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SOUTH GALILEE COAL PROJECT

LIFE OF MINE SUBSIDENCE DEFORMATIONS

metservesgcp-01 MARCH 2012

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Wednesday, 28 March 2012

REF: metservesgcp-01

Mr R Currie
Senior Consultant – Environment
Metserve
PO Box 306
Fortitude Valley QLD 4006

Dear Russell,

Re: Subsidence – South Galilee Coal Project

We are pleased to submit this report outlining subsidence prediction methods and our assessment of the likely subsidence to develop above the proposed longwall concept plans for the South Galilee Coal Project. Digital files of the predicted subsidence have been forwarded electronically.

Please contact the undersigned if you require further details.

Yours truly

Ross Seedsman

EXECUTIVE SUMMARY

This report addresses the modelled subsidence deformations predicted to develop above the proposed South Galilee Coal Project longwall mining area. It is understood that the conceptual longwall plan is based on limited specific geological and geotechnical information and provides an indication of a plan that will achieve maximum resource recovery.

Longwall extraction at the South Galilee Coal Project (SGCP) is proposed to extract both the D1 and D2 seams. At this early stage of concept planning, the longwall extraction voids are 360m wide with intervening chain pillar widths of 25m. The depth of cover to the D1 seam ranges from 50m to 240m. The D2 seam lies 12-15m below th3e D1 Seam

Subsidence engineering is based primarily on back analysis of subsidence outcomes in similar rock masses. As this information is not available for the Galilee Basin, the predictions are based on experience in the Bowen Basin which is assessed to be adequately similar. There is very little information available on the subsidence above multiple seam extraction so a greater level of engineering judgement is required for this aspect.

For the D1 seam in isolation, the maximum vertical subsidence is 2.55m, the maximum tilt is 78 mm/m, and the maximum strains are 24 mm/m. For the D2 seam in isolation, the values are 1.5m, 44mm/m and 14 mm/m respectively. For the combined layout of both the D1 and D2 seams, the predicted maximum vertical subsidence is 4.2m, the maximum tilt is 112 mm/m, and the maximum strain is 35 mm/m (tensile or compressive).

When apply the predicted deformations in a risk assessment context, the values should be increased by 20%. Recognising the uncertainties in the predictions, specific values of the various deformation parameters should not be used as constraints: any constraints to the mine design should be based on recognition of unacceptable consequences.

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Longwall extraction at the South Galilee Coal Project (SGCP) is proposed to extract both the D1 and D2 seams (Figure 1). At this early stage of concept planning, the longwall extraction voids are 360m wide with intervening chain pillar widths of 25m. The depth of cover to the D1 seam ranges from 50m to 240m. This report addresses the predicted subsidence outcomes of this proposed layout. The report does not address the mining conditions that may be associated with these panel and pillar widths. It is assumed for this subsidence analysis that the pillars will be stable during longwall retreat.

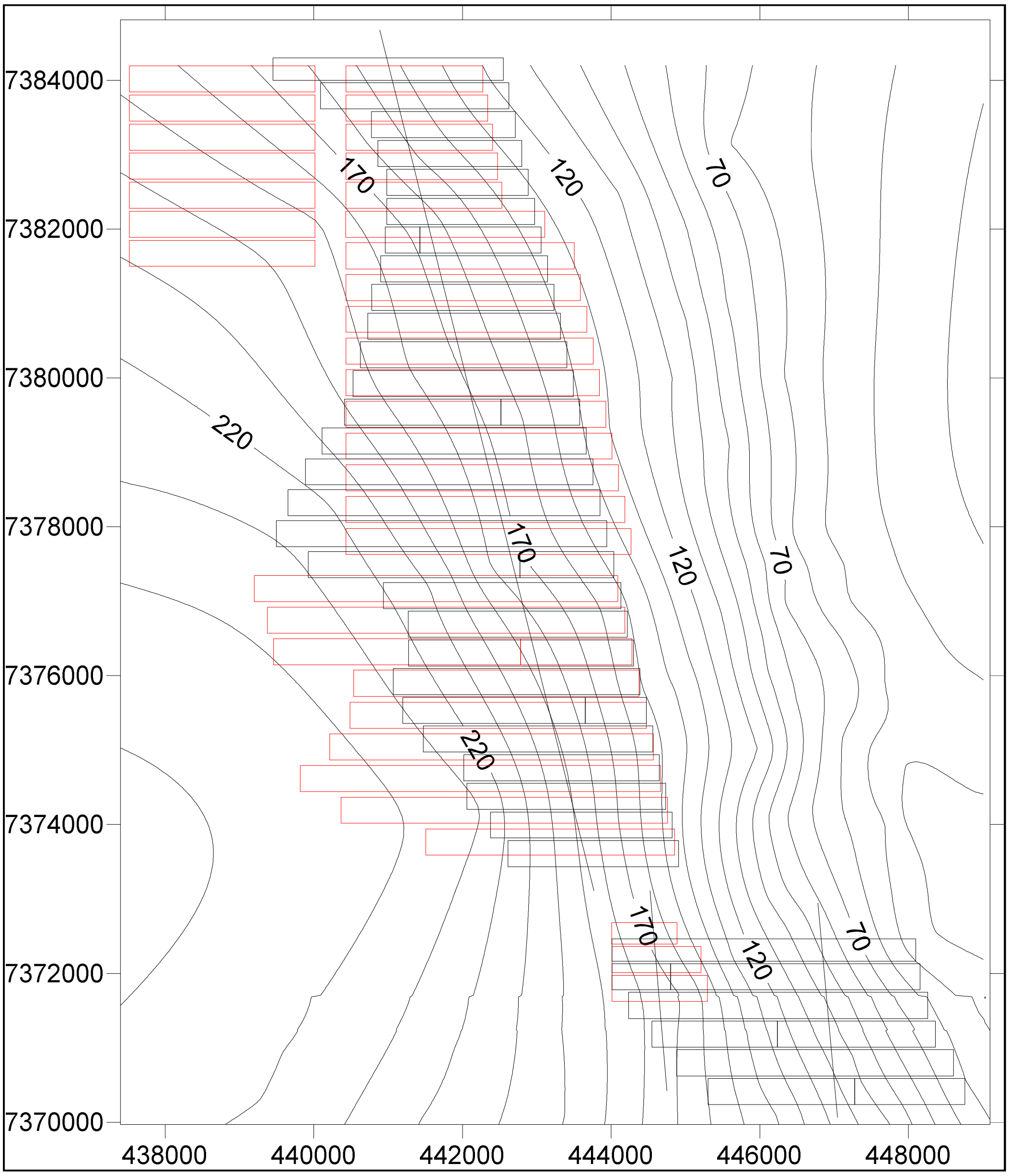


Figure 1 Outline of concept longwall extraction panels (D1 seam – black, D2 seam – red) and depth of cover to D1 seam.

2 SITE CONDITIONS

2.1 TOPOGRAPHY

The natural topography in the SGCP area is dominated by very gently undulating plains and rises of low relief. The plains in the east and north-east generally decline from more elevated low hills located along the western portion of MLA 70453. The elevation ranges from 350 to 600 metres Australian Height Datum (AHD) (Figure 2). The surface slopes are typically less than 1^{o} (17mm/m).

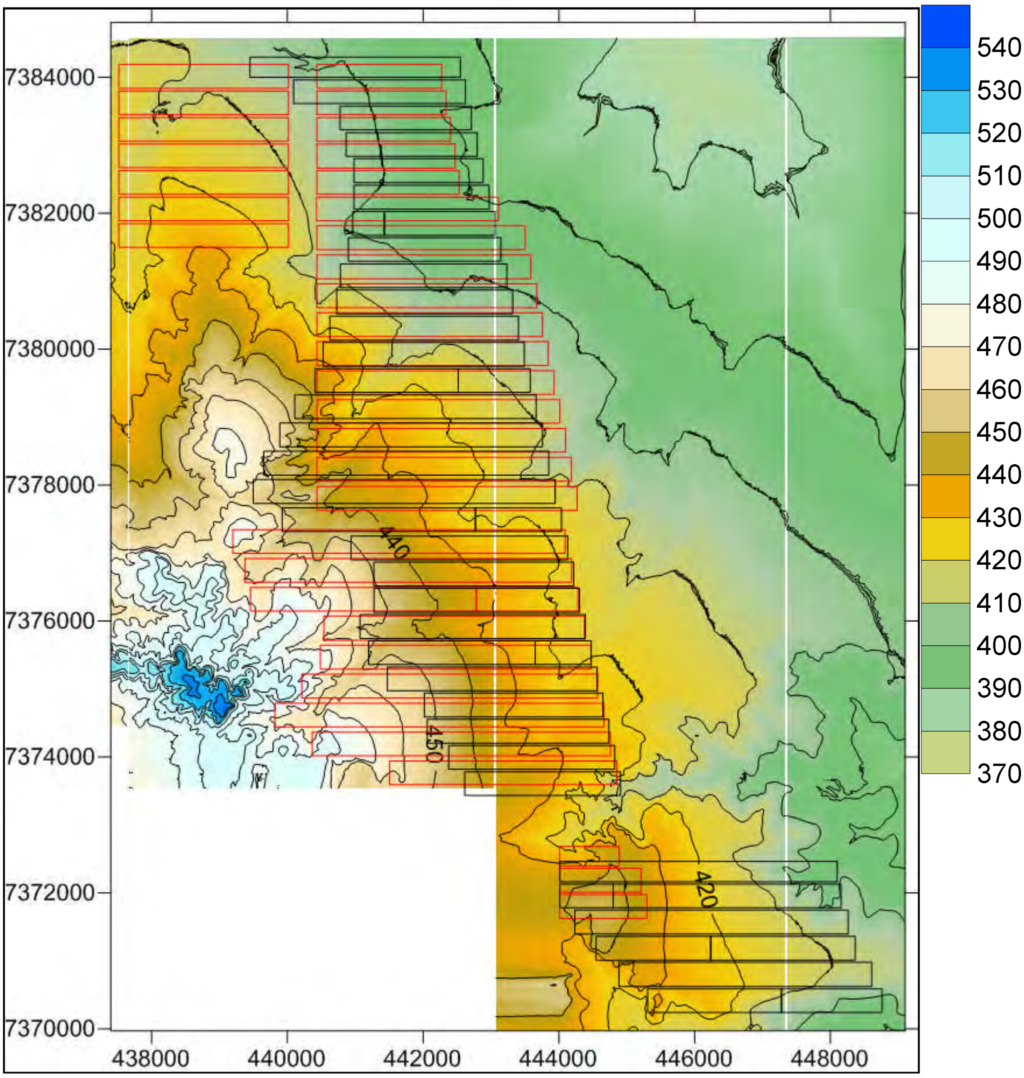


Figure 2 Surface elevation (AHD)

2.2 OVERBURDEN GEOLOGY

The D1 and D2 seams are contained within the Late Carboniferous-Middle Triassic Galilee Basin. The Late Permian age Bandanna Formation unit is the target formation of the SGCP and is composed of:

- grey slightly micaceous and silty, carbonaceous sub-fissile shale;
- grey argillaceous and carbonaceous siltstone;

- grey fine to medium grained fused, micaceous quartz, feldspathic sandstone; and
- multiple coal seams which are generally known as Seam A to Seam F.

The Rewan Group unconformably overlies the Bandanna Formation. The formation is composed of terrestrial alluvial sediments including meandering channel deposits and flood-basin siltstone and sandstone units. The Dunda beds are a transitional unit between the Early Triassic members of the Upper Rewan Formation and the Clematis Sandstone and consist of quartz labile sandstone and interbedded lutite. The Clematis Sandstone is a poorly sorted, fine to coarse grained, angular to sub-angular quartzose sandstone with minor red siltstone and mudstone and rare conglomerate and thin interbeds of variegated shale. The Moolayember Formation is a Late to Middle Triassic fluvio-lacustrine deposit consisting of light grey-green, yellow and brown, argillaceous siltstone, sandstone and mudstone units with slight interbedded mica. It is the uppermost unit of the Galilee Basin.

Tertiary deposits overlie the Galilee Basin and comprise consolidated siltstone and sandstone typically 5-15m thick and are thickest in the northern and central region of the SGCP area.

Quaternary deposits in the SGCP area are mostly alluvial and consist of gravel, sand and poorly consolidated clayey sandstone. Thickness of the Quaternary sediments varies over the Project area, but generally thickens to the east.

2.3 Engineering geology

The depth of cover to the D1 and D2 seams varies between approximately 50m and 240m (Figure 1). The D1 seam thickness is typically 4.0m to 4.5m and the D2 seam thickness is in the range of 2.4m - 2.8m. Structure contours on the roof of the D2 seam generally strike approximately 340-350^0 over the area. The structure roof contours on the D1 seam are very similar, situated about 12-15m above D2. Based on the geological and geophysical logging conducted to date, it is assessed that there are no very low strength roof or floor units that may adversely impact on pillar stability.

The overburden sequence consists of sandstones, mudstones and claystone with minor coal seams (Figure 3). From observations of the geological core and a review of the regional geology, it is assessed the overburden sequence does not contain massively bedded units (>10m thick) and consequently it is anticipated that it will cave readily during longwall operations.

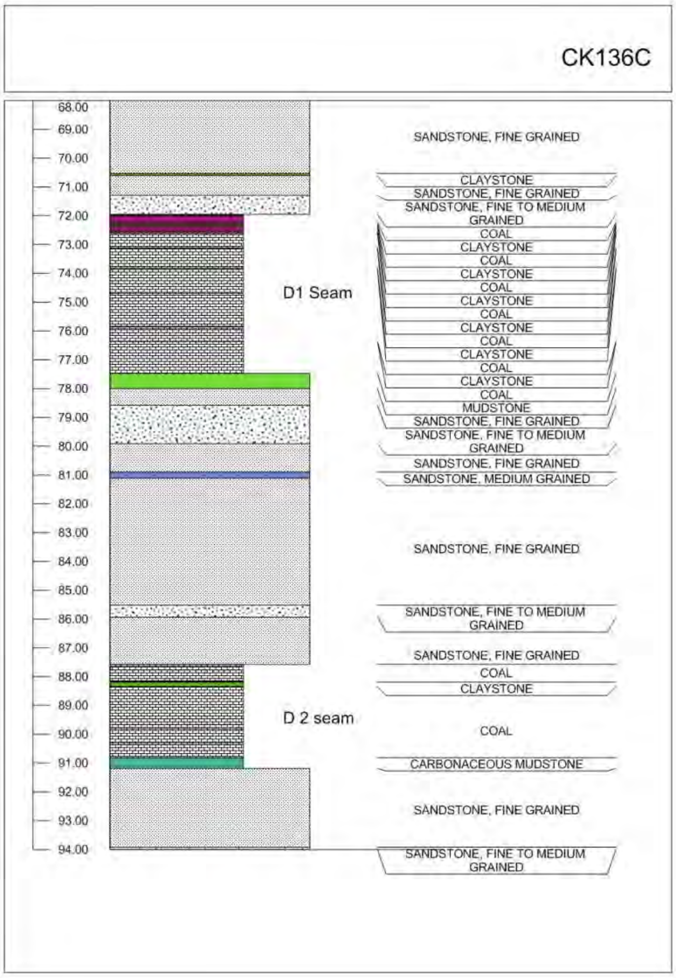


Figure 3 Detail of coal seams and immediate roof and floor

Exploration drilling within the proposed longwall mining area is still at an early stage and the drill hole spacing is in the order of 1500m. This spacing is not adequate to confidently identify faults at the coal seam level which will ultimately determine the layout of the longwall. As a rule of thumb in high production Australian longwall operations, faults with a throw more than half the seam thickness (i.e. throws of approximately 2m) can represent barriers to longwalls. As a frame of reference, experience in the Bowen Basin is that a drill hole spacing of about 250m is required before a longwall can be adequately planned. It is not known if the same spacing will be required for the Galilee longwall mines. Importantly, the mine plan being assessed is conceptual only at this stage– it is a mine plan that seeks to maximise resource recovery; the final mine layout will be one that optimises resource recovery with safety and productivity.

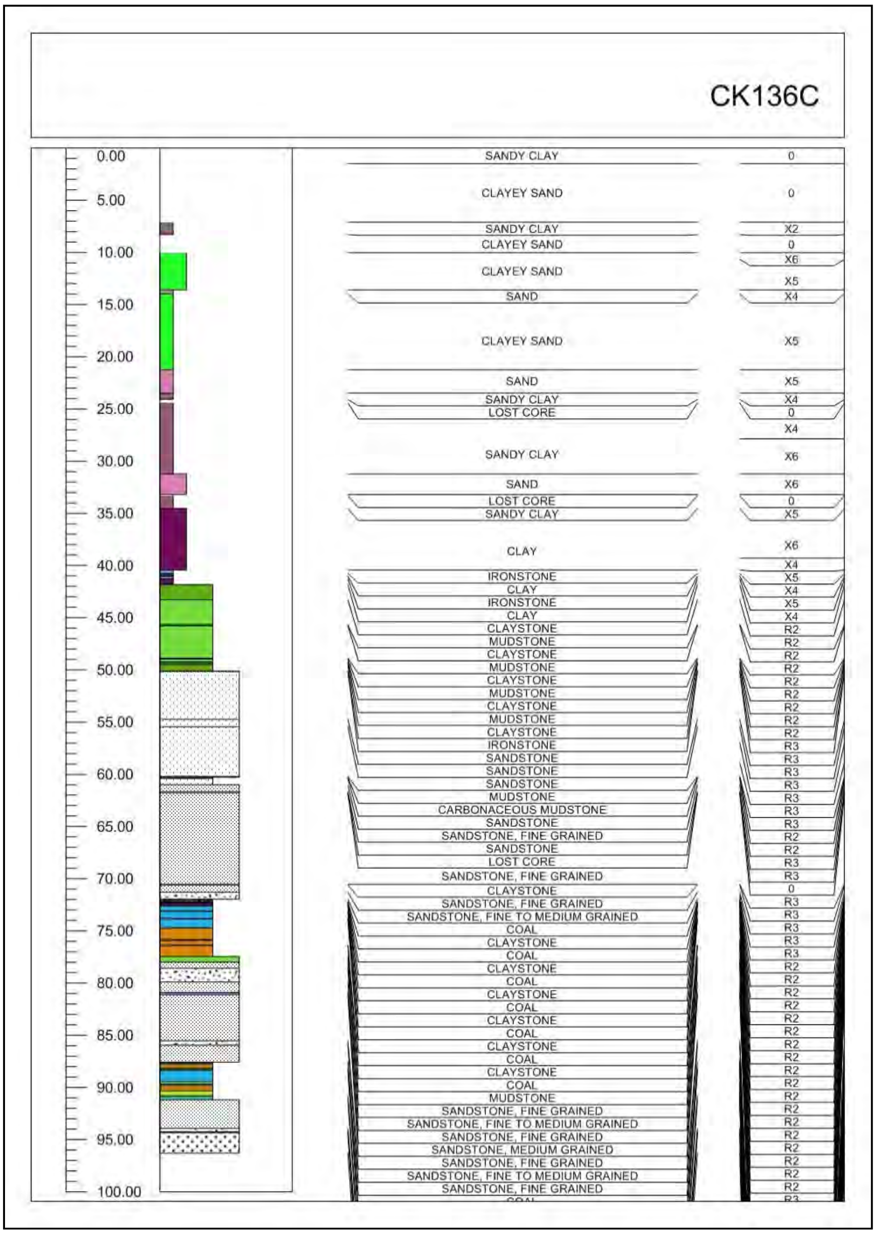
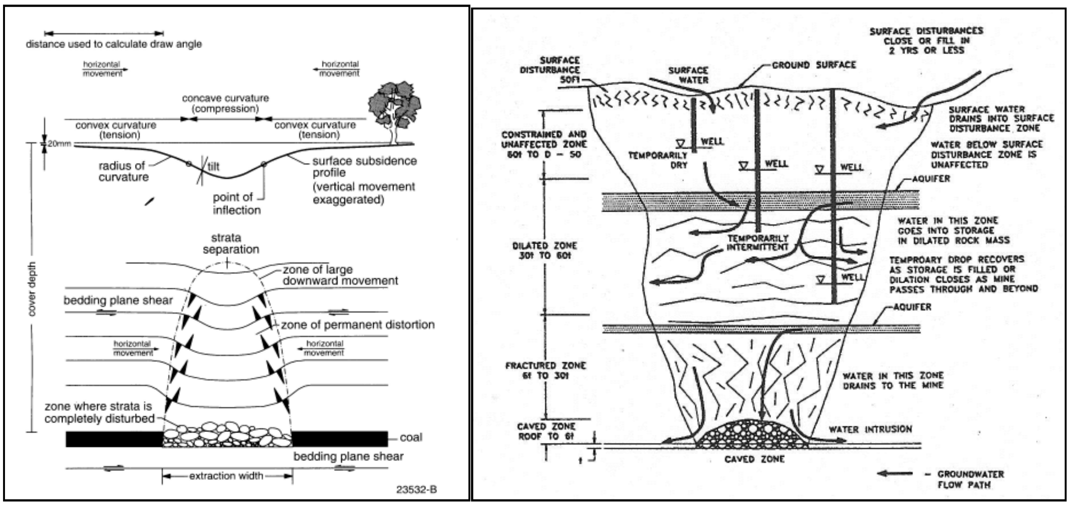


Figure 4 Typical overburden sequence

3 SUBSIDENCE PREDICTION AND VISUALISATION

A characteristic of longwall mining is the collapse of the overburden behind the mining front. This collapse may continue to the surface and result in a range of surface deformations (collectively known as subsidence). There are numerous diagrammatic representations of the deformations and fracturing that develop in the overburden and at the surface which differ in detail depending on the concepts being communicated (Figure 5). All the diagrams for the overburden used by subsidence engineers are derived by inductive reasoning from a limited set of observations – it is not possible to excavate a sufficient number of deep longwalls to examine the actual fracture and deformation patterns. Subsidence engineering is very much based on extrapolation from back analyses of what are perceived to be similar geological conditions.

Close to the extracted seam, there is a zone where the overburden rock is completely disturbed – this is typically considered to be 10m to 20m thick. Above this is a progressively narrower zone where the overlying beds remain generally intact with fracturing along the sides of the zone (Figure 5a). The height of this zone is a function of the width of the extraction and the presence of massive rock units in the overburden. In hydrogeological models (Figure 5b), this is the fractured zone: the reported thickness of this zone (6 to 30 times the extraction thickness) gives an indication of the possible variability in its dimensions. Above the fractured zone, the overburden rocks sag and bedding may separate in the dilated and constrained zones: there are changes in horizontal transmissivity but negligible changes in vertical transmissivity. The presence of dilated and constrained zones prevents water flowing from the surface to the mine. At greater depths the overburden rocks may span with only small deflections.



(a) Deformations and fracturing[1] **(b)** hydrogeological[2]

Figure 5 General models for subsidence behaviour

To characterise the surface deformations and to provide context to resulting impacts, subsidence engineers make reference to a number of parameters:

- Vertical movement: change in the relative level of the surface. This may be significant in terms of flooding low lying areas
- Tilt – differential vertical movement. This may alter the direction of flow in drainage channels.
- Horizontal movements associated with the sagging. By themselves, these typically have no impact.
- Strains – how the surface is stretched or compressed by relative horizontal movement. High levels of tensile strain can cause cracking in either the overburden rocks or the surface soils.

3.1 GENERAL SHAPE OF A SUBSIDENCE BOWL

The surface above a longwall extraction panel subsides in the form of a trough or a bowl (Figure 5a). The depth of the bowl is less than the thickness of the coal that is extracted and the width of the bowl

[1] Holla, L and Barclay, E. 2000 Mine subsidence in the Southern Coalfield, NSW, Australia. NSW Department of Mineral Resources.
[2] Bai, M. and Kendorski, FS. 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.

is greater than the width of the extraction. The general shape of a cross section through a subsidence bowl (Figure 6) reveals the following key features that are used to quantify subsidence deformations:

- The areal extent of subsidence is defined by the angle of draw. Conventionally the angle of draw is drawn to 20mm of vertical subsidence (not zero). It would be better if the term "angle of critical deformation" was used to make this distinction clear.
- The location of the maximum tilt corresponds with zero strain (inflexion point).
- The subsidence at the inflexion point should be half the maximum vertical movement.
- Offset of the inflexion point from the edge of the extraction or the edge of the goaf.
- The locations of the maximum tilts or strains do not necessarily correspond with the edge of the extraction.

As panels become wider with respect to depth, the maximum subsidence trends to a maximum percentage of the extraction thickness. The proposed SGCP panels are within this range. This is termed supercritical subsidence to differentiate it from subcritical behaviour for narrow panels with respect to depth. A feature of supercritical panels is that as well as no increase in maximum vertical subsidence, the maximum tilt and maximum strain also do not increase with increasing panel width (Figure 7). Supercritical subsidence infers more rock breakage at the surface, with the result the subsidence profile can deviate significantly from the smooth curves that are produced by any prediction method.

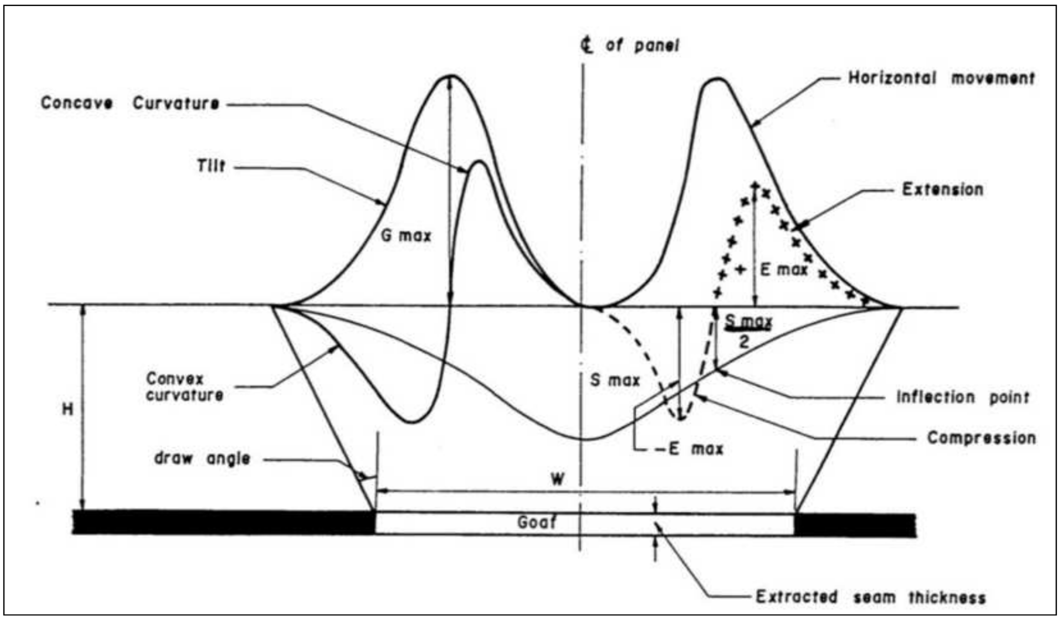


Figure 6 General characterisation of a subsidence cross line

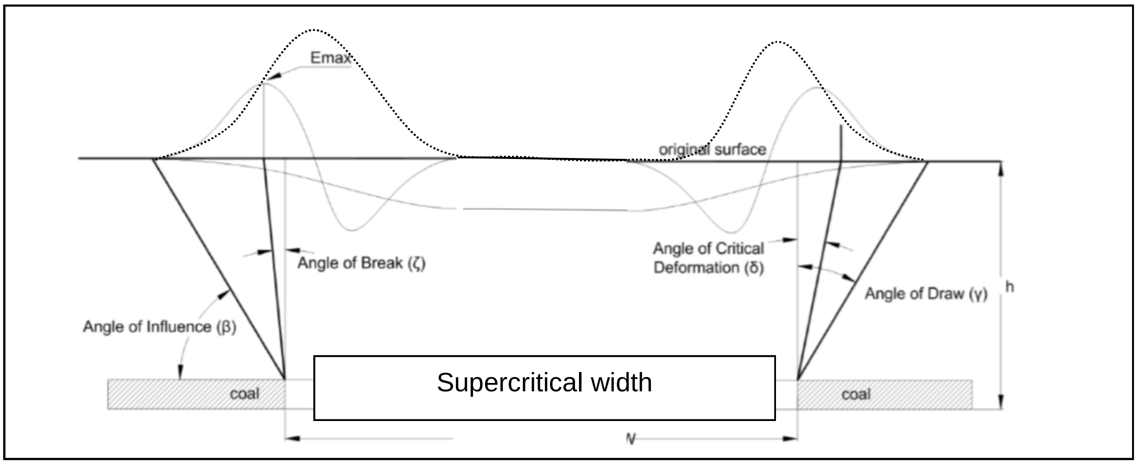


Figure 7 Maximum values do not change with increasing width of supercritical panels

3.2 PREDICTION METHODS

As subsidence deformations are spatially distributed, prediction is complex and requires estimates of values (vertical movement, tilt, strain) at a very large number of specific eastings and northings. For the SGCP, predictions have been conducted at 1.7 million points at 10m centres. In addition, subsidence engineers are dealing with a rock mass, which may behave as a blocky material such that a smooth continuous behaviour will not present (rocks break and do not deform like plastic). The available prediction methods assume a continuous surface.

"Accuracy" in a scientific measurement sense is therefore not an appropriate concept: subsidence engineers have developed various approaches to supply adequately reliable predictions to address the prediction uncertainties and allow engineering responses.

3.2.1 Ordered movements

By assuming a smooth continuous subsidence bowl and a horizontal surface, there are a number of prediction methods available. It is emphasised all of these methods require calibration/back analysis as subsidence engineering is empirically based rather than deterministic.

3.2.1.1 Discrete points

Subsidence prediction in New South Wales began last century by using local databases to predict maximum vertical movement, maximum vertical movement at the edge of the panel, maximum tilt, maximum strain, and the locations of the points of 20mm vertical movement. Smooth curves could then be drawn by hand through these points. It was found that separate datasets and recommendations were required for different coalfields and could only be determined after substantial mining experience.

A simplified version of this approach has been used by Waratah Coal for the Galilee Coal Project. Waratah Coal has assumed the maximum vertical subsidence will be 67% of the extracted thickness and has not sought to predict strains or tilts.

3.2.1.2 Profile functions

The profile function approach fits an arithmetic curve to subsidence data. Various functions have been used in the technical literature (exponential, trigonometric, hyperbolic) with possibly the most efficient one being the hyperbolic tangent[3]:

$$S(x) = 1/2 * S_{max} * (1 - \tanh(cx/B))$$

Where $S(x)$ = subsidence at x,
x = distance from the inflection point,
S_{max} = maximum subsidence of the profile,
B = distance from the inflection point to point of S_{max}, and
c = constant.

In New South Wales, there is an advanced version of the profile function method – the Incremental Profile Method[4]. The form of this profile function is a complex 5th order polynomial with 10 coefficients, the values of which and the methods to determine them are held confidential by the consultant. Consequently, the Incremental Profile Method is not available for engineering peer review.

In their EIS for Kevin's Corner, Hancock Coal uses an unpublished profile function method developed by their consultant based on extensive manipulation of a 3-order polynomial fit. Its application requires in-house developed subroutines and similarly the method is not available for engineering peer review.

3.2.1.3 Influence functions

Influence function methods are somewhat similar to profile functions and are based on incrementing the deformation of the surface for each element of the extraction of the seam. This allows complex and irregular mining layouts to be analysed and the results presented as surfaces instead of cross sections. Mathematical functions used have included trigonometric and exponential types. The readily available SDPS (Surface Deformation Prediction System)[5] uses a form of the Gaussian curve:

$$g(x, s) = S_o(x)/r * \exp[-\pi * (x-s)^2/r^2]$$

where:
r = the radius of principal influence = H/ tan(B),
H = the overburden depth,
B = the angle of principal influence,
s = the coordinate of the point, P(s), where subsidence is considered,
x = the coordinate of the infinitesimal excavated element, and
$S_o(x)$ = the convergence of the roof of the infinitesimal excavated element.

SDPS version 6.x was developed under a contract from the Office of Surface Mining, Reclamation and Enforcement, US Department of Interior. It appears to be a defacto standard for regulatory approval in the US. It is available for full engineering peer review. SDPS is the method used in this SGCP study and is described further in Section 5.

[3] Brady, BHG. and Brown, ET. 2004. Rock Mechanics for Underground Mining, 3rd Edition. George Allen and Unwin, London.
[4] www.minesubsidence.com
[5] www.carlsonsw.com

3.2.1.4 Analytical and numerical methods

For subcritical panels, analysis and prediction by way of the elastic deformation of blocky rock beams is possible. This can be done analytically (using voussoir beams) or numerically using discrete element codes such as UDEC. To justify the sophistication of these approaches a detailed site characterisation is necessary and at much greater level than is available at this stage of the SGCP. Like all numerical and analytical methods, the applications to engineering design are certainly not deterministic – once again they require calibration to mining in similar geotechnical environments.

It is possible to analyse the subsidence that develops above the chain pillars between the longwall panels by assuming that they behave as rigid elastic footings. There is an empirical approach to allow consideration of the yield of the coal pillars.

3.2.2 Disordered movements

The readily available prediction methods do not address the "disordered" movements that are well known to be present (i.e. the departures from the smooth continuous assumption required for the prediction). In terms of the total deformation field, these represent a very small fraction but they tend to receive a large degree of attention because of their "novelty" and unpredictability. Although they can be validly anticipated, the absolute movements are not predictable before the event: it is possible to build a database after the event to provide ongoing guidance. The appropriate strategy is to manage perceived unacceptable impacts with additional offsets to the extraction panels.

When the near-surface rocks break, the resulting blocks of rock interact and can produce localised movements (Figure 8a). This is particularly the case with supercritical extraction and thin soil cover. If there are faults or dykes in the overburden sequence, these can localise displacements near the surface (Figure 8b). This is relatively rare because longwalls are typically only deployed in large blocks of unfaulted coal. In the vicinity of valleys and any topographically dissected surface, the lack of sideways confinement to the surface rocks may allow lateral movement (Figure 8c): the lateral movements can be large if the longwall is directly below: outside the angle of critical vertical deformation the lateral movements are relatively small.

There is another set of disordered movements that relate to the definition of the subsidence footprint as being the onset of 20mm of vertical subsidence. The 20mm threshold was chosen to define the onset of subsidence partly because of the recognition of no damage to the surface and partly because of the resolution of survey techniques used at the time. As the resolution of survey methods has improved, it is now known the meteorological shrink and swell of the surface may be much greater than this. It is now possible to resolve vertical and horizontal movements much more precisely (to approximately 2-3mm). Subsidence engineers now regularly measure very small horizontal movements even when the vertical movements are less than 20mm – these have always been present and without adverse impact. Ongoing research into these movements is focussed on the possible disruption to the horizontal stresses in near-surface rocks.

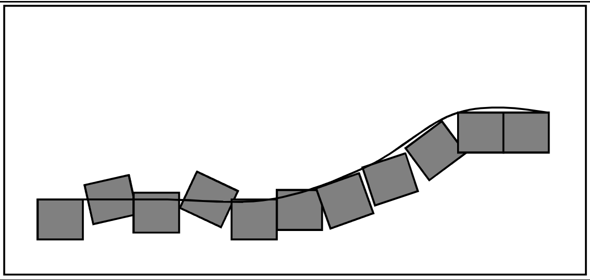
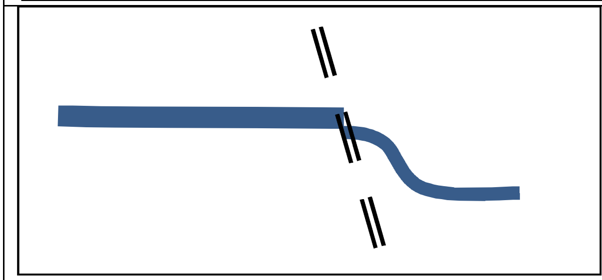
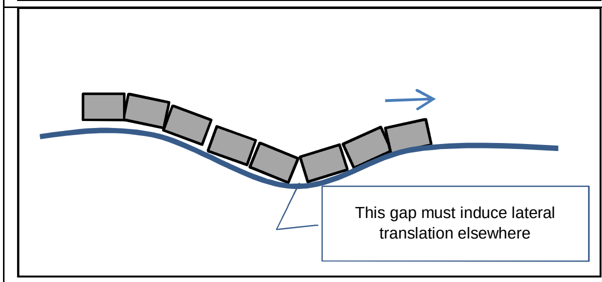
	(a) Bending of a layer of blocks will result in individual blocks rotating. Anomalous strains and tilts may be recorded.
	(b) Fault or dyke localises deformations. Longwall mining seeks to avoid the larger of the known faults and dykes.
	(c) Bending of a layer of blocks can induce lateral movement into a free face

Figure 8 Sources of disordered movements

4 SUBSIDENCE PREDICTION IN AUSTRALIA

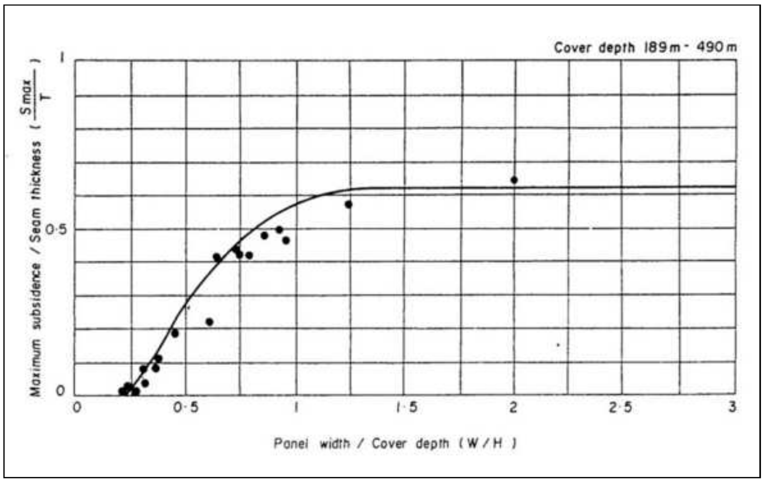
4.1 ISOLATED PANELS

The starting point for all the published prediction methods is an estimation the maximum vertical subsidence above a single longwall panel. In empirical methods, this estimate (Figure 9) is based on a cross plot of the maximum vertical subsidence (normalised to the extraction thickness) versus the panel width (normalised to the depth of cover).

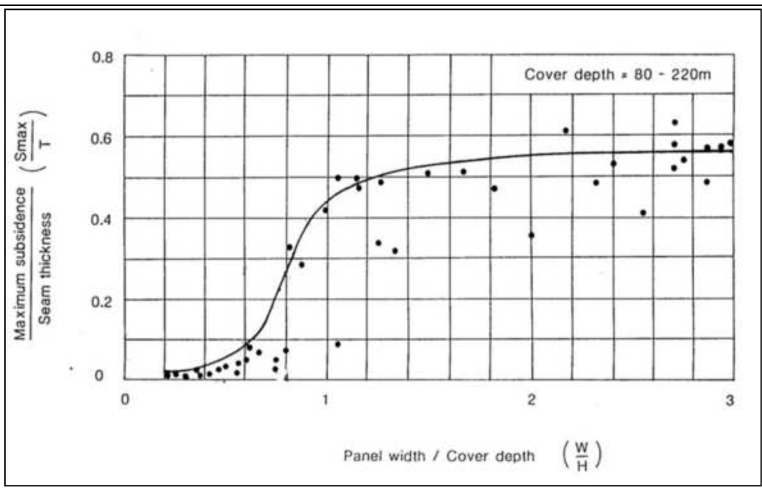
As longwalls were introduced into Australia longwalls, it was soon found that the plot from the British coal fields was not applicable to Australian conditions, and separate plots were published for the Southern, Newcastle, Western coalfields (Figure 9)[6,7,8]. There is no published curve for the Bowen Basin - possibly because the extraction is mostly supercritical. No data has been collated for the Galilee Basin. In each of the plots, a line was drawn to represent the maximum expected maximum subsidence. The significant differences in the plots are at low values of the width to depth ratio and these differences were inferred to be related to the presence massive overburden layers that could

[6] Holla Mine Subsidence in the Southern Coalfield, NSW, Australia. Department of Mineral Resources, 2000.
[7] Holla Mining Subsidence in New South Wales 3. Surface Subsidence Prediction in the Western Coalfield. Department of Minerals and Energy, January 1991
[8] Holla Mining Subsidence in New South Wales 2. Surface Subsidence Prediction in the Newcastle Coalfield. Department of Mineral Resources, January 1987

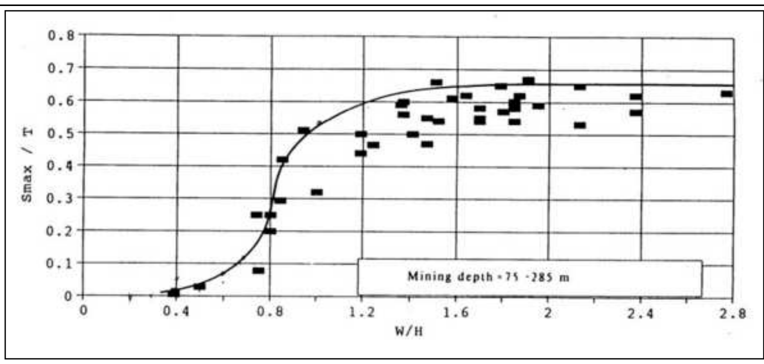
span. Note that the maximum subsidence for wide panels (supercritical) tends towards a constant value of around 60% in all three coalfields.



Southern



Newcastle



Western

Figure 9 Prediction of maximum vertical subsidence in NSW coalfields

A weakness with the empirical methods is the reliance on a relatively small database compared to the variability that may be found in a rock mass. As more longwalls were extracted in the Newcastle coalfield it was found that the initial recommended line was not valid and one that approached the Southern coalfield was more appropriate (Figure 10)[9].

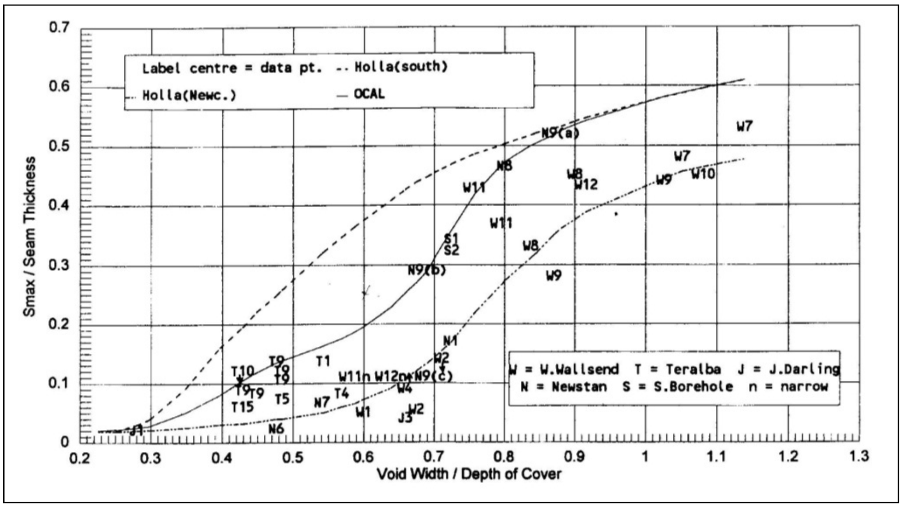


Figure 10 Changes to the Newcastle curve over time

The plots do give an indication of the achievable precision of subsidence prediction – in the range of 10% - 20%.

Close inspection of the Newcastle curve (Figure 9) reveals a number of subsidence outcomes that fall below the drawn maximum expected maximum subsidence line (for example a panel width/depth ratio of 1.05 and a normalised maximum subsidence of 0.10). In the redesign of Mandalong Mine[10], an analytical method (fractured rock beams) was used to investigate the deflection of massive rock beams. It was found that very thick beams can deflect up to 10% of the span without breaking. Mandalong has extracted longwall panels with a width to depth ratio of 1.0 and an equivalent deflection of about 50mm - 100mm for a 5m thick extraction (0.01 to 0.02). Such overburden rocks are not present at SGCP.

In the last 10 years, wider longwall panels have become technically and economically attractive. The larger width to depth ratios have resulted in a realisation that panels with subsidence normalised to depth of cover in the range of 0.4 may have been spanning and not fully supercritical.

Figures 9 and 10 highlight the variability in measured vertical subsidence and how this impacts on subsidence prediction. Predicting the shape of the subsidence bowl, through the prediction of maximum tilts and maximum strains introduces further uncertainty. The prediction of maximum values is by way of the relationship:

Maximum value = 1000 * Kn * Smax/H (n=1,2,3),

Where Smax is derived from Figures 9 or 10, H is the depth of cover, and K1 is a tensile strain factor, K2 is a compressive strain factor, and K3 is a tilt factor. Empirically derived values for K are provided as a function of panel width/depth ratio for Southern and Newcastle coalfield (Figure 11). They are not available for the Bowen Basin or for the Galilee Basin. In this case the recommended lines are

[9] Tobin C. 1998. A review of the Newcastle Coalfield subsidence prediction curve. The AusIMM proceedings,303(1), 59-63.
[10] Seedsman, RW. 2006. An analytical subsidence prediction method to maximize underground coal extraction under tight environmental constraints. *In* AMIREG 2006, Advances in Mineral Resources Management and Environmental Geotechnology, 2nd International Conference, 25-27 September, Hania, Greece.

"best fit", not maximum expected. High variability is apparent with possible values ranging +/-50% of the recommendation.

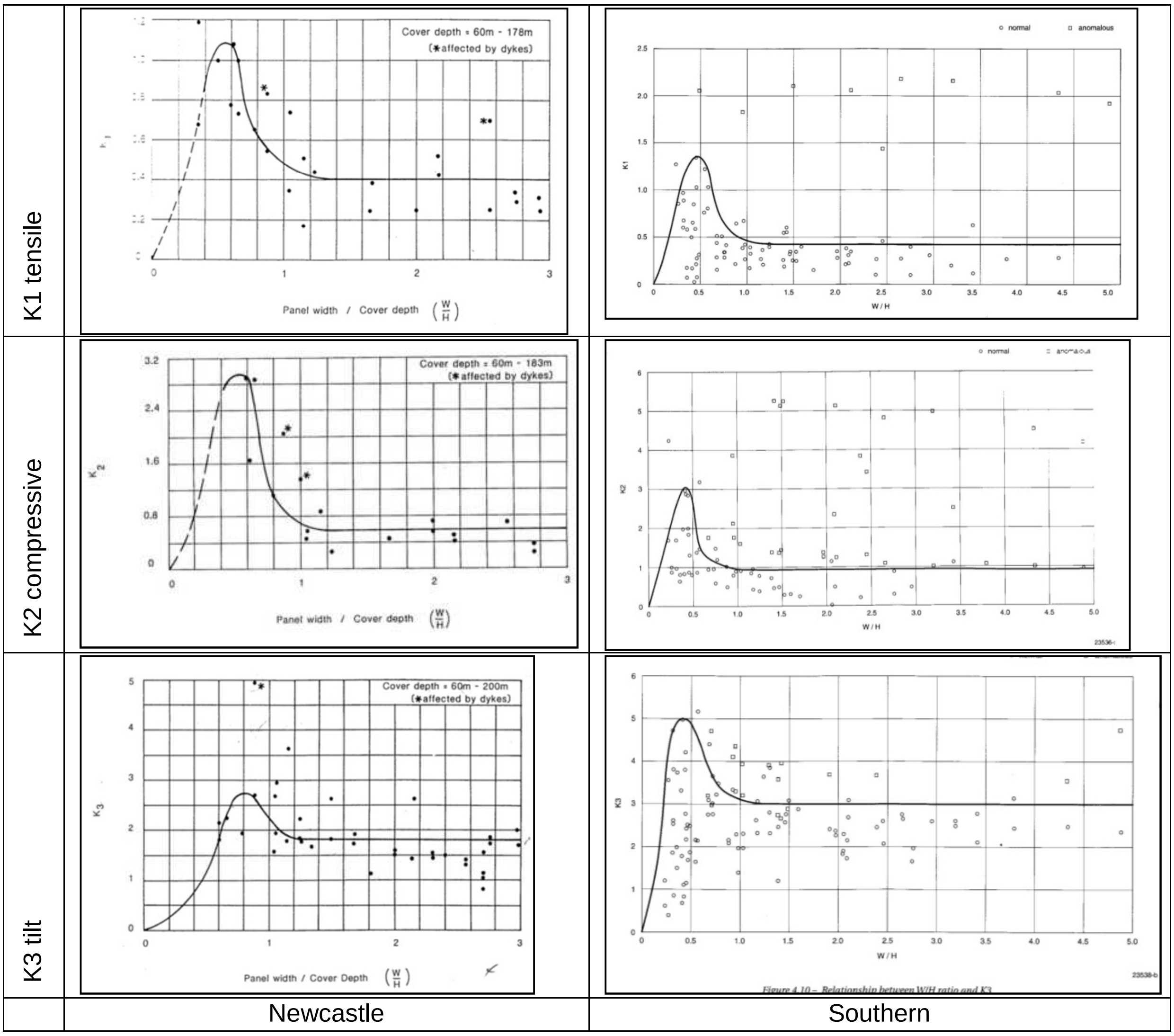
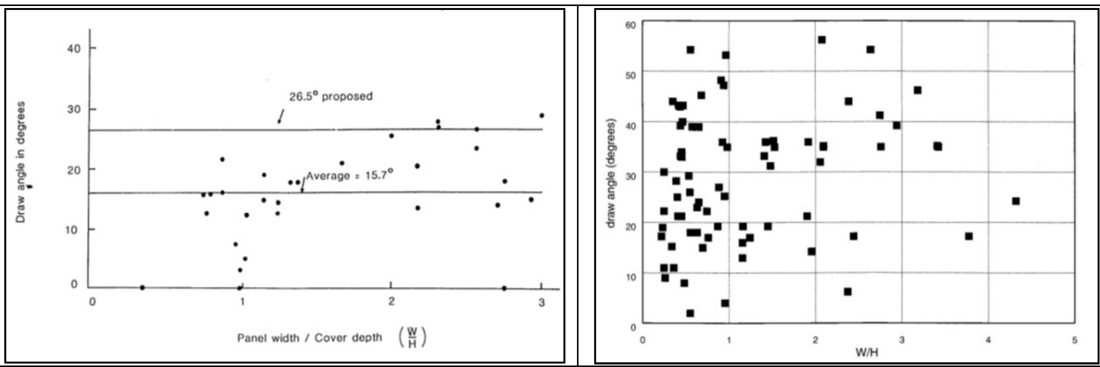


Figure 11 K values for the Newcastle and Southern coalfields

High variability is also a characteristic of the angle of critical deformation to 20mm of vertical subsidence (Figure 12) with values between 0^o and 60^o having been recorded. Much of this spread may be related to survey precision and failure to identify shrink/swell of the surface soils. A value of 26.5^o has been found to be a useful value for early mine planning: this implies the limit of subsidence deformations is located at a distance from the any longwall extraction equal to half the depth of cover.

Inspection of the curves in the previous figures leads to the inevitable conclusion that scientific "accuracy" is not a realistic outcome of subsidence prediction. As mentioned earlier, the goal is to derive appropriate predictions in order to allow appreciation of the potential environmental hazards so that risk strategies involving elimination, substitution, and engineering controls can be designed.



Newcastle	Southern

Figure 12 Variation in the angle of critical deformation for the Newcastle and Southern coalfields

For the SGCP, information in the various figures presented above, together with experience from the Bowen Basin, has been used to derive appropriate input values for the SDPS influence function program.

4.2 ADJACENT LONGWALLS AND THE INTERVENING PILLARS

The subsidence developed above a set of longwalls, separated by what are known as chain pillars, can be more than the addition of the subsidence of each panel (Figure 13). This is particularly the case at large depths of cover or where the roof and floor strata are particularly low strength and stiffness.

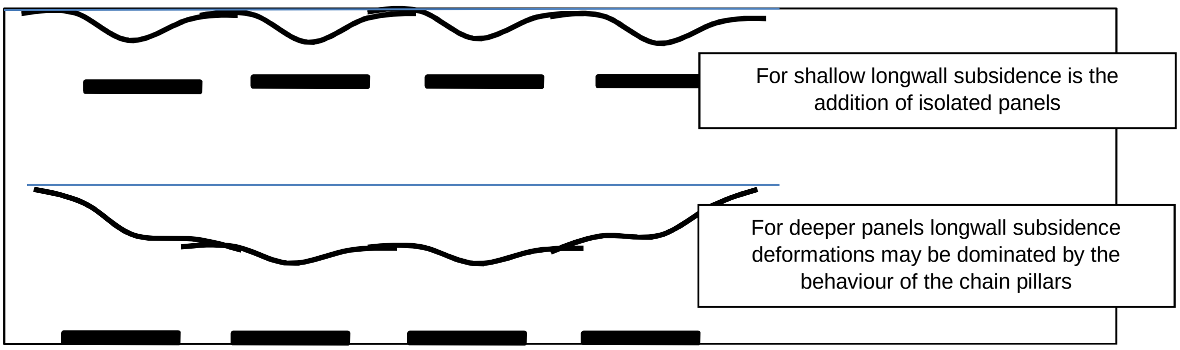


Figure 13 Sketch showing different way in which subsidence can develop above a chain pillar

The subsidence above a chain pillar results from the increase in the stresses applied to the pillars as the longwall extraction proceeds. The increased stresses cause compression of the immediate roof and floor rocks, compression of the coal seam and particularly any yielding of the coal pillars. In the Southern Coalfield, an empirical approach has been developed to predict pillar subsidence as a function of panel width, pillar width, and depth. At Mandalong, an analytical approach was adopted, exploiting detailed knowledge of the seam and the surrounding rocks[11]. There has been no specific examination of how strains and tilts differ when the pillar subsidence if the major part of the deformation field.

[11] Seedsman, R.W. 2010. Calibrated parameters for the prediction of subsidence at Mandalong Mine. COAL 2010 – Coal Operators Conference, AusIMM Illawarra Branch.

For most of the SGCP, the relatively shallow depths of cover allow a prediction based on the cumulative addition of isolated panels. An analysis of pillar compression has not been conducted for SGCP as there is insufficient geotechnical data and the design of the chain pillars has not been finalised.

4.3 MULTIPLE SEAMS

There has been very little multiple seam longwall mining in Australia to date, although many operations are being planned or are in the early stages of development. A recent paper[12] combined the limited Australian information with some international data and advocated applying a normalised vertical subsidence factor of 80% to both seams (compared to 60%) although the paper also referenced other confidential data which does not fit their model. This model omitted reference to other work on the importance of the thickness of the rocks between the coal seams.

Counter to the recent paper, it has been common practice to add the subsidence from each seam and recognise/manage the uncertainty until more data are available. This is the approach which has been adopted for the SGCP.

4.4 DISORDERED MOVEMENTS

Disordered movements have been intensively examined in the Southern Coalfield[13] where the steeply dissected topography is developed in a rock sequence which is conformable with the coal measures. When longwall extraction passed under drainage courses there were instances of buckling and cracking of rock bars. In addition, there are major items of surface infrastructure that could be considered "brittle" and not tolerant of differential horizontal movement (dams, bridges).

For the SGCP, the flat terrain and the nature of the weathered surface rocks mitigate against the likelihood of far field horizontal movements and valley closure effects.

4.5 SUBSURFACE

Experience in the NSW and Bowen Basin coalfields indicate that the hydrogeology model (Figure 5b) is appropriate for longwall panels up to 200m-250m wide. The author uses a value of 115m as the default height of the fractured zone above such longwall panels in single seams, which for seams with thicknesses of 3m - 3.5m implies a ratio of about 40.

Gale[14] provides a nomogram that relates water inflow rates to maximum subsidence and depth of cover (Figure 14). This chart is based on extrapolating from UK experience that surface tensile strains less than 10mm/m are required to prevent unacceptable inflows (from an underground safety and productivity perspective)

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[12] Li , G., Steuart, P., Paquet, R., and Ramage, R. 2010. A case study on mine subsidence due to multi-seam longwall extraction. 2nd Australasian Ground Control in Mining Conference, Sydney. 23-24 November.
[13] Waddington Kay and Associates. 2002. ACARP Management Information Handbook on the undermining of Cliffs, Gorges, and River Systems – Version 1.
[14] Gale, W. 2008. Aquifer inflow prediction above longwall panels. ACARP Project No C13013

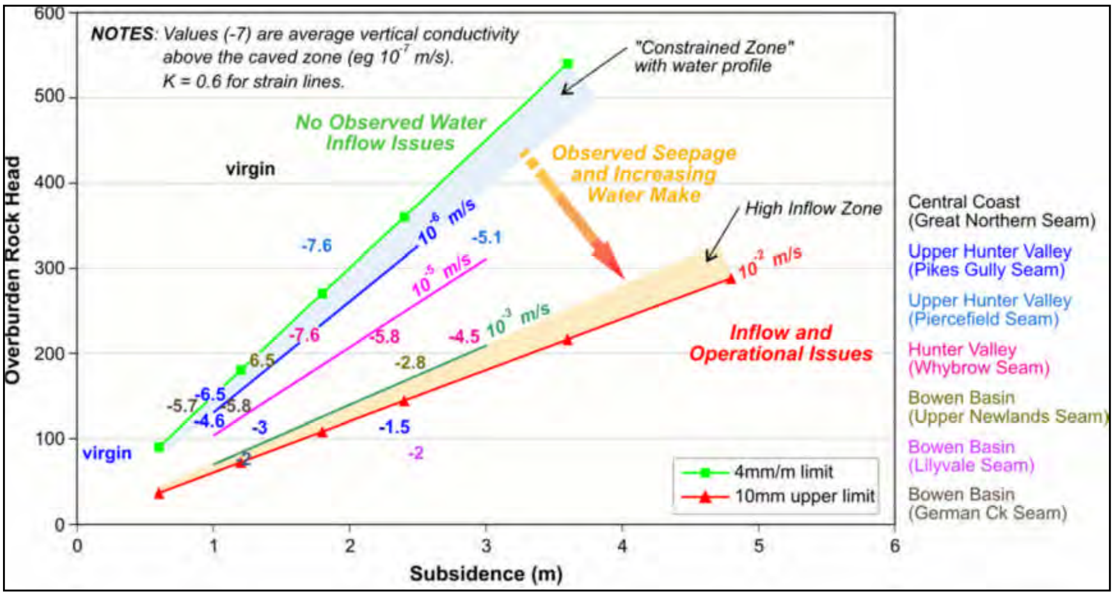

Figure 14 Water inflow nomogram

The height of the fractured zone may also be a function of the panel width and not just the extraction thickness as implied by Figure 5b [15]. In Figure 15, the fractured zone may be defined by Category 1 cracks which are defined by the angle of full subsidence. If this is the case, higher fractured zones may develop for wider longwall panels.

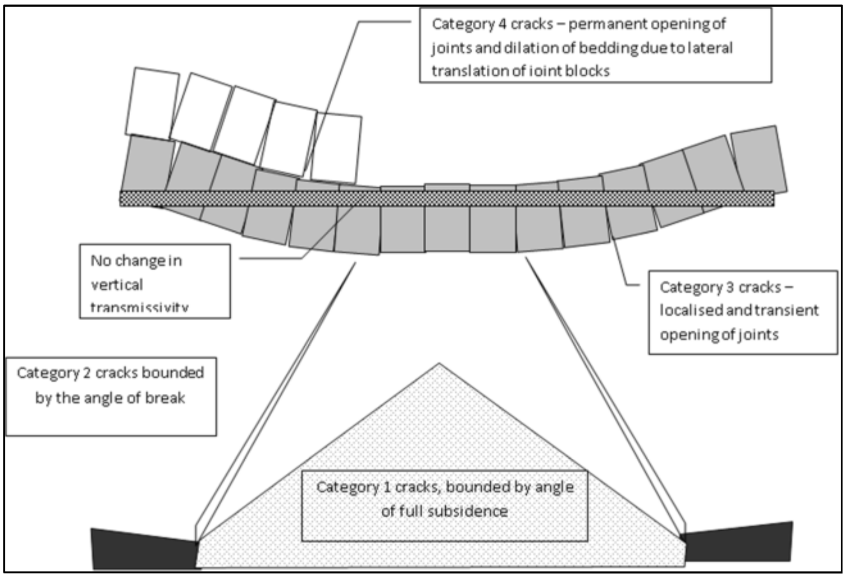

Figure 15 Composite model for fracturing above a longwall panel

[15] Seedsman, R.W. and Dawkins, A. 2006. Techniques to predict and measure subsidence and its impacts on the groundwater regime above shallow longwalls. ACARP Project No C23020

5 SGCP LIFE OF MINE PREDICTIONS

5.1 OVERVIEW

From the preceding discussion, it is apparent that a substantial amount of engineering judgement is required to predict subsidence in the first underground mine in a new coalfield. Reviewing subsidence outcomes from other Australian coalfields reveals a degree of variability. The lack of a precedent in the Galilee Basin and the preliminary nature of geotechnical information mean that the subsidence predictions for the SGCP should be used as an indication of likely deformations only. The influence function method is assessed an appropriate way of visualising the deformations.

5.2 SDPS - INFLUENCE FUNCTION METHOD

SDPS has been applied extensively to coal mines in the Bowen Basin[16] and after calibration has been found to produce very good predictions of subsidence.

The input parameters for SDPS are:

- Maximum vertical subsidence – derived from seam thickness and the subsidence factor.
- Goaf edge offset - the distance of the point of inflexion from a vertical projection of the edge of the longwall extraction.
- The tangent of the influence angle (Tan B) – a parameter that controls the maximum tilt that develops on a subsidence crossline. TanB is the same parameter as K3. The complement of this angle can be considered to be generally similar, but not exactly, to the angle of critical deformation (20mm of vertical subsidence).
- A strain coefficient – a value that is used to convert curvature to strain.

A key point to highlight is that none of these parameters can be determined analytically from the overburden geology. The state of the art is based on empirically-derived values – values measured from longwall mines in what are assessed to be appropriately similar. Obviously, there is no precedent in the Galilee Basin, so engineering judgement is required.

Figure 16 highlights the variations in the shape of the subsidence bowls for different selections of parameters. A lower tanB value results in a wider subsidence bowl with a lower maximum tilt; a higher strain factor results in higher strains. Note how a similar maximum strain value can be obtained for a combination of tanB=2.3 and a strain coefficient = 0.35 as for a combination of 4.4 and 0.20 respectively; of course the overall shape of the bowl is different.

[16] Byrnes R. 2003. Case studies in the application of influence functions to visualising surface subsidence. COAL2003 - 4th Underground Coal Operators Conference. AusIMM Illawarra Branch.

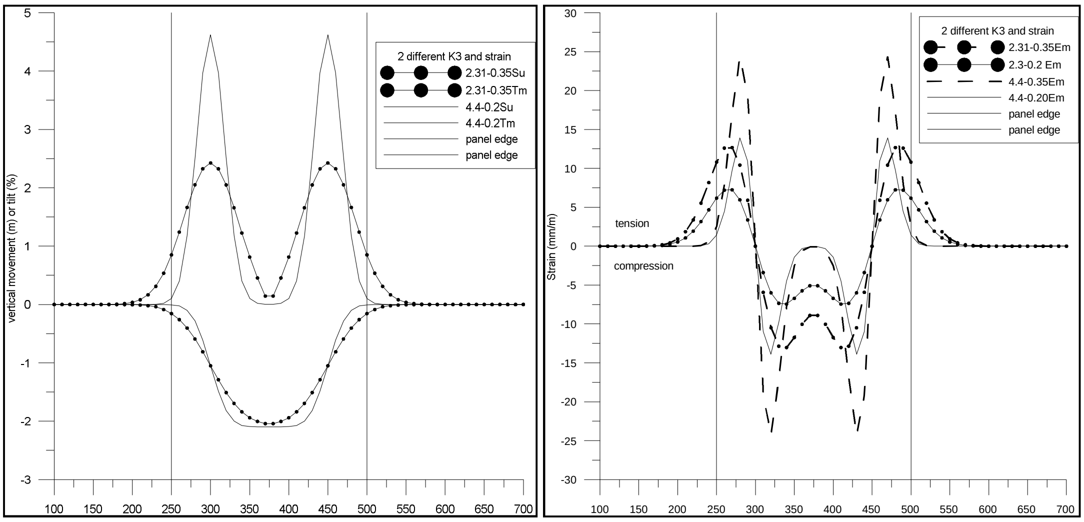

Figure 16 Variations in vertical subsidence (Su as m), tilt (Tm as %), and strain (Em as mm/m) for different tanB and strain coefficient values (250m wide panel, 200m depth, 3.5m thick seam, 60% subsidence factor)

SDPS was developed in the USA and provides a set of default input values based on experience in their Eastern coalfields. These default values have been found not to apply in Australia. Instead, values published for the NSW coalfields and values used in the Bowen Basin are presented in Table 1. In terms of depths and overburden geology, the mines of the Bowen Basin are more similar to those proposed in the Galilee Basin than the New South Wales examples. Conversely, there is more published information on the NSW mines than the Bowen Basin ones.

Table 1 Selection of SDPS parameters

	Smax/T	Offset	Tan B = K3	Strain coefficient
USA	0.19-0.76	0.20 conservative 0.25 average	2.31	0.35
NSW – Southern	0.5-0.64	0.20	3.0	na
NSW – Western	0.65	0.35	3.4	na
NSW- Newcastle	0.56	0.4	1.8	na
Bowen Basin	0.60	0.20	4.4	0.2
Galilee – this study	0.60	0.20	4.4	0.2

5.3 SELECTED PARAMETERS

By drawing an analogy to the Bowen Basin, the input parameters used for the SGCP predictions are:

- Subsidence factor – 60%.
- Goaf edge offset. From back analysis of Bowen Basin data, this is 0.20 of the depth of cover.
- Bowen Basin subsidence profiles suggest a typical value for tanB of 4.4. This gives an influence angle of 77^o. The complement of this angle (13^o) can be considered to be generally similar, but not exactly, to the angle of critical deformation (20mm of vertical subsidence). An angle of critical deformation of 26.5^o should be used.

- A strain coefficient – a value of 0.20 has been found to give reasonable estimates of the maximum strain. Note this is a relatively low value and part of this is the need to correct for the high curvatures that result from the use of a high Tan B value to maximise the tilts. Experience in the NSW fields suggests the maximum tensile strains are typically about half the maximum compressive strains – this observation cannot be directly incorporated in the current SDPS formulation.

- No specific analysis of pillar deformations.

- Multiple seam deformations based on the simple addition of the two seams.

It should be noted that the precision of the arithmetic in SDPS cannot be used to infer anything about the validity or accuracy of the predictions themselves.

The visualisation was conducted on 10m centres with a total of 1,738,935 calculation points. It is stressed that the visualisations generated by SDPS do not (cannot) include the small-scale disordered variations.

5.4 SUBSIDENCE BOWLS

5.4.1 Separate seams

Figure 17 and 18 illustrate the distribution of vertical subsidence for the D1 and D2 seams in isolation. At this scale, the plans do not reveal much of the detail: to provide some more information on how the various parameters are distributed, Figures 19 and 20 show the distribution of subsidence, tilts and strains along the north south AA' crossline.

For the D1 seam in isolation, the maximum vertical subsidence is 2.55m, the maximum tilt is 78 mm/m, and the maximum strains are 24 mm/m (Table 2). For the D2 seam in isolation, the values are 1.5m, 44mm/m and 14 mm/m respectively. For the combined layout of both the D1 and D2 seams, the predicted maximum vertical subsidence is 4.2m, the maximum tilt is 112 mm/m, and the maximum strain is 35 mm/m (tensile or compressive).

Table 2 Maximum subsidence parameters

Layout	Maximum vertical (m)	Maximum tilt (mm/m)	Maximum strain (mm/m)	Depth (m)
D1	2.55	78	24	60-240
D2	1.5	44	14	
D1 and D2	4.2	112	35	

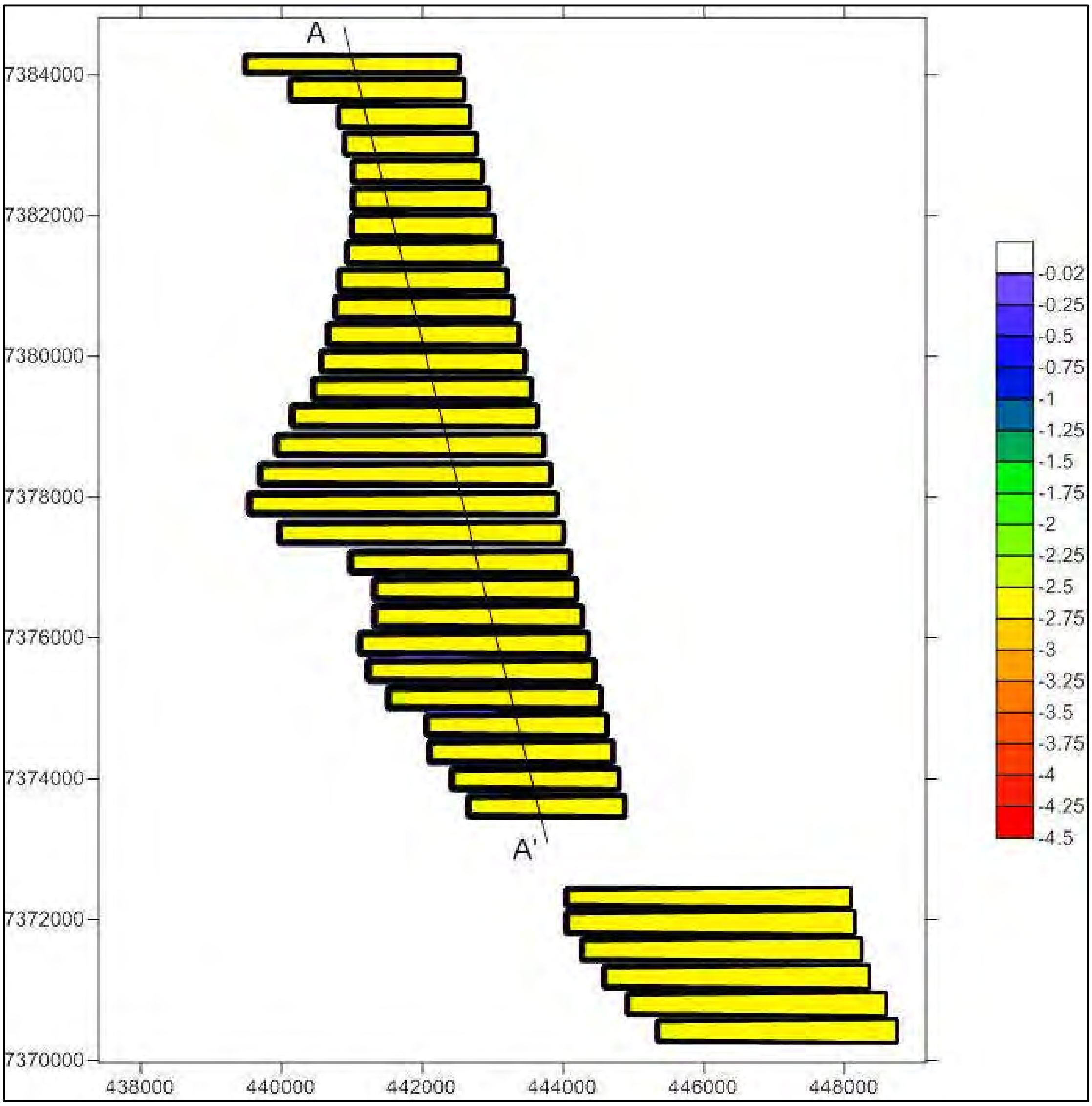

Figure 17 Distribution of vertical subsidence associated with just the D1 seam (in metres)

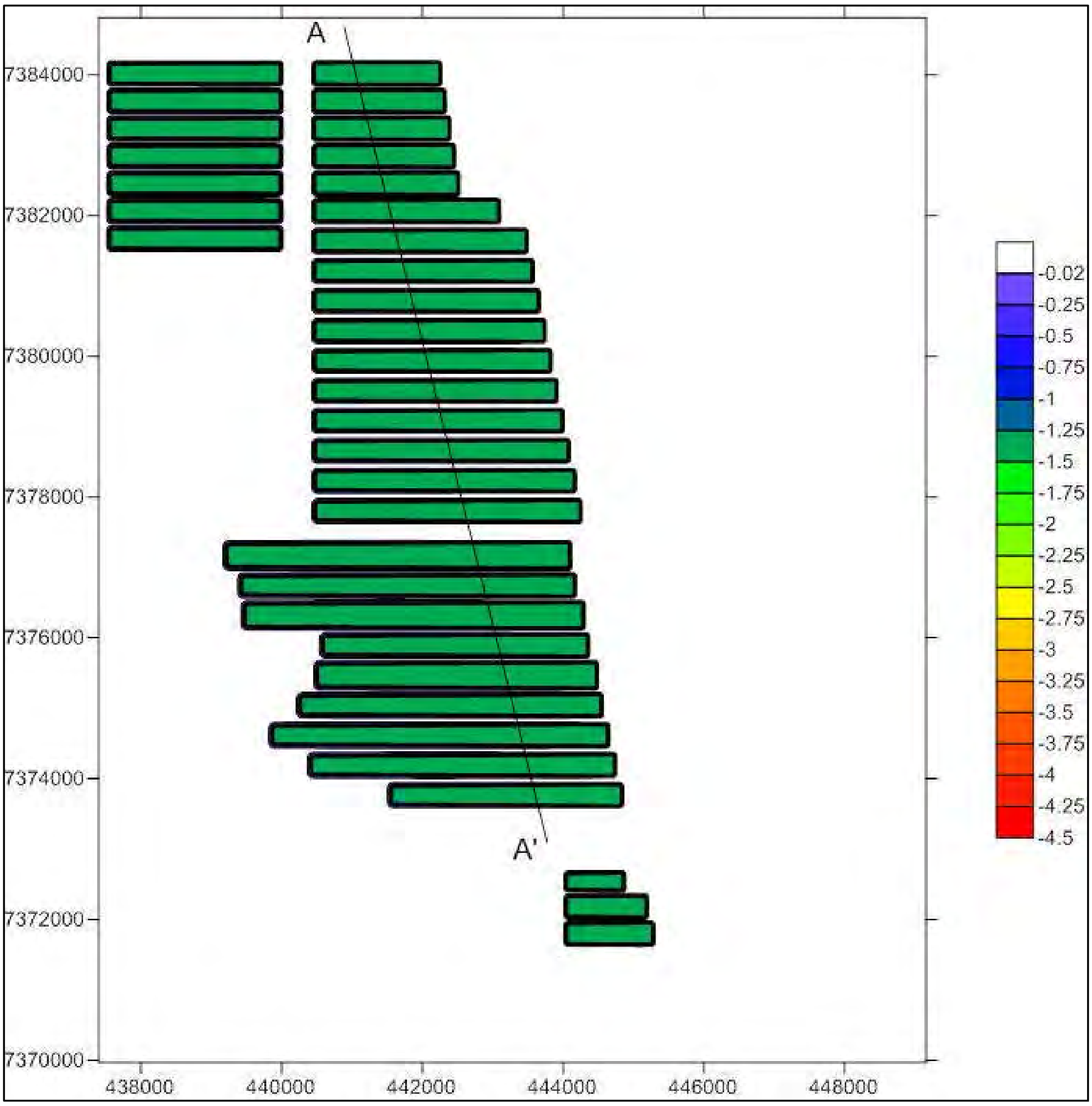

Figure 18 Distribution of vertical subsidence associated with just the D2 seam (in metres)

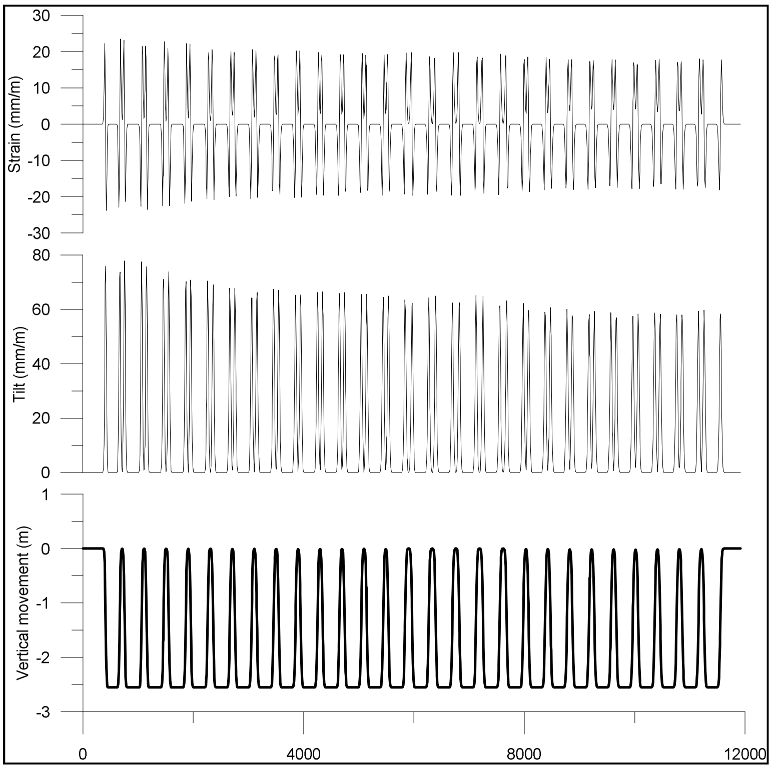

Figure 19 Distribution of vertical subsidence, tilts and strains along the AA' crossline for the D1 seam

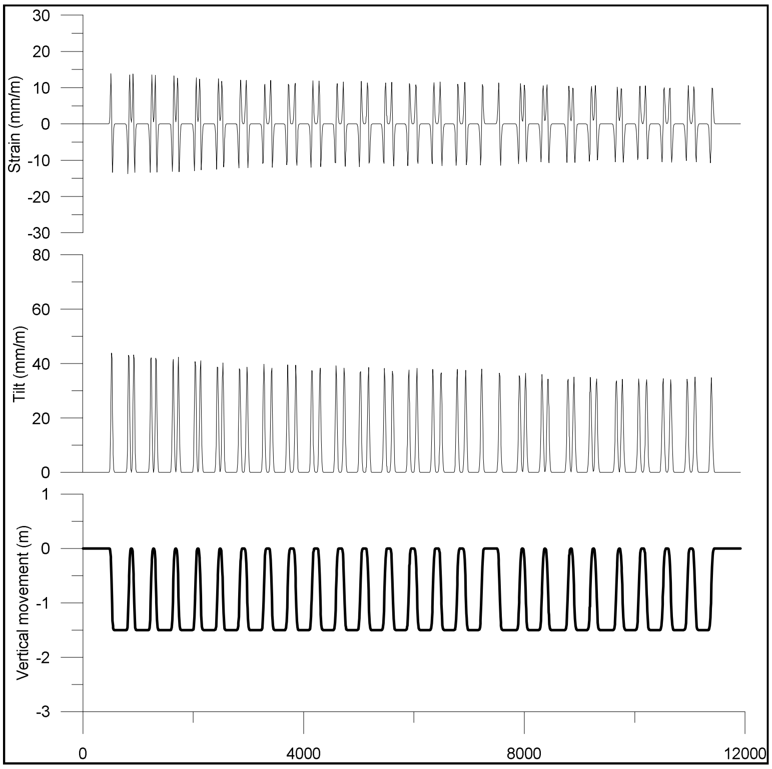

Figure 20 Distribution of vertical subsidence, tilts and strains along the AA' crossline for the D2 seam

5.4.2 Combined seams

The subsidence deformations for both seams (Figures 21-23) include a maximum vertical subsidence of 4.2m, a maximum tilt of 112 mm/m, and a maximum strain of 35mm/m. The distribution of parameters along the crossline is shown in Figure 24.

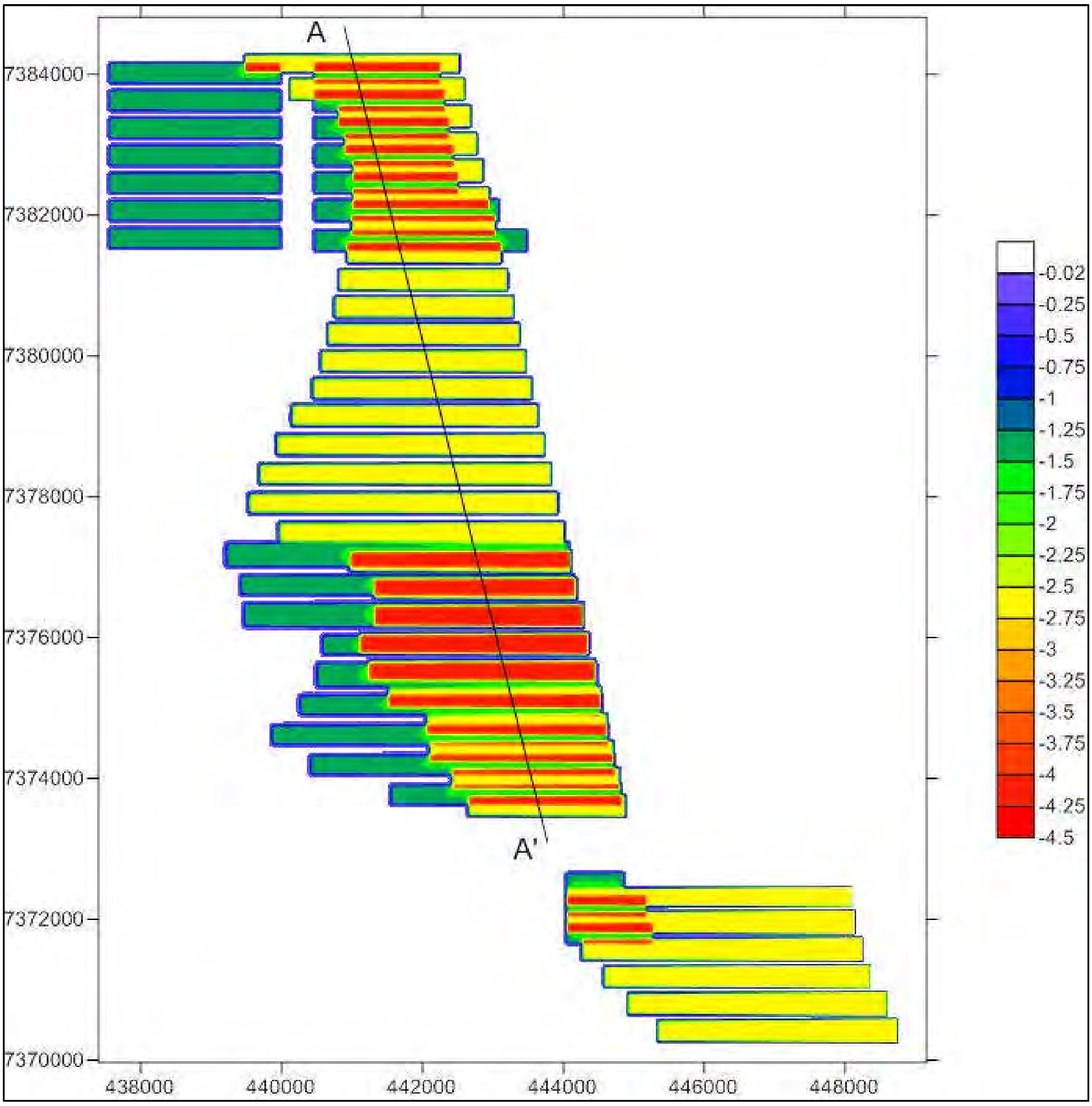

Figure 21 Vertical subsidence (m) – both seams

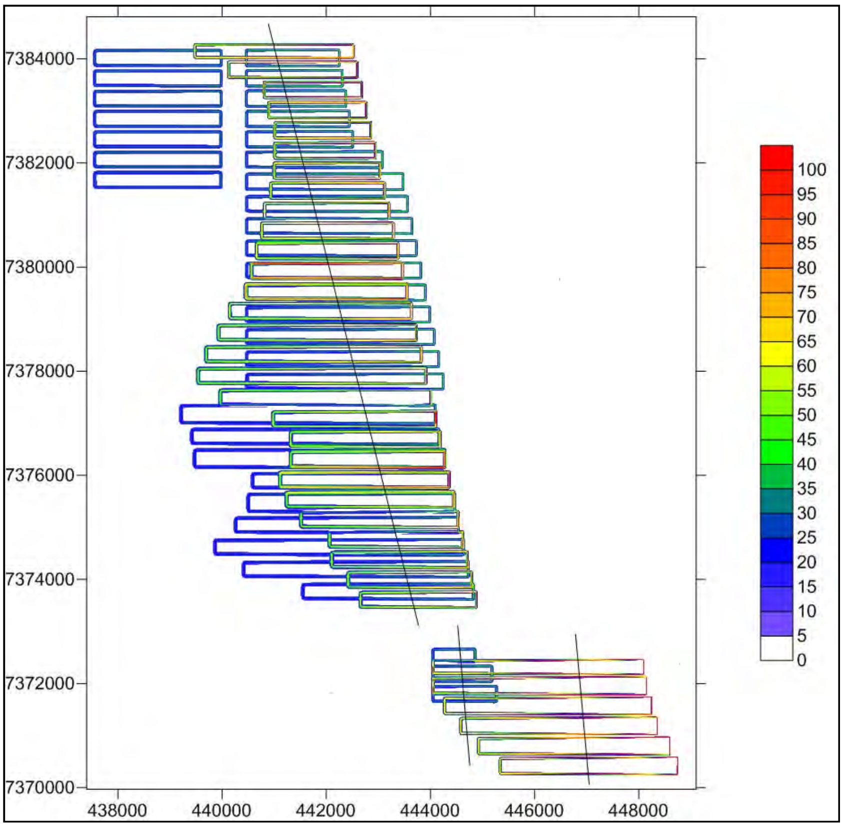

Figure 22 Tilt (mm/m) – both seams

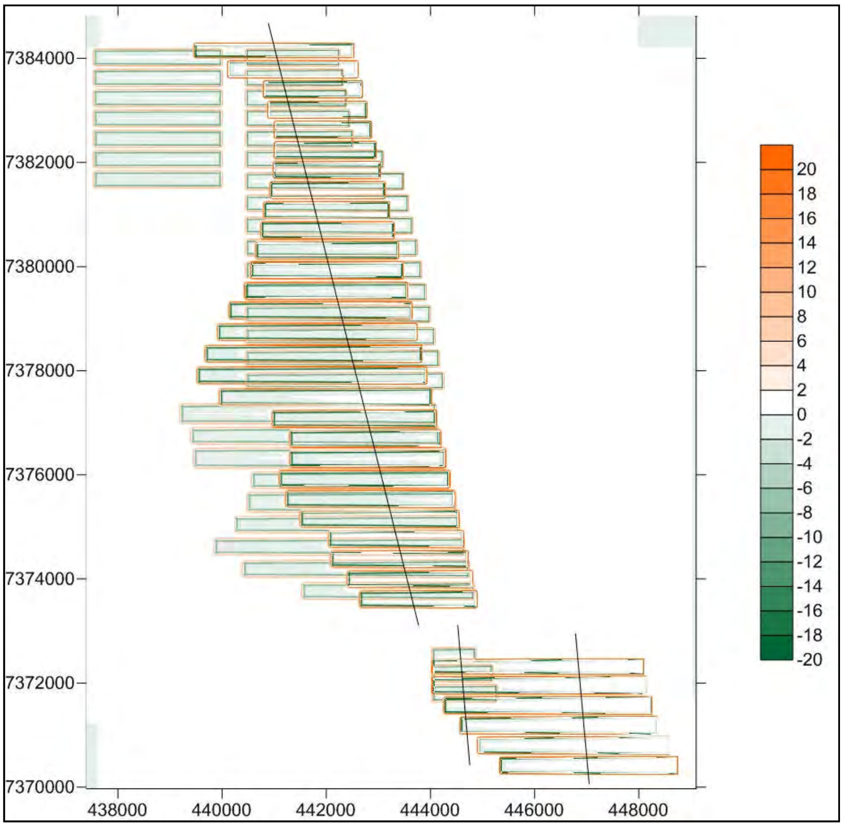

Figure 23 Strain (mm/m) – both seams

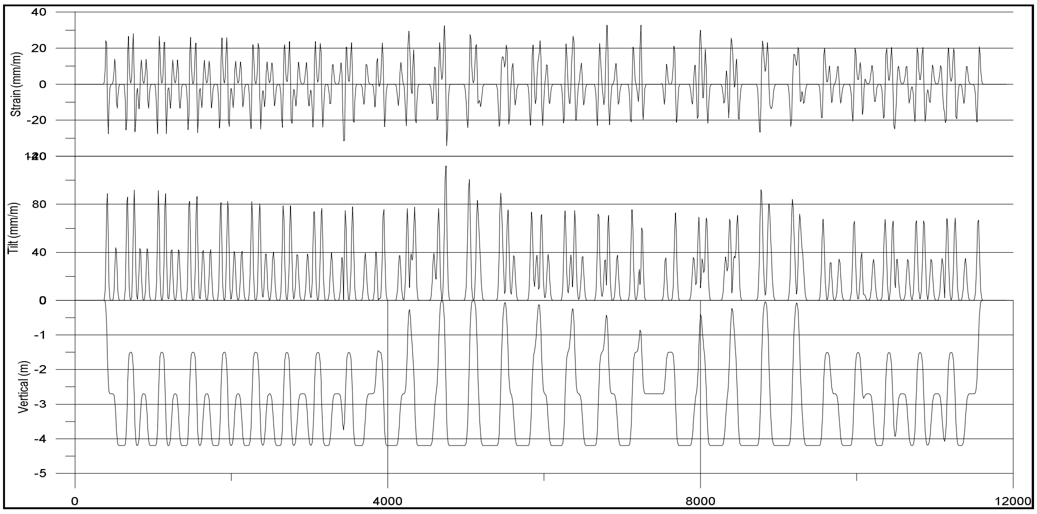

Figure 24 Subsidence parameters along crossline AA'

5.5 POST MINING TOPOGRAPHY

The post mining topography (i.e. topography of the ground surface following mining-induced subsidence) is shown in Figure 25. Figure 25 has 5m contour intervals to enable the impact of the longwall subsidence to be more readily discerned. The supplied dxf provides contours at 1m intervals.

6 POSSIBLE IMPACTS

6.1 SURFACE DRAINAGE

The predicted maximum vertical subsidence is 4.2m. Should the groundwater table lie closer than this to the surface, inundations will develop. A detailed groundwater assessment will be prepared separately by specialist groundwater consultants and will be appended to the SGCP EIS.

Following subsidence, short-term partial loss of surface water may be observed in waterways compared to the baseline conditions, particularly if the groundwater table is depressed after a long dry period. This loss is due to the greater volume of voids filled by surface water recharge. This is usually observed by a greater “lag” time for groundwater levels to recover after subsidence has occurred.

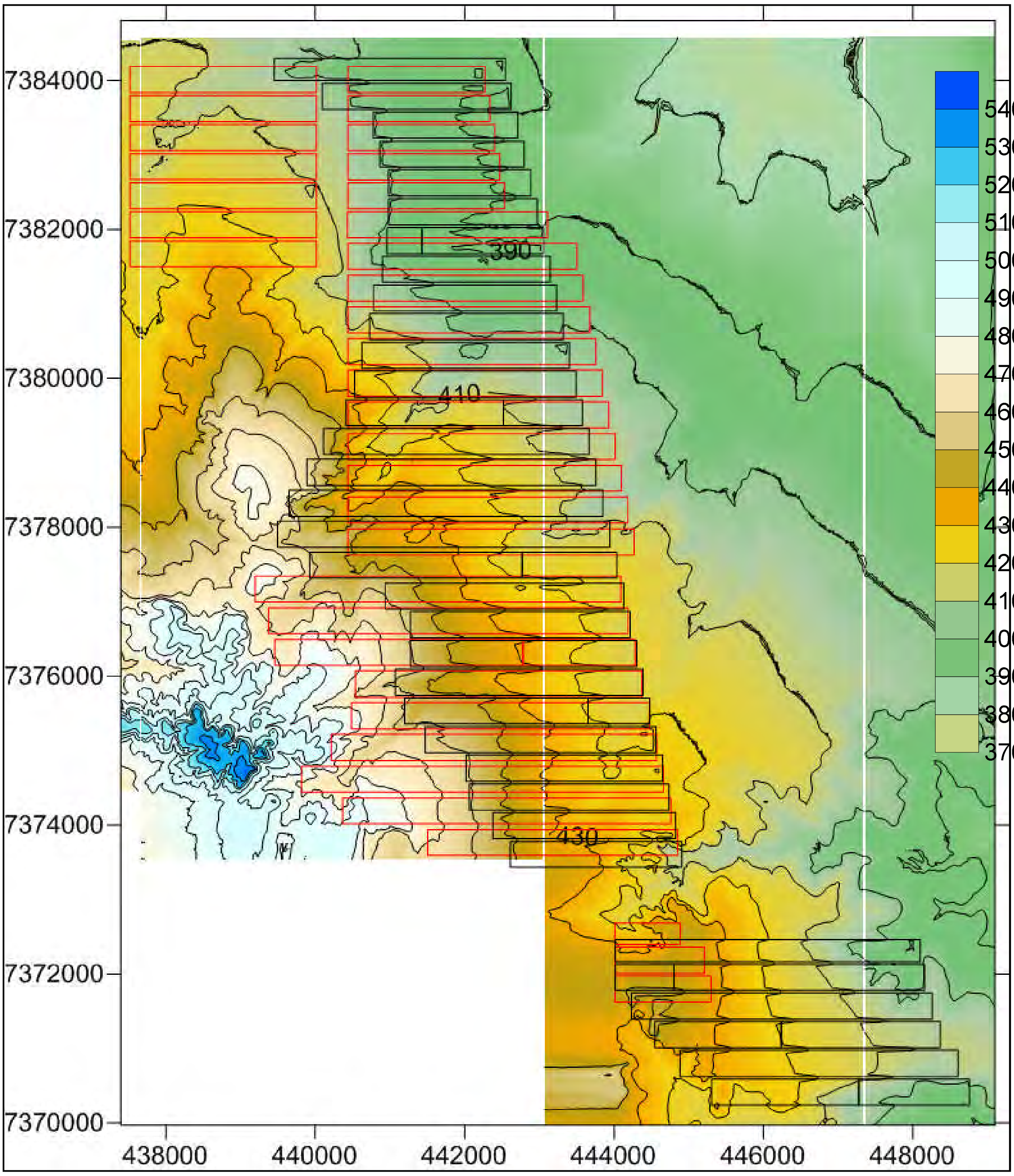

Figure 25 Post mining topography (compare with Figure 2)

6.2 SURFACE CRACKS

The development of cracking at the surface will depend on the nature of the soils and weathered rocks. There may be a large amount of shallow vertical cracks. Deeper and wider cracking (e.g. in excess of 50mm wide and 1m deep) could be associated with tensile strains in excess of 5mm/m. For the maximum tensile strains being predicted, the widest of the cracks is predicted to be in the order of 100mm - 200mm wide and extend to about 10 – 15m below ground level. Cracks of this nature can be readily remediated by reforming the surface with small excavators and dozers.

6.3 CONNECTION TO UNDERGROUND WORKINGS

The height of the fracturing or caving zone above longwalls and interaction with groundwater in this zone has been studied extensively. Data collected from Bowen Basin mines suggests the presence of a fractured zone extending 90m to 115m above a single seam longwall.

We are not aware of previous empirical studies examining the height of fracturing above multiple seam longwalls. The nomogram reproduced in Figure 14 would suggest significant water inflows to the mine workings for the combined seams. However, such an application to multiple seams may not be valid. Water inflows relate to the formation of zones of fractured rock and the dimensions of these cannot be directly related to the vertical subsidence developed on the surface. Recognising that fracture zones develop upwards from the longwall extraction, Figure 26 shows that the height of the fractured zones associated with a lower seam extraction are not higher than those associated with the upper seam. The vertical subsidence will be higher, and this can be considered as simply the overall lowering of the upper seam and its subsidence bowls.

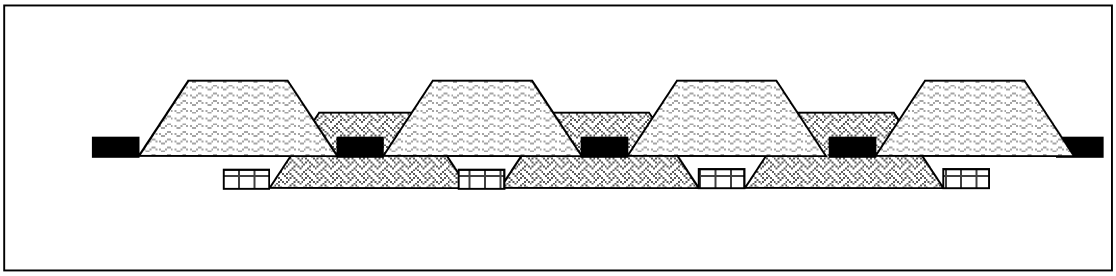

Figure 26 Overlapping fracture zones in multiseam longwalls

The model in Figure 26 has not been validated. In the face of the additional uncertainties with predicting fracturing heights above multiple seam longwalls, it would be good practice to assume a higher overall height of fracturing. For SGCP a value that is 50% higher than for a single seam should be used. For SGCP, this implies a fractured zone extending to 0.5 times the longwall extraction panel width.

6.4 SHALLOW GROUND WATER REGIME

Detailed groundwater assessments will be prepared separately by specialist consultants and will be appended to the SGCP EIS.

There is a potential for short to medium term transfer of surface water to the underlying groundwater system if the surface subsidence cracks connect to an underlying aquifer (Figure 27). The transient tensile strains associated with the subsidence wave may increase the effective pore space in the aquifer and hence there will be a reduction in piezometric head. The increase in bedrock void space may then be filled by surface water flowing into the cracks, temporarily reducing surface overland flow. This loss of surface water can persist for as long as required to fill the new crack voids. Provided that there is no discharge route from the groundwater system, surface flows are generally resurrected when the voids are filled. This filling may be by water, or on a more permanent basis by surface soils.

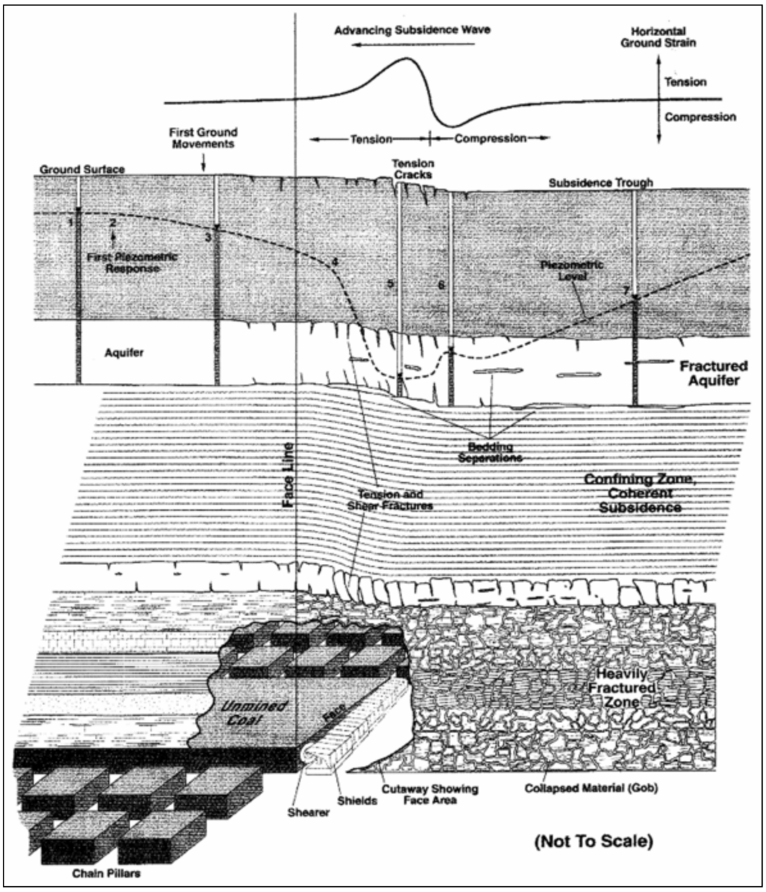

Figure 27 Conceptual model for the transient piezometric response of a near surface fractured rock aquifer above the longwall fractured zone (Booth, 2002)[17]

In deeper mines, localised loss of surface water may occur if there is transfer of water to a shallow groundwater system. This water usually discharges downstream in the catchment as upwelling groundwater without loss to the mine or loss from the overall catchment water budget. For this to happen, the surface flow path needs to be elevated above the groundwater system and this typically requires a steep topography and rocky bars/water falls. This condition is not present at SGCP.

6.5 WATER QUALITY

Water quality (in terms of water chemistry) does not generally change due to subsidence, except for a potential minor increase in salinity through enhanced connection to the underlying bedrock, and / or the increased content of stream bedload and dissolution of salts due to stream bed and bank erosion. Given the recent and Tertiary sediments, the former is unlikely.

Destabilisation of the stream bed and banks can be a significant effect from subsidence in a stream system as the new, post-mining trough and ridge profile along the stream is not geomorphologically stable. The maximum predicted tilts at the SGCP are well in excess of the current topographic slopes, so this impact should be anticipated.

[17] Booth, CJ. 2002. The effects of longwall coal mining on overlying aquifers. In Younger PL and Robins NS (eds) Mine Water Hydrogeology and Geochemistry. Geological Society, London, Special Publications, 198, 17-45

After subsidence, streams attempt to regain their original gradient and energy regime, which is generally achieved by eroding the stream bed and banks over chain pillars along with sedimentation in subsidence troughs. This also has the effect of increased discharge of suspended sediment downstream of the subsidence region.

Each time the creek flows, the new highs are reduced and the lows are filled in within the overall group of subsided panels. The greatest change in water quality is generally observed during flow periods directly after subsidence occurs, with the erosion / sedimentation reducing over time as a new stable state is attained.

Upstream of the overall subsidence region, headward bed erosion and bank destabilisation and / or widening can occur as the stream responds to the change in bed gradient, and attempts to re-establish a new stable state.

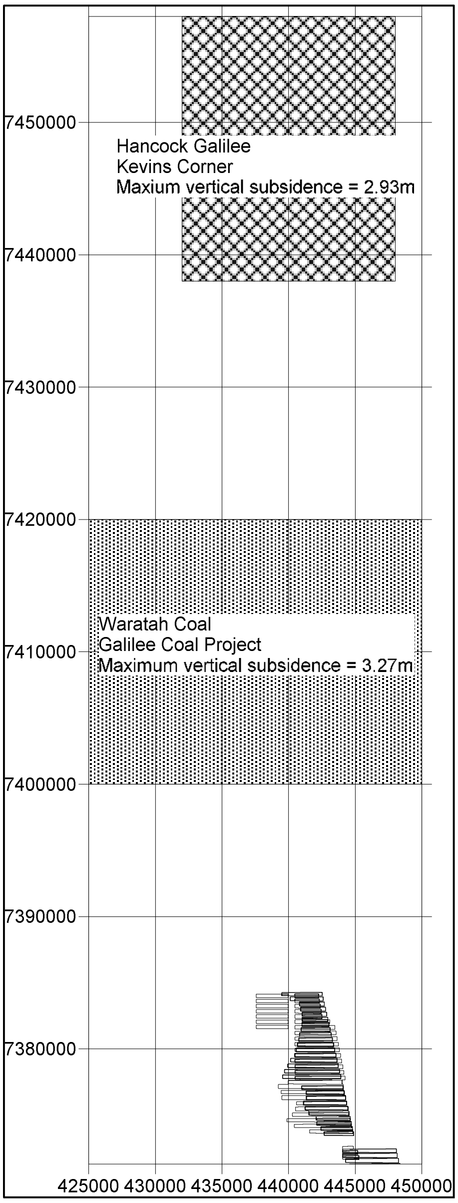

Figure 28 Other Galilee underground proposals

The downstream "edge" of the subsidence region will generally respond by an increase in sedimentation as the low point fills in an attempt to regain its original bed level.

6.6 CUMULATIVE SUBSIDENCE DEFORMATION IMPACTS

The margin figure (Figure 28) shows the location of the SGCP with respect to the other underground projects currently being proposed for the Galilee Basin. There is no underground at Hancock Coal's Alpha Coal Project . The nearest project (Waratah) is some 15 km to the north. In terms of subsidence deformations there will be no interaction between these projects.

7 RECOMMENDATIONS

The subsidence predictions provided in this report should be used as likely indicative maximums, but should not be interpreted as constraints to be applied to the mine design. The state of the art in subsidence modelling and prediction does not allow predictions in new mining districts with very high levels of certainty.

Tilts have been maximised by the selection of a high tanB value, and then somewhat reduced associated strains by a lower strain constant. This is based on previous experience in the Bowen Basin. A consequence is a footprint that is possibly smaller than will be encountered.

In the context of setting deformations for risk assessments, the following is recommended:

- Values 20% higher than in the visualisations.
- At an specific location, deformation values with a 20m radius should be considered.
- An angle of draw of 26.5^{o} be used for defining the subsidence foot print

Since much of the adverse impact with subsidence comes from the high tilts and strains associated with the edges of the extraction panels, wider panels may reduce the total impact. At this stage, the knowledge of the overburden suggests there is no opportunity to narrow the extraction panels to reduce subsidence impacts by reducing the maximum vertical subsidence to low levels.

The first of the longwall extraction panels should be extensively monitored to provide validated parameters to use in subsequent influence function predictions. The monitoring should include airborne laser surveys to produce detailed contour maps of the subsidence troughs and also some more conventional cross-line surveys to obtain values for tilts and strains. There should be subsurface monitoring to characterise the heights of the fractured zone.

It is likely the multiple seam extraction will begin well into the life of the mine after much more is known of the subsidence behaviour in the Galilee Basin. The monitoring programs used for the single seam can be modified and applied as appropriate to the multiple seam layout.