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DATE:	13 October 2015
TO:	Gary Brassington Manager Approvals Dendrobium Mine – Illawarra Coal / South 32
FROM:	Adam Skorulis and Will Minchin
RE:	Estimated Height of Connected Fracturing above Dendrobium longwalls
OUR REF:	BHP008- HC2015-27f

This letter outlines HydroSimulations' assessment and proposed work method for future assessment of the effects of longwall mining, specifically the estimated height of connected fracturing extending up above the panel. The letter has the following structure:

1. Introduction regarding effects of longwall mining and subsidence on overburden strata;
2. A summary of previous research in relation to estimating the extent of the deformed strata above longwall mining, both in general and at Dendrobium.
3. Summary of the revised estimates of the height of connected fracturing for Dendrobium longwalls using the Ditton 'Geology Model' (Ditton and Merrick, 2014). This is compared with previous estimates made using the Tammetta (2013) method.

This report has been reviewed by Steve Ditton of Ditton Geotechnical Services (DGS).

EFFECTS OF LONGWALL MINING AND SUBSIDENCE ON OVERBURDEN STRATA

Longwall mining involves the extraction of several adjacent panels within a coal seam, which can each be more than a kilometre (km) long (often several km), up to 400 m wide, and 2-5 m thick. Access to and ventilation of the longwall face require long and stable coal pillars (known as chain pillars) to be left between the panels.

As the longwall progresses along the seam, the removal of material results in the roof of the mine void collapsing, with subsidence of about 30-60% of the mined thickness at the surface above the mined panels (depending on the panel width v. the cover depth and the compression of the chain pillar system) . This results in deformation and fracturing of the strata above the mined seam, with the potential to alter the hydrogeologic nature of the system and its relation to stored water, surface water and groundwater.

The footprint of Illawarra Coal's Dendrobium Mine underlies and is in close proximity to a number of water features including: upland swamps, watercourses such as Sandy Creek and Wongawilli Creek, and the Avon and Cordeaux Reservoirs. Additionally there are a number of water-bearing rock units (Wongawilli and Bulli Coal Seams, the Scarborough and Bulgo Sandstones, and the shallower Hawkesbury Sandstone. As such, it is important to understand the effects of subsidence and the deformation of rock units associated with longwall mining and the impact these have on the hydrogeological conditions.

This subsidence causes deformation and fracturing of the rock strata above the extracted panel, as shown on **Figure 1** (from Parsons Brinckerhoff [PB], 2015).

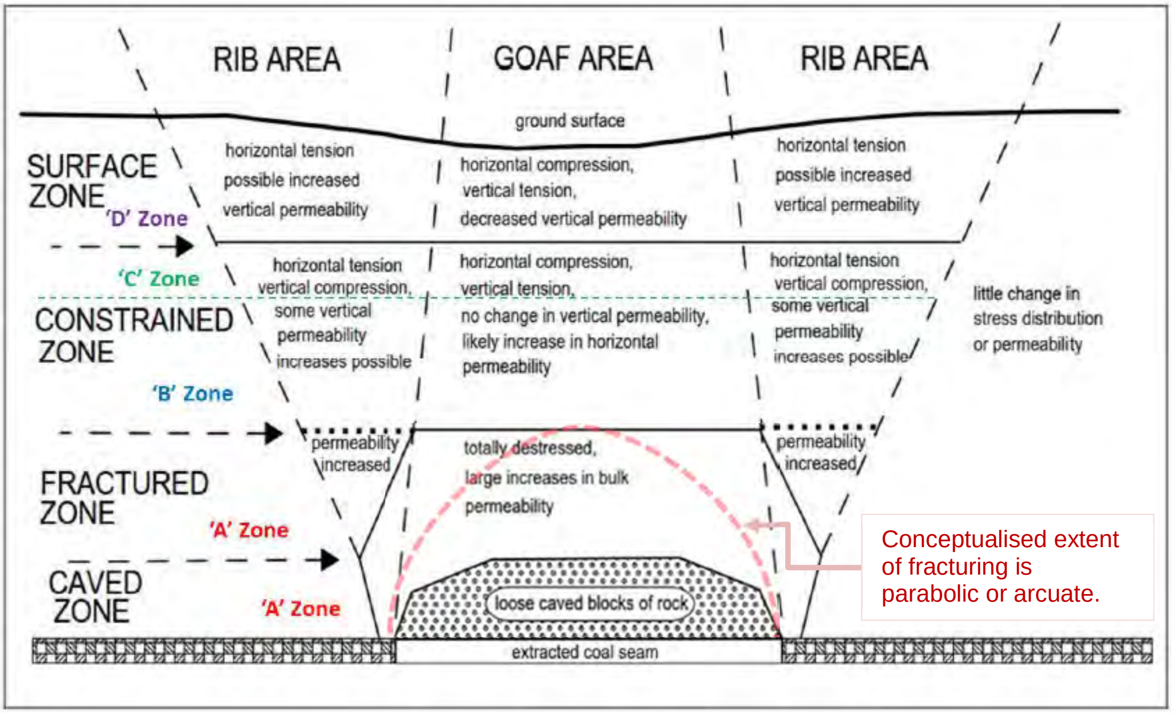

Figure 1 Zones of Disturbance and Hydrogeological Effects following Longwall Mining

The content on **Figure 1** is mainly from ACARP (2007), with the A, B, C and D-zone notation taken from work by Ditton Geotechnical Services (as presented in Ditton and Merrick, 2014).

As commented on **Figure 1**, that most authors conceptualise the zone of fracturing to be parabolic, or an arch, with the maximum height of fracturing occurring above the centre-line of a longwall panel. **Figure 2** shows the subsidence and deformation in a physical model (Whittaker and Reddish, 1989). HydroSimulations have added the arch shape for emphasis).

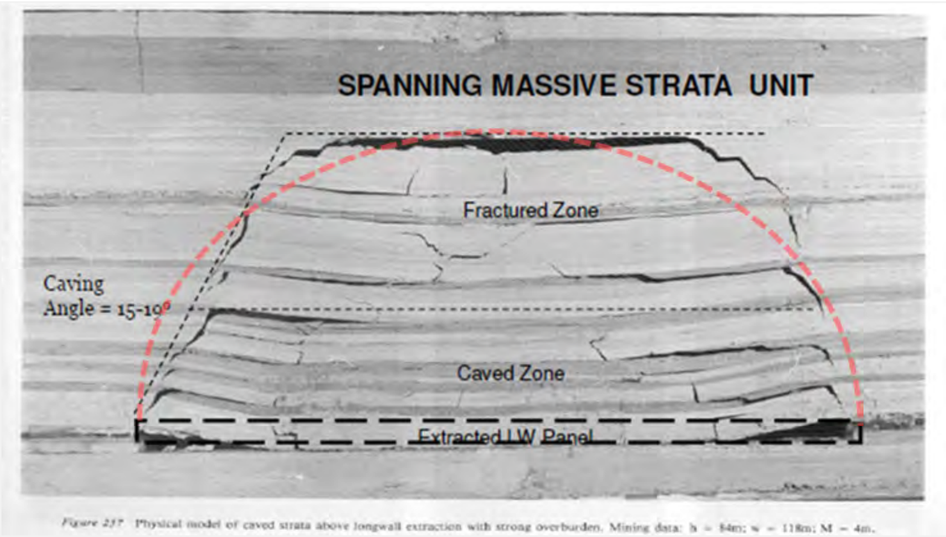

Figure 2 Physical Model of Caving and Fracturing above a Void

Parsons Brinckerhoff was commissioned by Illawarra Coal to carry out field investigation of the effects of subsidence within rock strata above Dendrobium Longwall 9. This study (PB, 2015) analysed data from a range of testing methods in bores located on a ridgeline above the longwall.

REVIEW OF PREVIOUS STUDIES

Classifying the nature and extent of the deformed zones above a longwall is a key element in developing a conceptual model and predicting the impacts of mining on local groundwater systems. In line with development applications over the past ten years, a number of geotechnical and groundwater assessments have been commissioned as part of applications for mining at Dendrobium. The following sections review these in light of selecting a method that most accurately describes the situation at Dendrobium to be used in conceptualisation and the development of numerical groundwater models. The review includes a brief summary of the conceptual models developed and the methods used in estimating the extent of fracturing and deformation above the mined seam, focussing on the height or extent of various zones of deformation and fracturing in the overburden, and specifically on the height of connected fracturing.

The following studies have been reviewed (full references at the end of the document):

- **Forster, 1995**. *Impact of underground mining on the hydrogeological regime, Central Coast, NSW.*
- **GHD, 2007**. *Dendrobium Area 3 Predicted Hydrogeologic Performance.*
- **Heritage Computing, 2009***. Mine Inflow Review, Conceptualisation and Preliminary Groundwater Modelling.*
- **Heritage Computing, 2010**. *Local Area Groundwater Modelling of Alternative Area 3A Longwall Panel Lengths.*
- **Heritage Computing, 2011**. *Recalibration of the Dendrobium Local Area Groundwater Model after Completion of Longwall 6 (Area 3A).*
- **Coffey, 2012a**. *Groundwater Study Area 3B Dendrobium Coal Mine Numerical Modelling.*
- **Coffey, 2012b**. *Groundwater Study Area 3B Dendrobium Coal Mine Data Analysis (2nd ed).*
- **HydroSimulations, 2014**. *Dendrobium Area 3b Groundwater Model Revision: Swamps, Stream Flows and Shallow Groundwater Data.*
- **Ditton and Merrick, 2014**. *A new sub-surface fracture height prediction model for longwall mines in the NSW coalfields.*
- **Parsons Brinckerhoff, 2015**. *Connected fracturing above longwall mining operations* [at Dendrobium], *Part 2: Post-longwall investigation.*

A brief summary of each is provided below, with a focus on evolution of the conceptualisation of strata deformation, and any estimates of and methods for estimating the height of connected fracturing.

Forster, 1995

While not specific to the Dendrobium area in the Southern Coalfield, this study from the Central Coast, NSW, led to an understanding of how underground coal mining modifies the hydraulic nature of a rockmass and served to create a model which identified various zones of deformation above an extracted longwall panel.

Caved zone – immediately above the mining interval and is composed of loose blocks that have collapsed from the roof once the longwall has progressed. Upward migration is limited by bulking of the collapsed loose rocks occupying a greater volume than solid rock. The caved zone height typically ranges from 5-10 x mined height.

Fractured zone – this zone contains disturbed units supported by the underlying caved zone. These units have sagged downwards, undergoing bending, fracturing, joint opening and bed separation. The fractured zone is based on hydrogeologic response with increases permeability in both the vertical direction (e.g. connected vertical fracturing) and horizontal direction (e.g. bed separation). Forster (1995) estimated that the upward limit of the fractured zone is 20-33 x the thickness of the mining interval.

Constrained zone – the constrained zone is comprised of the units overlying the fractured zone that have sagged, but have absorbed most of the strain energy without significant fracture or change to hydrogeologic properties. Some slippage, disconnected vertical fracturing and bed separation can be present. This zone is seen to be the most important in the maintenance of hydraulic pressures in overlying units and can form an effective barrier to vertical drainage. Forster (1995) found some increases in horizontal permeability as a result of longwall mining on the Central Coast but with no appreciable increase in vertical permeability.

Surface Zone – subsidence resulting from longwall extraction causes tensile and compressive strain in the unconfined units at the surface, which may result in surface cracking or ground heaving. For the Central Coast Study a thickness of 15 m for the surface zone was adopted with conclusions this zone would exist less than 30 m from the ground surface. Overburden soil and rock may absorb these strains without observable effect.

Rib Zone – is present at the sides of the longwall extraction area and provides a transition area between the subsiding overburden and surrounding rock present over solid coal.

GHD, 2007

GHD was commissioned by Illawarra Coal to characterise the existing hydrogeological conditions of the proposed mining Area 3, and predict the impacts of longwall mining on local stored water, surface water and groundwater. Focus was placed on specific issues such as;

- Impacts on stored water in Cordeaux Reservoir.
- Impacts on groundwater over Area 3 footprint.
- An estimate of groundwater ingress to the mine.

An understanding of the hydrogeologic conditions of the area was gained through the use of downhole geophysical logging, 'packer testing' to determine permeabilities, and the installation of vibrating wire piezometers (VWPs).

The conclusions found in the assessment of monitoring data included:

- Within Area 3, the Stanwell Park Claystone and overlying Bulgo and Hawkesbury Sandstones, groundwater levels were largely unaffected by mining activity in Dendrobium Areas 1 and 2. This suggested that the integrity of the Stanwell Park Claystone as an aquitard had been maintained.
- Mining resulted in the depressurisation of the Scarborough Sandstone, with the unit becoming unconfined. Partial depressurisation of the Wombarra Claystone is seen, however, the unit is not seen to become free-draining and maintains a degree of integrity as an aquitard. Significant depressurisation was observed in the Coalcliff Sandstone.
- Equilibrium head conditions are reached quite quickly after the longwall passed the monitoring sites.
- Chemical analysis of the groundwater inflow to the Area 1 and 2 mine workings showed the water entering the workings was relatively saline, assessed as having strong Bulli and Wongawilli Seam signatures, and also without the 'fingerprint' of lake water. This indicated "that the introduction of stratigraphically higher and overlying sources of water into the minewater has not occurred", either via flow through porous media or via geological structures. A discrete event in June 2007 was reported as an exception during the extraction of Longwall 3. In this event, which lasted one day, an increased flow of water in to the workings occurred. Geochemical analysis identified the origin of the water to be from the Scarborough Sandstone and not from any other source (such as the Cordeaux Reservoir). Following this event, mine water inflow rates and chemistry reverted back to previous values.

Also used was data gained from field testing and exploration over and adjacent to the now decommissioned Elouera Colliery located south of Dendrobium Area 3B. Boreholes drilled specifically over a previously mined longwall extracting the Wongawilli Seam at the Elouera Colliery, were used to provide additional data from longwall mining in the Southern Coalfield. GHD referred to previous work by Strata Control Technology (SCT, 2005), who assessed the area of disturbance above the mine based on extensometer monitoring over active longwalls providing an interpretation of the zones overlying the mined seam based on rock mechanics (refer to p. 37 of GHD, 2007 for summary of SCT, 2005 zones). GHD concluded that although hydrogeologic response is not accounted for, the zones were broadly applicable to those above in Forster (1995).

The GHD assessment of the impacts of longwall mining combined data from Dendrobium Area 1 and 2, the field data and conclusions from SCT's study at Elouera Colliery, and the zones described by Forster (1995), and concluded the following for the nature of the zones above a mined longwall for general situations with sufficient overburden in relation to W, the longwall panel width. GHD (2007) states:

- "A Caved Zone of high permeability will exist immediately above the mined area to a height of 5t to 10t (5 to 10 times the height of the mining interval).
- A Fractured Zone will exist above the Caved Zone, and extend to a height of about 0.4W (i.e. 0.4 times the width of the panel) above the floor of the mining interval). Within the Fractured Zone, large increases in permeability occur.
- A Constrained Zone will exist above the Fractured Zone, probably in an arch shape, up to a height of 1.5W or to within 15 to 30 metres of the ground surface within which little variation in vertical permeability exists, but increases in horizontal permeability occur through shearing and limited bed separation.
- A Surface Zone that undergoes limited impact (cracking) when the depth of cover over the mining interval is in excess of 1.5W ".

For the longwalls in Dendrobium 3A this translates to a caved zone 15-30 m above the floor of the mining interval. A Fractured zone height of approximately 100 m above the seam (to the Stanwell Park Claystone or Lower Bulgo Sandstone), and a Constrained zone to within 15 to 30 m from the ground surface. Also identified below the seam was a fractured or dilated zone caused by unloading, and extending a similar distance below the goaf. This zone of deformation below the seam is of little significance to the interaction between the goaf and shallow groundwater or surface water, so it has not been considered further within this report.

Heritage Computing 2009

This study was carried out by Heritage Computing at the request of Illawarra Coal in order to investigate the mechanism and source for high mine inflow events occurring in June 2007, February 2008 and June 2008 in Dendrobium Area 2.

A staged fracture zone was conceptualised to explain the periodic increases in mine inflow, in which goafing is not continuous, but occurs with unpredictable delay. Although caving above the mined seam may occur with the progression of the longwall, it may take some further time before additional rock strata located above the initial caved zone collapses into the goaf.

Heritage Computing analysed piezometric data in order to assess the height of the fractured zone above the mined seam, with an interpretation that it extends from the Wongawilli Seam up to and including the Stanwell Park Claystone (this equates to an approximate height of 115m above the mined Wongawilli Seam based on a representation of average unit thicknesses used by Heritage Computing (2009). Groundwater pressures are said to reduce to near atmospheric pressure at the base of the mined seam, with overlying rocks in the fractured zone having a higher vertical permeability (Kv). A constrained zone above this fractured zone was defined, serving to isolate shallower aquifer systems from the stresses applied to those in the caved zone.

Heritage Computing, 2010

The objective of this study was to assess the impacts of longwall mining in Dendrobium Area 3A, particularly in regards to mining 324 m from Cordeaux Reservoir for Longwalls 6 and 7 and 270 m from the reservoir at Longwall 8. This study relied on an updated version of the local area numerical model created by Heritage Computing (2009). Changes to the model included: a conversion to finer cell size, an adjustment to incorporate a longer timeframe as well as alterations to the fractured zone above the mined seams. As is seen in the local groundwater model (HC, 2009) the extent of the fracture zone is taken from analysed piezometric data. The zone of connected fracturing was interpreted as extending to the top of the Stanwell Park Claystone.

These changes to the way the fractured zone is represented in the model include:

- Applying a fractured zone immediately above mined panels but not roadways. Earlier, coarser models applied a fracture zone above the total mined seam without recognition of the partial protection above chain pillars.
- A uniform vertical permeability (Kv) of 0.003 m/day has been applied to the fractured zone (with the exception of the Bulli Seam, Kx=10 m/d and Kv 0.1 m/d). This is assigned from the mined Wongawilli Seam to the top of the Stanwell Park Claystone. Due to observed depressurisation seen to occur in the Bulgo Sandstone, the fractured zone extent is seen to effect higher units than previously thought. The extent of the fractured zone is still modelled to the top the Stanwell Park Claystone (an average of 115m above the mined Wongawilli seam), with depressurisation in the Bulgo Sandstone accounted for by increasing the Kv of the Stanwell Park Claystone. Kv used in the Heritage Computing (2009) report maintained host Kv for this unit.

Heritage Computing, 2011

This report serves as a continuation of work done by Heritage Computing (2009, 2010) and was conducted in regards to requirements from the Dam Safety Committee (DSC). The report determines the height of the fracture zone above Area 3A longwalls from analysis of piezometer results, and recalibrates the local area groundwater model (from HC 2009) following the full extraction of Longwall 6.

Piezometer results for Area 3A show the following:

- Total depressurisation in the Wongawilli Seam.
- Depressurisation of 25-70 m in units above the mined seam following the passing of Longwall 6, extending to the upper Bulgo Sandstone, with maximum depressurisation found in the lower Bulgo Sandstone.
- Some depressurisation of the lower Hawkesbury Sandstone following mining with upper Hawkesbury Sandstone aquifers remaining perched.

Although there is a loss of head seen in the Bulgo Sandstone, model calibrations (conducted by simulating mine inflow vs actual inflow) were achieved without altering its permeabilities, defining the Stanwell Park Claystone as the upper layer of the fractured zone. As is found in previous Heritage Computing (2009, 2010) models, the top of the Stanwell Park Claystone is about 115 m above the Wongawilli Seam. With a void width for Longwall 6 of 249 m, the report infers a fracture zone height/ void width (h/w) ratio of about 0.46.

Coffey, 2012a, 2012b

This study was commissioned by Illawarra Coal to estimate the effects of longwall mining on the groundwater around Dendrobium Area 3B. It investigated the groundwater system as well as the Avon and Cordeaux Reservoirs, for cases involving the extension of Longwalls 13 to 18 of the current mine plan. Predictive modelling was used in Coffey (2012b) to assess the loss of water from the reservoirs due to mining in Area 3B for the following components.

- Baseflow groundwater recharge that would normally flow to the reservoirs but is diverted due to mining activity.
- Seepage from stored water in the reservoirs due to the results of mining activity.

The Coffey 2012a report was undertaken to analyse a substantial database provided by Illawarra Coal in relation to a groundwater assessment of alternative panel length of Area 3B of the Dendrobium Mine. It serves to support numerical model development, calibration, predictive simulations and results also developed by Coffey (2012b)

Estimates for the nature and height of disturbance above the mined seam follow the method developed by Tammetta (2013) and detail a longwall caving process with two distinct zones above extracted panels, the Collapsed Zone, and the Disturbed Zone.

The Collapsed Zone is conceptualised as being parabolic in shape (see **Figure 2**) with severely disturbed strata that is completely drained of groundwater. Within this zone water is transported downwards into the mine working. The maximum height of the Collapsed Zone or "Height of Complete Groundwater Drainage" (H, in metres), can be estimated from the Tammetta (2013) method. H is a function of w (panel width), t (extracted thickness or cutting height), and d (overburden depth) [all units in metres], as follows:

$$H = 1438 \ln(4.312x10^{-5}u + 0.9818) + 26$$

where $u = w\, t^{1.4}\, d^{0.2}$.

The Disturbed Zone overlies the Collapsed Zone and maintains positive groundwater pressure heads. Although immediate lowering associated with the drainage of underlying strata is expected, the Tammetta method proposes relatively stable pressure heads in this zone, which leads to the conclusion that Tammetta's Disturbed Zone is analogous to the Constrained Zone in other conceptual models (e.g. Forster, 1995).

Collapsed Zone heights found by Coffey (2012a) for areas where mined seam thickness is 3.4 m and 3.6 m are approximately equal to the width of the mined voids, and extend upward to the Bald Hill Claystone and Lower Hawkesbury Sandstone. These conditions exist in Longwalls 1-8 and Longwall 19. However, for Longwalls 9 to 18, Coffey (2012b) -assumed a mined height of 4.5m. This results in a dramatic increase in H (Collapsed Zone height) that extends to above the height of the ground surface. Coffey (2012b) provides fracturing to surface height as a means of exacerbating mine inflows during high rainfall events.

The method of calculating connected fracture zone heights from Coffey (2012b) was also relied on in some subsequent modelling studies (e.g. HydroSimulations, 2013).

An independent review of the Coffey (2012a) numerical modelling was provided by Aquaterra (2012). Aquaterra found that, compared to local hydrogeological data, the height of the collapsed zone as estimated and modelled by Coffey (2012a) was conservative.

HydroSimulations, 2014

This study served as a revision of previous studies, including Coffey (2012b) and HydroSimulations (2013), in response to requirements from the Department of Planning and Infrastructure (DP&I) received by Illawarra Coal.

The numerical model underwent two main enhancements:

- The MODFLOW Drain boundary condition, which was previously used to simulate creeks and rivers, was replaced by the MODFLOW Stream Flow Routing (SFR1; Prudic *et al.*, 2004) boundary condition. This provides a 'stepping stone' toward integrated groundwater and surface water flow modelling, which is a critical avenue for potential mining impacts to water supply reservoirs around Dendrobium Mine. It also provides a more rigorous tool for simulating potential impacts on swamps, creeks and rivers than the Drain boundary does. Furthermore, it is better suited to achieving adequate calibration to shallow groundwater level data. The application of this enhancement will be taken further in future model development as required.
- Revision of the simulated height of fracture used by HydroSimulations (2013) using the method of Ditton (2013). This was done because the results from the earlier HydroSimulations (2013) and Coffey (2012b) reports were very conservative. More detail on this change is provided below.

In contrast to the two subdivisions provided by Tammetta (2013), the conceptual model presented in Ditton (2013) describes five zones of strata deformation above longwalls (this in turn is based on Guo *et al*, 2007).

Table 1 Sub-Surface Fracture Zone Summary (from Ditton, 2013 & Guo *et al*, 2007)

Zone Type	Zone	Fracture and Groundwater Response Description	Typical Vertical Strain (mm/m)
Surface Cracking Zone (un-constrained)	D	Vertical cracking due to horizontal strains extending to maximum depths of 10 - 15 m. Surface waters may be diverted below affected area and resurface downstream where interaction with B & C Zones occur.	<3
Elastic Deformation Zone (dilated bedding & constrained)	C	Generally unaffected by strains with some bedding parting dilation. Horizontal strains constrained by overlying/underlying strata. Groundwater levels may be lowered temporarily due to new storage volume in voids between beds, but likely to recover at a rate dependent on climate. Elastic Zone may not be present if B or A Zones extend up to Surface Zone.	<3
Discontinuous Fracture Zone (dilated bedding & constrained)	B	Minor vertical cracking due to bending that do not extend through strata units. Increased bedding parting dilation and similar groundwater response to Zone C. Some groundwater leakage may occur to B Zone, however, losses likely to be recharged by surface hydro-geological system.	<8
Continuous Fracture Zone (unconstrained)	A	Major vertical cracking due to bending that pass through strata units and allow a direct hydraulic connection to workings below. Full depressurisation of groundwater occurs in the Zone that may recover in the long term once mining is completed.	>8
Caved Zone (within the A-Zone)	A	Caved strata up to 3 to 5 x Mining Height above the workings. Collapsed roof bulks in volume to provide some support to overlying strata.	>80

The Ditton equations provide an analytical estimate of the height of the A-zone (connected cracking) and the B-zone (disconnected cracking), in relation to effective panel width (W'), a goaf load height factor (1/tanθ) , mined thickness (T) and effective strata unit thickness (t') with the equations providing the mean and 95% confidence limits.

The method recognises:

- An effective panel width (W') to acknowledge that increasing panel width beyond the critical width (1.4H) will not materially change the height of the fracture zone, and
- The overburden usually shears into thinner units or the height of continuous fracturing may be truncated by spanning strata (t').

Ditton's A-zone is seen as the most important in relation to simulating the drainage of groundwater from strata above mining. This zone is said to have fracturing through strata, allowing full depressurisation and groundwater flow down to the void.

The Ditton (2013) equation for A-zone height is:

$$A = 0.273\ (1/\tan\theta)^{1.26} W'^{0.89} T^{0.37} t'^{-0.26} \qquad +/- aW'$$

The HydroSimulations (2014) report applied both the Ditton (2013) and Tammetta (2013) methods to every groundwater model cell potentially affected by longwall mining. A comparison between estimates for Tammetta's 'height of complete drainage' (H) and Ditton's A-zone height (seen as conceptual equivalents) showed a large contrast in the results, with Ditton A-zone being about half those of Tammetta (2013).

HydroSimulations (2014) suggests that differences may have come from the database used to construct the Tammetta (2013) method not covering the conditions experienced at Dendrobium, or from differences in interpretation of the same data in formulating the methods.

- The Tammetta (2013) regression is derived from a combination of void width, cover depth and mined height. HydroSimulations (2014) highlights that much of the existing and proposed mined areas at Dendrobium have longwall geometries beyond the limits of the database upon which the Tammetta (2013) regression is based. Specifically, that database does not cover mined heights of greater than 4.1 m (4.5m mined height in Area 3B) or panel widths of greater than 260 m (305 m void widths in Areas 3A and 3B).
- Modelling of the fractured zone extending to the Hawkesbury Sandstone and above, as seen in Coffey (2012a, 2012b), indicates a greater risk of surface desaturation than modelled in HydroSimulations (2014). However, monitoring shows partial recovery in shallow groundwater levels in some boreholes, which does not support the conceptualisation of total desaturation extending to these upper units. The revised HydroSimulations (2014) model of connected fracturing is in more agreement with field data. This is further confirmed with the Ditton (2013) method for calculating the height of fracturing found by HydroSimulations (2014) to be a good match with observed data from Longwall 5, and to be in closer agreement with the local area model (Heritage Computing, 2011).

Ditton and Merrick, 2014

A new subsurface fracture height prediction model was developed by Ditton for longwall mines in NSW Coalfields, as presented in Ditton and Merrick (2014). It serves as a simplification of the earlier Ditton (2013) method, and similarly provides means of estimating A-zone (connected fracturing) and B-zone (disconnected fracturing) heights above the mined seam. The key parameters remain effective panel width (W'), cover depth (H) and mining height (T) along with the local geology parameter, the effective thickness of strata within or above the A zone (t'). Formulas are provided for two models:

- Geometry Model, dependent on W', H and T
- Geology Model, dependent on W', H, T and t'

With respective formulas for the A zone (fractured zone) height:

- Geometry Model: $A = 2.215\, W'^{0.357}\, H^{0.271}\, T^{0.372}$ $\pm aW'$
- Geology Model: $A = 1.52\, W'^{0.4}\, H^{0.535}\, T^{0.464}\, t'^{-0.4}$ $\pm aW'$

  where W' is the minimum of the panel width (W), and the *critical* panel width (1.4H),

  and ***a*** varies from 0.1 for supercritical panels to 0.16 (geometry model) or 0.15 (geology model) to give 95th percentile (maximum) A-zone heights.

With respect to the A-zone and A95%, Ditton (2013) states the following:

The terms 'mean' and 'Upper 95% Confidence Limit' (U95%CL) infer that the predicted maximum subsidence effect values may be exceeded by 50% and 5% of the observations above the mined panels respectively. Therefore on a small number of occasions, the predicted values and impacts may be exceeded due to the presence of adverse or anomalous geological or topographical conditions.

The selection of an appropriate 'credible worst-case' is normally defined by the U95%CL value, however, a higher confidence limit may need to be applied in consideration of the reliability of current survey technology, available mitigation techniques or likely response action times should an exceedance occur.

Dendrobium Longwall 9 Research (Parsons Brinckerhoff, 2015)

Parsons Brinckerhoff (PB) was engaged by Illawarra Coal to characterise pre- and post-mining groundwater conditions above Longwall 9 at Dendrobium Area 3B, and assess natural and mining-related horizontal and vertical flowpaths caused by subsidence and cracking. To do this, PB conducted a review of a number of models used to estimate the height of fracturing above longwall mining, while using established and experimental tracer techniques to establish baseline conditions and evaluate post mining change and connective fracturing. These techniques consisted of the following (from PB, 2015) review of monitoring data;

- drilling of 9 test holes, including 4 diamond core holes to a total depth of 288 m;
- geotechnical and geophysical logging of drilled holes;
- hydraulic testing in drilled holes (packer testing, step-rate pumping and injection);
- down-hole flow profiling and cross-hole tracer testing in select drill holes;
- Monitoring of adjacent stream and underground mine for tracer breakthrough.

PB (2015) selected to review five models used to estimate the height of fracturing for a pre mining assessment of Longwall 9. They included Forster (1995), Tammetta (2013), and Ditton and Merrick (2014) (as mentioned above), as well as models by Guo, Adhikary and Gaveva (2007), and Mills (2011). A summary of the models not previously discussed in this report is provided below (from PB 2015).

Mills (2011): Provides a summary of the characteristic styles of ground movement resulting from longwall mining based on surface and subsurface monitoring. Heights of disturbance zones are based on multiples of the mined panel width (W):

- Zone 5 (no disturbance): >3W;
- Zone 4 (vertical relaxation): 1.6 W to 3W;
- Zone 3 (vertical dilation): 1.0W to 1.6W;
- Zone 2 (large movement): to 1W;
- Zone 1 (caved): to 20 m above seam;

These zones broadly equate with zones used in the Ditton and Merrick (2014) or Guo *et al*, 2007 conceptual models.

Guo *et al* (2007): Model was developed in a study focused on the Springvale Colliery using field and numerical modelling methods. The study reviewed responses in deformation, pore pressure and permeability due to longwall mining. With numeric models carried out using COSFLOW. Zones are related to mined thickness (t) and cover depths > 350 m:

- Surface zone: <30 m below ground level (bgl); <1 mm/m vertical strain;
- Elastic Zone: to heights of 95~105 t; <3 mm/m vertical strain
- Constrained zone: to heights of 75~78 t; <8 mm/m vertical strain;
- Fractured zone: to heights of ~43 t; >10 mm/m vertical strain;
- Caved zone: to heights of 3~10 t; >30 mm/m vertical strain.

Longwall 9 at Dendrobium Area 3B has the following dimensions which were used to calculate fracture heights: Cover depth (H) = 400 m; panel width (W) = 310 m; mining thickness or height (T) = 3.7 m; and minimum beam thickness (t') = 30 m (following Ditton and Merrick (2014) estimate for LW5 of 32 m).

A summary of these results obtained using some of the alternative methods and models can be seen in **Table 2**. The resultant height of connected fracturing is estimated to range from 122 to 357 m above the seam, with the average being 220 m. The Ditton 'Geology Model' estimate of A-zone height is closest to the mean/median values.

Table 2 Comparison of Estimates of the Height of Connected Fracturing (Longwall 9)

MODEL	CONCEPTUAL ZONE	Height Above Seam [m]	Depth From Ground Surface [m]	STRATIGRAPHIC UNIT INTERSECTED
Forster (1995) (21 - 33T)	Fractured	78 - 122	322 - 278	Stanwell Park Claystone
Guo *et al*. (2007) (43T)	Fractured	159	241	lower Bulgo Sandstone
Mills (2011) (W)	Zone 2	310	90	mid Hawkesbury Sandstone
Tammetta (2013) (mean - U95%CL)	Groundwater Drainage H	357 - 394	43 - 6	upper Hawkesbury Sandstone
Ditton and Merrick (2014) (mean - U95%CL)	A (Geometry)	142 - 190	258 - 210	lower Bulgo Sandstone
Ditton and Merrick (2014) (mean - U95%CL)	A (Geology) (t'=30m)	175 - 220	225 - 180	mid-upper Bulgo Sandstone

These methods of estimating the extent and nature of the fractured zone were compared with the outcomes of the physical testing to identify the one that most accurately represented the situation above Longwall 9 at Dendrobium Area 3A. The main conclusions made by PB for the post-mining phase at Longwall 9 include:

- Significant depressurisation and downward hydraulic gradient developed within the lower Bulgo Sandstone.
- A slight depressurisation found in the lower Hawkesbury Sandstone, with groundwater in upper areas remaining perched.
- Undermined swamps show decreased water levels.
- Horizontal tracer tests (between two bores that extend down to the Stanwell Park Claystone) showing very fast breakthrough, indicating large increase in Kh.
- No vertical breakthrough in tracer tests (between bores located either side of the Bald Hill Claystone), indicating maintenance of the aquitard and low Kv in the B-zone.

The outcomes of the study suggest that the zone of most intense and vertically connected fracturing extends to the lower Bulgo Sandstone, and find the estimate made by the Ditton 'Geology Model' (Ditton and Merrick, 2014) to be the most accurate representation of the height of connected fracturing. Although the field observations are not precise enough to allow an exact height of fracture to be defined, the investigations by PB serve to provide constraints on the extent of mining related disturbance and its impacts on groundwater in the area.

PREDICTED HEIGHT OF CONNECTED FRACTURING AT DENDROBIUM

In regard to the vertical extent of deformation above longwalls at Dendrobium, following review of the PB (2015) report on Longwall 9 in Area 3B, and the analysis of the piezometric data in GHD (2007) and Heritage Computing (2011) for Areas 1, 2 and 3A, HydroSimulations supports PB's identification of the Ditton 'Geology Model' to provide the most accurate estimations of the height of the connected fractured zone at Dendrobium.

The following section extends the comparison of the Tammetta (2013) and Ditton (2014) methods to include all currently mined and planned areas of Dendrobium Mine. Comparisons are made in relation to estimated connected fracture heights (**Table 2**), as well as depth to and geological unit reached by the connected fracture zone (**Table 3**). The cutting heights used for the calculations are stated in **Table 2**, and are:

- Actuals for Longwall 1-11; and
- The proposed maximum (i.e. 4.5 m) for Longwalls 12-18.

A ratio of the continuous fracture zone height to panel width (A/W) of 0.46 for Longwall 6 was estimated in Heritage Computing (2011). The updated calculations using the Ditton (2014) 'Geology model' for the A-zone height (connected fracturing) gives an A/W ratio ranging from 0.55-0.65 (depending on cover depth) for Longwall 6 (**Table 2**). This slightly larger ratio calculated within this study could account for the perceived extension of the fractured zone into the Bulgo Sandstone as predicted, but not modelled, in Heritage Computing (2011).

HydroSimulations (2014) comments on a good match between observed data above Longwall 5 and the predictions of the Ditton (2013) method for estimating the height of connected fracturing. Using the ACARP (2003) database, Ditton (2012/13) provides an observed height of fracturing at 123 m, and calculates a mean height of fracturing at 122 m. The revised Ditton 'Geology model' (Ditton and Merrick, 2014) estimates a mean A of 124 m based on t'=32 m (updated for this project to t'=30 m based on Southern Coalfield data in Ditton and Merrick, 2014), which is in good agreement with the Ditton (2013) estimate and observed data.

The extent of the Ditton A-zone in relation to the geology and topography of the area is also visualised in the cross-section found in **Figure 2**. The cross-section encompasses all the approved mining areas at Dendrobium (3B, 3A, 2, 1) as shown in **Figure 3**.

The cross section in **Figure 3,** and those results presented in **Table 2** and **Table 3**, show the maximum height of connected fracturing, i.e. at the apex of the parabolic zone, or the height above the longwall centre-line. The cross-section in **Figure 3** indicates the predicted mean (Am) and Upper 95%CL (A95) values only and makes no attempt to present the parabolic or arcuate shape of the connected fracture zone.

The cross-section in **Figure 3** was constructed in a way to include significant features such as Avon and Cordeaux Reservoirs as well as Wongawilli and Sandy Creeks. The A-Zone is generally seen to extend into the Bulgo and laterally equivalent Colo Vale Sandstones in Areas 3B and 3A. Older (deeper) units such as the Scarborough Sandstone or Stanwell Park Claystone are estimated to be the upper limit of the connected fractured zone in some sections of Areas 1 and 2, where smaller panel width and lower cutting height reduce the vertical extent of the A-zone.

Table 3 Predicted Height of Connected Fracturing above Longwalls at Dendrobium

Area	Longwall	Start Date	End Date	Panel Width [m]	Depth of Cover [m]			Cutting Height [m]	Connected Fracturing - height of [m]								
									Height of complete drainage [H] (Tammetta, 2013)			A-zone (mean) (Ditton & Merrick, 2014)			A-zone (upper 95%ile) (Ditton & Merrick, 2014)		
					Min	Mean	Max		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
1	**1**	30-Mar-05	15-Dec-05	247	170	262	316	3.4	223	241	250	96	122	135	120	155	171
1	**2**	9-Feb-06	22-Jan-07	247	162	264	320	3.4	221	241	251	92	122	136	114	155	172
2	**3**	30-Mar-07	22-Nov-07	245	138	211	282	3.8	246	266	280	83	114	134	102	143	168
2	**4**	17-Dec-07	30-Sep-08	245	159	249	310	3.8	253	274	285	95	125	141	117	156	176
2	**5**	4-Dec-08	18-Dec-09	245	213	252	293	3.8	266	275	282	115	126	137	144	158	171
3A	**6**	9-Feb-10	28-Mar-11	249	287	345	389	3.9	295	305	311	138	152	162	172	189	199
3A	**7**	4-May-11	23-Jan-12	249	288	338	379	3.9	295	303	310	138	150	160	172	187	197
3A	**8**	24-Feb-12	29-Dec-12	305	261	321	373	3.9	348	361	371	142	158	172	177	199	215
3B	**9**	9-Feb-13	31-Dec-13	305	314	381	409	3.4-3.7	303	324	350	147	163	172	187	206	216
3B	**10**	27-Feb-14	10-Jan-15	305	325	383	406	3.7-4.5	350	384	447	160	178	191	200	222	236
3B	**11**	12-Feb-15	5-Jan-16	305	327	381	404	3.95	368	378	382	161	175	180	216	218	225
3B	**12**	7-Feb-16	17-Feb-17	305	329	376	404	4.5	432	442	448	172	184	192	222	228	236
3B	**13**	23-Mar-17	28-Jan-18	305	318	371	394	4.5	430	441	446	169	183	189	232	226	233
3B	**14**	2-Mar-18	19-Jan-19	305	286	366	391	4.5	422	440	445	159	182	188	200	224	232
3B	**15**	21-Feb-19	30-Dec-19	305	324	364	390	4.5	431	440	445	170	181	188	211	224	232
3B	**16**	2-Feb-20	1-Dec-20	305	297	354	390	4.5	425	438	445	162	178	188	201	221	232
3B	**17**	3-Jan-21	7-Nov-21	305	273	337	381	4.5	418	433	443	155	173	186	192	215	229
3B	**18**	10-Dec-21	1-Sep-22	305	287	331	371	4.5	422	432	441	159	172	183	197	213	226
3A	**19**	4-Oct-22	30-Mar-23	305	287	331	369	3.6	320	328	335	144	155	164	182	196	207

Note: Ditton A-zone heights calculated using spanning strata thickness (*t'*) of 30 m (based on Southern Coalfield data in Ditton and Merrick, 2014)

Table 4 Predicted Depth to the Zone of Connected Fracturing above Longwalls at Dendrobium

Area	Longwall	Panel Width [m]	Depth of Cover [m]			Cutting Height [m]	Depth from surface to top of zone of Connected Fracturing [m]						Geology intersected by the top of the connected fracture zone			
							Tammetta, 2013 (Height of complete desat.)			Ditton, 2014 (A-zone upper 95% confidence)			Tammetta (2013)		Ditton A-zone upper 95% confidence (2014)	
			Min	Mean	Max		Min	Mean	Max	Min	Mean	Max	Lower	Upper	Lower	Upper
1	**1**	247	170	262	316	3.4	-50	20	70	50	110	140	HBSS	Surface	SPCS	BGSS
1	**2**	247	162	264	320	3.4	-60	20	70	50	110	150	HBSS	Surface	SPCS	BGSS
2	**3**	245	138	211	282	3.8	-110	-50	0	40	70	110	upper HBSS	Surface	SPCS	BGSS
2	**4**	245	159	249	310	3.8	-90	-20	30	40	90	130	HBSS	Surface	BGSS	BGSS
2	**5**	245	213	252	293	3.8	-50	-20	10	70	90	120	HBSS	Surface	SBSS	BGSS
3A	**6**	249	287	345	389	3.9	-10	40	80	120	160	190	HBSS	Surface	CVSS	CVSS
3A	**7**	249	288	338	379	3.9	-10	30	70	120	150	180	HBSS	Surface	BGSS	CVSS
3A	**8**	305	261	321	373	3.9	-90	-40	0	80	120	160	upper HBSS	Surface	BGSS	CVSS
3B	**9**	305	314	381	409	3.4-3.7	70	80	90	130	170	200	HBSS	HBSS	CVSS	CVSS
3B	**10**	305	325	383	406	3.7-4.5	30	30	40	130	170	180	HBSS	Surface	CVSS	BACS
3B	**11**	305	327	381	404	4.5	10	30	70	130	160	180	HBSS	Surface	CVSS	BACS
3B	**12**	305	329	376	404	4.5	20	30	30	120	150	170	Surface	Surface	CVSS	HBSS
3B	**13**	305	318	371	394	4.5	40	50	50	110	150	160	Surface	Surface	CVSS	HBSS
3B	**14**	305	286	366	391	4.5	20	20	30	90	140	160	Surface	Surface	CVSS	HBSS
3B	**15**	305	324	364	390	4.5	-50	-50	-40	110	140	160	Surface	Surface	CVSS	HBSS
3B	**16**	305	297	354	390	4.5	-40	0	20	100	130	160	Surface	Surface	BACS	HBSS
3B	**17**	305	273	337	381	4.5	-40	0	20	80	120	150	Surface	Surface	CVSS	HBSS
3B	**18**	305	287	331	371	4.5	-100	-70	-40	90	120	150	Surface	Surface	BACS	HBSS
3A	**19**	305	287	331	369	3.6	-110	-70	-50	110	130	160	HBSS	Surface	CVSS	CVSS

Note: ‘HBSS’ = Hawkesbury Sandstone; ‘BGSS’ = Bulgo Sandstone; ‘CVSS’ = Colo Vale Sandstone; SPCS = Stanwell Park Claystone; ‘Surface’ means ground surface.

The purple triangle represents the lateral and vertical distance between Lake Cordeaux and nearest fractured zone.

The black triangle represents the same but between Lake Avon and the nearest fractured zone (overlain with the purple for comparison)

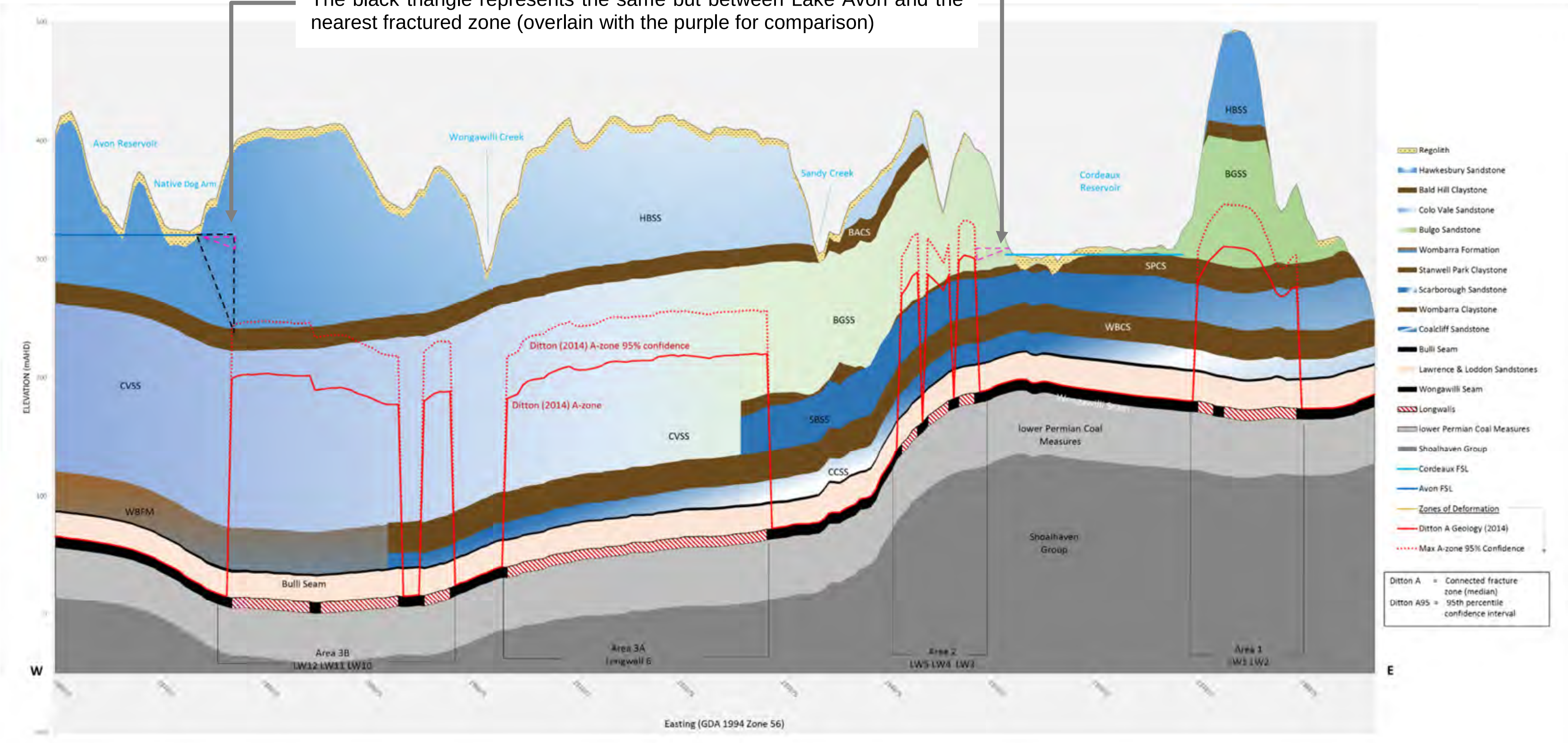

Figure 3 Cross-section through Dendrobium Areas 3B, 3A, 2, 1 estimates for height of fractured / depressurised zone using Ditton & Merrick, 2014 Geology Model.

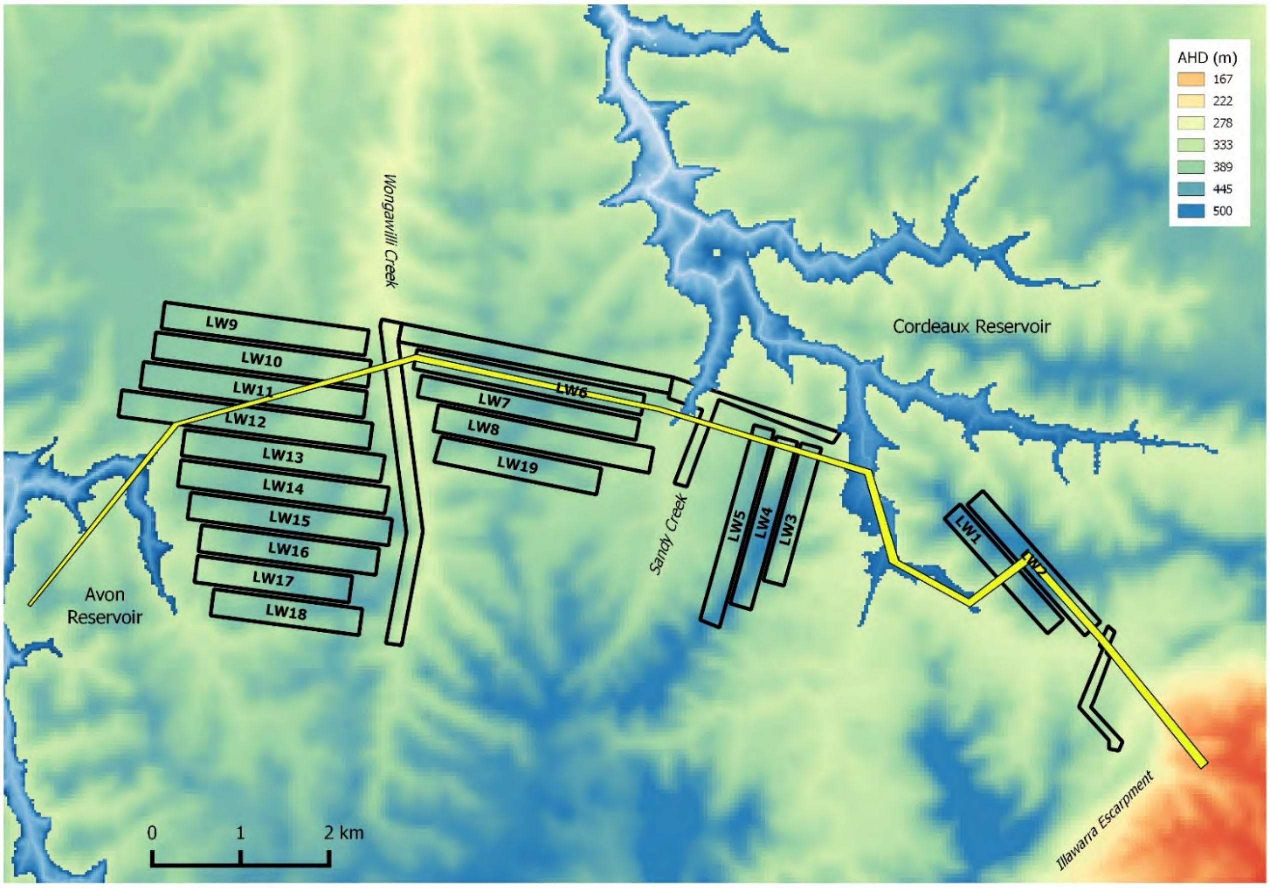

Figure 4 **Location of cross-section presented in Figure 3.**

A visual representation of the height of fracturing estimates presented in **Table 3** is shown in **Figure 4**, in which the depth to the top of the A-zone is shown across the extent of the longwall plans for Dendrobium. Although larger longwall void widths and cutting heights are found in Areas 3A and 3B, there is still at least 80 m of overburden present above the top of the calculated U95%ile A-zone (A95) in these areas.

The A-zone is estimated to be closest to the surface above Longwall 3 (Area 2) at a depth of approximately 36 m to 55 m based on A95 and Am predictions respectively. As discussed earlier, the Am predictions are closer to the measured A-Zone height than the A95 predictions.

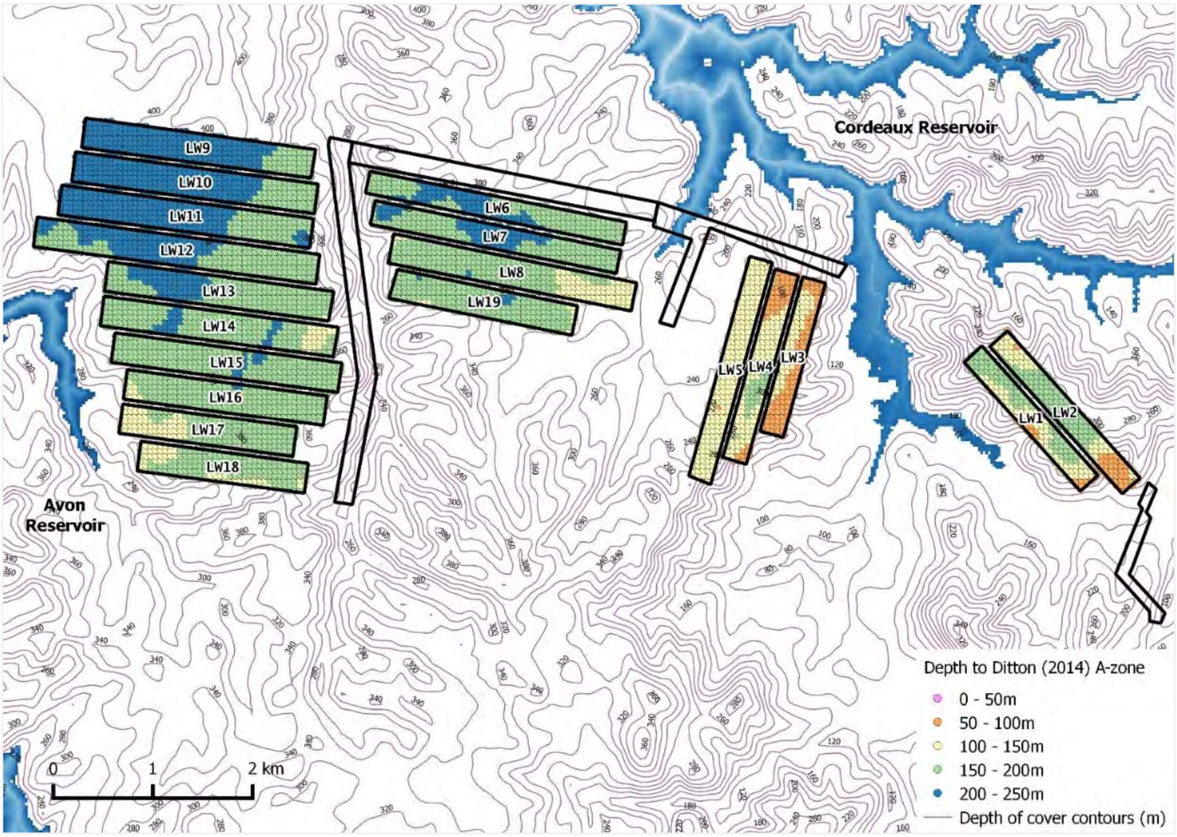

Figure 5 Estimated Depth to top of the Predicted Mean Connected Fracture zone

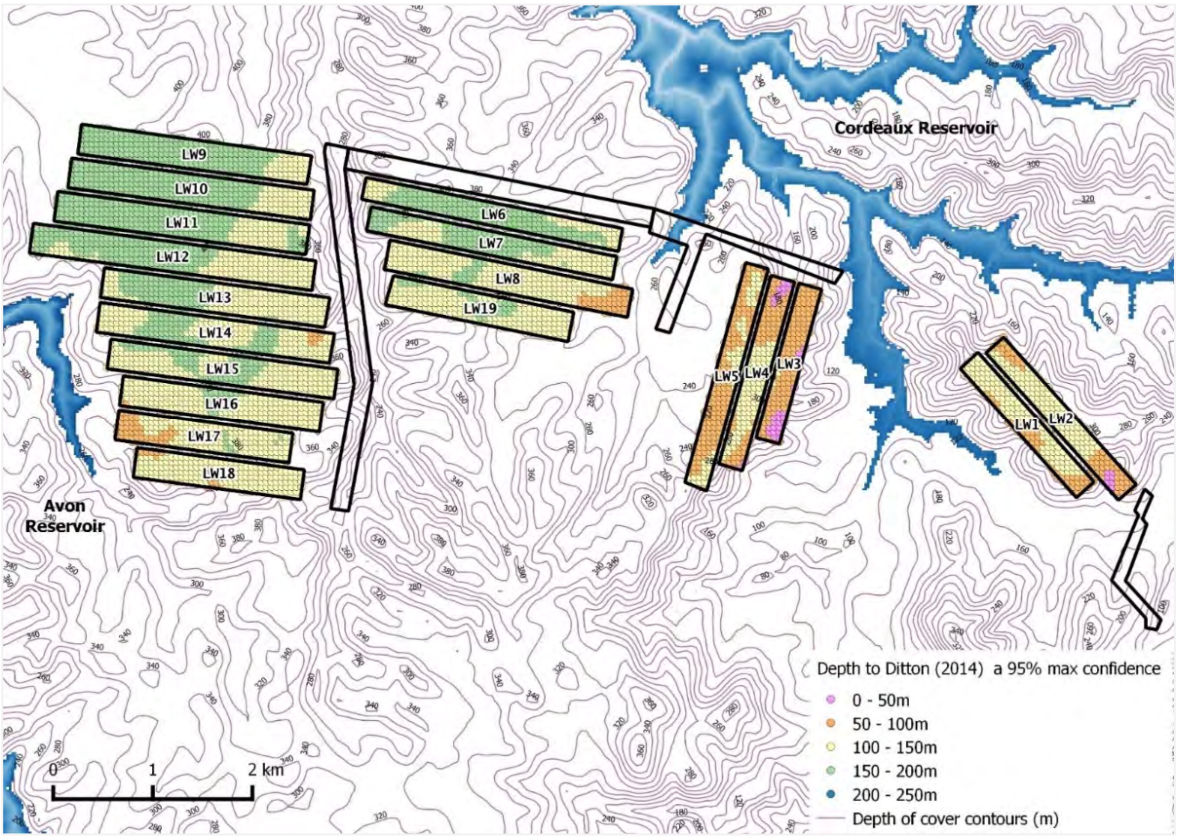

Figure 6 Depth to top of 95% Confidence Interval of Connected Fracture zone (Ditton & Merrick, 2014)

While the calculated A-zone heights are found to match the findings of field investigation, the A-zone 95% confidence level presented in both **Figure 3** and **Figure 6** provides conservative estimates to be used in assisting decision-making. For larger extraction heights (up to 4.5 m) and wider panels (to ~305 m), the A95 height is estimated to extend through the Bald Hill Claystone and into the lower Hawkesbury Sandstone. The minimum cover depth above the calculated A95 is approximately 76 m for Area 3B longwalls (LW17) (**Figure 6**). The predicted minimum depth of cover above any of the Dendrobium longwalls was 35 m (LW3).

Figure 7 presents the zone of connected fracturing based on the Tammetta (2013) method. This figure shows connected fracturing (or the height of complete groundwater drainage) extending above the ground surface for many of the proposed and mined longwalls at Dendrobium, with the lowest geologic unit intersected for all longwalls being the Hawkesbury Sandstone (see also **Table 4**). The height of complete groundwater drainage demonstrated in these areas is not supported by the analysis of bore data seen in GHD (2007), Heritage Computing (2011) and PB (2015), or recent End of Panel reports such as HydroSimulations (2015). While these studies report significant depressurisation in strata closely overlying the mined seam, with significant decreases in head often seen in the Bulgo Sandstone, complete groundwater drainage, as was conceptualised in Coffey (2012b), is not observed. Data from bore S1870, located on the eastern edge of Area 3A near Sandy Creek and 100 m east of Longwall 7 and 40 m North of Longwall 8, is assessed in HydroSimulations (2015). At this location, the Tammetta (2013) 'Collapsed Zone' was predicted to reach the surface, however the groundwater levels in shallow piezometers in S1870 do not show complete groundwater drainage. Instead, a decrease in head up to 80 m is observed in units below the Stanwell Park Claystone; a decrease in head of approximately 30 m in the Bulgo Sandstone; while heads in the overlying Hawkesbury Sandstone are very close to pre-mining conditions.

Similarly, the passing of Longwall 9 did not cause complete groundwater drainage at bore S1929 in Area 3B (200 m south of Longwall 9 and above the path of Longwall 10). Decreases in observed head of approximately 20 m were seen in the upper and lower Scarborough and Bulgo Sandstones, with the Hawkesbury Sandstone again maintaining pre-mining head conditions.

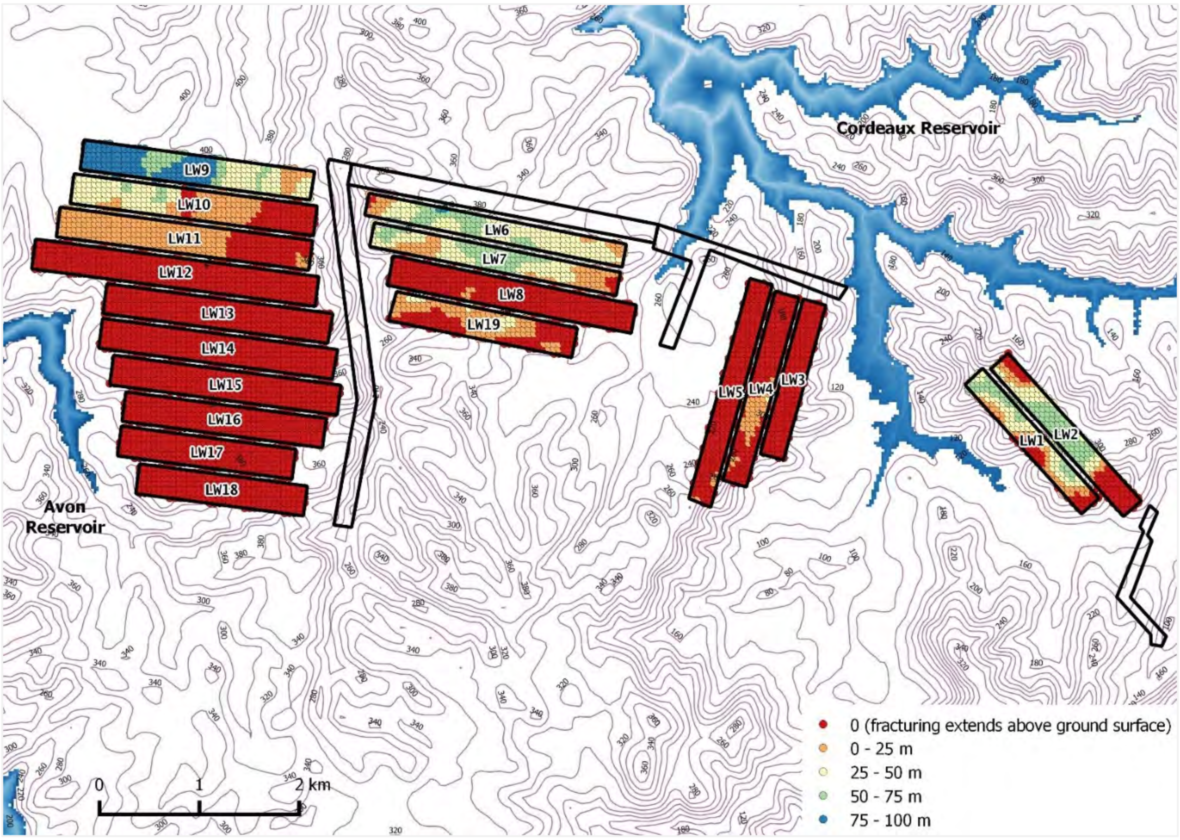

Figure 7 Estimated Depth to top of Collapsed Zone (Fractured Zone) (Tammetta, 2013)

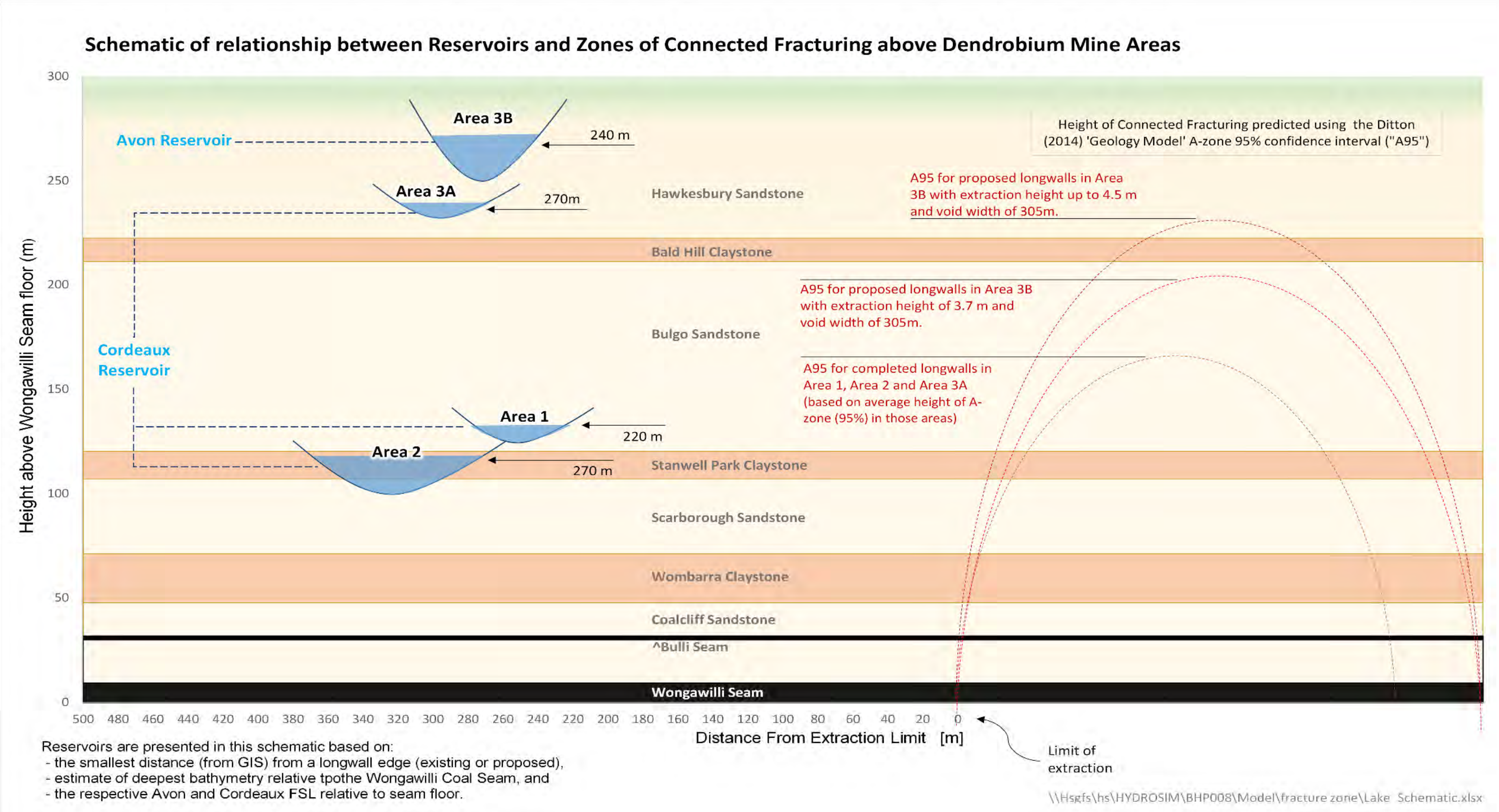

Figure 8 Schematic of Distance between Mine Areas, Fractured Zones and Reservoirs

Effects on Groundwater

With respect to historical effects on groundwater, GHD (2007) noted that the chemistry of water entering the underground mine in Areas 1 and 2 was distinct from Scarborough Sandstone waters, and without the 'fingerprint' of lake water. With reference to **Figure 3**, this suggests that although the top of the connected fractures above Area 1 and 2 longwalls might be considered to be close to Lake Cordeaux, it had not formed a significant connection between the reservoir and mine workings.

Figure 8 presents further analysis of the distances between the nearest arm of either Lake Cordeaux and Avon to each of the mine areas. Vertical elevations have been converted to a height above the seam in each area. Distances are based on GIS mapping of mine plans, lake shorelines, lake stage and Illawarra Coal's 3D geological mapping.

The lateral distance from Lake Avon and the nearest estimated (predicted) connected fracture zones of the proposed Area 3B longwalls is further than the lateral distance between the connected fracture zone above the previously mined longwalls in Areas 1 and 2 from Lake Cordeaux (see schematic representation in **Figure 8** and the purple and black triangles on **Figure 3**), and there is a greater (vertical) thickness of rock between Area 3B and Lake Avon. Based on distances, the risk from mining near Lake Avon appears less than for the historical mining of Areas 1 and 2 near Lake Cordeaux.

These revised estimates of the height of connected fracturing will be applied in on-going and future groundwater (numerical) modelling for Dendrobium. Modelling will incorporate not only the vertical and horizontal distances, but also account for the variation in bulk permeability expected between the Bulgo Sandstone and Hawkesbury Sandstone, which are the geological units that are critical to controlling groundwater flow around Lake Avon.

CONCLUSIONS

The review of previous reports and recent field investigation has led to the conclusion that the Ditton 'Geology model', as outlined in Ditton and Merrick (2014), is the most appropriate method for estimating the vertical extent of connected fracturing above longwalls at Dendrobium. As stated earlier, the research above Longwall 9 by PB (2015) supports this selection. The results of earlier reports such as GHD (2007) and Heritage Computing (2011), in which bore data was analysed in order to assess the height of the fractured zone, also correlate well with the mean fracture height predicted by the Ditton 'Geology Model'.

HydroSimulations' comparison of calculated A-zone and A95 heights (**Table 3**) and the findings of PB (2015) at Longwall 9 has led to the conclusion that the Ditton 'Geology Model' A95 is the more appropriate to use in environmental assessments as it is precautionary compared to the mean A-zone height. This is consistent with the discussion of Am and A95 presented earlier, where Ditton described the A95 estimate as a "*credible worst-case*".

Both the mean A-zone heights and the A95% confidence values have been presented herein to provide expected and conservative estimates for assessment in the approvals process.

Please contact us if further clarification required.

Yours sincerely

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REFERENCES

ACARP, 2003. *Review of Industry Subsidence Data in Relation to the Impact of Significant Variations in Overburden Lithology and Initial Assessment of Sub- Surface Fracturing on Groundwater.* ACARP Project No. C10023. S. Ditton and R. Frith, Strata Engineering Report No. 00-181-ACR/1.

Coffey Geotechnics (2012a). *Groundwater Study Area 3B Dendrobium Coal Mine Numerical Modelling*. Prepared for BHP Billiton, reference GEOTLCOV24507AA-AB2, dated October 2012.

Coffey Geotechnics (2012b). *Groundwater Study Area 3B Dendrobium Coal Mine Data Analysis (2nd Edition).*Prepared for BHP Billiton, reference GEOTLCOV24507AB-AB1, dated November 2012.

Ditton Geotechnical Services (2013). *Sub-Surface Fracture Height Review and Predictions for the Proposed Longwalls 42 to 47, 51 and 52 at West Wallsend Colliery, Killingworth.* Prepared for West Wallsend Colliery. Report WWD-012/8b 30th Aug 2013

Ditton, S., and Merrick, N.P. (2014). *A new sub-surface fracture height prediction model for longwall mines in the NSW coalfields*. Paper presented at the Australian Earth Science Convention, Newcastle NSW.

Forster, I. (1995). *Impact of underground mining on the hydrogeological regime, Central Coast, NSW*. Paper presented at the Engineering Geology of Newcastle - Gosford Region, Newcastle.

GHD (2007). *Dendrobium Area 3A Predicted Hydrogeologic Performance.* Report for BHP Billiton, Illawarra Coal. November 2007

Guo, H., Adhikary, D., and Gaveva, D. (2007). *Hydrogeological response to longwall mining*, ACARP Report C14033, CSIRO Exploration and Mining: Australian Coal Industry's Research Program (ACARP).

Heritage Computing, (2009). *Mine Inflow Review, Conceptualisation and Preliminary Groundwater Modelling.* For Illawarra Coal, Report HC2009/2, February 2009

Heritage Computing (2010). *Local Area Groundwater Modelling of Alternative Area 3A Longwall Panel Lengths.* For Illawarra Coal. Report HC2010/16 October 2010

Heritage Computing (2011). *Recalibration of the Dendrobium Local Area Groundwater Model after Completion of Longwall 6 (Area 3A).* For Illawarra Coal. Report HC2011/13. October 2011

HydroSimulations, (2013). *Dendrobium Area 3b Groundwater Model Revision: Swamps, Stream Flows and Shallow Groundwater Data.* For BHP Billiton. Report HC2013/28 October 2013

HydroSimulations (2014). *Dendrobium Area 3b Groundwater Model Revision: Swamps, Stream Flows and Shallow Groundwater Data.* For BHP Billiton. Report HC2014/4 March 2014

HydroSimulations (2015). *End of Panel Groundwater Assessment: Longwall 10 (Area 3B)*. Report HC2015/015 for Illawarra Coal.

Merrick, N.P. (2009). *Dendrobium Colliery groundwater assessment: Mine inflow review, conceptualisation and preliminary groundwater modelling*. Unpublished report commissioned by Illawarra Coal (pp. 70): Heritage Computing.

Merrick, N.P. and Akhter, N., (2010), *Local Area Groundwater Modelling of Alternative Area 3A Longwall Panel Lengths*. Heritage Computing Report HC2010/16, October 2010.

Mills, K. W. (2011). *Developments in understanding subsidence with improved monitoring*. Paper presented at the Mine Subsidence 2011: Proceedings of the Eighth Triennial Conference on Management of Subsidence, Pokolbin NSW.

Parsons Brinckerhoff (2015). *Connected fracturing above longwall mining operations, Part 2: Post-longwall investigation.* For BHP Billiton Illawarra Coal. Document number 2172268F-WAT-REP-002 RevB. 6 March 2015

Prudic, D.E., Konikow, L.F., Banta, E.R. (2004). *A New Streamflow-Routing (SFR1) Package to Simulate Stream-Aquifer Interaction with Modflow-2000*: U.S. Geological Survey Open-File Report 2004-1042.

Reynolds, R. G. (1976). *Coal mining under stored water - Report on an inquiry into coal mining under or in the vicinity of stored waters of the Nepean, Avon, Cordeaux, Cataract and Woronora Reservoirs, New South Wales, Australia* (pp. 124): NSW Department of Public Works.

RPS Aquaterra (2012). *Independent Assessment of Groundwater Component of Subsidence Management Plan (SMP) for Area 3B Dendrobium Mine.* Prepared for Dendrobium Community Consultative Committee.

Tammetta, P. (2013). *Estimation of the height of complete groundwater drainage above mined longwall panels*. Groundwater, 51(5), 723-734