Heritage Computing Pty Ltd ● ABN 75 392 967 126 ● T/A **HydroSimulations**
PO Box 241, Gerringong NSW 2534. Phone: (+61 2) 4234 3802

noel.merrick@heritagecomputing.com

DATE: 21 September 2014

TO: Peter Corbett
Technical Services Manager
Centennial Coal Angus Place

FROM: Dr Noel Merrick

RE: **Springvale/Angus Place Response to IESC - Fractured Zone Estimation**

OUR REF: HC2014/28

1 Background

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) was requested by the Australian Government Department of the Environment and the New South Wales (NSW) Department of Planning and Environment to provide advice on both the Centennial Angus Place Pty Ltd, Angus Place Mine Extension Project (APMEP) and the Springvale Coal Pty Ltd, Springvale Mine Extension Project (SMEP). Centennial Coal Company Limited (CCCL) has been invited to respond to these Advices.

In addition, the Office of Water Science (OWS) in the Commonwealth Department of the Environment has released three research reports (endorsed by the IESC) relevant to the Angus Place and Springvale operations[1]:

1. Commonwealth of Australia 2014, *Temperate Highland Peat Swamps on Sandstone: ecological characteristics, sensitivities to change, and monitoring and reporting techniques, Knowledge report*, prepared by Jacobs SKM for the Department of the Environment, Commonwealth of Australia;

2. Commonwealth of Australia 2014, *Temperate Highland Peat Swamps on Sandstone: evaluation of mitigation and remediation techniques, Knowledge report*, prepared by the Water Research Laboratory, University of New South Wales, for the Department of the Environment, Commonwealth of Australia; and

3. Commonwealth of Australia 2014, *Temperate Highland Peat Swamps on Sandstone: longwall mining engineering design—subsidence prediction, buffer distances and mine design options, Knowledge report*, prepared by Coffey Geotechnics for the Department of the Environment, Commonwealth of Australia.

The three projects involved literature reviews collating available information on peat swamps, and analysis of the significance of other relevant information to the ecological community. In summary the reports conclude (according to the OWS): "that swamps in

[1] Website iesc.environment.gov.au/publications.html

steeper terrain and with groundwater connection are most vulnerable to damage from subsidence; that more extensive monitoring of swamps is required prior to and during mining to understand ecological impacts; that quantifying horizontal ground movements associated with subsidence is key to understanding potential impacts; altering mine layout is the only mitigation measure to avoid damage to peat swamps; and that there are no successful examples of existing remediation techniques being used in peat swamps".[2]

Heritage Computing Pty Ltd, trading under the name HydroSimulations (HS), has been engaged to provide an opinion on the so-called "Tammetta model"[3] for ground deformation above a caved longwall panel. This model is featured in Report #2 at pages 118-119 and in Report #3 at pages 36-37. It should be noted that neither report makes any reference to an alternative conceptualisation and formulation known as the "Ditton model"[4].

2 Research Report #2

Research Report Extract 1

A key section of Report #2 is extracted here:

"Tammetta (2013) highlighted that, from a hydrogeological perspective, longwall mining and the associated caving process create two distinct zones above the panel: the unsaturated collapsed zone and the saturated disturbed zone (Figure 3.7)[5].

The extent of the collapsed and disturbed zones (Figure 3.7) depends on several factors, including the depth and width of the longwall panels, and the geology. Subsidence-induced cracks beneath water bodies may result in the loss of water to near-surface groundwater flows. If the water body is located in an area where the coal seam is less than 100 to 120 m below the surface, longwall mining can cause the water body to permanently lose flow (NSW Scientific Committee 2005a). If the coal seam is deeper than approximately 150 m, the water loss may be temporary unless the area is affected by severe geological disturbances, such as strong faulting. In most cases, surface waters lost to the subsurface re-emerge downstream via lateral faults (NSW Scientific Committee 2005a)."

Comment on Research Report Extract 1

Rather than the two zones in the Tammetta conceptual model, it is generally accepted in literature (e.g. Forster, 1995[6]) that there is a sequence of deformational zones illustrated in Figure 1(b) and usually described as:

- the caved zone;
- the fractured zone, consisting of:
  - a lower zone of connective-cracking; and
  - an upper zone of disconnected-cracking;
- the constrained zone; and
- the surface zone.

Ditton and Merrick (2014) describe four zones with different terminology but essentially the

---

[2] Email from Anthony Swirepik (OWS) to Centennial Coal dated 14 August 2014

[3] Tammetta, P. , 2012, Estimation of the Height of Complete Groundwater Drainage Above Mined Longwall Panels. Ground Water, online article 10.1111/gwat.12003, Blackwell Publishing Ltd, 12p.

[4] Ditton, S. and Merrick, N, 2014, A New Subsurface Fracture Height Prediction Model for Longwall Mines in the NSW Coalfields. Geological Society of Australia, 2014 Australian Earth Sciences Convention (AESC), Sustainable Australia. Abstract No 03EGE-03 of the 22nd Australian Geological Convention, Newcastle City Hall and Civic Theatre, Newcastle, New South Wales. July 7 - 10. Page 136.

[5] Figure 2(b) in this report.

[6] Forster, I.R., 1995. Impact of underground mining on the hydrogeological regime, Central Coast NSW. In: Sloan, S W and Allman, M.A. (Ed.), Engineering Geology of the Newcastle-Gosford Region, pp156-168.

same conceptualisation (Figure 1(a)):

- the A-Zone or "Continuous Cracking" zone - equivalent to the caved zone plus the connective-cracking part of the fractured zone;
- the B-Zone or "Lower Dilated" zone - equivalent to the disconnected-cracking part of the fractured zone, or the lower part of the constrained zone;
- the C-Zone or " Upper Dilated" zone - equivalent to the upper part of the constrained zone; and
- the D-Zone or "Surface Cracking" zone - equivalent to the surface zone.

It will be shown in a later section of this report that the "Collapsed Zone" of the Tammetta model corresponds with the A-Zone plus the B-Zone. As the B-Zone has disconnected fractures, it is not appropriate to ascribe complete collapse to this zone. Nor is it appropriate to infer unsaturated conditions for the entire zone. Unsaturated conditions would occur in the A-Zone, but need not necessarily occur throughout the entire A-Zone.

The rocks in the A-Zone would have a substantially higher vertical permeability than the undisturbed host rocks. This will encourage groundwater to move out of rock storage downwards towards the goaf. In the B-Zone, where disconnected-cracking occurs, the vertical movement of groundwater should not be significantly greater than under natural conditions, but horizontal permeability would be expected to be enhanced through dilation of bedding planes.

Depending on the width of the longwall panels and the depth of mining, and the presence of low permeability lithologies, there would be a constrained zone in the overburden that acts as a bridge. Rock layers are likely to sag without breaking, and bedding planes are also likely to dilate. As a result, some increase in horizontal permeability can be expected.

In the surface zone, near-surface fracturing can occur due to horizontal tension at the edges of a subsidence trough. Fracturing would be shallow (<20 m), often transitory, and any loss of water into the cracks would not continue downwards towards the goaf. The extract from Report #2 agrees that "surface waters lost to the subsurface re-emerge downstream via lateral faults". As "lateral faults" is a strange concept, are dilated bedding planes or opened joints intended as the mechanism?

The strata movements and deformation that accompany subsidence will alter the hydraulic and storage characteristics of aquifers and aquitards. As there would be an overall increase in rock permeability, groundwater levels will be reduced either due to actual drainage of water into the goaf or by a flattening of the hydraulic gradient without drainage of water (in accordance with Darcy’s Law).

Research Report Extract 2

Another key section of Report #2 is extracted here:

"To understand the changes to subsurface flow, it is important to consider the preferential flow path process. Darcy’s Law cannot be used to describe flow through discrete fractures at local scales. Instead, flow in discrete fractures can be described using the cubic law, with the general assumption that fracture walls are analogous to parallel plates separated by a constant aperture (Witherspoon et al. 1980; Bear 1993; Lapcevic et al. 1999). Consequently, for a given gradient, flow through a fracture is proportional to the cube of the fracture aperture, as expressed in equation 3.1 (Lapcevic et al. 1999).

$$Q=C(2b)^3\Delta h \qquad (3.1)$$

where:
Q = volumetric flow rate
C = constant related to the properties of the fluid and the geometry of the flow domain
b = aperture of the fracture
Δh = change in hydraulic head

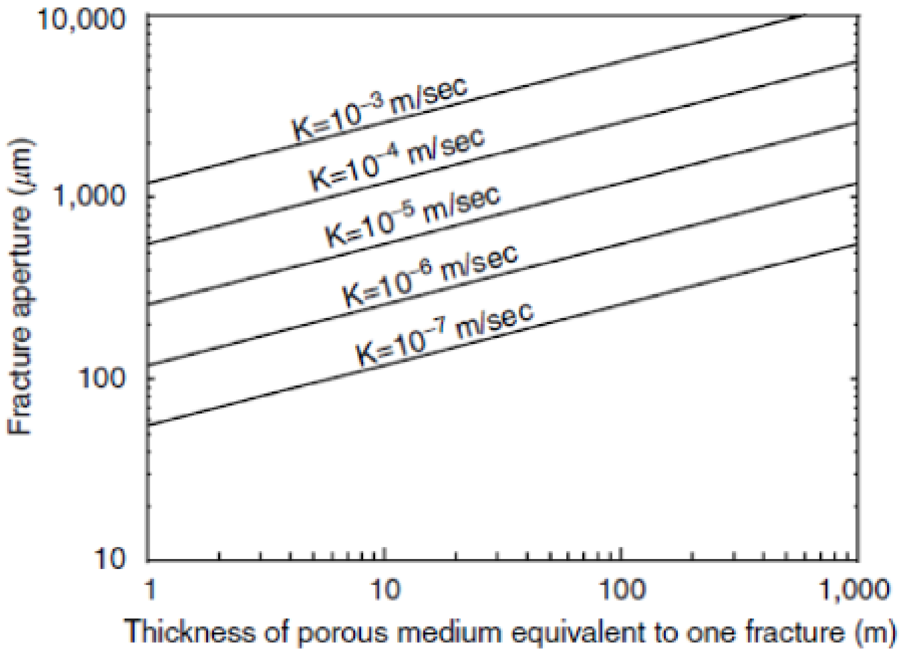
Flows through a fracture flow path are often significantly higher than flow through intact media. Figure

3.8 demonstrates this for a range of hydraulic conductivities. Figure 3.8 shows the thickness of a porous medium that would be equivalent to a single fracture of a given aperture. For example, under the same hydraulic gradient, the flow through a single fracture with an aperture of 1 mm is equivalent to the flow through a 10-m-thick layer of intact media with a hydraulic conductivity of 10 m/day (~10^{-4} m/s) (Lapcevic et al. 1999). The influence of fracture surface roughness can be accounted for by the inclusion of an additional factor, *f*, in equation 3.1. Witherspoon et al. (1980) conducted experimental studies using both radial and straight flow geometries and fractures of various rock types, with apertures ranging from 4 to 250 μm. In these experiments, *f* was observed to vary from 1.04 to 1.65. Consequently, a more generalised form of the cubic law exists (Witherspoon et al. 1980) (equation 3.2):

$$Q=(C/f)(2b)^3\Delta h \qquad (3.2)$$

where:
f=1 for smooth walls and f>1 for rough surfaces

Hence, predictions of groundwater flow based on the cubic law, where *f* = 1, are generally adequate for most conditions (Lapcevic et al. 1999). Flow velocities through discrete fractures (often measured in m/day) are substantially higher than flow velocities through porous media (typically between 1 and 100 m/year) (Cook 2003). The water velocity in the fracture is proportional to the square of the fracture aperture (Cook 2003).



© Copyright, de Marsily 1986

Figure 3.8 Comparison of aperture of a single fracture with equivalent thickness of porous media.

This summary and explanation of the physics of groundwater flow demonstrate that a few small cracks through the swamp substrate can lead to substantial vertical drainage. The cracks can have an aperture of millimetres, making them hard to detect through overlying sediment and vegetation. The increased flow volume and flow velocity through the fractures can have implications for remediation, as discussed in Section 5.1.

The ability of a swamp water body to recover depends on the width of the crack, the surface gradient, the substrate composition and the presence of organic matter (NSW Scientific Committee 2005a). An already-reduced flow rate due to drought conditions, or an upstream dam or weir, will increase the impact of water loss through cracking. The potential for self-closure of surface cracks is greater at sites with a low surface gradient; however, even temporary cracking, leading to loss of flow, may have long-term effects on ecological function in localised areas (NSW Scientific Committee 2005a). In general, the steeper the gradient, the more likely it is that suspended solids will be transported downstream, allowing the void to remain open, and the more likely is potential loss of flows to the subsurface (NSW Scientific Committee 2005a)."

Comment on Research Report Extract 2

The literature review in this report extract is inadequate because it ignores the substantial field of discrete fracture networks (e.g. Xu and Dowd, 2010)[7]. The review considers only continuous (infinite) fractures characterised by aperture and roughness, and the impression is given that very large effective permeabilities would result from fracturing by application of an unmodified cubic law.

The argument is flawed for a couple of reasons. First, the application of the cubic law is an assumption that ignores the most important feature of a fracture - its continuity. Crimping or closure or truncation of a fracture would terminate the flow path and reduce the flow rate to zero, unless the discrete fracture intersects another fracture. Nullification of flow could be achieved with equation 3.2 by use of a large *f* factor (for roughness). However, the chart in Figure 3.8 is restricted to a unit value for *f*, a most unlikely condition. Second, the application of an unmodified cubic law leads to hydraulic conductivities that this author has found to be 4-6 orders of magnitude greater than required to match observed mine inflows, using an equivalent porous medium approach to modelling. This suggests that the admittedly high permeabilities in individual fractures are modified by weighted averaging with the deformed rock mass in the fractured zone, or the fractures lack sufficient continuity to transmit large volumes of water.

A better model of fracture flow should be based on stochastic representations of discrete fracture networks, such as offered by discrete fracture ellipses in the FracSim3D code of Wu and Dowd (2010).

Without proper consideration of fracture continuity, and fracture density in the case of surficial cracking, the claim is not substantiated that "a few small cracks through the swamp substrate can lead to substantial vertical drainage". For observed field fracture densities, the cracks themselves would have very small water storage capacity compared to the volume of water held within the bulk of the swamp sediments. A weighted average of the void water and matrix water is appropriate to assess whether the loss of water through surficial fractures might be significant. The fracture density would have to be much higher than generally observed for the loss of water to be significant.

3 Research Report #3

Research Report Extract 3

A key section of Report #3 is extracted here:

"Tammetta (2012) estimated the height of complete groundwater drainage above subsided longwall panels (referred to as H) using a database of hydraulic head measurements made with multiple devices down the depth profile at a number of sites worldwide. H was shown to be relatively independent of most parameters except the geometry of the mined width and the overburden thickness. An empirical equation linking H (in metres) over a centre panel to these parameters was developed and is given by:

$$H = 1438 \ln(4.315 \times 10^{-5} u + 0.9818) + 26$$

where w is the mined width (equal to the panel width plus the adjacent heading widths), d is the overburden thickness, t is the mined height, and $u = w\, t^{1.4}\, d^{0.2}$. All dimensions are in metres.
In the equation, H depends only on the geometry of the mine opening and the overburden thickness. The equation applies to a variety of strata types and is considered a reliable tool for making predictive estimates of H. Host geology appears to play a minor role.

Tammetta also presents a ground deformation conceptual model from a groundwater perspective, shown in Figure 7.10[5].

[7] C. Xu and P. Dowd. A new computer code for discrete fracture network modelling. Computers & Geosciences, 36(3):292-301, Mar. 2010.

From a groundwater perspective, longwall caving creates two distinct zones above a continuously sheared panel (Tammetta 2012):

• the collapsed zone
• the disturbed zone.

These zones are illustrated in Figure 7.10. The collapsed zone is parabolic in cross-section, and reaches from the mined seam to a maximum height equal to H over the centre panel. This zone is severely disturbed and is completely drained of groundwater during caving. It is subsequently unable to maintain a positive pressure head. It will behave as a drain while the mine is kept dewatered. Within this zone, the matrix of rock blocks may continue draining for extended periods; however, the defects will immediately transport this water downward to the mine. Groundwater flow will not be laminar, and Darcy's equation is unlikely to be obeyed.

The disturbed zone overlies the collapsed zone. Positive groundwater pressure heads are maintained over most of the zone. Limited data for long-term groundwater behaviour in this zone suggest that hydraulic heads remain relatively stable, except for immediate lowering associated with drainage of lower strata and minor increases in void space after caving. Groundwater flow will be laminar, and Darcy's equation is likely to be obeyed. Desaturation in the disturbed zone occurs above the chain pillars. Here, H is smaller than over the centre panel, and may reduce to zero if the pillar is flanked by only one panel. H above the pillars is likely to be more strongly dependent on d than for the centre panel, and will probably also be dependent on the pillar width (see note 2 at the end of the chapter)."

Note 2: *"Ross Seedsman* believes that some of the larger figures for complete height of groundwater drainage (CHGD) provided in Tammetta (2012) should be considered in relation to a paper by Guo et al. (2007), which provides a different interpretation. Ross suggests that the representation of the collapsed zone in Figure 7.10 is questionable and also that there is a fundamental difficulty in using complete groundwater drainage as a measure of impact as it is difficult to allow for the time factor. The dilated zones in the current models allow for a temporary drop in piezometric level, which may take an extended period of time to recover if the pre-mining hydraulic conductivities are low."

Comment on Research Report Extract 3

Comments on the Tammetta conceptual model have been made earlier in "*Comment on Research Report Extract 1*". Additional comments are made in the following sections when comparing the Ditton and Tammetta conceptual models and analytical formulas.

There is agreement with the concept of an arched collapsed zone, but there is disagreement as to the height of this zone and also the requirement that it be fully unsaturated, that it "is completely drained of groundwater during caving" to the height H given by the cited formula. It is agreed that "Darcy's equation is unlikely to be obeyed" at local scale, but at the scale of numerical models an equivalent porous medium is a practical surrogate for characterising the fractured zone and accommodating the water throughput. As the fractured zone permeabilities required to match mine inflows are very much lower than would be expected for pure fracture flow, it is likely that weighted averaging with the fractured zone matrix is appropriate, or the fractures lack sufficient continuity to transmit large volumes of water. In the report extract, it is recognised that the matrix still contains water - "the matrix of rock blocks may continue draining for extended periods". Although the water pressure in the fractures is likely to be atmospheric, when combined with the water pressure in the matrix in an equivalent porous medium, it is likely that a net positive pressure would occur in the modelled representation of the upper part of a fractured zone.

HydroSimulations (2014)[8] conducted a peer review of the groundwater assessment by CSIRO (Adhikary and Wilkins, 2013)[9] for the Angus Place and Springvale Colliery Operations in which this statement was made: " Of particular interest are the resulting pressure head distributions above mined longwall panels (see Figures 62, 63, 76, 77, 78). The results show alternating zones of saturation and desaturation which significantly advances our conceptualisation of the saturation field associated with underground mining - a matter currently under debate in the

[8] HydroSimulations, 2014, Peer Review - Angus Place and Springvale Colliery Operations Groundwater Assessment. Letter Report HC2014/11 prepared for Centennial Angus Place Pty Ltd.
[9] Adhikary, D. P. and Wilkins, A., 2013, Angus Place and Springvale Colliery Operations Groundwater Assessment. CSIRO Report No EP132799 for Angus Place Colliery and Springvale Colliery. May 2013.

hydrogeology profession". Figures 63 and 77 are reproduced below for a North-South cross-section.

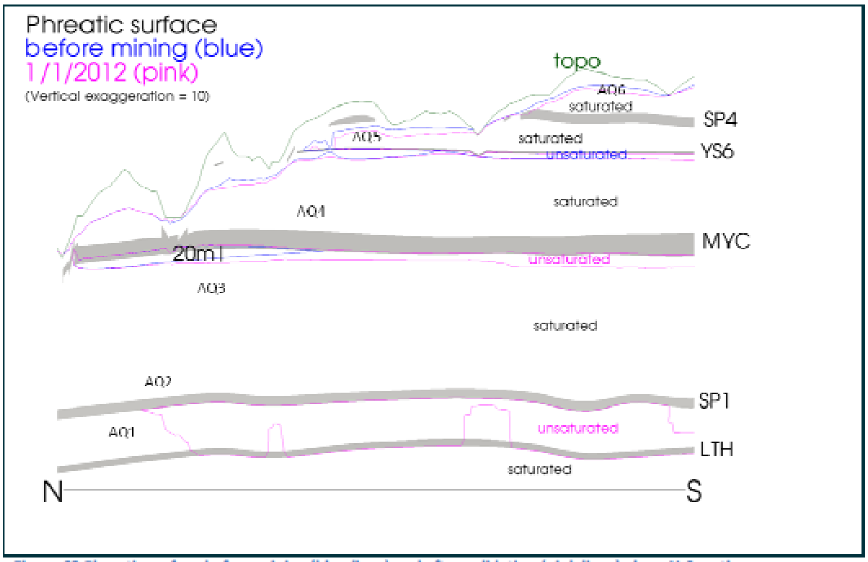


Figure 63 Phreatic surface before mining (blue lines) and after validation (pink lines) along N-S section

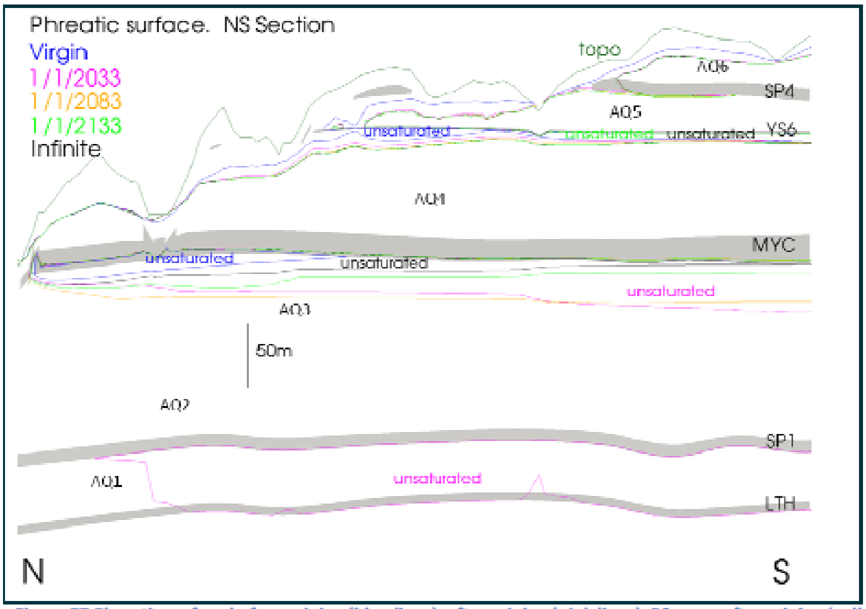


Figure 77 Phreatic surface before mining (blue lines), after mining (pink lines), 50 years after mining (yellow lines), 100 years after mining (green lines) and steady-state after mining (black lines) along N-S section

4 Alternative Fractured Zone Algorithms

There are only two known algorithms that aim to estimate the altitude of the deformed zone above an underground mine in terms of more than one causative factor.

The algorithms have been put forward in consulting reports by Steve Ditton of Ditton Geotechnical Services Pty Ltd (DGS) and in a journal paper by Paul Tammetta of Coffey Geosciences Pty Ltd[3]. Their formulas have been differentiated by Noel Merrick and Chris Nicol of HydroSimulations (not previously published) to reveal the sensitivity of fractured zone height to each causative factor. The two approaches have similar sensitivities for cover depth but differ for panel width and mining height. For mining height they are very different and trend in different directions.

The latest formulation of the Ditton model was presented at the Australian Earth Sciences Convention in Newcastle NSW in July 2014 (Ditton and Merrick, 2014)[4].

Both authors have found a relation between the height of some representation of the "fractured zone" and three key attributes of the mining system:

- Mining height [T (Ditton) or t (Tammetta)];
- Cover depth [H (Ditton) or h (Tammetta)]; and
- Longwall panel width [W (both authors)].

In addition, the Ditton model includes effective stratum thickness [t'] as a surrogate for roof rock integrity in one of his two developed models. The second model that uses only mining geometry, with no geology term, is directly comparable to the Tammetta model.

In this report, the underlying formulas for fractured zone height and sensitivity are presented, and then used to compare and contrast the predicted effects for varying panel width (for face widening), cover depth or mining height (for top coal caving).

5 Ditton Model Formulas

The Ditton conceptual model is illustrated in Figure 1.

The new Ditton model includes the key fracture height driving parameters of panel width (W), cover depth (H), mining height (T) and local geology factors to estimate the A-Zone and B-Zone horizons above a given longwall panel. Segregation between the A-Zone and B-Zone is based on a threshold vertical strain of 8 mm/m.

Formulas are offered for two models:

Geometry Model, which depends on W, H and T; and

Geology Model, which depends on W, H, T and t' (where t' is the effective thickness[10] of the stratum where the A-Zone height occurs).

The formulas for fractured zone height (A) for single-seam mining are:

Geometry Model: $A = 2.215\, W'^{0.357}\, H^{0.271}\, T^{0.372}$ $\pm$ [0.16 - 0.1 W'] (metres)

Geology Model: $A = 1.52\, W'^{0.4}\, H^{0.535}\, T^{0.464}\, t'^{-0.4}$ $\pm$ [0.15 - 0.1 W'] (metres)

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

The 95th percentile (maximum) A-Zone heights are estimated by adding aW' to A, where *a* varies from 0.1 for supercritical panels to 0.16 (geometry model) or 0.15 (geology model) for subcritical panels.

The models have been validated to 34 measured Australian case-studies (including West Wallsend, Mandalong, Springvale, Able, Ashton, Austar, Berrima, Metropolitan and Wollemi/North Wambo Mines) with a broad range of mining geometries and geological conditions included. The database also includes three cases in which connective cracking reached the surface (South Bulga, Homestead and Invincible Collieries). Statistics for the database are presented in Table 1, and best-fit back-calculated effective beam thicknesses for different coalfields are listed in Table 2.

[10] Typically 15-20 m in the Gunnedah Coalfield.

Table 1. Statistics for the Ditton Model Database for Australian Coalfields.

STATISTIC	Panel Width [W (m)]	Cover Depth [H (m)]	Mining Height [T (m)]
Mean	191	254	3.0
Standard Deviation	65	138	0.8
Minimum	110	75	1.9
Median	179	213	2.8
Maximum	355	500	6.0

Note that the maximum mining height in the database is 6.0 m.

Table 2. Minimum Effective Thickness of a Spanning Stratum.

COALFIELD	SOUTHERN	WESTERN	NEWCASTLE	HUNTER	GUNNEDAH
Normal Condition [t'(m)]	20 - 40	20 - 30	15 - 20	15 - 20	15 - 20
Adverse Condition [t'(m)]	15	10	10	10	10

The variation of the A-Zone height for each factor is illustrated in Figure 3 to Figure 6. In each figure, the other three parameters are held constant at their database median values.

Ditton (2014, pers. comm.) has a procedure for estimating the increased fractured zone height for multi-seam mining, in which the mining height (T) in the above formulas is replaced by an effective mining height (T') for the upper mined seam that accounts for the additional subsidence caused by mining other seams. This relies on theoretical estimates of subsidence for single or multiple seams. The ratio of the increase in subsidence (due to mining another seam) to the subsidence for a single seam is taken to apply also to the increase in the effective mining height[11].

6 Tammetta Model Formula

The Tammetta conceptual model is illustrated in Figure 2.

The Tammetta model includes the key fracture height driving parameters of panel width (W), cover depth (h), and mining height (t) to estimate the height of "complete groundwater drainage", which corresponds with the height of the zero-pressure region, an unsaturated "collapsed zone". The model relies on the same parameters as the Ditton Geometry Model. There is no geology factor corresponding to the effective thickness of Ditton's Geology Model.

The formula for collapsed zone height (H) for single-seam mining is:

Geometry Model: $H = 1438 \ln[(4.315 \times 10^{-5})\, h^{0.2}\, t^{1.4}\, W + 0.9818] + 26$ (metres)

Using Ditton's notation to avoid confusion, the formula for collapsed zone height (A) for single-seam mining is equivalent to:

Geometry Model: $A = 1438 \ln[(4.315 \times 10^{-5})\, H^{0.2}\, T^{1.4}\, W + 0.9818] + 26$ (metres)

The 95th percentile (maximum) A-height is estimated by adding 37 m.

The model has been validated to Australian and international case-studies, using hydraulic head and ground movement (extensometer) data. An important assumption is that "*H* is taken as being

[11] One unpublished case study in the Hunter Coalfield showed an increase in the effective mining height of about 70%. This had the effect of increasing the A-height by 27%.

equal to the top of the zone of large downward movement". This level is said to correspond with zero groundwater pressure, according to the examined head database. Statistics for the database are presented in Table 3.

Table 3. Statistics for the Tammetta Model Database for Australian and International Coalfields.

STATISTIC	Panel Width [W (m)]	Cover Depth [H (m)]	Mining Height [T (m)]
Minimum	110	64	1.2
Mean	179	243	2.5
Maximum	260	470	4.1

Note that the maximum mining height in the database is 4.1 m.

No formula is offered for multi-seam mining.

7 Sensitivity Formulas

The sensitivity of the A-zone height to each of the driving parameters is obtained by differentiation.

The sensitivity formulas for the Ditton Geometry Model are:

$$\frac{\partial A}{\partial H} = 0.600\ H^{-0.729}\ W'^{0.357}\ T^{0.372}$$

$$\frac{\partial A}{\partial T} = 0.824\ T^{-0.628}\ W'^{0.357}\ H^{0.271}$$

$$\frac{\partial A}{\partial W'} = 0.791\ W'^{-0.643}\ H^{0.271}\ T^{0.372}$$

The sensitivity formulas for the Ditton Geology Model are:

$$\frac{\partial A}{\partial H} = 0.813 * H^{-0.465}\ W'^{0.4}\ T^{0.464}\ t'^{-0.4}$$

$$\frac{\partial A}{\partial T} = 0.705\ T^{-0.536}\ W'^{0.4}\ H^{0.535}\ t'^{-0.4}$$

$$\frac{\partial A}{\partial W'} = 0.608\ W'^{-0.6}\ H^{0.535}\ T^{0.464}\ t'^{-0.4}$$

$$\frac{\partial A}{\partial t'} = 0.608\ \ t'^{-1.4}\ W'^{0.4}\ H^{0.535}\ T^{0.464}$$

The Tammetta model sensitivity formulas are:

$$\frac{\partial A}{\partial H} = \frac{0.2\ C1\ E1\ H^{-0.8}}{0.9818 + E1\ H^{0.2}}$$

$$\frac{\partial A}{\partial T} = \frac{1.4\ C1\ E2\ T^{0.4}}{0.9818 + E2\ T^{1.4}}$$

$$\frac{\partial A}{\partial W} = \frac{C1\ E3}{0.9818 + E3\ W}$$

where: C1 = 1438
C2 = 4.315×10^{-5}
E1 = C2 W $T^{1.4}$

$$E2 = C2\ W\ H^{0.2}$$
$$E3 = C2\ H^{0.2}\ T^{1.4}$$

The sensitivities to each causative factor are illustrated in Figure 7 to Figure 9, with comparison between Ditton and Tammetta models.

Figure 7 considers the increase in fractured zone height for an increase of 25 m in either the (effective) panel width or the cover depth. The findings for (effective) panel width are:

- The Ditton Geometry Model has an A-Zone increase of 3-10 m (12-40% of 25 m increment);
- The Tammetta (Geometry) Model has an A-Zone increase of 15-19 m (60-76% of 25 m increment); and
- The Ditton Geology Model has an A-Zone increase of 5-14 m (20-56% of 25 m increment).

The findings for cover depth are:

- The Ditton Geometry Model has an A-Zone increase of 1.5-8 m (6-32% of 25 m increment);
- The Tammetta (Geometry) Model has an A-Zone increase of 1.5-10 m (6-40% of 25 m increment); and
- The Ditton Geology Model has an A-Zone increase of 5-15 m (20-60% of 25 m increment).

Figure 8 considers the increase in fractured zone height for an increase of 0.5 m in mining height. The findings for mining height are:

- The Ditton Geometry Model has an A-Zone increase of 3.8-8.6 m (10-17 times the 0.5 m increment);
- The Tammetta (Geometry) Model has an A-Zone increase of 26-37 m (52-74 times the 0.5 m increment), and it trends in the opposite direction; and
- The Ditton Geology Model has an A-Zone increase of 6.5-14 m (13-27 times the 0.5 m increment).

As the Ditton model has a basis in geotechnical theory, while the Tammetta model is an empirical best-fit procedure, it is expected that the Ditton model would give the more correct sensitivity trend for mining height. The departure of the Tammetta model, in terms of trend and magnitude of its sensitivity to mining height, might be due to database limitations. It has previously been noted that the respective Ditton and Tammetta databases had maximum values of 6.0 m and 4.1 m for mining height. This means that the Tammetta model is uncontrolled for the higher mining heights.

Figure 9 shows the decrease in fractured zone height for an increase of 0.5 m in the effective thickness of a spanning beam. The finding for beam thickness is:

- The Ditton Geology Model has an A-Zone decrease of 0.3-7 m (0.6-14 times the 0.5 m increment).
- There is no equivalent parameter in the Tammetta model, but it is noted in Tammetta (2012) that "Host geology appears to play a minor role".

8 Database Probability Statistics

Representative statistics for characteristic ratios derived for the Ditton database are listed in Table 4 and Table 5. When applied to the Ditton database for Australian coalfields, the Tammetta formula leads to similar statistics in Table 6.

A common first-order estimate of fractured zone height is afforded by the ratio A/W, which is 0.45 for the Ditton concept at the median (Table 4) and 0.78 for the Tammetta concept at the median (Table 6). The Ditton B-Zone ratio is 0.60 at the median (Table 5).

Another common first-order estimate of fractured zone height is afforded by the ratio A/T, which is 21-37 for the Ditton concept (Table 4) and 33-61 for the Tammetta concept (Table 6). The Tammetta estimates would appear excessive and are likely to include areas of disconnected fractures given that the B-zone range, which does include disconnected fractures, is 27T to 71T.

Table 4. Exceedance Probabilities for Ditton Continuous Fracture Zone (A-Zone) Height for Australian Coalfields.

EXCEEDANCE PROBABILITY	Height of Fracture Zone / Panel Width [A/W]	Height of Fracture Zone / Cover Depth [A/H]	Height of Fracture Zone / Mining Height [A/T]
20%	0.38	0.23	21
50%	0.45	0.43	32
80%	0.73	0.69	37

For the parameters W, H and T in turn, the median B-height exceeds the median A-height by 33%, 100% and 34% (Table 5).

Table 5. Exceedance Probabilities for Ditton Discontinuous Fracture Zone (B-Zone) Height for Australian Coalfields.

EXCEEDANCE PROBABILITY	Height of Fracture Zone / Panel Width [B/W]	Height of Fracture Zone / Cover Depth [B/H]	Height of Fracture Zone / Mining Height [B/T]
20%	0.47	0.60	27
50%	0.60	0.86	43
80%	1.07	0.95	71

Table 6. Exceedance Probabilities for Tammetta Desaturated Zone Height for Australian Coalfields. [Derived using Tammetta formula applied to the database of Ditton]

EXCEEDANCE PROBABILITY	Height of Desaturated Zone / Panel Width [H/W]	Height of Desaturated Zone / Cover Depth [H/d]	Height of Desaturated Zone / Mining Height [H/t]
20%	0.61	0.32	33
50%	0.78	0.80	48
80%	1.02	1.13	61

There is a substantial difference between the Ditton A-height and the Tammetta desaturation-height. Table 7 shows comparative statistics for the Ditton and Tammetta conceptual models. For the parameters W, H and T in turn, the median desaturation-height exceeds the median A-height by 73%, 86% and 50%.

Table 7. Exceedance Probabilities for Ditton Continuous Fracture Zone (A-Zone) Height and for the Tammetta Desaturated Zone Height for Australian Coalfields.

STATISTIC	Height of Fracture Zone / Panel Width [A/W]		Height of Fracture Zone / Cover Depth [A/H]		Height of Fracture Zone / Mining Height [A/T]	
	Ditton	Tammetta	Ditton	Tammetta	Ditton	Tammetta
20%	**0.38**	0.61	**0.23**	0.32	**21**	33
50%	**0.45**	0.78	**0.43**	0.80	**32**	48
80%	**0.73**	1.02	**0.69**	1.13	**37**	61

9 Model Probability Distributions

Calculations of A-Zone and B-Zone heights, and associated ratios, for the entries in the Ditton database have been sorted and ranked to give cumulative probability distributions in Figure 10 to Figure 14. The Ditton Geology Model and Geometry Model track each other closely.

Comparative cumulative probability distributions (Ditton and Tammetta models) are shown in Figures 12, 13 and 14 where it appears that the Tammetta formulation agrees better with the B-zone definition. For the parameters W, H and T in turn, the median desaturation-height exceeds the median B-height by -0.4%, 5% and -8%.This suggests that the Tammetta formulation includes zones of disconnected fractures.

10 Conclusion

Opinions have been offered in this report on two literature reviews endorsed by the IESC:

A. Commonwealth of Australia 2014, *Temperate Highland Peat Swamps on Sandstone: evaluation of mitigation and remediation techniques, Knowledge report*, prepared by the Water Research Laboratory, University of New South Wales, for the Department of the Environment, Commonwealth of Australia; and

B. Commonwealth of Australia 2014, *Temperate Highland Peat Swamps on Sandstone: longwall mining engineering design—subsidence prediction, buffer distances and mine design options, Knowledge report*, prepared by Coffey Geotechnics for the Department of the Environment, Commonwealth of Australia.

The opinions are restricted to statements on surficial and deep fracturing as a result of underground mining:

1. The treatment of fractured zone algorithms in the literature reviews is inadeqate as the work of Ditton, documented in Ditton and Merrick (2014), is ignored;

2. The Ditton model for fractured zone height is considered superior to the Tammetta algorithm due to a basis in geotechnical theory, a correct trend for sensitivity to mining height, calibration to Australian conditions, and inclusion of a host geology term;

3. The association of the Collapsed Zone in the Tammetta model with complete desaturation is disputed, given the retention of significant volumes of water in the matrix of the rock material in this zone, and statistical correlation of the height of this

zone with the B-Zone altitude in the Ditton model, which marks the top of a zone that has disconnected fractures;

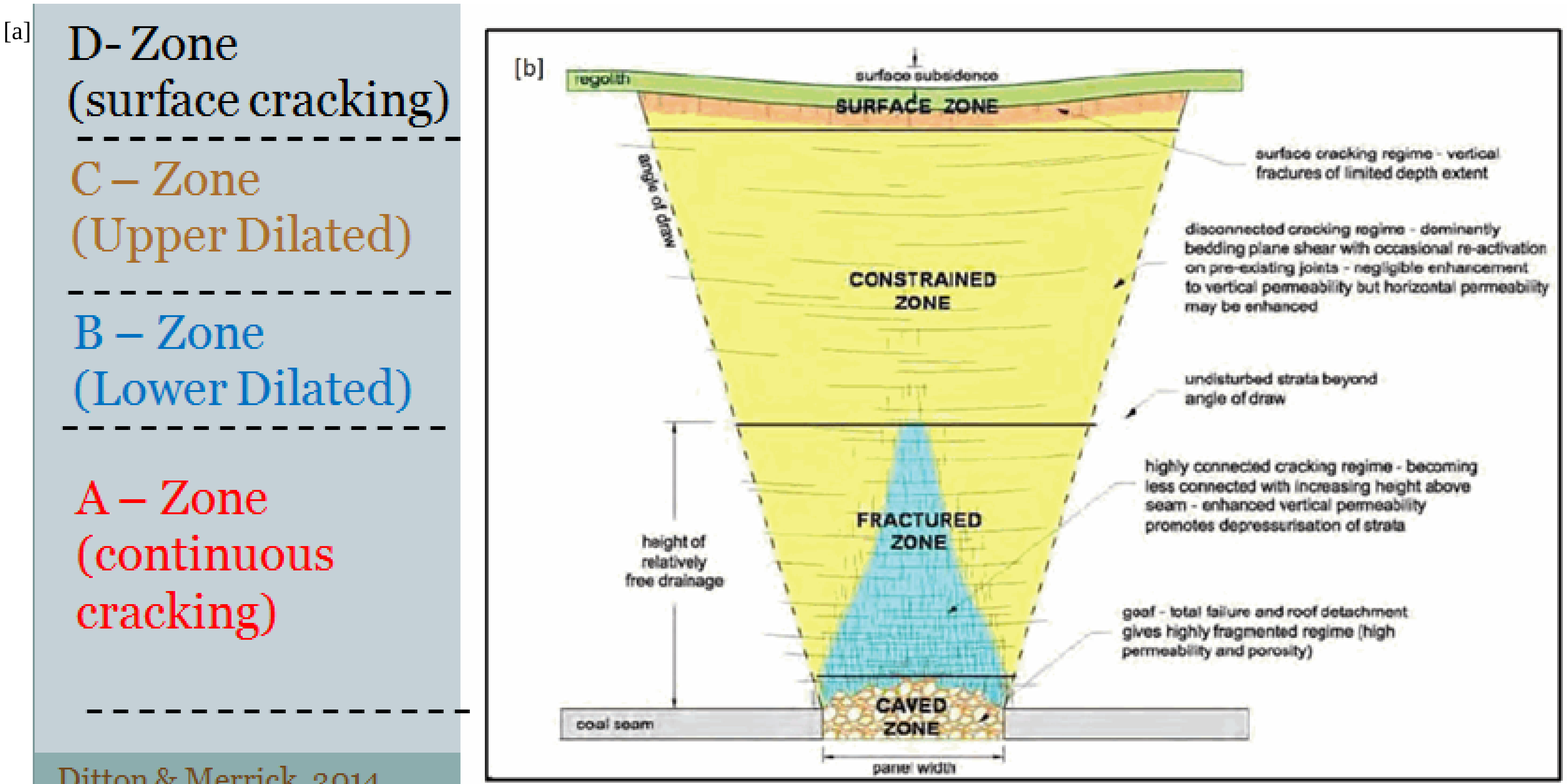
4. The treatment of fracture permeabilities in the literature review (in Report A) is inadeqate as the substantial body of work on discrete fracture networks is ignored;

5. The estimates for fracture permeability are simplistic and grossly overstated, due to lack of consideration of fracture connectivity influenced by closure or truncation;

6. The conclusion that "a few small cracks through the swamp substrate can lead to substantial vertical drainage" is invalid, due to over-reliance on the cubic law for relating water flow to aperture size, and lack of consideration of the relative sizing of water-holding cracks and the water stored within intact swamp sediments.

Yours sincerely

Dr Noel Merrick
Director



NSW Government Department of Planning (2008)

Figure 1. The Ditton Conceptual Model

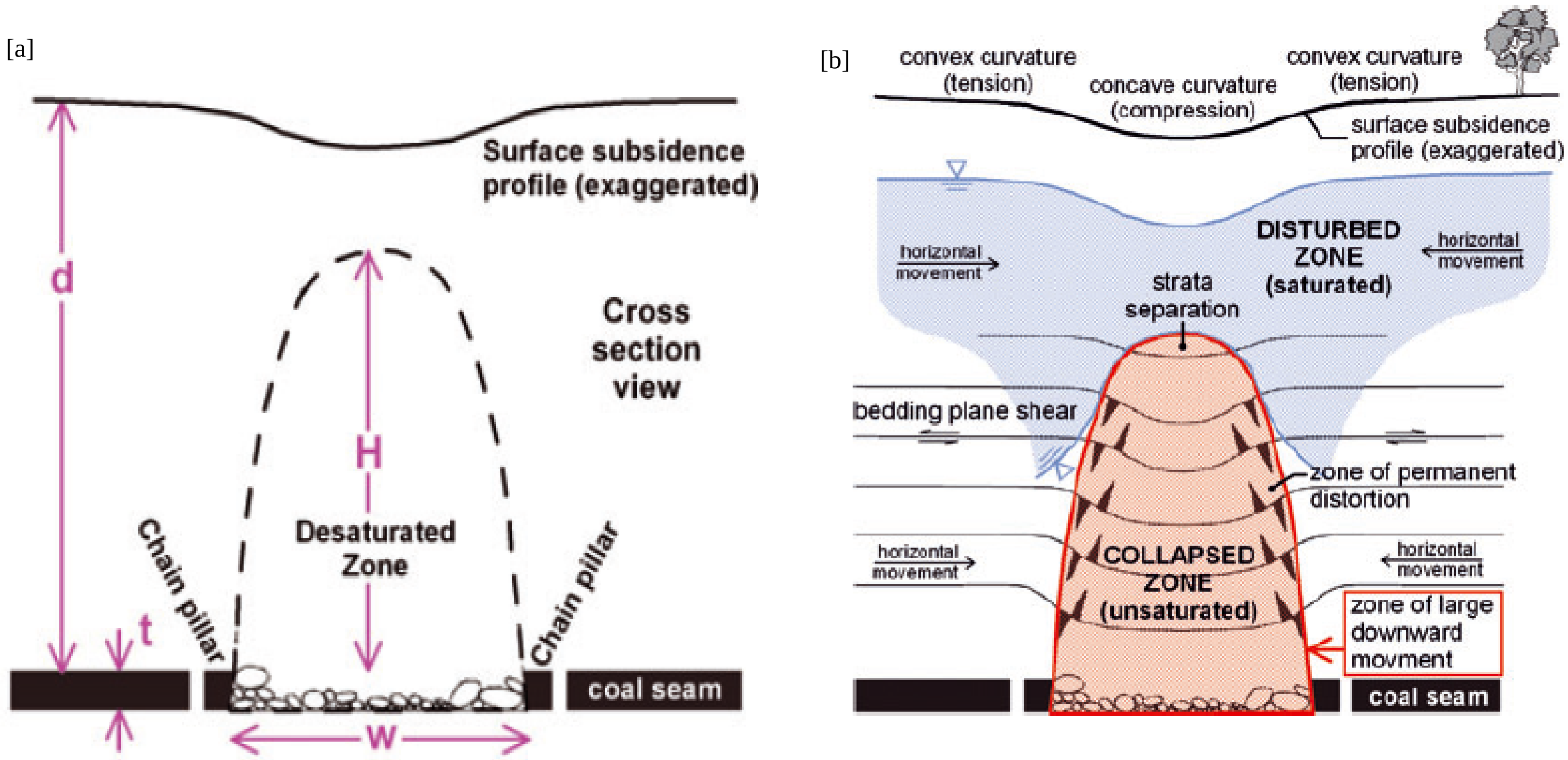


Figure 2. The Tammetta Conceptual Model [Figure 1b and Figure 10 from Tammetta (2012)]

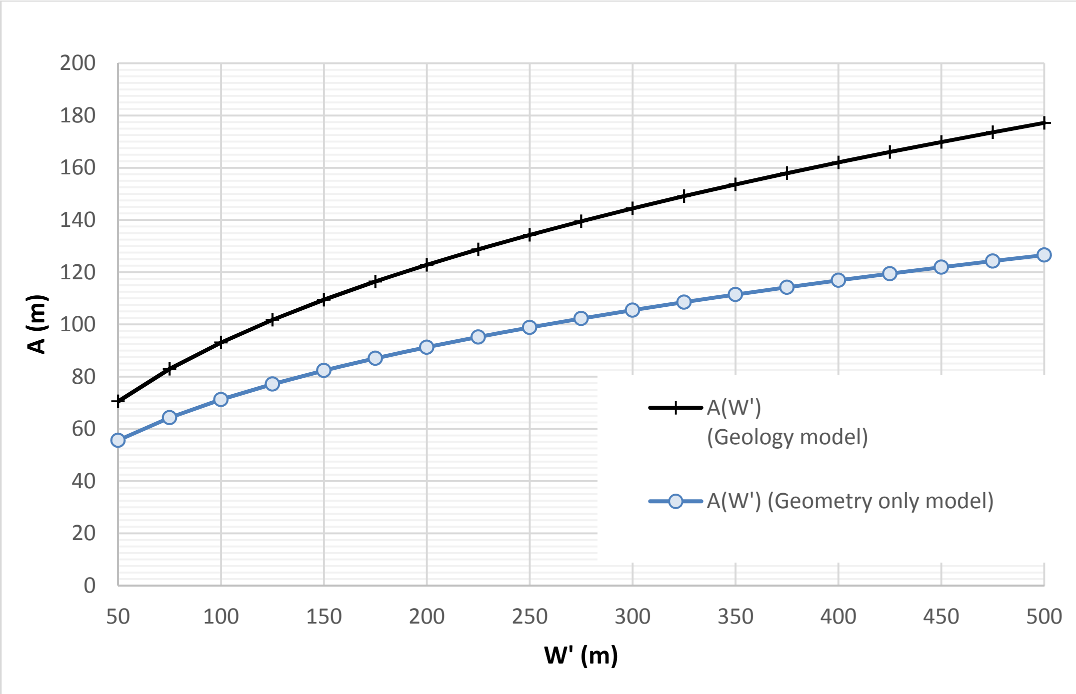


Figure 3. Variation of A-Zone Height for Varying Effective Panel Width for the Ditton Models [H, T and t' held constant at database median values]

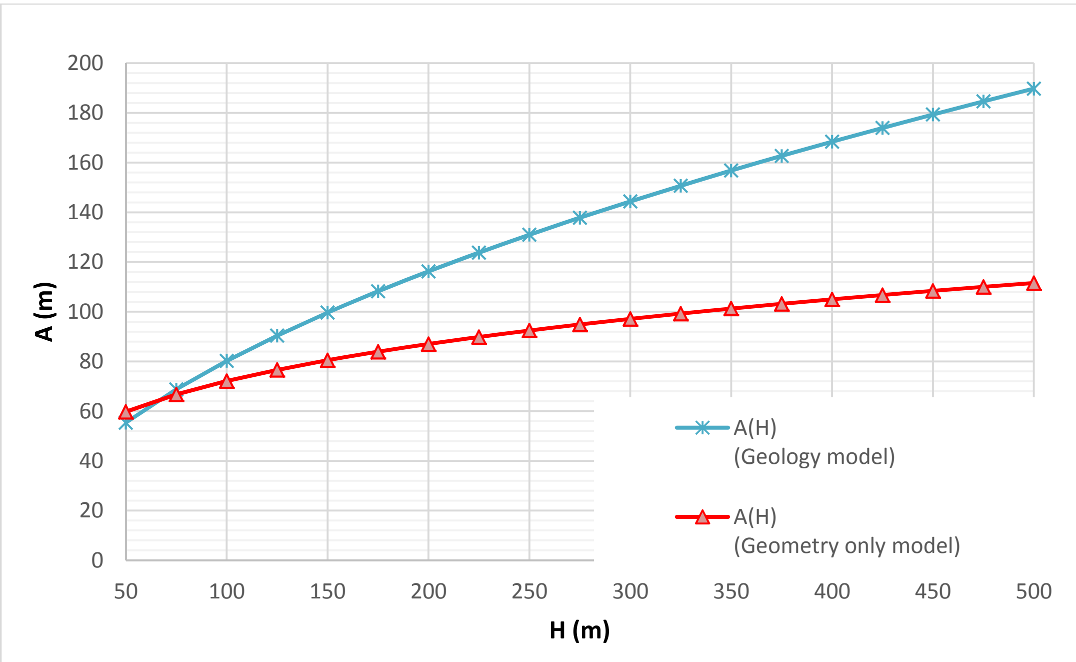


Figure 4. Variation of A-Zone Height for Varying Cover Depth for the Ditton Models [W', T and t' held constant at database median values]

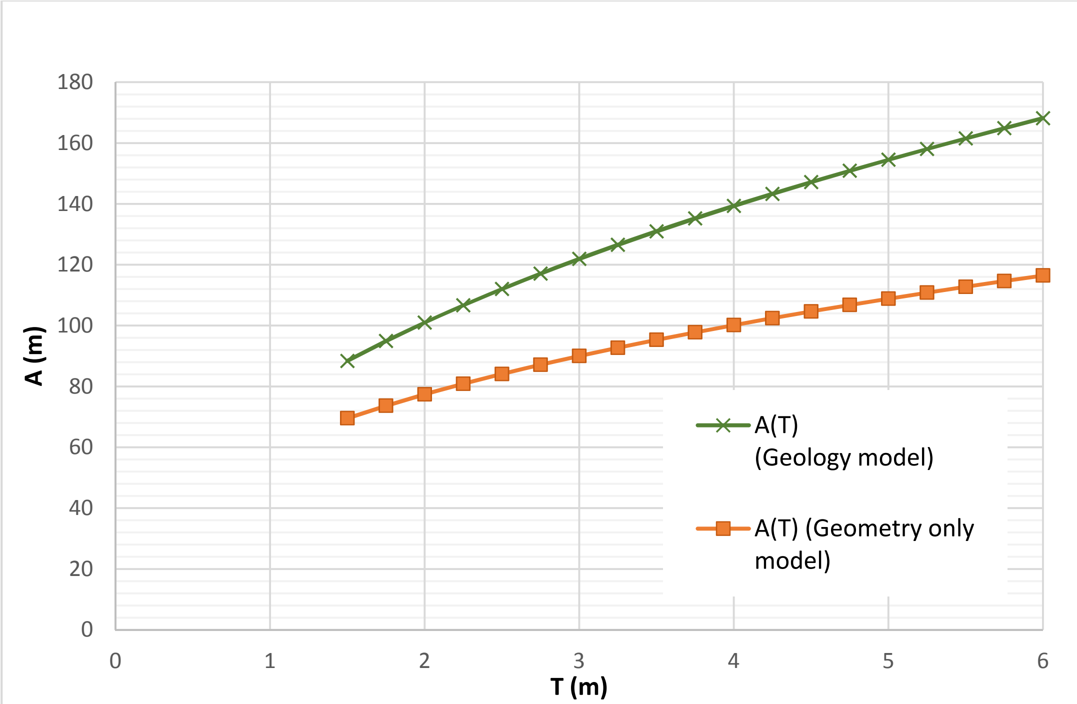


Figure 5. Variation of A-Zone Height for Varying Mining Height for the Ditton Models [W', H and t' held constant at database median values]

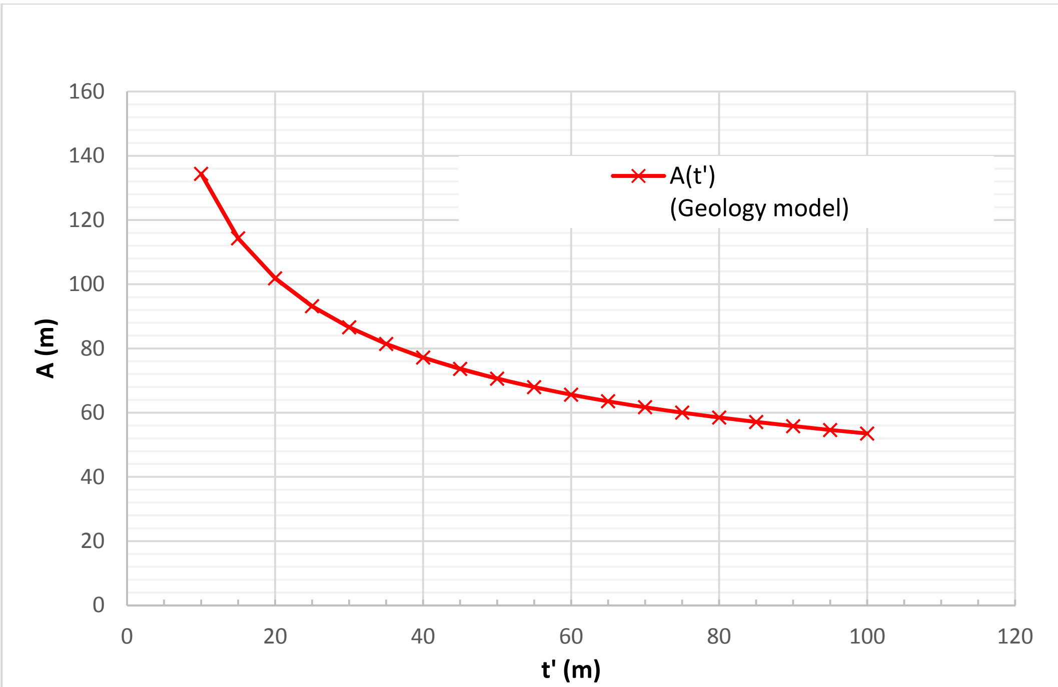
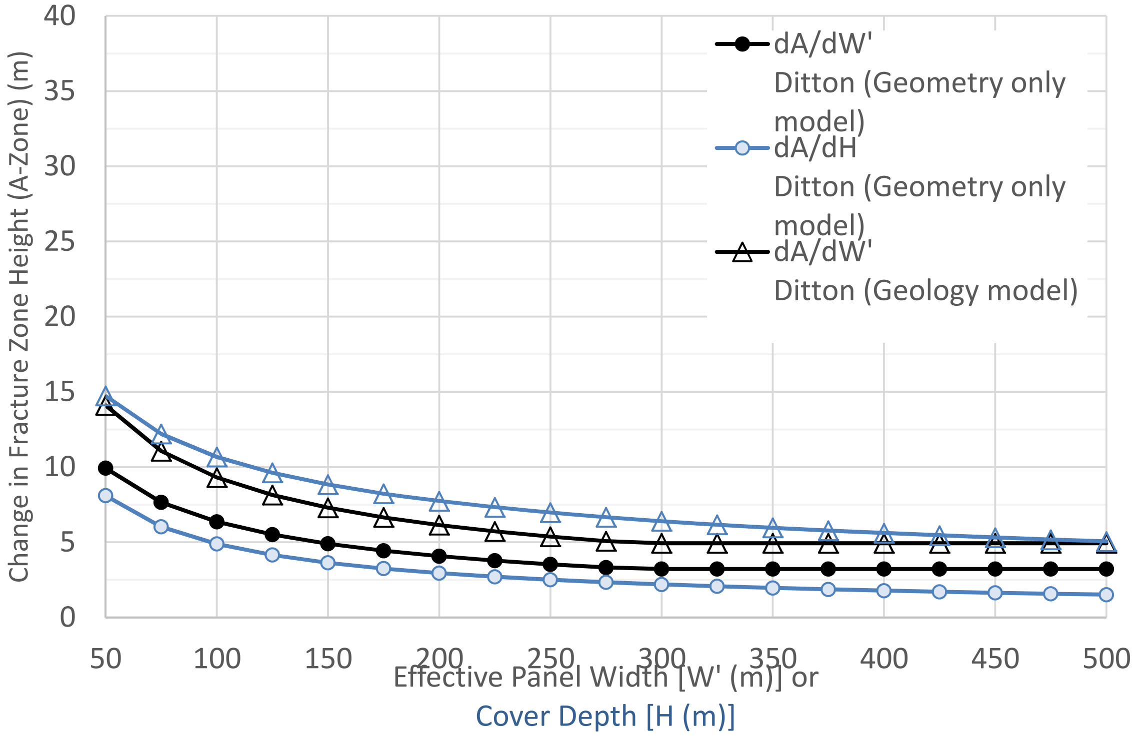


Figure 6. Variation of A-Zone Height for Varying Effective Stratum Thickness for the Ditton Model [W', H and T held constant at database median values]

[a]



[b]

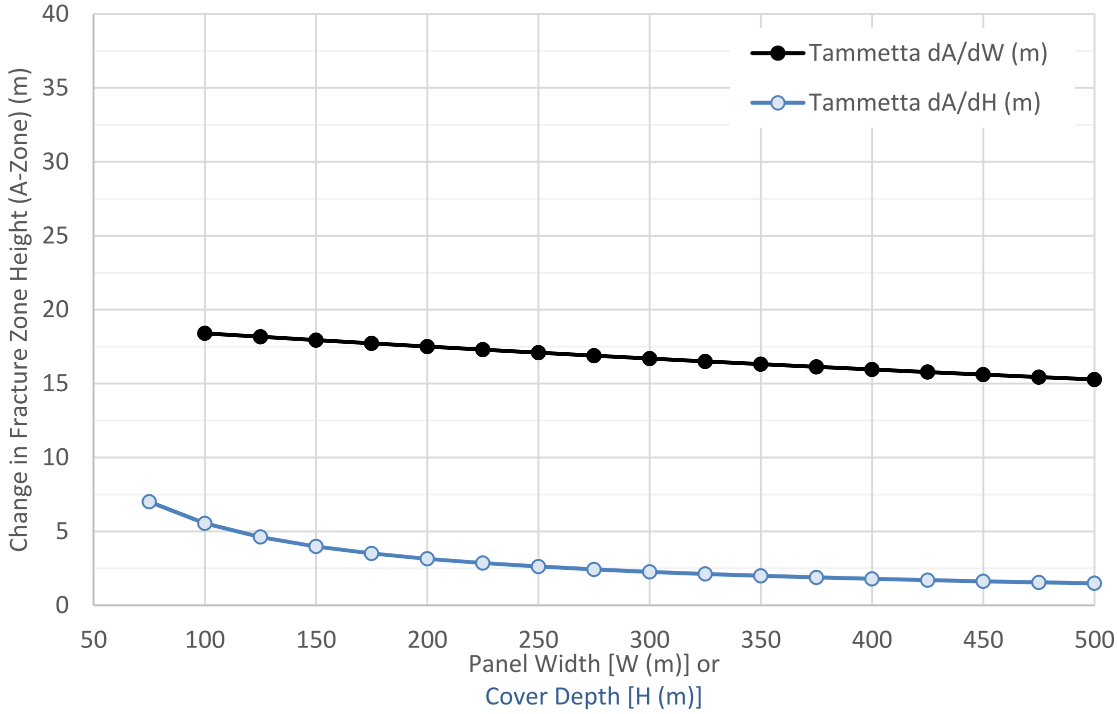
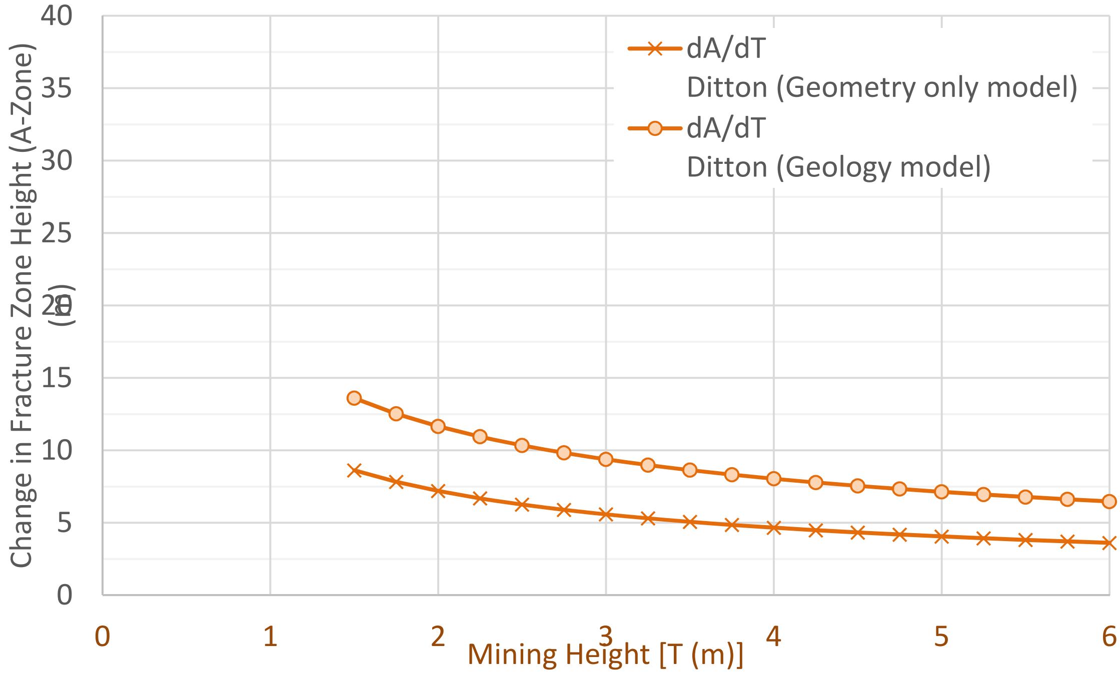


Figure 7. Sensitivity Analysis for the Change in A-Zone Height for 25 m Variation in Panel Width or Cover Depth: [a] Ditton Models; [b] Tammetta Model.

[a]



[b]

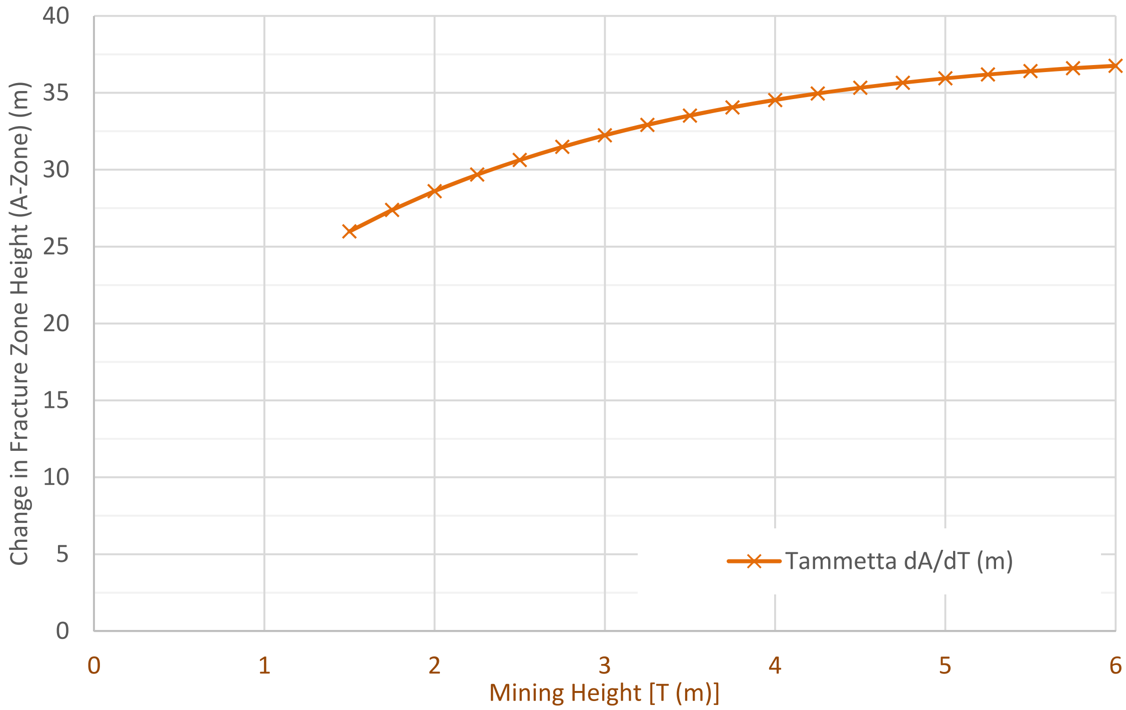


Figure 8. Sensitivity Analysis for the Change in A-Zone Height for 0.5 m Variation in Mining Height: [a] Ditton Models; [b] Tammetta Model.

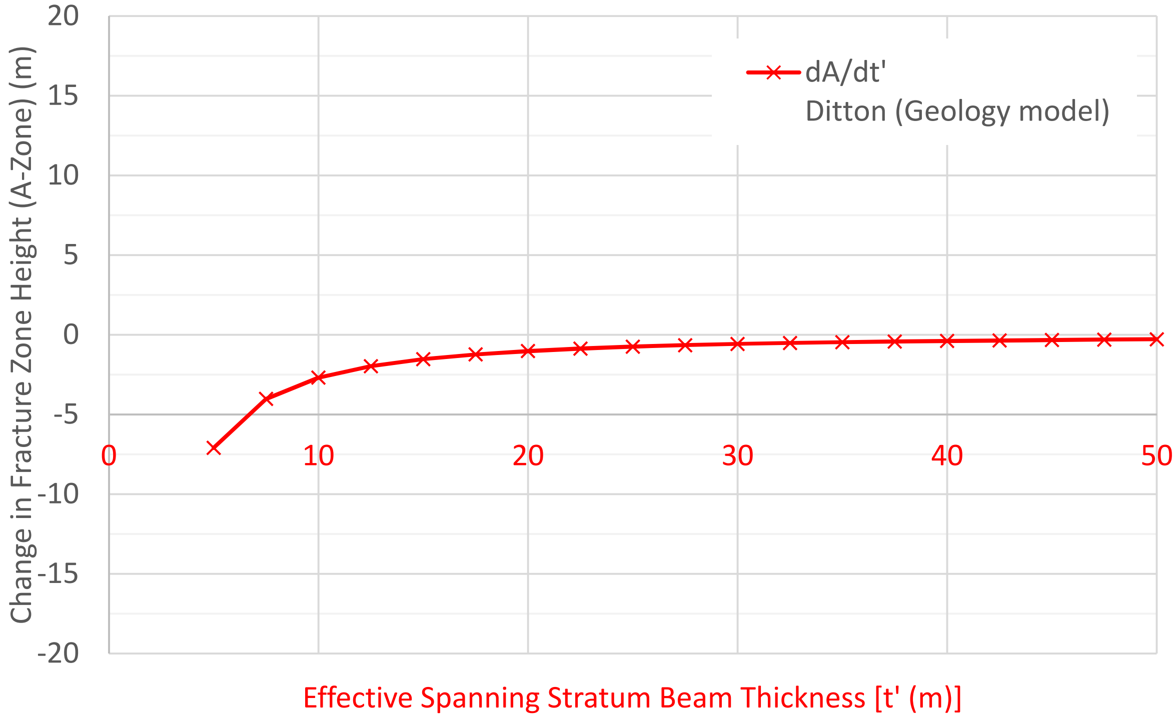
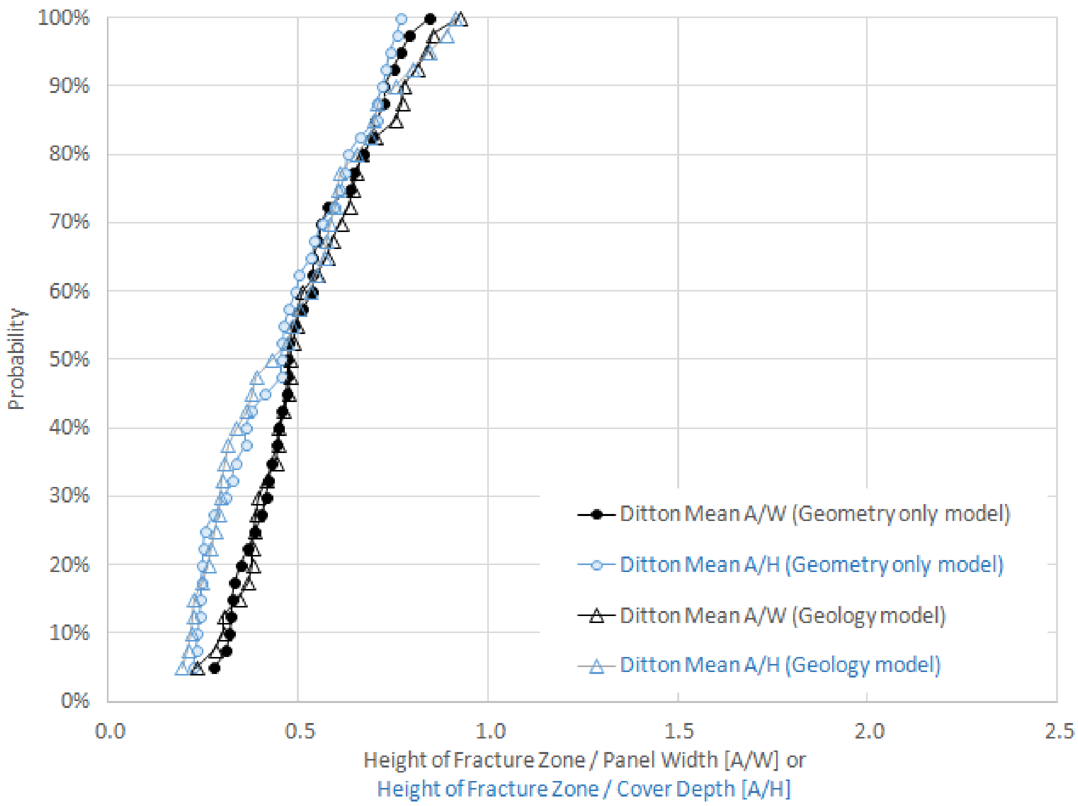


Figure 9. Sensitivity Analysis for the Change in A-Zone Height for 0.5 m Variation in Effective Stratum Thickness for the Ditton Geology Model.

[a]



[b]

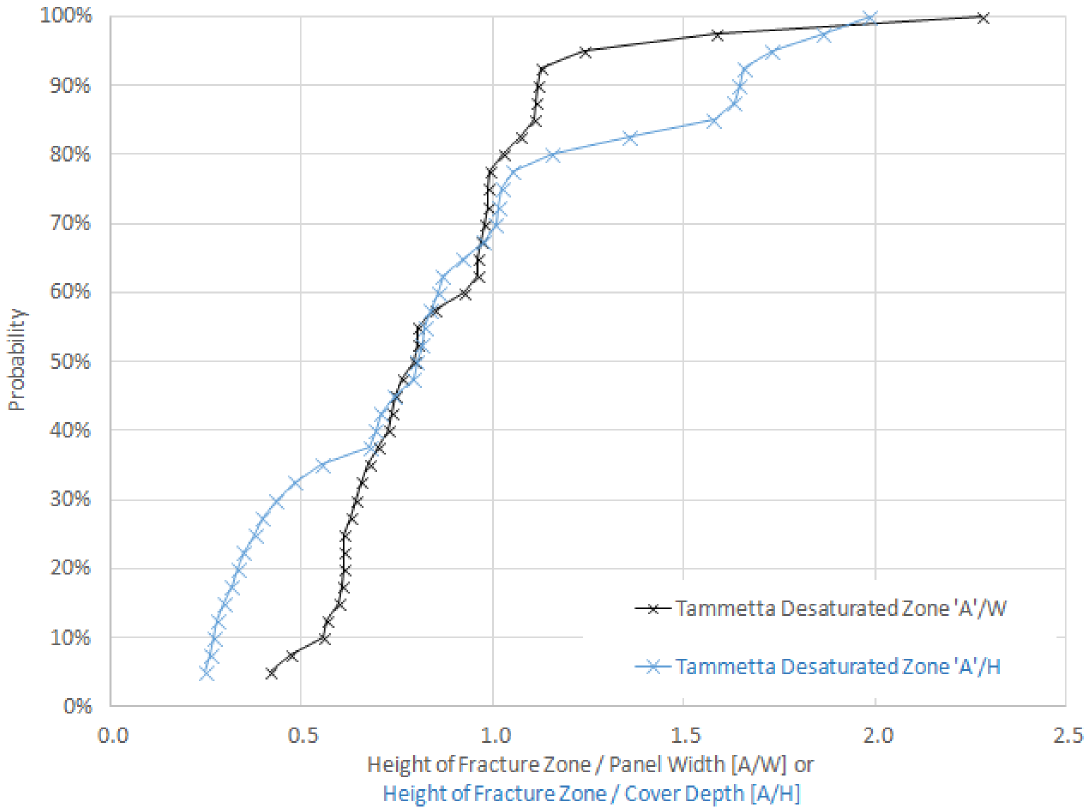
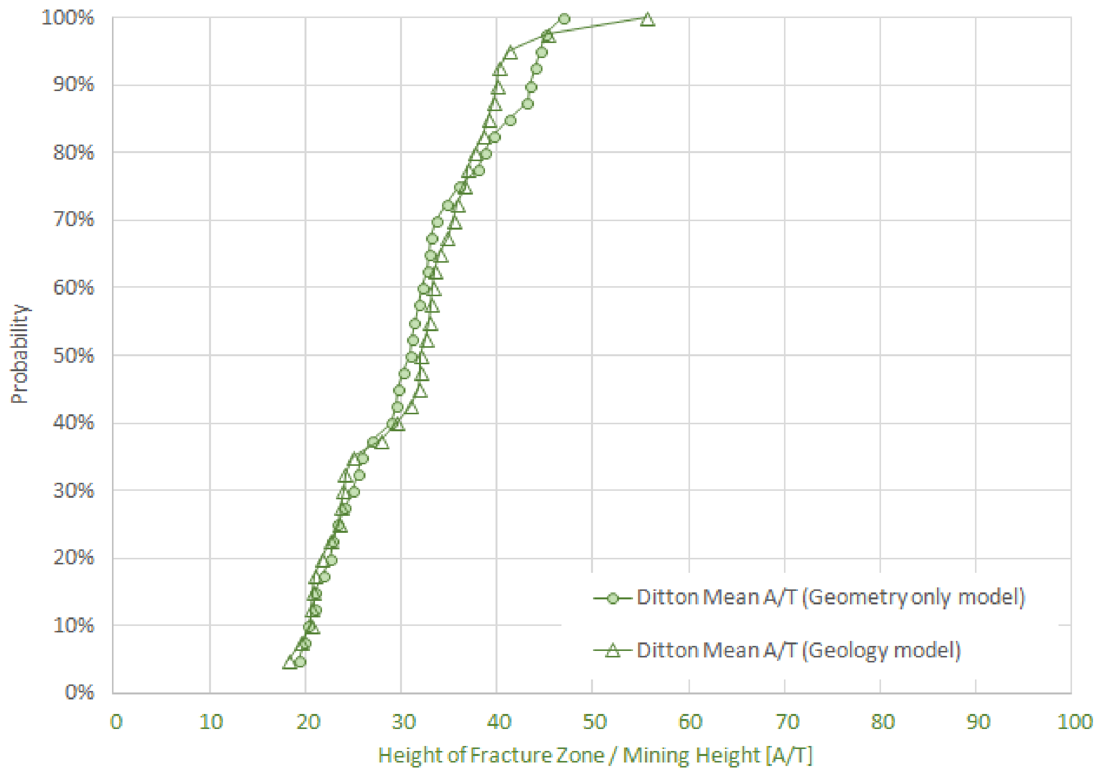


Figure 10. Probability Analysis for the Ratio of A-Zone Height to Panel Width or Cover Depth: [a] Ditton Models; [b] Tammetta Model.

[a]



[b]

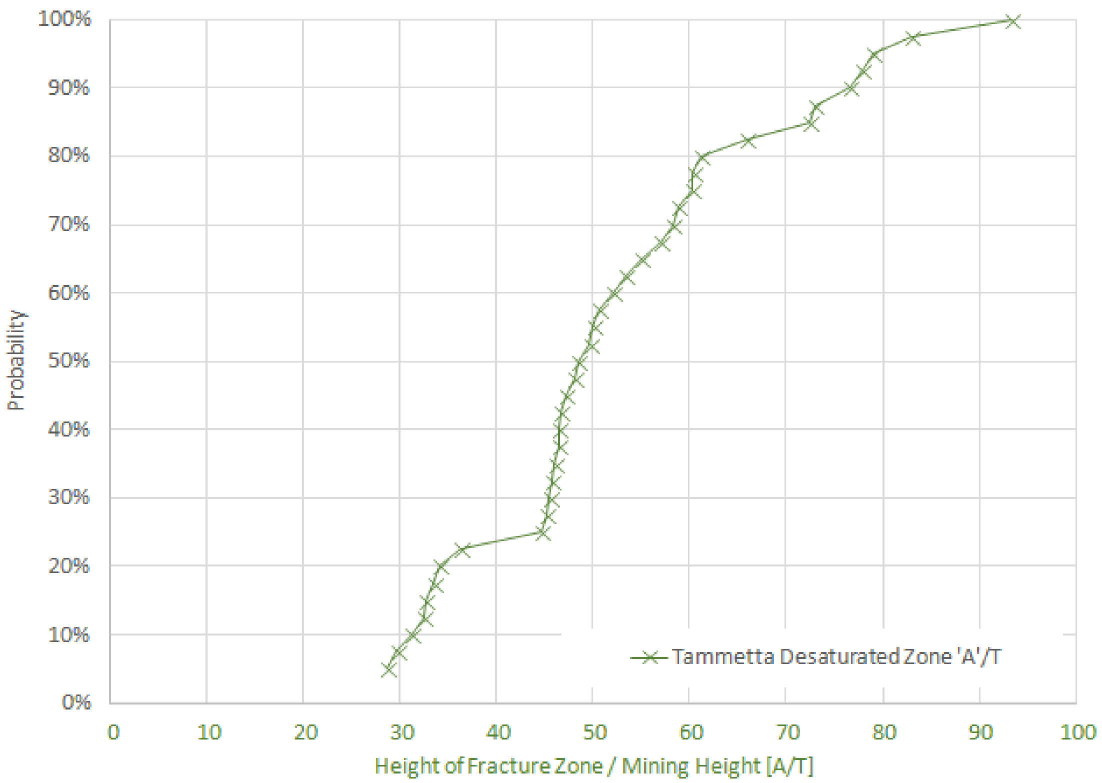


Figure 11. Probability Analysis for the Ratio of A-Zone Height to Mining Height: [a] Ditton Models; [b] Tammetta Model.

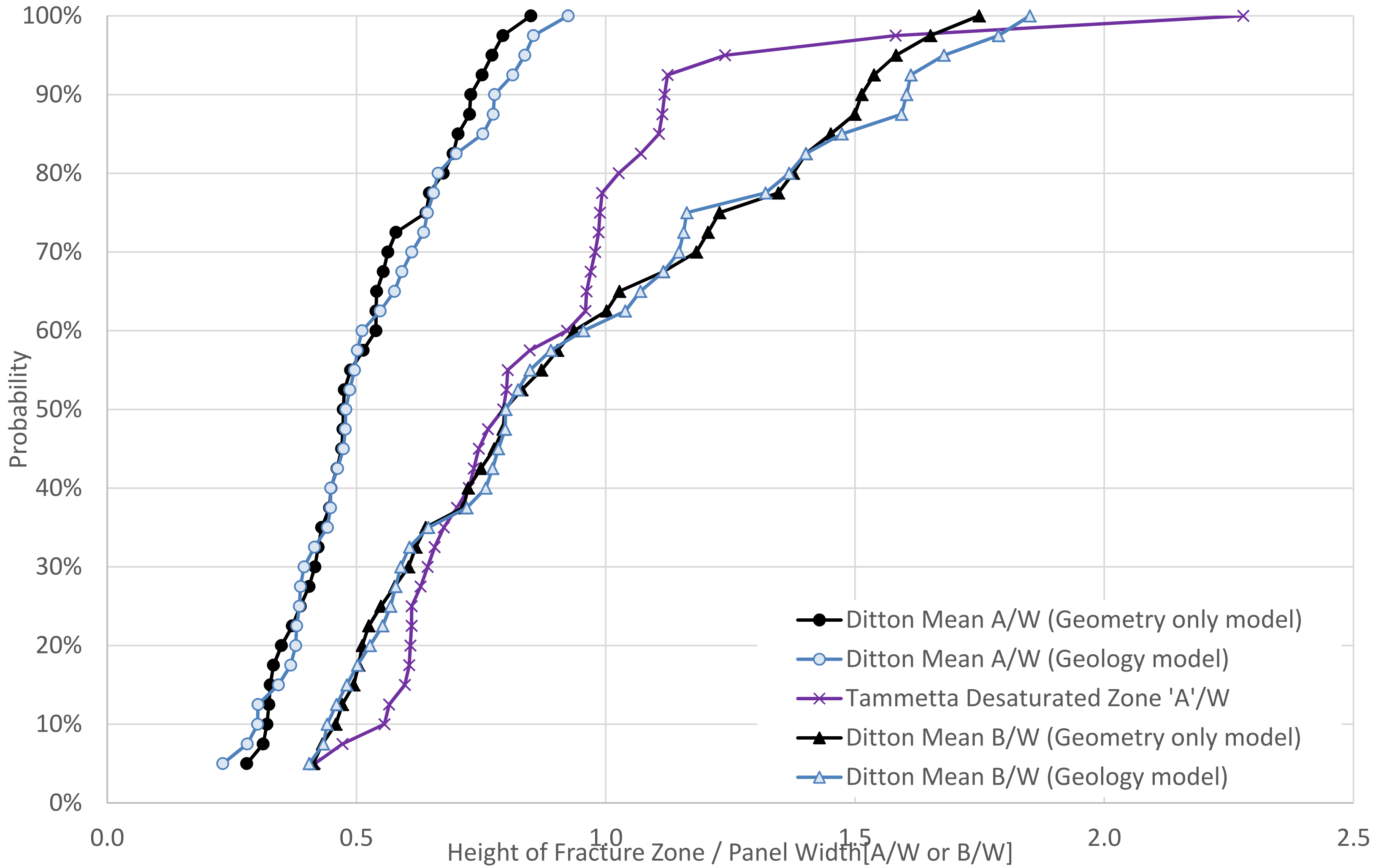


Figure 12. Probability Analysis for the Ratio of A-Zone and B-Zone Heights to Panel Width for Ditton and Tammetta Models.

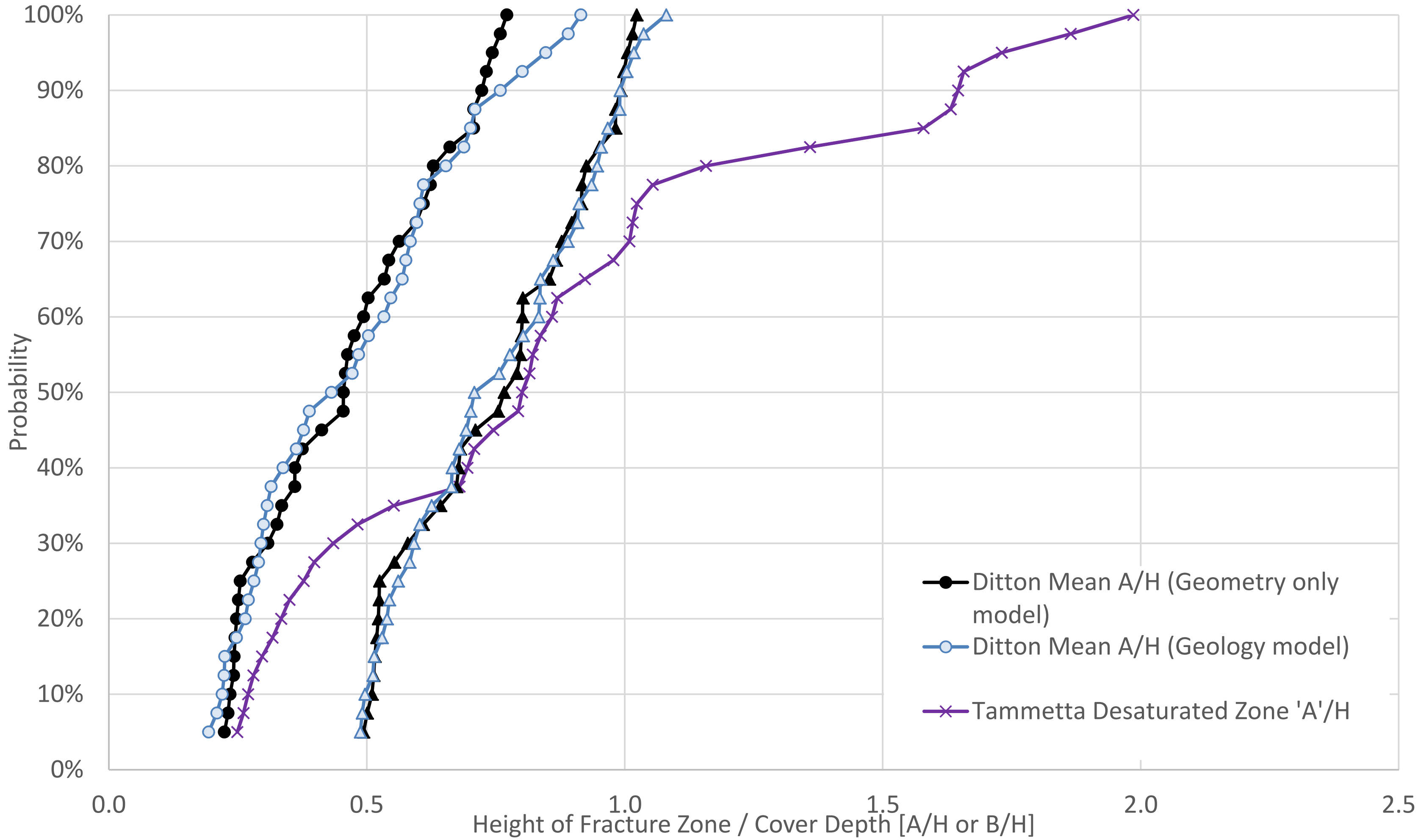


Figure 13. Probability Analysis for the Ratio of A-Zone and B-Zone Heights to Cover Depth for Ditton and Tammetta Models.

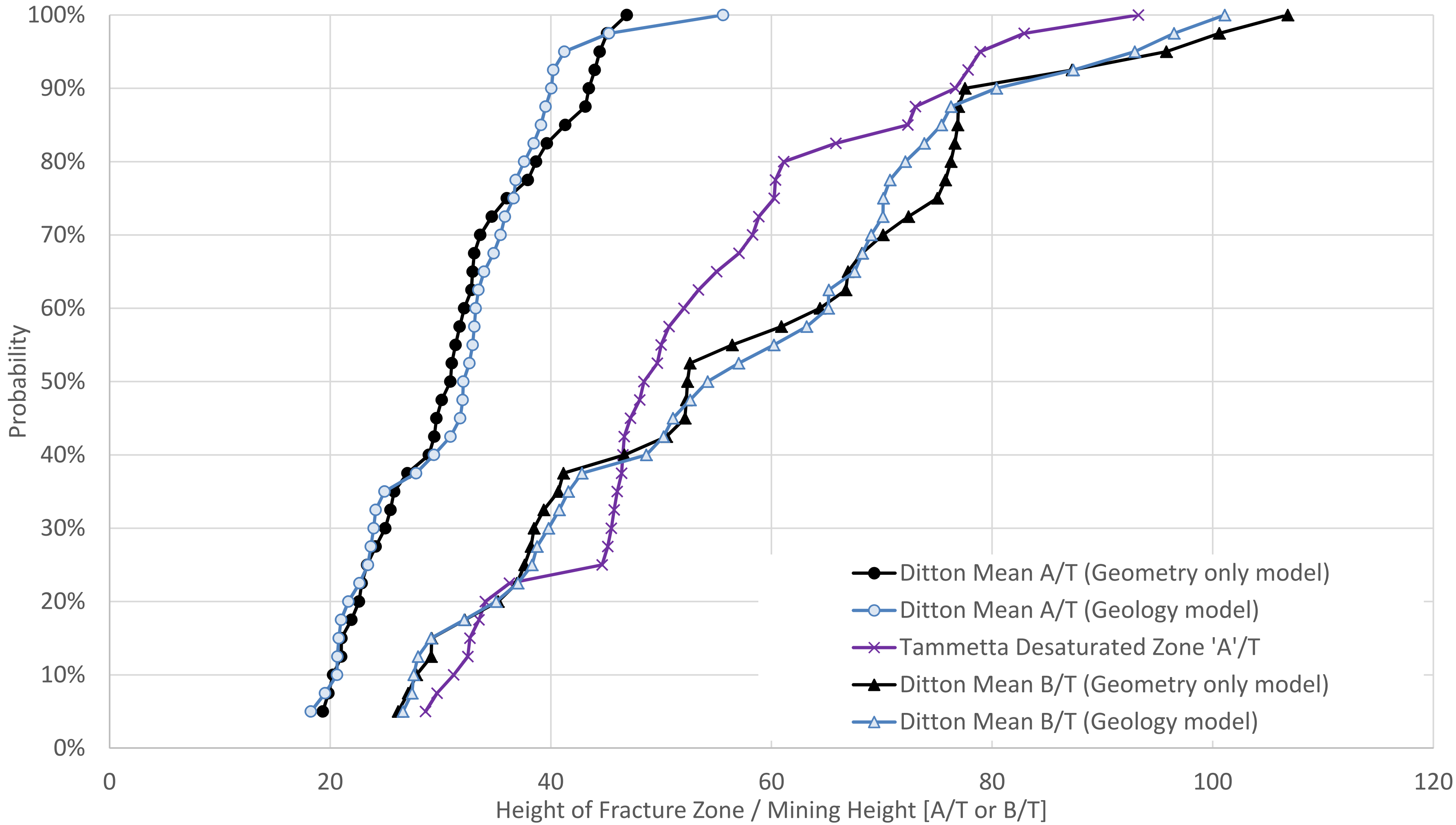


Figure 14. Probability Analysis for the Ratio of A-Zone and B-Zone Heights to Mining Height for Ditton and Tammetta Models.