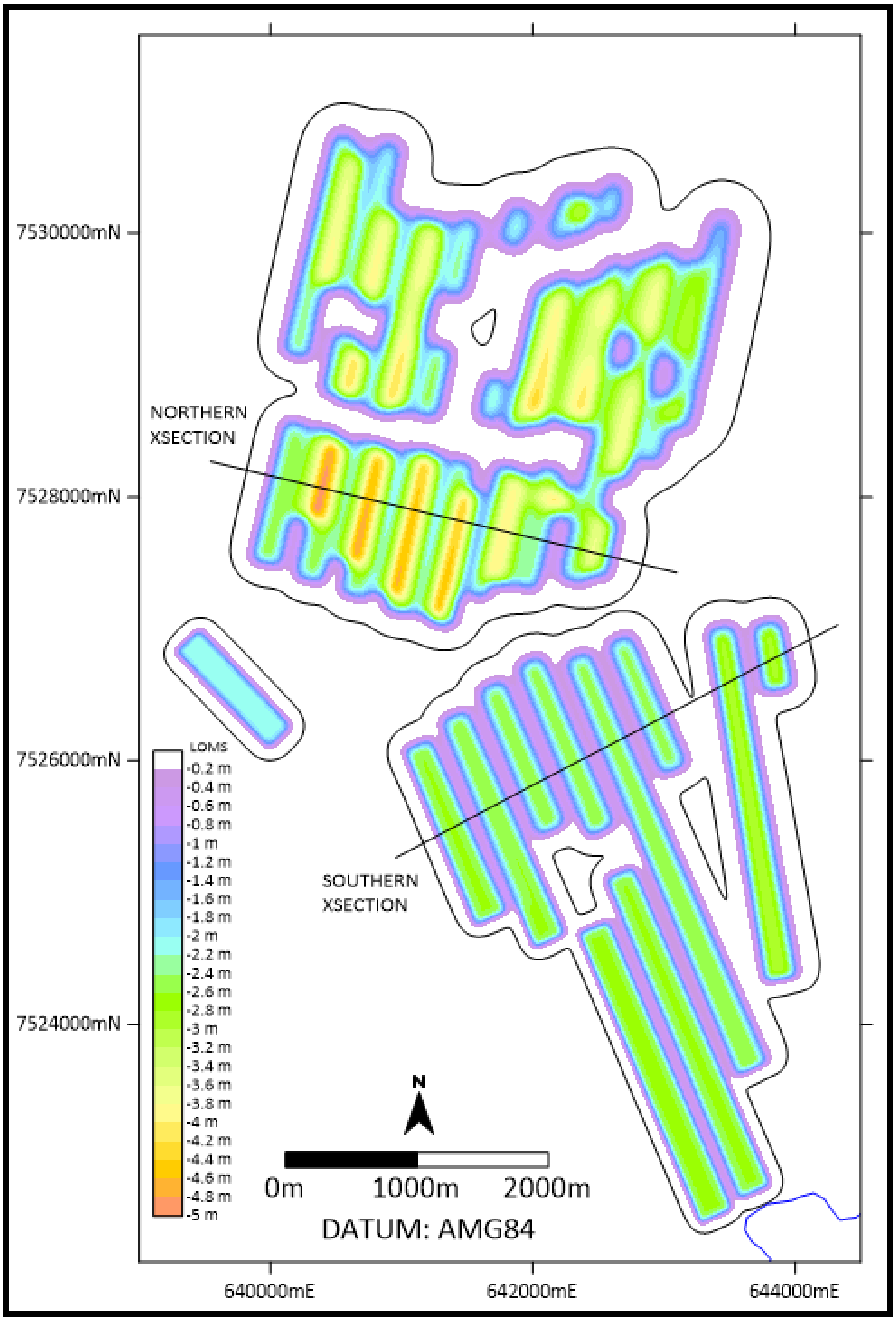


Figure 32. Subsidence after Extraction of both the LHL and VL Seams (m).

In the southern part of the area, where only the Vermont Lower Seam is mined, the vertical subsidence reaches a maximum of 2.9 m in the shallower part of the area (**Figure 32**). In the northern part of the area, where both the Leichhardt Lower and Vermont Lower seams are mined, the total subsidence reaches a maximum of 5 m (**Figure 32**).

Two cross sections across the northern and southern part of the area illustrate the variability in the predicted subsidence (**Figure 33 and Figure 34**). It should be highlighted that these sections have a high vertical: horizontal scale exaggeration.

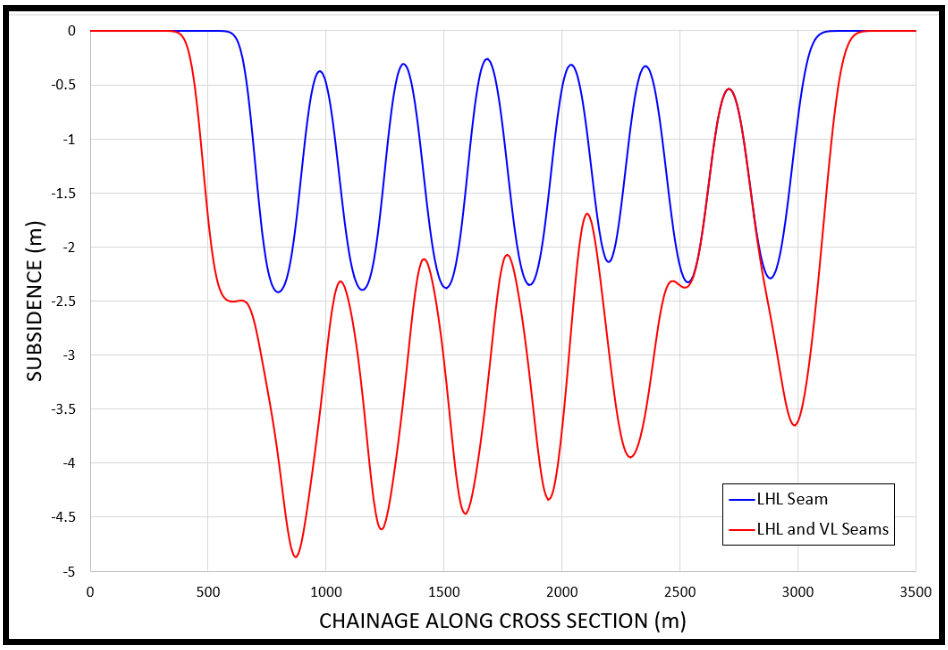


Figure 33. Subsidence - Northern Cross Section.

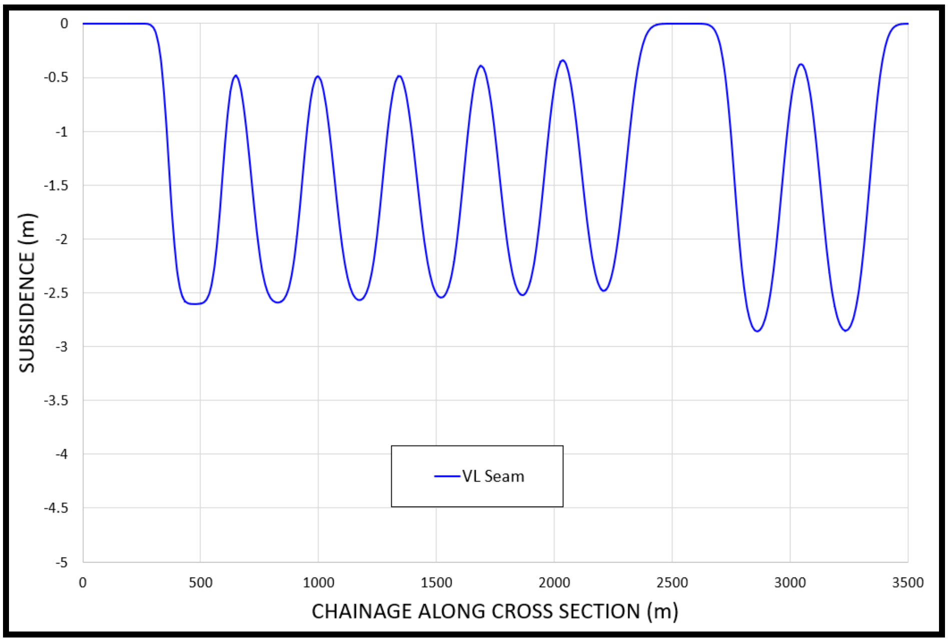


Figure 34. Subsidence – Southern Cross Section.

In the Leichhardt Seam, the subsidence above the chain pillars is around 0.4-0.5 m (**Figure 33 and Figure 34**). These values are consistent with a compression analysis using typical sedimentary Geological Strength Index (GSI) values of 50 and 45 for the roof and floor respectively and representative strength values. As such, the negative pillar subsidence factors were not adjusted.

4.1.2 Along Creeks

Boomerang and One Mile Creeks traverse the proposed northern and southern longwall panels respectively (**Figure 3**). Sections along these two creeks with exaggerated vertical: horizontal scales are shown in **Figure 35 and Figure 36**.

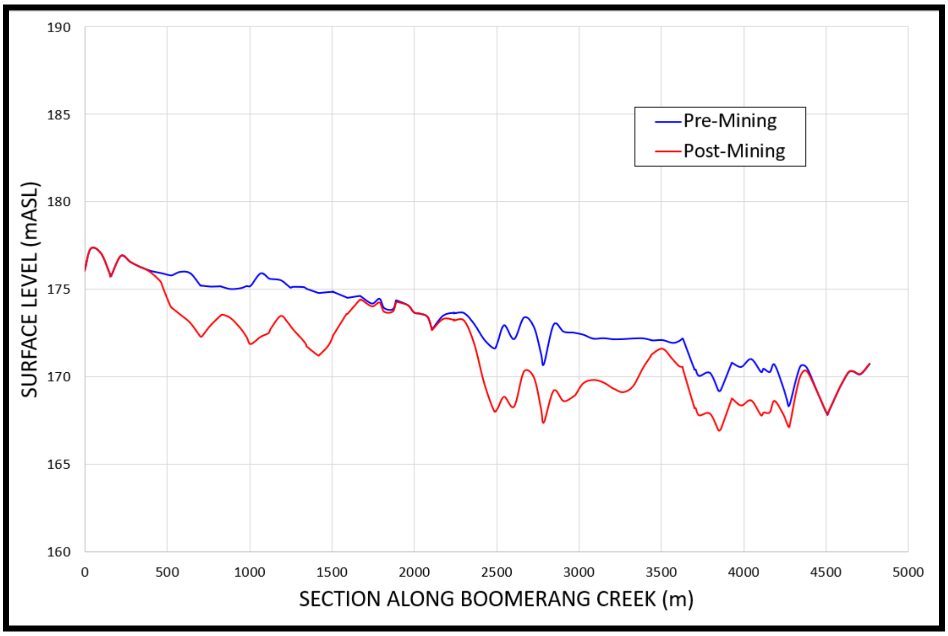


Figure 35. Subsidence – Cross Section along Boomerang Creek.

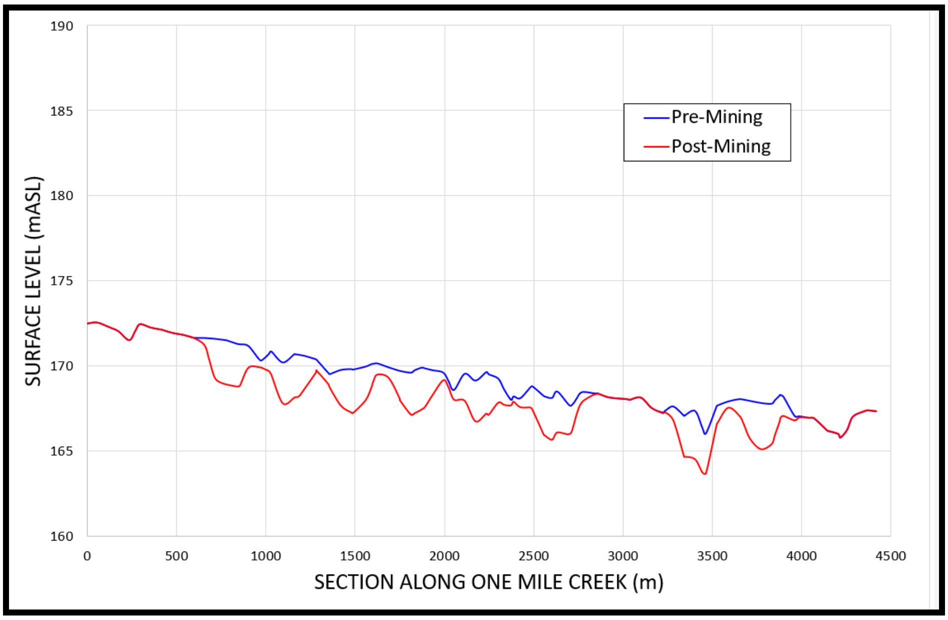


Figure 36. Subsidence – Cross Section along One Mile Creek.

4.1.3 Subsided Topography

Figure 37 shows the predicted topographic surface over the Meadowbrook area at the completion of longwall mining, with a z axis exaggeration of 25. The distinct ridges above the chain pillars and troughs over the goaf areas are clearly evident in this figure (**Figure 37**).

These troughs may become areas for the ponding of water. Similarly, the profile of Boomerang and One Mile creeks will change as mining continues in this area, which may increase the rate of water flow and the potential for erosion in the short term until the troughs become silted up (**Figure 35 and Figure 36**).

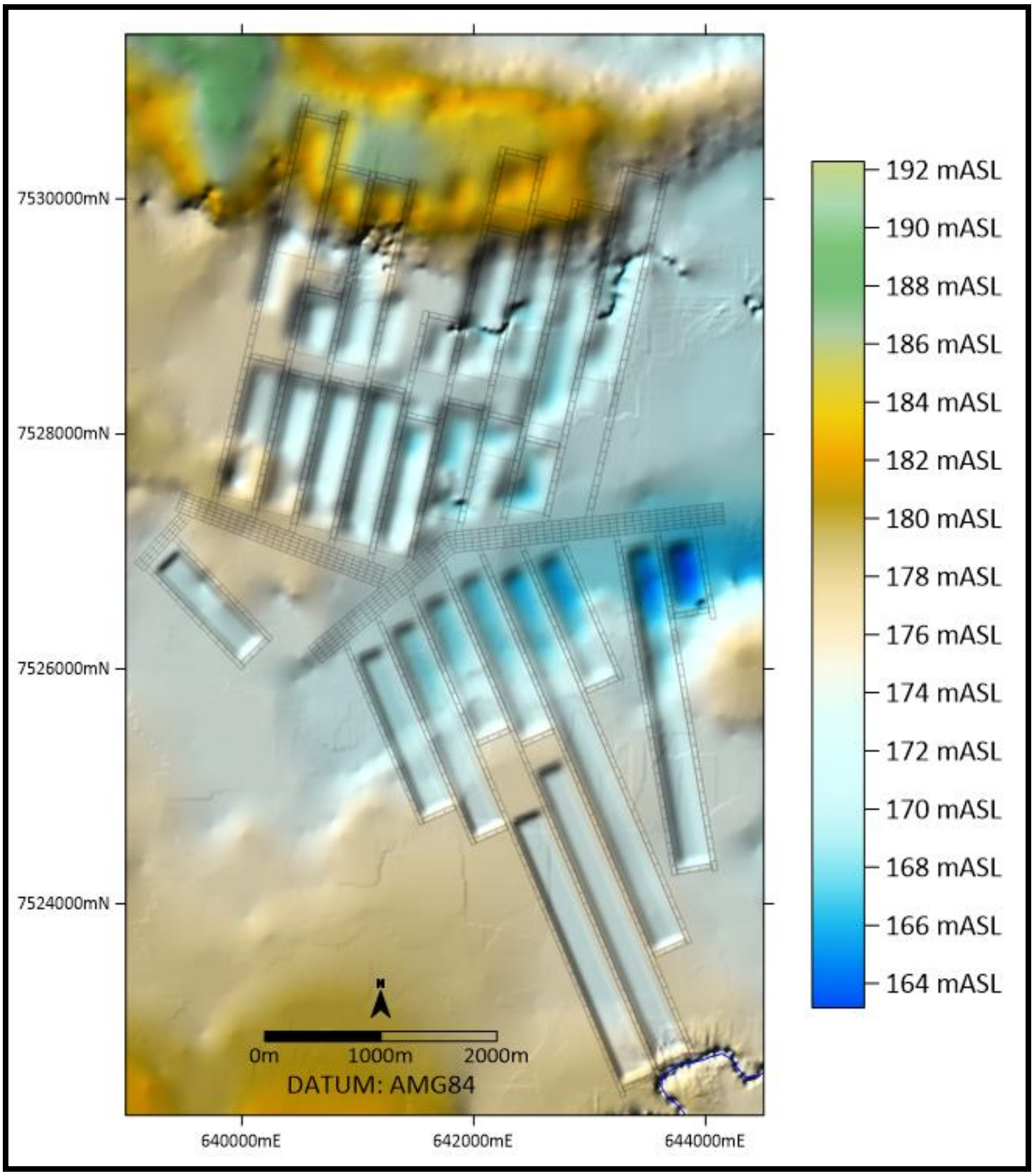


Figure 37. Post Mining Topography after Extraction of both the LHL and VL Seams (Z=25).

4.2 Horizontal Movements

As well as vertical movement, horizontal ground movements also occur at the surface due to underground mining. These movements are more relevant if key surface infrastructure is located above the longwall extraction area.

The maximum horizontal ground movements predicted at the surface above the Meadowbrook longwall area are typically less than 1 m in the southern Vermont Lower Seam area (**Figure 38**). Higher horizontal ground movements, up to 1.6 m, are predicted in the northern part of the area where both seams are extracted (**Figure 38**).

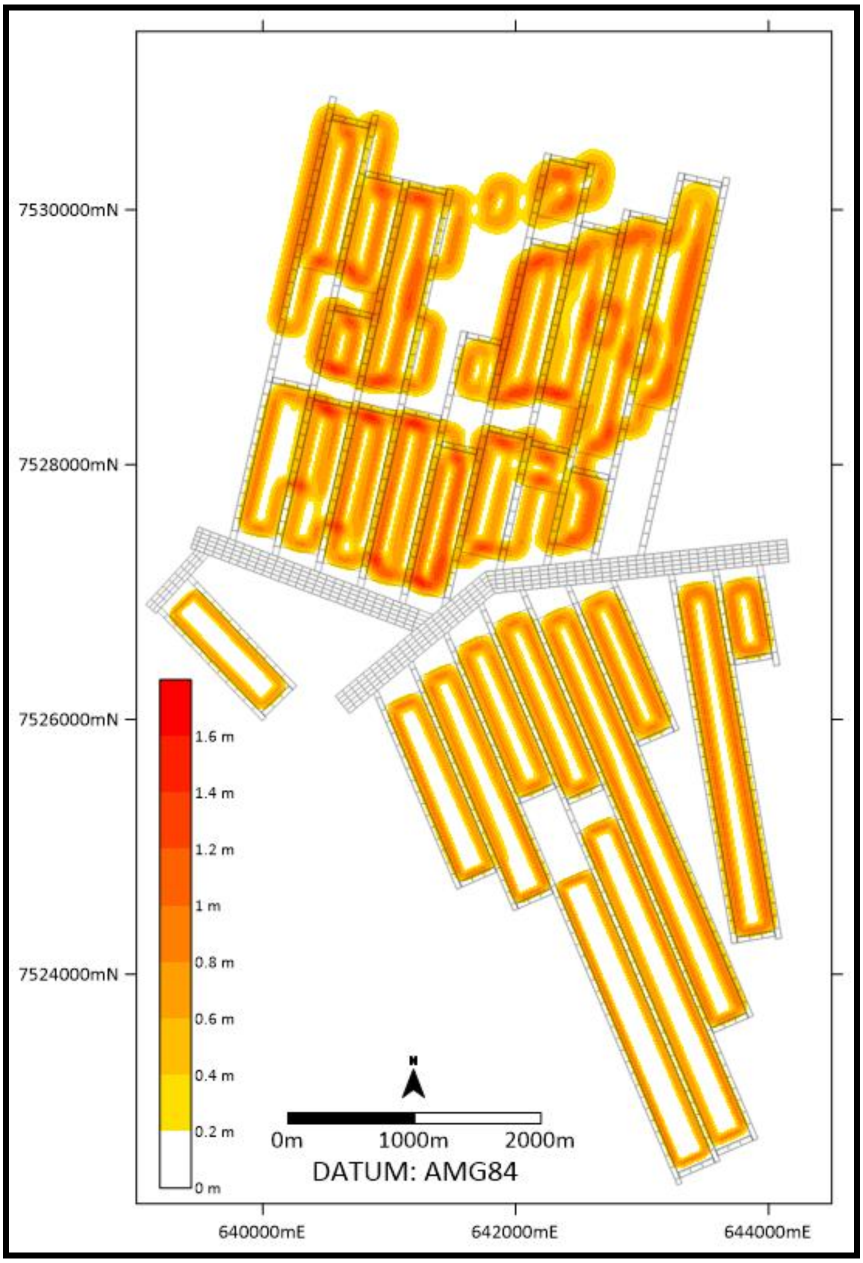


Figure 38. Horizontal Movement after Extraction of both the LHL and VL Seams (m).

4.3 Strain

Surface strain is caused by bending and horizontal movements in the strata. Measured strain is determined from monitored survey data by calculating the horizontal change in length of a section of a subsidence profile and dividing this by the initial horizontal length of that section.

The maximum tensile strains due to extraction in the Meadowbrook longwall mining area, range in magnitude up to 24 mm/m (**Figure 39**). Maximum compressive strains range up to 28 mm/m (**Figure 39**).

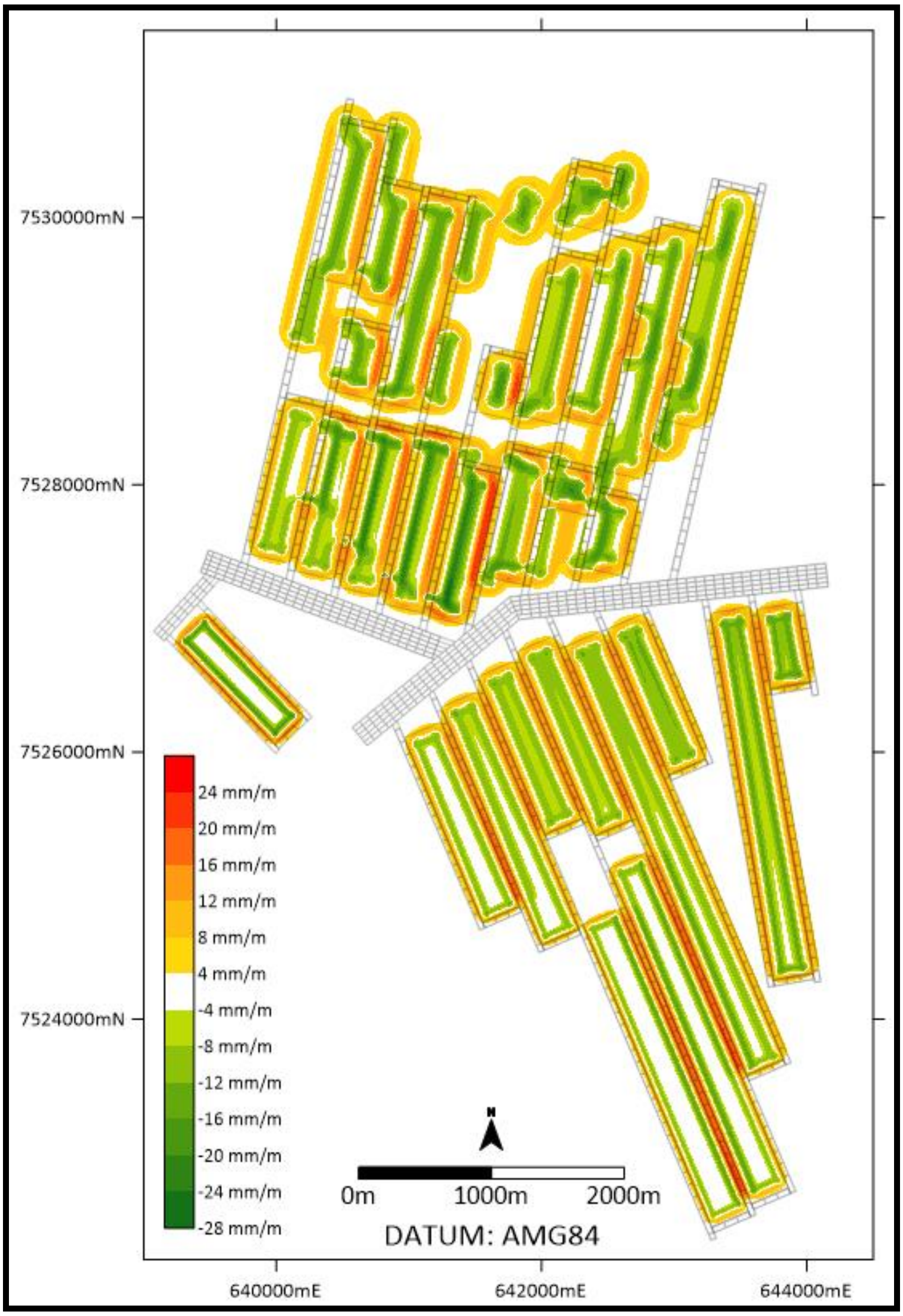


Figure 39. Strain after Extraction of both the LHL and VL Seams (mm/m).

4.4 Tilt

Tilt is the slope of subsided land over a given distance and is calculated by determining the change in subsidence between two points and dividing this by the distance between those points. The physical result of this is that post mine surface slopes become steeper in localized areas along the edges of the subsidence troughs.

The maximum tilts developed due to longwalling in the Meadowbrook area range up to 3.8% or 38 mm/m (**Figure 40**).

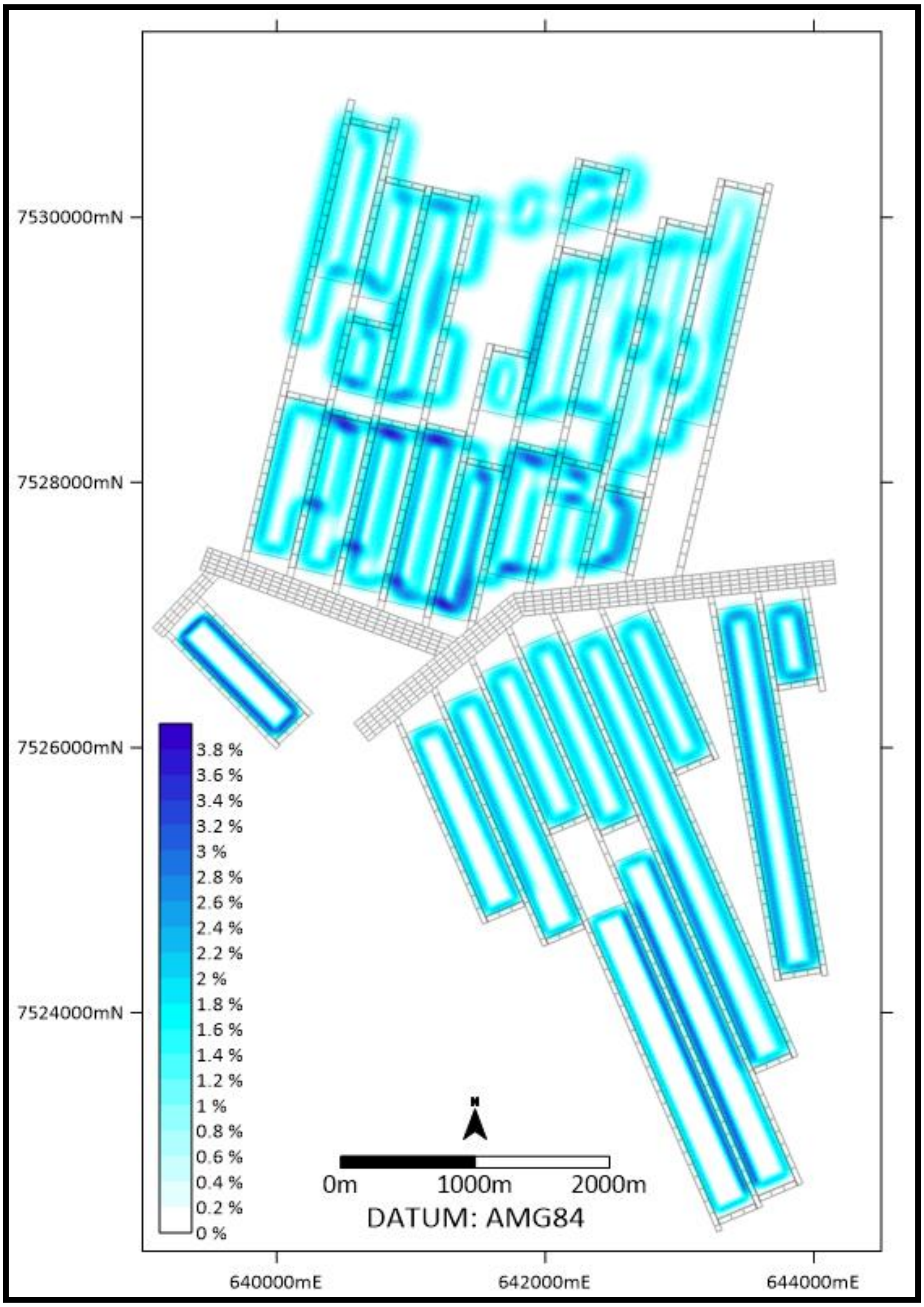


Figure 40. Tilt after Extraction of both the LHL and VL Seams (%).

4.5 Limitations of the Subsidence Predictions

The subsidence predictions are final subsidence values after longwall mining is completed. The nature of the longwall mining method means that subsidence does not increase further over time. Based on subsidence monitoring at other mines in the Bowen Basin typically greater than 97% of the maximum subsidence will occur within 6 weeks after longwall mining is completed, assuming an industry average retreat rate of 100 m/week.

Based on the available data for the Meadowbrook longwall mining area, there are no localised features or variations in the geology, geotechnical conditions or surface topography that are considered likely to result in any significant deviations from the subsidence predictions presented in this report. The faulting regime in the Meadowbrook area suggests that there is a possibility that non-vertical faults, whilst avoided at seam level, may impact to some degree on surface deformations if they hade over the longwall extraction area.

As is good engineering practice, a review of the predictions should be conducted as any new geological/geotechnical data and subsidence monitoring becomes available. This practice can be implemented through the Subsidence Management Plan, requiring a review by a suitably qualified and experienced person.

Overall, the subsidence predictions are based on well-established methodologies that have been proven to provide reliable predictions at numerous similar mining operations. In any areas of uncertainty, conservative assumptions have been applied. The predictions are therefore considered suitable for assessing the potential significant impacts of subsidence on the environment.

5 OVERVIEW OF GENERAL SUBSIDENCE EFFECTS

The previous section has documented the predicted surface deformations associated with longwalling in the Meadowbrook area. This section reviews the effects that these deformations may have on both the overburden rock mass and the surface.

5.1 Subsurface Cracking

5.1.1 Background to Subsurface Subsidence Cracking

Longwall mining methods can induce a range of subsurface subsidence effects. In the context of changes to the hydrogeological regime, the key issue associated with longwall subsidence is the creation of subsurface subsidence cracks in the rock mass. These cracks may provide new flow paths for groundwater and alter the permeability of the strata overlying longwall mining areas. The potential changes in the hydrogeological characteristics of the rock mass are dependent upon a number of variables that may affect the behaviour of subsurface subsidence cracking, such as:

- Mine geometry.
- Extracted seam thickness.
- Thickness and geomechanical properties of the overburden.
- Presence of tuffaceous horizons that may restrict the vertical flow of groundwater and
- The bulking and compaction of the goaf material.

For operating longwall mines, it is possible to measure key subsurface subsidence cracking characteristics including the height of cracking above the extracted coal seam. This information can be correlated to measured changes in the water regime, for example decreases in groundwater levels in boreholes or inflows to underground mining areas. This provides accurate site-specific data on the known characteristics and impacts of subsurface subsidence cracking within the geological sequence.

A range of different methodologies are used to determine the heights of subsurface subsidence cracking associated with existing mining operations, such as:

- Borehole extensometers.
- Piezometer records.
- Drilling records.
- Comparison of permeability testing and
- Microseismic monitoring.

5.1.2 Prediction of Subsurface Subsidence Cracking Effects due to Single Seam Extraction

The prediction of subsurface subsidence cracking above single seam extraction longwall panels has been extensively studied using both empirical and numerical modelling methods.

Models based upon empirical evidence such as observation and measurement are commonly used to predict the effects of subsidence. Empirical hydrogeological models for subsided strata are typically based on the interpretation of water inflow events.

A commonly referenced empirical model developed for predicting subsurface subsidence cracking effects on groundwater and surface water is the Bai and Kendorski (1995) model (**Figure 41**). The key principle of this model is that subsurface subsidence cracking can be characterised by the following zones:

- **Constrained** zone – unaffected by subsurface subsidence cracking.
- **Dilated** (or **discontinuous** cracking) zone – no changes in vertical permeability, possible changes in horizontal permeability and storativity.
- **Fractured** (or **continuous** cracking) zone – changes in vertical and horizontal permeability are possible.

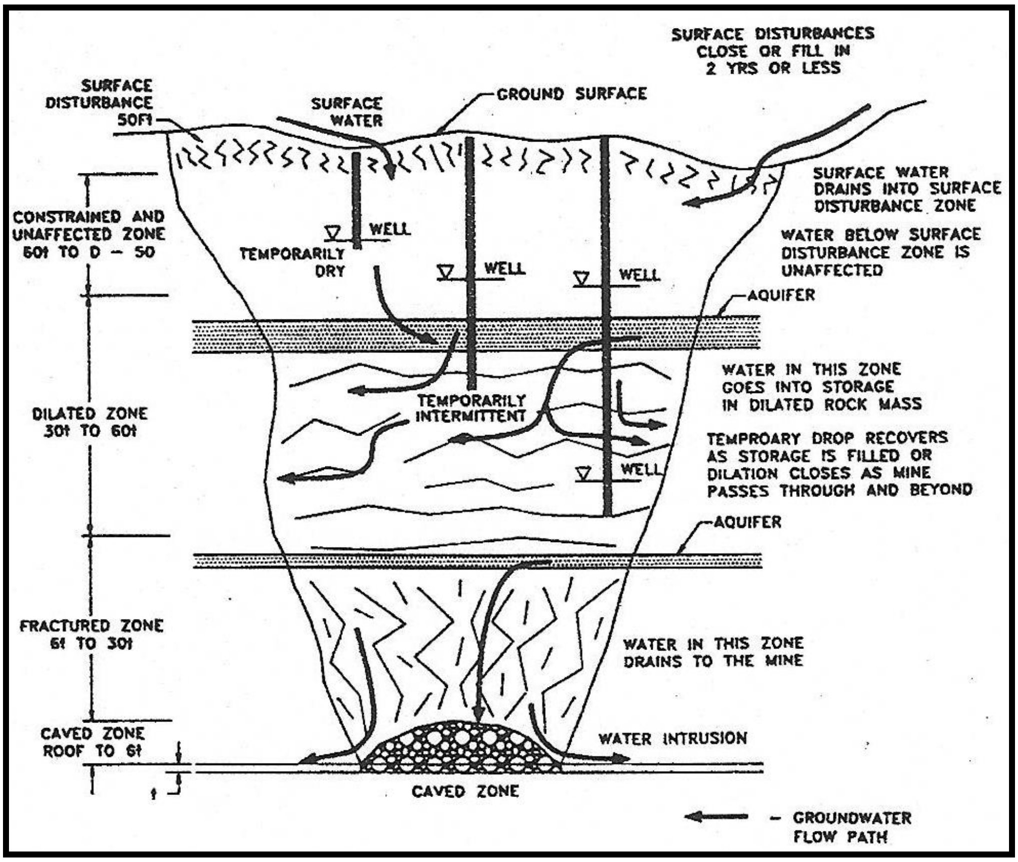


Figure 41. Hydrogeological Model for Fracturing above Longwalls (Bai and Kendorski, 1995).

In this model, cracking within the **dilated** (or **discontinuous** cracking) zone is dominantly horizontal, with negligible vertical cracks. In this zone, there may be an increase in horizontal permeability but this is not likely to result in significant inflows to the underground workings. The **fractured** zone nomenclature is related to the zone of vertical hydraulic connectivity (or unrestricted **continuous** inflow) and does not imply the limit of all cracking.

This hydrogeological model concludes that water will enter an underground mine or be lost from an aquifer or surface water body if:

- The zone of **continuous** subsurface cracking intersects the water body, or
- There is a connection between the **continuous** subsurface cracking zone and any surface subsidence cracking.

The heights of subsurface subsidence cracking in hydrogeological models such as that of Bai and Kendorski are related to extracted coal thickness. In **Figure 41**, the **fractured** zone is shown to range from 6 to 30 times the extracted seam thickness.

Measured data taken from comparable mining operations in equivalent geology can also be used to assist with the prediction of the likely extent of each subsurface cracking zone and, in particular, the boundary between **discontinuous** and **continuous** zones of subsurface subsidence cracking.

Alternative models such as Ditton and Merrick (2014) and Tammetta (2014) are available, which relate the height of continuous cracking to the seam thickness, panel width, depth and overburden geology. However, the overall concept of dividing the rock mass into different cracking zones is common to all methods and is a well-established and valid approach to explain the measured differences in field observations arising from subsurface subsidence cracking (Gale, 2008).

As detailed by Byrnes Geotechnical (2022), these models are valid for assessing water inflows into the underground workings. More recently however, PSM (2017) have documented monitoring data from Dendrobium mine in NSW, where it was concluded that a 310 m wide longwall panel, at 350 m depth of cover, connected fracturing to the surface and impacted a shallow groundwater system.

Of significance, this data is from NSW and similar connection to the surface has not been identified in the Bowen Basin. However, it is recognised that there is a possibility of low conductivity fracture connection to the surface in the Meadowbrook area and this should be considered in the groundwater modelling.

The behaviour of the subsided rock mass can also be assessed using numerical modelling methods. Commercially available modelling software includes the Fast Lagrangian Analysis of Continua (FLAC) model. Numerical modelling of subsurface cracking requires robust calibration, verification and validation to minimise the potential for erroneous results and requires reference to measured data.

Consequently, numerical modelling would not provide a higher level of accuracy than empirical methods in the prediction of subsurface cracking, as the basis of the predictions would be essentially the same.

5.1.3 Prediction of Subsurface Subsidence Cracking Effects due to Dual Seam Extraction

GGPL is not aware of empirical studies examining the height of subsurface cracking above dual seam longwalls, however, some physical modelling work by Ghabraie and Ren (2014) is detailed below to provide an understanding of the subsurface strata movement in a dual seam longwall mine.

Ghabraie and Ren built a physical model to investigate the mechanism of surface and subsurface movements of the strata in a dual seam longwall environment (**Figure 42**). The upper seam, located 24 m above the lower seam, was extracted first. The panel width in both seams was 120 m and the extraction height was 4.5 m. The depth of cover above the upper seam was 80 m, indicating supercritical subsidence behaviour (panel width to depth of cover ratio of 1.5).

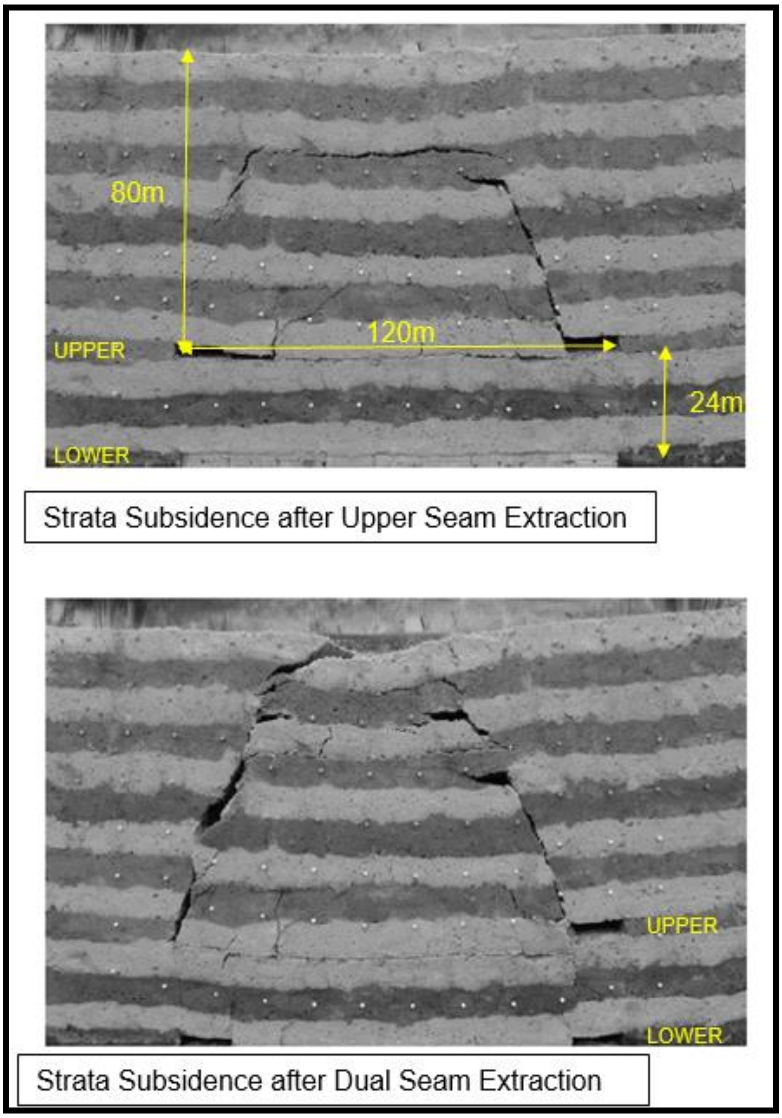


Figure 42. Results of Physical Modelling of Dual Seam Subsidence (Ghabraie and Ren, 2014).

As shown in **Figure 42**, some reworking of the upper seam goaf occurs when the lower seam is extracted. The model indicates that the height of cracking above the upper seam is increased once both seams are extracted. It is noted that additional cracking was not observed outside the previously caved zone. A conceptual model for this reworking of the upper seam goaf is shown in **Figure 43**.

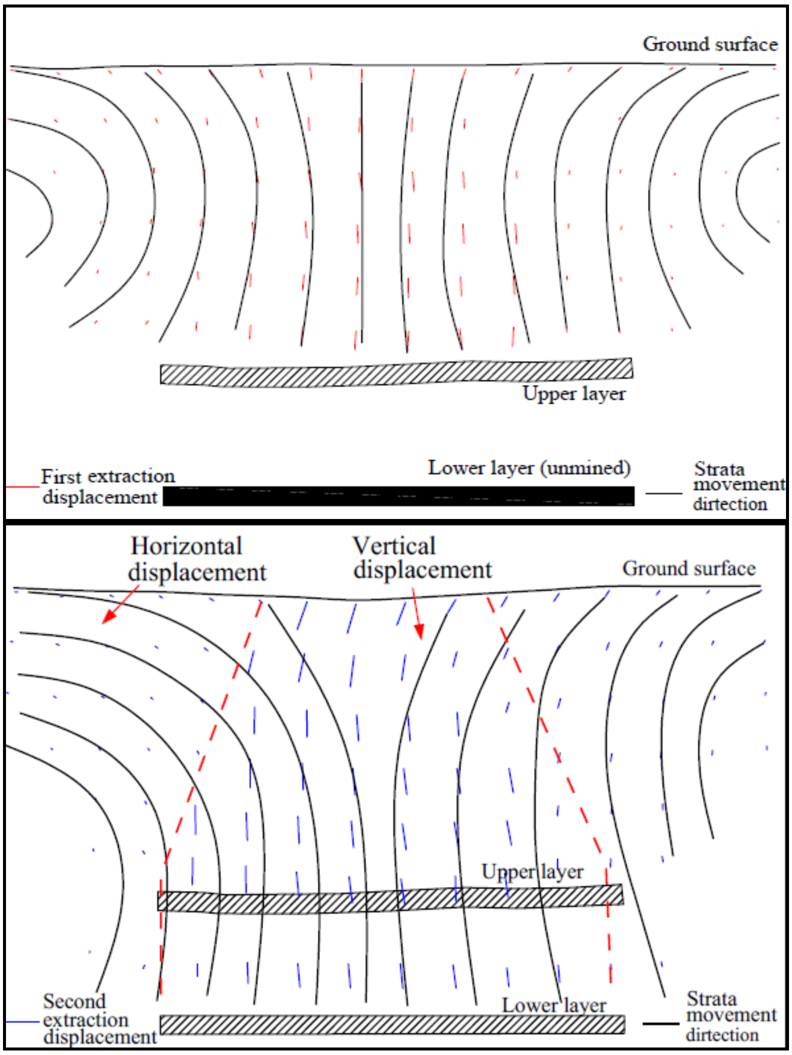


Figure 43. Displacement Profiles of Upper and Lower Seam Extraction (Ghabraie and Ren, 2014).

The interburden between the seams in the Meadowbrook area is 20-30 m and similar to the Ghabraie and Ren model in **Figure 42**. The extraction height is also similar to the thicker parts of the Leichhardt Lower and Vermont Lower Seam longwall areas. It is noted that the depth of cover and panel width are somewhat less than in the Meadowbrook area, albeit supercritical behaviour was still modelled.

In summary, whilst the physical model has some differences to the proposed dual seam mining in the Meadowbrook area, it provides useful insight to the potential subsurface cracking mechanism, particularly the reworking of the upper seam goaf material.

Ghabraie and Ren (2014) found that the initial cracks formed by the extraction of the upper seam could change the crack propagation above the lower seam. Subsidence from the extraction of the lower seam opens up existing cracks and induces greater bedding separation. This is highlighted by the different displacement profiles for the two mining scenarios (**Figure 43**).

The subsurface strata cracking profile after extraction of the upper seam shows a balanced movement between horizontal and vertical components (**Figure 43**). In comparison, after the lower seam is extracted, the vertical movement is mainly restricted to a wedge shaped area, shown by dotted red line in **Figure 43**. Outside this wedge area, the horizontal displacement is the predominant displacement component.

5.1.4 Comparative Assessment of Subsurface Subsidence Cracking Predictions for Single Seam Extraction

5.1.4.1 Microseismic Monitoring Data

Microseismic monitoring involves the use of geophones installed in boreholes to record the development of fractures by measuring microseismic events. Microseismic monitoring is one of the most reliable tools for determining the interface between continuous and discontinuous subsurface subsidence cracking. Published monitoring data is available from two Bowen Basin longwall mines.

At North Goonyella Mine, microseismic monitoring of a 250 m wide longwall panel, at approximately 150 m depth of cover was carried out. The extraction height was up to 4 m high. As shown in **Figure 44**, the majority of microseismic events occur within 120 m of the extracted seam. These results indicate the monitored limit of continuous cracking is 120 m.

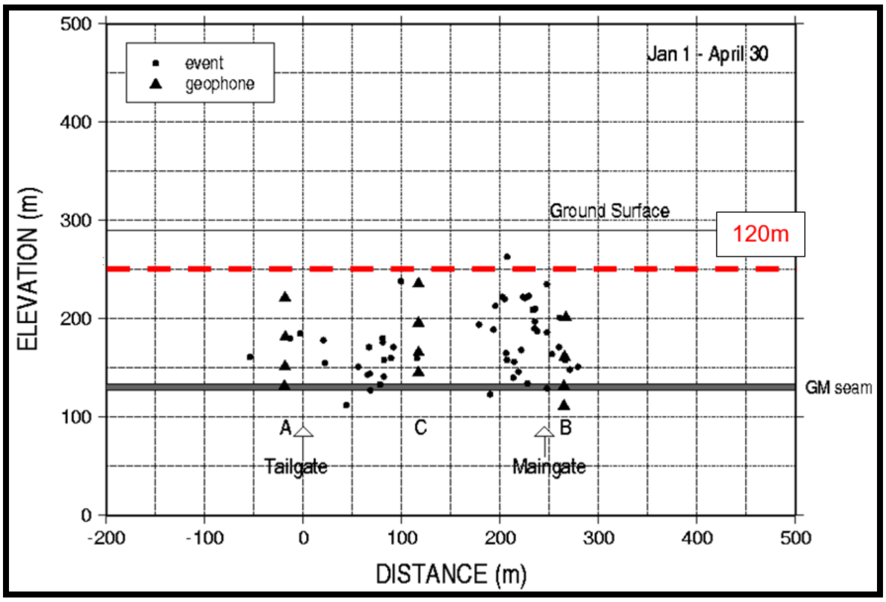


Figure 44. Location of Microseismic Events above LW3 at the North Goonyella Mine (Kelly and Gale, 1999).

Similarly, microseismic monitoring above the 200 m wide, LW101 panel at Kestrel Mine indicates a marked reduction in events (i.e. cracking) at 90 m above the seam (**Figure 45**). This was taken to be the limit of monitored continuous cracking. No microseismic events were recorded higher than 120 m above the extracted seam (**Figure 45**). The depth of cover and extraction height in this area of the mine was 220 m and 3 m, respectively.

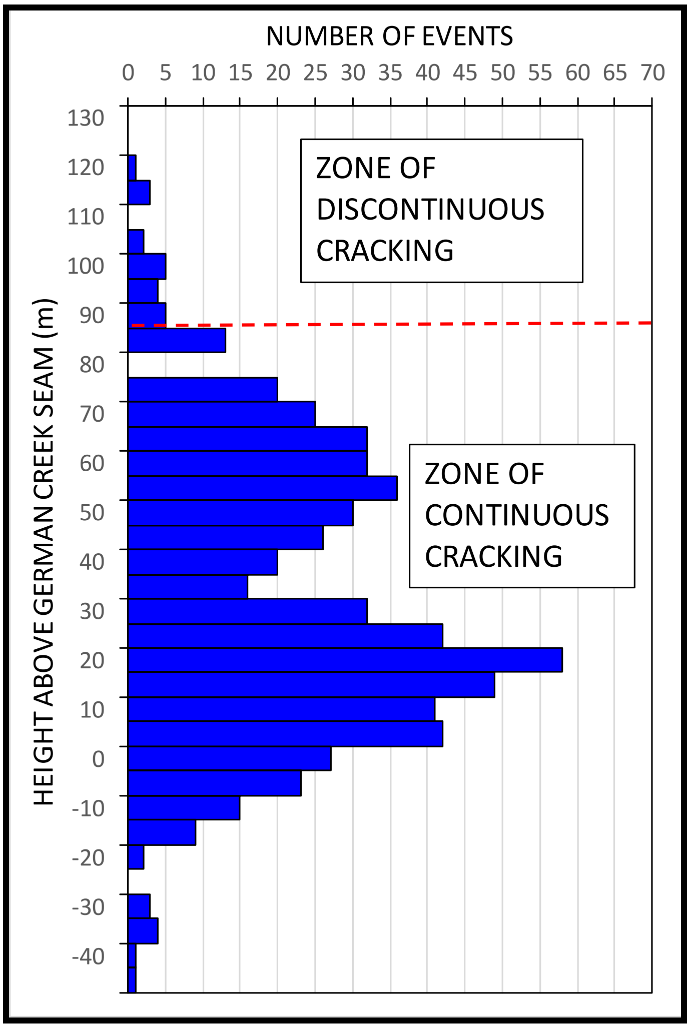


Figure 45. Location of Microseismic Events around LW101 at Kestrel Mine (Reproduced from Kelly and Gale, 1999).

5.1.4.2 Water Inflow Events in the Bowen Basin

Seedsman and Dawkins (2006) provide a comprehensive summary of subsurface subsidence cracking and water inflow events in the Bowen Basin. Seedsman and Dawkins report that:

- No major **surface water** inflows to longwall mining areas have occurred in the Bowen Basin where the depth of cover has exceeded **120 m**; and

- No major groundwater inflows to longwall mining areas have occurred in the Bowen Basin where the distance from the seam to the **aquifers** is more than approximately **90 m**.

Klenowski (2000) reports on the inflow of water at the Oaky Creek Mine and the German Creek mining complex in the central part of the Bowen Basin. These mines target the German Creek Coal Measures, which comprise a sequence of sandstones, siltstones, mudstones and coal seams.

Klenowski concluded that unrestricted inflow (i.e. from the zone of **continuous** cracking) generally occurs to a height of about 120 m above the active mine area. The inflow rates for different heights of cracking in the German Creek mining complex, as well as other comparable mining operations, extracting single seam longwalls, throughout the Bowen Basin, Australia and overseas, are plotted in **Figure 46**.

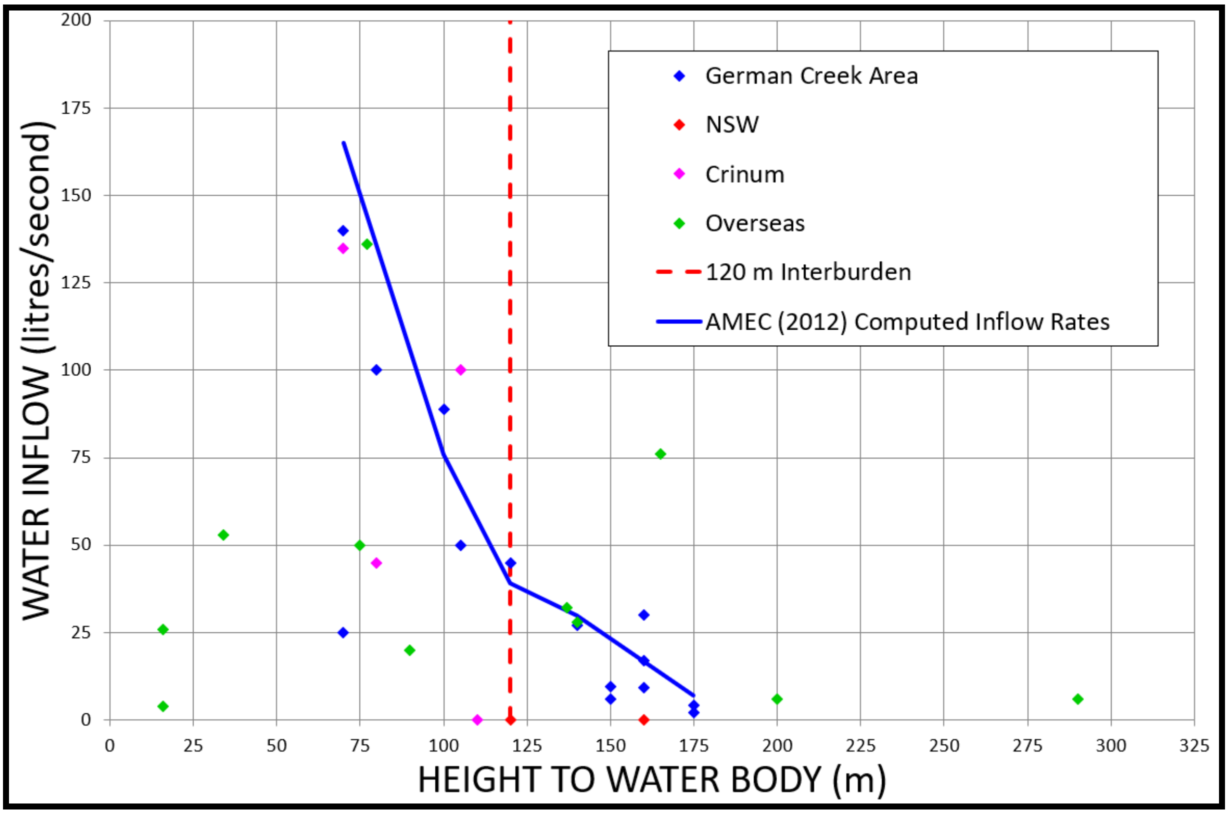


Figure 46. Summary of Water Inflow Events.

Evidence from Crinum Mine and Kestrel Mine, suggests that the presence of Tertiary clay materials in the overburden within the cracking zone may have retarded water inflow rates to underground workings (Seedsman and Dawkins (2006) and Gale (2008)).

5.1.4.3 Numerical Modelling

Published numerical modelling studies by Gale (2008) in the Oaky Creek area showed a distinct decrease in the vertical conductivity to around 10^{-6} m/s, at beyond 90 to 100 m above the coal seam (**Figure 47**). This is also consistent with the field observations described above. The progressive reduction in vertical conductivity from 1 m/s close to the extracted seam, decreasing to 10^{-4} m/s at the top of continuous cracking zone is shown in **Figure 47**.

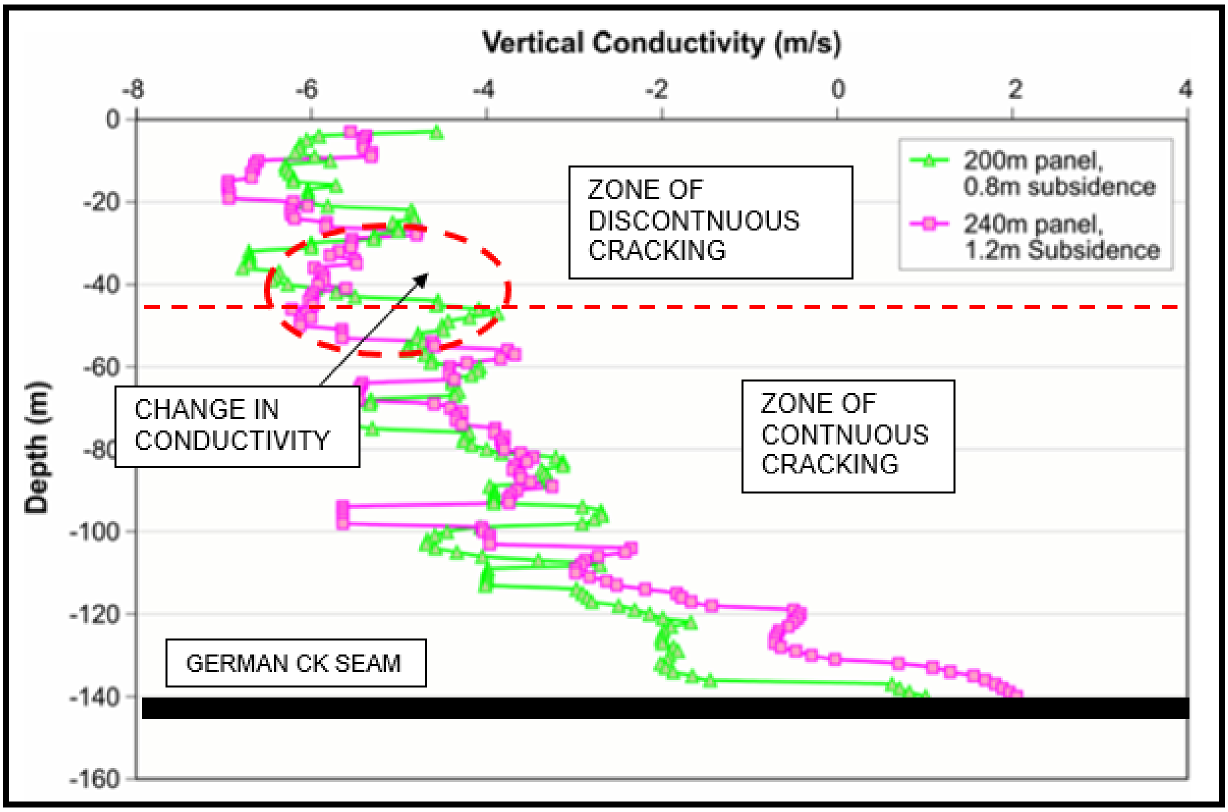


Figure 47. Vertical Conductivity through a Numerical Model in the Southern-Oaky Creek Area (Gale, 2008).

5.1.4.4 Summary of Data

Field observations of heights of subsurface subsidence cracking from mines in QLD, NSW and overseas are summarised in **Table 1**.

Gale (2008) also reports that 105 m of rock head is used as a standard buffer distance to minimise the risk of inflow events in the UK.

These thicknesses are consistent with monitoring conducted in NSW mines, where the potential for surface water to flow into underground longwall workings is recognised if the longwall panel is less than 100 m to 150 m below the surface.

Mining Area	Height of Cracking	Discussion/Evidence
Crinum, QLD	90-100 m	Height to overlying basalt/sand aquifers in the Tertiary (Seedsman and Dawkins, 2006).
NSW	100-150 m	The potential for surface water to flow into underground longwall workings is recognised if the longwall panel is less than 100 m to 150 m below the surface (Seedsman and Dawkins, 2006).
Oaky Creek and German Creek, QLD	<160 m	For ponded water at cover depths greater than 160 m, remedial works are generally not required and standard underground pumping systems are capable of handling minor increases in flow (Klenowski, 2000). Unrestricted inflow generally occurs to a height of about 120 m above the active mine area, with inflow rates progressively reducing as the depth of cover increases above 120 m (Klenowski, 2000).
Kestrel, QLD	<115 m	Microseismic monitoring of LW101. (Kelly and Gale, 1999).
North Goonyella	<120 m	Microseismic monitoring of LW3. (Kelly and Gale, 1999).
Wyee, NSW	40-63 m	Wide panels and strong, massive roof strata (Forster and Enever, 1992).
Cooranbong, NSW	58 m	Wide panels and strong, massive roof strata (Forster and Enever, 1992).
Wistow Mine, UK	77 m	Limestone aquifer (Whittaker and Reddish, 1989).
UK	<105 m of rock head	Guideline to minimise the risk of inflow (Gale, 2008).
Northern Bowen Basin	<170-250 m	Longwalls (312 m wide and 4.5 m high) successfully extracted beneath the Isaac River.

Table 1. Field Observations and Guidelines for the Height of Cracking.

5.1.5 Conclusions

The estimation of the height and behaviour of subsurface subsidence cracking is a complex issue and there is no simple calculation to estimate the height of the continuous and discontinuous zones.

5.1.5.1 Single Seam Extraction

Based upon the measured data, microseismic monitoring and empirical guidelines the subsurface subsidence cracking predictions due to single seam longwall extraction of either the Leichhardt Lower or Vermont Lower seams can be summarised as:

- A zone of **continuous** cracking extending up to **120 m** above the extracted seam; and

- A zone of **discontinuous** cracking extending no higher than **180 m** above the extracted seam.

This is consistent with the available data from other longwall mining operations in QLD, NSW and overseas and hence provides a robust basis for the assessment of potential groundwater impacts into the underground workings associated with continuous cracking in single seam longwall mining areas.

Based on experience from NSW, it is recognised that there is also a possibility of low conductivity fracture connection to the surface in the Meadowbrook area above the discontinuous cracking zone and this should be considered in the groundwater modelling.

5.1.5.2 Dual Seam Extraction

The estimation of the height and behaviour of subsurface subsidence cracking for dual seam mining is further complicated by the lack of monitoring data available. The physical model studies detailed earlier provide a better understanding of the failure mechanisms in the overburden.

Due to potential weakening of the overburden strata in the **discontinuous** cracking zone above the Leichhardt Lower Seam, by the extraction of the Vermont Lower Seam, the zone of **continuous** cracking is conservatively inferred to extend to **180 m** above the Leichhardt Lower Seam extraction.

This 50% increase from the predicted continuous cracking height for single seam extraction should more than adequately account for the uncertainty associated with dual seam extraction and therefore provide a conservative basis for the purposes of assessing potential worst case groundwater impacts.

As detailed above, the possibility of low conductivity fracture connection to the surface above the discontinuous cracking zone, after the extraction of both target seams, should also be considered in the groundwater modelling.

5.1.5.3 Connective Cracking to the Surface

In any areas where the depth of cover to the extracted coal seam is less than the combined height of the continuous cracking and surface crack depth, continuous cracking to the surface could occur leading to significant inflows of potential water sources to the underground workings.

In the southern part of the area, where only the Vermont Lower Seam is extracted, the depth of cover above the longwall panels is 125-330 m, the extension of continuous cracking to the surface is not anticipated.

Similarly, in the northern part of the area, the depth of cover is >270 m where both seams are extracted. Even assuming a conservative 180 m height for continuous cracking, significant water inflows from surface water bodies are not anticipated.

In the overlying zone of discontinuous cracking there may be an increase in horizontal permeability but this increase is not likely to result in significant inflows to the underground mine workings. Above the discontinuous cracking zone, the conductivities are predicted to be even lower. For completeness, these have been included in the groundwater model for the Meadowbrook underground area.

In terms of surface watercourses, where Phillips Creek is located closest to the Vermont Lower Seam longwall panels, the depth of cover is >150 m and the angle of draw is >26.5^{o}. In this area, no interconnection is anticipated.

Similarly, where One Mile Creek flows over the southern Vermont Lower Seam longwall panels the depth of cover is 240-320 m and again no significant interconnection with the underground workings is anticipated.

In the northern part of the area, where longwall extraction is carried out in both seams below Boomerang Creek, the predicted 180 m height of continuous cracking above the Leichhardt Lower Seam is located well below the minimum depth of 320 m.

5.2 Surface Cracking

5.2.1 Overview

The differential lowering of the ground surface due to subsidence creates areas of residual tensile strain around the perimeter of the subsidence troughs. After longwall mining has been completed, permanent tension cracks can potentially develop in the areas of residual tensile strain.

Although the zone of residual strain (i.e. the zone where surface subsidence cracking can occur) is generally located around the perimeter of each longwall panel, the exact location and extent of the zone of residual strain for a particular longwall panel varies depending on the depth of cover, panel and pillar width, and the geology. Less surface cracking (both in terms of number of cracks and size of cracks) occurs when mining is undertaken at greater depths, compared to shallower mining.

Transient tension cracks may also form in areas of transient tensile strain above the retreating longwall. However, these cracks typically close again after a short period (within days) as the longwall retreats and the transient subsidence wave and associated transient tensile strain passes.

5.2.2 Tension Cracks

Subsidence related cracking of the surface will develop in the Meadowbrook longwall mining area. Whether it is discernible from the natural cracking that characterises some of the soils of the Meadowbrook longwall mining area will depend on the interaction between the cracks, the soil, and water. The areas with the highest potential for cracking are those located at the panel edges where the maximum tensile strain occurs (**Figure 39**).

5.2.2.1 Single Seam

Experience from operating single seam longwall extraction mines in the Bowen Basin indicates the majority of subsidence cracks in the Meadowbrook area are anticipated to be <1 m deep. This is confirmed by the excellent database of crack parameters that has been recorded at Grasstree Mine above twelve longwall panels at depths of 260-500 m, similar to the Lake Vermont area.

At Grasstree, characteristics such as crack depth, length and width are recorded along transects located 50 m and 100 m either side of the chain pillars in the area of maximum tensile strain. Every crack is surveyed and labelled in the field to assist the rehabilitation and ongoing crack maintenance process.

As shown in **Figure 48**, the average crack depth is 0.51 m, with >90% <1 m deep. It should be highlighted that this average is based on a very large data set of 870 cracks (**Figure 48**).

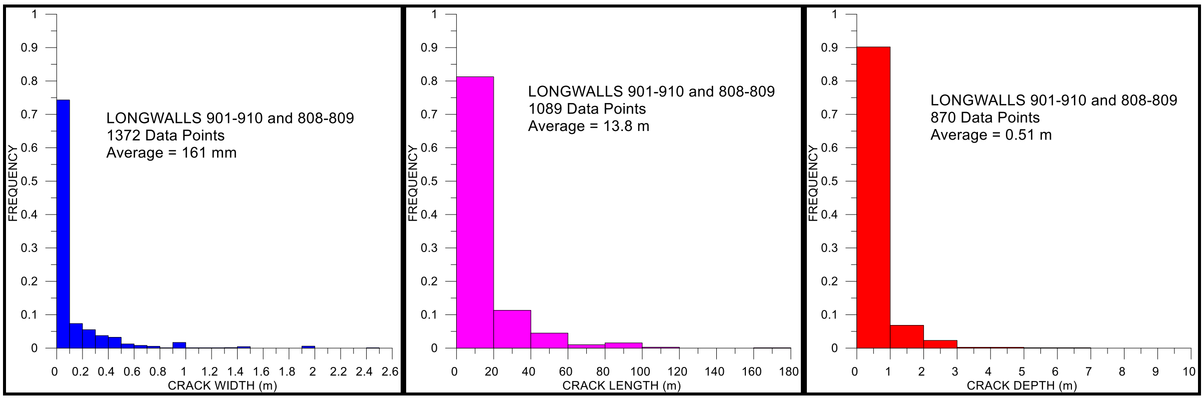


Figure 48. Crack Data – Grasstree Mine (GGPL, 2021).

It is noted that based on the principles of fracture mechanics, there is likely to be a direct relationship between crack width and crack depth i.e. narrow surface cracks will be shallower than wide cracks.

MSEC (2007) also proposed a relationship between crack width and depth of cover with the severity and frequency of surface cracking reducing as the depth of cover increases (**Figure 50**). This relationship is also evident at Grasstree, as the depth of cover increases (**Figure 49**).

Based on **Figure 50**, and experience at a number of operating Bowen Basin longwall mines, maximum crack widths up to 200 mm could be expected in the shallower parts of the Meadowbrook longwall area, decreasing to <50 mm wide in the deeper areas (**Figure 50**).

Figure 49. Narrow Cracks at 480 m Depth of Cover – Grasstree Mine.

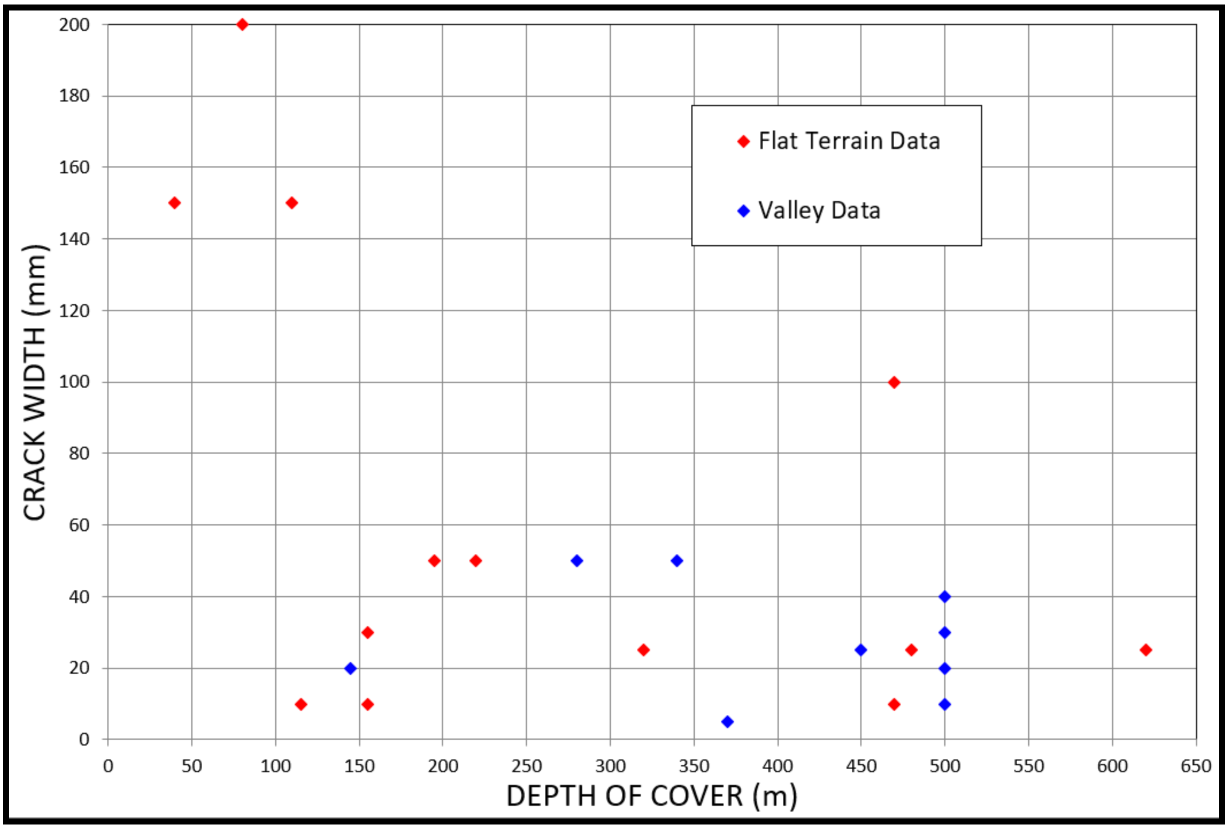


Figure 50. Crack Width and Depth of Cover (reproduced from MSEC, 2007).

5.2.2.2 Dual Seam

Similar strains are anticipated in the dual seam mining areas and some reworking and widening of existing cracks is predicted.

5.2.2.3 Prediction

Based on experience at a number of operating Bowen Basin longwall mines, maximum crack widths up to 200 mm could be expected above the shallower longwalls, decreasing to less than 50 mm in the deeper parts of the Meadowbrook longwall mining area during single seam extraction. Some reworking and widening of existing cracks is anticipated in dual seam mining areas.

The maximum predicted depth of cracking above the longwall panels in the Meadowbrook longwall mining area is 10-15 m, with the majority of cracks predicted to be less than 1 m deep.

Cracks of this width and depth are amenable to small scale rehabilitation works that are routinely carried out at other longwall mines in the Bowen Basin such as Grasstree (**Figure 51**). This typically involves stripping of the topsoil, excavating and backfilling of the cracks. The topsoil is then respread over the area and the site allowed to regenerate naturally from the seed bank in the topsoil, as well as from rootstock and recruitment from adjacent vegetation.

As shown in **Figure 51**, all cracks at Grasstree are also photographed both pre- and post-rehabilitation work. This rehabilitation process can be documented in a Subsidence Management Plan (SMP).

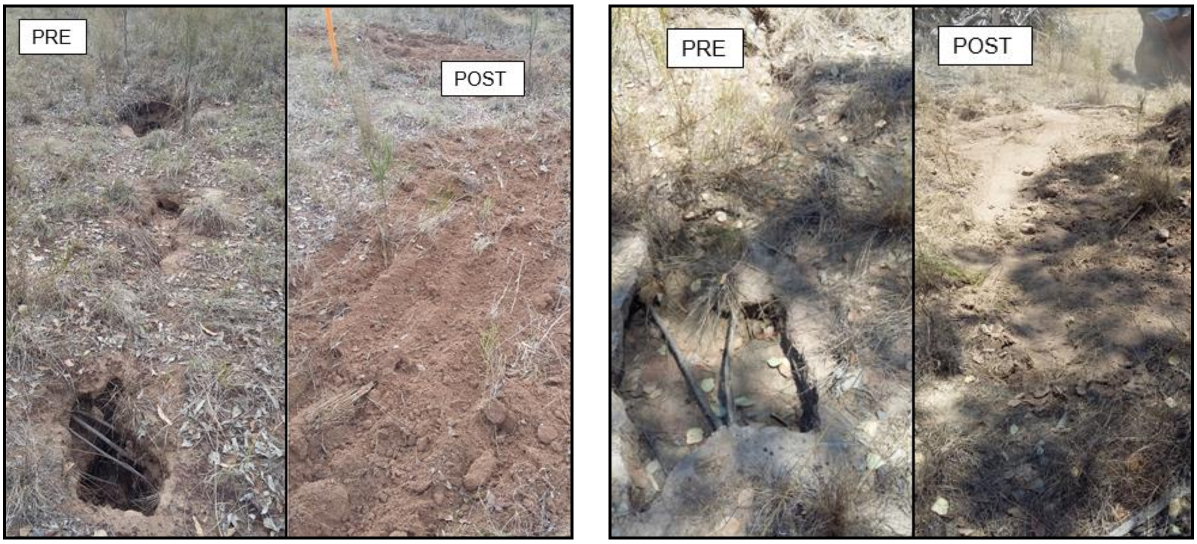


Figure 51. Examples of Crack Rehabilitation at Grasstree Mine (GGPL, 2020).

5.3 Buckling and Heaving

When the near-surface strata break, the resulting blocks of rock interact and can produce localised movements. As well as surface cracking, other subsidence effects include buckling and heaving of the surface.

These types of effects tend to occur less frequently than tension cracks and occur more commonly within the centre of the longwall panel area, rather than around the perimeter.

5.4 Surface Drainage Effects

Subsidence can result in the formation of localised depressions in the surface topography that can cause ponding of surface drainage. The post-subsidence surface topography has been used to assess the potential for ponding detailed in the Surface Water Section of the Meadowbrook EIS.

The surface inspections at Grasstree mine also include the section of German Creek where it has been subsided up to 1.8 m by longwall extraction. As shown in **Figure 52**, there are no visual indications of longwall mining below the creek in this area.

Figure 52. German Creek above Extracted Longwall Panels – Grasstree Mine.

6 CONCLUSIONS

The key conclusions from this report include:

1. Based on subsidence data from the Bowen Basin, the following parameters were used for modelling in the proposed Meadowbrook longwall mining area:

    - Panel Adjustment Factor of 0.2.
    - Influence Angle of 70º.
    - Maximum Subsidence Factor of 65% for extraction in virgin ground and 95% for Vermont Lower Seam extraction below Leichhardt Lower Seam goaf areas.
    - Strain Coefficient of 0.35.

2. The maximum vertical subsidence ranges from 2.9 m in the southern part of the area where the Vermont Lower Seam is extracted, up to a maximum of 5 m in the northern part of the area where both the Leichhardt Lower and Vermont Lower seams are extracted.

3. The maximum tensile strains due to longwall extraction range in magnitude up to 24 mm/m. Maximum compressive strains range up to 28 mm/m.

4. The maximum tilts developed range up to 3.8% or 38 mm/m, which is equivalent to a change in slope of 2.2 degrees.

5. There is confidence in the subsidence predictions due to the amount of information available from other Bowen Basin mines. This data has allowed a good calibration to be achieved and provided a sound basis to enable conservative prediction of potential environmental impacts due to subsidence effects. It is not considered that there will be significant deviations from the current predictions due to topographic, geological or geotechnical variations.

6. Based on field measurements and observations in Australia and overseas, continuous subsurface subsidence cracking up to 120 m is predicted in the single seam extraction areas and may result potentially in inflows from potential water sources to the underground workings. This height may extend to a conservative 180 m in areas where both the Leichhardt Lower and Vermont Lower Seam are extracted. This 50 % increase in the continuous cracking height in the dual seam areas should more than adequately account for the uncertainty associated with the continuous cracking height predictions and therefore provide a conservative basis for the purposes of assessing potential worst case groundwater impacts.

7. In the discontinuous cracking zone above the continuous cracking zone, there may be an increase in horizontal permeability but this is not likely to result in significant inflows to the underground mine workings.

8. Based on experience from NSW, it is recognised that there is also a possibility of low conductivity fracture connection to the surface in the Meadowbrook area above the discontinuous cracking zone and this should be considered in the groundwater modelling.

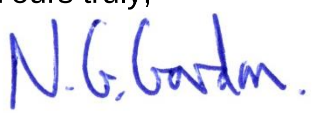
9. The depth of cover above the Meadowbrook longwall mining area indicates that subsurface subsidence cracking is not predicted to extend to the ground surface, including Boomerang, One Mile and Phillips creeks

10. Surface subsidence cracks will develop in the proposed longwall mining areas. The areas with the highest potential for cracking are those located at the panel edges where the maximum tensile strain occurs. The widest of these cracks are predicted to extend to no more than 10-15 m below ground level, with the majority <1 m deep. Maximum surface crack widths up to 200 mm could be expected in the shallower parts of the area, decreasing to <50 mm at greater depths. Some reworking and widening of existing cracks is predicted where both seams are extracted. Cracks of this size can be readily remediated.

11. In regards to post-closure stabilisation of the underground workings, the potential for unplanned subsidence is not anticipated:

    a. At the completion of mining in the Meadowbrook area, the sealing of the drifts and shafts, should be carried out using standard design practices to mitigate the risk of unplanned subsidence. The design of the bulkhead seals should consider aspects such as the materials used, the requirement for additional ground support and the impact of groundwater.
    b. Subsidence monitoring at other longwall mines, indicates that greater than 97% of the maximum subsidence will typically occur within 6 weeks after mining is completed, assuming an industry average retreat rate of 100 m/week. Residual subsidence above the longwall panels is therefore not anticipated once the longwall goaf areas have compacted.
    c. The Mains development pillars have also been designed with Factors of Safety >2.11 and high width: height ratios, to ensure long term stability. Furthermore, after mining is completed the buoyancy effect of water can reduce the vertical load on the pillars by up to 40%.
    d. Based on experience at other mining operations around the world, the risk of sinkhole subsidence occurring in the Meadowbrook area, where the depth of cover is greater than 120 m, is considered to be without known precedent.

Yours truly,



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7 BIBLIOGRAPHY

1. Agioutantis, Z. and Karmis, M. (2002). Surface Deformation Prediction Manual.
2. AUSIMM (2009). Australasian Coal Mining Practice – Monograph Series 12. Pp. 881.
3. Bai, M, and Kendorski, F.S. (1995). Chinese and North American high extraction underground coal mining strata behaviour and water protection experience and guidelines. 14th Conference on Ground Control in Mining. 209-217.
4. Byrnes R. (2003). Case studies in the application of influence functions to visualising surface subsidence. COAL2003 - 4th Underground Coal Operators Conference. AusIMM Illawarra Branch.
5. Byrnes Geotechnical Pty Ltd (2022). Review of Subsidence Prediction Report by Gordon Geotechniques Pty Ltd.
6. Carlson Website - www.carlsonsw.com.
7. Ditton, S., and Merrick, N. M. (2014). A New Sub-surface Fracture Height Prediction Model for Longwall Mines in the NSW Coalfields. Paper presented at the Australian Earth Sciences Convention.
8. Forster, I. and Enever, J. (1992). Hydrogeological response of overburden strata to underground mining, Central Coast, NSW. Office of Energy Sydney.
9. Gale, W. (2008). Aquifer inflow prediction above longwall panels. ACARP Project C13013.
10. GGPL (2020). Annual Subsidence Inspection Grasstree Mine – October 2020. Report No. Grasstree20-R1.
11. GGPL (2021). Annual Subsidence Inspection Grasstree Mine – September 2021. Report No. Grasstree21-R1.
12. GGPL (2022). Feasibility Geotechnical Assessment of the Meadowbrook Underground Area. Report No. LakeVermont22-R1.
13. Ghabraie, B and Ren, G. (2014). Investigating characteristics of strata movement due to multiple seam mining using a sand-plater physical model. Proceedings of the 9th Triennial Conference on Mine Subsidence.
14. Kelly, M. and Gale, W. (1999). Ground behaviour about longwall faces and its effect on mining. ACARP Project C5017.
15. Klenowski, G. (2000). The influence of cracking on longwall extraction. ACARP Project C5016.
16. Li G, Steuart P, Paquet, R, and Ramage, R. (2010). A Cast Study on Mine Subsidence Due to Multi-Seam Longwall Extraction Proceedings of Second Australasian Ground Control in Mining Conference Sydney N.S.W. 23-24 November 2010 pp 191-200.
17. Mills, K. and Wilson, S. (2021). Further insights into the mechanics of multi-seam subsidence from Ashton Underground Mine. Proceedings of the 2021 Resource Operators Conference. Pp. 101-114.
18. Minserve (2017). ML70528/MDL303/MDL429/MDL3001 (Lake Vermont Northwest) - Statement of Coal Resources North of ML70331 and West of the Isaac Fault. Project No. LV03M.
19. MSEC (2007). General discussion on systematic and non-systematic mine subsidence ground movements. Revision A, August 2007.

20. MSEC (2012). An Independent Review of Mine Subsidence Predictions and Impact Assessments - Upper Liddell Seam, Longwalls 1 to 8. Report No. MSEC541 Rev A.
21. PSM (2017). Height of Cracking – Dendrobium Area 3B. Prepared for the NSW Department of Planning. Report No. PSM3021-002R, Mar. 2017.
22. Seedsman, R.W. and Dawkins, A. (2006). Techniques to Predict and Measure Subsidence and its Impacts on the Groundwater Regime Above Shallow Longwalls. Project No. C13009.
23. Seedsman Geotechnics Pty Ltd (2012). South Galilee Coal Project - Life of Mine Subsidence Deformations. March 2012.
24. Sofianos, A. and Kapensis, A.P. (1998). Numerical evaluation of the response in bending of an underground hard rock voussoir beam roof. International Journal of Rock Mechanics and Mining Sciences, 35(8), 1071-1086.
25. Tammetta, P. (2014). Estimation of the height of complete groundwater drainage above mined longwall panels. Ground Water, 51(5):723-734.
26. Whittaker, B.N. and Reddish, D.J. (1989). Subsidence – Occurrence, Prediction and Control. Elsevier.