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Subsurface Fracture Zone Assessment above the Proposed Springvale and Angus Place Mine Extension Project Area Longwalls

DgS Report No. SPV-003/7b

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10th September, 2014

Peter Corbett
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PO Box 198
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Report No. SPV-003/7b

Dear Peter,

Subject: Subsurface Fracture Zone Assessment above the Proposed Springvale and Angus Place Mine Extension Project Area Longwalls

This report has been prepared in accordance with the brief for the above projects.

Please contact the undersigned if you have any questions regarding this matter.

For and on behalf of
Ditton Geotechnical Services Pty Ltd

Steven Ditton
Principal Engineer

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1.0 Introduction

This report provides subsurface fracture zone height predictions for the proposed longwalls in the Springvale and Angus Place Mine Extension Project Areas.

The longwalls included in this study are:

- Springvale Mine LWs 415 to 423
- Springvale Mine Extension Area LWs 424 to 432 and 501 to 503
- Angus Place Mine Extension Area LWs 1001 to 1019

The predictions have been based on the Geometry and Geology Pi-Term models presented in **DgS, 2014** and the interpreted sub-surface fracture zones above Springvale Mine's LWs 409, 411 and 412. The Geometry Pi-Term models refer to panel void width (W'), cover depth (H) and mining height (T), whereas the Geology Pi-Term model includes an additional term, the effective strata unit thickness (t'), which is the average thickness of the bending or shearing beam in the B-Zone (i.e. the dilated zone above the Continuous Fracture Zone or A-Zone).

The purpose of the review was to (i) calibrate the Geology Pi-Term model with the measured subsurface fracturing zones, and (ii) assess the likely A and B-Zone fracture zone heights above the proposed project area panels.

The original assessment of the subsurface fracture zone assessment due to LWs 411 and 412 and the geological structure beneath East Wolgan Creek (**DgS, 2013**) has been superseded by the updated Pi-Term models and borehole data used in this study.

2.0 Method

The subsurface fracture heights above the proposed longwall mining areas have been estimated based on:

- A review of the overburden geology above completed and future mining areas.
- The observed strata responses measured with borehole extensometer and vibrating wire piezometers installed above Springvale LWs 409, 411 and 412.
- Water table monitoring in stand pipe piezometers on the ridges above Angus Place LW 950 and Springvale LWs 411, 415 and 420.
- The results of sub-surface fracture (micro-seismic event) monitoring above LW413.
- Calibration of the Geology 'Pi-Term' Model to the measured heights of continuous subsurface fracturing (A Zone Horizon) and discontinuous fracturing and strata dilation (B-Zone Horizon).
- Comparison of measured sub-surface fracture zones with the Geometry Pi-term model predictions.

A summary of the Pi-Term models is presented in **Section 5** with development details in **Attachment A**.

3.0 Mining Geometry

The geometry of the completed Springvale Mine longwalls and proposed new project area longwall layouts are summarised in **Table 1**. The mining layouts with cover depth contours are presented in **Figures 1a** to **1c**.

Table 1 - Completed and Proposed Longwall Panel Geometry

Mine	LW No.	Panel Width W' (m)	Cover Depth, H (m)	Mining Height T (m)	W/H	MG Chain Pillar Width w_{cp}
Springvale Mine	1,401-408	255, 265	385	2.7, 2.95	0.75 - 0.85	40
	409	265	385	3.25	0.69	40
	410	315	370	3.25	0.85	40
	411	315	290 - 368	3.25	0.86 - 1.08	42
	412	315	400	3.25	0.79	43
	413	315	400	3.25	0.79	43
	414 - 415	315	412	3.25	0.76	43 - 47
	416 - 423	261	340 - 420	3.25	0.63 - 0.78	58
Springvale Mine Extension Project Area	424 - 431	261	290 - 415	3.25	0.63 - 0.90	58
	432	229	270 - 405	3.25	0.57 - 0.85	58
	501	261	180 - 325	3.25	0.80 - 1.45	-
	502	243	180 - 305	3.25	0.80 - 1.35	35.2
	503	236	245 - 310	3.25	0.76 - 0.96	-
Angus Place Mine Extension Project Area	1001 - 1003	293	350 - 410	3.25	0.71 - 0.83	55
	1004 - 1006	261	280 - 430	3.25	0.61 - 0.93	55
	1007 - 1015	360	270 - 440	3.25	0.82 - 1.33	55
	1016 - 1017	261	305 - 355	3.25	0.74 - 0.86	55
	1018 - 1019	360	320 - 420	3.25	0.86 - 1.13	55

Shaded - Completed LWs.

The completed panels to-date had 'sub-critical' to 'critical' geometries with W/H ranging from 0.69 to 1.08. The proposed longwalls in the proposed mine extension areas will have 'sub-critical' to 'super-critical' mining geometries, with W/H values ranging from 0.57 to 1.45. *Note: It has been previously assessed in* ***DgS, 2010*** *that the transition point between 'sub-critical' and 'critical' panels occurs at W/H of 0.9 and between 'critical' and 'super-critical' behaviour at W/H of 1.4.*

In the future mining areas adjacent to shrub swamps, the mine design has been specifically designed for sub-critical panel geometries. The width to depth ratios for these proposed longwalls vary between 0.6 and 0.9, but are typically within the range of 0.65 and 0.75 and therefore, are less than those for the previously extracted longwalls at Angus Place and Springvale Collieries.

The effect of the apparent increases in panel 'criticality' and panel geometry on the subsurface fracture height zones is discussed further in **Section 6.0**.

4.0 Site Conditions

4.1 Surface Conditions

4.1.1 Completed Longwalls

The completed longwall panels at the Springvale Mine (LW1, 401 to 415) have been extracted below the Newnes State Forest and Plateau, which is vegetated by eucalypt tree species and sensitive shrub swamps. The terrain is gently to moderately undulated with ground slopes generally < 15^o with some bedrock exposures along the creek beds. Slopes with gradients > 18^o exist in the northern ends of valleys adjacent to East Wolgan and Narrow Swamps.

Several tributaries or ephemeral drainage gullies and shrub swamps associated with the Wolgan River (including West Wolgan, and East Wolgan Creek) have been undermined by Springvale and Angus Place Colliery longwalls.

There were no sensitive features such as sandstone cliff lines > 20 m high, rock formations (pagodas) > 5 m high or Aboriginal Heritage Sites within an angle of draw distance of 26.5^o (0.5 times the cover depth) of the previous panels with > 20 m high cliffs adjacent to the north side of the Wolgan River near the starting ends of LWs 411 and 412; see **Figure 2a**.

4.1.2 Proposed Mine Extension Project Area Longwalls

The proposed longwall panels (Springvale 416 to 423, Springvale Mine Extension Project Area LWs 424 to 432 & 501 to 503 and Angus Place Mine Extension Project Area LWs 1001 to 1019) will also be extracted below the Newnes State Forest and Plateau. The terrain is gently to moderately undulating with ground slopes < 15^o. There are several tributaries or ephemeral drainage gullies and shrub swamps associated with the Wolgan River (including Sunny Side East, Carne West and Carne East Creeks) that drain the plateaux to the east and west.

There are several sensitive landscape features such as sandstone cliff lines > 20 m high, rock formations (pagodas) > 5 m high and steep slopes > 18^o within the Springvale and Angus Place Mine Extension Project Areas. The proposed longwalls have been set back from these features by an angle of draw distance of 26.5^o (0.5 times the cover depth); see **Figures 2b** and **2c**.

4.2 Subsurface Conditions

4.2.1 Springvale Mine LWs 409 to 412

Lithological and geophysical logging of the overburden above Springvale Mine's LW 409, 411 and 412 has been summarised in **Table 2** and **Figure 3a**.

Table 2 - Springvale Mine's Overburden Stratigraphy

Strata Unit	Depth to base of Unit z (m)	Height above Mine Roof y (m)	Formation Thickness t (m)	Lithology	UCS (MPa)
Burralow Formation	60 - 79	306 - 318	60 - 79	Interbedded Sandstone & Claystone (weathered)	2 - 10
Banks Wall Sandstone	156 - 164	221 - 222	85 - 96	Sandstone, massive	30 - 50
Mount York Claystone	171 - 188	198 - 207	23 - 27	Claystone, variable thickness	30 - 70
Burra Moko-Head Sandstone	210 - 225	160 - 168	27 - 37	Sandstone, massive	30 - 90
Upper Caley Formation	234 - 264	121 - 144	24 - 39	Sandstone	30 - 70
Lower Caley Formation	261 - 274	111 - 117	18 - 27	Siltstone: Sandstone	30 - 70
Katoomba & Middle River Seams	285 - 292	87 - 93	24 - 24	Coal/shale	10 - 20
Denman Formation	373 - 379	5 - 6	88 - 103	Sandstone: Siltstone	20 - 50
Lidsdale/Lithgow Seam	376 - 383	0	3.9 - 3	Coal	10 - 20

Shaded - strong sandstone units.

4.2.2 Proposed Mine Extension Project Areas

Based on the cross sections through the proposed Mine Extension Project Areas provided by Palaris, it is assessed that the geology is similar to the current mining conditions (see **Section 7**).

4.2.3 Subsidence Reduction Potential of Massive Sandstone Units

The Subsidence Reduction Potential (SRP) of an overburden is related to the presence of strong, thickly bedded strata and refers to the potential reduction in subsidence due to the overburden being able to either 'bridge' across an extracted longwall panel or have a greater bulking volume when it collapses into the panel void (if close enough to seam level). The term was defined in an **ACARP, 2003** study into this phenomenon and is common in NSW Coalfields were massive sandstone and conglomerate stratigraphy exists.

The overburden above the Springvale and Angus Place Mine Extension Project Areas has massive sandstone units, such as the Banks Wall and Burra-Moko Head Sandstone Units, that have the capacity to span over the proposed longwall panels and reduce subsidence (i.e. 'High' to 'Moderate' SRP). Longwall panels in other coalfields with similar geometries that do not have massive strata present, tend to have higher subsidence and lower SRP (i.e. 'Low' SRP).

A comprehensive review of the measured subsidence and predictions for LWs 1 and 401 to 415 is presented in **DgS, 2012**. The spanning capability of the sandstone units above the current mining area is further demonstrated in the following sub-sections.

4.2.4 Geological Structure

A review of the subsidence results for all of the extracted longwalls at Springvale show significant increases in subsidence (and impact) above the six wider longwalls (LWs 410 to 415) compared to the first ten 265 m wide longwalls (LWs 1 and 401 to 409). The increases are attributed to mining geometry changes and the influence of geological structure (Wolgan and Deanes Creek Lineaments). The interaction of subsidence with rapidly varying topography (plateau and valley formations) has also influenced tilt and strain above all panel geometries.

Palaris, 2013 and **DgS, 2011** has established that there are four types (Type 1 to 4) of geological structure within the Springvale Mining Lease that appear to have had some to no effect on subsidence measurement. A summary of each structure type and its effect on subsidence development is presented below:

- Interpretation work indicates several Major Type 1 faults associated with the Wolgan, Deanes Creek and Kangaroo Creek lineaments. These lineaments (and associated faults) extend over strike lengths of several kilometres, and are associated with variable topography (ranging from incised valleys to plateau areas). Subsidence monitoring indicates that there have been localised subsidence, tilt and compressive strain increases associated with incised valleys. Where Type 1 fault zones are associated with plateau topography, subsidence increases have not been measured.

- Type 2 faulting is similar to Type 1, however, it is not as persistent as Type 1 structure with only limited surface expression (e.g. single sided valleys or steep slopes). Subsidence increase potential above Type 2 Structure is unknown at this stage as they have not yet been undermined by any Springvale longwalls.

- Minor Type 3 faulting commonly exists at seam level but show no surface expression across the mining area (e.g. mildly undulating terrain and plateau areas). Subsidence monitoring indicates that there have been no subsidence effect increases above the Type 3 structure areas.

- Type 4 structures are basement structures only, which, despite being common, do not have structural features associated with these at the Lithgow Seam level or have expression at the surface. No surface subsidence changes have occurred above Type 4 structure.

The location of the geological structure above the current and proposed Springvale and Angus Place Mine Extension Project Areas are shown in **Figures 3b** to **3d**.

The influence of geological structure on height of fracturing development (and future predictions) has been assessed from the extensometer and piezometer data for LWs 409 to 412 collected to-date and is presented in **Section 5**.

4.2.5 Surface and Subsurface Groundwater Aquifers

The groundwater regime has been assessed in **CSIRO, 2007** above LWs 409 to 412 and indicates that the following sub-surface aquifers (AQ1-5) exist above the proposed workings (in ascending order):

- AQ1 - The Lidsdale Seam
- AQ2 - Sandstone, coal and siltstones of the Farmers Creek Formation (includes the Gap Sandstone Member, Middle River and Katoomba Coal Seams)
- AQ3 - Conglomeratic Sandstone in Narrabeen Group's Burra-Moko Head Formation
- AQ4 - Conglomeratic Sandstone in lower Narrabeen Group's Banks Wall Sandstone
- AQ5 - Conglomeratic Sandstone in upper Narrabeen Group's Banks Wall Sandstone

Aquifers AQ1 to AQ4 are defined as confined aquifers with the AQ5 defined as an unconfined aquifer. The Mount York Claystone forms a semi-impermeable aquitard between the AQ4 and AQ5 aquifers, and is approximately 200 m above the Lithgow Seam. There are currently no privately owned groundwater extraction bores in the project areas.

4.3 Subsurface Monitoring Results

The strata and groundwater response to longwall mining at Springvale and Angus Place have been measured with the following devices:

- Two borehole extensometer No.s SPR40 (LW411) and SPR52 (LW412) to measure strata dilation and vertical strain. *Note: A third borehole exto (SPR65) was installed above LW413a; however, it malfunctioned during mining.*
- Four vibrating wire (VW) piezometer No.s SPR32, 39 and 48 above the chain pillars between LWs 411 and 412 and central panel VW piezometer SPR31 above LW409.

The devices consisted of 4 to 8 VW piezometers to measure changes to groundwater pressure heads in the overburden for each longwall.

- Six screened standpipe piezometers (known as the Ridge Piezometers No.s RNW, REN, SSE, RSS and RCW) to measure changes to water table levels before and after mining impacts.

- Micro-seismic event monitoring was undertaken by CSIRO in 2010 at the southern end of LW413b in five boreholes on a 400 m grid spacing. The geophones were located at depths from 100 m to 415 m (refer to **CSIRO, 2011** for details).

The locations of the extensometer and piezometric monitoring points above the completed Angus Place and Springvale Mine longwalls are shown in **Figure 1a**.

4.3.1 Borehole Extensometer data for LWs 411 and 412

Two multi-anchor borehole extensometers, SPR40 and SPR52, were installed above LWs 411 and 412 respectively prior to mining.

Several reviews of the extensometer data have been completed in **Aurecon, 2009**, **CSIRO, 2007** and **CSIRO, 2008**. All of the reviews have identified three distinct zones of sub-surface fracturing that indicate continuous fracturing between strata units (A-Zone), discontinuous fracturing and strata dilation (B-Zone) and a deformed elastic Zone (C-Zone).

The EWS and M subsidence monitoring lines are the closest lines to the extensometers and indicate the surface above LW411 and 412 has been subsided by 1.25 and 1.33 m respectively.

The strata displacement (relative to the surface), dilation and vertical strains measured between the anchors in SPR40 and SPR52 are summarised in **Tables 3A** and **3B** respectively and shown together graphically in **Figures 4a** to **4c** (SPR40) and **Figures 4d** to **4f** (SPR 52).

Table 3A - Extensometer Data Summary for SPR40

Anchor No.	Depth z (m)	Height above LWs y (m)	Mid-Height y_m (m)	Anchor RL (AHD)	Anchor Displacement Relative to Surface (mm)		Strata Dilation (mm)		Vertical Strain (mm/m)		HoF Zone*
					7/01/2008 (LW411)	27/03/2009 (LW412)	411	412	411	412	
Surface	0	368	-	1129	-	-	-	-	-	-	D
20	40	328		1089	0	0	-	-	-	-	C
19	51	317	322.5	1078	9	9	9	9	1	1	C
18	62	306	311.5	1067	51	51	41	42	4	4	C
17	73	295	300.5	1056	56	51	5	0	0	0	C
16	84	284	289.5	1045	23	105	-32	54	-3	5	B
15	95	273	278.5	1034	112	95	89	-10	8	-1	B
14	106	262	267.5	1023	87	60	-26	-35	-2	-3	B
13	118	250	256	1011	220	174	134	115	11	10	B
12	129	239	244.5	1000	417	362	197	187	18	17	B
11	140	228	233.5	989	516	461	99	100	9	9	B
10	151	217	222.5	978	543	500	26	39	2	4	B
9	170	198	207.5	959	745	699	202	199	11	10	B
8	200	168	183	929	1044	990	300	291	10	10	B
7a	*234*	*139*	*153.5*	*895*	*1454*	*1400*	*410*	*410*	*12*	*12*	*B*
7	268	100	119.5	861	2842	2841	1388	1441	41	42	A
6	280	88	94	849	2848	2847	6	6	0	0	A
5	294	74	81	835	2863	2861	15	14	1	1	A
4	310	58	66	819	2842	2840	-21	-21	-1	-1	A
3	339	29	43.5	790	2725	2653	-117	-187	-4	-6	A
2	353	15	22	776	2848	2847	123	194	9	14	A
1	365	3	9	764	3000	3000	152	153	13	13	A

shading - Interpreted subsurface fracture zone; * - Height of Fracturing Zone definitions in **Attachment A**; *italics* - interpolated result based on borehole data for SPR40.

The measured heights of fracturing for the A-Zone and B-horizons in SPR40 were estimated to be 139 m and 288 m above the longwalls. The horizons were based on the anchor displacements in SPR40 and the response of piezometric data in SPR39 (see **Section 4.3.7**).

Reference to the lithology log for SPR39 indicates that the A-Zone horizon is coincident with the base of Caley Formation Sandstone unit, which together with the overlying Burra-Moko Head Sandstone Formation is approximately 51 m thick.

The anchors in the A-Zone were displaced vertically by 2842 to 3000 mm by the collapsing strata, and represents ~90% of the mining height. The maximum vertical strain between the anchors was 42 mm/m with goaf consolidation resulting in the development of several zones of compressive strain after subsidence was fully developed.

The strata in the B-Zone were displaced between 60 and 1454 mm, or 2% to 45% of the mining height. The strata were dilated between 39 and 410 mm with vertical strains from 4 to 17 mm/m.

The strata in the C-Zone were displaced between 9 and 54 mm, or 0.3% to 1.7% of the mining height. The strata were dilated between 0 mm and 52 mm with vertical strains between 0 and 4 mm/m.

Table 3B - Extensometer Data Summary for SPR 52

Anchor No.	Depth z (m)	Height above LWs y (m)	Mid-Height y_m (m)	Anchor RL (AHD)	Anchor Displacement Relative to Surface (mm)		Strata Dilation (mm)		Vertical Strain (mm/m)		HoF Zone*
					LW412 (19/06/09)	LW413 (13/04/11)	412	413	412	413	
Surface	0	400	-	1165.2	-	-	-	-	-	-	D
20	20	380	390	1145.2	3	3	-	-	-	-	C
19	40	360	370	1125.2	23	23	20	20	1	1	C
18	55	345	352.5	1110.2	30	30	7	7	0	0	C
17	62	338	341.5	1103.2	63	63	33	33	5	5	C
16	65	335	336.5	1100.2	47	47	-16	-16	-5	-5	C
15	75	325	330	1090.2	61	80	14	33	1	3	C
14	85	315	320	1080.2	102	102	41	22	4	2	C
13	100	300	307.5	1065.2	130	130	28	28	2	2	C
12	120	280	290	1045.2	293	293	163	163	8	8	B
11	140	260	270	1025.2	431	431	138	138	7	7	B
10	160	240	250	1005.2	516	516	85	85	4	4	B
9	180	220	230	985.2	1021	1021	505	505	25	25	B
8	220	180	200	945.2	1023	1023	2	2	0.1	0.1	B
7	255	145	162.5	910.2	1255	1255	232	232	7	7	B
6	292	108	126.5	873.2	2826	2826	1571	1571	42	42	A
5	330	70	89	835.2	3000	3000	174	174	5	5	A
4	362	38	54	803.2	3000	3000	0	0	0	0	A
3	380	20	29	785.2	3000	3000	0	0	0	0	A
2	384	16	18	781.2	3000	3000	0	0	0	0	A
1	394	6	11	771.2	3000	3000	0	0	0	0	A

shading - Interpreted subsurface fracture zone;* - Height of Fracturing Zone definitions in **Attachment A**; *italics* - interpolated result based on borehole data for SPR40.

The measured heights of fracturing for the A-Zone and B-horizons in SPR52 were estimated to be 145 m and 300 m above the longwalls. The horizons were based on the anchor displacements in SPR52 and the response of piezometric data in SPR31 and SPR48 (see **Section 4.3.7**).

Reference to the lithology log for SPR32 indicates that the A-Zone horizon is coincident with the base of Caley Formation Sandstone unit, which together with the overlying Burra-Moko Head Sandstone Formation is approximately 55 m thick.

The anchors in the A-Zone were displaced vertically by 2826 to 3000 mm by the collapsing strata, and represents ~90% of the mining height. The maximum vertical strain between the anchors was 42 mm/m after subsidence had fully developed.

The strata in the B-Zone were displaced between 293 and 1255 m, or 9% to 39% of the mining height. The strata were dilated between 2 and 505 mm with vertical strains ranging from 4 to 25 mm/m.

The strata in the C-Zone were displaced between 3 and 130 mm, or 0.1% to 4% of the mining height. The strata were dilated between 7 and 33 mm with vertical strains between 0 and 5 mm/m.

4.3.2 Piezometric Response to LW409

Eight Vibrating Wire Piezometers (VWPs) were installed in Borehole SPR31, which was located in the middle of LW409. The effects of undermining on the groundwater regime is presented in **Figure 5a** and summarised in **Table 4A**.

Table 4A - Summary of Piezometer Pressure Head Changes in SPR31 above LW409

Piezo #	Piezo Depth z (m)	Piezo Height above LWs y (m)	Piezo RL (AHD)	Pressure Head (m)			HoF Zone*
				Pre-Mining	Post-Mining	Change	
Surface	0	385	1168.2				
8	90	295	1078.2	8	10	2	C
7	173	212	995.2	91	58	-33	B
6	293	92	875.2	213	64	-149	A
5	305	80	863.2	227	74	-153	A
4	360	25	808.2	283	73	-210	A
3	380	5	788.2	302	61	-248	A
2	384	1	784.2	309	59	-250	A
1	393	-8	778.2	321	35	-286	A

* - Height of Fracturing Zone definitions in **Attachment A.**

The results indicate groundwater pressure head drops in the A Zone ranging from 149 m to 286 m during the relatively short monitoring period between 2nd and 5th December, 2003. The top two piezos were considered to be located in the B-Zone and C-Zones with pressure head changes of -33 m and +2 m respectively. As there were no extensometer data to correlate the piezometer response to the interpreted fracture zones, the results presented should be viewed with caution at this stage until more recent readings can be obtained.

4.3.3 Piezometric Response to LW411 and 412 (SPR39)

Nine Vibrating Wire Piezometers (VWPs) were installed in Borehole SPR39, which was located above the chain pillars between LW411 and 412. The effects of undermining on the groundwater regime is presented in **Figure 5b** and summarised in **Table 4B**.

Emergency mine water discharges (EMWDs) were released along East Wolgan Creek during the period from March 2008 through to February 2009. The response of the piezometers in borehole SPR39 to mining effects and EMWDs in 2009 have enabled the heights of fracturing zones to be confidently defined. The depth of fault dilation due to interaction with LW411 and 412 subsidence deformations was also able to be determined from the piezometer responses.

The piezometer and EMWD flow data has been previously presented in **Aurecon, 2009**.

Table 4B - Summary of Piezometer Pressure Head Changes in SPR39 between LW411 & 412

Piezo #	Piezo Depth z (m)	Piezo Height above LWs y (m)	Piezo RL (AHD)	Pressure Head (m) Pre-Mining	Total Pressure Head Change (m)		HoF Zone*
					LW411	LW412 (EMWDs)	
Surface	0	378	1135	-	-		D
9	50	328	1085.6	-0.84	-1.3	-1.3	C
8	80	298	1055.6	36.75	-36.0	-39.5	B
7	140	238	995.6	50.31	-46.5	**-38.4**	B
6	155	223	980.6	58.71	-51.4	**-44.6**	B
5	240	138	895.6	63.72	-52.3	**-18.9**	B
4	270	108	865.6	33.27	-25.9	*-28.6*	A
3	340	38	795.6	33.38	*-30.3*	*-30.3*	A
2	374	4	761.5	15.90	*-17.5*	*-17.5*	A
1	380	-2	755.9	8.60	*-8.2*	*-8.2*	A

* - Height of Fracturing Zone definitions in **Attachment A**;
italics - reading prior to loss of instrument due to bedding shear or excessive strata dilation.
bold - pressure head partially recovered during EMWDs.

Piezo's 5-8 (SPR39) demonstrates that the water is being stored in the dilated strata and not draining into the A-Zone. These four piezos also clearly indicate that the groundwater in the Banks Wall and Burra Moko-Head Units (B / C Zones) are connected by a network of jointing, however, compressive strains due to natural or voussoir arching above panels also appear to have reduced the vertical rock mass permeability between dilated bedding partings and the recovery rates of groundwater levels in the upper strata.

The increase in pressure head above Piezos 5-8 during the EWMDs is the strongest evidence that surface waters were being stored in the B and C-Zones and then compressed by strata consolidation (see exto data in **Section 4.3.1**). Drops in pressure are coincident with dilation in the sagging strata as 411 and 412 passed beneath the instruments. The lag time of ~ 1 week between discharge dates and piezo response also indicates the pooling of groundwater higher up in the strata has increased the pressure at the piezos below the point of groundwater entry only.

Piezo's 5-7 (SPR39) also indicate that it is very unlikely that the fault dilation has extended to depths > 240 m due to the pressure head increases observed. It is considered that the fault is probably open near the surface and has allowed water to move deeper into the strata than it normally would have. **Aurecon, 2009** has estimated that the discharge waters may have reached a depth of 80 m below the creek, which coincides with Piezo No. 8.

4.3.4 Piezometric Response to LW411 and 412 (SPR32)

Four Vibrating Wire Piezometers (VWPs) were installed in Borehole SPR32, which was also located above the chain pillars between LW411 and 412 and 690 m south of SPR39. The effects of undermining on the groundwater regime after the mining of both panels is presented in **Figure 5c** and summarised in **Table 4C**.

Table 4C - Summary of Piezometer Pressure Head Changes in SPR32 between LW411 & 412

Piezo #	Piezo Depth z (m)	Piezo Height above LWs y (m)	Piezo RL (AHD)	Pressure Head (m) Pre-Mining	Pressure Head (m) Post-Mining	Total Pressure Head Change (m)	HoF Zone*
Surface	0	395	1162.6	-	-	-	D
1	30	365	1132.6	2.5	-1.8	-4.3	C
2	170	225	992.6	85.7	21.1	*-64.6*	A
3	320	75	842.6	103.5	45.2	*-58.3*	A
4	344	51	818.6	132.0	74.3	*-57.7*	A

italics - last reading before instrument sheared off by strata movements.

The results indicate groundwater pressure head drops ranging from 4.3 m to 64.6 m during the monitoring period between August 2004 and March 2009. The bottom three piezos were sheared off by strata displacements and considered to be in the A Zone. The interpreted zones are correlated with the exto data in **Section 4.3.7**.

4.3.5 Piezometric Response to LW412 and 413 (SPR48)

Eight Vibrating Wire Piezometers (VWPs) were installed in Borehole SPR48, which was located above the chain pillars between LW412 and 413 and adjacent to SPR52. The effects of undermining on the groundwater regime after the mining of both panels is presented in **Figure 5d** and summarised in **Table 4D**.

Table 4D - Summary of Piezometer Pressure Head Changes in SPR48 between LW412 & 413

Piezo #	Piezo Depth z (m)	Piezo Height above LWs y (m)	Piezo RL (AHD)	Pressure Head (m) Pre-Mining	Pressure Head (m) Post-Mining	Total Pressure Head Change (m)	HoF Zone*
Surface	0	395	1167	-	-	-	D
8	30	365	1137	2.5	0.0	-2.4	C
7	50	345	1117	3.4	2.2	-1.2	C
6	70	325	1097	17.1	13.5	-3.6	C
5	90	305	1077	14.8	7.2	-7.6	B
4	110	285	1057	34.2	12.3	-21.8	B
3	140	255	1027	58.1	14.0	*-44.2*	B
2	170	225	997	39.8	10.2	*-29.6*	B
1	200	195	967	36.3	7.5	*-28.8*	B

italics - last reading before instrument sheared off by strata movements.

The results indicate groundwater pressure head drops ranging from 1.2 m to 3.6 m in the C-Zone and from 7.6 m to 44.2 m in the B-Zone during the monitoring period between March 2008 and May 2009. The bottom three piezos were sheared off by strata displacements, but still considered to be in the B-Zone based on extensometer results (SPR52). The interpreted zones are correlated with the exto data in **Section 4.3.7**.

4.3.6 Standpipe (Ridge) Piezometers

Five standpipe piezometers to 70 m depth were installed above Angus Place and Springvale Mines. The locations of the piezometers are shown on **Figure 1a**.

The purpose of the standpipes were to monitor the water table during mining. The results are summarised in **Table 4E** and **Figure 5e**.

Table 4E - Summary of Ridge Piezometers and Mining Geometry

Piezometer No.	LW	Surface RL	Piezo Depth (m)	Maximum Observed Post-Mining Depth to Water Table (m)	Date	Latest Observed Post-Mining Depth to Water Table (m)	Date
RNW	950	1158	57	56.05	27/09/10	51.90	22/7/13
REN	950	1151	56	55.05	07/08/11	51.13	22/7/13
RSE	412	1150	51	50.50	27/05/13	50.30	22/7/13
RSS	415	1157	36	32.38	29/05/07	27.60	22/7/13
RCW	420	1098	32	27.41	29/05/07	24.67	22/7/13

The results indicate that the groundwater table during the monitoring period has responded to the change in cumulative rainfall deficit and had not been affected by longwall mining up to the last readings.

4.3.7 Interpreted Sub-Surface Fracture Zone Summary

The borehole and extensometer results have been compared with mining geometry and overburden lithology at the Springvale Mine in **Figures 6a** (LW409), **6b** (LWs 411 and 412) and **6c** (LWs 412 and 413).

The predicted mean and Upper 95% Confidence Limits for the A and B-Zone have been determined using the Geometry and Geology Pi-Term Models and have been estimated for comparison with the interpreted fracture zones. The comparison summary and prediction methodology is described in **Section 5**.

4.3.8 Micro-Seismic Data

Microseismic monitoring data for Springvale Mine's LW413 was undertaken in five boreholes with eight triaxial geophones (**CSIRO, 2011**). The depth of cover was 410 m and the panel width was 315 m to give a *sub-critical* W/H of 0.77.

More than 100,000 micro-seismic events were recorded that ranged from strong shear wave events (indicating structural feature slip or rock mass shear failures in compression) to weaker ones (indicating tensile failures and bedding slip). The majority of events occurred between 70 m and 120 m above the Lithgow Seam as shown in **Figure 7**.

It was assessed that the majority of strong events were due to the crushing of the Katoomba Seam coal under abutment loading conditions and movements on domain boundaries or lineaments. Strong shearing events or compression failures also occurred in the Caley Formation sandstone and siltstone beds. The frequency of strong events peaked at 35 between 85 m and 90 m above the seam with >10 events occurring within the above mentioned boundary limits.

The results correlate well with the interpreted heights of the A-Zone, which ranged from 139 m to 145 m above LWs 411 and 412. The previous assessment that the upper Caley Formation sandstone and Burra-Moko Head Sandstone are spanning across the A-Zone (and therefore within the B-Zone) appears to be correct. It is also noted that the thickness of the sandstone units immediately above the A-Zone is approximately 55 m thick.

A lower frequency of seismic events (between 1 and 10/5m distance) occurred up to the Mount York Claystone at a distance of 200 m above the Lithgow Seam. It is considered that these events are associated with bedding shear and dilating strata movements. Only one event was recorded in the Banks Wall Sandstone at a distance of 343 m above the Lithgow Seam.

5.0 Height of Fracturing Prediction Models

5.1 DgS, 2014 Geometry Pi-Term Model

The model was developed in 2013-14 in response to several Planning and Assessment Committees (PACs) reports and general industry concerns in regards to large apparent differences between established prediction methods that use only one parameter in a particular coalfield (e.g. the mining height v. panel void width models).

The Geometry Pi-term model considers the influence of the panel width, cover depth and mining height on the height of continuous fracturing above a longwall panel. A dimensionally consistent product and power rule has been derived using non-linear regression analysis of measured cases in the NSW Coalfields. The model considers the key mining geometries and indirectly includes the influence of a wide range of geological conditions; see **Attachment A**.

The Pi-terms have been derived (by experiment) using Buckingham's Pi-Term theorem and refer to the dimensionless ratios of key independent variables with a repeating variable of influence (the panel width) as follows:

$\underline{\text{Mean } A/W' = 2.215\,(H/W')^{0.271}(T/W')^{0.372}}$ $R^2 = 0.61$ & rmse= 0.12W'(21%)

$\underline{\text{U95\%CL } A/W' = \text{Mean } A/W' + a}$

where a = 0.16, 0.16 - 0.086(W/H-0.7) and 0.1 for sub-critical, critical & supercritical panels

H = cover depth = maximum potential goaf load height.

W' = effective panel width = minimum of W and 1.4H.

T = mining height.

Re-arranging the above equation in terms of A gives:

$\underline{A = 2.215W'^{0.357}H^{0.271}T^{0.372}}$ +/- aW'

Note: The dimensions & powers on both sides of the equation are consistent.

For estimating the height of the dilated B-Zone using the Geometry Pi-Term Model:

$\underline{\text{Mean } B/W' = 1.621\,(H/W')^{0.55}(T/W')^{0.175}}$ R^2 = 0.86 & rsme = 0.12W'(13%)

$\underline{\text{U95\% } B/W' = \text{Mean } B/W' + b}$

where b = 0.16, 0.16 - 0.086(W/H - 0.7) and 0.1 for sub-critical, critical & supercritical panels.

Re-arranging the above equation gives $\underline{B = 1.621\, W'^{0.275}H^{0.55}T^{0.175}}$ +/- bW'

5.2 DgS, 2014 Geology Pi-Term Model

Further to the Geometry Model, the Pi-term Geology model also considers the influence of the effective strata unit thickness (t') on the A-Zone fracture height development. The effective strata unit thickness refers to the thickness of the beam in the B-Zone that spans the continuous fracture zones above a longwall panel. Using a product and power rule and non-linear regression analysis of measured cases, the range of 'effective beam thicknesses' for a given mining geometry was derived for the NSW Coalfields; see *Figure A42e in* **Attachment A**.

The pi-terms have also been derived (by experiment) using Buckingham's Pi-term theorem and refer to the dimensionless ratios of key independent variables with a repeating variable of influence (the panel width) as follows:

$\underline{\text{Mean } A/W' = 1.52\,(H/W')^{0.535}(T/W')^{0.464}(t'/W')^{-0.4}}$ $R^2 = 0.8$ & rmse = 0.09W'(15%)

$\underline{\text{U95\%CL } A/W' = \text{Mean } A/W' + a}$

where a = 0.15, 0.15 - 0.12(W/H-0.7) and 0.1 for subcritical, critical and supercritical panels.

H = cover depth = maximum potential goaf load height.

W' = effective panel width = minimum of W and 1.4H.

T = mining height.

t' = effective strata unit thickness in the strata above the A-Zone (see *Section A11.4.4* in **Attachment A**) at Springvale and Angus Place Collieries = 42 m, which has been back-analyzed from the measured heights of fracturing and borehole stratigraphy.

Re-arranging the above equation gives $\underline{A = 1.52W'^{0.4}H^{0.535}T^{0.464}t'^{-0.4}}$ +/- aW'

For estimating the height of the dilated B-Zone using the Geology Pi-Term Model:

$\underline{\text{Mean } B/W' = 1.873\,(H/W')^{0.635}(T/W')^{0.257}(t'/W')^{-0.097}}$ $R^2 = 0.86$ & rmse = 0.13W'(15%)

$\underline{\text{U95\% } B/W' = \text{Mean } B/W' + b}$

where b = 0.15, 0.15 - 0.12(W/H - 0.7) and 0.1 for subcritical, critical & supercritical panels.

Re-arranging the above equation gives $\underline{B = 1.873\,W'^{0.205}H^{0.635}T^{0.257}t'^{-0.097}}$ +/- bW'

5.3 Difference between Geometry and Geology Pi-Term Models

It is considered that the Geology Pi-term model is superior to the Geometry Pi-term model as it may be calibrated to local height of A-Zone fracture height measurements.

The Geology Pi-term model is calibrated to the measured values by adjusting the effective strata thickness until the predicted mean values for the model match the measured values above known mining geometry. The U95%CL values then provide an additional factor of safety to allow for natural variation within the database.

The Geometry Pi-Term model uses only the proposed mining geometry and cannot be calibrated to geology data directly. The effect of geological conditions across the database will therefore be ‘averaged’ and may therefore result in the predictions at a particular site being more or less conservative.

Overall, both the models are likely to provide conservative predictions if massive strata is present in the overburden with the capability to span the goaf and ‘truncate’ the A-Zone heights. As discussed earlier, it is assessed that the Springvale and Angus Place Mine extension Project Areas have several massive sandstone strata units (Upper Caley, Burra Moko-Head and Banks Wall Sandstone) above the Katoomba Seam that could span the continuous fracture zones above the proposed 260 m to 315 m wide panels.

Further details of A-Zone and B-Zone height prediction model development are provided in **Attachment A**.

6.0 Calibration and Validation of Pi-Term Models

The subsurface fracture zone predictions above LWs 409, 411 and 412 are summarised in **Tables 6A** (Geology Pi-Term Model) and **6B** (Geometry Pi-Term Model) with measured values derived from the borehole extensometer and VWP data.

Table 6A - Measured v. Predicted Height of Fracturing Review Summary for Springvale Mine's LW 409, 411 & 413 based on the Geology Pi-Term Model

Panel	Panel Width W (m)	Cover Depth	Mining Height T (m)	Effective Strata Thickness t'	Predicted A-Zone Horizon above Mine Workings Roof* (m)	Measured A-Zone Horizon above Mine Workings Roof (m)	Predicted B-Zone Horizon above Mine Workings Roof* (m)	Measured B-Zone Horizon above Mine Workings Roof (m)
409	265	385	3.25	42	133 - 172	**133**	243 - 296	**254**
411	315	368	3.25	42	139 - 182	**139**	244 - 300	**288**
412	315	400	3.25	42	145 - 190	**145**	258 - 377	**300**

* - Predictions based on Pi-Term model are mean and U95%CL values (i.e. mean + 1.65 standard deviations). The standard deviations are < 25% mean values.
Bold - measured values plot between predicted range.

Table 6B - Measured v. Predicted Height of Fracturing Review Summary for Springvale Mine's LW 409, 411 & 413 based on the Geometry Pi-Term Model

Panel	Panel Width W (m)	Cover Depth	Mining Height T (m)	Predicted A-Zone Horizon above Mine Workings Roof* (m)	Measured A-Zone Horizon above Mine Workings Roof (m)	Predicted B-Zone Horizon above Mine Workings Roof* (m)	Measured B-Zone Horizon above Mine Workings Roof (m)
409	265	385	3.25	120 - 162	**133**	243 - 296	**254**
411	315	368	3.25	126 - 172	**139**	244 - 300	**288**
412	315	400	3.25	129 - 177	**145**	258 - 377	**300**

* - Predictions based on Pi-Term model are mean and U95%CL values (i.e. mean + 1.65 standard deviations). The standard deviations are < 25% mean values.
Bold - measured values plot between predicted range.

The results indicate that the Geology Pi-term model, which has the mean or expected values calibrated to measured values at Springvale, predicts a 10% to 12% higher range of A and B-Zone fracturing than the Geometry Pi-term model. The reason for this is that the Geometry model includes the geological effects of all coalfields/sites within the database and is likely to be biased towards the average conditions across the database. It is recommended that the Geology model results be adopted for future area predictions for the Springvale and Angus Place Mine Extension Project Areas.

The Geology Pi-term model predictions have been plotted with the measured results in **Figures 6a** to **6c**.

7.0 Predicted Sub-surface Fracture Zones for Proposed Mining Areas

7.1 Springvale Mine's LWs 415 to 423

The predicted A-Zone and B-Zone fracture heights above the proposed Springvale longwalls LW415 to 423 and Ridge Piezometers (RNW, REN, RSE, RSS & RCW) are summarised in **Tables 7A**.

Table 7A - Predicted Height of Fracturing Summary for Springvale Mine's LW 415 to 423 based on Geology and Geometry Pi-Term Models

Panel	Panel Width W (m)	Cover Depth H (m)	Mining Height T (m)	Effective Strata Thickness t' (m)	Predicted Geology Model A-Zone Horizon above Mine Workings Roof* (m)		Predicted Geometry Model A-Zone Horizon above Mine Workings Roof* (m)		Predicted Geology Model B-Zone Horizon above Mine Workings Roof* (m)		Predicted Geometry Model B-Zone Horizon above Mine Workings Roof* (m)	
					mean	U95%	mean	U95%	mean	U95%	mean	U95%
415	315	400	3.25	42	145	190	136	184	258	303	262	310
	315	420	3.25	42	149	195	138	187	266	312	269	318
416 - 423	265	340	3.25	42	124	162	122	163	224	263	228	269
	265	350	3.25	42	126	165	123	164	228	267	232	273
	265	360	3.25	42	128	167	124	166	233	272	235	277
	265	380	3.25	42	132	171	126	168	241	280	242	285
	265	400	3.25	42	135	175	128	170	249	288	249	292
	265	420	3.25	42	139	179	129	172	257	296	256	299
RNW (LW950)	293	368	3.25	42	135	177	129	174	241	283	245	289
REN (LW950)	293	372	3.25	42	136	178	130	174	242	285	246	291
RSE (LW411)	315	360	3.25	42	137	180	132	178	241	284	247	293
RSS (LW415)	315	413	3.25	42	148	193	137	186	263	309	266	315
RCW (LW420)	260	380	3.25	42	131	170	125	167	240	279	241	283

* - Predictions are mean - U95%CL values; shaded - Preferred predictions.

The predictions for the A-Zone Heights are shown graphically in **Figures 8a** to **8c**.

The predictions indicate that the A-Zone is likely to occur up to the Upper Caley Sandstone with the B-Zone developing in the Burra-Moko Head and Banks Walls Sandstone. The Upper 95%CL A and B-Zones are contained within the above units.

7.2 Springvale Mine Extension Area LWs 424 to 432 and 501 to 503

The predicted A-Zone and B-Zone fracture heights above the proposed Springvale Mine Extension Area LWs 424 to 432 and 501 to 503 are summarised in **Tables 7B**.

Table 7B - Predicted Height of Fracturing Summary for the Springvale Mine Extension Area LWs 424 to 432 and 501 to 503 based on Geology and Geometry Pi-Term Models

Panel	Panel Width W (m)	Cover Depth H (m)	Mining Height T (m)	Effective Strata Thickness t' (m)	Predicted Geology Model A-Zone Horizon above Mine Workings Roof* (m)		Predicted Geometry Model A-Zone Horizon above Mine Workings Roof* (m)		Predicted Geology Model B-Zone Horizon above Mine Workings Roof* (m)		Predicted Geometry Model B-Zone Horizon above Mine Workings Roof* (m)	
					mean	U95%	mean	U95%	mean	U95%	mean	U95%
424 - 431	260.9	290	3.25	42	113	149	116	154	202	238	208	245
	260.9	310	3.25	42	117	154	118	157	211	247	216	254
	260.9	330	3.25	42	121	159	121	160	219	257	223	263
	260.9	350	3.25	42	125	164	122	163	228	266	231	271
	260.9	370	3.25	42	129	168	124	166	236	275	238	280
	260.9	390	3.25	42	133	172	126	168	244	283	245	287
	260.9	410	3.25	42	136	175	128	170	252	291	252	293
	260.9	415	3.25	42	137	176	128	170	254	293	253	295
432	229	270	3.25	42	103	135	109	143	188	220	193	227
	229	290	3.25	42	107	140	111	146	197	230	201	236
	229	310	3.25	42	111	145	113	149	205	239	208	244
	229	330	3.25	42	115	150	115	152	214	248	216	252
	229	350	3.25	42	119	153	117	154	222	256	223	259
	229	370	3.25	42	122	157	119	155	230	264	230	266
	229	390	3.25	42	126	160	120	157	238	272	236	273
	229	405	3.25	42	129	163	122	158	243	278	241	278
501	260.9	180	3.25	42	87	112	101	126	148	173	159	184
	260.9	200	3.25	42	93	121	105	134	160	188	170	198
	260.9	220	3.25	42	98	128	108	139	170	200	179	210
	260.9	240	3.25	42	102	134	111	144	179	211	188	221
	260.9	260	3.25	42	107	140	113	148	189	222	196	231
	260.9	280	3.25	42	111	146	115	152	198	232	204	241
	260.9	300	3.25	42	115	151	117	155	207	243	212	250
	260.9	325	3.25	42	120	158	120	159	217	255	222	261
502-503	243.4	180	3.25	42	85	111	100	125	147	172	157	182
	243.4	200	3.25	42	90	118	103	131	157	185	166	195
	243.4	220	3.25	42	95	124	105	136	167	197	175	206
	243.4	240	3.25	42	100	131	108	140	177	208	184	216
	243.4	260	3.25	42	104	136	110	144	186	218	192	226
	243.4	280	3.25	42	108	142	112	148	195	228	200	236
	243.4	300	3.25	42	112	147	115	151	204	238	208	245
	243.4	310	3.25	42	114	149	116	153	208	243	212	249

* - Predictions are mean - U95%CL values; shaded - Preferred predictions.

The predictions for the A-Zone Heights are shown graphically in **Figure 9a** to **9e**.

The predictions indicate that the A-Zone is likely to occur up to the Upper Caley Sandstone with the B-Zone developing in the Burra-Moko Head and Banks Walls Sandstone. The Upper 95%CL A and B-Zones are contained within the above units.

7.3 Angus Place Mine Extension Area LWs 1001 to 1019

The predicted A-Zone and B-Zone fracture heights above the proposed Angus Place Mine Extension Area longwalls 1001 to 1019 are summarised in **Tables 7C**.

Table 7C - Predicted Height of Fracturing Summary for Angus Place Mine Extension Area LWs 415 to 423 based on Geology and Geometry Pi-Term Models

Panel	Panel Width W (m)	Cover Depth H (m)	Mining Height T (m)	Effective Strata Thickness t'	Predicted Geology Model A-Zone Horizon above Mine Workings Roof* (m)		Predicted Geometry Model A-Zone Horizon above Mine Workings Roof* (m)		Predicted Geology Model B-Zone Horizon above Mine Workings Roof* (m)		Predicted Geometry Model B-Zone Horizon above Mine Workings Roof* (m)	
					mean	U95%	mean	U95%	mean	U95%	mean	U95%
1001 - 1003	293	350	3.25	42	131	172	128	171	233	274	238	282
	293	370	3.25	42	135	177	130	174	242	284	246	290
	293	390	3.25	42	139	182	131	177	250	293	253	298
	293	410	3.25	42	143	186	133	180	258	302	260	306
	293	430	3.25	42	146	190	135	182	266	310	267	314
1004 - 1006, 1016, 1017	261	280	3.25	42	111	146	115	152	198	233	204	241
	261	310	3.25	42	117	154	118	157	211	247	216	254
	261	330	3.25	42	121	159	121	160	219	257	223	263
	261	350	3.25	42	125	164	122	163	228	266	231	272
	261	370	3.25	42	129	168	124	166	236	275	238	280
	261	390	3.25	42	133	172	126	168	244	283	245	287
	261	410	3.25	42	136	175	128	170	252	291	252	294
	261	430	3.25	42	140	179	129	171	260	299	258	300
1007-1015	360	270	3.25	42	124	162	128	166	206	244	219	257
	360	290	3.25	42	129	169	130	172	216	256	227	268
	360	310	3.25	42	133	176	133	176	225	267	236	279
	360	330	3.25	42	138	182	135	181	234	278	244	290
	360	350	3.25	42	142	188	137	185	243	289	252	300
	360	370	3.25	42	147	194	139	189	252	299	260	309
	360	390	3.25	42	151	199	141	192	261	309	267	318
	360	420	3.25	42	157	207	144	197	273	323	279	331

* - Predictions are mean - U95%CL values.

The predictions for the A-Zone Heights are shown graphically in **Figure 10a** to **10d**.

The predictions indicate that the A-Zone is likely to occur up to the Upper Caley Sandstone with the B-Zone developing in the Burra-Moko Head and Banks Walls Sandstone. The Upper 95%CL A and B-Zones are contained within the above units.

8.0 Conclusions and Recommendations

Based on subsurface monitoring of strata displacements, groundwater pressures and microseismic activity, the continuous HoF (A-Zone) has ranged from 133 m to 145 m height above Springvale Mine's LW 409 and 411 to 413 (0.33W to 0.46W; 0.36H to 0.38H; and 41T to 45T). The development of the A-Zone has stopped at a sandstone unit approximately 55 m thick comprising the Upper Caley Sandstone and the Burra-Moko Head Sandstone.

Strata dilation and discontinuous fracturing (the B-Zone) has developed up into the Banks Wall Sandstone for distances ranging from 254 m to 300 m (0.91W to 0.96W; 0.66H to 0.78H; and 78T to 92T). The development of significant pressure head in the B-Zone indicate that the hydraulic connections between the A and B Zones are likely to be limited by compression arching across joints in the rock mass.

The piezometers in Borehole SPR39 also indicate that the Wolgan River Lineament fault dilation that occurred above LW411 has allowed Emergency Mine Water Discharges along East Wolgan Creek to penetrate into the strata to depths between 80 m and 140 m. It is noted by **Aurecon, 2009** that the water pooled within the B-Zone and allowed piezometric pressures to almost recover to pre-mining values. Despite the fault allowing surface waters to move deeper into the strata than they normally would have, the B-Zone has not been 'connected' directly to the A-Zone because of it.

Two sub-surface fracture height models (known as the Geometry and Geology Pi-Term models) have been developed by DgS over the past 12 to 18 months from a broad database of 34 case histories within the NSW Coalfields and two from the Bowen Basin in Queensland. The models include the panel width, cover depth, mining height and in the case of effective strata unit thickness to estimate heights of continuous (A-Zone) and Discontinuous fracturing (B-Zone) horizons.

The Geology Pi-Term model has been calibrated to the measured heights of fracturing using back analysis techniques to determine an effective B-Zone strata unit thickness of 42 m. The t' value correlates well to (i) the 55 m thick sandstone noted in the bore logs above the measured A-Zone heights between 139 m and 145 m and (ii) the minimum inferred beam thickness range of 32 m to 40 m indicated by subsidence data (i.e. twice the Horizontal Strain to Curvature Ratio = the bending beam thickness).

The Geometry only Pi-Term model predicts similar outcomes to the Geology Pi-term model (+/-12%). It is considered the Geology model results are likely to be more reliable of the two models, as it has been calibrated to local strata conditions.

The predicted sub-surface fracture height outcomes for each of the proposed mining layouts based on the Geology Pi-Term Model is summarised below:

Springvale Mine's LWs 415 to 423

- predicted expected (mean) and credible worst-case (U95%CL) heights of continuous fracturing (i.e. the A-Zone) above the 315 m wide longwall panel (LW415) range between 145 m and 195 m (0.46W to 0.61W; 0.36H to 0.46H; and 45T to 60T).

- predicted expected (mean) and credible worst-case (U95%CL) heights of continuous fracturing (i.e. the A-Zone) above the 265 m wide longwall panels range between 124 m and 179 m (0.47W to 0.68W; 0.33H to 0.48H; and 38T to 55T).

- predicted credible worst-case (U95%CL) heights of discontinuous fracturing (i.e. the B-Zone) above all the 315 m wide longwall panels range between 258 m and 312 m (0.62W to 0.99W; 0.65H to 0.74H; and 79T to 96T).

- predicted credible worst-case (U95%CL) heights of discontinuous fracturing (i.e. the B-Zone) above all the 265 m wide longwall panels range between 224 m and 296 m (0.84W to 1.12W; 0.61H to 0.70H; and 69T to 91T).

Springvale Mine Extension Area LWs 424 to 432 and LWs 501 to 503

- predicted expected (mean) and credible worst-case (U95%CL) heights of continuous fracturing (i.e. the A-Zone) above the 229 m to 261 m wide longwall panels range between 85 m and 176 m (0.35W to 0.67W; 0.33H to 0.42H; and 26T to 54T).

- predicted credible worst-case (U95%CL) heights of discontinuous fracturing (i.e. the B-Zone) above all the 229 m to 261 m wide longwall panels range between 147 m and 293 m (0.60W to 1.1W; 0.71H to 0.82H; and 45T to 90T).

Angus Place Mine Extension Area LWs 1001 to 1019

- predicted expected (mean) and credible worst-case (U95%CL) heights of continuous fracturing (i.e. the A-Zone) above the 261 m wide longwall panels range between 111 m and 179 m (0.42W to 0.69W; 0.32H to 0.52H; and 34T to 55T).

- predicted expected (mean) and credible worst-case (U95%CL) heights of continuous fracturing (i.e. the A-Zone) above the 293 m wide longwall panels range between 131 m and 190 m (0.44W to 0.65W; 0.33H to 0.49H; and 40T to 58T).

- predicted expected (mean) and credible worst-case (U95%CL) heights of continuous fracturing (i.e. the A-Zone) above the 360 m wide longwall panels range between 124 m and 207 m (0.34W to 0.58W; 0.37H to 0.6H; and 38T to 64T).

- predicted credible worst-case (U95%CL) heights of discontinuous fracturing (i.e. the B-Zone) above all the 261 m wide longwall panels range between 198 m and 299 m (0.75W to 1.14W; 0.57H to 0.83H; and 61T to 92T).

- predicted credible worst-case (U95%CL) heights of discontinuous fracturing (i.e. the B-Zone) above all the 293 m wide longwall panels range between 233 m and 310 m (0.79W to 0.94W; 0.78H to 0.85H; and 72T to 95T).

- predicted credible worst-case (U95%CL) heights of discontinuous fracturing (i.e. the B-Zone) above all the 360 m wide longwall panels range between 206 m and 323 m (0.57W to 0.90W; 0.65H to 0.90H; and 63T to 99T).

The predictions for the future mining areas indicate that the A-Zone is likely to occur up to the Upper Caley Sandstone and possibly the Burro-Moko Head Sandstone. The Upper 95%CL A and B-Zones are also contained within the above units.

Except for the proposed Springvale Mine Extension Area LWs 501 to 503, the U95% CL for the B-Zone will develop into the Banks Walls Sandstone and is likely to be below the Burralow Formation. The B-Zone above the LWs 501 to 503 may intersect with the Surface Cracking Zone (D-Zone). It is understood however, that there are now surface water or shrub swamp features of significance above these panels.

It is recommended that a subsurface fracturing monitoring program that includes borehole extensometers and groundwater piezometers during the extraction of the panels be implemented with a view to monitor groundwater and surface alluvium response for after single seam and multi-seam mining conditions.

It is understood that the mine also intends to complete an investigation drilling program to establish the existence of the B-Zone. Camera inspections and geophysics logging of dry and wet holes may allow the bedding separation and or shear zones to be detected and allow the measurement of the effective beam thickness development in the B-Zone.

9.0 References

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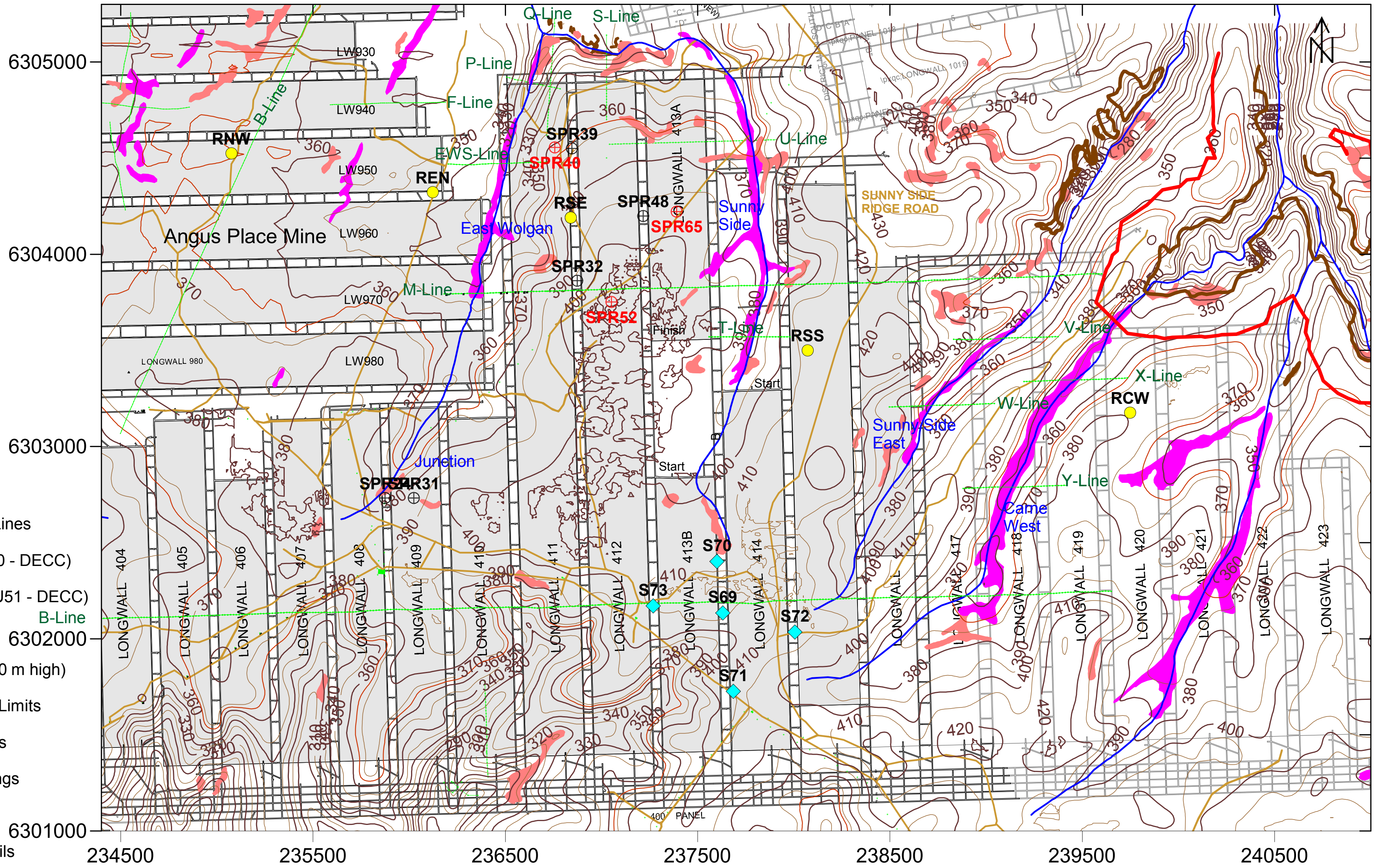
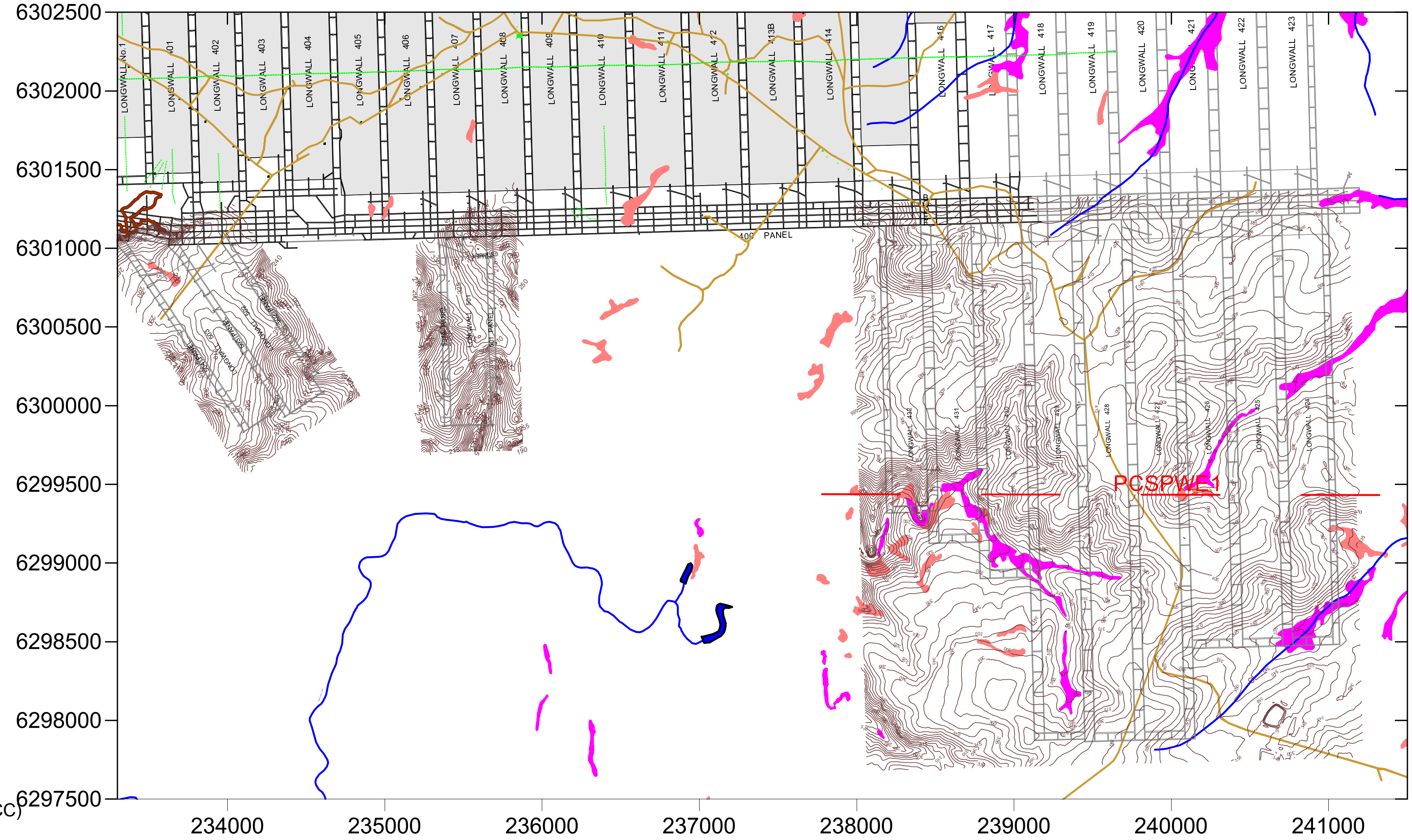


Key

- Cover Depth (m)
- Existing Subsidence Lines
- Shrub Swamps (MU50 - DECC)
- Hanging Swamps (MU51 - DECC)
- Creeks
- Rock Formations (5-20 m high)
- Design Cliff Set Back Limits
- Existing mine workings
- Proposed mine workings
- Extracted longwall
- NSW Forests Fire Trails
- Borehole Extensometer
- Vibrating Wire Piezometer
- Standpipe Piezometer
- Microseismic Geophones

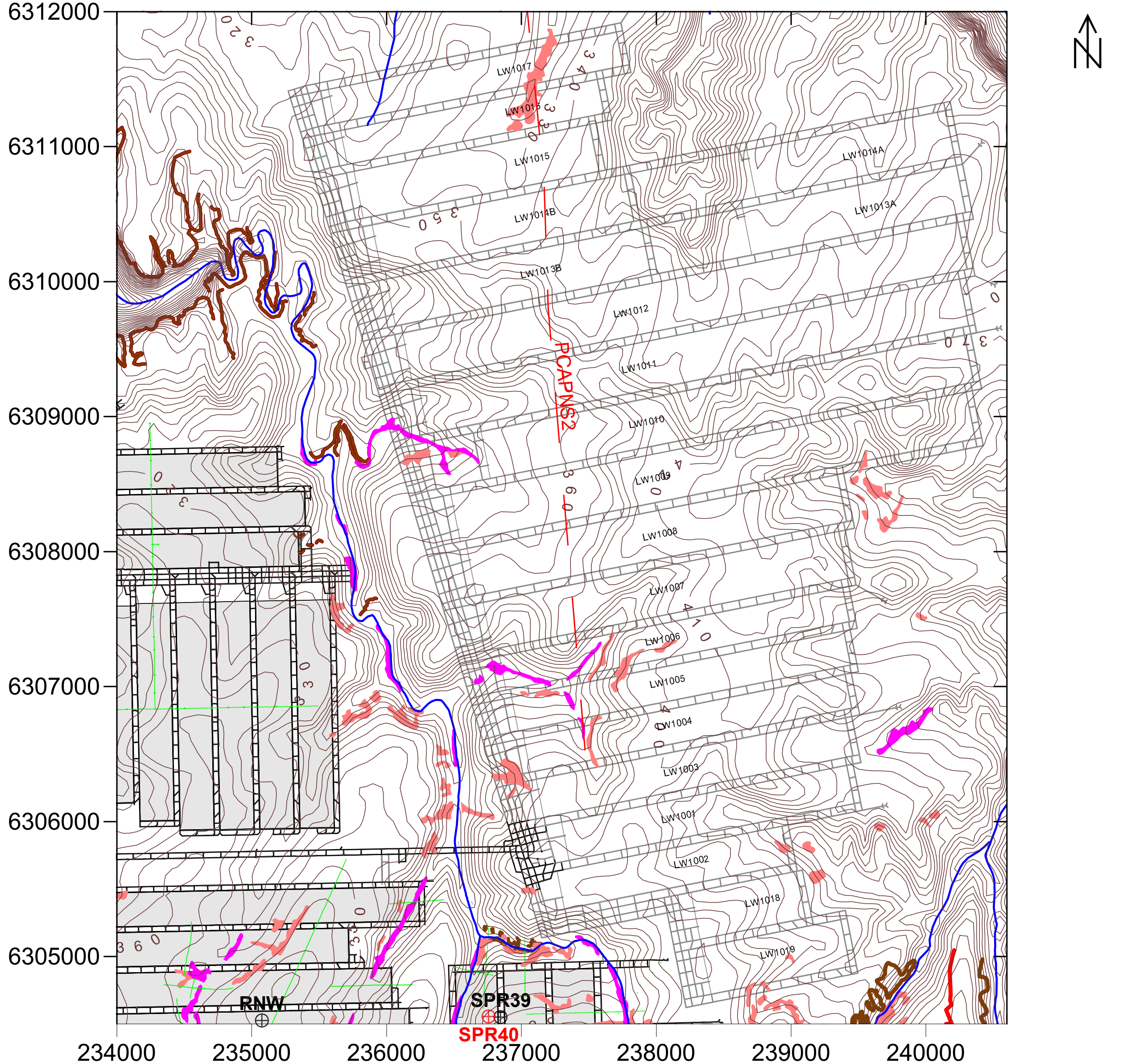
DgS Ditton Geotechnical Services Pty Ltd	Engineer: S.Ditton Drawn: S.Ditton Date: 17.08.14	Client:	Centennial Springvale SPV-003/7b	
		Title:	Cover Depth Contours and Borehole Monitoring Locations above the Springvale Mine Longwalls 404 to 423	
		Scale:	1:30,000	Figure No: 1a



Key

- Cover Depth (m)
- Existing Subsidence Lines
- Shrub Swamps (MU50 - DECC)
- Hanging Swamps (MU51 - DECC)
- Creeks
- Rock Formations (5-20 m high)
- Existing mine workings
- Proposed mine workings
- Extracted longwall
- NSW Forests Fire Trails
- Stratigraphy Cross Section

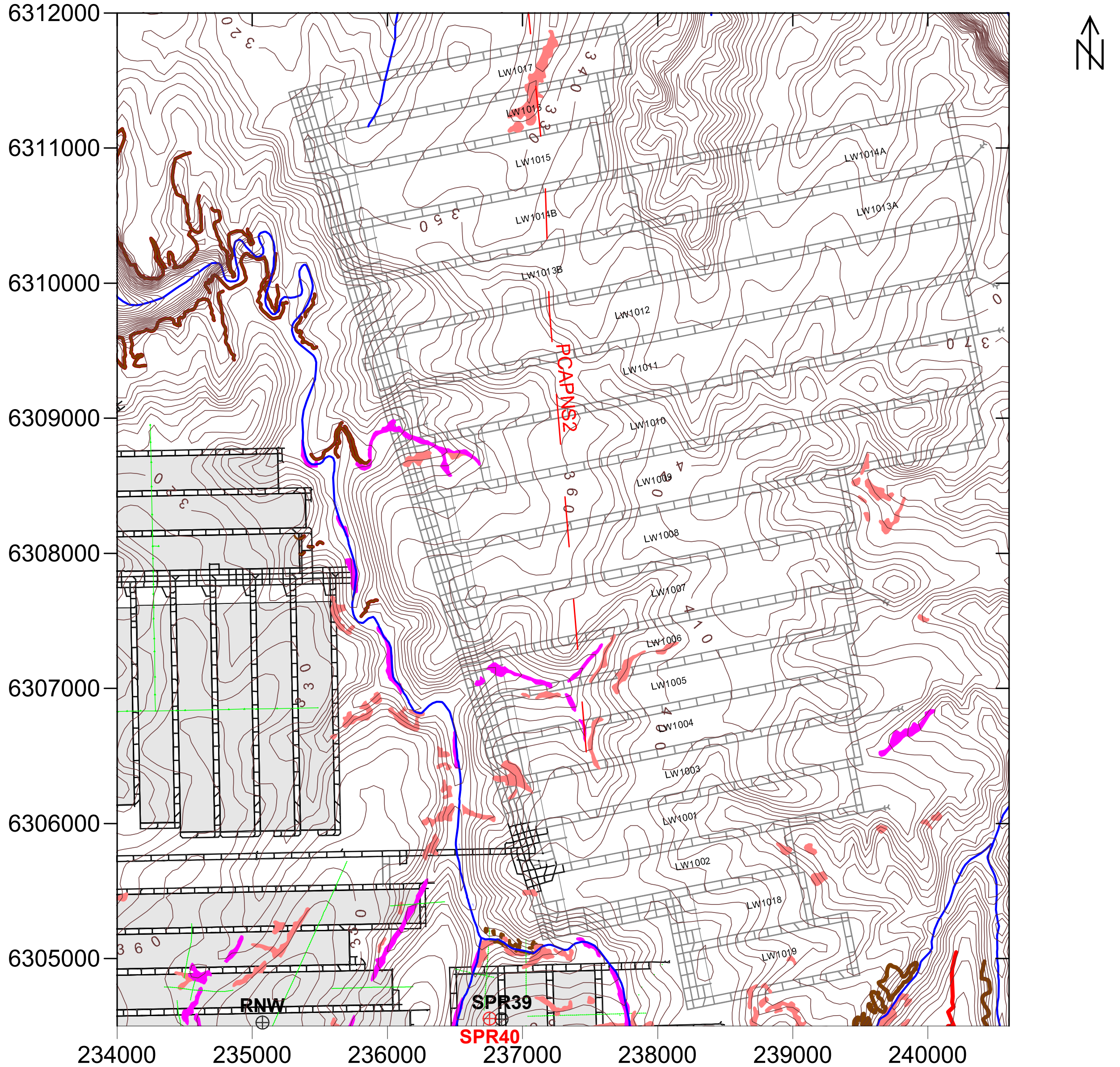
DgS	Engineer:	S.Ditton	Client:	Centennial Springvale SPV-003/7b
	Drawn:	S.Ditton		
	Date:	17.08.14	Title:	Cover Depth Contours above the Proposed Springvale Mine Extension Project Area Longwalls 424 to 432 & 501 to 503
	Ditton Geotechnical Services Pty Ltd			
			Scale:	1:40,000
			Figure No:	1b



Key

- Cover Depth (m)
- Existing Subsidence Lines
- Shrub Swamps (MU50 - DECC)
- Hanging Swamps (MU51 - DECC)
- Creeks
- Rock Formations (5-20 m high)
- Existing mine workings
- Proposed mine workings
- Extracted longwall
- NSW Forests Fire Trails
- Borehole Extensometer or Piezometer
- Stratigraphy Cross Section

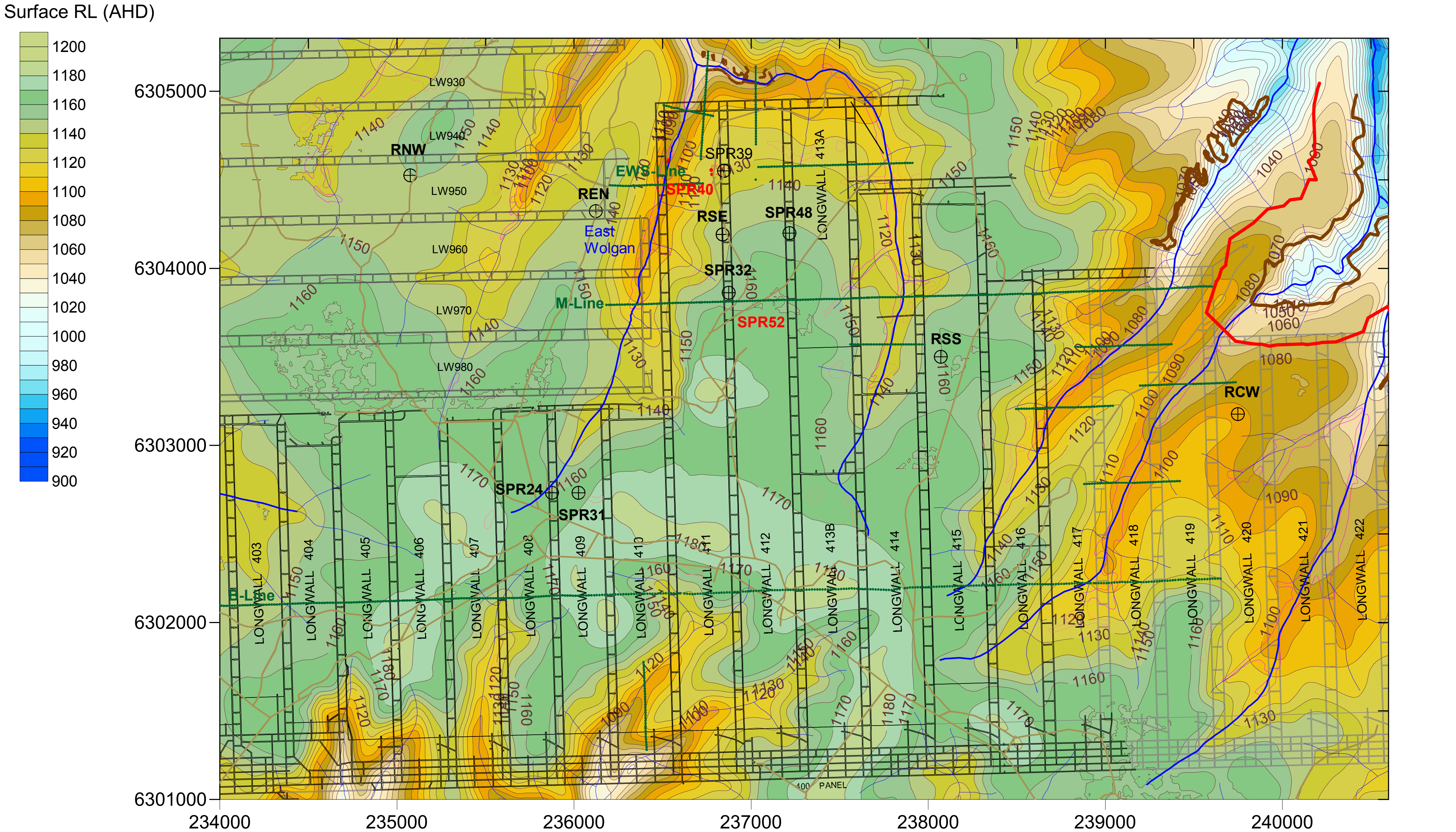
DgS Ditton Geotechnical Services Pty Ltd	Engineer: S.Ditton Drawn: S.Ditton Date: 17.08.14	Client:	Centennial Springvale SPV-003/7b
		Title:	Cover Depth Contours and Proposed Mining Layout in the Angus Place Extended Project Area
		Scale:	1:50,000 — Figure No: 1c



Key

- Cover Depth (m)
- Existing Subsidence Lines
- Shrub Swamps (MU50 - DECC)
- Hanging Swamps (MU51 - DECC)
- Creeks
- Rock Formations (5-20 m high)
- Existing mine workings
- Proposed mine workings
- Extracted longwall
- NSW Forests Fire Trails
- Borehole Extensometer or Piezometer
- Stratigraphy Cross Section

DgS	Engineer: S.Ditton	Client:	Centennial Springvale SPV-003/7b
Ditton Geotechnical Services Pty Ltd	Drawn: S.Ditton Date: 17.08.14	Title:	Cover Depth Contours and Proposed Angus Place Mine Extension Project Area Longwalls 1001 to 1019
		Scale:	1:50,000 — Figure No: 1c

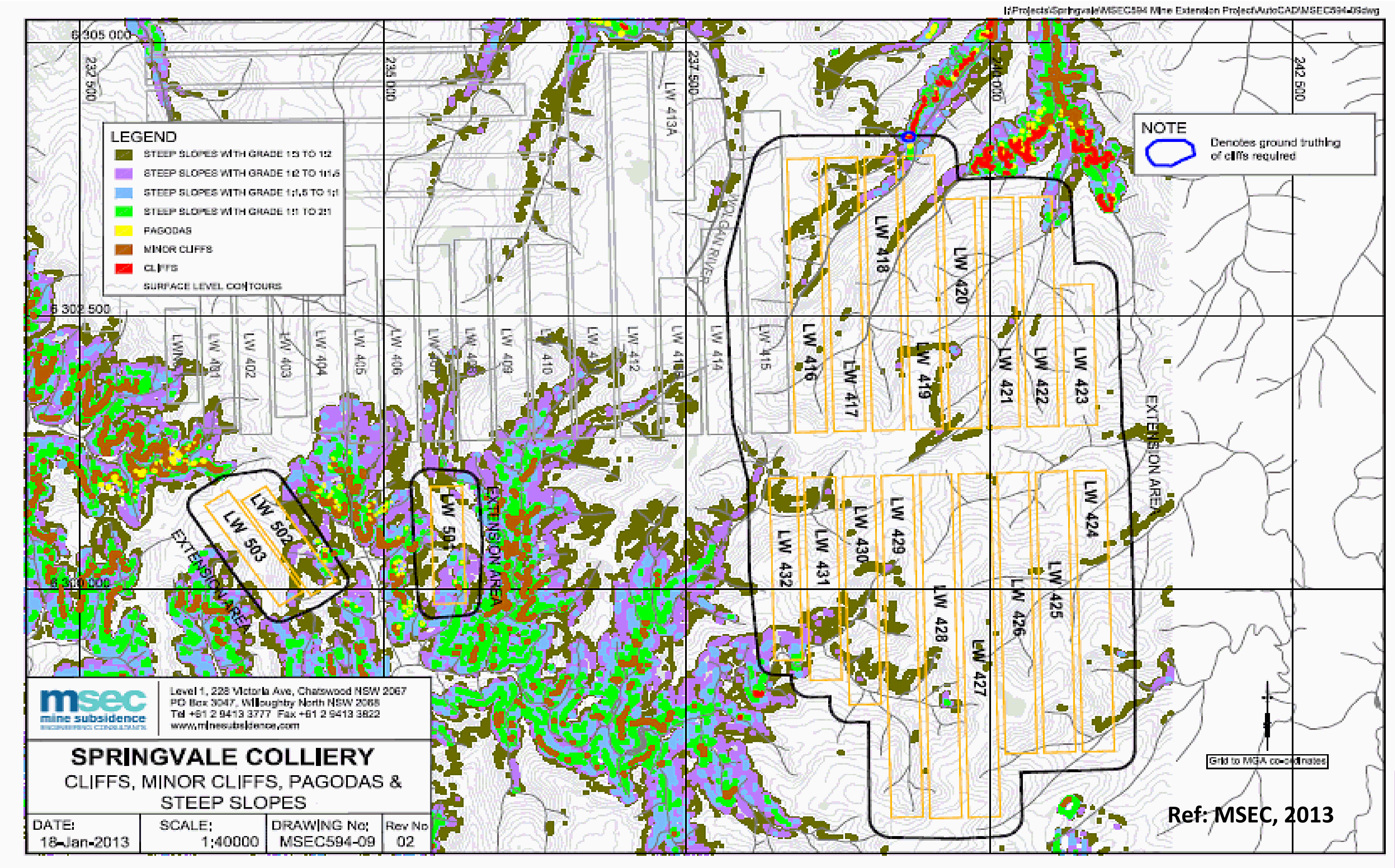


Key

Borehole Extensometer

Borehole VW Piezometer/
Screened Well (Stand Pipe)

DgS	Engineer: S.Ditton	Client:	Centennial Springvale SPV-003/7b
	Drawn: S.Ditton		
	Date: 17.08.14	Title:	Surface Level Contours and Borehole Extensometers / Piezometers Locations above the Existing Springvale and Angus Place Longwall Mines
	Ditton Geotechnical Services Pty Ltd	Scale:	1:30,000 — Figure No: 2a



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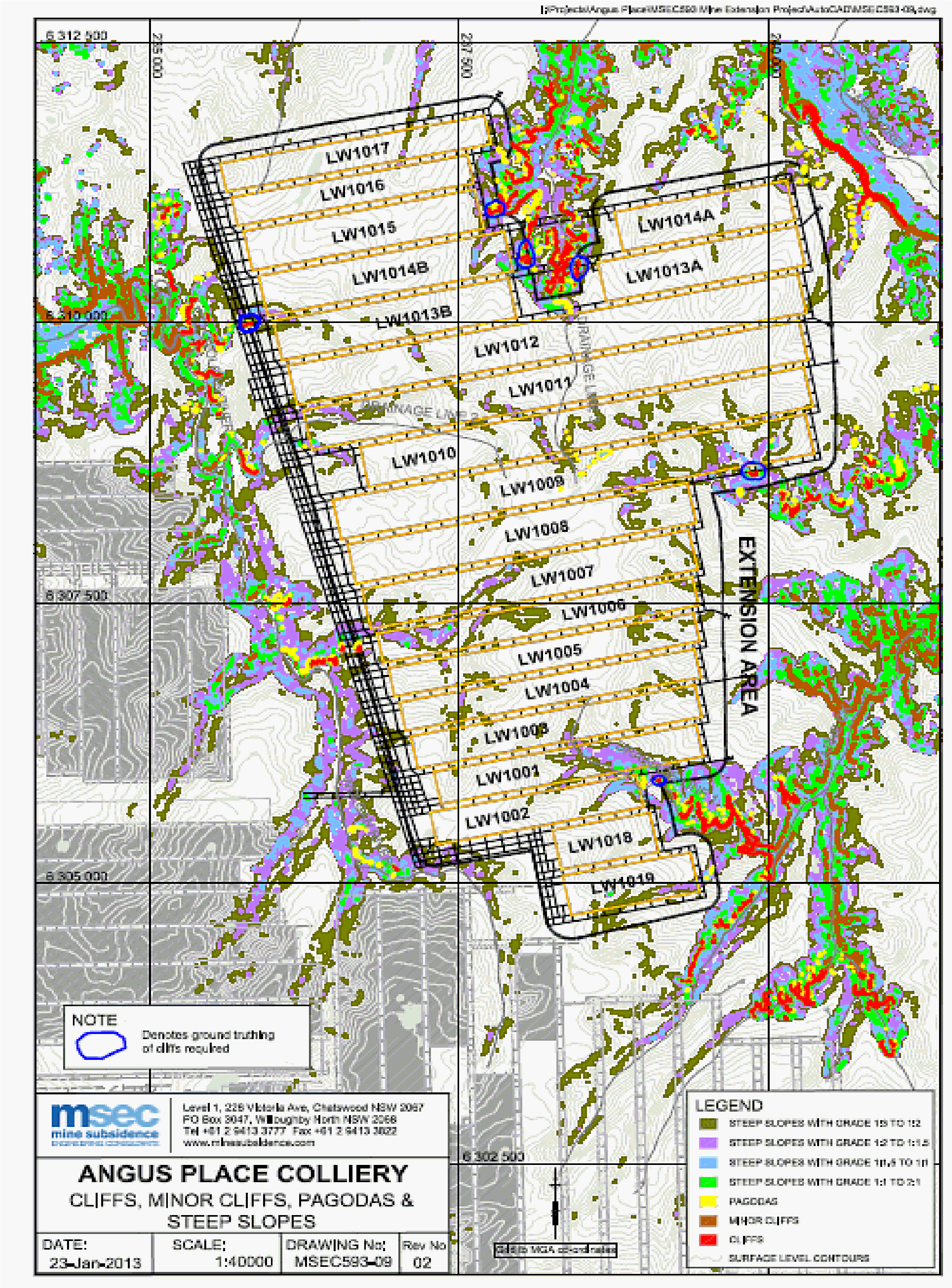
	Drawn:	S.Ditton					
	Date:	15.10.13	Title:	Surface features and Level Contours above the Proposed Springvale Mine Extension Area LWs 416 to 432			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS		Figure No:	2b



Ref: MSEC, 2013

DgS	Engineer: S.Ditton	Client:	Centennial Springvale Coal Pty Ltd	
	Drawn: S.Ditton		SPV-003/7b	
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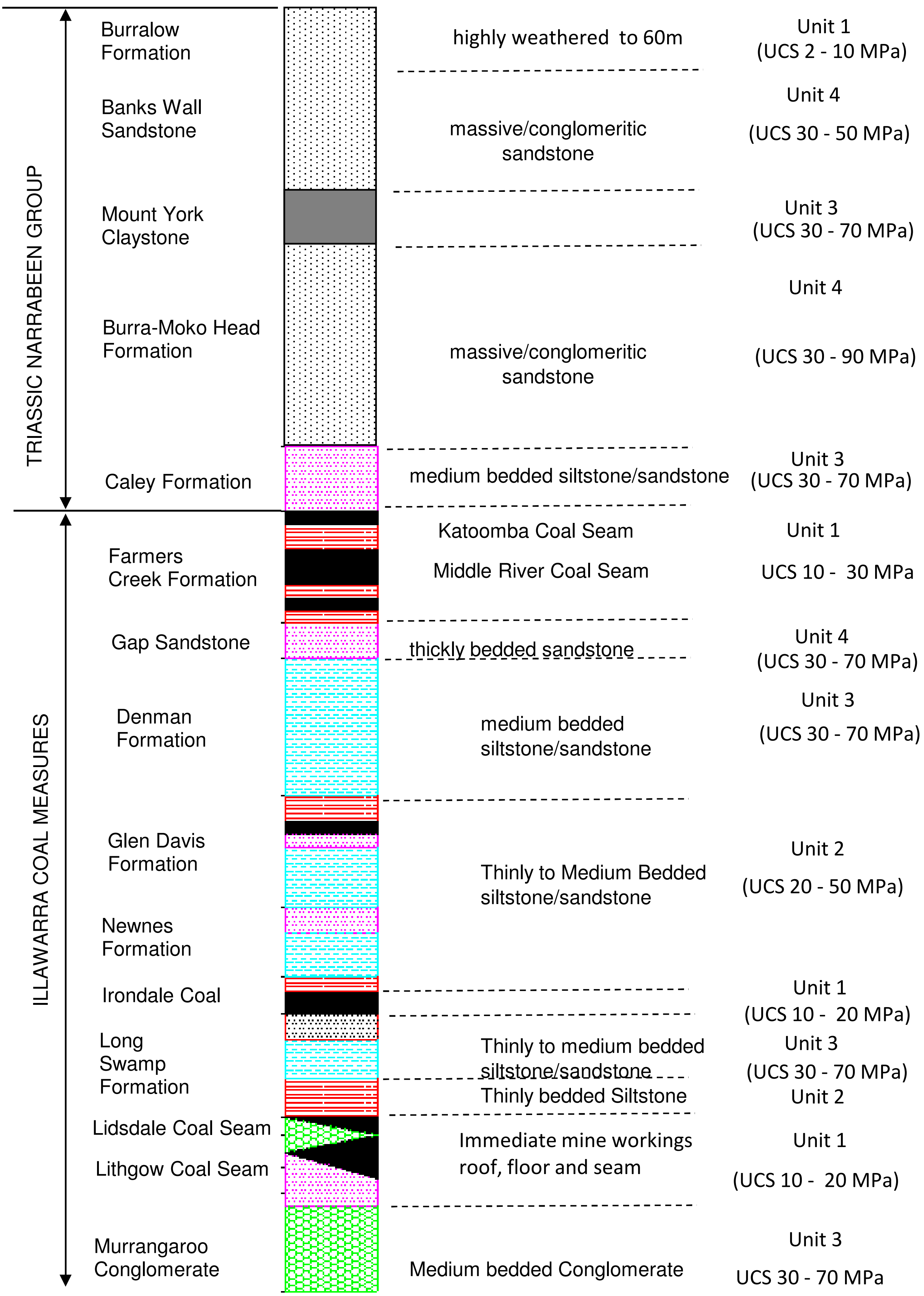
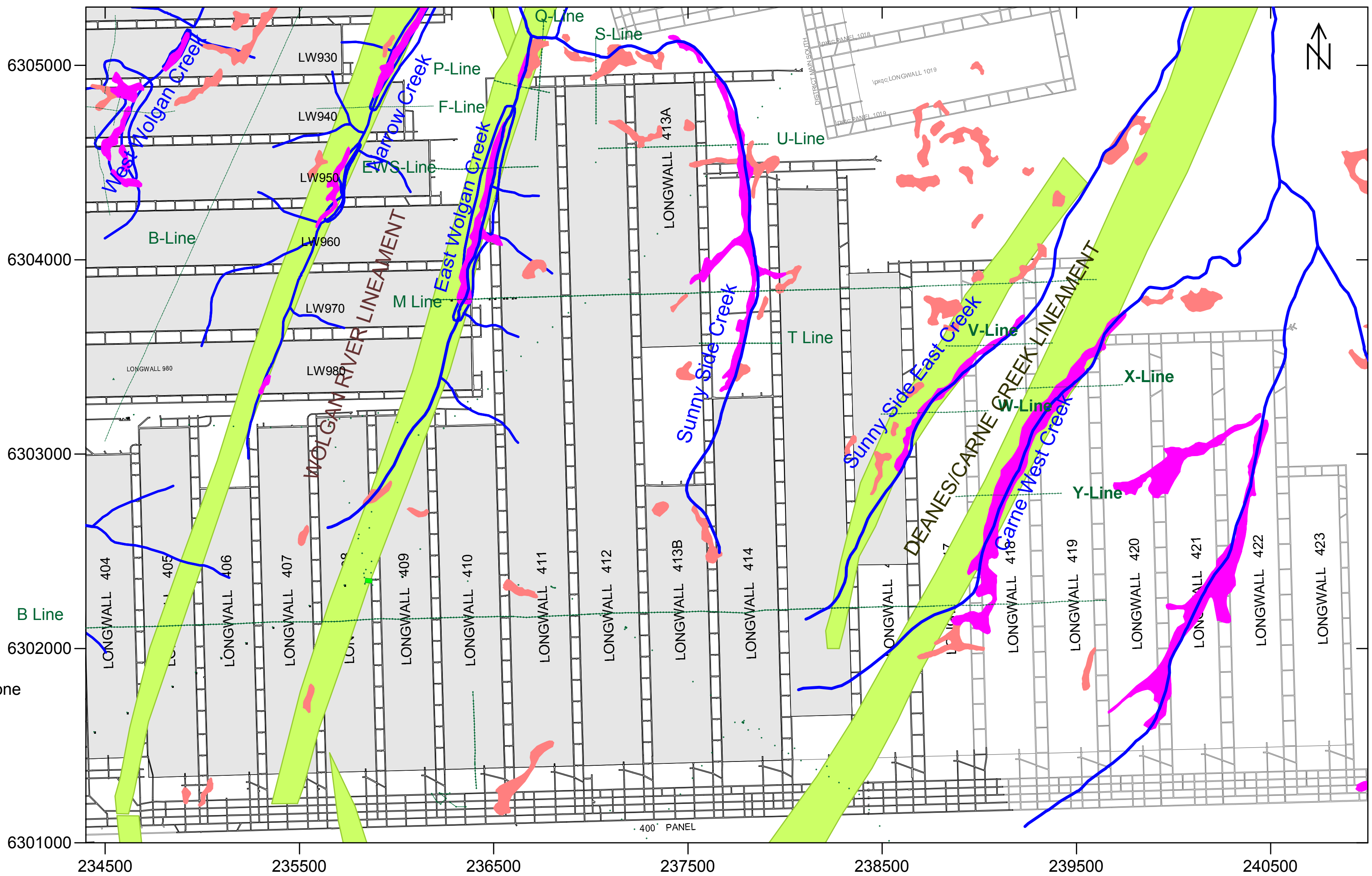
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No: 2c



DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd			
	Drawn:	S.Ditton		SPV-003/7b			
	Date:	22.08.14	Title:	Typical Overburden Stratigraphy above the Project Areas			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	3a	



Key:

- Type 1 Structure Zone (see Palaris, 2013)
- Watercourses
- Shrub Swamps (MU50 - DECC)
- Hanging Swamps (MU51 - DECC)
- Cliff lines (>20 m high)
- Rock Formations (5 - 20 m)
- Extracted Longwall Blocks
- Proposed Longwalls
- Installed Subsidence Lines

DgS

Engineer:	S.Ditton	Client:	Centennial Springvale Coal SPV-003/7b	
Drawn:	S.Ditton			
Date:	09.04.13	Title:	Interpreted/Mapped Geological Structure above the Springvale and Angus Place Mines	
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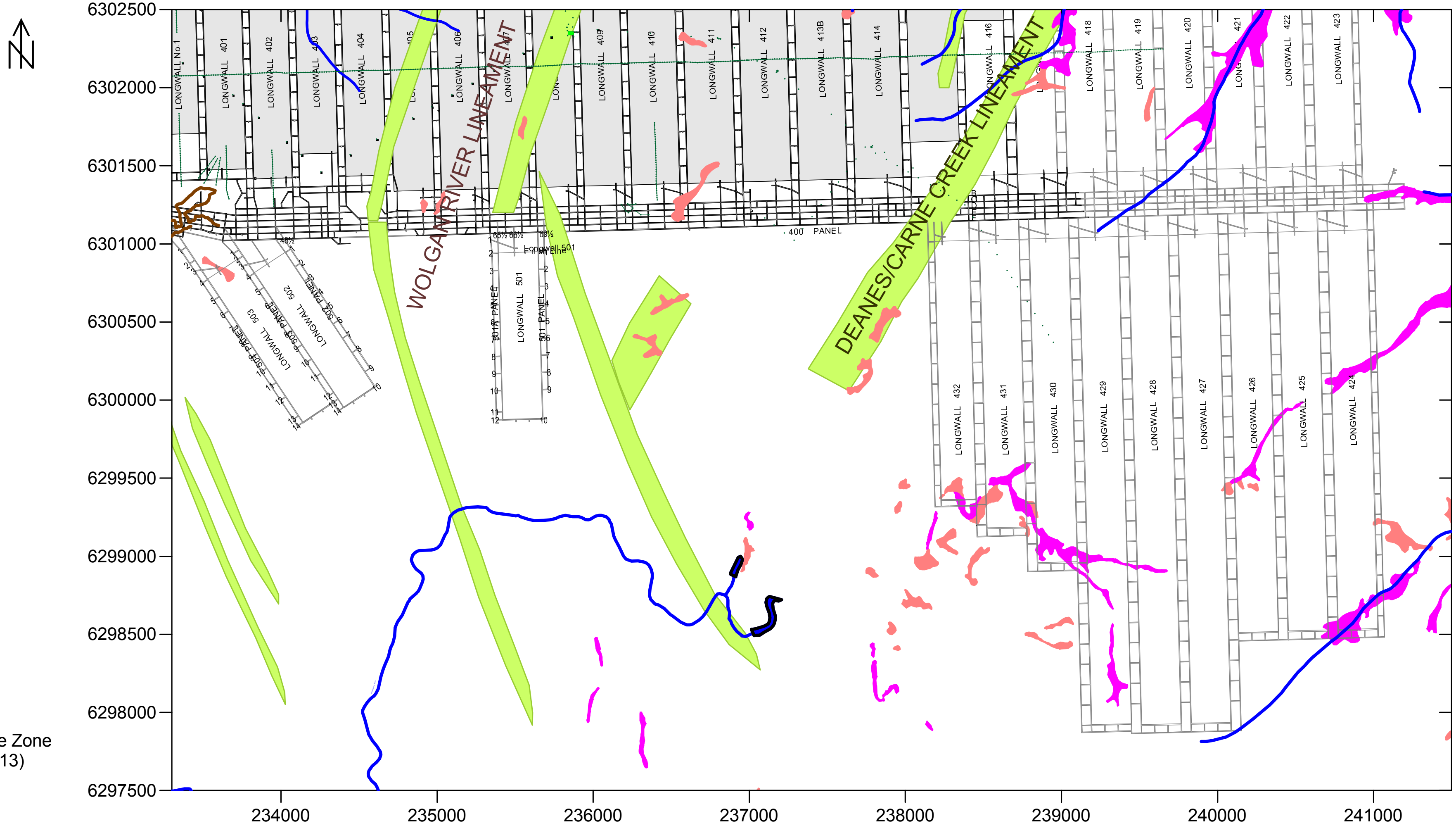

Key:

- Type 1 Structure Zone (see Palaris, 2013)
- Watercourses
- Shrub Swamps (MU50 - DECC)
- Hanging Swamps (MU51 - DECC)
- Cliff lines (>20 m high)
- Rock Formations (5 - 20 m)
- Extracted Longwall Blocks
- Proposed Longwalls
- Installed Subsidence Lines

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal SPV-003/7b
	Drawn:	S.Ditton		
	Date:	22.08.14	Title:	Interpreted/Mapped Geological Structure above the Proposed Springvale Mine Extension Project Area LWs 424 to 432 & 501 to 503
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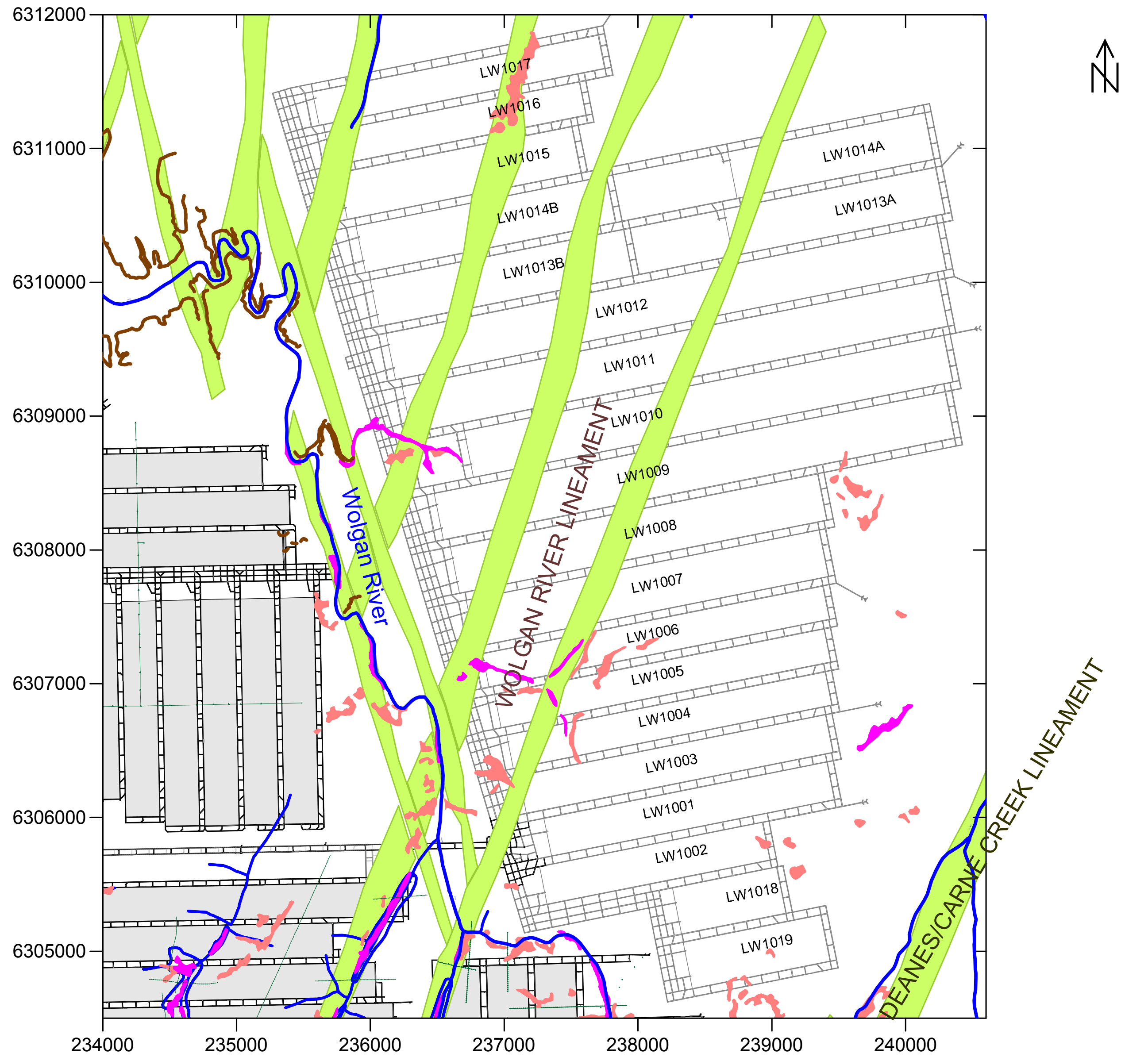

Key:

- Type 1 Structure Zone (see Palaris, 2013)
- Watercourses
- Shrub Swamps (MU50 - DECC)
- Hanging Swamps (MU51 - DECC)
- Cliff lines (>20 m high)
- Rock Formations (5 - 20 m)
- Extracted Longwall Blocks
- Proposed Longwalls
- Installed Subsidence Lines

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	22.08.14	Title:	Interpreted/Mapped Geological Structure above the Proposed Angus Place Mine Extension Project Area LWs 1001 to 1019		
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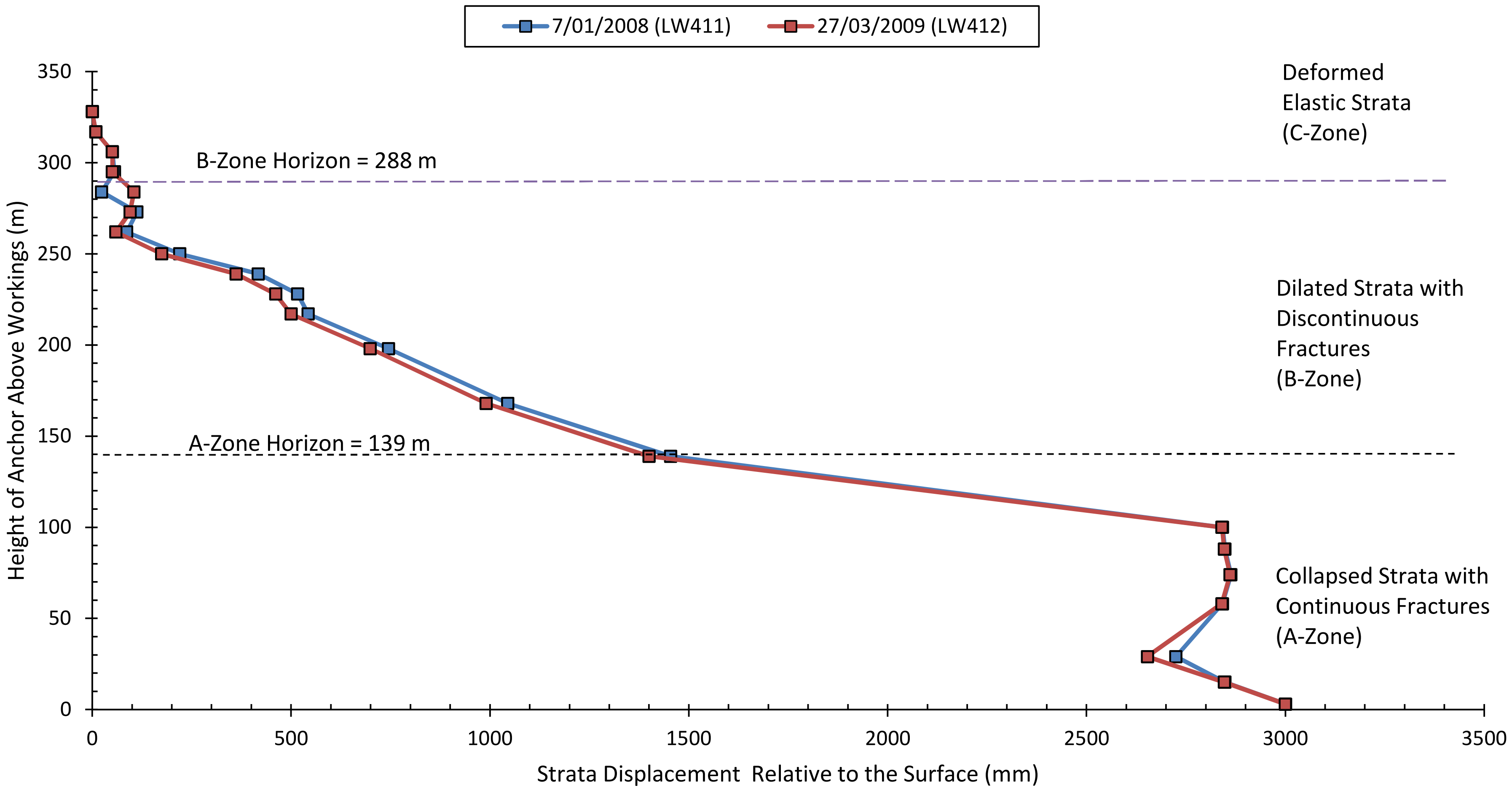
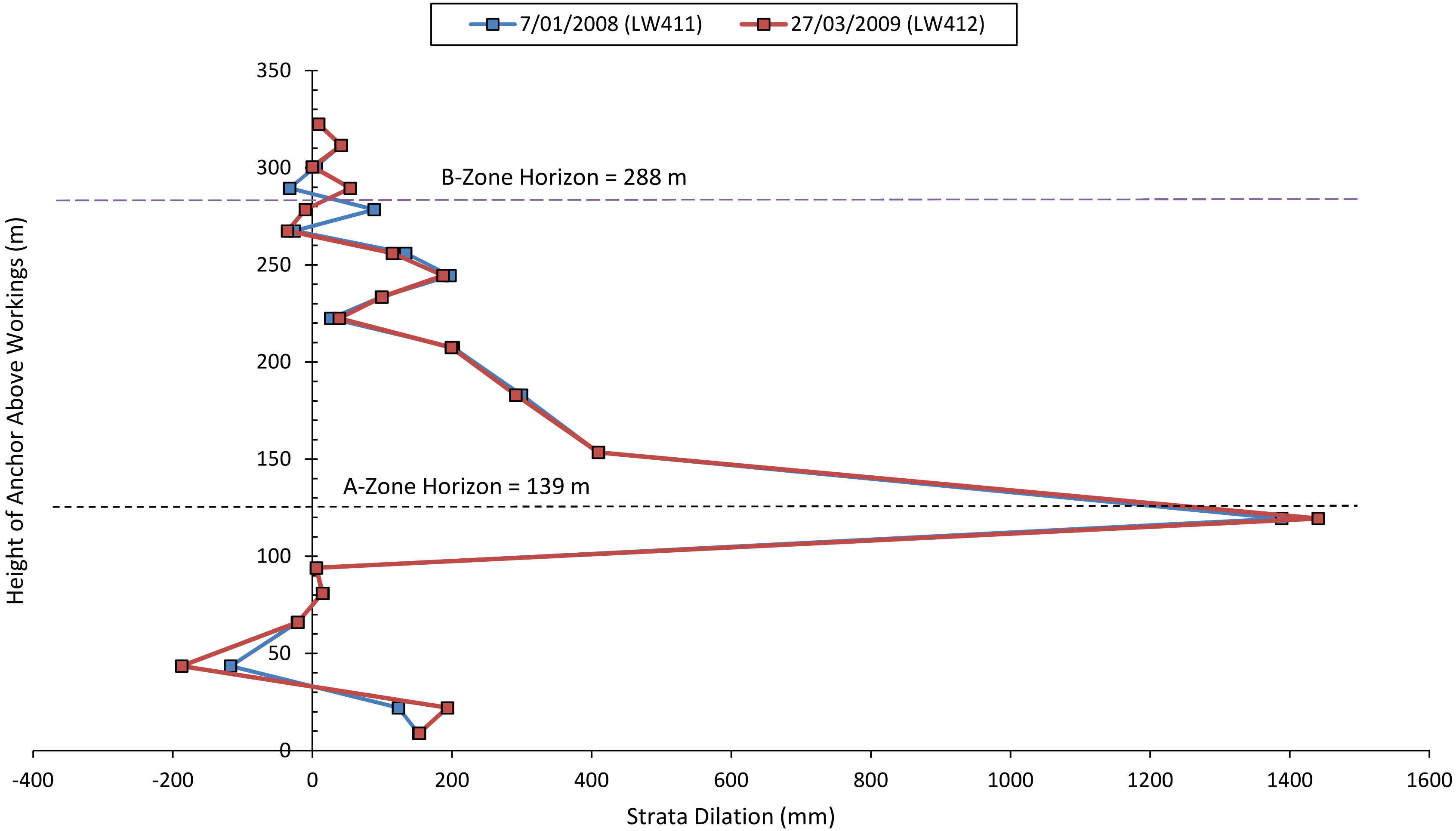


DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	26.08.14	Title:	Measured Strata Displacement Relative to Surface in SPR40 (LW411)		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	4a



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	Drawn:	S.Ditton		
	Date:	26.08.14	Title:	Measured Strata Displacement Relative to Surface in SPR40 (LW411)
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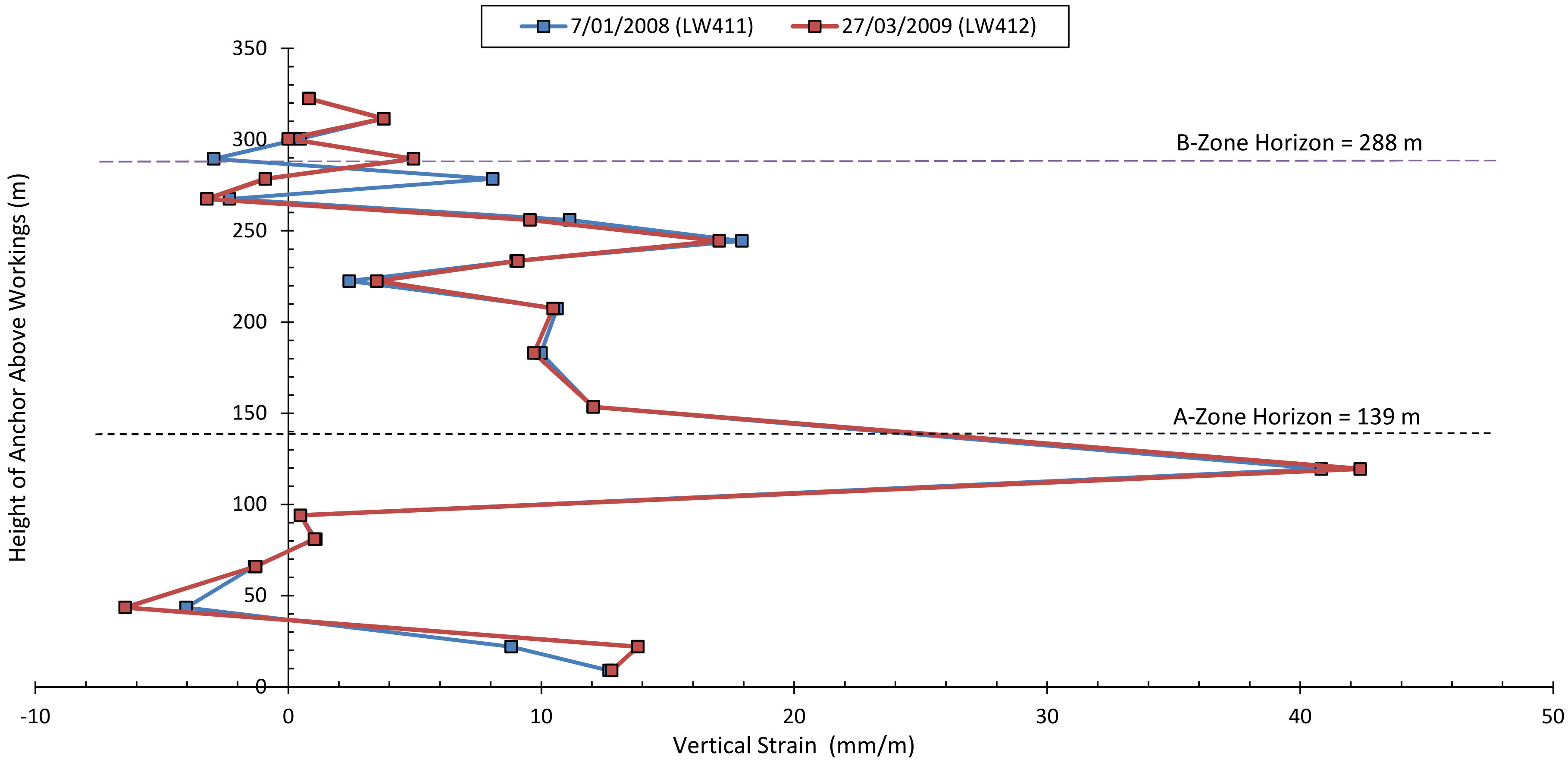

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	26.08.14	Title:	Measured Strata Displacement Relative to Surface in SPR40 (LW411)		
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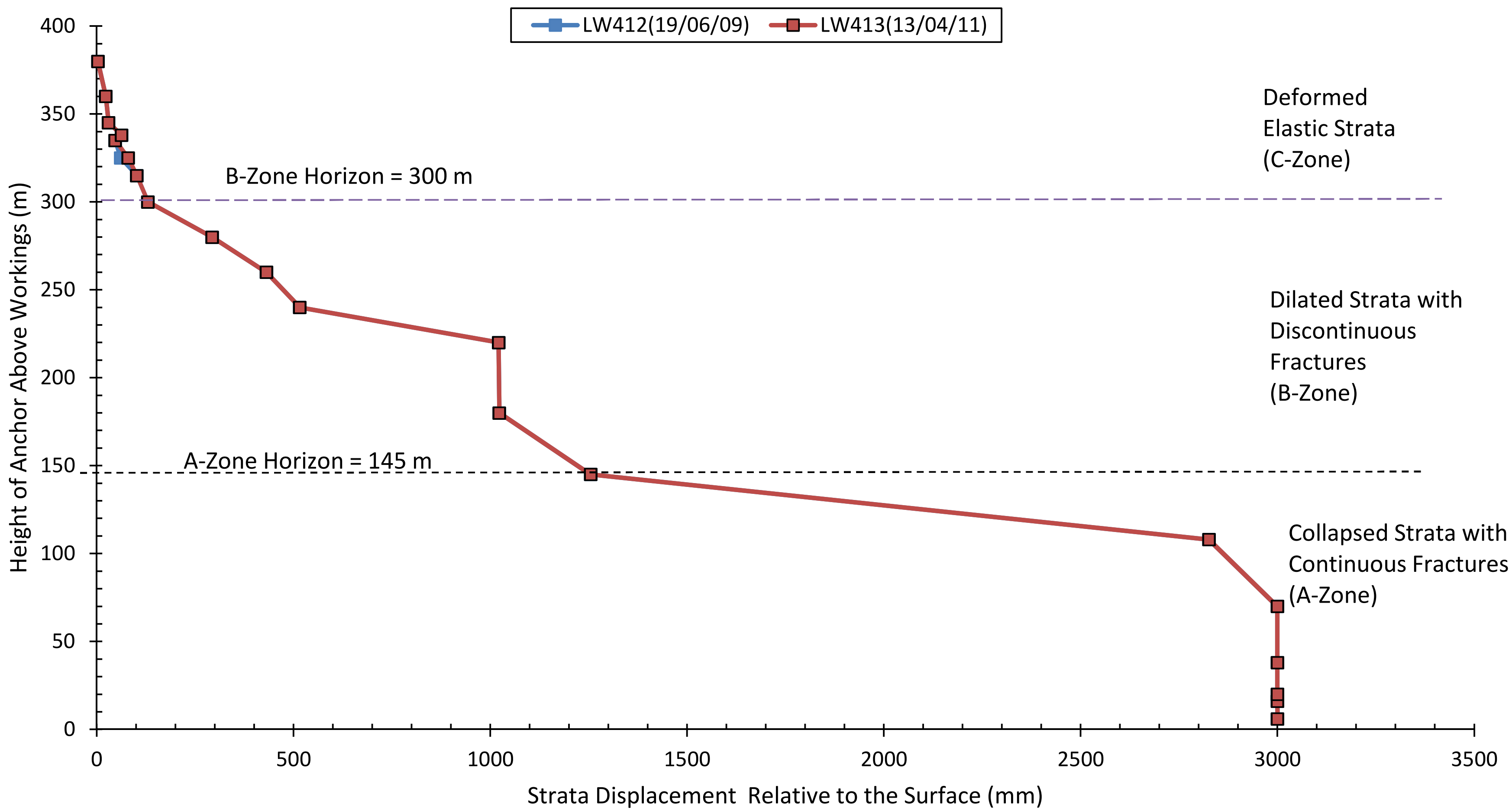

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	Drawn:	S.Ditton		
	Date:	26.08.14	Title:	Measured Strata Displacement Relative to Surface in SPR52 (LW412)
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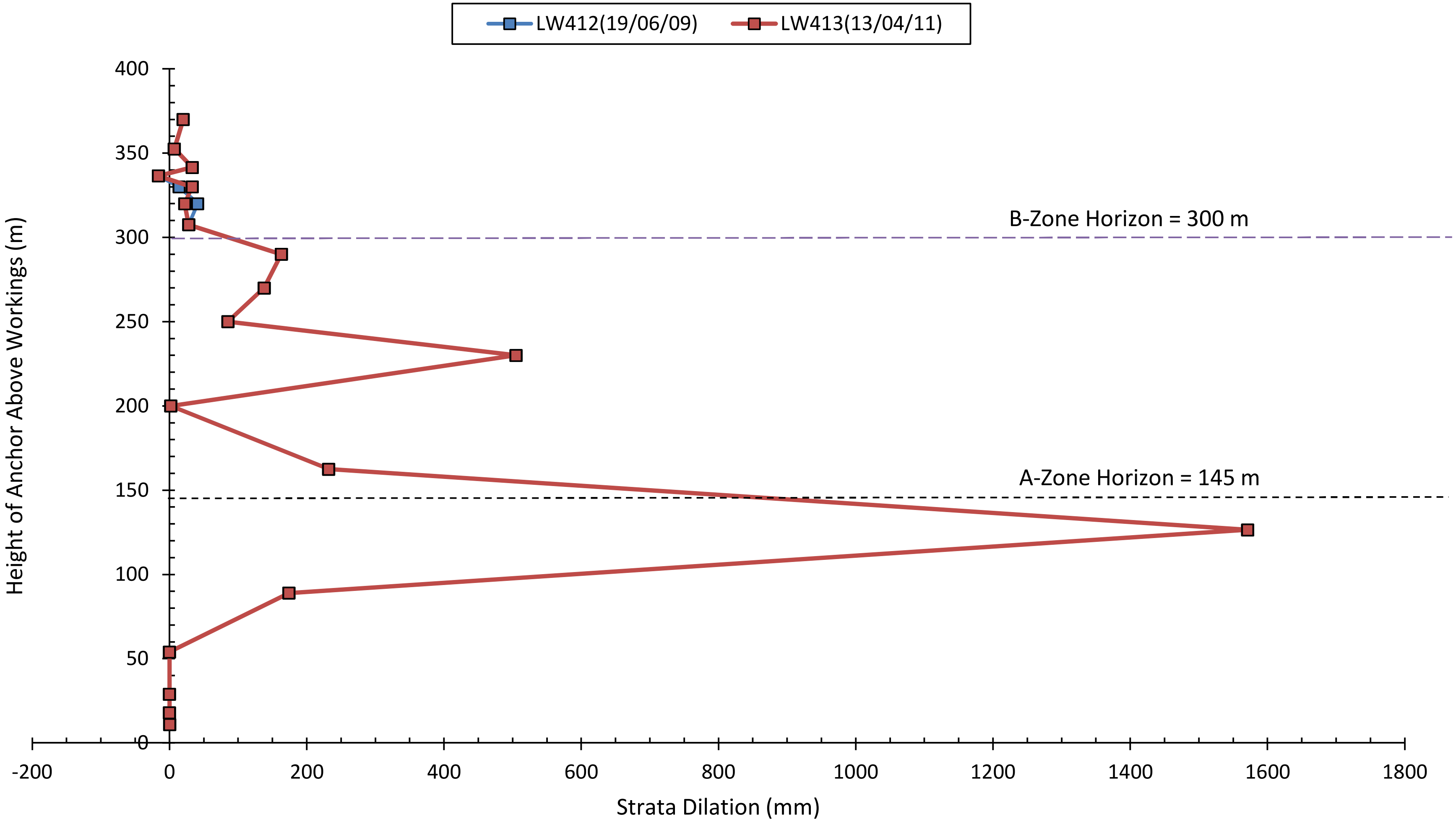
			Figure No:	4d



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	Drawn:	S.Ditton				
	Date:	26.08.14	Title:	Measured Strata Displacement Relative to Surface in SPR52 (LW412)		
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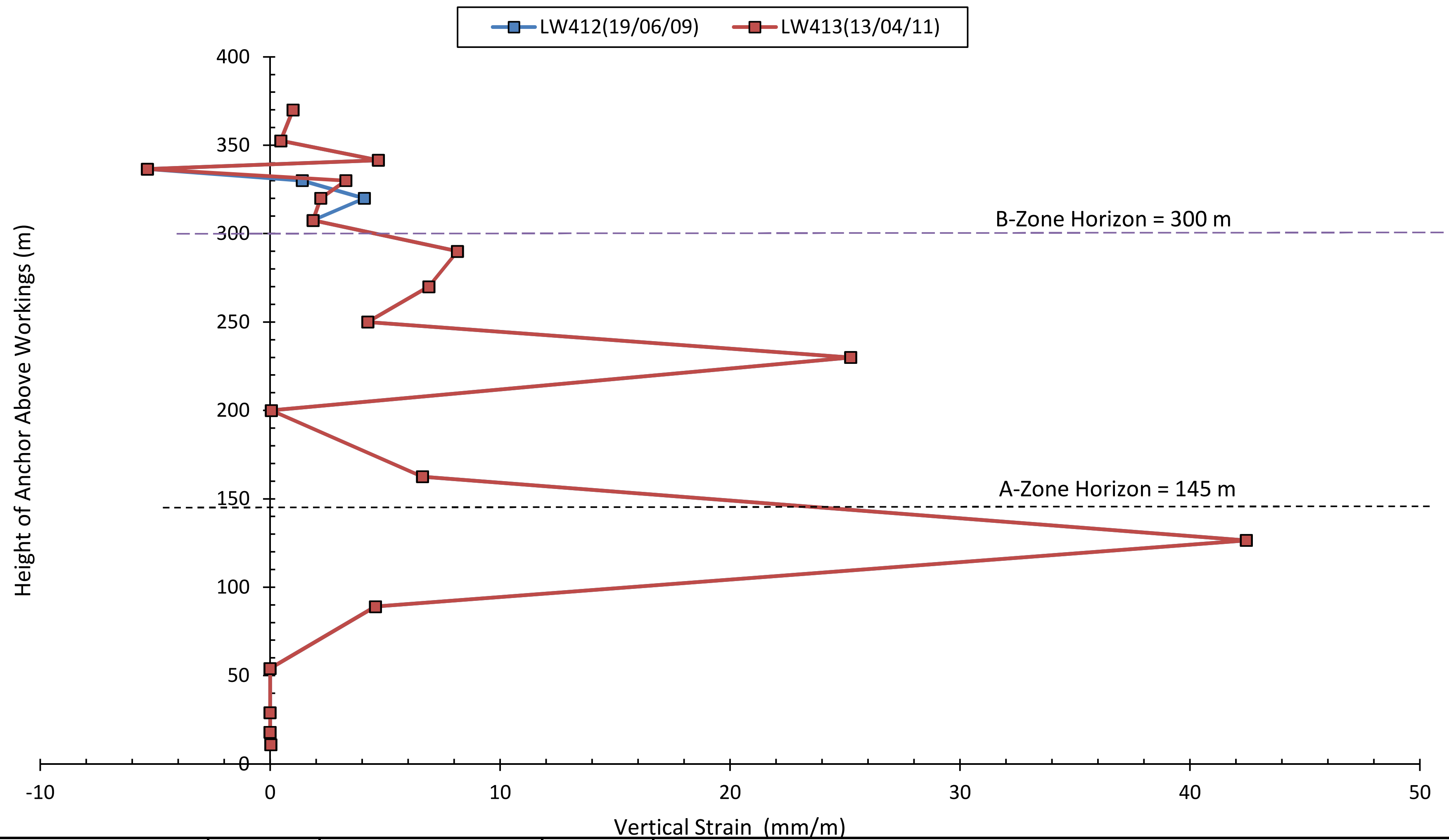

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	26.08.14	Title:	Measured Strata Displacement Relative to Surface in SPR52 (LW412)		
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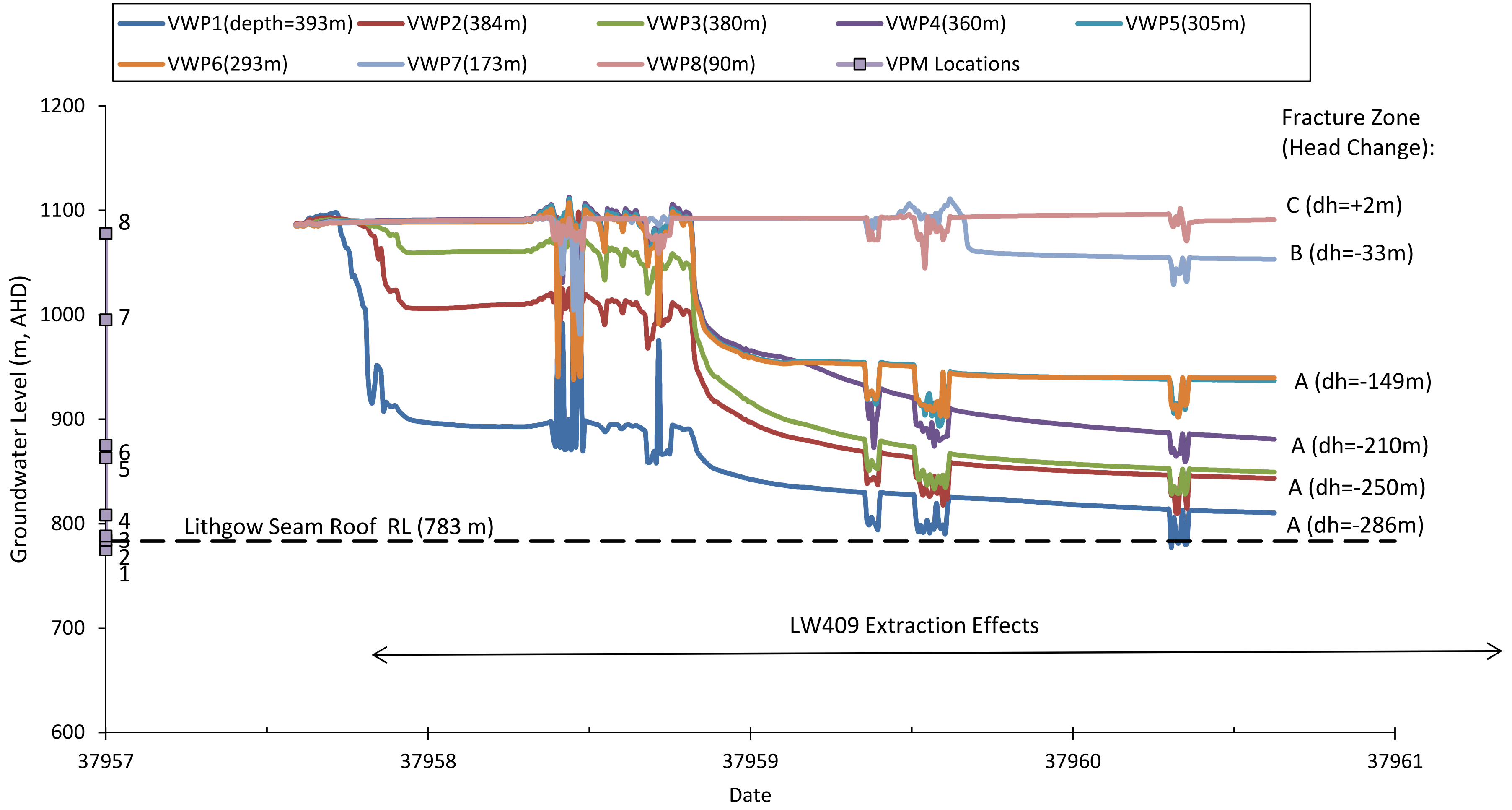

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	26.08.14	Title:	Measured Piezometric Response to LW409 (SPR 31)		
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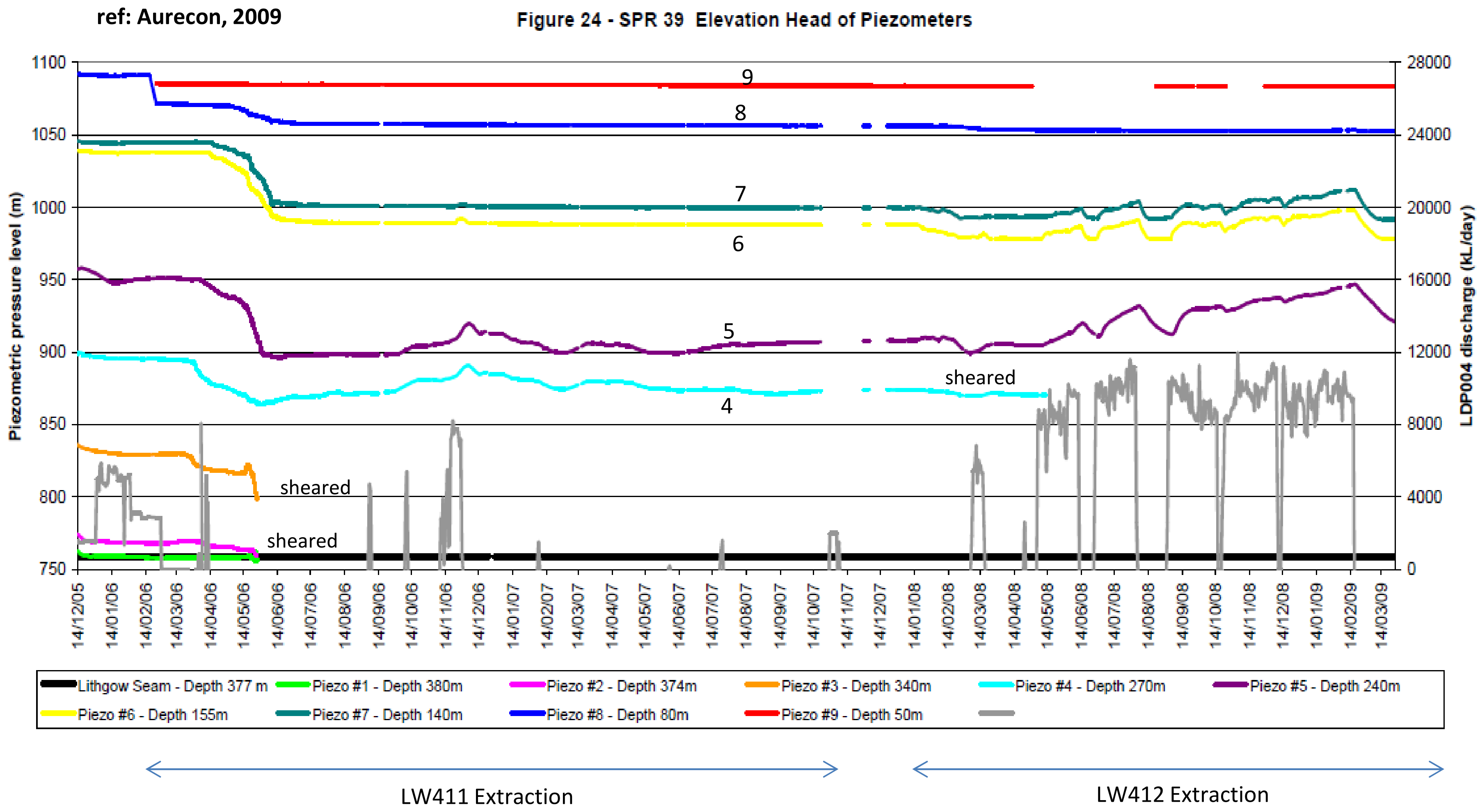

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	26.08.14	Title:	Measured Piezometric Response to LW411 (SPR 39)		
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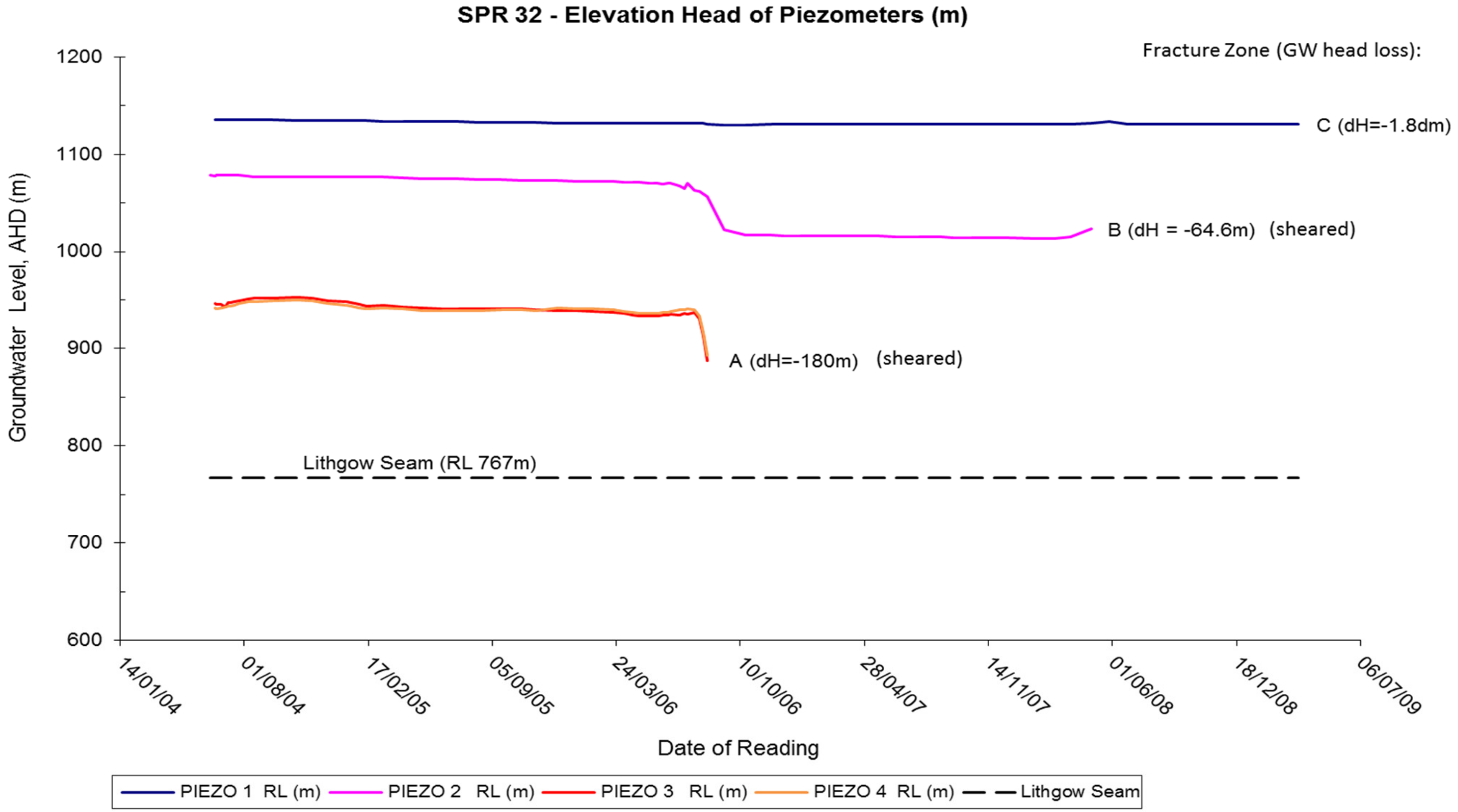
			Scale:	NTS	Figure No:	5b



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	Drawn:	S.Ditton				
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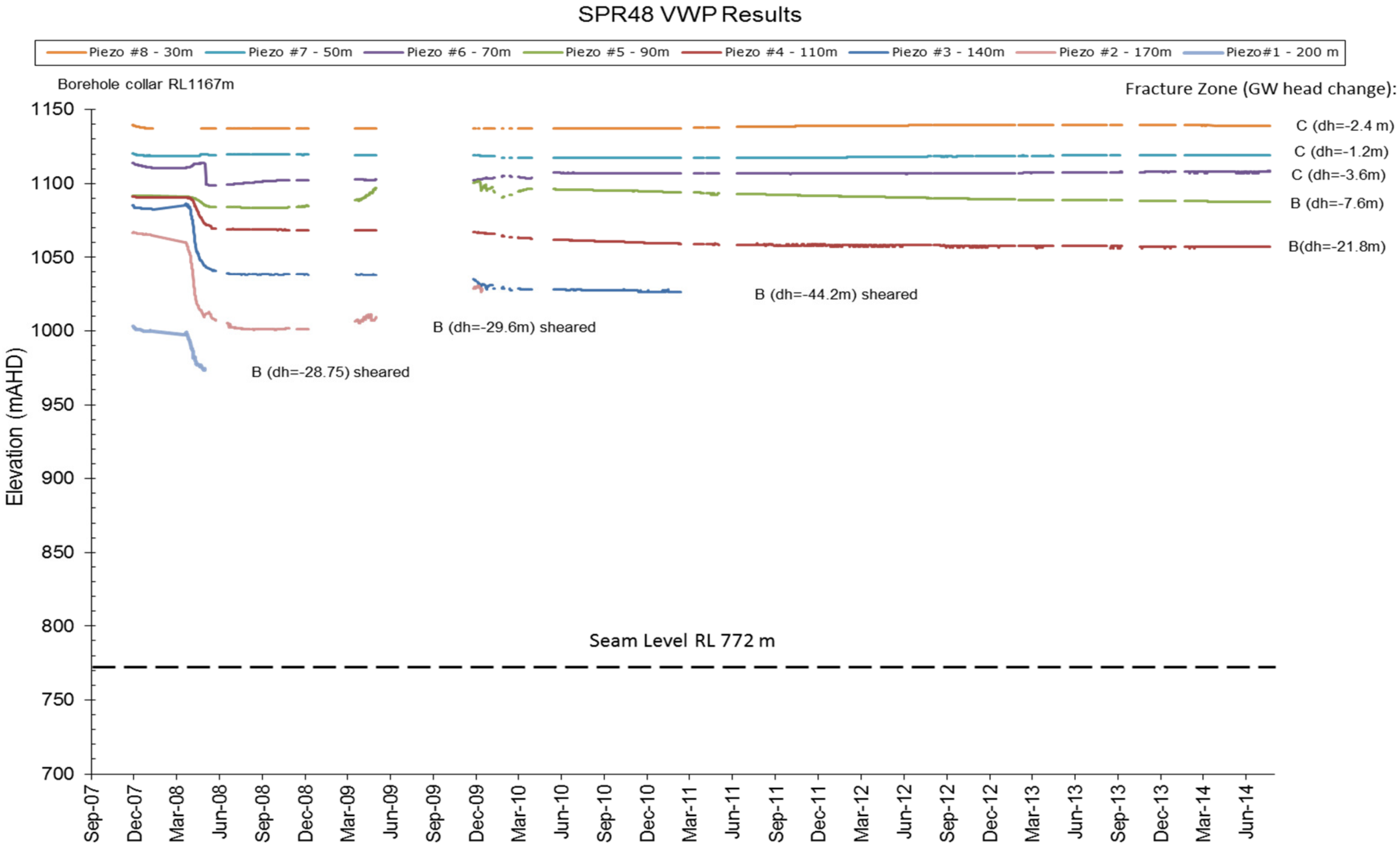

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	Drawn:	S.Ditton				
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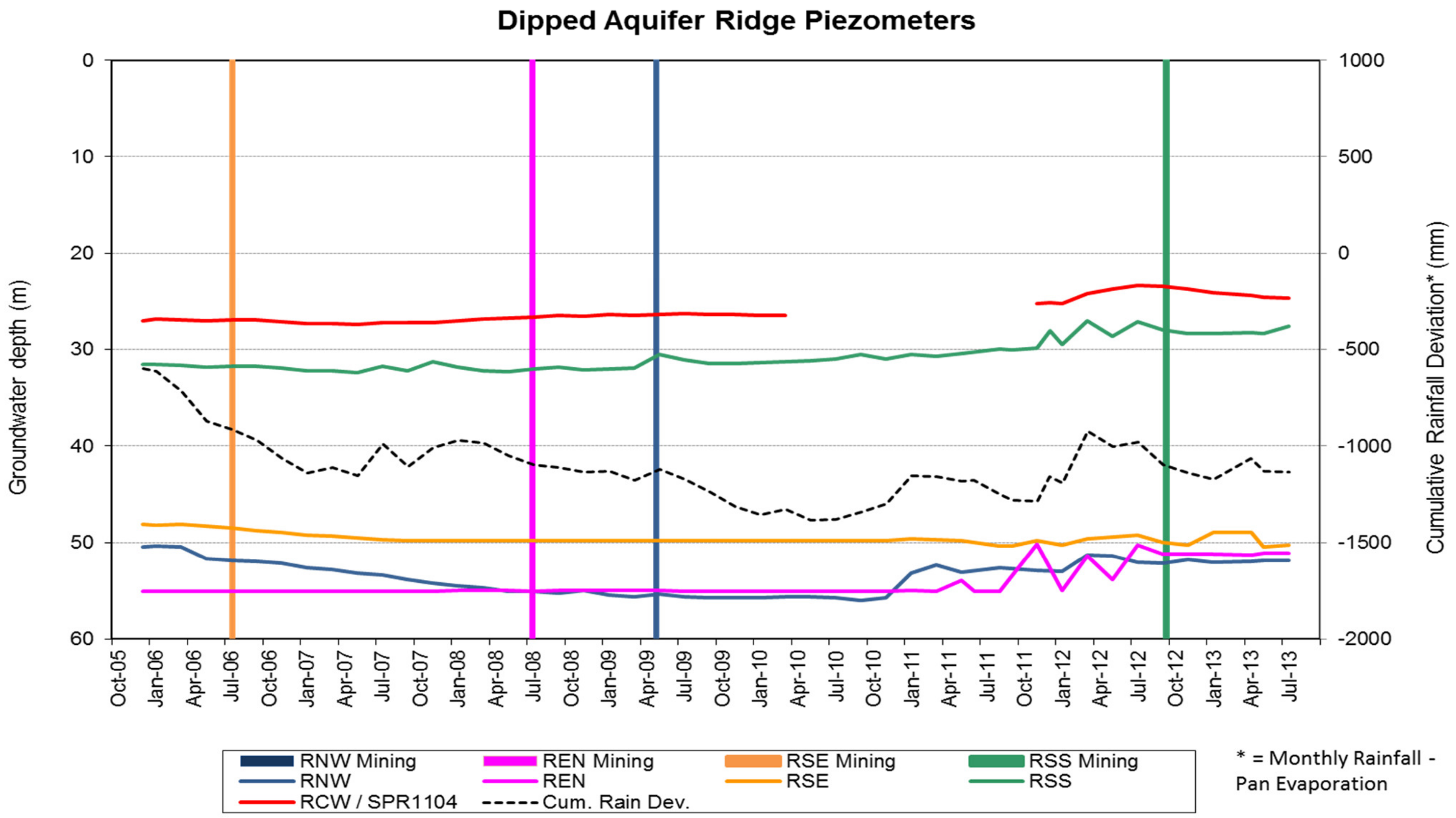

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	26.08.14	Title:	Measured Groundwater Depths in Ridge Piezometers between Jan 2006 and August 2013		
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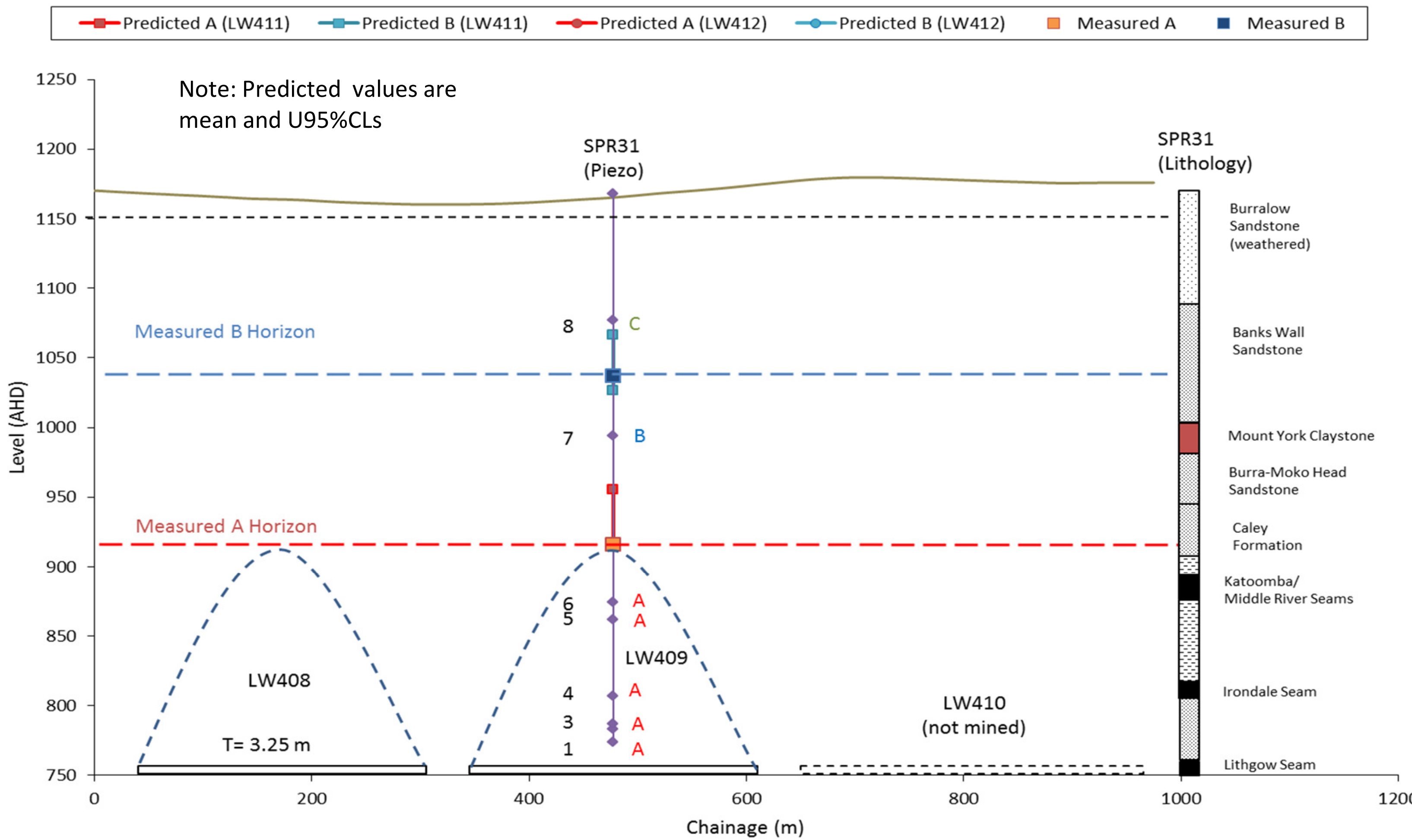
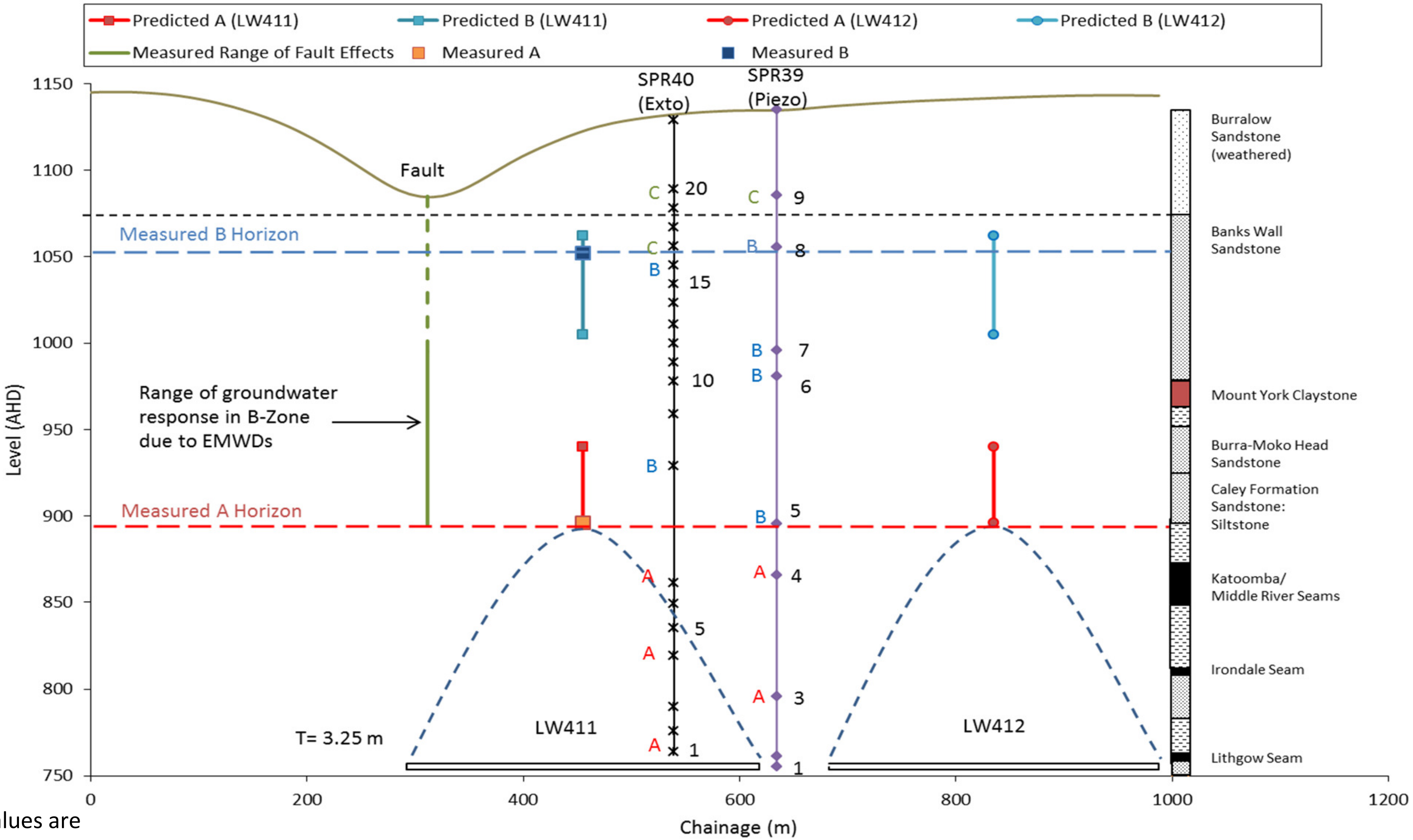
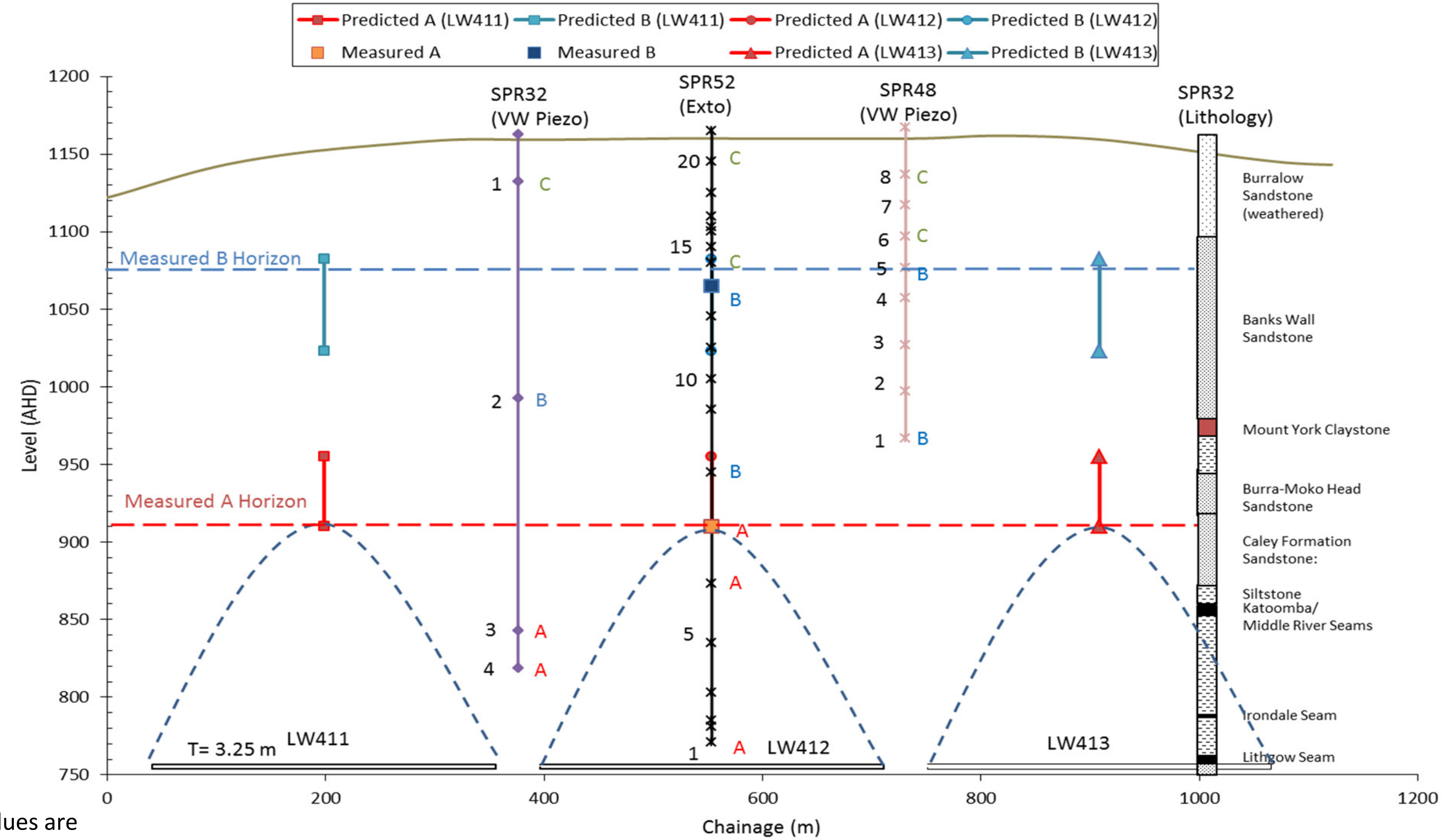


DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7			
	Drawn:	S.Ditton					
	Date:	20.09.13	Title:	Predicted v. Measured Sub-surface Fracture Zone Assessment Results Summary for LW409			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	6a	



Note: Predicted values are mean and U95%CLs

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7		
	Drawn:	S.Ditton				
	Date:	20.09.13	Title:	Predicted v. Measured Sub-surface Fracture Zone Assessment Results Summary for LWs 411 and 412		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	6b



Note: Predicted values are mean and U95%CLs

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd SPV-003/7		
	Drawn:	S.Ditton				
	Date:	20.09.13	Title:	Predicted v. Measured Sub-surface Fracture Zone Assessment Results Summary for LWs 412 and 413		
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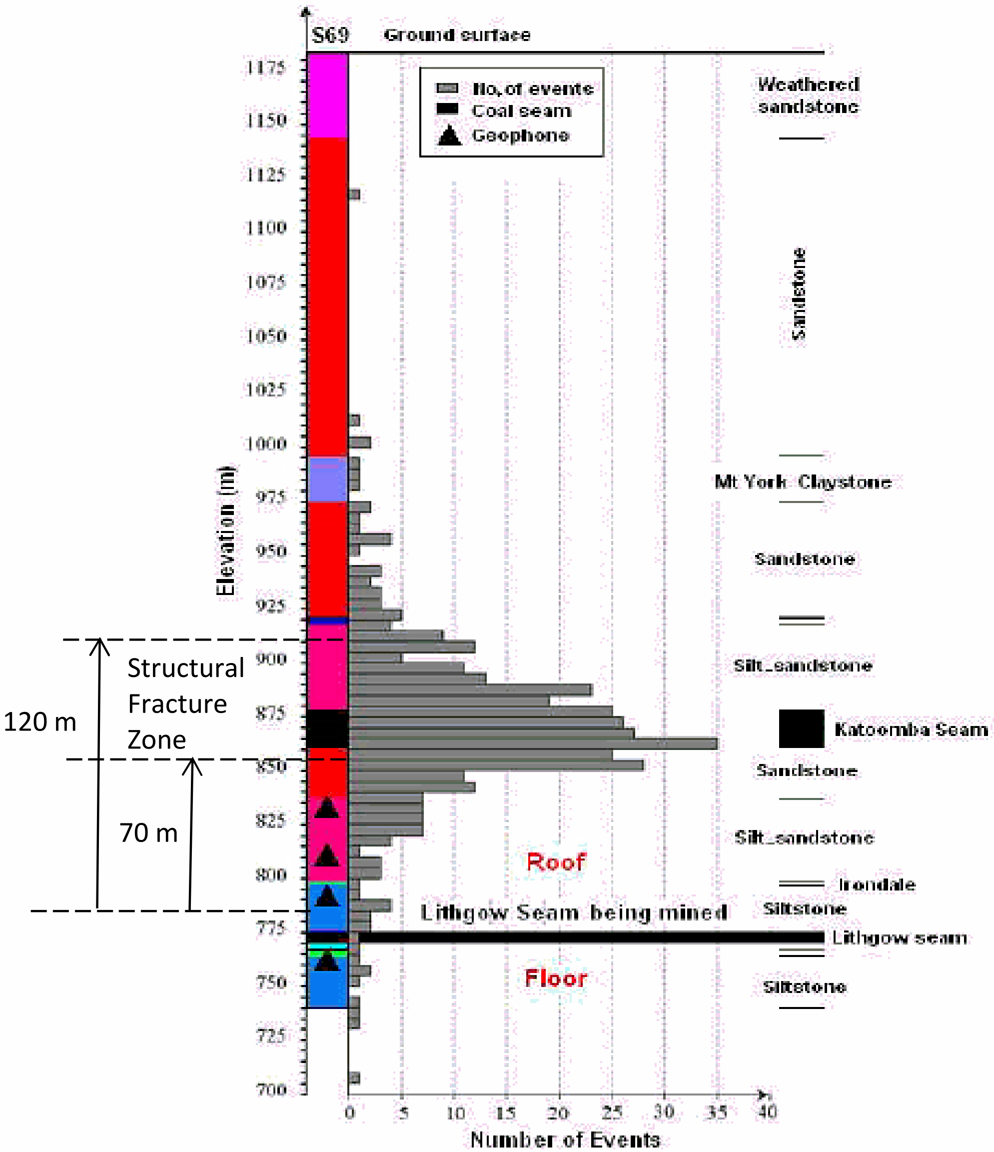
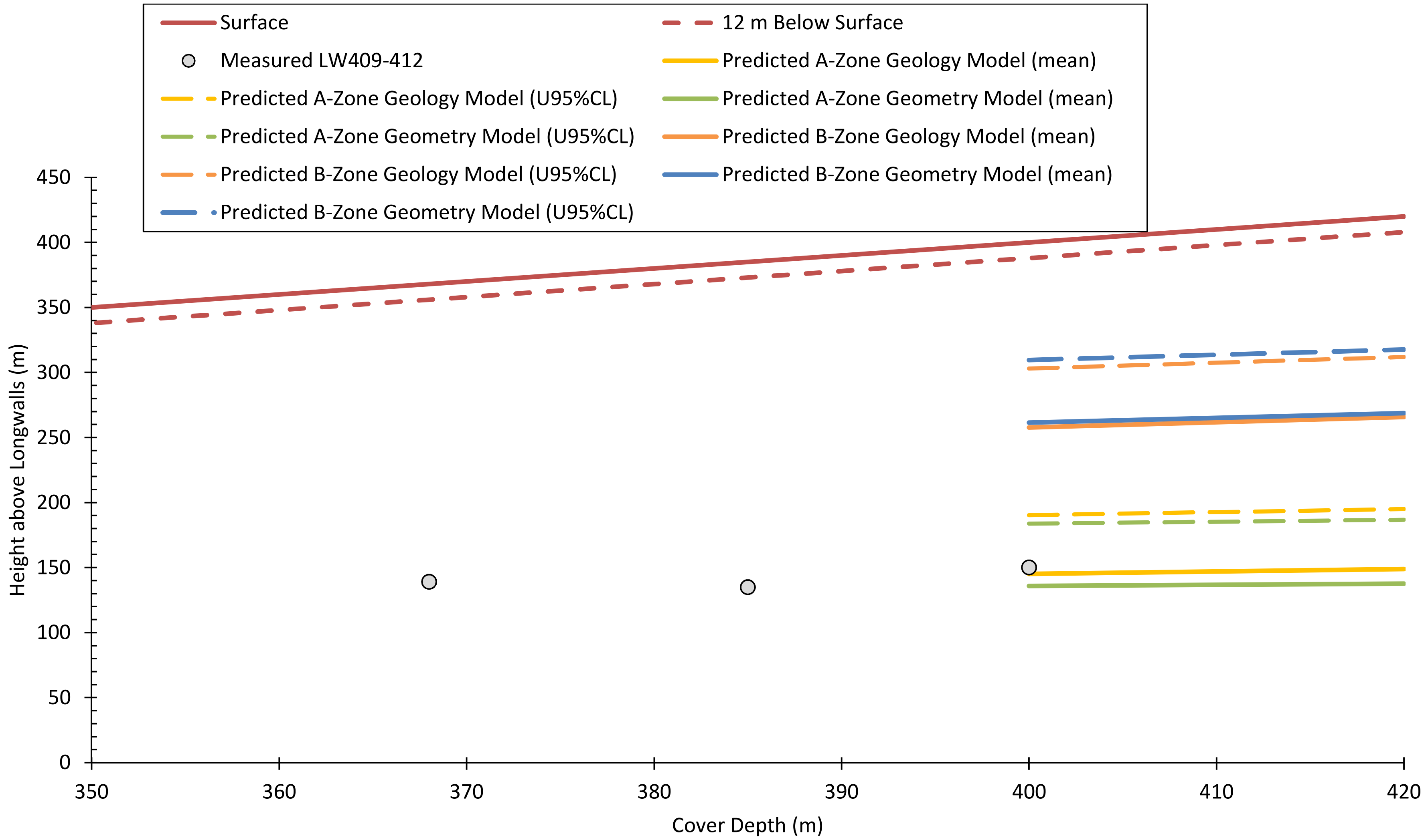


Figure 20 **Depth distribution of the located events and simplified geology of borehole S69.**

Ref: CSIRO, 2011

DgS	Engineer:	S.Ditton	Client:	Centennial Springvale Coal Pty Ltd		
	Drawn:	S.Ditton		SPV-003/7b		
	Date:	28.08.14	Title:	Microseismic Event locations in Overburden above LW413 in Borehole S69		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	7



DgS	Engineer:	S.Ditton	Client:	Springvale Pty Ltd
	Drawn:	S.Ditton		SPV-003/7b
	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A and B-Zones) for Springvale Mine's LW 415
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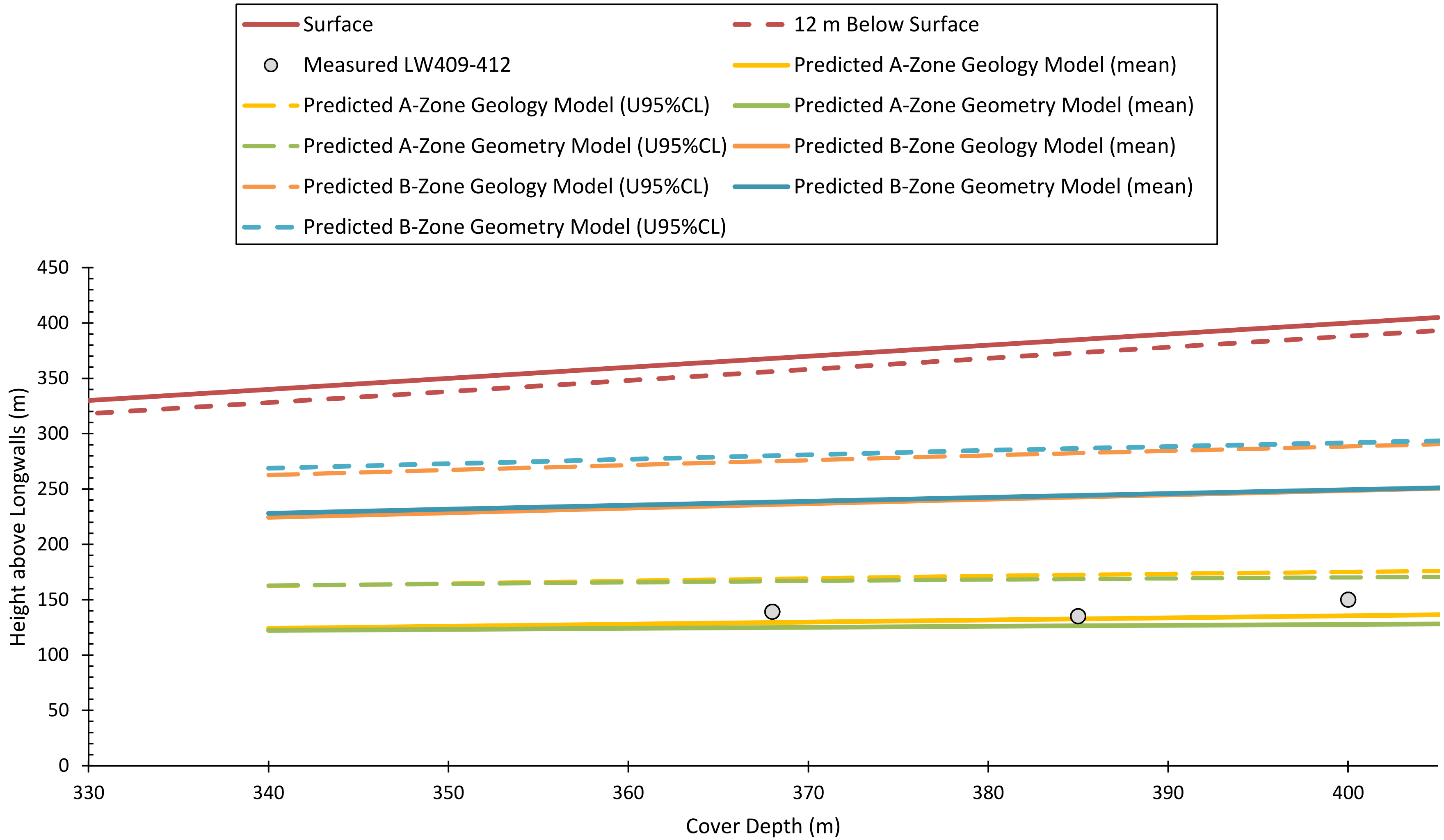
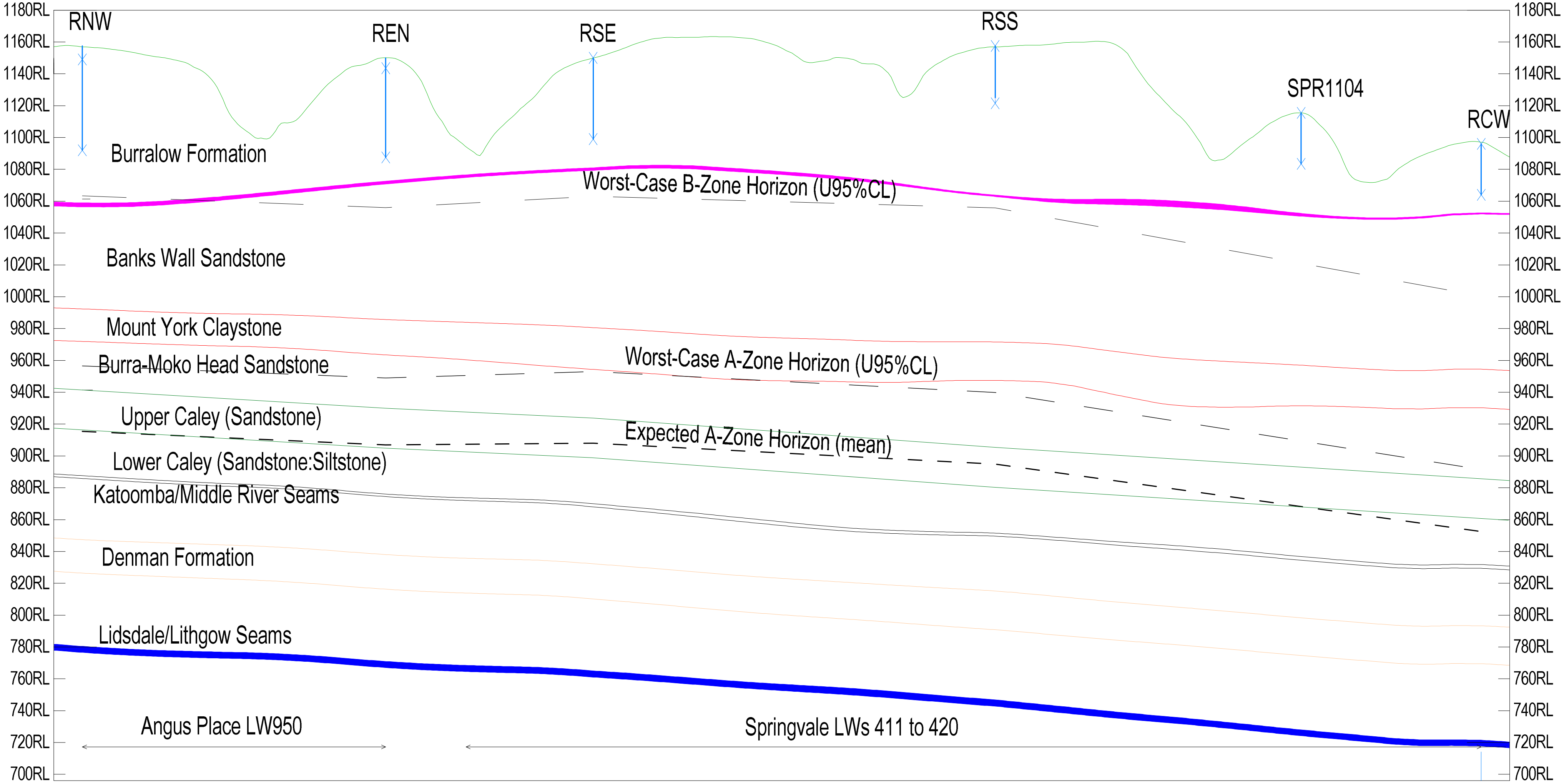


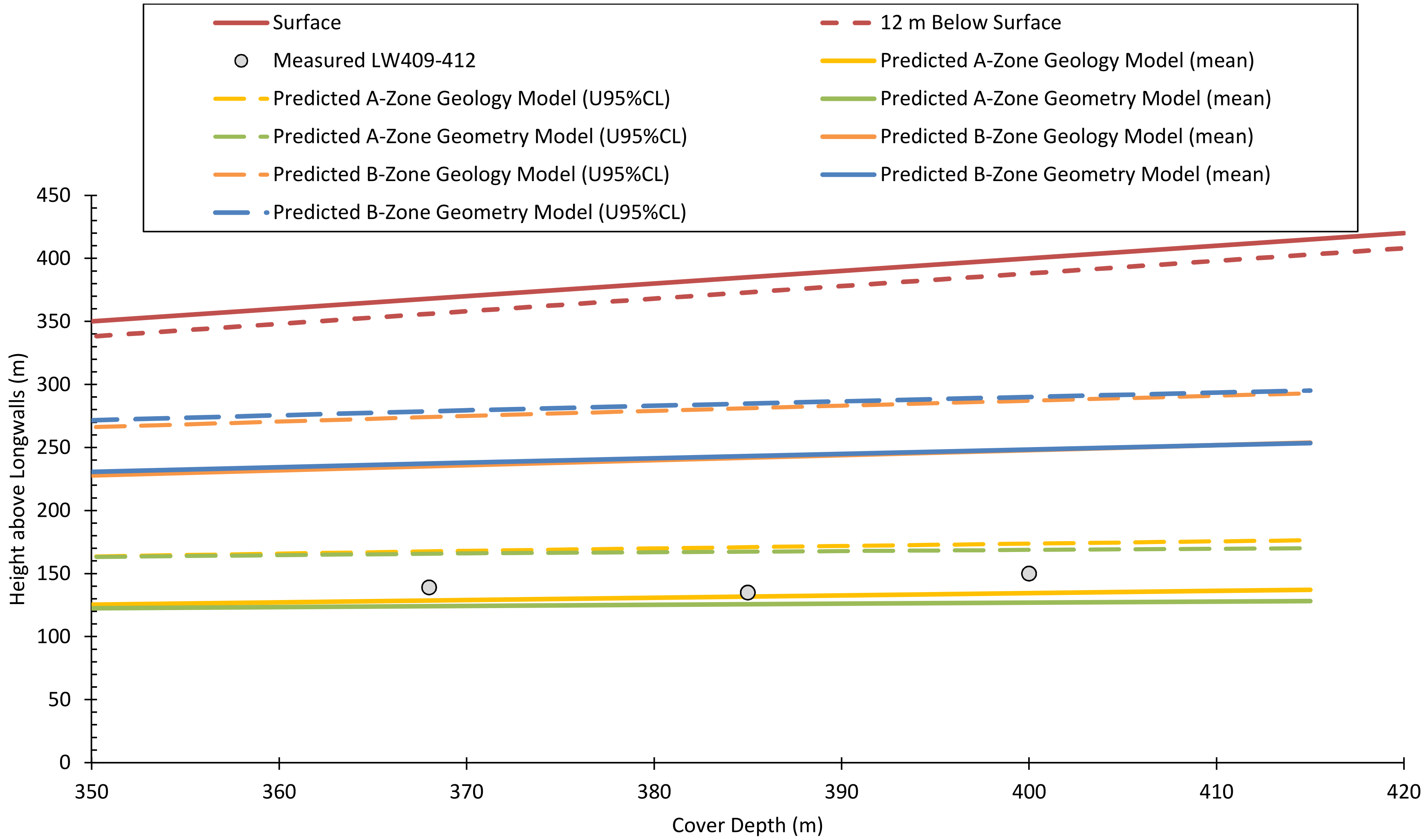
DgS	Engineer:	S.Ditton	Client:	Springvale Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A and B-Zones) for Proposed Springvale Mine LWs 416 to 423		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	8b



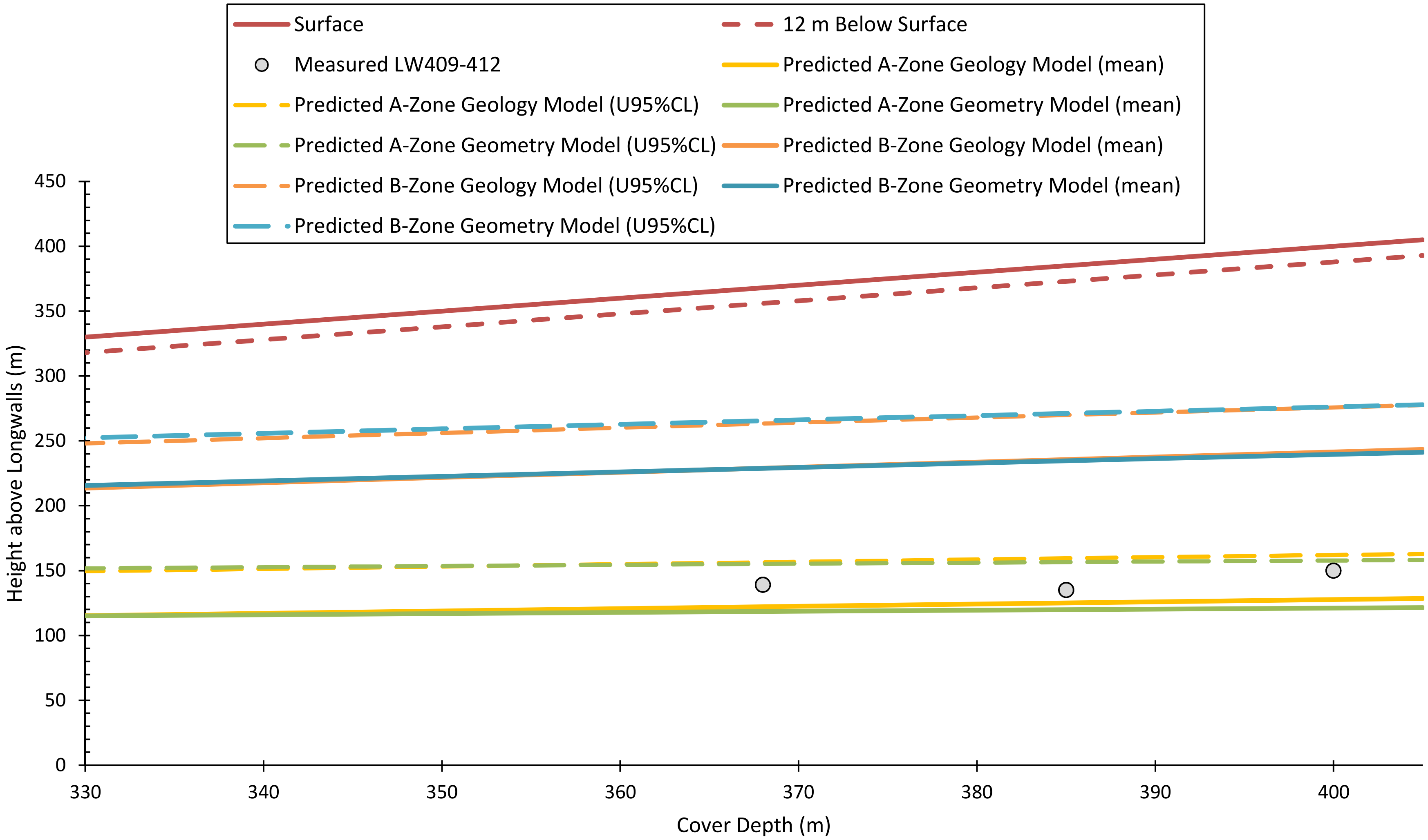
Key:

- Seam YS6
- Seam MYC
- Seam MDRU
- Seam DEN
- Seam LTH

DgS Ditton Geotechnical Services Pty Ltd	Engineer: S.Ditton Drawn: S.Ditton Date: 17.08.14	Client:	Centennial Springvale SPV-003/7b
		Title:	Stratigraphy Section and Predicted Sub-Surface Fracture Zone Horizons for the Ridge Piezometers
		Scale:	NTS — Figure No: 8c



DgS	Engineer:	S.Ditton	Client:	Springvale Pty Ltd SPV-003/7b		
	Drawn:	S.Ditton				
	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A and B-Zones) for the Proposed Springvale Mine Extension Area LWs 424 to 431		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	9a



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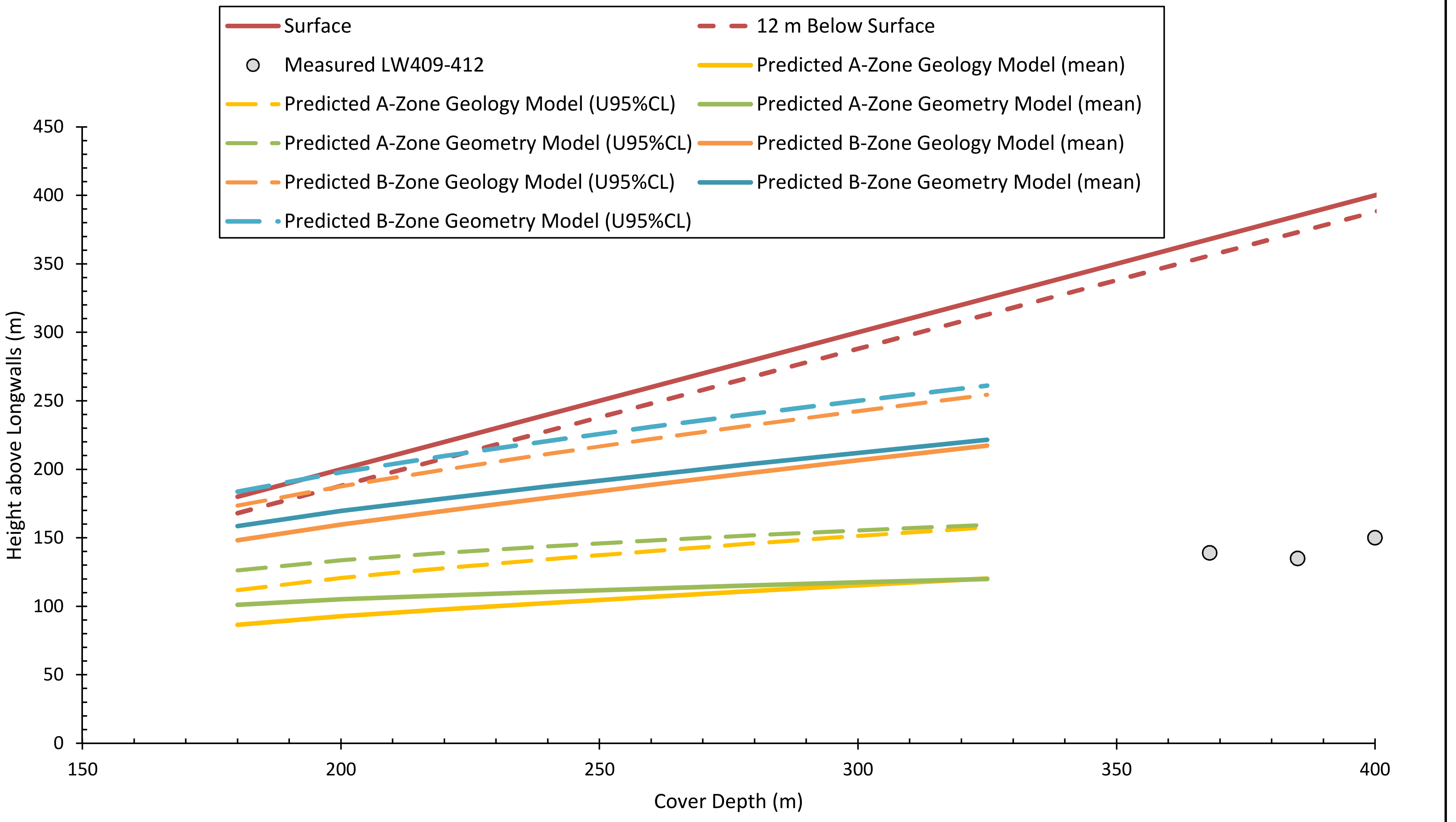
	Drawn:	S.Ditton					
	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A and B-Zones) for the Proposed Springvale Mine extension Area LW 432			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	9b	



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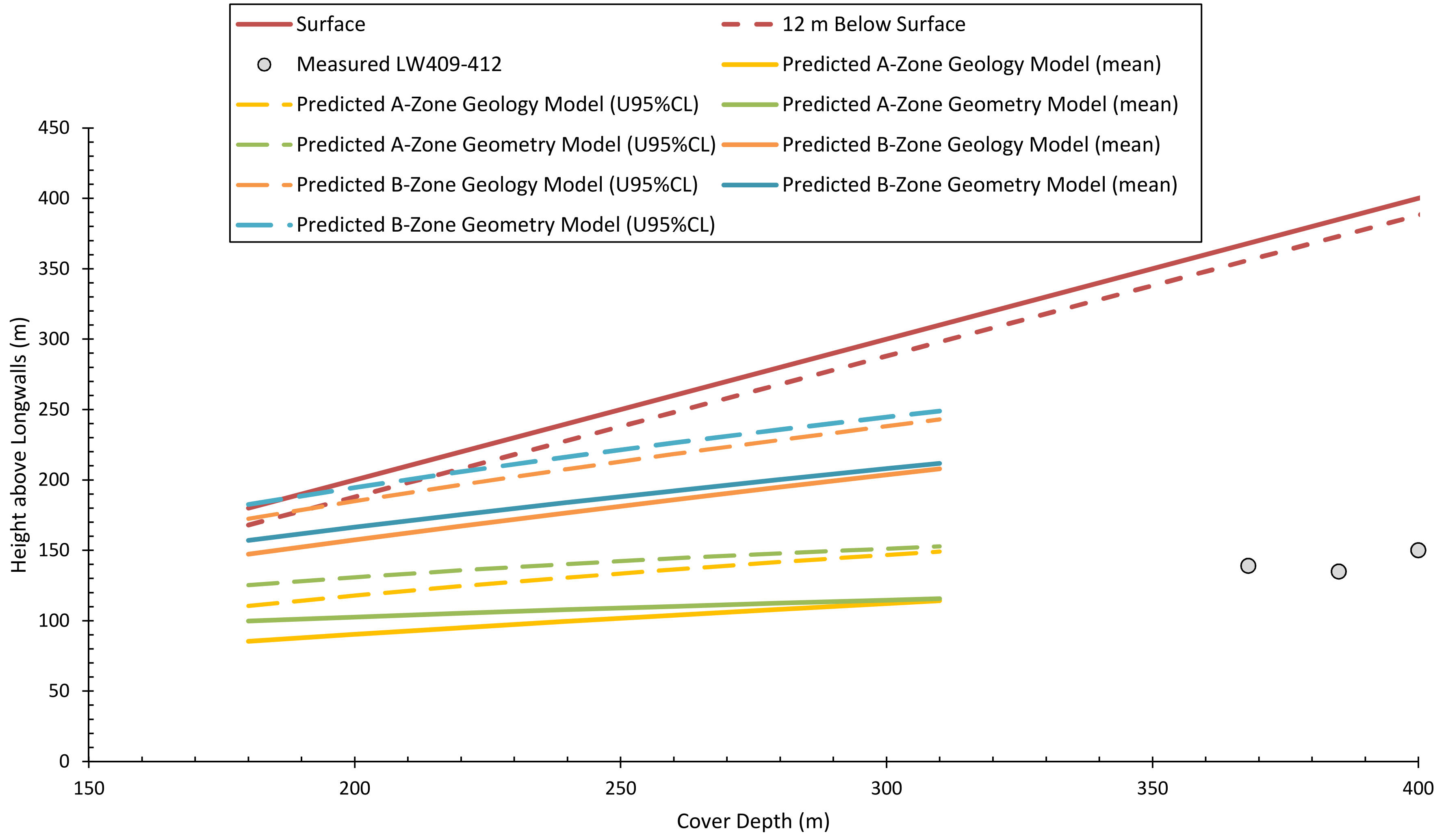

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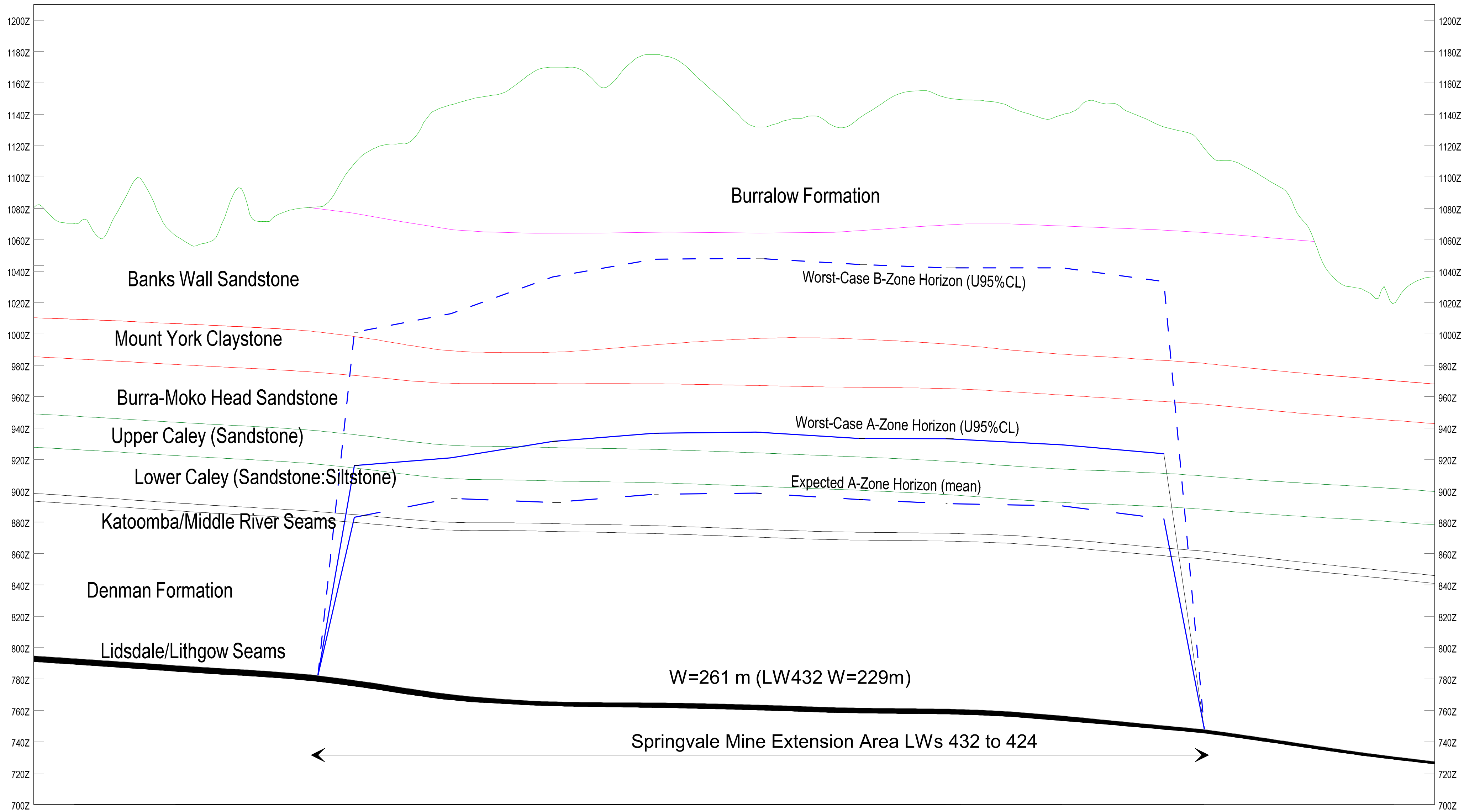
	Drawn:	S.Ditton		SPV-003/7b		
	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A and B-Zones) for the Proposed Springvale Mine Extension Area LW 502		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	9d



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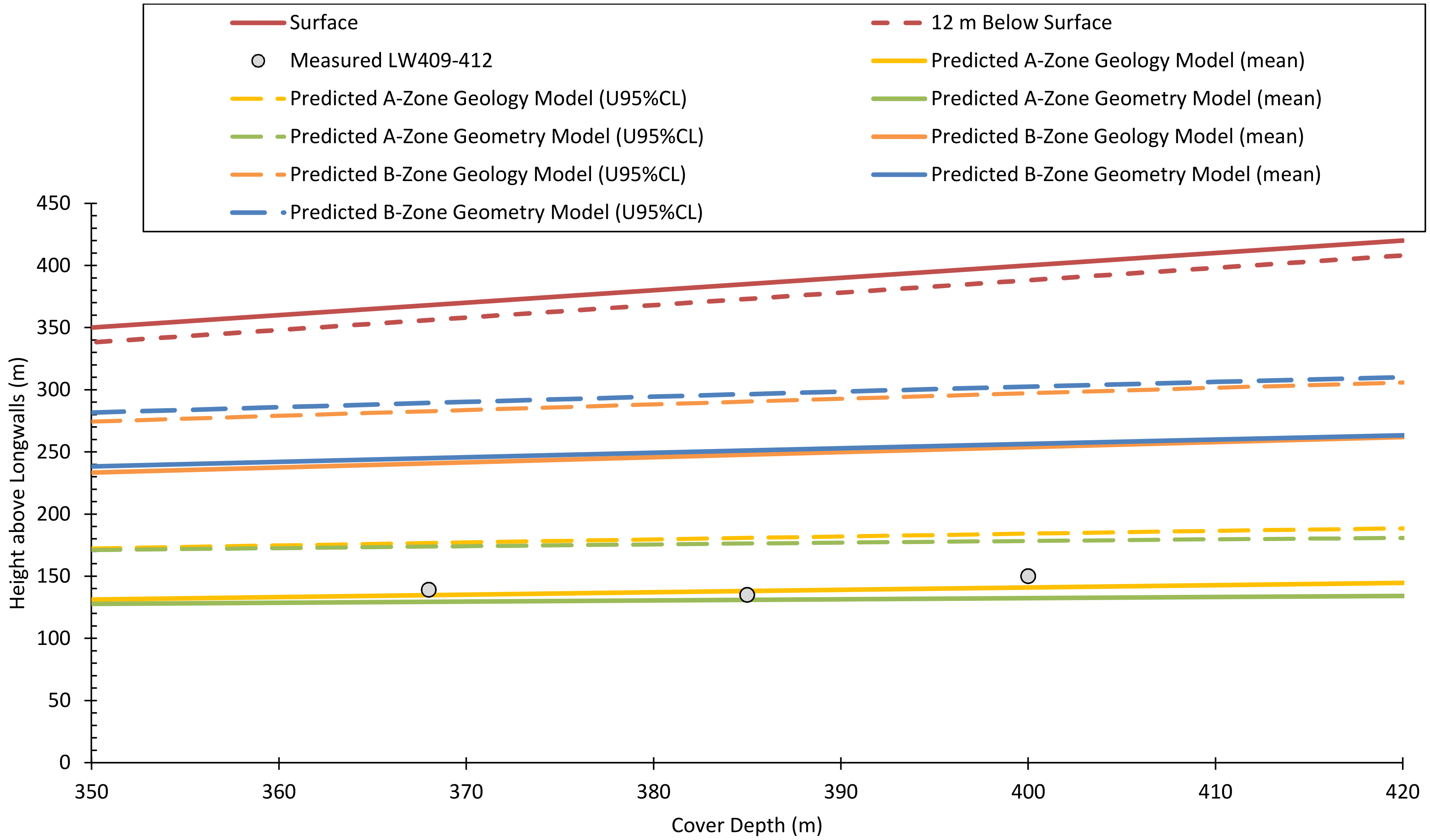
	Drawn:	S.Ditton		
	Date:	17.08.14	Title:	Stratigraphy Section and Predicted Sub-Surface Fracture Zone Horizons for the Proposed Springvale Mine Extension Project Area LWs 432 to 424
	Ditton Geotechnical Services Pty Ltd			
			Scale:	NTS
			Figure No:	9e



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	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A and B-Zones) for Proposed Angus Place Mine Extension Area LWs 1001 to 1003
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS
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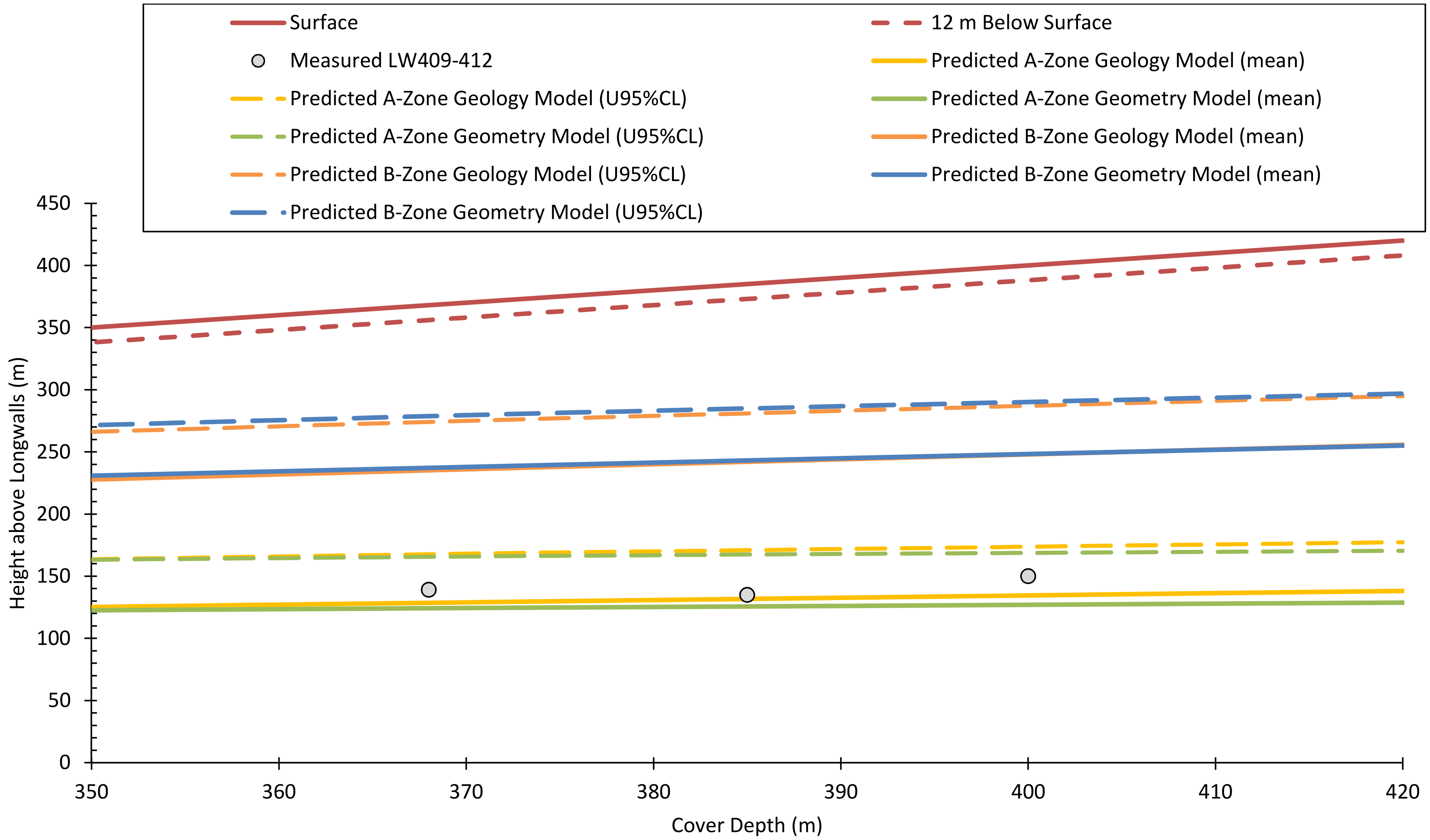

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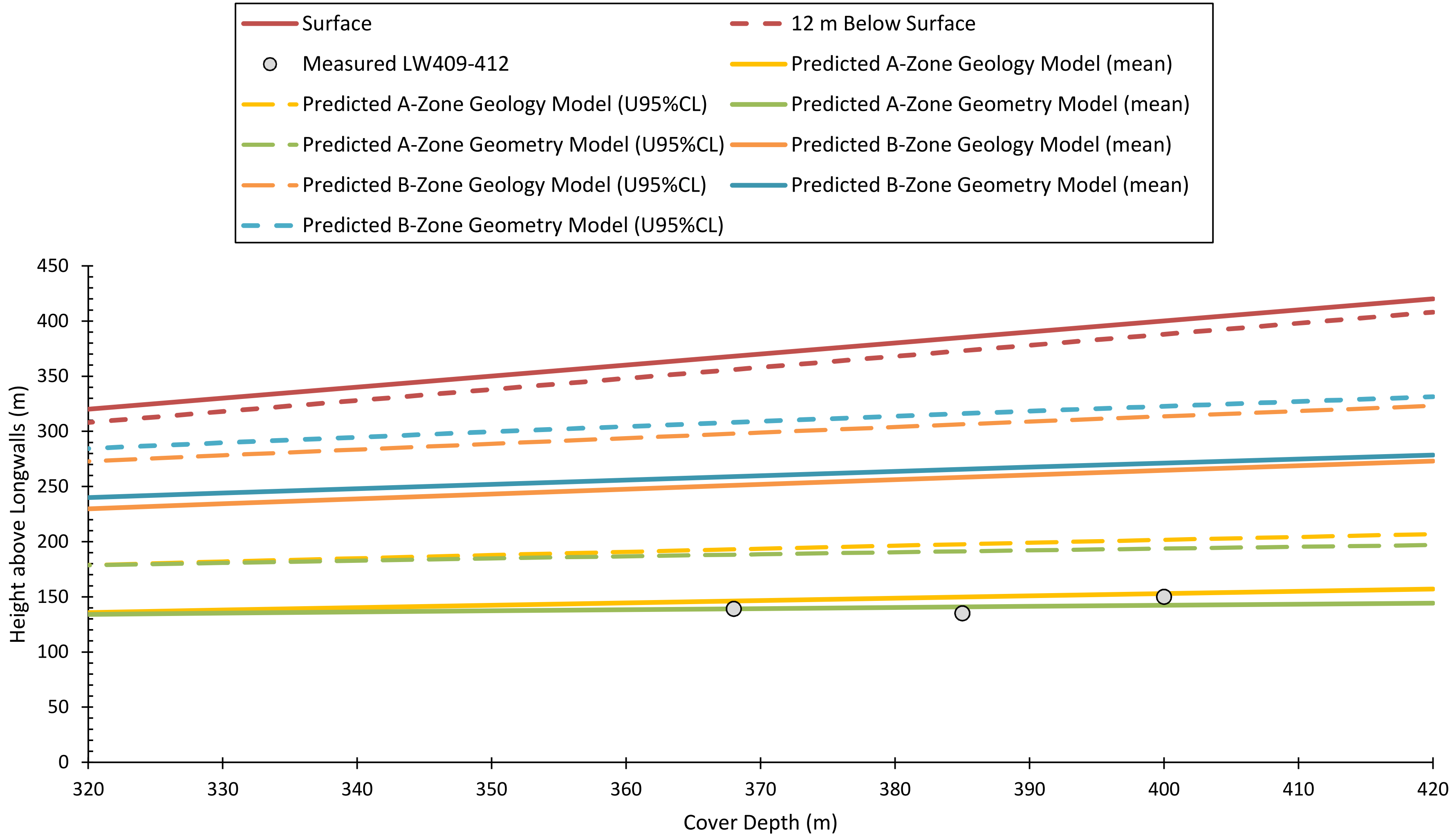
	Drawn:	S.Ditton				
	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A & B Zones) for Proposed Angus Place Mine Extension Area LWs 1004-1006 & 1016-1017		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	10b



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	Date:	11.08.14	Title:	Predicted Continuous and Discontinuous Sub-Surface Fracture Heights (A & B Zones) for Proposed Angus Place Mine Extension Area LWs 1007-1015 & 1018-19		
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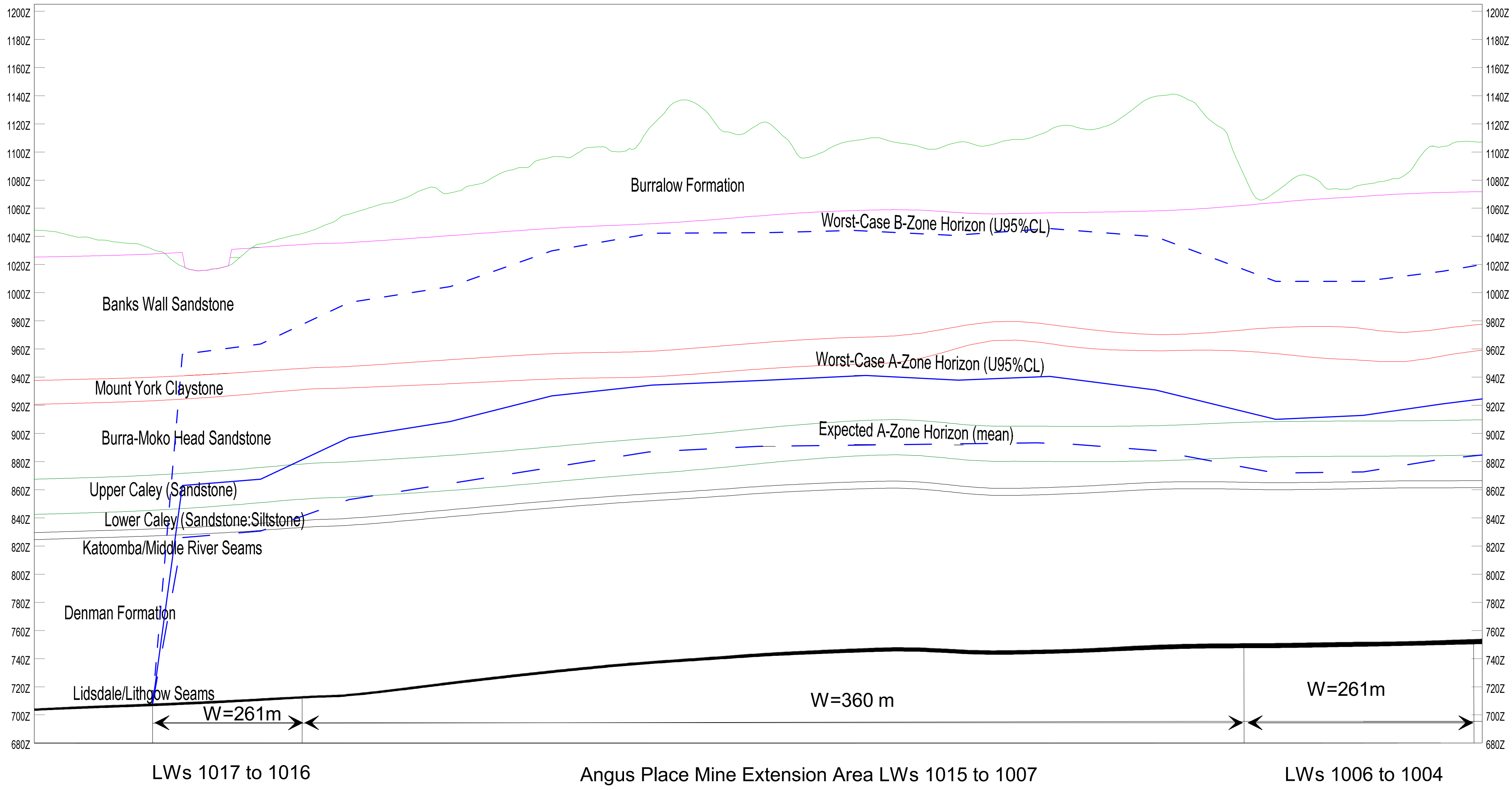

DgS Ditton Geotechnical Services Pty Ltd				
Engineer:	S.Ditton	Client:	Centennial Springvale SPV-003/7b	
Drawn:	S.Ditton			
Date:	17.08.14	Title:	Stratigraphy Section and Predicted Sub-Surface Fracture Zone Horizons for the Proposed Angus Place Mine Extension Area LWs 1004 to 1017	
		Scale:	NTS	Figure No: 10d

Attachment A - Height of Subsurface Fracturing Review and Pi-Term Model Development Details

A11 Sub-Surface Fracturing Model

A11.1 Sub-Surface Fracturing Zones

The caving and subsidence development processes above a longwall panel usually result in sub-surface fracturing and shearing of sedimentary strata in the overburden, according to **Peng and Chiang, 1984** (see **Figure A40a**) and **Whittaker and Reddish, 1989** (see **Figure A40b**). The height of fracturing (HoF) is dependent on mining geometry and overburden geology.

International and Australian research on longwall mining interaction with groundwater systems indicates that the overburden may be divided into essentially four or five zones of surface and subsurface fracturing. The zones are defined in **Table A4** (in descending order):

Table A4 - Sub-Surface Fracture Zone Summary

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 dependant 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 (included in 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 characteristics of each HoF zone are further described below:

Starting from the seam level, the **Caved Zone** (included in the **A-Zone**) refers to the immediate mine workings roof above the extracted panel, which has collapsed into the void left after the coal seam has been extracted. The Caved Zone usually extends for 3 to 5 times the mining height, T, above the roof of the mine workings due to bulking factors of 1.3 to 1.5, and sometimes from 10 to 15T if the strata have low bulking properties (e.g. bulking factors of 1.10 to 1.15). Thinly bedded and laminated strata are likely to have lower bulking factors than thickly bedded or massive units within the Caved Zone.

The **Continuous Fracture Zone (A-Zone)** has been affected by a high degree of bending deformation, resulting in significant fracturing and bedding parting separation and shearing of the rock mass. Vertical tensile strains range from -10 to 140 mm/m with strata dilation in excess of 1 m. Compressive strains tend to develop at horizontal bedding separations after initial fracturing and overlying strata deflections occur resulting in re-compaction of the goaf and disturbed strata.

Continuous sub-surface fracturing refers to the zone of cracking above a longwall panel that is likely to result in a direct flow-path or hydraulic connection to the workings. All groundwater (or surface waters) within this Zone would be expected to drain vertically into the mine workings goaf.

The **Strata Dilation Zone (B-Zone)** refers to the section of overburden immediately above the A-Zone that has also been deformed by bending action, but to a lesser degree than the A-Zone. The B-Zone will have bedding parting separations and discontinuous fractures through bending strata units due to vertical strains ranging from -2 to 8 mm/m and strata dilation from 30 mm to 400 mm, depending on the panel width. An increase to horizontal rock mass permeability (hydraulic conductivity) is expected in the B-Zone with groundwater flowing horizontally into dilated strata.

Only minor vertical permeability increases are expected in the B-Zone due to alternating horizontal tensile and compression zones associated with Voussoir Beam action above the A-Zone. It is noted in **Whittaker and Reddish, 1989**, that some groundwater leakage from the B-Zone to the A-Zone is possible due to limited crack or joint interaction between the zones.

Overall, the majority of the B-Zone is considered to be a ‘constrained’ and ‘dilated’ zone with low connectivity potential to the mine workings. The B-Zone therefore represents a sub-surface fracturing zone that causes temporary groundwater system disturbance.

The **Elastic Deformation Zone (C-Zone)** is located above the B Zone and is the zone where the strata may have suffered minor bending and disturbance. Impacts include horizontal shearing and minor bed separations or dilation of up to 30 mm due to vertical tensile strains between 1 and 2 mm/m. The bedding separations may result in minor increases to horizontal hydraulic conductivity and negligible changes to vertical hydraulic conductivity. Groundwater system disturbance is expected to be negligible in this zone.

The development of the Elastic Deformation Zone (C-Zone) will depend on the mining geometry and the presence of spanning strata. The C-Zone is probably only likely to develop above critical to sub-critical mining geometries (i.e. W/H < 1.4) but may also be present above super-critical panels also if favourable geological conditions exist.

The strata in the B and C-Zones are also likely to be in compression due to natural arch formation (above sub-critical and critical panels). The arch will also act as barrier to vertical drainage of groundwater despite the presence of naturally occurring vertical joints in the rock mass. Low permeability strata such as claystone, tuff and mudstone will also limit rock mass 'gaps' and further retard vertical flow rates through these zones.

In the absence of significant geological structure (i.e. faults and dykes), the overall effect on the surface groundwater system due to leakage through the B and C-Zones will be minimal, with re-charging of groundwater losses likely to occur from the surface hydrological system. The presence of significant geological structure may increase the drainage rates through these strata zones however. Monitoring of mine groundwater makes v. rainfall - runoff data will determine the rate of leakage that is occurring through these zones.

The **Surface Cracking Zone (D-Zone)** includes the vertical cracking due to horizontal tensile and compressive strains caused by mine subsidence deformation. The D-Zone may extend to depths ranging from 5 m to 20 m (typically < 15 m) in the Newcastle Coalfield, and is dependent on near-surface geology and surface topography.

For mine design purposes, typical D-Zone depths in relatively flat terrain may be assumed to range from 10 m to 12 m (i.e. < 15m). *Note:* ***Forster and Enever, 1992*** *adopted a D-Zone thickness of <15 m based on data from Wyee and Cooranbong Collieries, and included it in the minimum cover depth formula of 45T+10 m for designing supercritical panels below tidal waters of Lake Macquarie in the Newcastle Coalfields.*

A11.2 Impact on Rock Mass Permeability

In regards to changes to rock mass permeability, **Forster, 1995** indicates that horizontal permeabilities in the fractured zones above longwall mines could increase by 2 to 4 orders of magnitude (e.g. pre-mining $k_h = 10^{-9}$ to 10^{-10} m/s; post-mining $k_h = 10^{-7}$ to 10^{-6} m/s).

Vertical permeability's could not be measured directly from the boreholes but could be inferred by assuming complete pressure loss in the 'A Zone', where direct hydraulic connection to the workings occurs. Only a slight increase in the 'B zone' or indirect / discontinuous fracturing develops (mainly due to increase in storage capacity) from bedding parting separation. It is possible that minor vertical flows will occur from B zone into A zone (and workings) as well.

Discontinuous fracturing would be expected to increase rock mass storage capacity and horizontal permeability without direct hydraulic connection to the workings. Rock mass permeability is unlikely to increase significantly outside the limits of extraction.

A11.3 Mine Design Criteria for Sub-Surface Fracture Height Control

When designing mining layouts for sub-surface fracture control, the A-Zone is the most significant in regards to groundwater and surface water interaction as it represents the region of broken ground whereby a hydraulic connection to the mine workings will most certainly occur.

The B-Zone is probably just as important as it represents the transition zone between the continuously fractured ground and elastic deformation or surface zones. The B-Zone also includes strata which are confined and where bedding parting separations (i.e. dilations) occur in the sagging rock mass above the caved and broken strata units in the A-Zone.

The C-Zone has been deformed as well, but not to the same extent as the B-Zone.

Note: It is difficult to define the boundary between the B and C-Zones without vertical strain measurements from extensometers. Both zones are considered to be 'constrained' and 'dilated' and will act as an effective barrier between the A-Zone and near surface groundwater and surface watercourses.

The formation and thickness of the HoF Zones will firstly be dependent on the 'criticality' of the proposed longwall panel. The same terms used for subsidence prediction are also referred to below and are based on the ratio between panel width (W) and the cover depth (H) at Springvale Colliery:

- Subcritical refers to panels with W/H < 0.9;
- Critical refers to panels with W/H > 0.9 and < 1.4; and
- Supercritical refers to panels with W/H > 1.4.

Several case studies have been referred to below which consider super-critical and sub-critical panel geometries separately due to their fundamental differences in spanning behaviour.

Conceptual models of the A and B-Zones above supercritical panels are presented in **Whittaker & Reddish, 1998** and are based on physical modelling results. **Forster and Enever, 1992** indicated similar strata zoning from field monitoring (**Figure A40c**) above supercritical, total pillar extraction panels in the Lake Macquarie Area of the Newcastle Coalfield.

A conceptual model that includes the B and C-Zones was presented in **ACARP, 2007** (**Figure A40d**) for sub-critical mining geometries in the Western Coalfield. A similar sub-surface fracture zoning is also suggested by **Mark, 2007** (**Figure A40e**) for the US Coalfields and **Kendorski, 1993** for the UK Coalfields (**Figure A40f**).

From the above conceptual height of fracturing models, several simple empirical models have been developed over the years to estimate the thicknesses of the A, B and C-Zones for the purpose of avoiding groundwater and surface water connectivity with underground mines.

The suite of HoF prediction models that probably represent the state-of-the-art are summarised in the following sections.

A11.3.1 Wardell, 1975, Reynolds, 1977 and Singh and Kendorski, 1981

Wardell, 1975 recommended a minimum rock cover depth of 50T - Surface Zone thickness above total extraction or longwall panels when mining under tidal waters in the Newcastle Coalfield. The minimum cover depth (H) was based on a maximum horizontal tensile strain limit of 7.5 mm/m and the Newcastle Holla curves. It is noted that a maximum horizontal tensile strain of 10 mm/m has been specified in the UK when mining below permanent waters.

Wardell has also recommended a minimum cover depth of 60T (which included a Surface Zone thickness ranging from 12 m to 15 m) for mining below stored waters with longwalls in the Southern Coalfield.

The Wardell Guidelines recommended that panel widths should be limited to <0.4H to maximize the thickness of the Constrained Zone (i.e. B and C-Zones) beneath tidal waters. **Reynolds, 1977** recommended 0.33H for maximum panel widths at depths more than 120 m below the reservoirs in the Southern Coalfield.

The height of continuous fracturing was not estimated in the Wardell Guidelines, but probably assumed to be significantly lower than 50T - the 15 m thick surface cracking zone. **Holla, 1991** noted that the 60T value is dependent on the S_{max} and K ratio (and hence W/H ratio) and should not be applied blindly to all mining geometries.

Singh and Kendorski, 1981 adopted a general height of A-Zone Fracturing of $56T^{0.5}$ based on a review of international case studies with a minimum Constrained plus Surface Zone thickness of 45 m for mudstone and 57 m for sandstone strata conditions when mining below tidal waters. The model recognizes that fracturing may extend further through massive strata than thinly bedded units due to their propensity to carry greater load.

A11.3.2 Whittaker and Reddish Physical Model, 1989

It is considered that the published physical modeling work in **Whittaker and Reddish, 1989** provides valuable insight into the mechanics of sub-surface fracturing over longwall panels. The outcomes included specific guidelines (over and above such work as the Wardell, 1975 Guidelines) for the prevention of inundation of mine workings beneath surface and sub-surface water bodies.

The **Whittaker and Reddish, 1989** height of fracturing model was developed in response to the water ingress problems associated with early longwall extraction at the Wistow Mine in Selby, UK. The longwall panel was located at 350 m depth and experienced groundwater inflows of 121 to 136 litres/sec when sub-surface fracturing intersected a limestone aquifer 77 m above the seam.

The physical model is a scaled down version of the real-world, and therefore requires compatible material strength properties (i.e. plaster) to generate fracturing from the laboratory-sized void widths and mining heights being simulated. The pattern of cracking and heights of fracturing observed should therefore not be dismissed because of the materials used to create the model.

The Whittaker and Reddish model identifies two distinct zones of fracturing above super-critical width extractions (continuous A-Zone and discontinuous B-Zone fracturing) and indicates the height of each is a function of maximum tensile strain at the surface. As such, its use is also based upon being able to make credible subsidence and strain predictions. The mechanical concepts of the model are shown in **Figure A40b**.

The definition of the 'continuous' height of fracturing refers to the height in which a zone of direct hydraulic connection for groundwater inflows to the mine workings develops (i.e. the A-Zone).

The definition of the extent of 'discontinuous' height of fracturing refers to the height at which the horizontal permeability increases as a result of strata de-lamination and incomplete fracturing through the strata beds (i.e. the B-Zone). Minor occurrences of direct connection of fractures to the workings is considered possible, but will depend on the geology (e.g. the presence of persistent vertical structure such as faults and dykes).
The outcomes of the modeling work resulted in two logarithmic type curves that relate the surface horizontal strain to the measured A and B fracture heights normalized to the cover depth (see **Figure A40b**).

The physical modeling work that was completed to derive the prediction curves is summarised below:

- The physical model was constructed from multiple 1.25 cm thick layers of coloured sand and plaster with sawdust bond breakers placed between each successive layer. Based on a real world/model ratio of 92, the model layers represented 1.15 m thick layers in the real world. The model was initially devoid of vertical joints or cracks.

- The scale and mechanical properties of the model satisfied dimensional analysis and similitude laws. *Note: This aspect of mechanical models is very important, as overburden strength properties will not fracture if they are too high for the model's mining geometry.*

- The plaster layers for the model were equivalent to a rock mass with a density of 2.35 t/m^3, a UCS of 10.94 MPa and Youngs Modulus, E, of 984 MPa.

- The model was used to simulate the overburden behaviour of a panel with a W/H ratio of 1.31 and a progressively increasing working height range that commenced at 1.2 m and finished at 10.8 m. The advancing longwall face was simulated by removing timber blocks at the base of the model in 1.2 m to 2.0 m lift stages.

- The extent or heights of ‘continuous’ and ‘discontinuous’ fracturing above the longwall ‘face’ were measured and plotted with the associated peak tensile strain predictions at the surface. The subsidence and strains were measured from a grid and calculated using the method provided in the **UK Subsidence Engineers Handbook, 1975**.

- The fracturing path progressed up at an inward angle of approximately 18° to 19° from the solid rib and increased towards the centre of the panel higher up into the strata. Continuous fracturing occurred in the cantilever bending zone close to the rib-side only, as fracturing in the overburden above the middle portion of the panel tended to ‘close’ and did not appear to represent an area where groundwater inflows into the workings would eventuate.

- Surface cracks extended down from the surface for a depth up to 7.5 m.

- Other similar models were also prepared and used to demonstrate the “ability of strong overburden at the surface to cause bridging of the strata in this manner is dependent upon the strength and general competence of the rocks near to the surface, in addition to the width of the extracted region.”

- Any groundwater inflow conditions were therefore considered to be “mainly associated with the longwall rib-side fracture zone [or tensile strain zone]” above longwall panels.

The findings above are considered reasonable for super-critical longwall geometries where panel widths are greater than the critical width (i.e. 1.2 - 1.4H) and the height of fracturing is likely to be controlled primarily by the mining height and strata properties.

Using the analytical model equations derived in **Section A11.4.2**, the progression of the height of continuous fracturing was back analysed by DgS using the maximum compressive beam stress for spanning strata units under full loading conditions (Equation 1) and goaf supported strata units (Equation 2):

$$\sigma_c = 0.75\gamma(H - A)(W - 2A\tan\theta)^2/t_i^2 \quad \text{(Lower Beam)} \quad (1)$$

$$\sigma_c = 4\Delta E t_i/(W - 2A\tan\theta)^2 \quad \text{(Upper Beams)} \quad (2)$$

It was noted that the goaf did not ‘bulk’ in the model, resulting in no reduction in subsidence between the seam and surface (i.e. $S_{max} = T$) and measured surface strain/curvature ratio indicated $\Delta = 0.5T$ over the effective span, $W_i = W - 2y\tan\theta$ above the goaf.

The results of the model are summarized in **Table A5** below:

Table A5 - Physical Model Results Summary for the Height of Continuous Fracturing Development above a Supercritical Longwall Panel

Lift No	Mining Height T (m)	S_{max} (m)	E_{max} (mm/m)	A (m)	Effective Beam Span W_i (m)	Measured Beam Curvature in Spanning Strata (km^{-1})	Measured Effective Beam Thickness t_i (m)	Stress in Lowest Beam after Lift & Prior to Collapse (MPa)	Stress in Spanning Unit above Goaf (MPa)	Predicted Minimum Beam Thickness Required to Span Goaf (m)
1	1.2	1.2	7.6	23.96	137.55	0.51	105 (47.9)	12.0	4.82	**56.7**
2	2.4	2.4	15.3	43.26	120.77	0.66	81 (38.6)	12.5	7.81	**43.6**
3	4.2	4.2	26.8	67.38	107.25	1.46	62 (24.1)	17.3	6.55	*26.6*
4	6.0	6.0	38.2	85.60	90.36	2.94	38 (18.2) (9.1)	13.8	10.10	*10.8*
5	8.4	8.4	53.5	99.57	77.60	5.58	19.4 (14) (7)	19.2	7.45	*5.6*
6	10.8	10.8	68.8	105.0	67.81	9.39	5.4 (2.7)	12.5	-	*3.0*

Wi = Effective Span above mine workings at A-Zone Limit Horizon (W - 2Atanθ).
(9.1) - Bedding thickness halved as bedding sheared under load > it's shear strength during test.
Bold - stress limited to UCS based on full cover load (Equation 1).
italics - stress limited to UCS based on deflecting strata curvature (Equation 2).
UCS = 10.94 MPa; E = 984 MPa; θ=19.3°.

The measured strata unit thickness (t_i) required to span the goaf voids and limit the height of continuous fracturing (A) after each successive lift were back-analysed using the measured A-Zone heights and Equation (2); see **Figure A40g**. The minimum beam thickness required to span the goaf was also estimated based on the two analytical model Equations (1) and (2) and compared to the measured beam thickness at the A-Horizon in **Figure A40h**.

Several further salient points are apparent from the results as follows:

- After extraction of the panel, all of the spanning units deflected under gravity loading until the tensile, shear and compressive stresses in some of the rock mass bedding units were exceeded.

- It was apparent from the modelling data that the overburden above each mining stage resulted in the beam shearing into two or three separate beams, with the lower beam collapsing and the upper beam(s) left to span the void. It is noted that the maximum shear stress acting on the initial beam would have developed on the bedding surface near the middle of the beam section, so it would be expected to shear or slip there first.

- If the strata unit separated from the overlying rock mass, it either collapsed into the void below (if the stress exceeded the UCS of the beam) or it was thick enough to span under its own self weight. The sagging beam units were also supported by the underlying goaf to some degree.

- The rock mass units caved up into the overburden at an angle of break (θ) and effectively reduced the span of overlying units to $W_i = W\text{-}2y\tan(\theta)$.The potential load acting on the strata units also decreased linearly with the reduction in overlying cover.

- The height of continuous fracturing (i.e. the A-Zone) was defined as the point where the overlying strata were spanning the cracked and collapsed strata below it.

- The A-Zone height increased after the mining height T was increased, with no change to panel width or cover depth.

- The strata units continued to deflect after each incremental increase in mining height, with the lower units collapsing when the UCS of the beam was exceeded. In some of the lifts, it is apparent that the spanning strata units sheared into units that were approximately half the thickness of the original spanning beam. The beam stress was also subsequently decreased if shearing occurred. Estimates of shear stress at mid-beam thickness exceeded the shear strength of the strata unit (or bedding plane surface) in these instances, assuming a friction angle of 20^o along the bedding planes.

- The spanning strata lost stiffness when their thickness was decreased, resulting in further deflection (and stress acting in the beam).

- Collapsed strata units provided support to the sagging strata above and ultimately controlled the deflection of the overlying units.

- The A/T ratio ranged from 20 to 10 as the mining height increased from 1.2 m to 10.8 m. For real world mining heights of 2.4 m to 6 m, the A/T ranged from 18 to 14.

Further discussion on the analytical height of fracturing models for real world conditions is presented in **Section A11.4.2**.

A11.3.3 Forster and Enever, 1992

A comprehensive monitoring program above two supercritical pillar extraction and one longwall panel in the Great Northern Seam was presented in **Forster and Enever, 1992**.

The outcomes of the work was to recommend a reduction in the minimum rock cover limit required to extract coal beneath Lake Macquarie to 45T + 10 m, and was based on borehole piezometric and rock mass permeability testing before and after total extraction mining. The 10 m was not added to account for the surface cracking zone, but to allow for localized depressions that could reduce the rock cover thickness to < 45T. The surface cracking zone of <15 m was therefore included in the 45T+10 m criterion.

The height of continuous fracture zone was assessed to have ranged between 21T and 33T above the mine workings. The thickness of the Constrained Zone was defined as being dependent on the cover depth, but should be > 12T + 10 m below tidal waters.

The thickness of the 'Constrained Zone' above the 'Fractured Zone' was also considered to have greater importance in regards to providing a groundwater drainage path barrier than the tensile strain limit of 7.5 mm/m set by **Wardell, 1975**. It was considered that the thickness of the Constrained Zone and the presence of low permeability lithologies, such as mudstone and claystone, were more likely to influence the performance of the strata barrier above the A-Zone than putting a limit on surface strain. The strain limit criterion has subsequently been left out of sub-aqueous mine design criteria in NSW Coalfields.

A11.3.4 ACARP, 2006

This report reviews the impacts of shallow longwall mining on the groundwater systems based on fieldwork conducted in the Hunter Valley, NSW (Beltana Mine) and Bowen Basin, Queensland (Gregory Crinum Mine).

The **ACARP, 2006** report suggests that continuous cracking is likely to occur through the strata beams within the Fractured Zone defined by an "angle of break" of 12^o to the vertical and extending inwardly from the rib-sides. International research suggests a range between 10^o and 15^o.

A complementary set of fractures would also be expected to develop further inside the panel on the undersides of the bending units where full subsidence develops in the strata. The angle to full subsidence ranges from 25^o to the vertical according to **ACARP, 2006** and from 32^o to 45^o in **Li and Cairns, 2000**.

Back analysis of the angles of break suggest that surface to seam cracking could theoretically reach the surface above panels that are wide enough to prevent the opposing cantilevering abutments to interact together and limit fracturing. For a panel width of 200 m, this would occur where cover depths are < 370 m to 470 m (due to angles of break of 12^o to 15^o). It is also noted that the inferred height of fracturing is very sensitive to the assumed angle of break.

Note: The panel geometry discussed is actually still in the sub-critical range (i.e. W/H < 0.7) and it is considered by DgS that theoretical fracturing to the surface can only occur in the critical to supercritical panel width range.

ACARP, 2006 also notes an absence of surface to seam fracturing connection or groundwater inflows in the literature, where sub-aqueous mining has occurred below a depth of cover of 120 m to 160 m (for assumed critical to super-critical panel widths). The reason for this phenomenon is considered to be related to the observation that cracked and rotated blocks may still interact and provide low permeability regions in the zones of compressive strain above and below tensile cracking in the deflected beams. It was assessed that the reduction in effective span due to the cantilever effect over the ribs and increase in support that develops to overlying strata units may also allow strata units as thin as 10 m or so span across the fractured zone.

The report concluded that the height of continuous fracturing is therefore likely to be controlled by either spanning strata units or units that are not spanning which are thick enough to stop fracturing occurring right through the unit.

In the case of the non-spanning strata mechanism, **ACARP, 2006** did not have the resources available to fully evaluate what the minimum strata thickness range is likely to be in order to limit the continuous fracturing height.

Note: A similar conclusion was reached by DgS after a case by case review by DgS of supercritical longwall geometries in the NSW Coalfields in this study. It is also considered likely that this phenomenon would require the compressive stress in the deformed rock mass units to exceed their unconfined compressive strength for complete break-through to occur. However, it is also apparent that the presence of thin strata units that deform predominately in shear along slipping bedding partings, can also limit vertical cracking developing to the surface cracking zones.

A11.3.5 MSEC, 2011 and SCT, 2001

The MSEC and SCT models are based on several published case-studies for mining impacts in the NSW Coalfields and their own internal analytical and numerical modeling results. The 'heights of fracturing' are predicted based on longwall and total pillar extraction panel widths and indicate maximum values ranging from 1W to 1.5W (SCT) and 1.374 (W-30) (MSEC). The database of 'observed heights of fracturing' and the above panel width models are presented in **Figure A40i**.

Based on a review by DgS of the database from which the MSEC and SCT models are derived, and extensometer and vertical strain measurements at other mines, it is apparent that the models include cases of both A and B-Zone fracture heights (see **Figure A40j** and **Section 11.4** for further details). DgS concludes that the MSEC and SCT 'height of fracturing' models are probably conservative.

It is also apparent that there are three reported cases in the database which indicate 'fracturing through to the surface' has occurred (LW1 at Invincible, LW11 at Angus Place and LWE1 at South Bulga). A review of the extensometer data published by **Holla, 1991** for the Invincible case study, DgS concurs with the assessment that continuous fracturing has probably extended to the surface cracking zone (or to within 10 m below the surface). No data is available for the latter two cases, however, based on the above discussion, it is considered possible that surface to seam connectivity of the B-Zone (and not the A-Zone) occurred at these sites (further discussion on these sites are included in the following sections).

A11.3.6 Bulli Seam PAC, 2010

The NSW Government Planning and Assessment Commission (PAC) for the Bulli Seam Project Application in 2010 identified several apparent deficiencies in the commonly used 'height of sub-surface fracturing' models as follows:

- It is apparent that the prediction models based on panel width only indicated significantly greater sub-surface fracture heights than the models based on mining height.

- The panel width only-based models did not distinguish between continuous and discontinuous fracture heights.

- The authors and reviewers of the prediction models all recognize the deficiencies in the height of fracturing models that are based solely on panel width or mining height. They also indicate that more thorough analysis is probably required to determine a 'more definitive' function that relates the height of connective cracking to the mining geometry.

Based on the PAC report and review of available published data the following comments are made by DgS:

- The data on which the Panel Width-Only models are based are likely to include both A and B type fracturing zones (hence the review of MSEC and SCT database presented in **Figures A40i** & **A40j**).

- The Panel Width only models appear to have been developed mainly from data obtained at deep, sub-critical mines of the Southern and Western Coalfields.

- The height of fracturing is considered unlikely to extend further up into the strata once the critical panel width is reached (for a given mining height) and no further deformation of the overburden can occur.

- The behaviour of the overburden is more likely to be influenced by panel width for sub-critical panels and mining height for supercritical panels.

A11.3.7 State of the Art Summary and Gap Analysis for Alternative Models

In summary, the literature review outcomes indicate the following:

- The A-Zone is assessed to range from 21T to 33T above supercritical panels and up to 43T above critical and sub-critical panels. The B and C-Zone thicknesses will generally depend on the cover depth less the A-Zone Horizon estimate.

- The models that are based on the longwall panel widths only indicate maximum 'heights of fracturing' that range from 1.0W to 1.5W (SCT) and 1.374(W-30). These models however, probably include both A and B-Zone fracture heights in some instances and are therefore likely to be conservative.

- It is apparent that the published height of fracturing models based on mining height alone varies significantly for supercritical, critical and sub-critical mining geometries.

The A-Zone could (and does) extend higher up into the overburden above sub-critical panel geometries as the fracturing due to strata deformation is also influenced by the panel width.

- It is also reasonable to assume that the maximum height of the A-Zone will probably occur above the centre of a sub-critical longwall panel with a naturally spanning catenary arch.

- Surface drilling investigations above subsided longwall panels in NSW and QLD have found the maximum height of fracturing is in fact 'dome-shaped' and develops somewhere between the point of maximum tensile strain and the centre of the panels.

- In order to distinguish between A and B-Zones it is considered best-practice to install borehole extensometers and multiple-piezometers (deep and shallow) above longwall panels and measure the various fracture and dilated zones based on anchor displacements, vertical strain and the short to medium term impacts to established groundwater regimes.

- When longwall mining beneath lakes and sensitive groundwater aquifers, it is essential that the mining geometry be controlled to provide an effective B/C-Zone or Constrained Zone thickness to minimise the potential for connective cracking to develop up to the feature. The presence of geological structure should also be considered as it may act as a potential groundwater conduit between the A and B-Zones.

- Based on **Forster and Enever, 1992**, the minimum Constrained Zone (B/C Zone) thickness above the Fractured A-Zone should be >12T + 10 m and include the surface cracking zone thickness of <15 m beneath Lake Macquarie. The minimum B/C Zone thickness does not include weathered material and/or alluvial sediments.

- For cases where permanent water bodies do not exist, but surface to seam hydraulic connection is not desirable, it is recommended that the continuous height of fracturing zone should not encroach within the surface cracking zone (ie. A minimum of 10 m to 12 m below the surface should be assumed generally, but may need to be increased up to 20 m for steep topography affects).

- As mentioned earlier, the height of A-Zone fracturing is strongly dependant on the presence of the bridging capability of massive conglomerate or sandstone units above a given panel. Therefore, estimating the height of A and B-Zone fracturing also requires a review of the overburden lithology and the presence of geological structure.

- It is also apparent from a case by case review, that the height of fracturing may be controlled by strata that is not actually spanning, but may be thick enough or flexible enough to stop fracturing occurring right through the strata unit. For this scenario, it is considered the height of fracturing will be controlled by (i) the thickness and/or flexibility of the strata unit relative to the panel width and its location above the workings, (ii) the thickness of compressible goaf material that will induce curvature in the overlying strata units as the goaf is compressed, and (iii) the presence of confined, semi-impermeable strata units such as mudstone and claystone in the B and C-Zones that will swell in the presence of groundwater and effectively seal off small width cracks.

- For the case of sub-critical panels, the maximum non-spanning strata height and load acting on the goaf may be limited by the 'natural' or catenary arch that can form across the mined void width. It is noted that the A-Zone has not intersected the surface above any of the 13 sub-critical longwall panels in the NSW Coalfields.

- For super-critical panels however, the height of fracturing could theoretically reach the surface and the maximum load acting on the goaf will probably equal the cover depth. It is noted that the A-Zone has not intersected the surface above critical and supercritical panels at 17 out of 20 longwalls (85%) in NSW and Queensland Coalfields.

- Near surface geology will affect the potential for surface cracking to intersect the sub-surface fractures above supercritical longwall panels. Based on physical modelling results and mine site case studies, thinner and weaker strata units may actually reduce the likelihood of cracking zone interconnection compared to thicker and stronger units.

- Subsidence effect data (i.e. Horizontal strain/curvature ratios or K Factors) also suggest that the near surface strata will behave like a beam with a thickness equal to twice this ratio or the observed cracking depths (i.e. the depth to the neutral axis of bending). For the Newcastle Coalfield, the effective beam thickness ranges from 10 m to 30 m (i.e. K Factors of 5 to 15). The Western and Southern Coalfields have effective beam thickness ranges from 30 m to 60 m (i.e. K Factors of 15 to 30).

Based on the HoF prediction model review, it was considered necessary in this study to:

(i) review and expand the database of continuous and discontinuous cracking to include a representative range of mining geometries on which to base the empirical models on;

(ii) update and re-evaluate the **ACARP, 2003** models;

(iii) attempt to develop further subsurface fracturing models that included the panel width, mining height, cover depth and lithology (effective strata unit thicknesses and their properties).

(iv) provide a clearer definition of the surface cracking depth (D-Zone).

A11.4 Expansion of the Database and Review of Sub-Surface Fracturing Prediction Models Presented in ACARP, 2003

A recent review of the **ACARP, 2003** database and the inclusion of new HoF data has recently been undertaken by DgS in 2012 and 2013 for various projects in the Newcastle/Lake Macquarie and Hunter Valley Coalfields. The up-dated database is presented in **Table A6.1** and includes a greater number of cases where A and B-Zone fracture heights have been determined from borehole extensometer and piezometeric data collected over a reasonable period of time (i.e. > 12 months after mining impacts). Surface and groundwater interaction may also be established by other means in the absence of piezometers and extensometer results (e.g. mine water make increases several days or weeks (instead of months) after rainfall events, would indicate direct hydraulic connection to the surface).

The measured coalfield data base presented in **ACARP, 2003** was based mainly on a dataset of post-mining drilling data to estimate heights of fracturing for the A and B-Zones (except for the **Forster and Enever, 1992** data). The updated model database now includes further extensometer and/or piezometric data from the Southern, Western and Hunter Valley Coalfields in NSW, including Newcastle (West Wallsend, Mandalong, Wyee, Cooranbong, Teralba), Lower Hunter Valley (Abel, Austar, Ellalong); the Upper Hunter Valley (Homestead, Ashton, South Bulga), Southern Coalfield (Berrima, Metropolitan, Kemira, Belambi West, West Cliff, Tahmoor, Dendrobium, Appin) and the Western Coalfield (Springvale, Invincible). Two cases for Queensland (Oaky Creek and Crinum) were also included in the database.

Based on a review of published extensometer results presented in **Holla, 1991**, **Frith, 2006, MSEC, 2011** and **ACARP, 2007**, it is assessed that there are six cases in the database presented in **MSEC, 2011** that appear to include the A and B-Zones and four cases whereby the ‘height of fracturing’ are claimed to have reached the surface at distances above the workings of 21T (Homestead Mine, LWs 9/9A), 39T (Invincible Colliery, LW1), 57T (South Bulga, LWE1) and 106T (Angus Place, LW11).

In order to use the height of fracturing data presented in **MSEC, 2011** with the **ACARP, 2003** data, it was necessary to identify the likely A-Zone cases and B-Zone cases based on the following fracture zoning criteria:

(i) A-Zones are likely to have vertical strains > 20 mm/m and large strata dilations > 200 mm; and

(ii) B-Zones are likely to have vertical strains of < 8 mm/m and strata dilations < 200 mm, based on measured values for cases with piezometer-established B-Zone strains measured at other mines.

Note: it does not necessarily follow that uniform vertical strains throughout the strata mean the height of continuous fracturing is likely to have reached the surface. The uniform strains may also be due to strata bedding dilations if strains are < 8 mm/m. Rock mechanics theory also indicates that a vertical tensile strain of 8 - 9 mm/m will induce a horizontal tensile strain of 2 - 3 mm/m in the rock mass due to

Poisson's ratio effect. The theoretical strain to fracture a joint-free sample of rock is 0.3 to 0.6 mm/m. It has been observed in the field that existing joints and bedding in the rock mass allow it to 'absorb' higher levels of tensile strain before developing fresh cracks at around 2 - 3 mm/m. The use of the proposed vertical strain of 8 mm/m is therefore considered to be a reasonable indicator that fresh cracking is likely to occur in the rock mass.

The following cases were changed from A to B-Zone fracturing horizons or reinterpreted by DgS based on the above criteria:

- Tahmoor LW3 (extensometer interpretation by **Holla & Buizen, 1991**)
- Westcliff / Endeavour Drift BH3 (post-mining bore interpretation by **MSEC, 2006**)
- Angus Place LW11 (fractures to surface interpreted by **Kay, 1990**)
- Springvale LW411 (extensometer & piezometer interpretation by **CSIRO, 2007**)
- Springvale LW409 (piezometer interpretation by **CSIRO, 2007**)
- Ellalong LW2 (extensometer interpretation by **Holla, 1986**)

The height of continuous fracturing for LWE1 at South Bulga (**SCT, 2000**) has been assumed to extend to within 10 m of the surface and into the surface cracking zone as the extensometer or piezometric data is not available to review at this stage.

The assessment in **Kay, 1990** that the height of fracturing above LW11 at Angus Place extended to the surface was well above previous ranges (106T) measured at the mine to-date. Further discussions by the mine with the author recently indicates that a 100 m high cliff face probably affected the overburdens spanning capability, resulting in a greater than normal level of subsidence and near surface cracking. Although the surface flows in the creeks may have been re-routed into near surface cracks at the time, it is not likely that a surface to seam connection occurred.

It has also been decided to remove two case study points (Central and Southern German Creek Mines) from the original **ACARP, 2003** data base as they appear to be much lower than other cases with similar geology and geometry and were based on drilling data only.

The results of the database review and re-assignment of A- to B-Zones are shown in **Figure A40j** with the reinterpreted values summarised in **Table 6.1.** A summary of several representative extensometer results that were used to review the published heights of fracturing data presented in **Table A6.1** are provided in **Table A6.2**.

The expanded database presented in **Table A6.1** has subsequently been used to (i) update the strain and curvature index-based models presented in **ACARP, 2003** and (ii) develop more technically concise models that allow variations in geology and geometry to be assessed in each coalfield. The results are presented in the following sections.

Table A6.1 - Updated HoF Model Database for Australian Coalfields

Site	Panels	Mine	Seam	W (m)	H (m)	W/H	T (m)	A (m)	B (m)	A/T	ACARP 2003 Model Predictions				
											t^ (m)	y^ (m)	Unit SRP*	U95% CL S_{max} (m)	U95% CL E_{max} (mm/m)
1	MW508	Bellambi W.	Bulli	110	421	0.26	2.50	92	-	37	100	90	High	0.30	2
2	LW10	Metropolitan	Bulli	140	460	0.30	3.40	130	-	38	100	130	High	0.29	3
3	LW1-4	South Coast	Bulli	110	325	0.34	2.50	85	-	34	100	85	High	0.24	3
4	LW6	Kemira	Wong.	117	335	0.35	2.75	98	-	36	100	98	High	0.16	2
5	LW20	Metropolitan	Bulli	163	450	0.36	3.40	100	-	29	100	100	High	0.34	2
6	LWA1	Austar	Greta	159	417	0.38	6.00	*87*	277	15	100	80	High	0.56	4
7	LW514	Bellambi W.	Bulli	150	400	0.38	2.70	90	-	33	100	90	High	0.29	2
8	LW28	Appin	Bulli	200	500	0.40	2.30	90	-	39	120	90	*High*	0.27	1
9	*LW2*	*Ellalong*	*Greta*	*150*	*368*	*0.41*	*3.50*	*113*	*210*	*32*	100	113	*High*	*0.40*	*3*
10	*LW3*	*Tahmoor*	*Bulli*	*180*	*424*	*0.42*	*2.18*	-	204	-	100	100	*High*	*0.29*	*2*
11	LW9	Teralba	YW	150	350	0.43	2.70	*110*	150	41	34	110	High	0.32	2
12	*TE*	*West Cliff*	*Bulli*	*200*	*446*	*0.45*	*2.50*	*101*	*245*	40	100	101	*High*	*0.30*	*1*
13	TE	Berrima	Wong.	120	176	0.68	2.3	76	112	33	100	76	High	0.50	3
14	*LW409*	*Springvale*	*Lithgow*	*265*	*385*	*0.69*	*3.25*	*133*	*254*	41	55	133	High	*0.6*	*3*
15	LW9	Mandalong	WW	160	220	0.73	4.50	-	-	-	30	160	High	0.5	3
16	***LW11***	***Angus Place***	***Lithgow***	***211***	***263***	***0.80***	***2.47***	**-**	***253***	**-**	100	***253***	High	***0.5***	***3***
17	*411*	*Springvale*	*Lithgow*	*315*	*368*	*0.86*	*3.25*	139	288	43	55	139	High	*0.68*	*5*
18	LW5	Mandalong	WW	160	179	0.89	3.70	118	154	32	25	83	*Mod*	1.38	3
19	LW5	Dendrobium	Wong.	245	255	0.96	3.75	123	-	33	80	123	High	1.25	5
20	LW1	Wyee	Fassifern	216	206	1.05	3.44	126	-	37	30	126	High	1.09	5
21	**LW1**	**Invincible**	**Lithgow**	**145**	**116**	**1.25**	**2.70**	**106**	***111***	**39**	**15**	**106**	**Low**	**1.62**	**16**
22	TE1	Abel	U. Don.	120	95	1.26	2.55	45	*75*	20	15	41	Low	1.51	22
23	LWs	Ashton	Pikes Gully	216	154	1.40	2.55	82	*130*	32	30	82	Low	1.5	15
24	LW40	WWC	WBH	179	113	1.58	3.80	80	*108*	21	20	80	Low	2.28	21
25	**LWE1**	**Sth Bulga**	**Whybrow**	**259**	**155**	**1.67**	**2.55**	**145**	**150**	**57**	**20**	**145**	**Low**	**1.53**	**8**
26	LW41	WWC	WBH	179	105	1.70	3.80	72	100	19	20	72	Low	2.28	24
27	LW9	Crinum	Lillyvale	280	155	1.81	3.50	85	*150*	24	35	105	High	1.82	8
28	LW39	WWC	WBH	179	97	1.84	3.90	68	92	17	20	68	Low	2.18	25
29	TE-3D	Wyee North	GN	355	185	1.92	1.90	63	*143*	33	50	63	High	1.14	4
30	TE-355	Wyee North	GN	355	180	1.97	1.90	40	-	21	50	40	High	1.14	4
31	Panel2	Abel	U. Don	150	76	1.97	1.88	45	71	24	15	33	Low	1.13	23
32	TE-Nth B	Cooranbong	G.N	150	75	2.00	2.80	58	*70*	21	20	58	Low	1.68	33
33	LW1	Oaky Ck	German Ck.	205	95	2.16	3.20	55	*90*	17	30	55	Low	1.92	25
34	**LW9/9a**	**Homestead**	**Whybrow**	**200**	**80**	**2.50**	**3.40**	**75**	**75**	**23**	**15**	**65**	**Low**	**1.98**	**29**

- = not available; **bold** - surface to seam fracturing assessed by others; *italics* - Continuous Fracture Zone heights (A-Zone) was originally reported by others and included the Discontinuous Fracture and Dilated Zone (B-Zone). A and B- Zone height of the B-Zone heights were re-assessed by DgS based on a review of available measured vertical strains and piezometric data (see **Figure A40i and A40j**); No shade - Sub-critical panels (W/H<0.7); Light grey shade - Critical panels (0.7<W/H<1.4); Grey shade - Supercritical panels (W/H>1.4).
* - SRP = Subsidence Reduction Potential for strata unit with thickness t and distance y above the workings. The SRP may be due to spanning or bulking behavior over the range of W/H and is also considered to be an indicator of whether a strata unit will limit the height of continuous fracturing; ^ - likely values assessed from borehole and subsidence data; Wong. = Wongawilli; YW= Young Wallsend; WW = West Wallarah; U. Don = Upper Donaldson; WBH = West Borehole; GN - Great Northern.

Table A6.2 - Summary of Measured A, B, C & D Zone Strains in Extensometers*

Parameter	**Underground Coal Mines**									
	Angus Place[$]		**West Wallsend**				**Abel^**			
Panel No.	LW11		LW39		LW40		Panel 1		Panel 2	
Cover Depth H (m)	211		97		113		95		76	
Panel Width W (m)	263		179		179		120		150	
W/H	0.8		1.84		1.58		1.26		2.0	
Mining Height, T	2.5		3.8		3.9		2.1		2.1	
Fracture Zone	Dilat-ion (mm)	**Strains[#] (mm/m)**	Dilat-ion (mm)	**Strains[#] (mm/m)**	Dilat-ion (mm)	**Strains[#] (mm/m)**	Dilat-ion (mm)	**Strains[#] (mm/m)**	Dilat-ion (mm)	**Strains[#] (mm/m)**
D-Zone	-	***3 - 5***	-	***25***	-	***24***	-	***24***	-	***23***
C-Zone	-	**-**	-	**-**	-	**-**	-	**-**	-	**-**
B-Zone	~60 - 120	**5 - 6**	8 - 17	**1 - 2**	25 - 50	**5 - 8**	14 - 19	**1 - 2**	<20	**-1 - 0**
A-Zone	~1000	**100**	234 - 957	**115 - 139**	390 - 769	**39 - 77**	279 - 1289	**28 - 129**	158 - 185	**16 - 19**
Parameter	**Mandalong**		**Austar**		**Ellalong**		**Invincible**		**Tahmoor**	
Panel No.	LW5		LWA1		LW2		LW1		LW3	
Cover Depth H (m)	179		453		368		116		424	
Panel Width W (m)	160		159		150		145		180	
W/H	0.89		0.35		0.41		1.25		0.42	
Mining Height, T	3.7		6.0		3.5		1.26		2.2	
Fracture Zone	Dilat-ion (mm)	**Strains[#] (mm/m)**	Dilat-ion (mm)	**Strains[#] (mm/m)**	**Strains[#] (mm/m)**		**Strains[#] (mm/m)**		**Strains[#] (mm/m)**	
D-Zone	-	***5***	-	***3***	***3***		***10***		***1***	
C-Zone	<20	**<1**	<10	**<1**	**<1**		**-**		**<1**	
B-Zone	19 - 29	**2 - 5**	24 - 133	**1 - 7**	**1 - 5**		**<5**		**1 - 4**	
A-Zone	73 - 672	**80**	222 - 1177	**11 - 59**	**>10**		**10 - 75**		**N/A**	

* - A, B & C-Zone strains are vertical and approximately 3 to 4 times the horizontal strain due to Poisson's ratio effect; *italics* - D-Zone strains are horizontal.
# - tensile strains are positive. Negative strains or compression develops after full subsidence occurs and goaf compresses under load from sagging overburden strata; ^ - Effective mining height for total pillar extraction (Te = 0.85T); $ - Strain data not available and quoted from published literature.

Table A6.2 (Cont…) - Summary of Measured A, B, C & D Zone Strains in Extensometers*

Parameter	**Underground Coal Mine**			
	Springvale			
Panel No.	LW411		LW412	
Cover Depth H (m)	368		400	
Panel Width W (m)	315		315	
W/H	0.90		0.79	
Mining Height, T	3.25		3.25	
Fracture Zone	**Dilation (mm)**	**Strains# (mm/m)**	**Dilation (mm)**	**Strains# (mm/m)**
D-Zone	-	*3*	-	*3*
C-Zone	<42	<5	<33	<5
B-Zone	39 - 410	4 - 10 (**17**)	2 - 505	4 - 8 (**25**)
A-Zone	194 - 1441	14 - 42	174 - 1571	5 - 42

* - A, B & C-Zone strains are vertical and approximately 3 to 4 times the horizontal strain due to Poisson's ratio effect; *italics* - D-Zone strains are horizontal.
# - tensile strains are positive. Negative strains or compression develops after full subsidence occurs.
^ - Effective mining height for total pillar extraction (Te = 0.85T).
bold - measure strain near the top of the B-Zone where a bedding separation occurred. Piezometer data indicates the height of continuous fracturing is further below this point.

A11.4.1 Updated Tensile Strain Model

The physical model presented in **Whittaker and Reddish, 1989** related the ratio of the height of continuous and discontinuous fracturing (A and B) above longwall panels over cover depth (H) with the maximum tensile strain (E_{max}) at the surface due to mine subsidence. Actual drilling data over extracted longwall panel goaf was subsequently used to define a real-world relationship between these variables at several Australian Coalfield mines in **ACARP, 2003**.

The additional data presented in **Table A6.1** has been added to the original database and the regression equations have been revised below:

{A-Line} Mean A/H $= 0.180 \, Ln(E_{max}) + 0.1405$, $R^2 = 0.70$

U95%CL A/H* $= 0.180 \, Ln(E_{max}) + 0.3742$.

{B-Line} Mean B/H $= 0.146 \, Ln(E_{max}) + 0.5315$, $R^2 = 0.47$

U95%CL B/H* $= 0.146 \, Ln(E_{max}) + 0.8426$.

* - Maximum A/H and B/H = 1.

where

A, B = height above workings to A and B-Zone horizons,
H = cover depth,

E_{max} = the maximum predicted tensile strain for a 'smooth' subsidence profile.

The new tensile strain model is presented in **Figure A41a** and has a much stronger fit to the new database for the A-Zone than the **ACARP, 2003** model, with only a slight improvement for the B-Zone horizon. The R^2 value for the logarithmic regression curve fitted to the revised A-Zone data was previously 0.44 and is now 0.70. The R^2 value for the B-Zone was previously 0.46 and is now 0.47.

The measured database model still appears to indicate a similar height of fracturing trend to the **Whittaker and Reddish, 1989** physical model. However, as was concluded in **ACARP, 2003**, the predicted heights of 'continuous' and 'discontinuous' fracturing in the real world were again higher for a given tensile strain at the surface, and probably due to the influence of jointing in the rock mass (compared to none in the physical model).

The real world database indicates that the tensile strain probably needs to be >32 mm/m for surface to seam connection to occur, and is approximately 50% of the physical model value of 60 mm/m. It should also be noted that if connective cracking is likely to extend into the Surface Cracking Zone (a depth of 10~15 m below the surface), then the maximum tensile strain for surface to seam connection reduces to 25 mm/m. It is assessed however, that the predicted strains are also dependent on surface crack width development and should therefore not be used to assess surface to seam connectivity directly without considering the near surface B and C-Zone lithologies.

Considering the potential difficulties with predicting strains after the onset of cracking, it is still assessed that it is unlikely that the tensile strain-based model will be reliable. **ACARP, 2003** attempted to modify the strain-based model to a curvature-based approach. The resulting regression equations however, did not improve the correlation between the adopted variables (i.e. both methods had R^2 values of 0.44). The curvature-based model of height of sub-surface fracture prediction was subsequently revised with the expanded model database in **Section A11.4.2** to see if the regression equations could be improved upon.

A11.4.2 Updated Overburden Curvature Index Model

The Overburden Curvature Index or S_{max}/W'^2 term was introduced in **ACARP, 2003** in an attempt to provide a readily measurable field parameter that would not be compromised as much by surface strain concentration effects (i.e. cracking). The logarithmic regression lines were re-derived using the expanded database to give new predictions of the mean and U95%CL values for both A and B-Zones as follows:

{A-Line} Mean A/H $= 0.198\ Ln(S_{max}/W'^2) + 1.1518$, $R^2 = 0.66$

U95%CL A/H* $= 0.198\ Ln(S_{max}/W'^2) + 1.3915$.

{B-Line} Mean B/H $= 0.152\ Ln(S_{max}/W'^2) + 1.3265$, $R^2 = 0.52$;

U95%CL B/H* $= 0.152\ Ln(S_{max}/W'^2) + 1.5928$.

* - Maximum A/H and B/H = 1.

where

A, B = height above workings to A and B Horizons,
H = cover depth (m).
S_{max}/W'^2 = Overburden Curvature Index,
W' = lesser of W and 1.4H

Note: It is reasonable to assume the effective mining width (W') and height of fracturing (A/B) will be limited beyond the point where the maximum subsidence or strata deformation has been reached above supercritical mining geometries (i.e. W/H > 1.4).

The revised regression results are shown in **Figure A41b**.

Despite the apparent improvement in the regression equations, the same apparent differences still remain between the Australian height of fracturing database and the UK physical modelling results. One obvious difference is that the UK physical model represents a supercritical case study where the panel width and cover depth was constant (i.e. W/H = 1.34). The Australian database however, has a significant range of sub-critical, critical and super-critical panel geometries and further investigation of this difference is therefore required (see **Section A11.4.4**).

A11.4.3 Influence of Lithology on Sub-Surface Fracture Heights

An assessment was made in **ACARP, 2003** on whether massive lithology had the potential to control or limit the height of fracturing above a longwall panel. The expanded model database presented in **Table A6.1** still indicates that it does, with the A-Horizon likely to have coincided with the base of the massive strata units in 17 out of 21 cases with 'Moderate' to 'High' SRP strata units.

The potential for massive strata units to mitigate the height of continuous fracturing above the workings should therefore not be ignored where subsidence magnitudes and HoF are clearly being controlled by spanning strata.

Overall, the HoF results suggest that the presence of massive sandstone or conglomerate lithology can control the height of hydraulic fracturing due to their spanning capability or thickness generally. However, as has been observed at Mandalong and Springvale Mines, the presence of geological structure (faults, dykes, seam rolls and shear zone or joint swarms) has resulted in a weakening of the overburden by the tectonic activity and there has been increased subsidence due to the breakdown of massive sandstone / conglomerate into several thinner units and (ii) increased shearing and tensile stress acting on the discontinuities has resulted in groundwater conduits developing deeper into the overburden.

It is therefore usually recommended that a mine undertake a sub-surface fracture-monitoring program which includes a combination of borehole extensometer and piezometer measurements during extraction in non-sensitive areas of the mining lease. Mitigation strategies for longwall mining are generally limited to (i) reducing the extraction height, (ii) decreasing the panel width and (iii) panel location adjustment. On-going monitoring of surface alluvium and near surface rock mass aquifers is also undertaken with standpipe piezometers to check the post-mining integrity of ground water dependent ecosystems (GDE) and surface water systems generally.

A11.4.4 Height of Fracturing Angle Model, DgS 2012

Due to the currently held belief in the Australian mining industry that the sub-surface fracture heights are strongly influenced by panel width and mining height, an alternative model was developed by DgS in 2012 using a different approach to analysing the UK model data presented in **ACARP, 2003**.

Predictions of the heights of continuous and discontinuous fracturing (the A and B-Zone horizons) were re-analysed using the panel width, the mining height and a simple parabolic profile formula to estimate A and B-Zone fracture heights from a calibrated abutment angle at seam level (θ_A and θ_B) as follows:

- Continuous Fracture Zone Height, A = W'/(4tan(θ_A))
- Discontinuous Fracture Zone Height, B = W'/(4tan(θ_B))

where,

W' = Effective Panel width or minimum of W and 1.4H.

θ_A = abutment angle to estimate height of A-Zone

θ_B = abutment angle to estimate height of B-Zone

When the UK model's fracture height data is plotted as a height of fracturing angle (estimated from an assumed parabolic fracturing profile between rib abutments), a strong correlation is apparent between the mining height for a given panel width and cover depth (W/H = 1.34); see **Figures A41c** and **A41d** for A and B-Zone Horizons respectively.

The regression analysis indicates the following fracture height angles (in degrees) apply for estimating A and B-Zone fracture heights in the real world:

$\theta_A = 41.617T^{-0.467}$ (mean) and $25.083T^{-0.401}$ (lower 95%CL)

$\theta_B = 21.806T^{-0.233}$ (mean) and $17.295T^{-0.238}$ (lower 95%CL)

Real world fracture height data measured with piezometers and borehole extensometers indicates a similar trend as the physical model results, although there is more scatter in the data that is probably due to both mining geometry (W/H) and geological variability.

The UK physical model assessed mining heights of 1.2 m to 10.8 m, and generated fracture height angles at the abutments ranging from 55^o to 18^o for the A-Zone and from 37^o to 18^o for the B-Zone horizon. The fracture height angle tends to follow a decaying power law as the mining height increases.

For real-world mining heights of 1.9 m to 6.0 m (median of 3.0 m), the calibrated fracture height angles range from 34^o to 18^o for the A-Zone, and from 22^o to 13^o for the B-Zone. One A-Zone case had a fracture height angle of 58^o due to the apparent 'truncating' effect of a 40 m thick conglomerate strata unit 40 m to 60 m above a supercritical panel in the Great Northern Seam (Wyee Colliery's North-3D Panel).

As was found in the strain and curvature-based model's, the presence of pre-existing jointing in the rock mass is likely to have contributed to greater fracture heights determined from the field data compared to the laboratory model.

The effect of massive strata units is apparent in the database (see **Figure A41c**) and further measurements are necessary to develop a more discerning prediction model that allows 'Low' and 'High' SRP strata to be assessed separately using this model. The height of fracturing model proposed at the time was considered likely to be conservative for greenfields sites if based on the lower bound fracture height angles and to give upper bound fracture height predictions.

Further review of sub-critical, critical and supercritical panel case studies in 2013 has found that the A and B-Zone fracture height angle model could also be further divided into sub-critical, critical and supercritical panel geometries (see **Figure A41e** and **A41f**) as follows:

$\theta_A = 32.448T^{-0.241}$ for the mean fracture height angle.

Upper 95%Confidence limits for the A-Zone were estimated by reducing the mean angle by 5^o, 7^o and 10^o for supercritical, critical and sub-critical longwalls respectively.

$\theta_B = 31.5T^{-0.373}$ for the mean fracture height angle for supercritical panels
$= 25.4T^{-0.373}$ for the mean fracture height angle for critical/sub-critical panels

Upper 95%Confidence limits for the B-Zone were estimated by reducing the mean angle by 3.5^o, 7^o and 7^o for supercritical, critical and sub-critical longwalls respectively.

The review outcomes suggest that heights of subsurface fracturing appear to increase above sub-critical panels for a given mining height, but are also likely to be due to the panel width and changes in macro-scale structural behaviour of the overburden as well.

Whilst the trend from sub-critical to supercritical panel geometries appears reasonably consistent across the abutment angle model database (with a few cases where thick strata has clearly limited the fracture heights) it is noted that the predicted heights of fracturing are highly sensitive to the selected value of theta. It was therefore considered that a new modelling approach based on Dimensional Analysis and Buckingham's Pi-Theorem would be needed to reasonably establish definitive relationships between the key variables over a broader range of mining geometries and geological conditions.

A11.5 Alternative Sub-surface Fracture Model Development

Starting with the influence of mining height (T) on the height of A-Zone fracturing, if we firstly consider a supercritical panel of a given width (W) and cover depth (H), **Whittaker and Reddish, 1989** and **Singh & Kendorski, 1991** each demonstrated that the height of continuous fracturing (A) will increase with the square root of the mining height, $T^{\sim 0.5}$, or a power rule of the form $A = aT^b$, as shown in **Figure A41g**. It is apparent that the database of real-world fracture heights with W/H range from 0.3 to 2.22 has greater scatter than the UK model curve for supercritical panel geometry, and therefore indicates that other factors such as the panel width and geology should probably be considered. The apparent under prediction of A-Zone fracture heights by the **Forster and Enever, 1992** model, also supports this view.

If the fracture heights are plotted against panel width (W) only, a similar ‘scattered’ outcome results as shown in **Figure A41h**. The conservative nature of the height of fracturing models presented by SCT and MSEC is also demonstrated in the figure and suggests that both A and B-Zones are included in their models.

A slightly improved regression analysis results if A is plotted against W/H in **Figure A41i** or when normalized to the panel width (A/W) and is plotted against T in **Figure A41j** for sub-critical, critical and super-critical panel geometries.

Based on these plots, it is clear that consideration needs to be given to the structural behavior of the overburden across the full range of mining geometries, its constituent strata units (or ‘beams’) and the influence of mining height, T on the development of fracture heights above longwall panels.

A11.5.1 Strata Behaviour Mechanisms that Influence Fracture Heights above Longwalls

Based on structural analysis theories, a conceptual model of the macro-scale and micro-scale mechanisms of sub-surface fracture height development are described below and shown graphically in **Figure A42a**:

<u>Macro-Scale Mechanisms</u>:

- For sub-critical panels, a natural catenary will probably form and transfer the weight of the top half to 2/3 of the overburden to the abutments. The strata below the arch will be subject to sagging or bending forces caused by the void formation. Depending on the span and thickness of individual strata units, the strata in the immediate roof will bend, separate, crack and ultimately cave into the extracted coal void (see *Micro-scale Mechanisms* below).

- Natural catenary arching action infers that the spanning overburden can remain entirely in compression and there is an absence of tensile and shear or ‘bending’ stresses. Subsidence data indicates that catenary arching stops occurring once W/H exceeds 0.7.

- Once W/H exceeds 0.7, the overburden will still attempt to span, however, the geometry of the arch will be too shallow for a catenary arch to develop, resulting in bending and cracking of the rock mass.

- The load will still be able to be carried over the void by the overburden, provided the rock mass has adequate strength and stiffness to resist the applied bending moments and shear and tensile stresses (along with increased compressive stresses from inward strata block rotation). This type of behaviour is known as Voussoir or 'cracked beam' behaviour, and is basically a flatter, but a less stiff version of a catenary arch.

- Shallow arching or Voussoir beam action will continue across the panel until it can no longer support the span or weight of the shallow arch. This is usually assumed to have occurred once W/H reaches 1.2 to 1.4H. The weight of the overburden will then be fully supported by the goaf beyond this point and subsidence will be a function of the mining height and cover depth or goaf load.

- The above macro-mechanisms will influence the behavior of the overburden strata units and subsequent development of the sub-surface fracture heights as follows:

<u>Micro-scale Mechanisms</u>:

- Soon after the coal seam is extracted from beneath the overburden, its constituent 'beams' in the immediate roof will generally deflect and behave elastically until the tensile and shear stresses within the rock mass units exceed the material and/or bedding parting strength of the units.

- The strata units will subsequently crack at the abutments and mid-span and the confinement will be partially lost. The cracked beam segments will then rotate inwardly and create a shallow compression arch within the beams (Voussoir action) that may or may not support the load.

- The cracks in the beams at this stage are likely to be discontinuous, with the beam continuing to behave pseudo-elastically with zones of compressive stress above and below the tensile cracks.

- The beam will continue to span and deflect under the applied loading until the compressive strength of the beam is reached, where the beam will then either collapse into the available void, or yield and load the previously failed strata units and goaf below it.

- Based on the physical model results presented in **Whittaker and Reddish, 1989**, the beams may also shear into two or three thinner units before the lower units ultimately crush if their UCSs are exceeded. Bending beam theory indicates that the maximum shear stress will occur at mid-beam thickness. The beams are therefore likely to break down into half their thickness units each time shearing occurs along bedding partings.

- The goaf will compress and cause further overlying strata units to deflect, shear and crack. The goaf load will continue to increase as cracking continues up into the strata.

- The curvature induced in the beams will probably not cause complete fracture to develop through the beam until the compressive strength of the beam materials is reached. The induced curvature will therefore be a function of the stiffness of the goaf, the stiffness (and thickness) of the deflecting beam and the load acting on it.

- The goaf stiffness will initially be a function of the mining height and the bulking properties of the collapsed roof materials. The goaf stiffness will also increase as the load acting upon it increases (i.e. strain hardening behavior).

- The goaf load will be a function of the rock mass density and effective height of rock above it. The effective goaf load height is likely to be somewhere between the height to the underside of the spanning arch (above sub-critical and critical panels) and the full cover depth. Full load spanning of strata units above supercritical panel geometries are unlikely to occur and full cover depth load may be assumed to act upon the goaf.

A11.5.2 Analytical Height of Fracturing Model

An analytical model of how sub-surface fracturing develops in the overburden is described below in an attempt to define the likely relationships between the mining geometry and overburden as described in the previous section.

<u>Initial Conditions - Elastic Beam Response to Longwall Mining</u>

The maximum horizontal tensile stress before fracturing (σ_t) in a beam of thickness (t) with an effective span of W_i at a distance (y) above the workings will be:

$$\sigma_t = 6M/t^2 = 3\gamma(H-y)W_i^2/4t^2$$

where

M = surcharge load x span^2 /12 = $\gamma D W_i^2/12 = \gamma(H-y) W_i^2/12$

γ = unit weight of the rock mass

D = the depth to the base of the spanning beam (or H-y)

The equation shows that the tensile stress in a stack of beams will be greatest near the roof of the mine workings and then decrease linearly towards the surface. The effective span W_i of the beam will decrease as a function of the angle of break of the collapsing strata in the

Caving Zone. The angles of break (θ) are likely to range between 12^o and 19^o according to the literature and underground observations.

Elastic beam Cracking and Voussoir Beam Development

The fracturing will continue to progress higher up into the strata until a beam of a certain critical thickness is reached that can either span the distance between the naturally occurring abutments or is thick enough not to fracture right through the beam after it has failed. It is also important to note that the angle of break is not the same as the height of fracturing angles (θ_A and θ_B) discussed in **Section A11.3.4**, as the latter angles were back-calculated from measured heights of continuous fracturing and assumed parabolic fracture limit profiles.

As discussed earlier, the cracking of the strata will lead to the development of Voussoir arching or 'cracked beam' behaviour. The stability of the Voussoir beam will depend upon the compressive stress (σ_c) developed in the beam of thickness (t) that is located a distance, y, above the workings with an effective span (W_i) as follows:

$$\sigma_c = \gamma(H'-y)W_i^2/(4nt^2(1-0.667n))$$

where

n = the proportion of the beam t in compression and may be determined iteratively by minimizing σ_c as the arch shortens under load and develops a new equilibrium (and provided the stress remains in the elastic region or is less than the UCS). Voussoir analysis results based on the method presented in **Diedrichs and Kaiser, 1999**, indicate that 'n' can range from 0.5 and 0.75 in spanning beams, and will be closer to 0.5 when beam crush conditions are reached.

W_i = W - 2ytanθ = effective span of the bending beam at distance, y above the mine workings.

H' = Effective Goaf Load Height, H' or Cover Depth, H.

Voussoir Beam Crushing and Height of Continuous Fracturing

It follows then, that the height of continuous fracturing, A, is likely to develop up to the point where the beam crushes or σ_c = UCS and infers the following relationship exists at the point where the beam starts to yield or crush:

$$UCS = \gamma(H'- A)(W-2A\tan\theta)^2/(4nt^2(1-0.667n))$$

$$= 0.75\gamma(H'- A)(W-2A\tan\theta)^2/t^2 \qquad (1)$$

where

θ = the angle of break that subtended to vertical from the rib side and ranges from 12^o - 19^o based on subsidence data and underground observations.

H'- A = thickness of rock supported by the beam and may decrease to t (the beam thickness) if the strata beds shear and dilate during subsidence development.

n = 0.5 (conservative).

Equation (1) indicates that the height of A-Zone fracturing is likely to be a cubic function that is dependent on the following variables:

- Panel width, W
- Effective Goaf Load Height, H' or Cover Depth, H.
- Thickness, location and strength and stiffness of the strata units within the overburden (t, y, UCS, E)
- Angle of break, $\tan\theta$

Stresses in Overlying Beams Supported by Collapsed/Fractured Beams

It is noted that Equation (1) ignores the presence of collapsed and fractured material within the A-Zone itself. The formation of the goaf will provide support to overlying fractured units, but also influence the magnitude of curvature and bending stress in the overlying beams as the goaf is compacted and the beams deflect. The curvature of the overlying 'beams' (p_i) may be estimated as follows:

$$p_i = 8\Delta/(y+W_i)^2 = 8(S_{max})/(y+W_i)^2 = 8(\varepsilon_g\,4T)/(y+W_i)^2 = 32(\sigma_g/E_g)T/(y+Wi)2$$
$$= 32(\gamma H'/E_g)T/(y+W_i)^2$$

where

Δ = mid-span deflection of beam with an effective span, $W_i = W - 2y\tan\theta$.
ε_g = vertical strain of goaf with thickness of 4T (T+3T) and a bulking factor of 1.3.
σ_g = maximum vertical stress acting on the goaf = $\gamma H'$.
H' = effective goaf load height = minimum of H and W'/(4tanθ)).
E_g = stiffness of the goaf, which is likely to be a function of H, W, T and t.

From the estimated curvature of the strata units above the compacting goaf, the bending stress in the beam may be estimated as follows:

$$\sigma_c = 2M/(Znt) = 2p_i E't^3/[12(nt^2(1-0.667n))] = 16(\gamma H)T\,t\,E'/(E_g(A+W_i^2)) \qquad (2)$$

where

E' = rock mass Young's Modulus = 100 - 300UCS (depending on rock mass Geological Strength Index (**Hoek & Diderichs, 2006**));

n = 0.5 for beam at the yield point (i.e. σ_c = UCS)

As before, if σ_c exceeds the UCS, the cracking may extend right through the beam and the height of fracturing, A, may then continue to develop up to the next strata unit. The following relationship will therefore exist at the A horizon:

$$\sigma_c = UCS = 16(\gamma H')T\ t\ E' / E_g\ (W+A(1-2\tan\theta))^2$$

Overall, the equations represent the physical relationships for either spanning strata (Equation (1)) or non-spanning strata (Equation (2) that are of sufficient thickness to limit fracture continuation through it for a given UCS and mining geometry. As discussed in the following sections, the goaf modulus is likely to be dependent on the mining geometry (W, T and H').

The above equation indicates a complex system with a significant number of independent variables that will influence the height of fracturing outcomes.

Considering the complexity of the above equation and uncertainty in regards to assigning the rock mass and goaf properties, the physical relationship between the variables may also be assessed practically with Dimensional Analysis, a commonly used tool by hydraulics engineers (see **Section A11.5.3**).

A11.5.3 Dimensional Analysis and Buckingham's Pi Theory

According to **Vennard and Street, 1982**, Dimensional Analysis is "the mathematics of dimensions of quantities" built on Fourier's 1882 "principle of dimensional homogeneity". The underlying principle states that "an equation expressing a physical relationship between quantities must be dimensionally homogeneous" i.e. the dimensions of each side of the equation must be the same. It is a valuable means of determining physical relationships between variables in complex systems that defy analytical solution and must be solved by empirical means (i.e. observation, intuition or experiment).

Buckingham's Pi-theory accomplishes this by the formation of dimensionless groups of independent variables that are measureable in the field. For the theory to work, the Pi-terms together must represent all of the three fundamental or primary dimensions of Mass (M), Distance (L) and Time (T), be independent of each other, and not break down into further dimensionless groups.

Buckingham's Pi theory states that in order to determine the physical relationship between a set of 'n' independent parameters in a complex system, it follows that n-3 dimensionless parameters (known as Pi-terms) will be required to reasonably define the dependent variable.

The final equations obtained are in the form of:

$$\pi_1 = f\ (\pi_2, \pi_3 \ldots \pi_{n-3}) \text{ or } f'(\pi_1, \pi_2 \ldots \pi_{n-3}) = 0$$

From the previous analytical equations derived in **Section A11.5.2**, it is assessed that up to 10 variables may influence the height of Continuous Fracturing (A) and Discontinuous Fracturing (B) as follows:

$$A, B = f(W, H, T, t, \rho, UCS, E, E_g, \tan\theta)$$

The above variables may then be expressed as a combination of products and powers:

$$A, B = aW^b H^c T^d t^e UCS^f, \rho^g E^h E_g^i \tan\theta^j$$

Seven dimensionless Pi-terms will therefore be necessary to describe the relationships between ten variables identified in a system driven by horizontal and vertical stress, panel width, cover depth, mining height, rock mass density, rock mass strength and stiffness, goaf stiffness, caving angle or angle of break and the location of competent or relatively thick strata units in the overburden.

Notes:
1. The y term may be ignored as it corresponds with the dependent variable (A or B).
2. The goaf modulus (E_g) and caving angle (θ) are considered to be dependent on the mining geometry and may therefore be precluded from the regression analysis.
3. The beam thickness, t refers to the thickness likely to exist just above the fracture height location (t is the most difficult of the parameters to assess, as the strata units may 'break down' into thinner units during subsidence development. The assignment of the appropriate t value therefore requires engineering judgment and analysis that includes a review of borehole logs and rock mass properties with extensometer and piezometer data (if available).

The first step in the analysis is to select a suitable set of recurring variables that cannot themselves be formed into a dimensionless group and can be used to represent one or more of the fundamental dimensions. The recurring variable set selected included the panel width, W, rock mass strength, UCS, and density, ρ, and were used to express the fundamental variables as follows:

Length, L: W; Mass, M: ρW^3; Time, T: $\rho^{0.5} W / UCS^{0.5}$

The dimensionless π terms for the remaining independent variables were then assessed using the recurring variable set as follows:

π_1: $A \cdot L^{-1} = A/W$ (Height of Fracturing Term)

π_2: $H \cdot L^{-1} = H/W$ (Goaf Load Index Term)

π_3: $T \cdot L^{-1} = T/W$ (Strata Curvature Index Term)

π_4: $t \cdot L^{-1} = t/W$ (Strata Unit Thickness Term)

π_5: $E \cdot M^{-1} L^1 T^2 = E/UCS$ (Strata Unit Stiffness Term)

which gives:

$$A/W = a\,(H'/W)^b (T/W)^c\,(t/W)^d\,(E/UCS)^e$$

The constants and powers for each Pi-term can now be determined using measured values in the field and non-linear regression techniques.

If we assume for the moment that the last π term representing the ratio of rock mass stiffness over strength for all cases in the database will be constant (E is typically 250 to 300 times the UCS), then the full equation of dimensionless π terms may be simplified as follows:

$$A/W = a\,(H/W)^b\,(T/W)^c\,(t/W)^d \text{ and } B/W = e\,(H'/W)^f\,(T/W)^g\,(t/W)^h$$

The form of the dimensionless π term equations will be explained in the following sections.

Note: Some of the published literature recommends that the super-critical panel width W' = 1.4H should be used instead of the Panel Width, W, for estimating the height of fracturing above super-critical panels. This is because it was argued that the height of fracturing would probably not continue to develop higher into the strata once the overburden had reached the critical width and had already completely failed. The author agrees with this view and considers the height of continuous fracturing beyond this point would then be controlled by the mining height, cover depth (or goaf load) and geological conditions only.

A11.5.4 Pi-Term Model for Predicting Height of Continuous Fracturing (A) above Longwalls based Mining Geometry Only (i.e. Geometry Model)

For the purposes of demonstrating that height of fracturing prediction models need to consider the influence of geology, a regression analysis was completed without the strata unit thickness Pi-term (t'/W') included. Based on the empirical database presented in **Table A6.1**, the statistics software XLSTAT® was used to complete a multi-nonlinear regression analyses on the first three Pi-terms defined earlier as follows:

$$\underline{\text{Mean } A/W' = 2.215\,(H/W')^{0.271}(T/W')^{0.372}} \qquad R^2 = 0.61 \text{ \& r.m.s.e.} = 0.12W' \text{ (21\%)}$$

$$\underline{\text{U95\% } A/W' = \text{Mean } A/W' + a}$$

where a = 0.16 for subcritical panels; 0.16 - 0.085(W/H - 0.7) for critical panels; and 0.10 for supercritical panels.

W' = Effective Panel Width = minimum of W and 1.4H.

T = Mining Height.

Re-arranging the above equation in terms of A gives:

$$\underline{A = 2.215W'^{0.357}H^{0.271}\,T^{0.372} \qquad +/- aW'}$$

The regression results suggest that the height of continuous fracturing (A) will increase with effective panel width (W'), the cover depth or goaf load (H) and the mining height (T) all raised to powers ranging from 0.27 to 0.37.

The above equation(s) may be used to estimate A-Zone fracture heights in the absence of specific geological information (i.e. borehole data). The predicted v. measured outcomes using the "geometry" Pi-terms only model are presented in **Figures A42b** to **A42d**.

The plots indicate that the 'geometry only' Pi-term model is likely to provide reasonably conservative predictions, provided that the geology is not too dissimilar to the conditions that were present for the given mining geometry. For cases where the geology is significantly different above a proposed mining geometry, the above equation may underestimate or overestimate the fracture heights by a significant amount.

The development of a Pi-term model that considers the influence of overburden geology is subsequently addressed in **Section A11.5.5**.

A11.5.5 Pi-Term Model for Predicting Height of Continuous Fracturing (A) above Longwalls with the Geology Pi-Term Included

The presence of massive strata units such as sandstone, conglomerate and igneous rock that may span the fractured strata in the A-Zone is likely to limit the potential range of continuous fracture height development above the mine workings. Based on the analytical models (Equations (1) and (2)), the minimum thickness required to span the A-Zone or limit its development will depend on a number of factors, including span, thickness and rock mass axial and diametric strength. The minimum strata unit thickness required to span the A-Zone may be estimated using empirical and analytical methods, and are described in **Sections A11.5.6** and **A11.5.7** respectively.

If no obvious strata unit thickness is present in the overburden, then it will be necessary to adopt an appropriate minimum value based on subsidence data and typical or atypical geological conditions. The minimum effective t' values are also defined in **Section A11.5.6**.

Based on the empirical database presented in **Table A6.1**, the statistics software XLSTAT® was used to complete a multi-nonlinear regression analyses on the first four Pi-terms defined earlier as follows:

$\underline{\text{Mean } A/W' = 1.52\,(H/W')^{0.535}(T/W')^{0.464}(t'/W')^{-0.4}}$ $R^2 = 0.81$ & rmse = 0.09W'(15%)

$\underline{\text{U95\% } A/W' = \text{Mean } A/W' + a}$

where a = 0.15 for subcritical panels; 0.15 - 0.0714(W/H - 0.7) for critical panels; and 0.10 for supercritical panels.
H = cover depth = the maximum potential goaf load height.
W' = effective panel width = minimum of W and 1.4H.
T = mining height.
t' = effective strata unit thickness; see **Sections A11.5.6**.

Re-arranging the above equation in terms of A, gives:

$$\underline{A = 1.52W'^{0.4}H^{0.535}T^{0.464}t'^{-0.4} \quad +/- \; aW'}$$

The regression results indicate that the height of continuous fracturing (A) will increase with effective panel width (W'), the cover depth or goaf load (H) and mining height (T), all raised to powers ranging from to 0.4, 0.54 and 0.46 respectively and decrease with effective strata unit thickness (t') raised to the power of -0.4. The form of the power rule equation requires the powers to sum to unity to achieve dimensional consistency. The back-analysed powers are also similar in magnitude to the analytical models previously discussed.

A11.5.6 Effective Strata Unit Thickness Estimates for the Geology Pi-Term Model using Empirical Modelling Techniques

In order to calibrate the geological Pi-term model, it was necessary to use back-analysis techniques to estimate the likely strata unit thicknesses that existed immediately above the measured heights of continuous fracturing for a given mining geometry.

One of the difficulties in estimating the effective strata thickness from borehole data is the uncertainty in regards to the response of the 'bedded' strata under bending forces and whether they will break down into thinner units.

For example, a 33 to 40 m thick unit of Munmorah Conglomerate existed 80 m above LW5 at the Mandalong Mine and extensometer data measured the beam shearing into 15 m and 20 m thick units, which reduced the effective thickness of the conglomerate beam by approximately 50% (i.e. 15 m to 20 m). The height of continuous fracturing was estimated to occur at 118 m or near the top of the conglomerate, based on piezometer data.

Other longwalls with similar geometry at Mandalong did not break down into thinner units (based on measured subsidence data). The presence of a seam roll and thrust fault to the near the panel was identified in the mine workings and indicates that the strata may have been significantly 'worked' and weakened by tectonic activity prior to mining. It is suggested that assessments in greenfields sites should consider the outcome of massive units shearing into two beams for worst-case geological condition scenarios.

Initial values of t' were therefore estimated from borehole log and extensometer data to derive the general form of the equation presented in **Section A11.5.5**. The resulting regression equation indicated the strata unit thickness should be raised to a power of -0.4 to -0.5. A single iteration was then required to re-define the coefficients and remaining Pi-term powers. The results of the analysis are summarized in **Table A6.3a** and **Figure A42e**.

The results indicate that the back-analysed (or measured) t' values ranged between 18 m and 80 m (median of 46 m) for the *sub-critical* panels; from 8.5 m to 42 m (median of 25 m) for the *critical* panels and between 6 m and 34 m (median of 23 m) for the *supercritical* panel geometries. The measured t' values for the deeper panels appear to be generally thicker than the panels at lower depth of cover in areas with similar geological conditions (i.e. massive sandstones and conglomerate units capable of spanning the longwall voids were present in both cases). Further review of the geomechnical properties of the overburden is necessary to increase our understanding of this phenomenon.

Table A6.3a - Effective Strata Unit Thicknesses (t') Back Analysed from HoF Model Database for Australian Coalfields

Site	Panels	Mine	W (m)	H (m)	W/H	A (m)	Back Analysed t' (m)	Bore log t_{log} (m)	t_{max} 95% goaf span probability	Rock Mass Conditions (see TA6.3b)	t_{min} from subsidence data (m)	Effective Strata unit thickness* t' (m)
1	MW508	Bellambi W.	110	421	0.26	92	36.5	100	49	Normal	30	49
2	LW10	Metropolitan	140	460	0.30	130	31.5	100	49	Normal	30	49
3	LW1-4	South Coast	110	325	0.34	85	31.5	100	41	Normal	20	41
4	LW6	Kemira	117	335	0.35	98	27	100	40	Normal	20	40
5	LW20	Metropolitan	163	450	0.36	100	68	100	70	Normal	30	70
6	LWA1	Austar	159	417	0.38	*87*	160	100	78	Normal	30	78
7	LW514	Bellambi W.	150	400	0.38	90	54	100	64	Normal	30	64
8	LW28	Appin	200	500	0.40	90	80	120	103	Normal	40	103
9	LW2	Ellalong	150	368	0.41	113	37	100	49	Normal	30	49
10	LW3	Tahmoor	180	424	0.42	-	60	100	74	Normal	30	74
11	LW9	Teralba	150	350	0.43	*110*	27	34	48	Normal	30	30
12	TE	West Cliff	200	446	0.45	*101*	57	100	85	Normal	30	85
13	TE	Berima	120	176	0.68	*76*	18	100	29	Normal	20	29
14	LW409	Springvale	265	384	0.69	*133*	42	55	78	Normal	32	32
15	LW9(11)	Mandalong	160	220	0.73	-	30	30	25	Normal	20	25
16	LW11	Angus Place	211	263	0.80	-	30	100	26	Normal	10	26
17	411	Springvale	315	368	0.86	139	42	55	86	Normal	32	32
18	LW5	Mandalong	160	179	0.89	118	14.5	25	37	Normal	20	20
19	LW5	Dendrobium	245	255	0.96	123	32	80	55	Normal	20	55
20	LW1	Wyee	216	206	1.05	126	18.2	30	39	Normal	20	20
21	**LW1**	**Invincible**	**145**	**116**	**1.25**	**96**	**8.5**	**15**	19	**Adverse**	**10**	**10**
22	TE 1	Abel	120	95	1.26	45	18	15	29	Normal	15	15
23	LWs	Ashton	216	154	1.40	82	25.5	30	44	Normal	15	15
24	LW40	WWD	179	113	1.58	80	21	20	25	Normal	20	20
25	**LWE1**	**Sth Bulga**	**259**	**155**	**1.67**	**145**	**6.2**	**15**	28	**Adverse**	**10**	**10**
26	LW41	WWD	179	105	1.70	72	23	20	24	Normal	20	20
27	LW9	Crinum	280	155	1.81	85	34	35	36	Normal	20	20
28	LW39	WWD	179	97	1.84	68	22.5	20	22	Normal	20	20
29	TE (3D)	Wyee North	355	185	1.92	63	54	50	78	Normal	20	20
30	TE(LW4)	Wyee North	355	180	1.97	40	>54	50	109	Normal	20	20
31	TE	Abel	150	76	1.97	45	15.5	15	26	Normal	15	15
32	TE(NthB)	Cooranbong	150	75	2.00	58	12.5	20	16	Normal	20	16
33	LW1	Oaky ck	205	95	2.16	55	29	30	25	Normal	15	25
34	**LW9/9a**	**Homestead**	**200**	**80**	**2.50**	**70**	**11**	**15**	16	**Normal**	**15**	**15**

W' = minimum (W, 1.4H); t_{min} - minimum beam thickness values at A-Horizon based on subsidence and borehole extensometer data; t' = effective beam thickness above A-Zone derived from back analysis techniques; * - t' is selected by consideration of tlog, t_{max} and t_{min} (see text below).
Bold - surface to seam fracturing reported by others; *italics* - Continuous Fracture Zone heights (A-Zone) was originally reported and included the Discontinuous Fracture and Dilated Zone (B-Zone). The A and B- Zone heights were re-assessed by DgS based on a review of available measured vertical strains and piezometric data (see **Figure A40i and A40j**).

In order to be able to make credible height of continuous fracturing predictions at a 'green fields' site based on borehole data alone, it was necessary to identify strata unit thicknesses that did and did not stop the height of fracturing.

To do this, the effective strata unit thicknesses from the database that appeared to have stopped the height of fracturing were normalized to the effective panel width (t'/W') and plotted against the unit's location factor (y/H); see **Figure A42f**. A similar exercise was completed for the strata units that did not stop the height of fracturing development, and are plotted on the above figure as well.

The two strata thickness categories were subsequently used in a logistic regression analysis to define the probabilistic power line equation below to indicate whether a strata unit is likely to span the goaf and limit the development of the height of fracturing at a given horizon above the workings:

$$P(i=1)=50\% \text{ for } t_{max} = W'[0.035(y/H)^{-1.3}]$$

where

i = 1 for a spanning unit, and

P(i=1)=50% for t_{max} refers to a 50% probability that a beam of a given thickness will span the fractured zone at a given location in the overburden.

A similar exercise was completed in order to define for the 95% probability of spanning equation:

$$P(i=1)=95\% \text{ for } t_{max} = W'[0.12(y/H)^{-0.85}]$$

where

i = 1 for a spanning unit, and

P(i=1)=95% for t_{max} refers to a 95% probability that a beam of a given thickness will span the fractured zone at a given location in the overburden.

The two above equations above are shown in **Figure A42f** with the database of 'goaf spanning' and 'non-goaf spanning' units.

For conservative or worst-case height of fracturing prediction, subsidence data was also reviewed to indicate the minimum effective beam thickness values (t_{min}) when massive strata units are not obviously present to span and limit the height of the A-Zone.

For this scenario, it is considered that t_{min} is likely to equal twice the measured peak surface strain to curvature ratios or twice the depth of observed cracking (whichever is the greater). For the Newcastle and Hunter Coalfields, a t_{min} range from 15 m to 20 m is indicated from subsidence monitoring data, with a t' range from 30 m to 40 m indicated for the Western and Southern Coalfields.

The t_{min} values for the likely cover depths are provided in **Table A6.3b**.

Table A6.3b - Minimum Effective Strata Thickness Based on Subsidence Data for Normal and Adverse Rock Mass Conditions in Australian Coalfields

Cover Depth H (m)	Minimum Effective t_{min}					
	Normal*					Adverse**
	Southern	Western	Newcastle/ Greta	Tomago/Hunter Valley/Narrabri	Bowen Basin	All Coalfields
>450	40	-	-	30	30	15
350 - 450	40	40	30	20	20	15
250 - 350	20	20	20	20	20	10
150 - 250	20	20	20	15	15	10
<150	20	15	20	15	15	10

* - Normal conditions refer to rock mass behaviour that is unlikely to be adversely affected by geological structure or atypical rock mass conditions (e.g. deep weathering or a lack of low permeability units in the B-Zone).
** - Adverse are likely to be affected by geological structure or atypical rock mass conditions (see definition above).

Validation of the model involved the application of the following algorithm to check that the predicted beam thickness values (t') from the available borehole data (t_{log}) were consistent with the back-analysed results and the maximum (t_{max}) and minimum thicknesses (t_{min}) derived from borehole and subsidence data that is required to span the goaf:

- If $t_{log} > t_{max\ (for\ 95\%\ spanning\ probability)}$ then $t' = t_{max\ (for\ 95\%\ spanning\ probability)}$ (so as not to bias the database above the required t' to span the goaf at a given horizon);

- If $t_{log} < t_{max\ for\ 95\%\ spanning\ probability}$ then $t' = t_{min\ based\ on\ subsidence\ data}$ (see below).

A summary of the back analysis v. predicted effective strata unit thickness presented in **Table A6.3a** are compared graphically in **Figure A42g**. It is assessed that the proposed algorithm to estimate the likely strata unit thickness for the Pi-Term model is reasonable to give an R^2 value of 0.8 and root mean square area of 15%.

The predicted v. measured outcomes using the "Geology" Pi-term model are presented in **Figures A42h** to **A42j**. Further validation of the Geology Pi-term model outcomes are presented in **Sections A11.5.7** and **A11.5.8**.

A11.5.7 Analytical Models of Goaf Spanning Strata Unit Thickness

The minimum thicknesses of the strata units required to limit the height of continuous fracturing have also been estimated analytically for the following scenarios:

(i) Strata units that can support the full overburden load.

(ii) Single goaf spanning units, which are single strata units that have sheared / dilated away from the overlying rock mass but are able to support their own weight and span any partial voids immediately below.

For Scenario (i) the minimum strata unit thickness to fully support the overburden above it was assessed using Voussoir Beam theory presented in **Diedrichs and Kaiser, 1999**. For a factor of safety against crushing of 2:

$$t_{min,\ full} = \sqrt{(1.5\gamma(H-y)(W-2y\tan\theta)^2/UCS)}$$

For Scenario (ii) the minimum strata unit thickness to support its self-weight only was also assessed using Voussoir Beam theory presented in **Diedrichs and Kaiser, 1999**. For a factor of safety against crushing of 2:

$$t_{min,\ single} = 1.5\gamma(W-2y\tan\theta)^2/UCS$$

Note: The above equations were derived from Equation (1) and assume that the compression arch forms within 50% of the beam thickness (conservative).

Back analysis of the database indicated the angle of break increases with W/H and ranges from $\theta = 12^o$ for sub-critical panels and 19.3^o for supercritical panels. The following equations give the best fit to the geology model presented in **Section A11.5**:

$\theta = 12^o$	or W/H <0.45
$\theta = 9.63^o + 4.42(W/H) + 1.8(W/H)^2$	for 0.45 < W/H < 1.4
$\theta = 19.3^o$	for W/H > 1.4

Published laboratory UCS testing data on sandstone / conglomerate / igneous core samples from each coalfield were adopted as shown in **Table A6.4**.

A summary of the analytical goaf spanning equation results and back analysed strata unit thicknesses and beam stresses are presented in **Table A6.4**. It is considered that the minimum beam stress will govern the loading/spanning scenario for a given mining geometry. The results again demonstrate the complexity of how the fracture zone heights develop and the difficulties involved with using analytical or numerical techniques v. empirical methods.

The analytical beam thicknesses estimated for the goaf spanning scenarios are also plotted in **Figure A42f**. It is apparent the minimum thicknesses determined for the full rock mass loading case scenario and single spanning unit scenario generally plot above and below the logistic regression line for a 50% Probability of Spanning respectively. This would suggest that the Scenario (i) model is more likely to reflect the loading behaviour of the rock mass compared to Scenario (ii) (assuming the rock mass properties adopted are reasonable).

The predicted v. observed A values for the proposed Geology Pi-term model are presented in **Figures A42f** and **Figure A42g** respectively. The residual errors reasonably follow a normal probability distribution about the regression curve according to Central Limit Theory in statistics (see **Figure A42h**).

Table A6.4 - Minimum Strata Unit Thicknesses Required for Spanning the Goaf based on Analytical Models of the Overburden

Site	Panels	Mine	W (m)	H (m)	W_i	UCS (MPa)	t (m)	y (m)	y/H	Back analysed t' (m)	Full Load t_{min} (m)	Single Beam t_{min} (m)	Full Beam Load Stress (MPa)	Goaf Supported Beam Stress (MPa)
1	MW508	Bellambi W.	110	421	71	70	100	90	0.21	36.5	30	3	23	72
2	LW10	Metropolitan	140	460	85	70	100	130	0.28	31.5	36	4	45	49
3	LW1-4	South Coast	110	325	74	70	100	85	0.26	31.5	26	3	25	66
4	LW6	Kemira	117	335	75	70	100	98	0.29	27	27	3	35	52
5	LW20	Metropolitan	163	450	120	70	100	100	0.22	68	52	8	21	100
6	LWA1	Austar	159	417	122	70	100	80	0.19	160	51	8	18	208
7	LW514	Bellambi W.	150	400	112	70	100	90	0.23	54	46	7	25	75
8	LW28	Appin	200	500	162	70	120	90	0.18	80	76	14	31	61
9	LW2	Ellalong	150	368	102	70	100	113	0.31	37	38	6	36	59
10	LW3	Tahmoor	180	424	180	70	100	100	0.24	60	75	17	72	85
11	LW9	Teralba	150	350	103	70	34	110	0.31	27	37	6	66	34
12	TE	West Cliff	200	446	157	70	100	101	0.23	57	68	13	49	45
13	TE	Berima	120	176	84	70	100	76	0.43	18	19	4	40	34
14	LW409	Springvale	265	384	201	70	55	133	0.27	78	74	22	108	26
15	LW9(11)	Mandalong	160	220	160	67	30	160	0.73	30	29	14	-	-
16	LW11	Angus Place	211	263	211	70	100	*253*	0.96	30	15	24	-	-
17	411	Springvale	315	368	242	70	100	139	0.38	42	85	31	142	20
18	LW5	Mandalong	160	179	97	67	25	83	0.46	14.5	18	5	51	23
19	LW5	Dendrobium	245	255	177	70	80	123	0.48	32	47	17	75	28
20	LW1	Wyee	216	206	143	70	30	126	0.61	18.2	30	11	92	18
21	**LW1**	**Invincible**	**145**	**116**	**83**	**70**	**15**	**106**	**0.91**	8.5	9	**4**	36	15
22	TE 1	Abel	120	95	91	30	15	41	0.43	18	23	10	24	20
23	LWs	Ashton	216	154	158	30	30	82	0.53	25.5	47	31	52	10
24	LW40	WWD	179	113	102	30	20	80	0.71	21	21	13	15	22
25	**LWE1**	**Sth Bulga**	**259**	**155**	**115**	**30**	**20**	**145**	**0.94**	6.2	13	**17**	65	2
26	LW41	WWD	179	105	97	30	20	72	0.69	23	20	12	11	28
27	LW9	Crinum	280	155	157	130	35	105	0.68	34	22	7	28	79
28	LW39	WWD	179	97	88	30	20	68	0.70	22.5	17	10	8	32
29	TE (3D)	Wyee North	355	185	215	70	50	63	0.34	54	55	25	36	28
30	TE(LW4)	Wyee North	355	180	224	70	50	40	0.22	<u>156</u>	61	27	37	34
31	TE	Abel	150	76	75	30	15	33	0.43	15.5	15	7	14	18
32	TE(NthB)	Cooranbong	150	75	64	67	20	58	0.77	12.5	8	2	8	47
33	LW1	Oaky ck	205	95	94	30	30	55	0.58	29	21	11	8	37
34	**LW9/9a**	**Homestead**	**200**	**80**	63	**30**	**15**	**65**	**0.81**	11	8	5	6	18

W' = minimum (W, 1.4H); t_{min} - minimum beam thickness values at A-Horizon based on subsidence and borehole extensometer data; t' = effective beam thickness above A-Zone derived from back analysis techniques;
Bold - surface to seam fracturing reported by others;
<u>Underlined</u> - Conservative estimate of t' returned.
italics - Continuous Fracture Zone heights (A-Zone) was originally reported and included the Discontinuous Fracture and Dilated Zone (B-Zone). The A and B- Zone heights were re-assessed by DgS based on a review of available measured vertical strains and piezometric data (see **Figure A40i** and **A40j**).

A11.5.8 Pi-Term Model for Predicting Heights of Discontinuous Fracturing (B) Above Longwalls without using the Geology Pi-Term (Geometry Model)

Based on the empirical database presented in **Table A6.1**, the statistics software XLSTAT® was used to complete a multi-nonlinear regression analysis as follows for estimating the height of the dilated B-Zone :

Mean B/W' = 1.621 $(H'/W')^{0.55}(T/W')^{0.175}$ $R^2 = 0.86$ & rsme = 0.12W' (13%)

U95% B/W' = Mean B/W' + b

where b = 0.16 for subcritical panels, 0.16-0.085(W/H-0.7) for critical panels and 0.10 for supercritical panels.

H' = Goaf Load Height = H

W' = Effective Panel Width = minimum of W and 1.4H.

T = Mining Height.

Re-arranging the above equation in terms of B gives:

$B = 1.621\ W'^{0.275}H^{0.55}T^{0.175}$ +/- bW'

The predicted v. observed B/W' and B' values are presented in **Figure A42k** and **Figure A42l** respectively. The residual errors follow a normal probability distribution about the regression curve as expected according to Central Limit Theory in statistics (see **Figure A42m**). The regression indicates a relatively weaker relationship exists between the height of B-Zone fracturing and the mining height compared to the A-Zone relationship.

A11.5.9 Pi-Term Model for Predicting Heights of Discontinuous Fracturing (B) Above Longwalls using the Geology Pi-Term

Based on the empirical database presented in **Table A6.1**, the statistics software XLSTAT® was used to complete a multi-nonlinear regression analysis as follows for estimating the height of the dilated B-Zone :

Mean B/W' = 1.873 $(H'/W')^{0.635}(T/W')^{0.257}(t'/W')^{-0.097}$ $R^2 = 0.86$ & rmse = 0.13W'(15%)

U95% B/W' = Mean B/W' + b

where b = 0.15 for subcritical panels; 0.15-0.0714(W/H-0.7) for critical panels and 0.10 for supercritical panels.

H' = Goaf Load Height = H

W' = Effective Panel Width = minimum of W and 1.4H.

T = Mining Height.

t' = Effective strata unit thickness; see **Section A11.5.6**.

Re-arranging the above equation in terms of B gives:

$$B = 1.873\, W'^{0.205} H^{0.635} T^{0.257} t'^{-0.097} \quad +/- \; bW'$$

The predicted v. observed B/W' and B' values are presented in **Figure A42n** and **Figure A42o** respectively. The residual errors follow a normal probability distribution about the regression curve as expected according to Central Limit Theory in statistics (see **Figure A42p**). The regression indicates a relatively weaker relationship exists between the height of B-Zone fracturing, the mining height and strata unit thickness compared to the A-Zone relationship.

A11.5.10 Pi-Term Model Validation

Validation of the proposed Pi-Term model has been completed as follows:

(i) A review of the range of independent variables within the database to check if the model is likely to be biased towards a particular parameter or mining geometry.

(ii) Comparison of predicted v. measured A and B-Horizons for each model to check model reliability.

(iii) Sensitivity analysis of the model to the assumed input parameters (based on method applied in **Hydrosimulations, 2013**).

(iv) Comparison of model results with other models over a representative range of mining geometries and overburden geologies.

(i) Database Variable Review

In regards to the data base, the following parameters from **Table A6.1** were plotted against the W/H ratio in **Figures A43a** to **43d** to test for sample bias:

- Panel Width (W)
- Cover Depth (H)
- Mining Height (T)
- Height of A-Zone Fracturing (A)
- Height of B-Zone Fracturing/Strata Dilation (B)

It is assessed that the database has sufficient coverage in regards to panel width, cover depth and mining height to reliably estimate HoF Zones above sub-critical to super-critical panels with W/H values ranging from 0.3 to 2.2.

(ii) Model Reliability

In regards to prediction model reliability, the minimum effective strata unit thickness assessed for each site has used to estimate the height of A and B-Zones and the residual areas subjected to a Normality test. The distributions of model residual errors should follow the Central Limit theorem for regression analysis. That is, a normal distribution of errors would be expected to occur about the regression line of 'best-fit'. If the regression lines are deemed to meet this requirement, the assessment of predicted confidence limits will then be possible. It would then be expected that < 5% of measured values would exceed the predicted U95%CL values on average.

The regression results for the A-Zone Geological model are summarised in **Table A6.5** and **Figure A42j**. The results demonstrate the model errors satisfy normality tests with 61% of the measured values below the predicted mean values and 97% of the measured values below the Upper 95%CL predictions. A slightly lower reliability outcome was achieved for the Geometry Model for the B-Zone with 55% of measured values below the mean and 90% below the U95%CL (see **Table A6.6**).

It is therefore considered that the reliability of the Pi-Term geology model is acceptable for worst-case estimates of A-Zone fracture heights at new or existing coal mines in Australia until local performance data either confirms or supersedes it.

The results for the B-Zone geology model checks also indicate the model errors satisfy normality tests as shown in **Figure A42p** and are summarised in **Table A6.7**. The proposed mean and U95%CL model satisfactorily over predicts 52% and 95% of the measured B-Zone data (i.e. within 5% of the expected values). A slightly lower reliability outcome was achieved for the Geometry Model for the B-Zone (see **Table A6.8**).

Overall, it is considered that the reliability of both the Pi-Term Models is acceptable for estimates of B-Zone discontinuous fracture height assessments at new or existing coal mines in the NSW Coalfields and should be confirmed or re-calibrated with local measurement data.

The above results indicate that the model is likely to provide reasonably conservative estimates of the height of continuous fracturing for the full range of mining geometries, based on the effective panel width, effective goaf load height (cover depth), mining height and effective strata unit thickness in the A or B-Zones.

Table A6.5 - Summary of Measured v. Predicted Height of Continuous Fracture A-Zones for the Geology Model

Site	**Panel**	**Mine**	**Panel Width W (m)**	**Cover Depth H (m)**	**W/H**	**Mining Height T (m)**	**Predicted t' (m)**	**Predicted A (m)**		**Measured A (m)**	**Pass = 1; Fail = 0**	
								mean	U95%CL		m	U95
1	MW508	Bellambi W	110	421	0.26	2.50	49	82	98	**92**	0	**1**
2	LW10	Metropolitan	140	460	0.30	3.40	49	109	130	**130**	0	**1**
3	LW1-4	South Coast	110	325	0.34	2.50	41	76	93	**85**	0	**1**
4	LW6	Kemira	117	335	0.35	2.75	40	84	102	**98**	0	**1**
5	LW20	Metropolitan	163	450	0.36	3.40	70	99	124	**100**	0	**1**
6	LWA1	Austar	159	417	0.38	6.00	78	118	142	***87***	1	**1**
7	LW514	Bellambi W	150	400	0.38	2.70	64	84	106	**90**	0	**1**
8	LW28	Appin	200	500	0.40	2.30	103	81	111	**90**	0	**1**
9	LW2	Ellalong	150	368	0.41	3.50	49	101	123	**113**	0	**1**
10	LW3	Tahmoor	180	424	0.42	2.18	74	80	107	**-**	-	**-**
11	LW9	Teralba	150	350	0.43	2.70	30	106	128	***110***	0	**1**
12	TE	West Cliff	200	446	0.45	2.50	85	86	116	***101***	0	**1**
13	TE-SW1	Berrima	120	176	0.68	2.3	29	63	81	***76***	0	**1**
14	LW409	Springvale	265	384	0.69	3.25	32	148	188	**133**	0	**1**
15	LW9	Mandalong	160	220	0.73	4.50	25	115	139	**-**	-	**-**
16	LW11	Angus Place	211	263	0.80	2.47	16	129	159	**-**	-	**-**
17	411	Springvale	315	368	0.86	3.25	32	156	199	**139**	0	**1**
18	LW5	Mandalong	160	179	0.89	3.70	20	103	125	**118**	0	**1**
19	LW5	Dendrobium	245	255	0.96	3.75	55	100	132	**123**	0	**1**
20	LW1	Wyee	216	206	1.05	3.44	20	121	148	**126**	0	**1**
21	*LW1*	*Invincible*	*145*	*116*	*1.25*	*2.70*	*15*	90	106	*96*	**0**	**1**
22	TE1	Abel	120	95	1.26	2.30	15	59	72	**45**	1	**1**
23	LWs	Ashton	216	154	1.40	2.55	15	101	123	**82**	1	**1**
24	LW40	WWD	179	113	1.58	3.80	20	81	97	**80**	1	**1**
25	*LWE1*	*South Bulga*	*259*	*155*	*1.67*	*2.55*	*15*	120	142	*145*	**0**	**0**
26	LW41	WWD	179	105	1.70	3.80	20	76	91	**72**	1	**1**
27	LW9	Crinum	280	155	1.81	3.50	20	105	127	**85**	1	**1**
28	LW39	WWD	179	97	1.84	3.90	20	71	85	**68**	1	**1**
29	TE-3D	Wyee North	355	185	1.92	1.90	20	60	86	**63**	0	**1**
30	TE-355	Wyee North	355	180	1.97	1.90	20	59	84	**40**	1	**1**
31	Panel2	Abel	150	76	1.97	1.88	15	45	56	**45**	1	**1**
32	TE - North B	Cooranbong	150	75	2.00	2.80	16	53	64	**58**	0	**1**
33	LW1	Oaky Ck	205	95	2.16	3.20	25	58	71	**55**	1	**1**
34	*LW9/9a*	*Homestead*	*200*	*80*	*2.50*	*3.30*	*15*	62	73	***70***	0	**1**
										Percentage of Measured < Predicted Value	39	97

italics - Surface to seam connection reported by authors.

Table A6.6 - Summary of Measured v. Predicted Height of Continuous Fracture A-Zones for the Geometry Model

Site	Panel	Mine	Panel Width W (m)	Cover Depth H (m)	W/H	Mining Height T (m)	Predicted A (m)		Measured A (m)	Pass = 1; Fail = 0	
							mean	U95%CL		m	U95
1	MW508	Bellambi W	110	421	0.26	2.50	86	103	**92**	0	1
2	LW10	Metropolitan	140	460	0.30	3.40	107	130	**130**	0	1
3	LW1-4	South Coast	110	325	0.34	2.50	80	98	**85**	0	1
4	LW6	Kemira	117	335	0.35	2.75	85	104	**98**	0	1
5	LW20	Metropolitan	163	450	0.36	3.40	113	139	**100**	1	1
6	LWA1	Austar	159	417	0.38	6.00	135	161	***87***	1	1
7	LW514	Bellambi W	150	400	0.38	2.70	97	121	**90**	1	1
8	LW28	Appin	200	500	0.40	2.30	108	140	**90**	1	1
9	LW2	Ellalong	150	368	0.41	3.50	105	129	**113**	0	1
10	LW3	Tahmoor	180	424	0.42	2.18	97	126	**-**	-	-
11	LW9	Teralba	150	350	0.43	2.70	94	118	***110***	0	1
12	TE	West Cliff	200	446	0.45	2.50	108	140	***101***	1	1
13	TE	Berrima	120	176	0.68	2.3	68	87	***76***	0	1
14	LW409	Springvale	265	384	0.69	3.25	126	169	**133**	0	1
15	LW9	Mandalong	160	220	0.73	4.50	102	128	**-**	-	-
16	LW11	Angus Place	211	263	0.80	2.47	95	127	**-**	-	-
17	411	Springvale	315	368	0.86	3.25	133	179	**139**	0	1
18	LW5	Mandalong	160	179	0.89	3.70	90	113	**118**	0	0
19	LW5	Dendrobium	245	255	0.96	3.75	116	150	**123**	0	1
20	LW1	Wyee	216	206	1.05	3.44	101	129	**126**	0	1
21	*LW1*	*Invincible*	*145*	*116*	*1.25*	*2.70*	69	85	**96**	**0**	**0**
22	TE1	Abel	120	95	1.26	2.30	57	71	**45**	1	1
23	LWs	Ashton	216	154	1.40	2.55	84	105	**82**	1	1
24	LW40	WWD	179	113	1.58	3.80	80	105	**80**	0	1
25	*LWE1*	*South Bulga*	*259*	*155*	*1.67*	*2.55*	84	119	**145**	**0**	**0**
26	LW41	WWD	179	105	1.70	3.80	76	100	**72**	1	1
27	LW9	Crinum	280	155	1.81	3.50	95	129	**85**	1	1
28	LW39	WWD	179	97	1.84	3.90	73	95	**68**	1	1
29	TE-3D	Wyee North	355	185	1.92	1.90	84	126	**63**	1	1
30	TE-355	Wyee North	355	180	1.97	1.90	83	123	**40**	1	1
31	Panel2	Abel	150	76	1.97	1.88	48	65	**45**	1	1
32	TE-NthB	Cooranbong	150	75	2.00	2.80	55	72	**58**	0	1
33	LW1	Oaky Ck	205	95	2.16	3.20	67	88	**55**	1	1
34	*LW9/9a*	*Homestead*	*200*	*80*	*2.50*	*3.30*	61	79	***70***	0	1
Percentage of Measured < Predicted Value										45	90

italics - Surface to seam connection reported by authors.

Table A6.7 - Summary of Measured v. Predicted Height of Dilated B-Zones for the Geology Model

Site	Panel	Mine	Panel Width W (m)	Cover Depth H (m)	W/H	Mining Height T (m)	t' (m)	Predicted B (m)		Measured B (m)	Pass = 1; Fail = 0	
								mean	U95%CL		m	U95
1	MW508	Bellambi West	110	421	0.26	2.50	49	198	214	**-**	-	-
2	LW10	Metropolitan	140	460	0.30	3.40	49	238	259	**-**	-	-
3	LW1 to 4	South Coast	110	325	0.34	2.50	41	170	187	**-**	-	-
4	LW6	Kemira	117	335	0.35	2.75	40	181	198	**-**	-	-
5	LW20	Metropolitan	163	450	0.36	3.40	70	234	258	**-**	-	-
6	LWA1	Austar	159	417	0.38	6.00	78	254	278	**277**	0	1
7	LW514	Bellambi West	150	400	0.38	2.70	64	203	225	**-**	-	-
8	LW28	Appin	200	500	0.40	2.30	103	227	257	**-**	-	-
9	LW2	Ellalong	150	368	0.41	3.50	49	211	233	**210**	1	1
10	LW3	Tahmoor	180	424	0.42	2.18	74	204	231	**204**	0	1
11	LW9	Teralba	150	350	0.43	2.70	30	200	223	**150**	1	1
12	TE	West Cliff	200	446	0.45	2.50	85	220	250	***245***	0	1
13	TE SW1	Berrima	120	176	0.68	2.3	29	119	137	**112**	1	1
14	LW409	Springvale	265	384	0.69	3.25	32	249	289	***254***	0	1
15	LW9	Mandalong	160	220	0.73	4.50	25			**-**	-	-
16	LW11	Angus Place	211	263	0.80	2.47	16	177	208	***253***	0	0
17	411	Springvale	315	368	0.86	3.25	32	251	295	**288**	0	1
18	LW5	Mandalong	160	179	0.89	3.70	20	150	171	**154**	0	1
19	LW5	Dendrobium	245	255	0.96	3.75	55	186	218	**-**	-	-
20	LW1	Wyee	216	206	1.05	3.44	20	171	198	**-**	-	-
21	LW1	Invincible	145	116	1.25	2.70	**10**	110	116	***111***	**0**	**1**
22	TE1	Abel	120	95	1.26	2.30	15	86	95	***75***	1	1
23	LWs	Ashton	216	154	1.40	2.55	15	135	154	***130***	1	1
24	LW40	WWD	179	113	1.58	3.80	20	112	113	***108***	**1**	1
25	LWE1	South Bulga	259	155	1.67	2.55	**10**	141	155	**150**	**0**	**1**
26	LW41	WWD	179	105	1.70	3.80	20	100	105	**100**	1	1
27	LW9	Crinum	280	155	1.81	3.50	20	143	155	***150***	0	1
28	LW39	WWD	179	97	1.84	3.90	20	92	97	**92**	0	1
29	TE-3D	Wyee North	355	185	1.92	1.90	60	128	154	***143***	0	1
30	TE-355	Wyee North (LW4)	355	180	1.97	1.90	60	125	150	**-**	-	-
31	Panel2	Abel	150	76	1.97	1.88	15	69	76	**71**	0	1
32	TE-North B	Cooranbong	150	75	2.00	2.80	16	70	75	***70***	1	1
33	LW1	Oaky Ck	205	95	2.16	3.20	25	91	95	***90***	1	1
34	LW9/9a	Homestead	200	80	2.50	3.30	15	75	80	**75**	**1**	1
Percentage of Measured < Predicted Value											**43**	**96**

Table A6.8 - Summary of Measured v. Predicted Height of Dilated B-Zones for the Geometry Model

Site	Panel	Mine	Panel Width W (m)	Cover Depth H (m)	W/H	Mining Height T (m)	Predicted B (m)		Measured B (m)	Pass = 1; Fail = 0	
							mean	U95%CL		m	U95
1	MW508	Bellambi West	110	421	0.26	2.50	192	210	**-**	-	-
2	LW10	Metropolitan	140	460	0.30	3.40	228	250	**-**	-	
3	LW1 to 4	South Coast	110	325	0.34	2.50	167	184	**-**	-	-
4	LW6	Kemira	117	335	0.35	2.75	175	194	**-**	-	-
5	LW20	Metropolitan	163	450	0.36	3.40	235	261	**-**	-	-
6	LWA1	Austar	159	417	0.38	6.00	247	272	**277**	0	0
7	LW514	Bellambi West	150	400	0.38	2.70	206	230	**-**	-	-
8	LW28	Appin	200	500	0.40	2.30	246	278	**-**	-	-
9	LW2	Ellalong	150	368	0.41	3.50	206	230	**210**	0	1
10	LW3	Tahmoor	180	424	0.42	2.18	216	245	**204**	1	1
11	LW9	Teralba	150	350	0.43	2.70	192	216	**150**	1	1
12	TE	West Cliff	200	446	0.45	2.50	234	266	***245***	0	1
13	TE SW1	Berrima	120	176	0.68	2.3	120	139	**112**	1	1
14	LW409	Springvale	265	384	0.69	3.25	244	286	***254***	0	1
15	LW9	Mandalong	160	220	0.73	4.50	165	191	**-**	-	-
16	LW11	Angus Place	211	263	0.80	2.47	177	209	***253***	0	0
17	411	Springvale	315	368	0.86	3.25	250	296	**288**	0	1
18	LW5	Mandalong	160	179	0.89	3.70	143	166	**154**	0	1
19	LW5	Dendrobium	245	255	0.96	3.75	195	229	**-**	-	-
20	LW1	Wyee	216	206	1.05	3.44	165	193	**-**	-	-
21	LW1	Invincible	145	116	1.25	2.70	104	116	***111***	0	1
22	TE1	Abel	120	95	1.26	2.30	86	95	***75***	1	1
23	LWs	Ashton	216	154	1.40	2.55	134	154	***130***	1	1
24	LW40	WWD	179	113	1.58	3.80	111	113	***108***	1	1
25	LWE1	South Bulga	259	155	1.67	2.55	134	155	**150**	0	1
26	LW41	WWD	179	105	1.70	3.80	104	105	**100**	1	1
27	LW9	Crinum	280	155	1.81	3.50	142	155	***150***	0	1
28	LW39	WWD	179	97	1.84	3.90	92	97	**92**	0	1
29	TE-3D	Wyee North	355	185	1.92	1.90	148	174	***143***	1	1
30	TE-355	Wyee North (LW4)	355	180	1.97	1.90	144	170	-	-	-
31	Panel2	Abel	150	76	1.97	1.88	71	76	**71**	0	1
32	TE-North B	Cooranbong	150	75	2.00	2.80	70	75	***70***	1	1
33	LW1	Oaky Ck	205	95	2.16	3.20	93	95	***90***	1	1
34	LW9/9a	Homestead	200	80	2.50	3.30	75	80	**75**	1	1
Percentage of Measured < Predicted Value										**48**	**91**

(iv) Parameter Sensitivities

A review of the sensitivity of the Pi-Term Models has been completed in **Merrick, 2014** and demonstrates that the model is not overly sensitive to changes to the input parameters, W, H and T. The influence of the effective strata thickness t' has a greater impact on the height of fracturing for values < 20 m than the cases with t'> 20 m. This is not surprising as the spanning capabilities of the strata units will probably decrease rapidly below this thickness range as it corresponds with the point where the bending beam stress starts to exceed the UCS of the rock mass.

The model variable sensitivity charts are presented in **Figures A43e** to **A43h**.

(v) Comparison with other models

Three critical cases were identified in the analysis where the A-Zone extended to within 10 m of the surface (Invincible, South Bulga, and Homestead Mines) with a minimum t' value of 10 m assumed. Adopting a minimum beam thickness of 10 m will generally indicate the maximum likely height of continuous fracturing for all cases in the database (see **Figure A42g**).

For completeness, four case studies have been selected from the sub-critical, critical and supercritical panel geometries and plotted with varying panel widths in **Figures A43i** to **A43l** to demonstrate the sensitivity of the models to changes in mining geometry. Several sub-surface fracture height models (**Foster, 1995; SCT, 2008; ACARP, 2007** and **Tammetta, 2013**) that have been referred to by OEH and PACs during recent project approval applications are also plotted with the Pi-term model results. It is apparent that the models are based on a smaller number of key variables and some were developed from data in a particular coalfield only. The application of the models in other coalfields with significantly different geological conditions and mining geometries are considered to have resulted in a larger range of 'error' compared to the Pi-term models.

Finally, the width-based models also do not consider the effect of cover depth or mining height and assume the A-Zone will continue to increase above *supercritical* panel geometries. This usually means that surface to seam connectivity will always be predicted for critical and supercritical panel widths. It is noted that only 2 or 3 cases out of 14 (15% - 20%) or 1 in 5 supercritical longwalls have resulted in surface to seam connectivity; see **Figure 43m**.

This outcome suggests that other factors such as cover depth, mining height and geological conditions should also be considered than just the panel width alone when estimating heights of fracturing above longwall panels.

A11.5.11 Definition of Surface Cracking Zone

During the development of the Pi-term model it has also been necessary to better define the surface cracking zone depth. The depth of the surface cracking zone has been estimated from subsidence data, surface crack observations and published measurements as follows:

- The literature review findings presented in **Section A11.3** indicate that surface cracking depths above longwalls are likely to be < 15 m generally.

- The Mean and median strain/curvature ratios of 5.3 m and 7.4 m mentioned earlier in Section derived from subsidence data measurements for Newcastle Coalfield (see **Figures A43n** and **A43o**) indicates the ***average surface cracking depth***. The ratio is considered to be a direct measurement of the depth to the neutral axis of bending where tensile strains cross over to compressive strain. This also suggests near surface strata beam thicknesses are twice the depth to the neutral axis of bending or 11 m to 15 m. It is apparent that these values are consistent with near surface beam thicknesses assumed in the Pi-Term Geology Model.

- Borehole measurement devices measured depths of cracking at the base of sandstone valleys in the Southern Coalfield of up to 12 m after mine subsidence effects (refer **Mills, 2007**).

- Measured crack depths of up to 20 m have been measured along the crests of steep slopes above LW41 (ref to **RCA, 2013**).

Based on the above information, it is assessed that the following conservative crack depths presented in **Table A6.9** may be assumed when assessing surface to seam connectivity potential above longwalls beneath varying topography:

Table A6.9 - Suggested Maximum Cracking Depths for Impact Assessment

Location and Topography	**Surface Cracking Depth (m)**
	Newcastle/Hunter Valley - Southern/Western Coalfield
Flat Terrain with Moderate Slopes up to 18^{o}	7.5 - 12
Bases of Valleys	12 - 15
Low side of panel beneath steep slopes > 18^{o} (not valley floor)	3.5 - 5
Crests or high side of panel beneath steep slopes > 18^{o}	15 - 20

A11.5.12 Summary

The geometry and geology Pi-term models presented in **Section A11.5** for estimating the A-Zone and B-Zone fracture horizons are generally consistent with the prevailing view that the panel width, cover depth and mining height will have the greatest influence on fracture development heights above longwall panels. The Pi-term models for A and B-Zone Fracture

Heights are also generally consistent with **Whittaker and Reddish, 1990**, **Singh & Kendorski, 1991** and the analytical models presented earlier.

The spanning or non-spanning capability of strata units in the overburden cannot be ignored however, when assessing the potential fracturing heights above a longwall panel. Where local extensometer and piezometric data are available, the influence of spanning strata may be used to calibrate the Geology Pi-term model to a given site.

Predictions based on the up-dated Strain, Overburden Curvature Index and Fracture Height Angle Models are still also considered relevant and will provide similar, if not more conservative outcomes. These models may be used to provide a range of predictions at a greenfields site for risk assessment purposes. It should be understood however, that only the Geology Pi-term model will allow the influence of strata unit thickness or local site geology to be included directly in the predictions of sub-surface fracture height.

It should be understood that the vagaries of the rock mass do not usually allow the strata unit thickness term to be assessed directly from borehole data without back analysis of overburden performance measurements. The database presented in this appendix has been used to derive a minimum beam thickness of 10 m to estimate worst-case heights of fracturing for adverse rock mass conditions. A thickness of 15 m to 20 m corresponds to the minimum beam thicknesses assessed from surface strain and curvature measurements (and a cracking depth of 7.5 m to 10 m).

Subsequent measurements of continuous heights of fracturing may require a thinner strata unit thickness to be used to calibrate the model. At this stage, there are three cases in the database that have been reported to have fractured through to the surface, which required a beam thickness of 6 to 11 m to match the Pi-term model exactly and intersect the surface cracking zone (or D-Zone). One of the cases (South Bulga LWE1) however, may have included the B-Zone in the interpretation of the 'height of fracturing' at the time it was assessed.

It is assessed that the assumptions that the height of fracturing will be limited when either:

- critical panel widths exceed 1.4H;
- spanning strata exists that can bridge the fractured zone or the presence of plastic, low strength strata that tends to shear along bedding partings when deformed through bending action, rather than crack vertically, may also limit continuous cracking heights.

All of these outcomes are intuitively correct and correlate well with observed behaviour across sub-critical to supercritical mining geometries. It is also noted that the strata unit thickness term enables all of the database and subsequent regression equations to be used with a reasonable level of confidence, such that the predicted worst-case values will not be unduly biased by the database itself. The geology Pi-term t'/W' was back analysed for each of the 34 case studies to give an exact fit between the predicted and measured fracture heights. The set of measured t' values were correlated with the predicted t' with a high R^2 of 0.9. The predicted v. measured heights of continuous fracturing were also correlated and returned an R^2 value of 0.8, which is also a good fit.

For estimates of HoF above partial pillar extraction panels, the HoF zones may be based on the effective mining height, T_e (if remnant pillars are likely to fail) or the maximum span between stable remnant pillars.

The use of the Pi-term models for multi-seam mining environments will also require consideration of the interburden thicknesses and cumulative effects of the A-Zones if they likely to intersect overlying longwall goafs. The multi-seam affect may be estimated for an overlying seam by converting the multi-seam subsidence increase to an effective mining height.

A13 References

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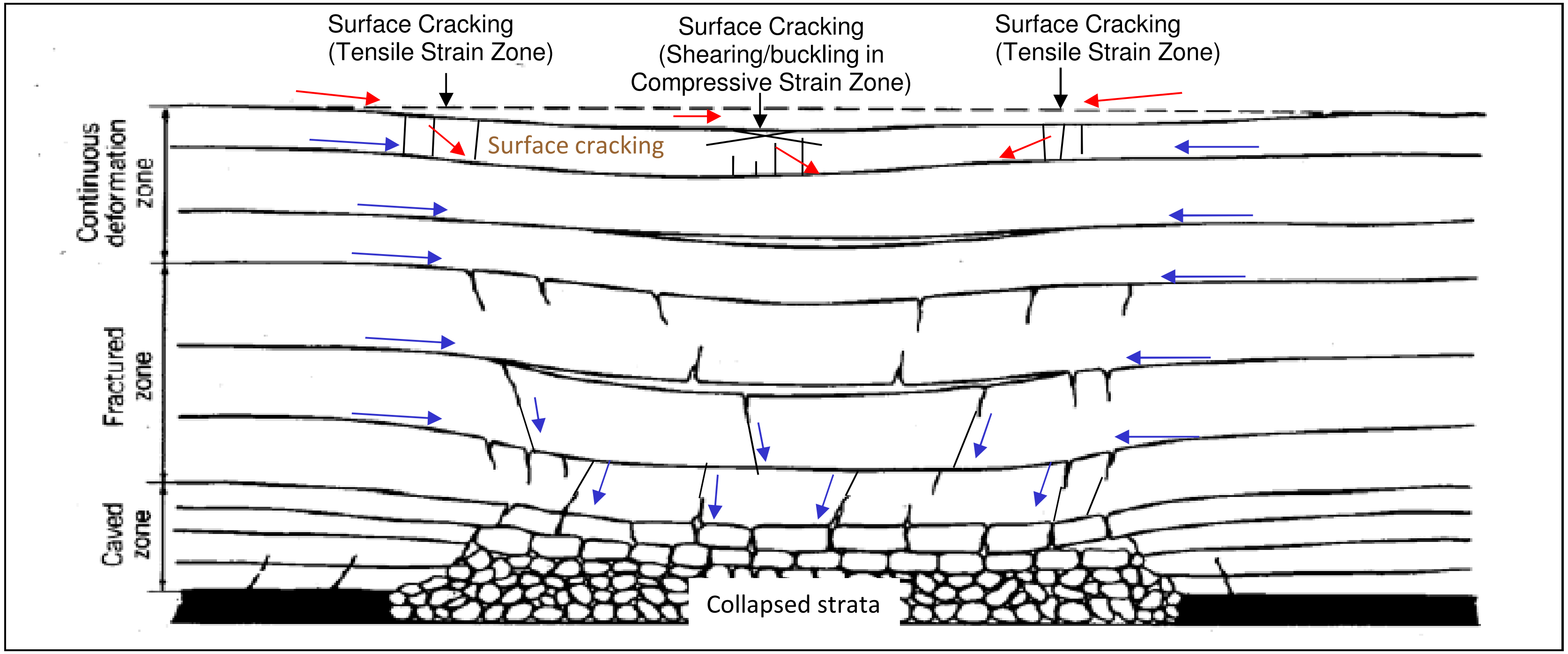
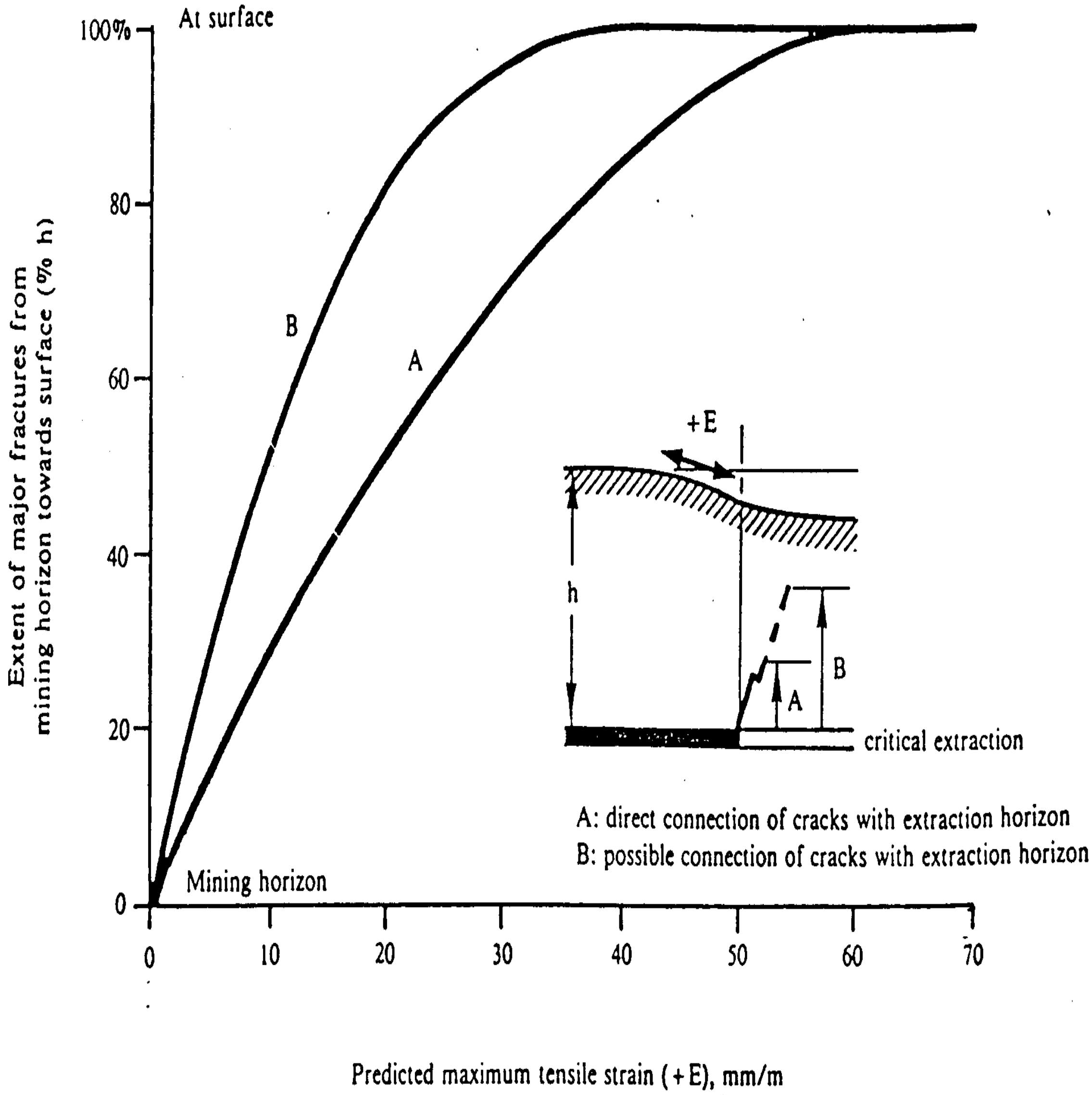


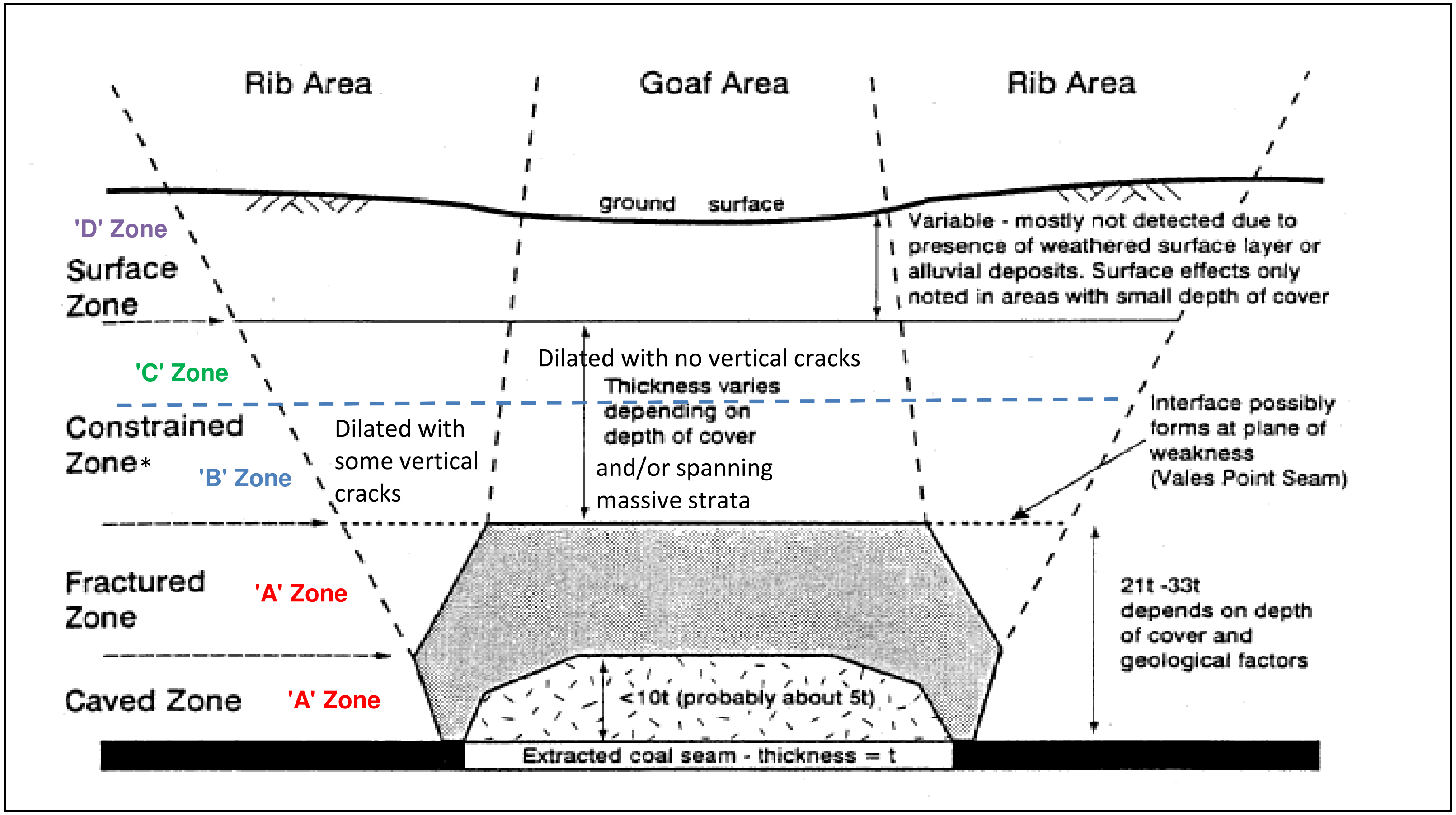
Zones in the Overburden According to Peng and Chiang (1984)

Key
Surface water flow path
Sub-surface water flow path

DgS	Engineer:	S.Ditton	Client:	Appendix A		
	Drawn:	S.Ditton				
	Date:	23.11.12	Title:	Schematic Model of Overburden Fracture Zones Above Longwall Panels		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A40a



DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	30.04.07	Title:	Enpirically Based Sub-Surface Fracturing Model Presented in Whittaker & Reddish, 1989		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A40b



Zones in the Overburden according to Forster (1995)

* - Constrained Zone generally means B-Zone, but may include C-Zone, depending on W/H ratio and geology

DgS	Engineer:	S.Ditton	Client:	Appendix A			
	Drawn:	S.Ditton					
	Date:	23.11.12	Title:	Schematic Model of Overburden Fracture Zones in **Forster, 1995** Model (based on Piezometric Data Above High Extraction Panels in the Newcastle Coalfield)			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A40c	

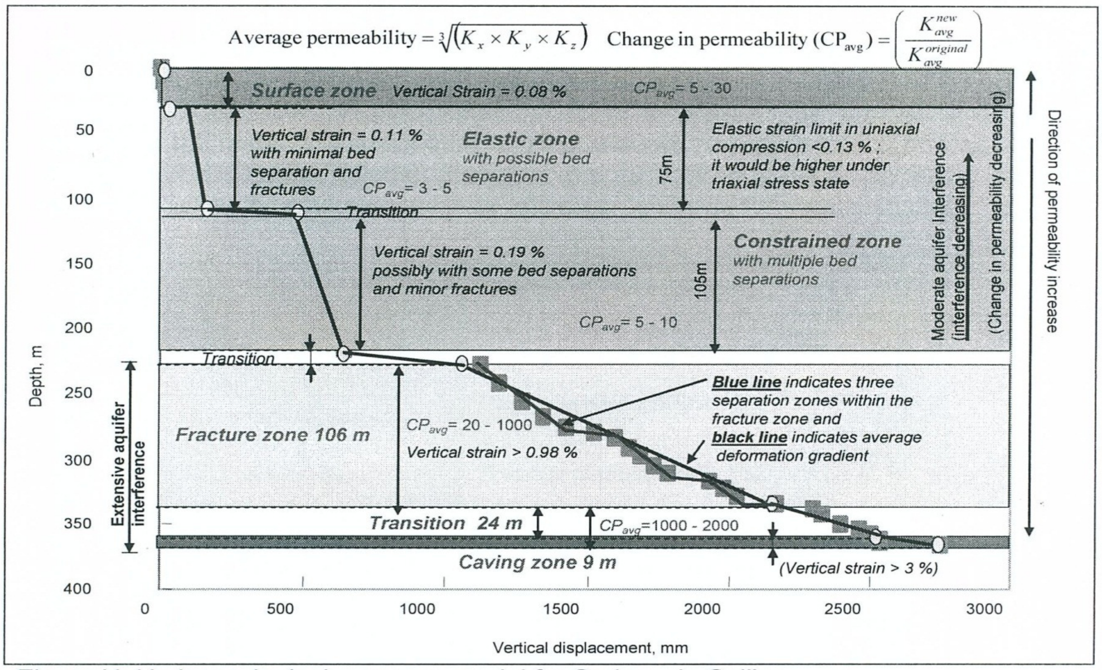


Figure H. Hydrogeological response model for Springvale Colliery

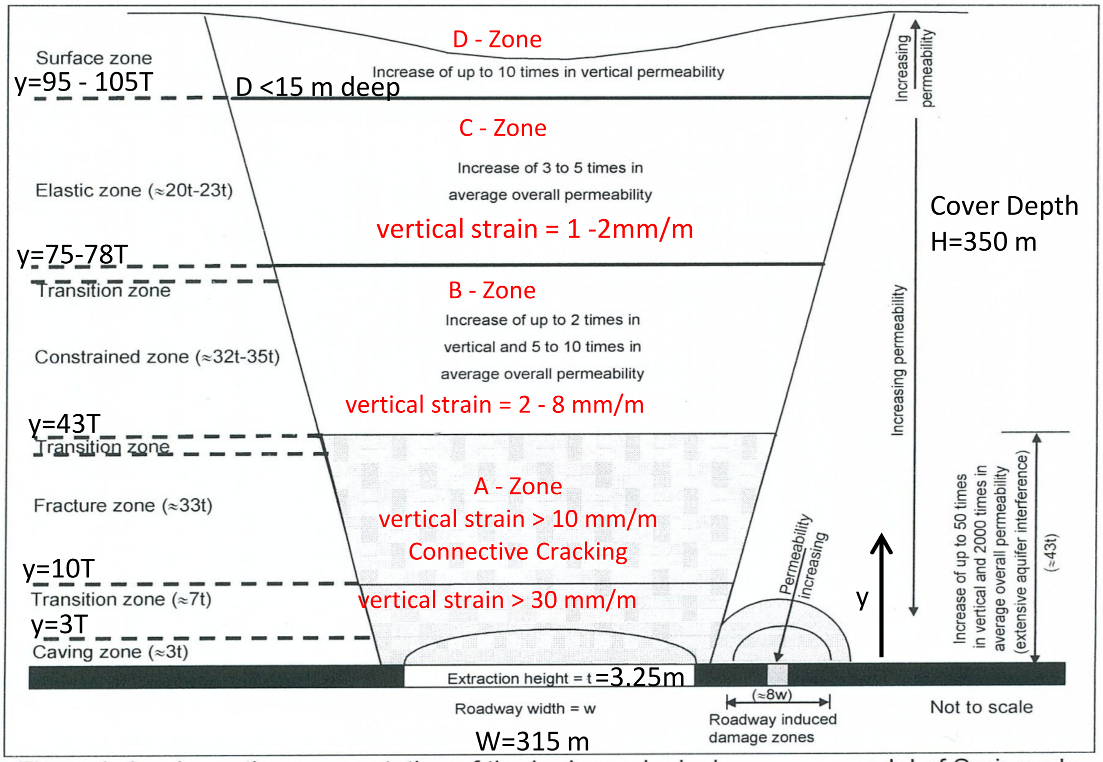


Figure I. A schematic representation of the hydrogeological response model of Springvale Colliery

DgS	Engineer:	S.Ditton	Client:	Appendix A		
	Drawn:	S.Ditton				
	Date:	23.11.12	Title:	Schematic Model of Overburden Fracture Zones **in ACARP, 2007**		
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No:	A40d

Figure 6 is a conceptual model that illustrates the type of damage that can be expected within the overburden due to subsidence above a full-extraction panel. Five broad zones can be identified [Singh and Kendorski 1981; Peng and Chiang 1984; Kendorski 1993, 2006]:

1. The *complete caving zone*, in which the roof rock is completely disrupted as it falls into the gob, normally extends two to four times the extracted seam height (h).
2. The *partial caving zone,* in which the beds are completely fractured but never lose contact with one another, extends up to 6–10 h.
3. The *fracture zone,* within which the subsidence strains are great enough to cause new fracturing in the rock and create direct hydraulic connections to the lower seam. The top of this zone can be as high as 24 h above the lower seam.
4. The *dilated zone,* where the permeability is enhanced but little new fracturing is created, extends up to 60 h.
5. The *confined zone,* where subsidence normally causes no change in strata properties other than occasional bed slippage. This zone extends from the top of the dilated zone to about 50 ft below the surface.

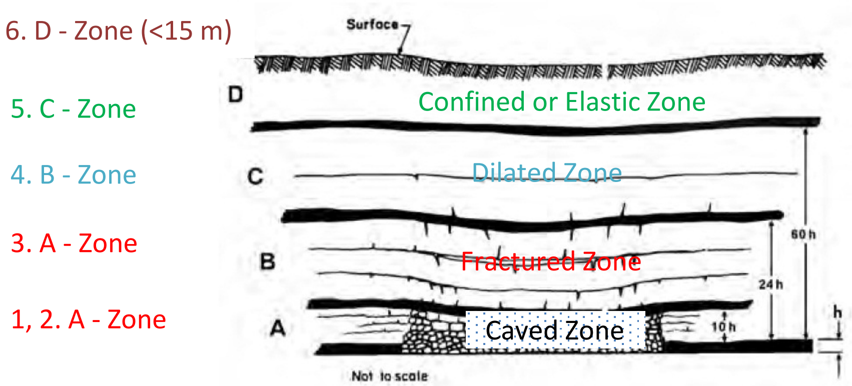


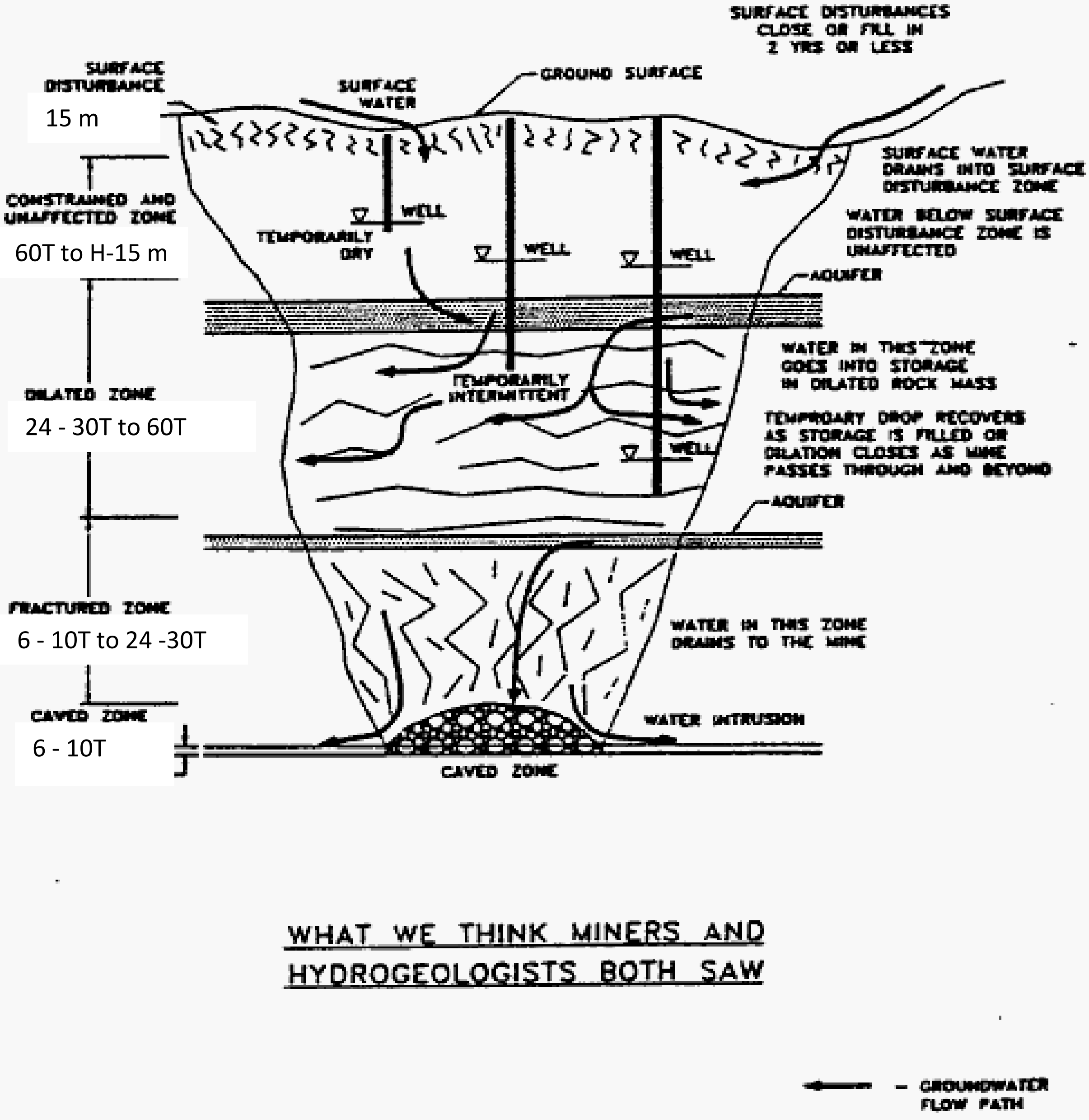
Figure 6.—Overburden response to full-extraction mining: (A) caving zones, (B) fracture zone, (C) dilated zone, and (D) confined zone.

The dimensions of these zones vary from panel to panel because of differences in geology and panel geometry. The implication of this model for multiple-seam mining is that when the interburden thickness exceeds approximately 6–10 times the lower seam thickness, the upper seam should be largely intact, although the roof may be fractured or otherwise damaged.

Note: Equivalent **ACARP, 2007** model zones A to D also shown down the left side.

DgS	Engineer:	S.Ditton	Client:	Appendix A		
	Drawn:	S.Ditton				
	Date:	03.06.13	Title:	Model of Overburden Fracture Zones above US Longwall Mines According to Mark, 2007		
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No:	A40e

Zone and Thickness Ranges
(based on Mining Height, T)



DgS	Engineer:	S.Ditton	Client:	Appendix A		
	Drawn:	S.Ditton				
	Date:	03.06.13	Title:	Model of Overburden Fracture Zones above UK Longwall Mines According to Kendorski, 1993		
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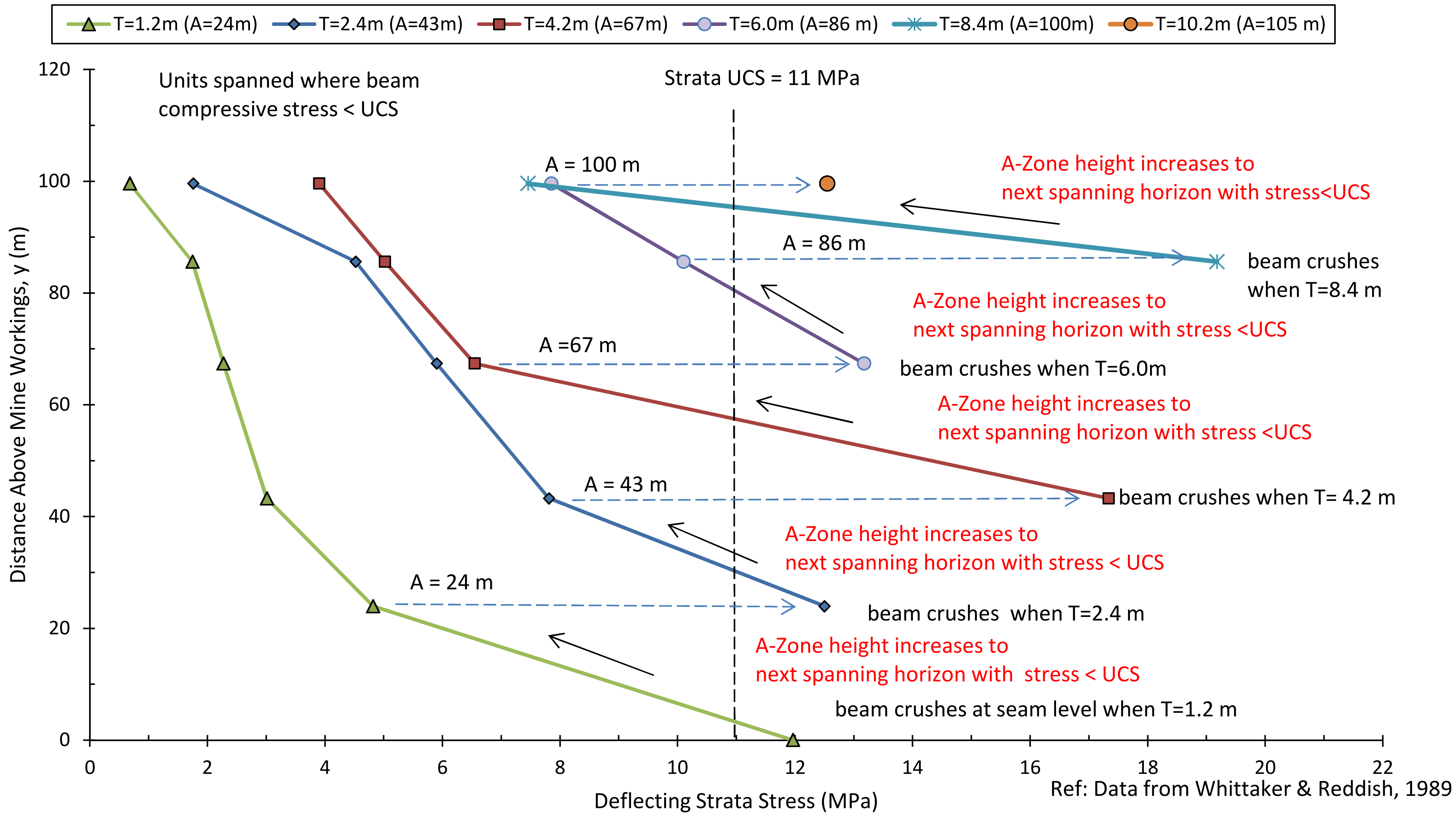
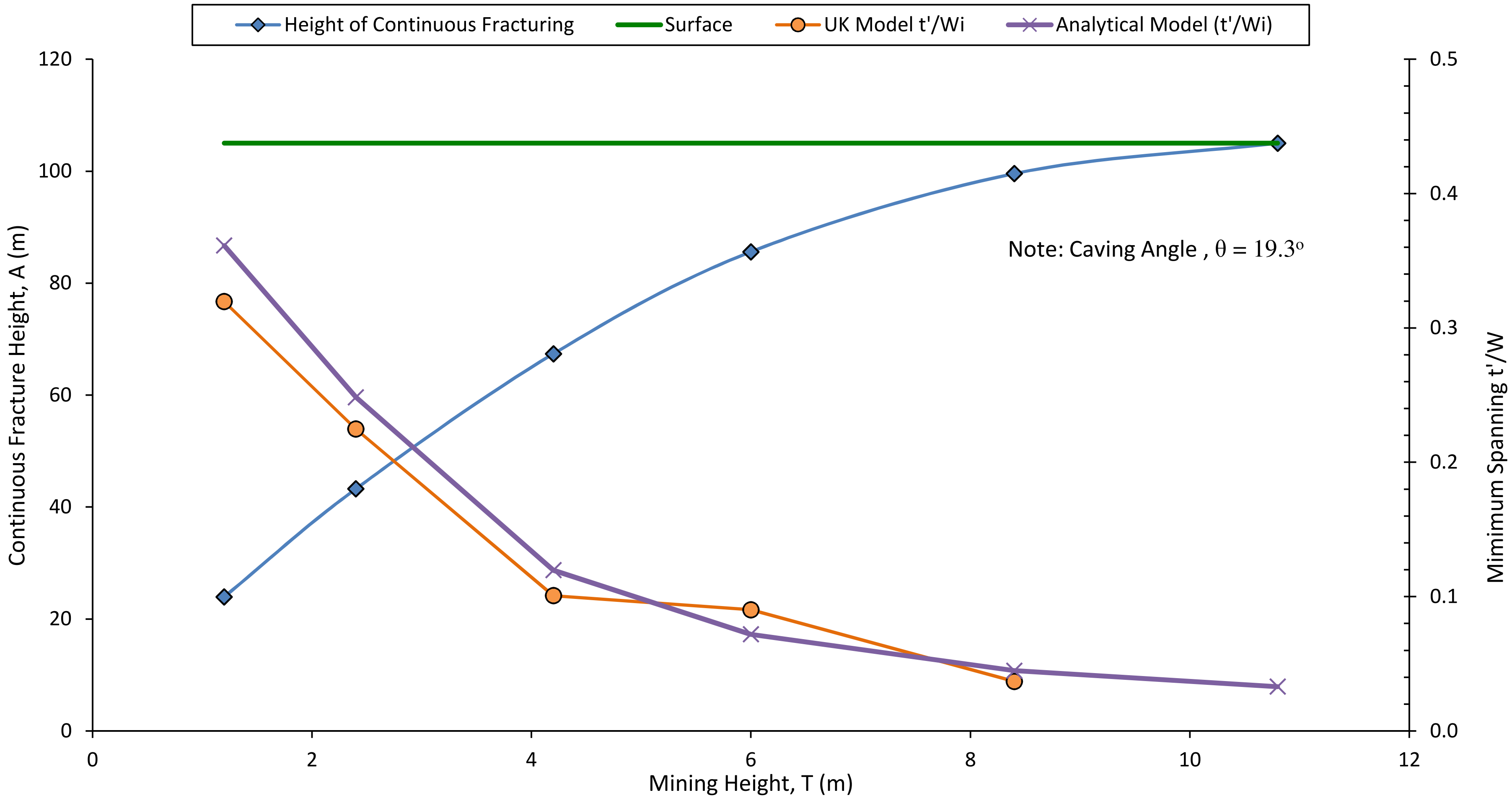
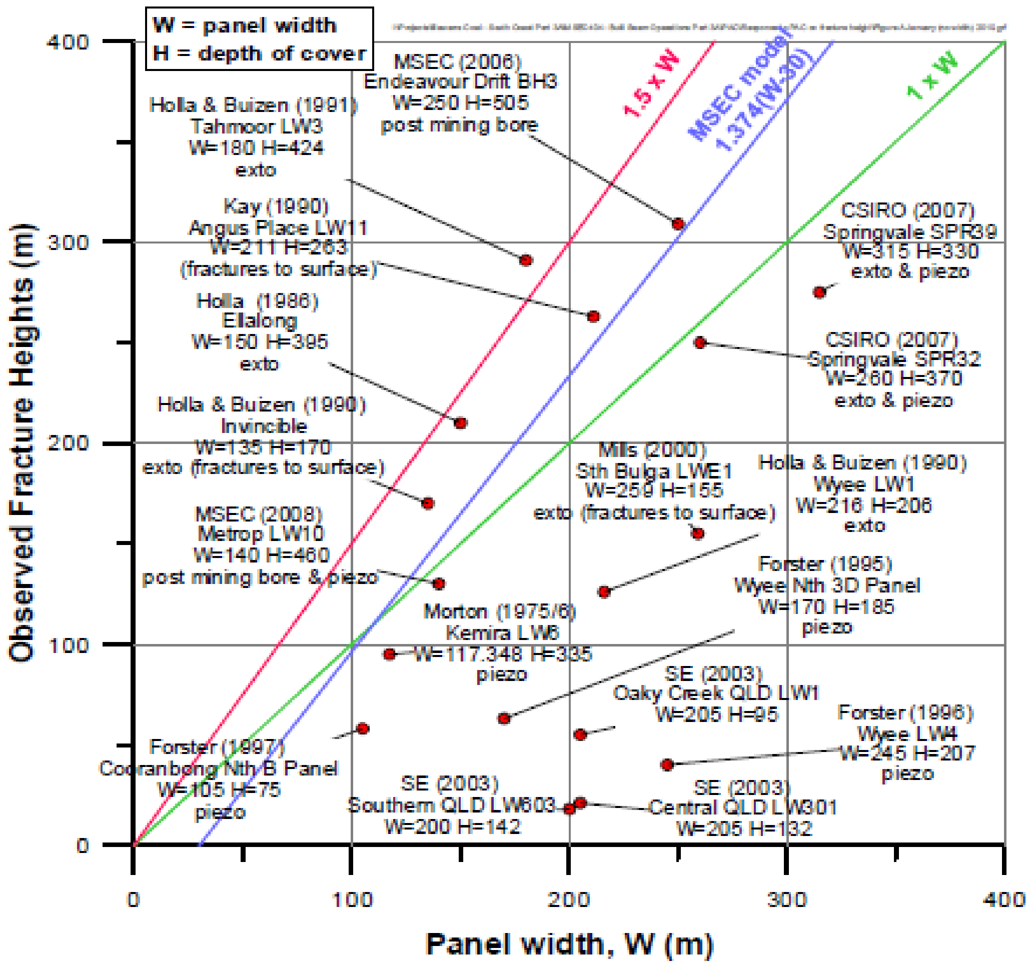


DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	07.06.13	Title:	Interpreted Beam Stress in Spanning Units of Physical Model of Laminated Overburden above a Longwall		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A40g



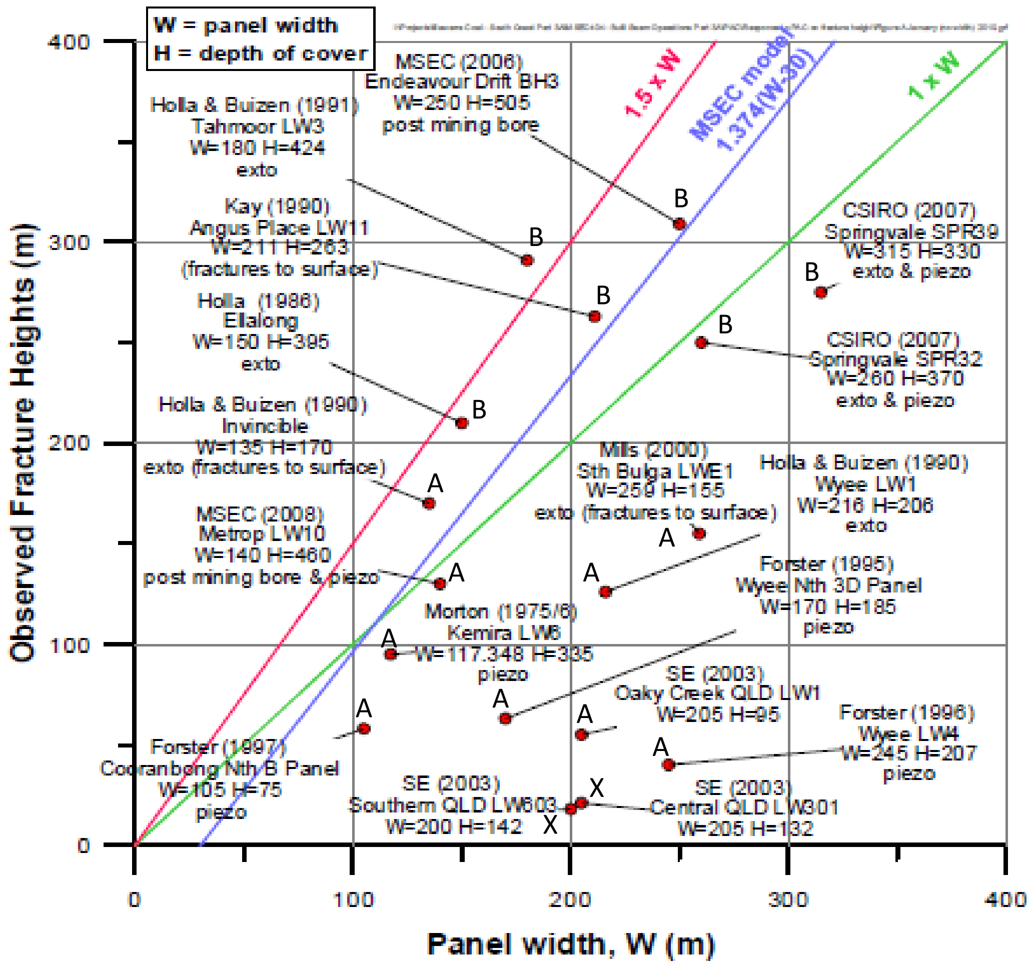
Ref: Data from Whittaker & Reddish, 1989

DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	07.06.13	Title:	Analytical v. Physical HoF Model Mimimum Beam Thickness Required to Span the Continuous Fracture Zone		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A40h



Ref: MSEC, 2011

DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton	Title:	Observed Fracture Height Models presented by SCT and MSEC	
	Date:	07.06.13			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A40i



Key

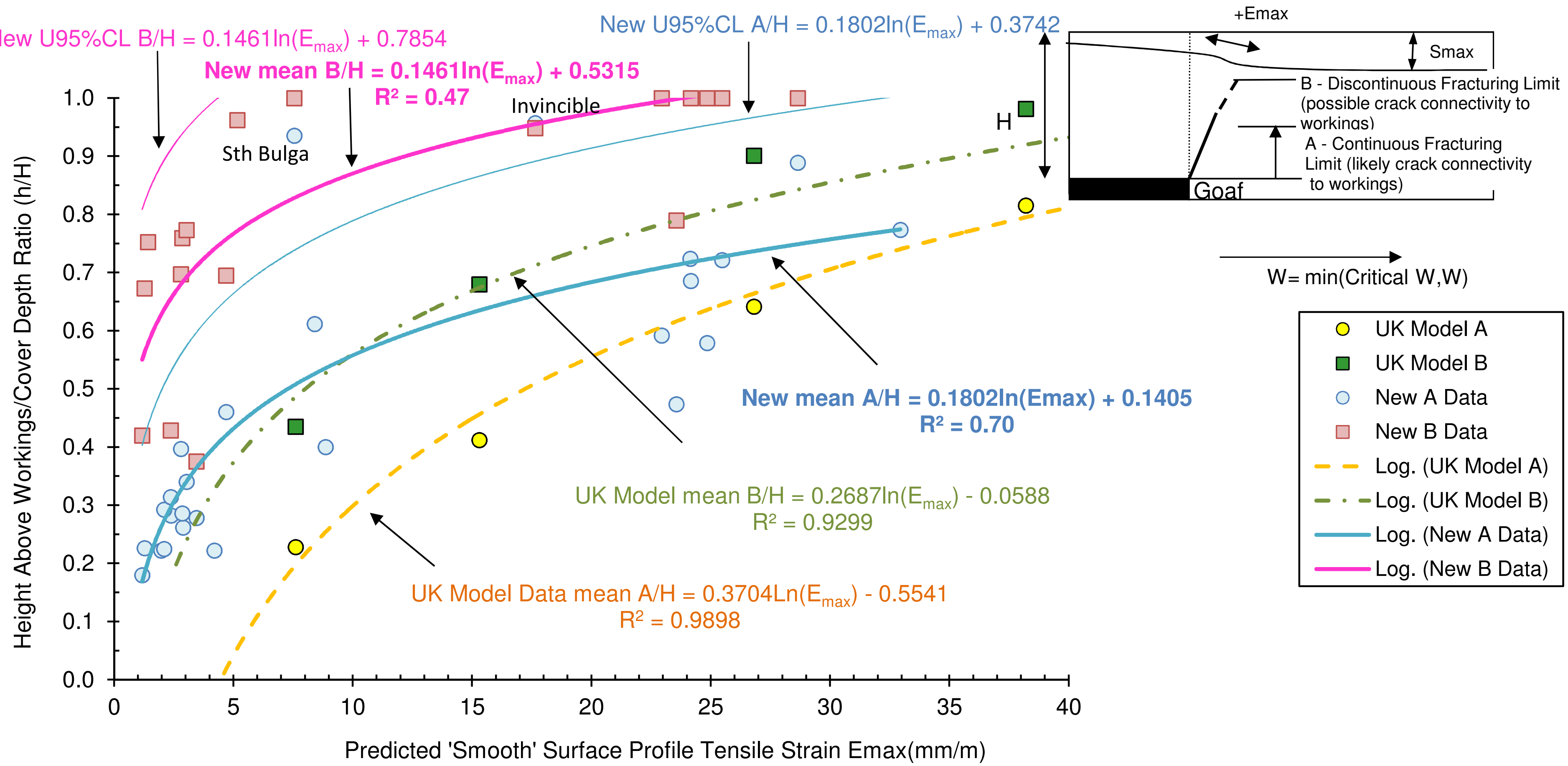
A: A-Zone Horizon

B: B-Zone Horizon

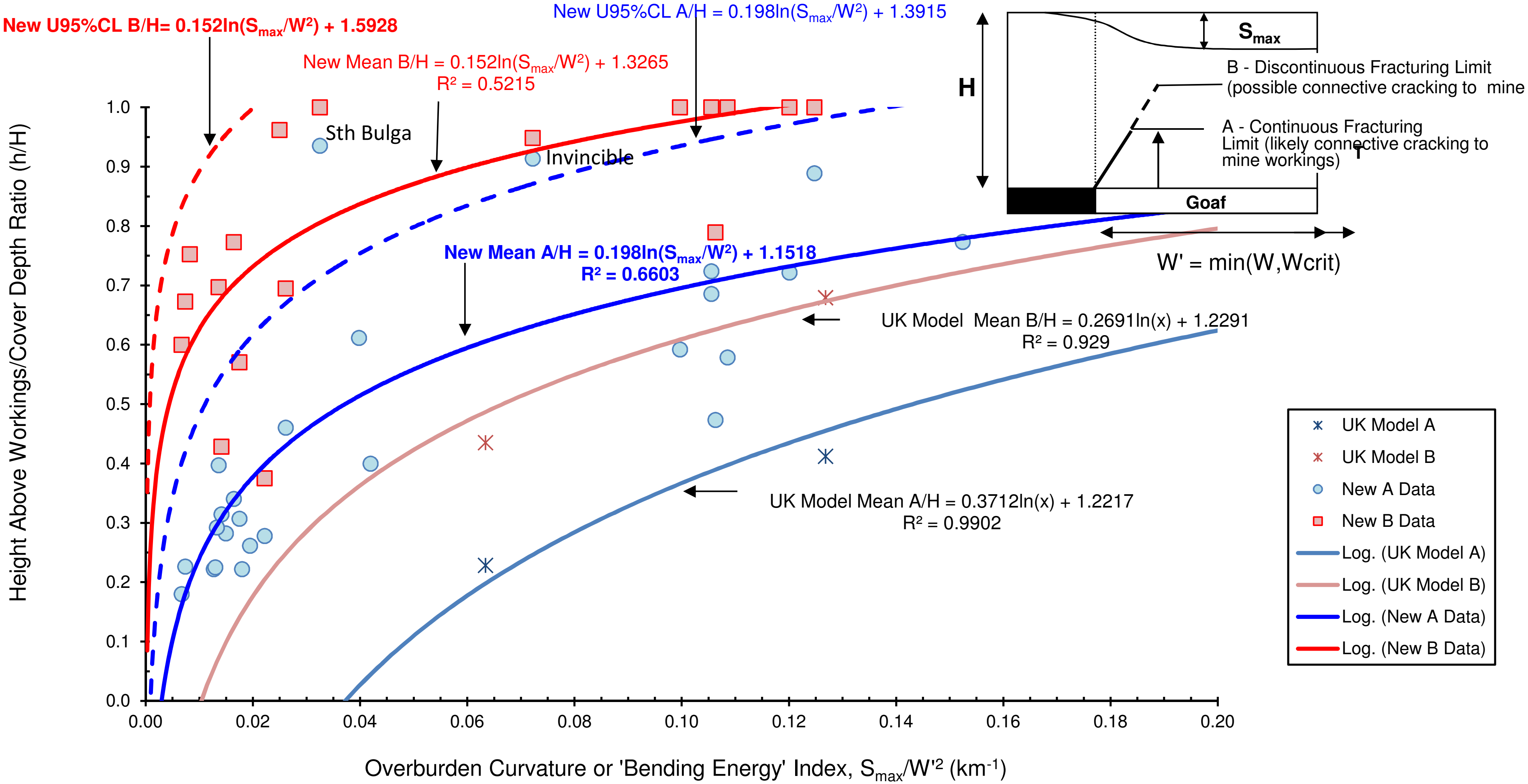
X: In-conclusive data

Ref: MSEC, 2011

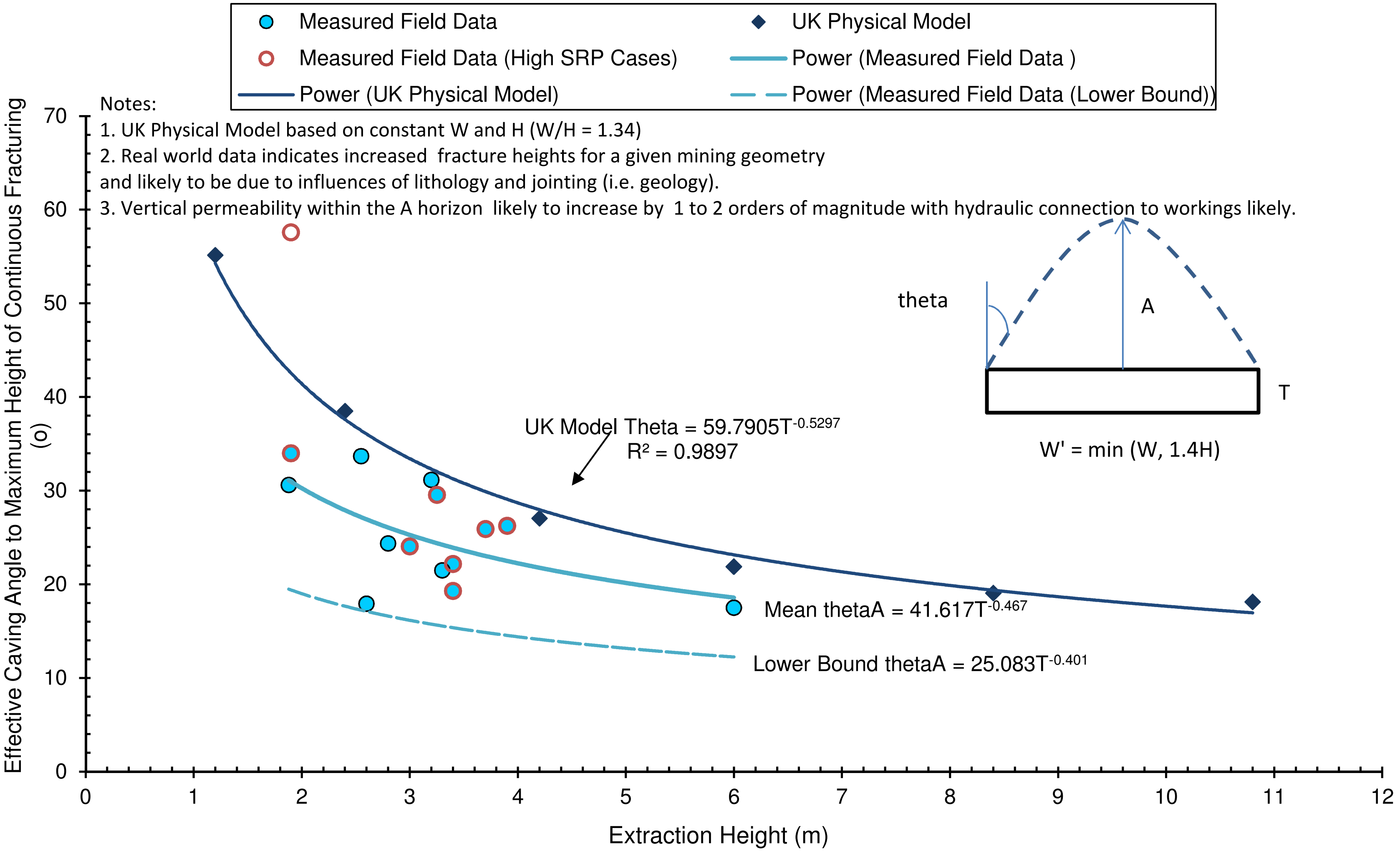
DgS	Engineer: S.Ditton		Client:	Review of Height of Fracturing Data
	Drawn: S.Ditton		Title:	Review of Observed Fracture Height Models presented by SCT and MSEC v. Whittaker & Reddish Sub-Surface Fracture Model Zoning
	Date: 07.06.13			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS — Figure No: A40j



DgS	Engineer: S.Ditton	Client:	Updated Whittaker and Reddish Model presented in ACARP, 2003	
	Drawn: S.Ditton			
	Date: 18.11.12	Title:	Continuous and Discontinuous Sub-Surface Fracture Height Model above Longwalls using Surface Tensile Strains as the Key Indicator	
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No: A41a



DgS	Engineer:	S.Ditton	Client:	Updated from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	03.12.12	Title:	Continuous and Discontinuous Sub-Surface Fracture Heights above Longwalls (based on ACARP, 2003)		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A41b



DgS						
	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003 (DgS,2012)		
	Drawn:	S.Ditton				
	Date:	15.11.12	Title:	Alternative ACARP, 2003 A-Zone Sub-Surface Fracture Height Model based on Panel Width and Mining Height as Key Parameters		
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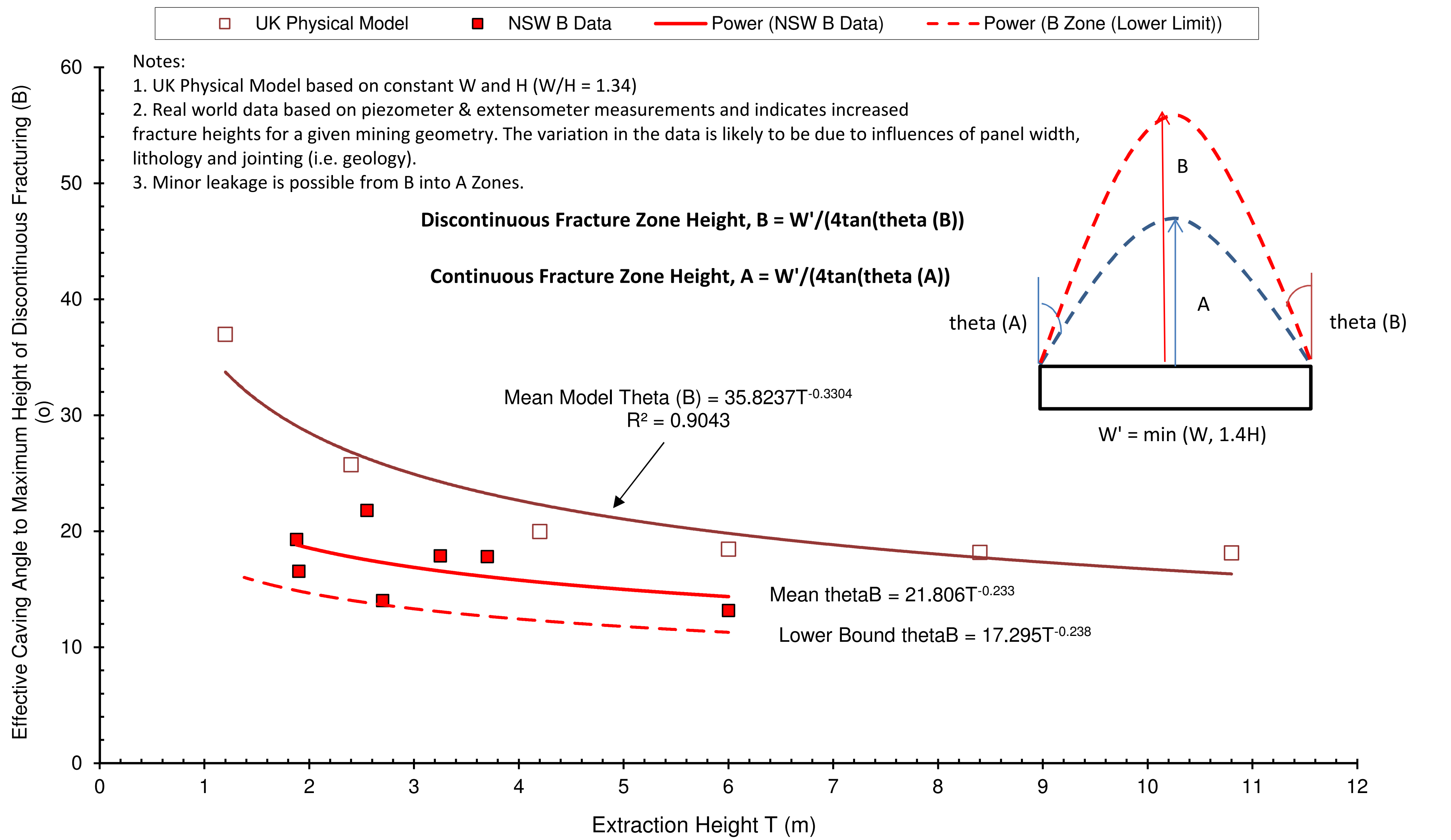
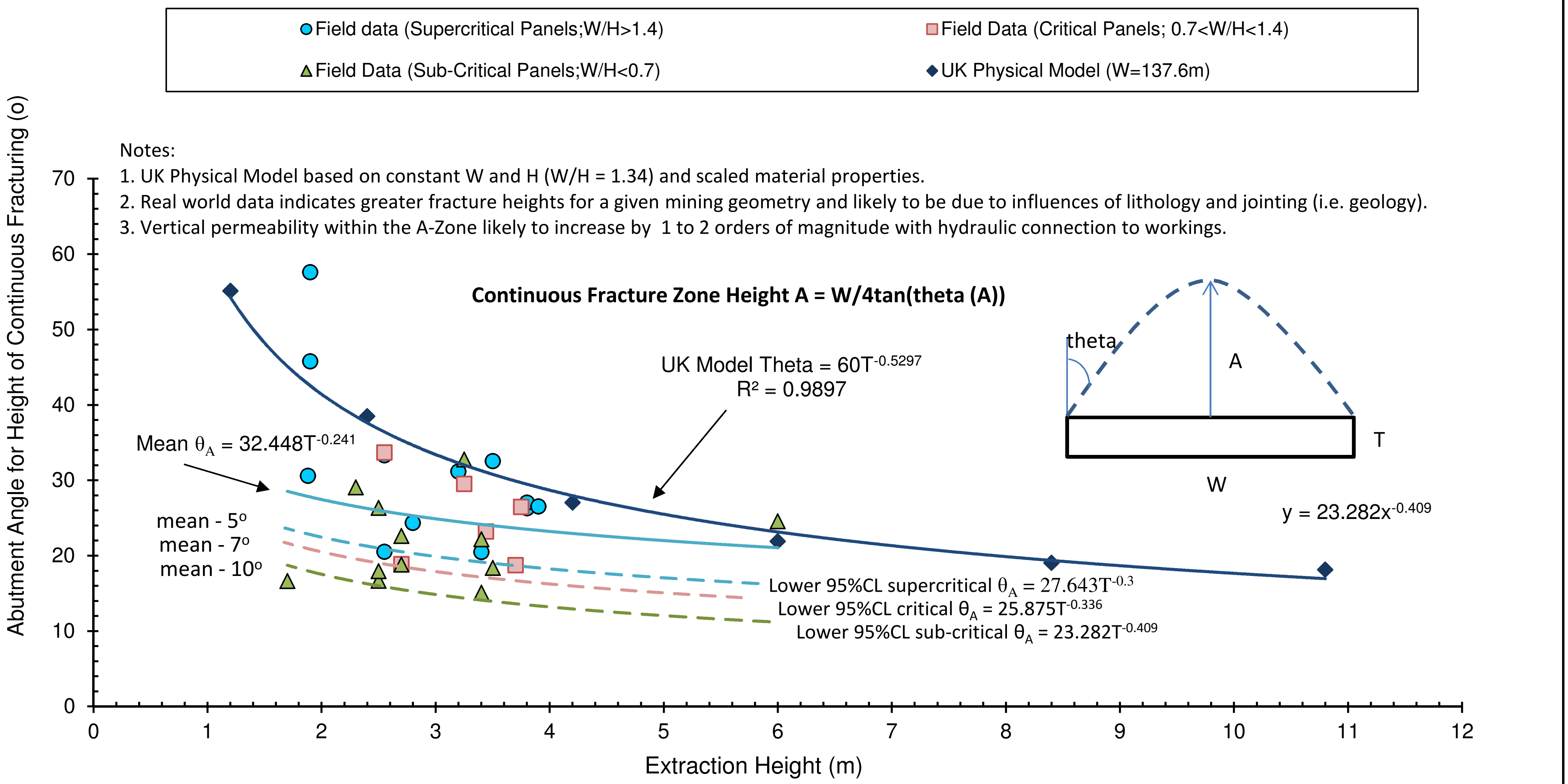
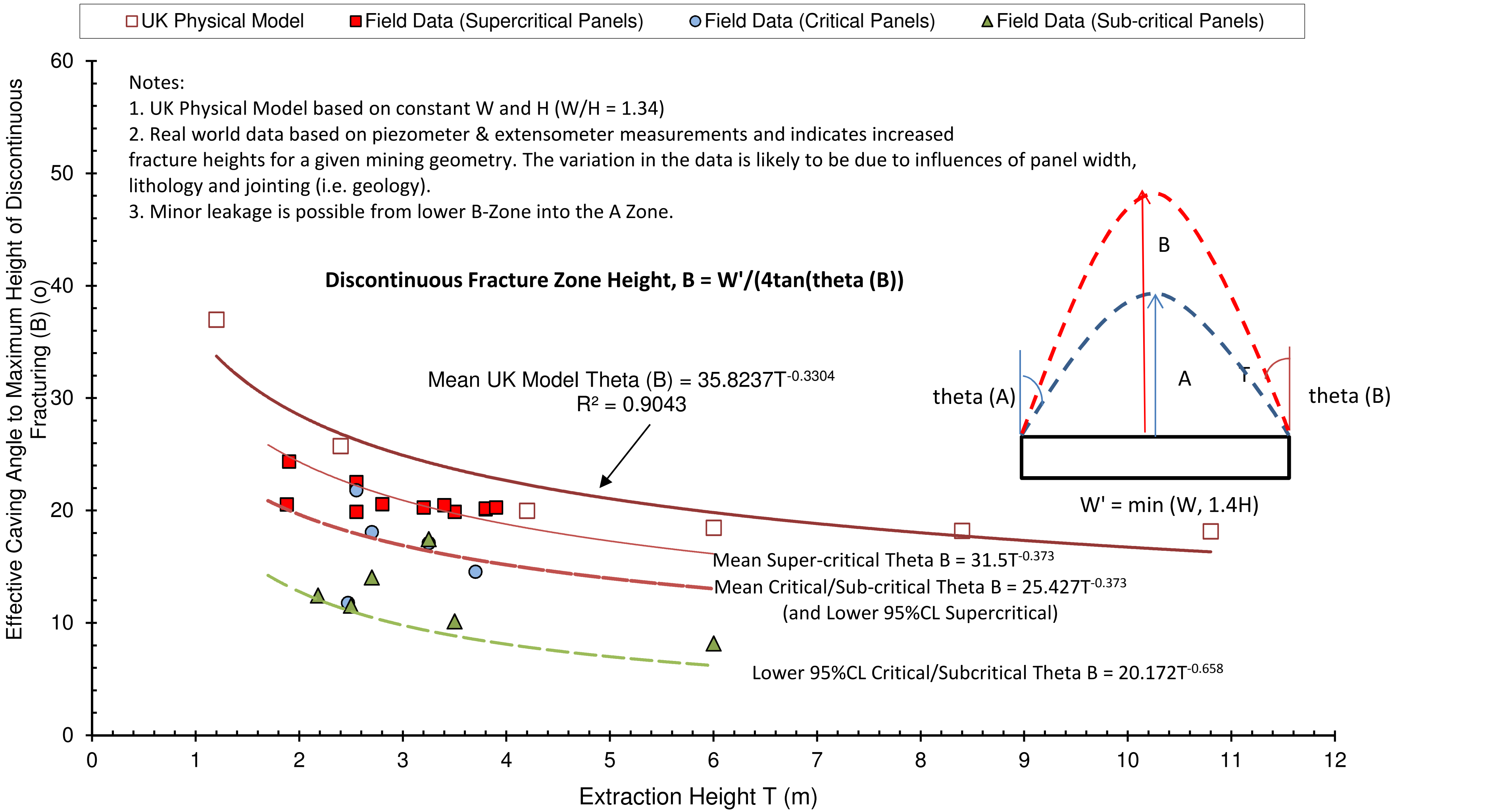


DgS				
Engineer:	S.Ditton	Client:	Modified from ACARP, 2003 (DgS,2012)	
Drawn:	S.Ditton			
Date:	15.11.12	Title:	Alternative ACARP, 2003 B-Zone Sub-Surface Fracture Height Model based on Panel Width and Mining Height as Key Parameters	
Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41d



DgS	Engineer: S.Ditton	Client:	Modified from ACARP, 2003	
	Drawn: S.Ditton			
	Date: 10.06.13	Title:	Predicted Height of Continuous Fracturing Based on HoF Angle and Mining Height	
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No: A41e



DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003
	Drawn:	S.Ditton		
	Date:	10.06.13	Title:	Predicted Height of Discontinuous Fracturing Based on Measured Heights of Discontinuous Fracture Angles and Mining Height
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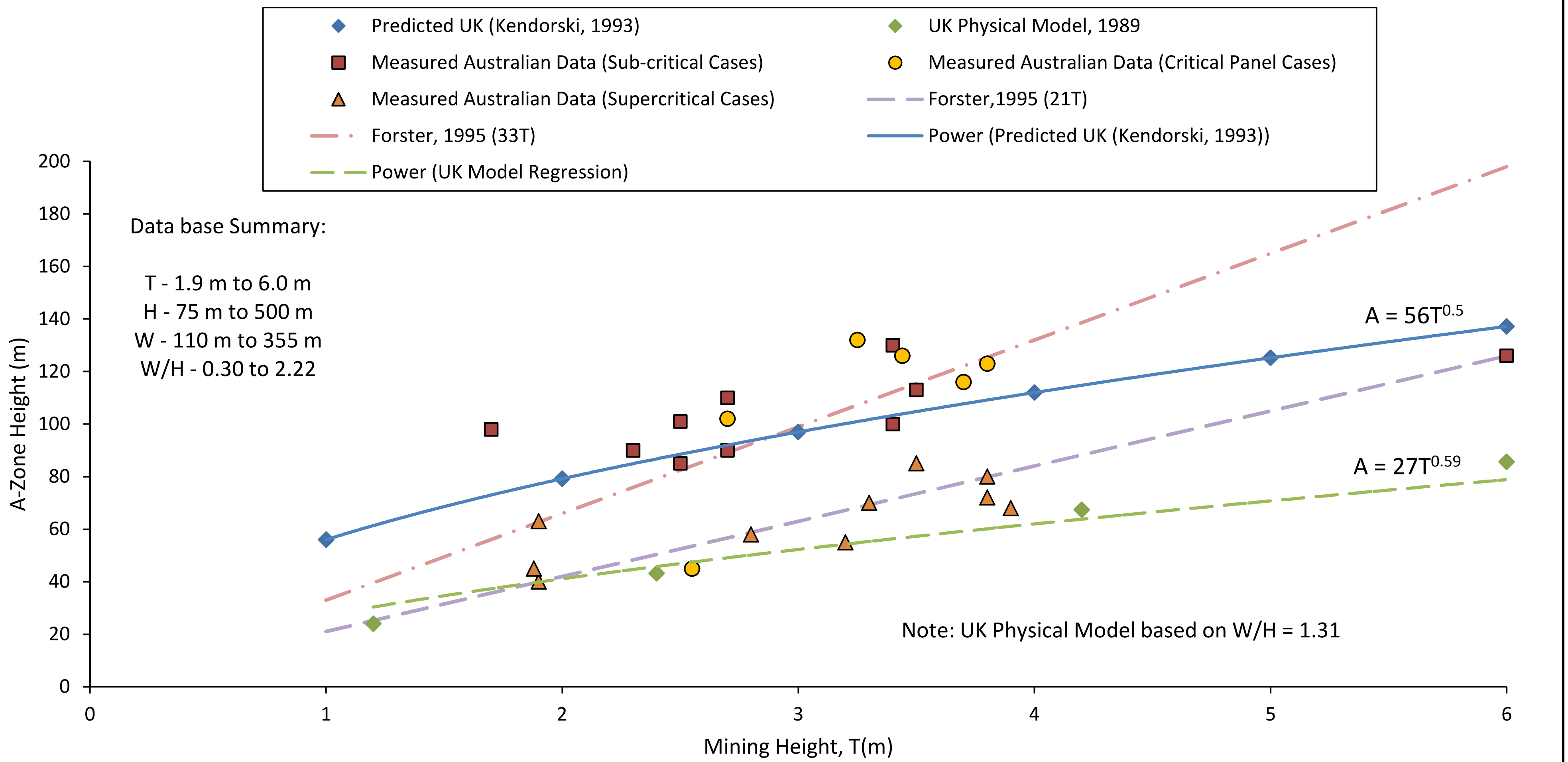
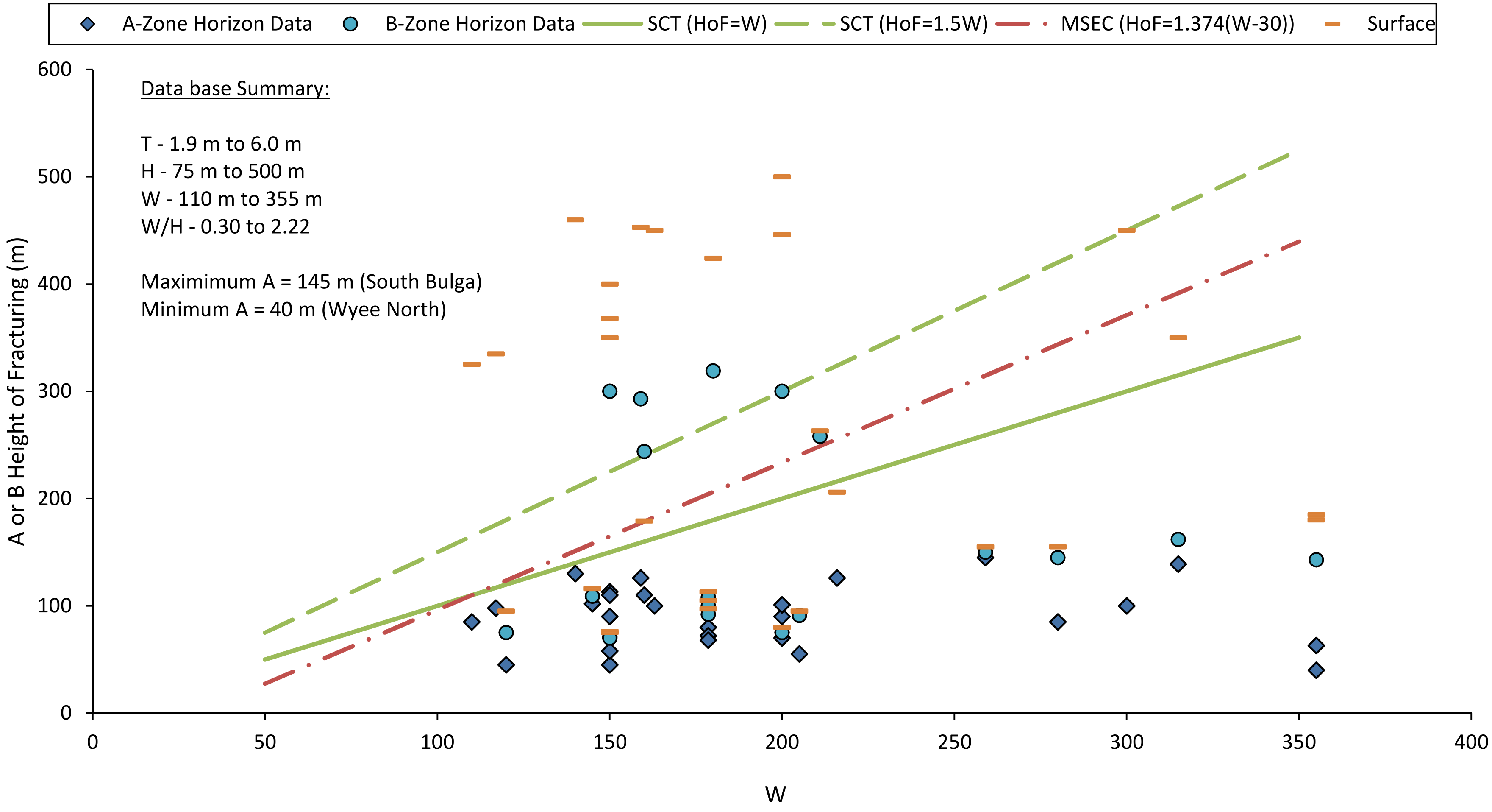
			Figure No:	A41f



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	07.06.13	Title:	Continuous UK Fracture Height Models based on Mining Height Only v. Measured Australian Database		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A41g



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	07.06.13	Title:	Continuous Australian Fracture Height Model based on Panel Width Only Database		
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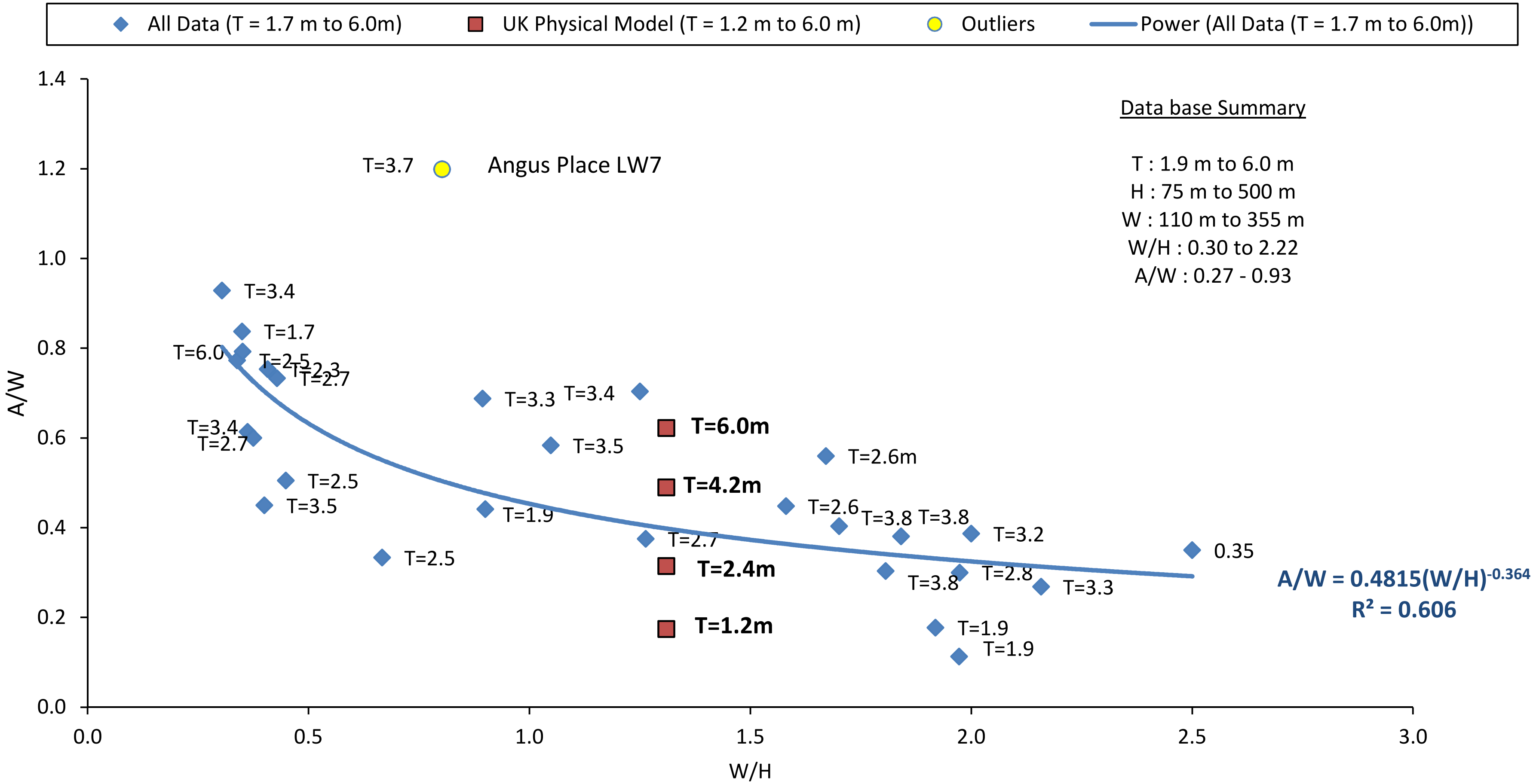

DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	07.06.13	Title:	Continuous Australian Fracture Height Model based on A normalised to Panel Width with Influence of Mining Height Included		
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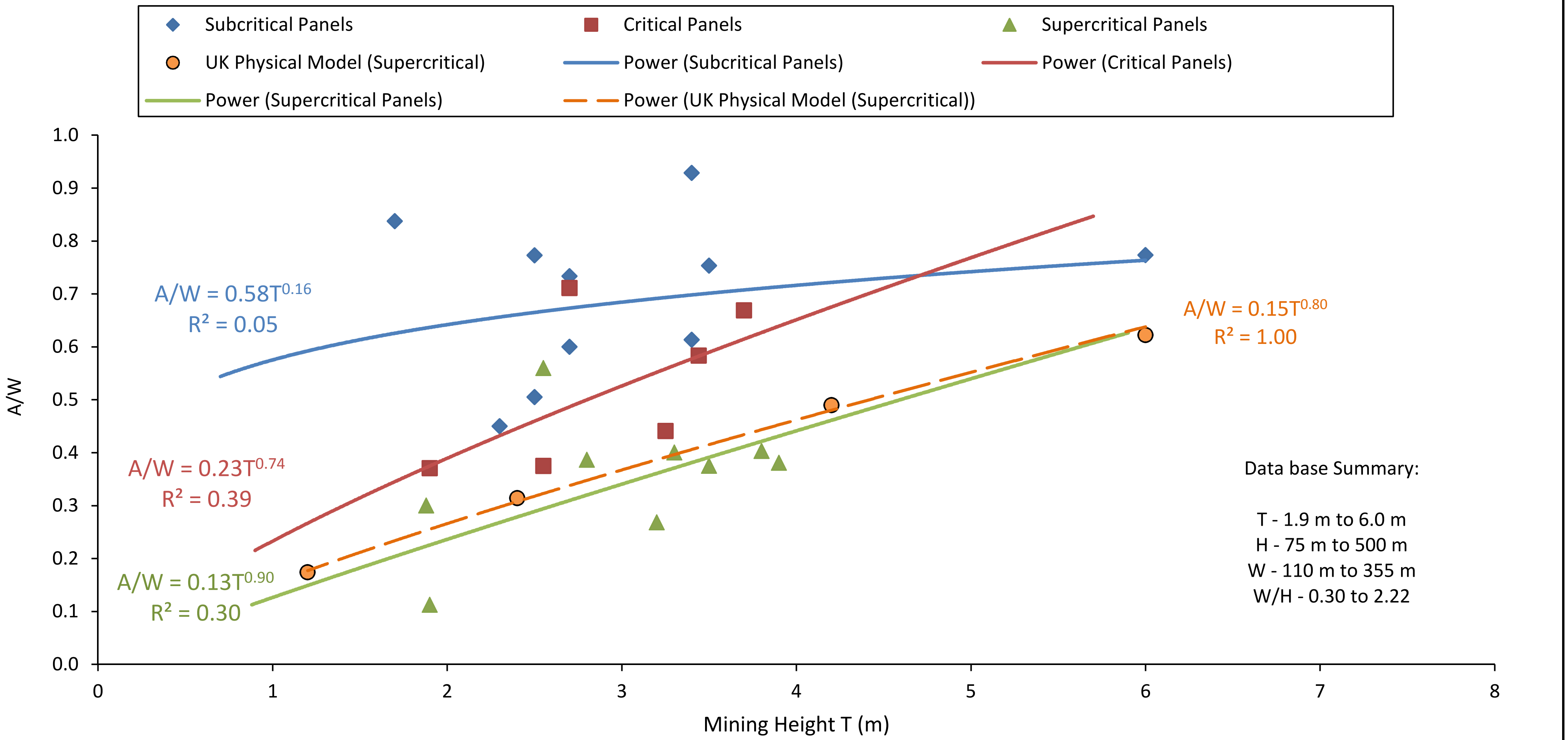

DgS	Engineer: S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn: S.Ditton			
	Date: 07.06.13	Title:	Continuous Australian Fracture Height Model based on A normalised to Panel Width v. Mining Height	
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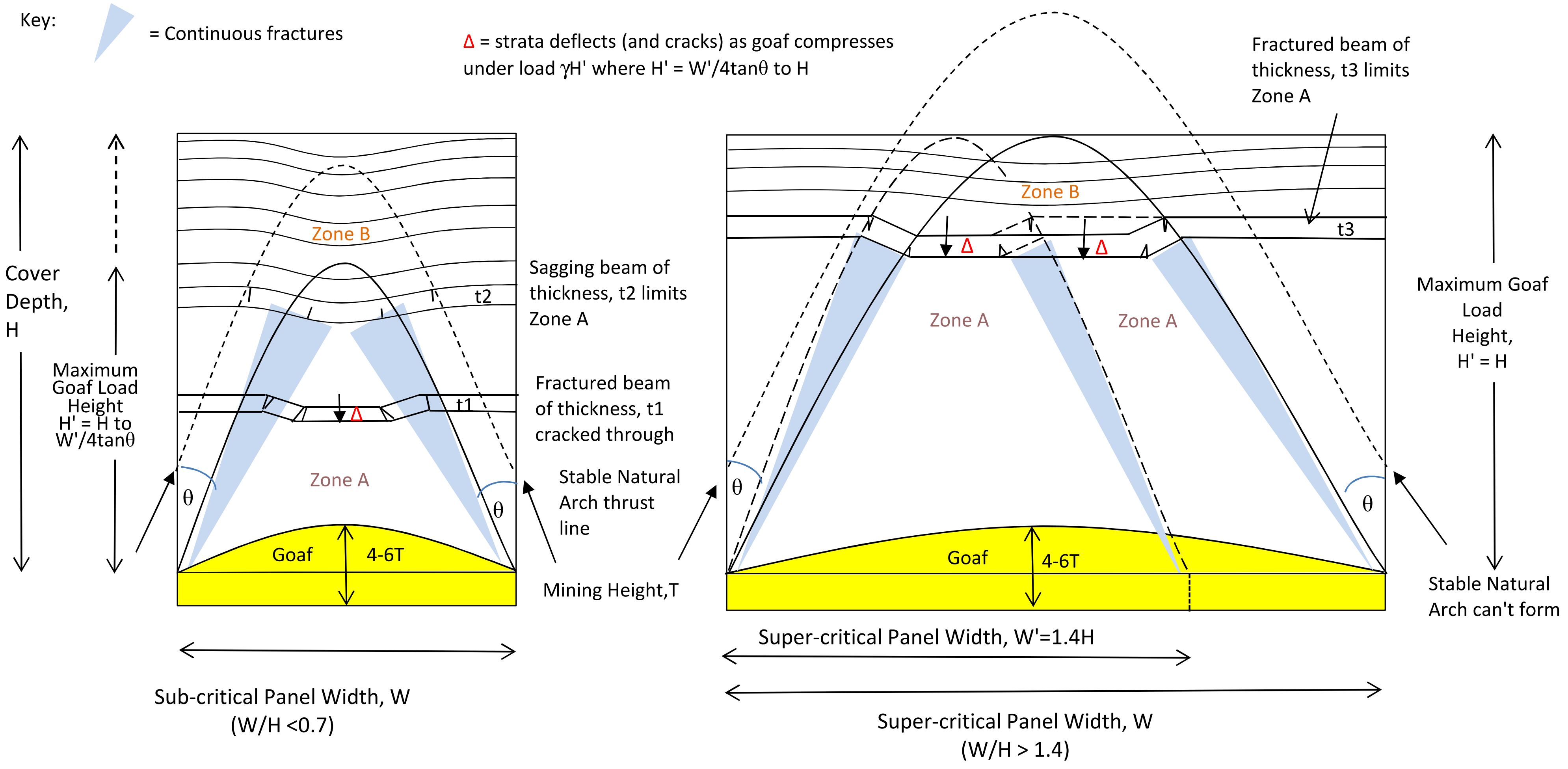
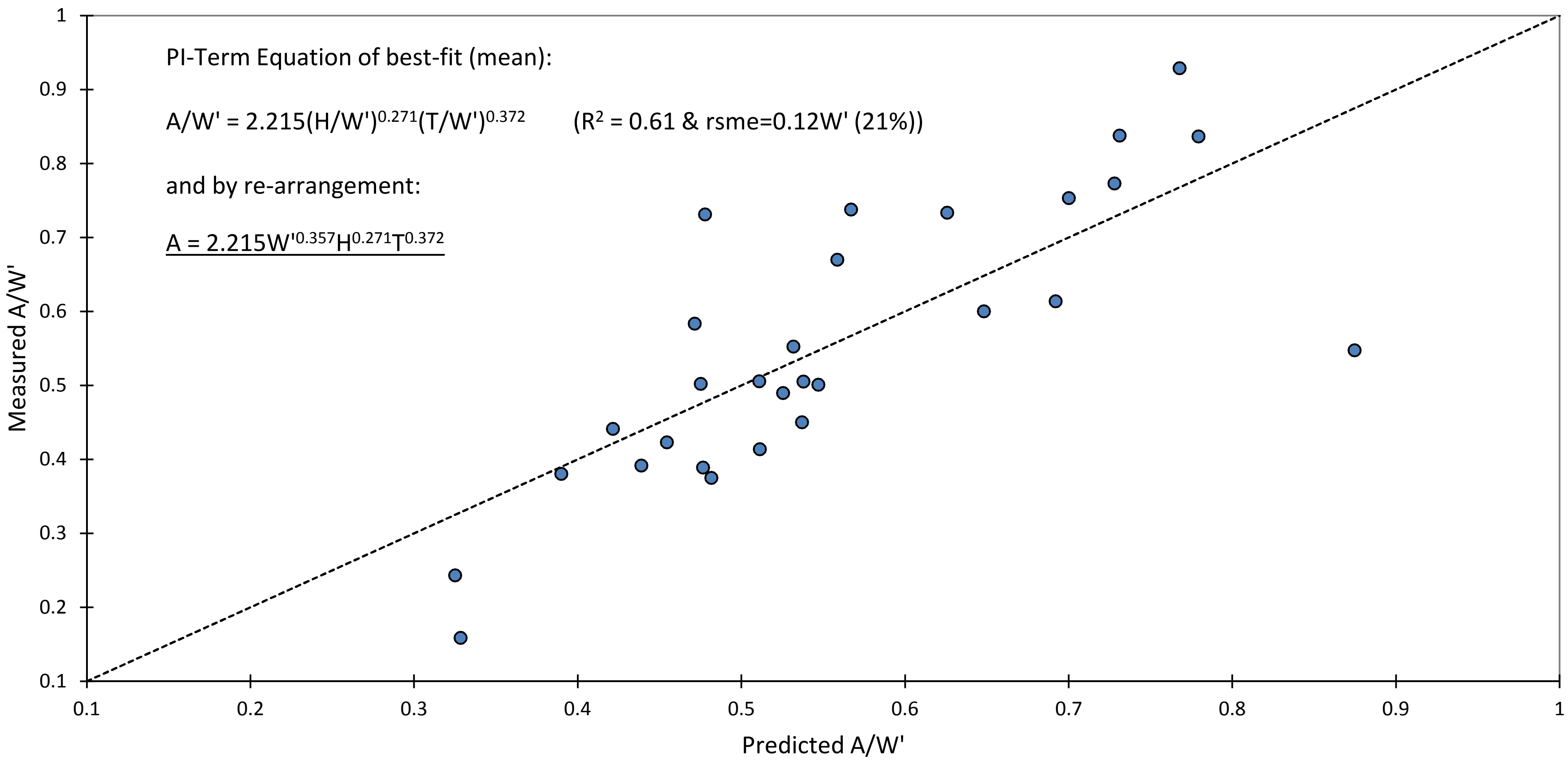


DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data
	Drawn:	S.Ditton		
	Date:	26.08.13	Title:	Conceptual Model for Development of Height of Continuous Fracturing Zone for a range of Longwall Panel Geometries
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS — Figure No: A42a

Mine Geometry Only PI-Term Model



DgS	Engineer: S.Ditton		Client:	Review of Height of Fracturing Data
	Drawn: S.Ditton			
	Date: 01.05.14		Title:	Results of Non-Linear Regession Analysis: Predicted v. Measured Value Analysis for Height of A-Zone Fracturing for the Geometry PI-Term Model
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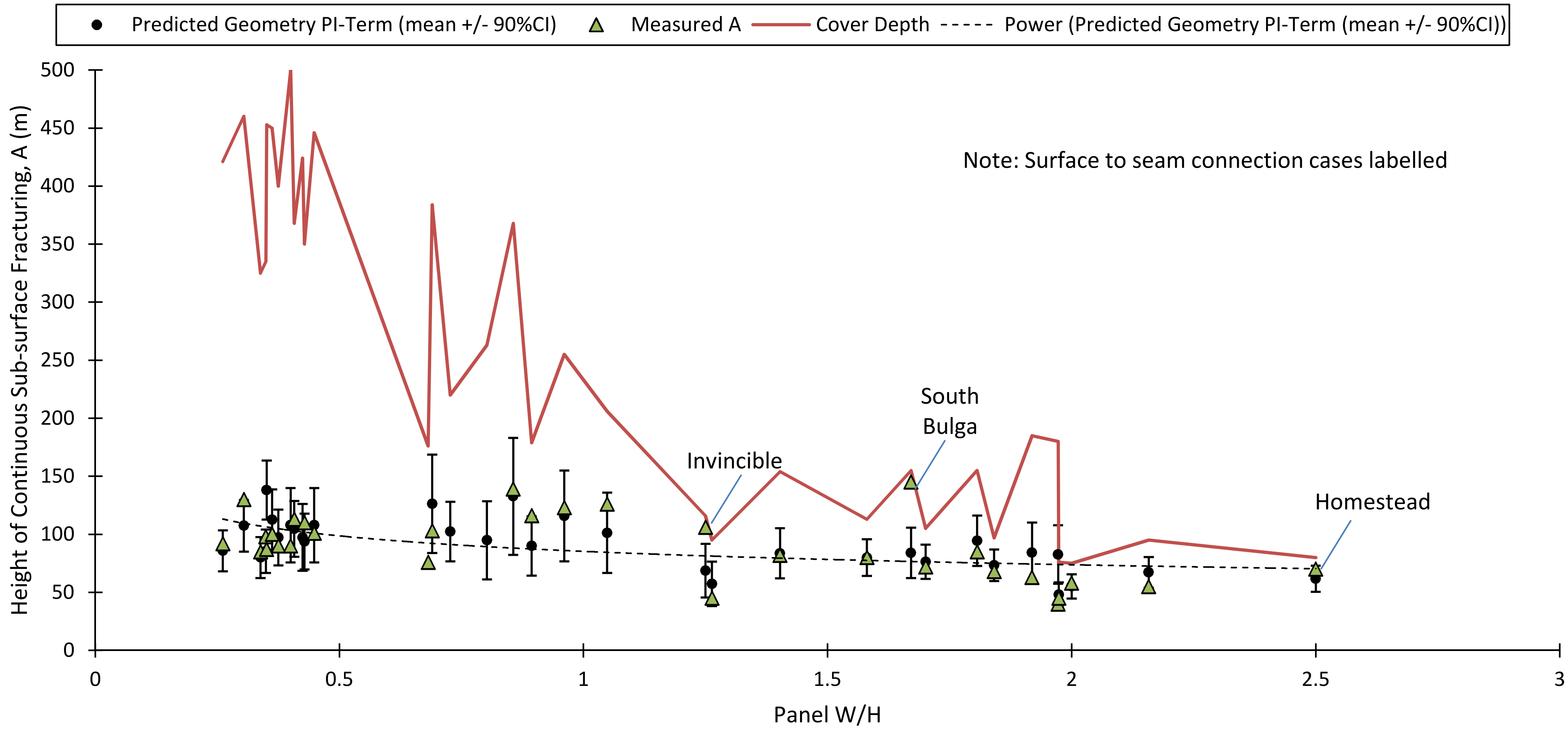
			Figure No:	A42b



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data			
	Drawn:	S.Ditton					
	Date:	01.05.14	Title:	Results of Non-Linear Regession Error analysis for Geometry PI-Terms Only Height of A-Zone Prediction Model (Geology Pi-Term Not Included)			
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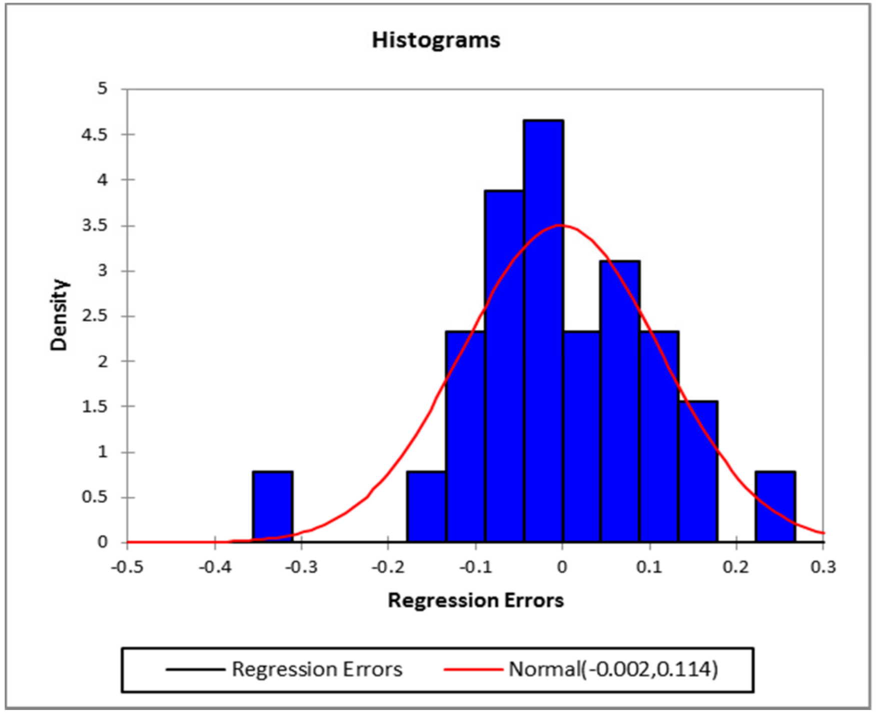
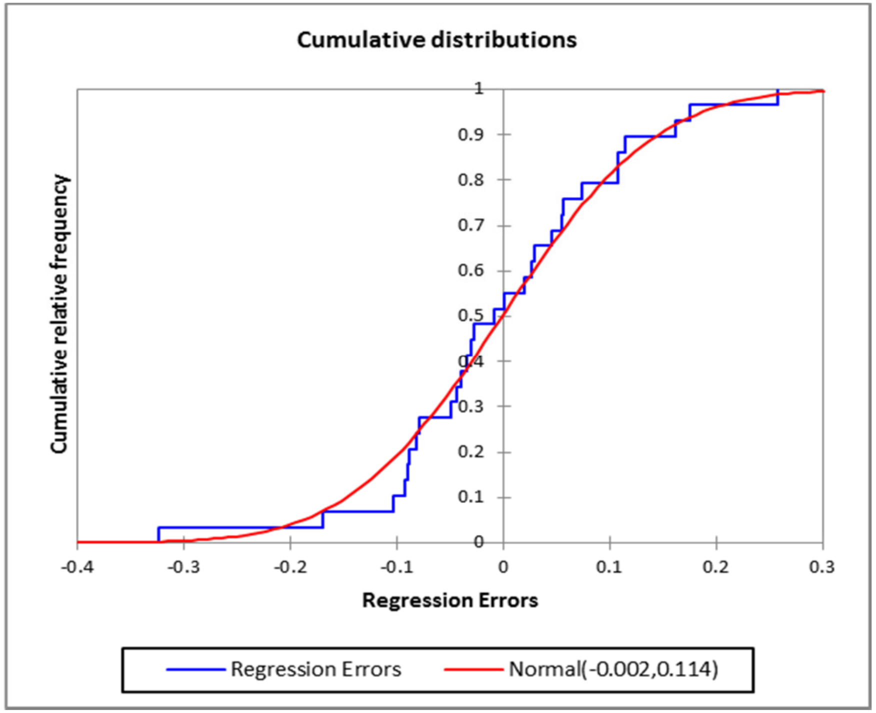


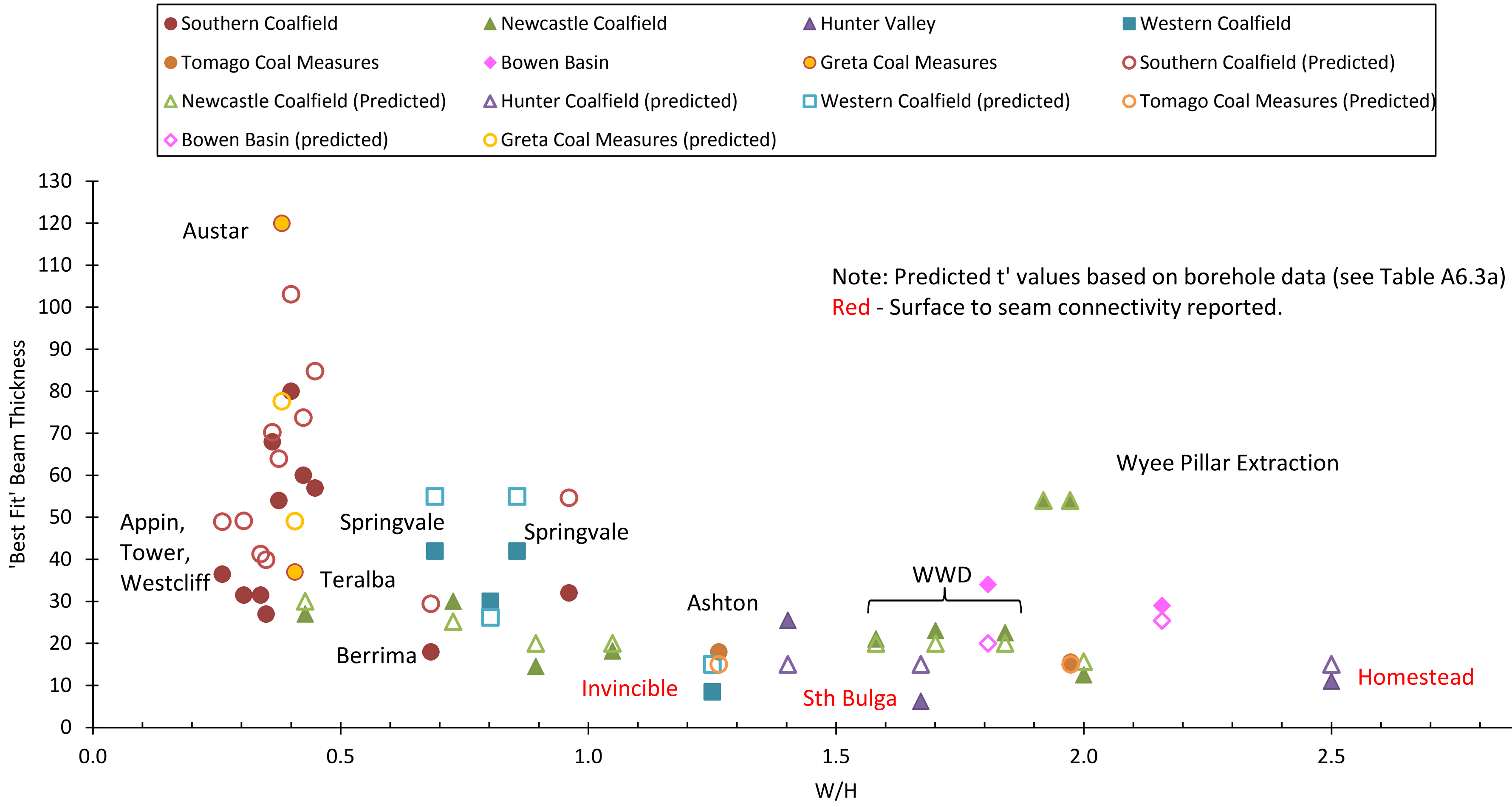


Kolmogorov-Smirnov test:

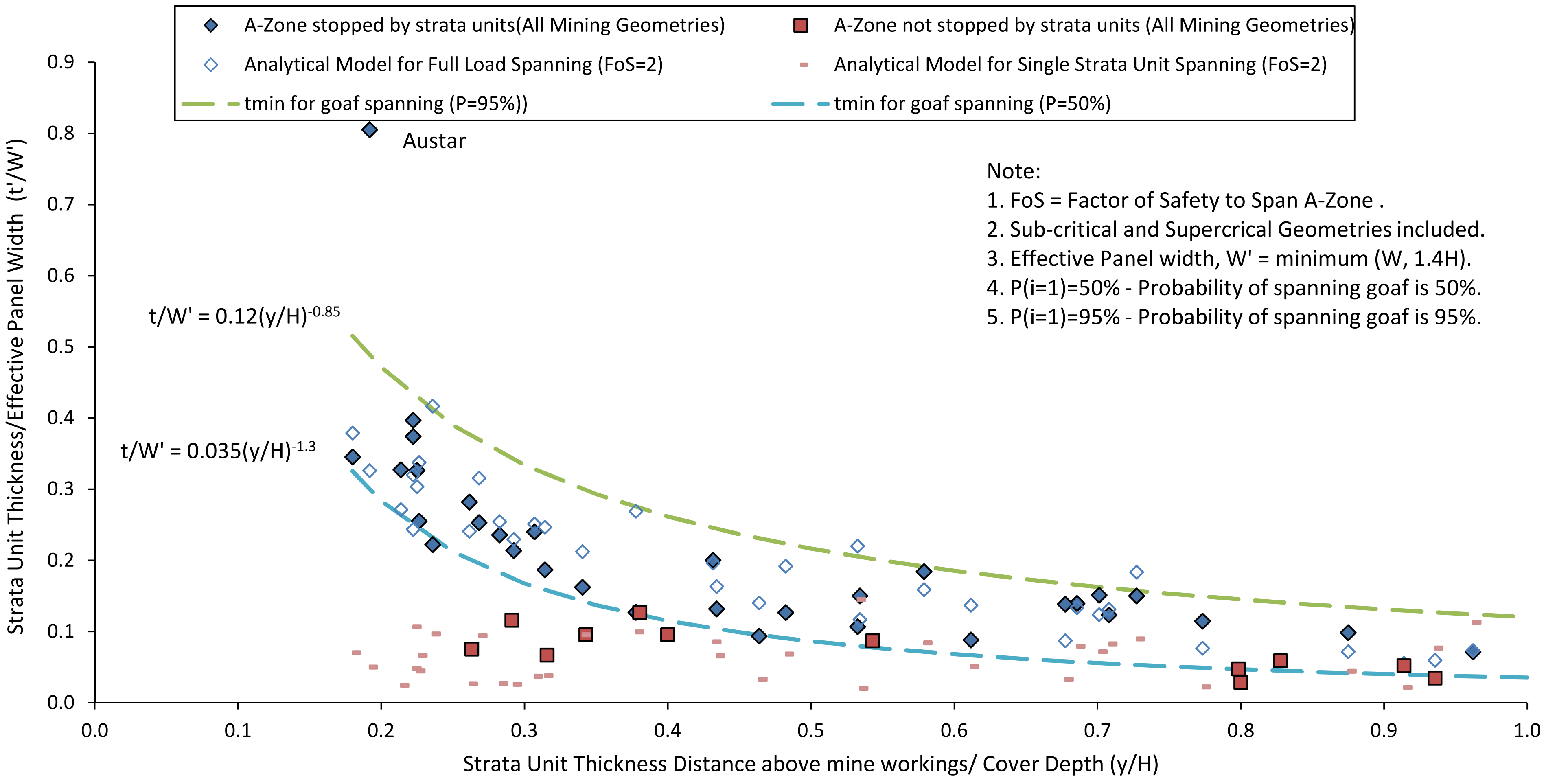
D	0.117
p-value	0.798
alpha	0.05

Test interpretation:
H0: The sample follows a Normal distribution
Ha: The sample does not follow a Normal distribution
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.
The risk to reject the null hypothesis H0 while it is true is 79.75%.

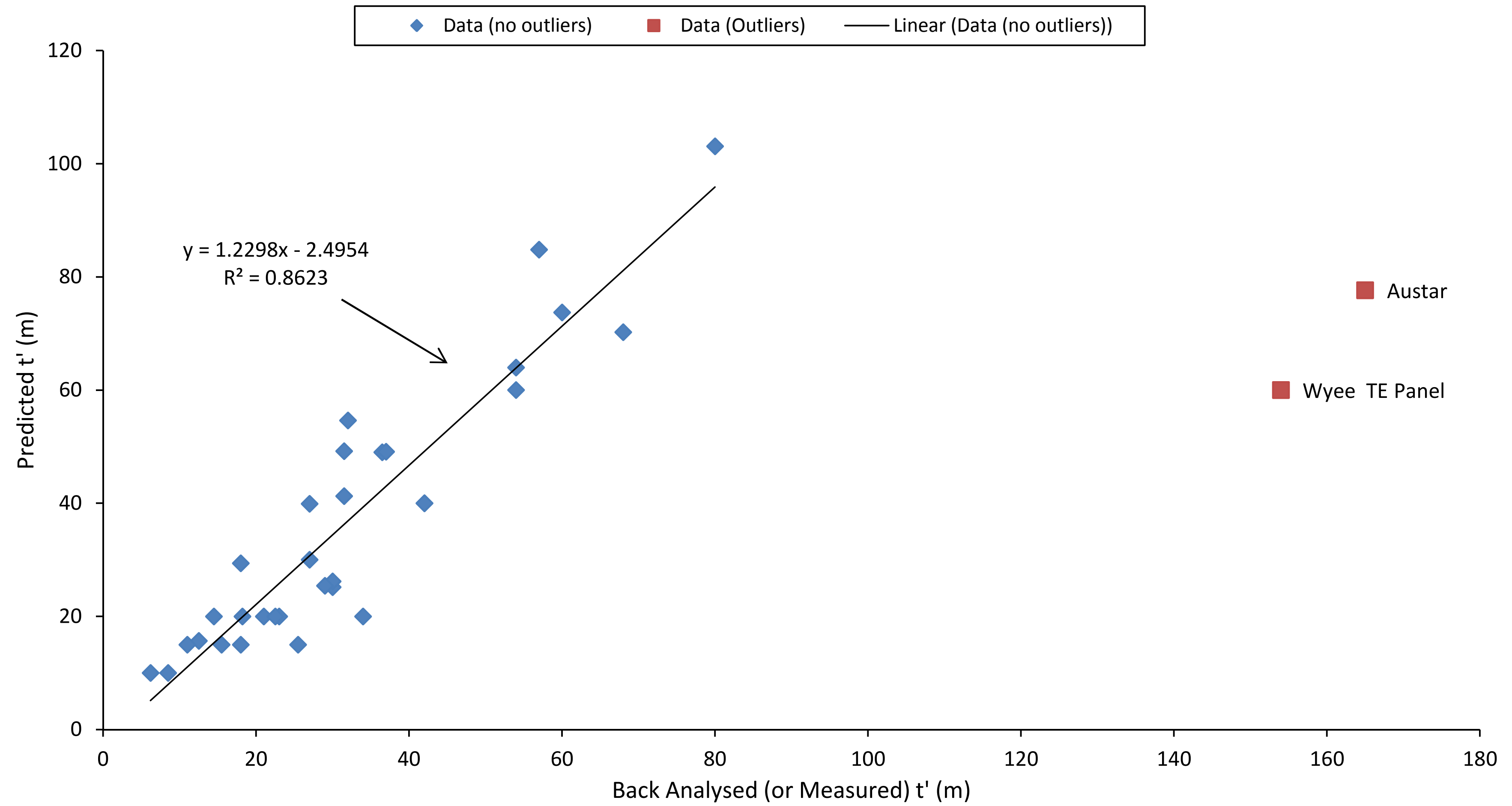
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	01.05.14	Title:	Results of Non-Linear Regession Error analysis for Geometry Pi-Term Height of A-Zone Prediction Model: Regression Error Normal Distribution Test		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42d



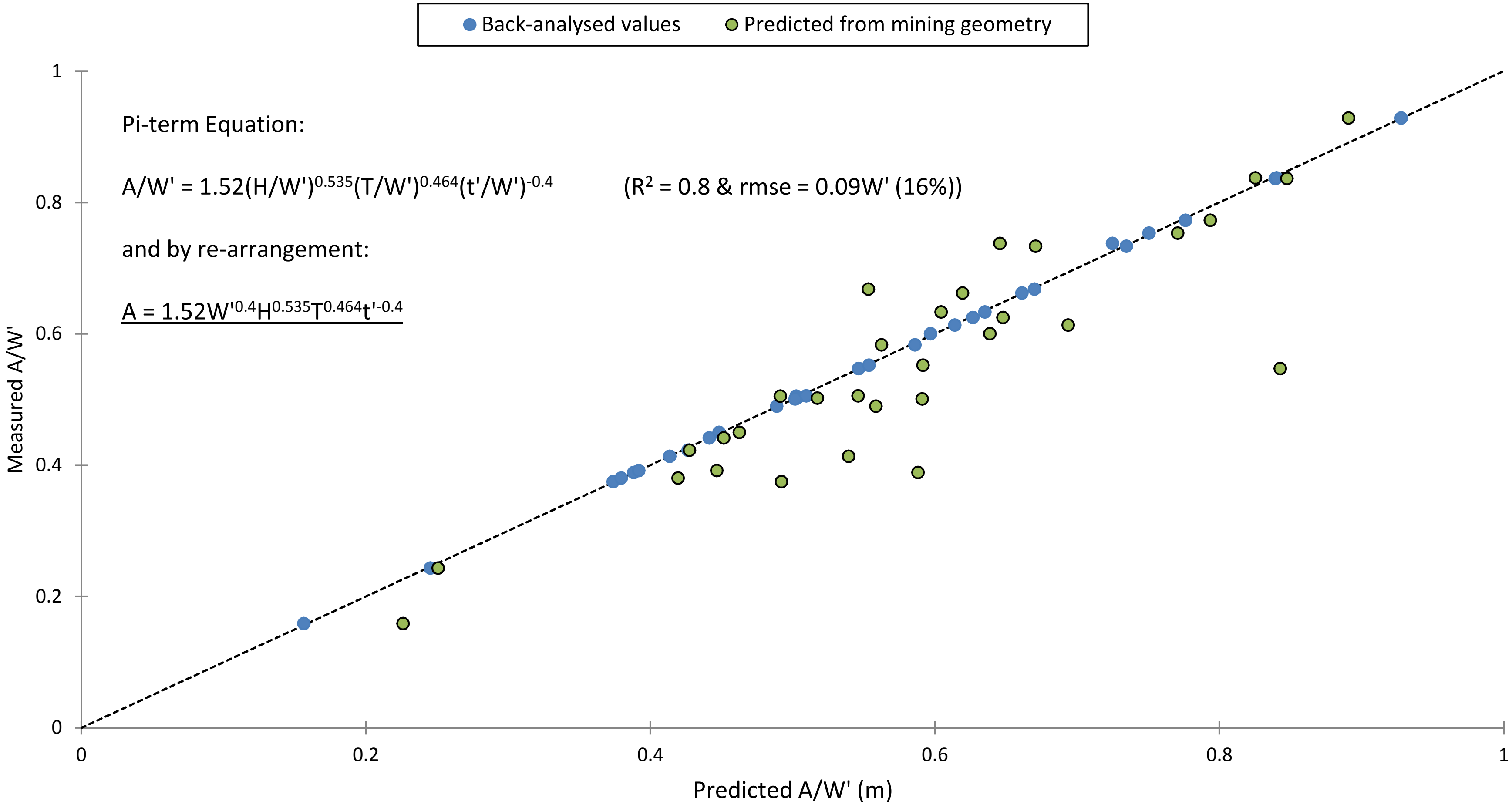
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton	Title:	Results of Back-analysis of Effective Strata Units required to Match the Observed A-Zone Heights above Longwall Panel Goafs using the Geology Pi-Term Model		
	Date:	01.05.14				
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42e



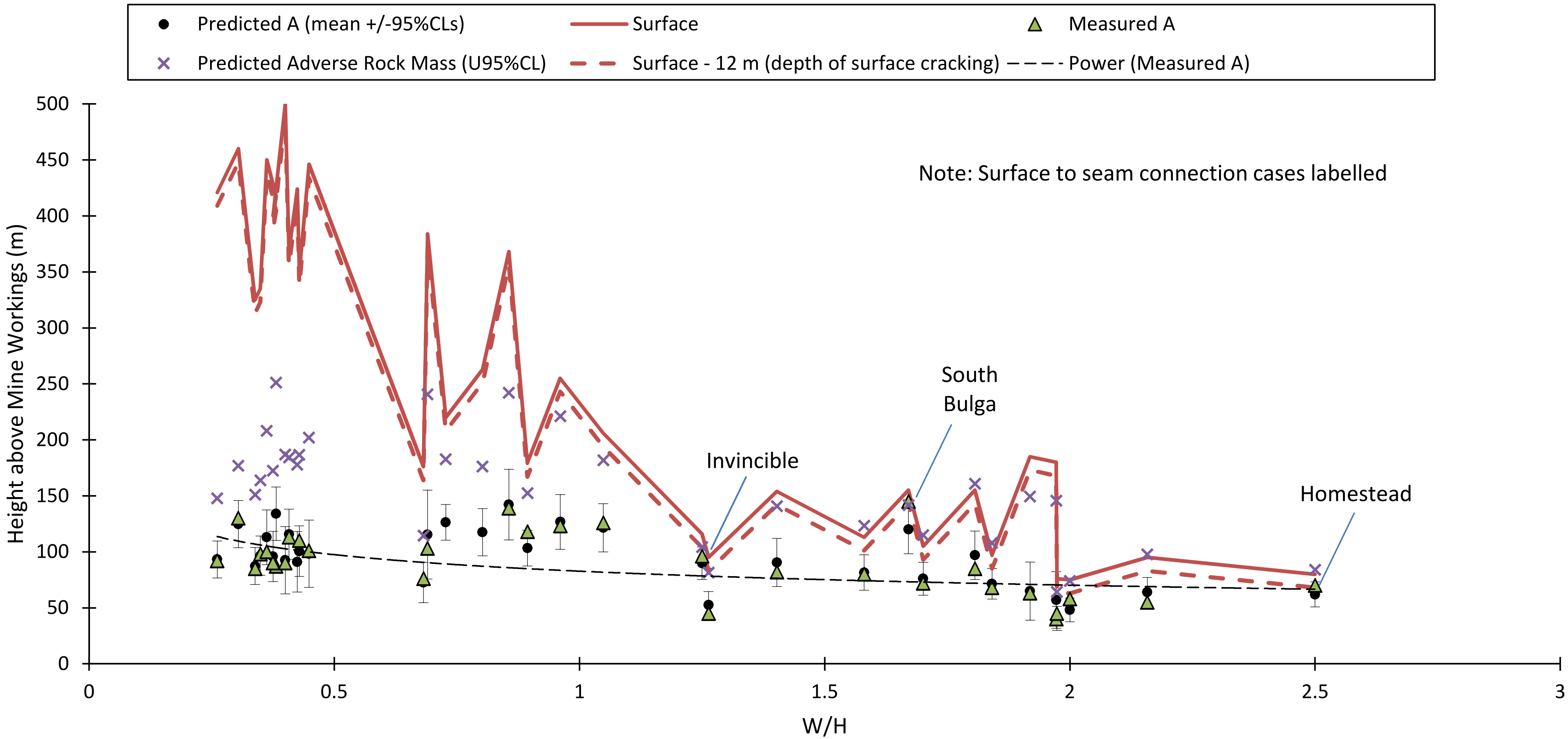
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	01.05.14	Title:	Minimum Effective beam Thickness Required to Span the A-Zone, based on Back Analysis Results for the Geology Pi-Term Model (see Figure A42e)		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42f



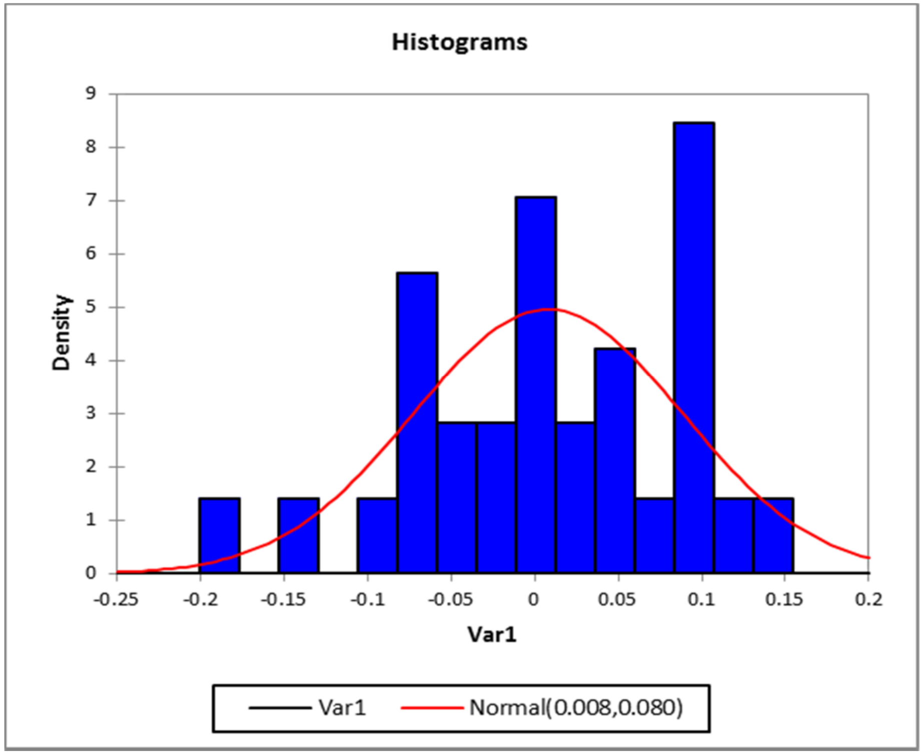
DgS	Engineer: S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn: S.Ditton				
	Date: 01.05.14	Title:	Comparison of Back-Analysed (or measured (t') v. Predicted t' for the Geological PI-Term		
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No:	A42g

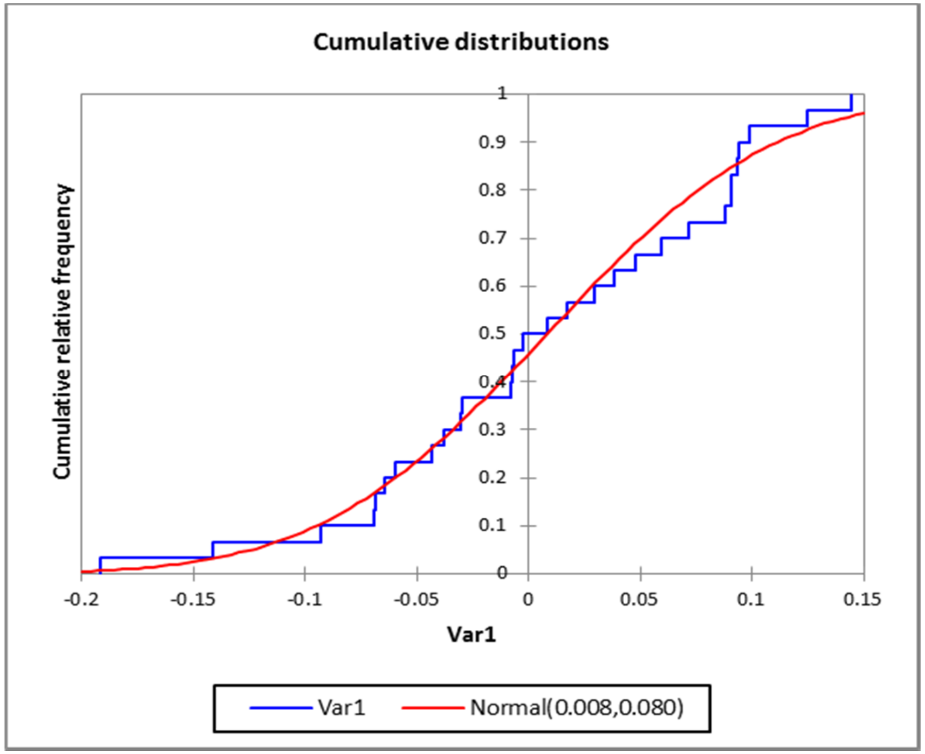


DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton	Title:	Results of Non-Linear Regession Analysis: Predicted v. Measured Value Analysis for Height of A-Zone Fracturing for Geology Pi-Term Model		
	Date:	01.05.14				
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42h



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	01.05.14	Title:	Results of Non-Linear Regession Error analysis for Height of A-Zone Prediction Model with Geology Included		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42i



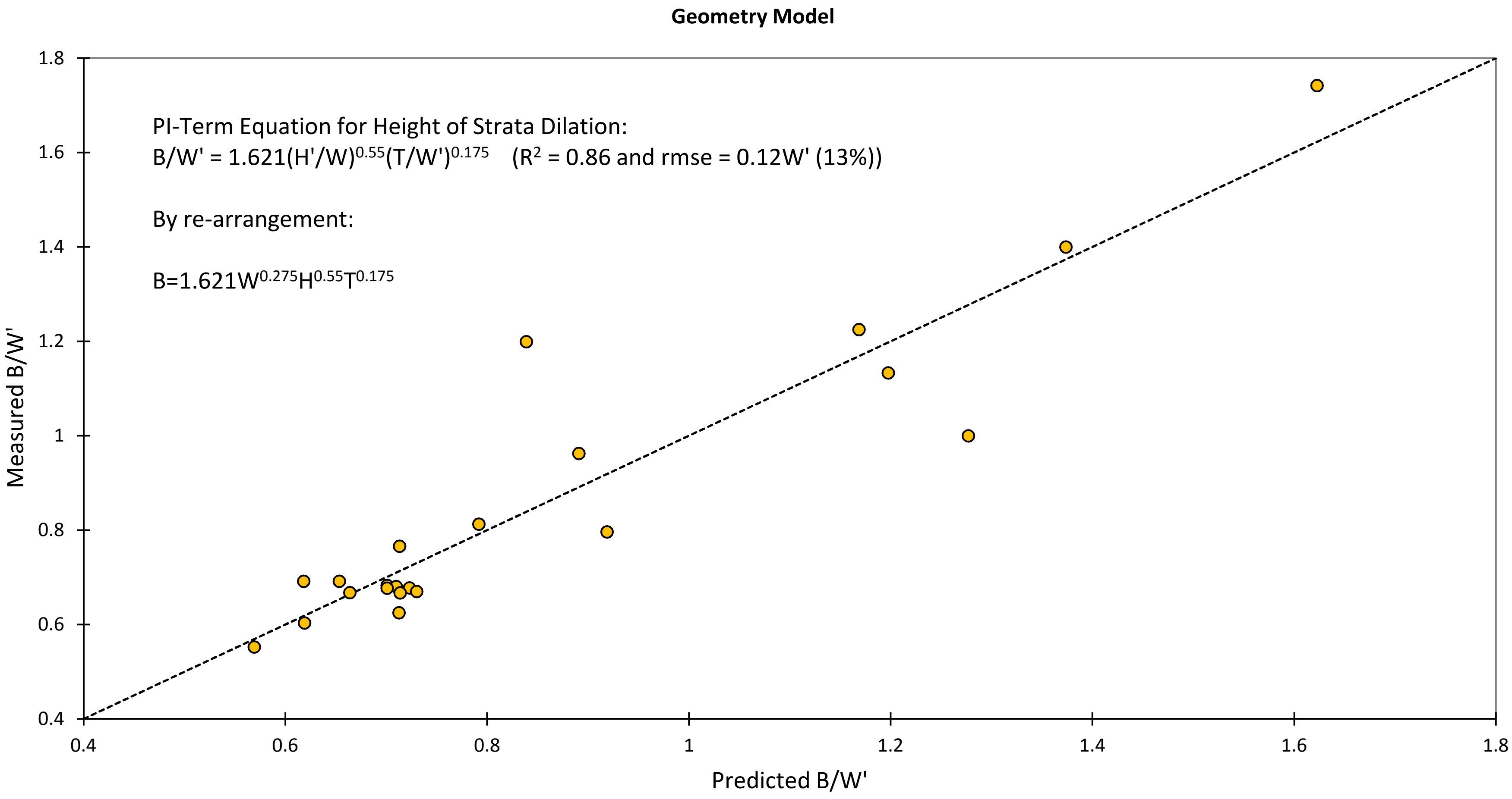


Kolmogorov-Smirnov test:

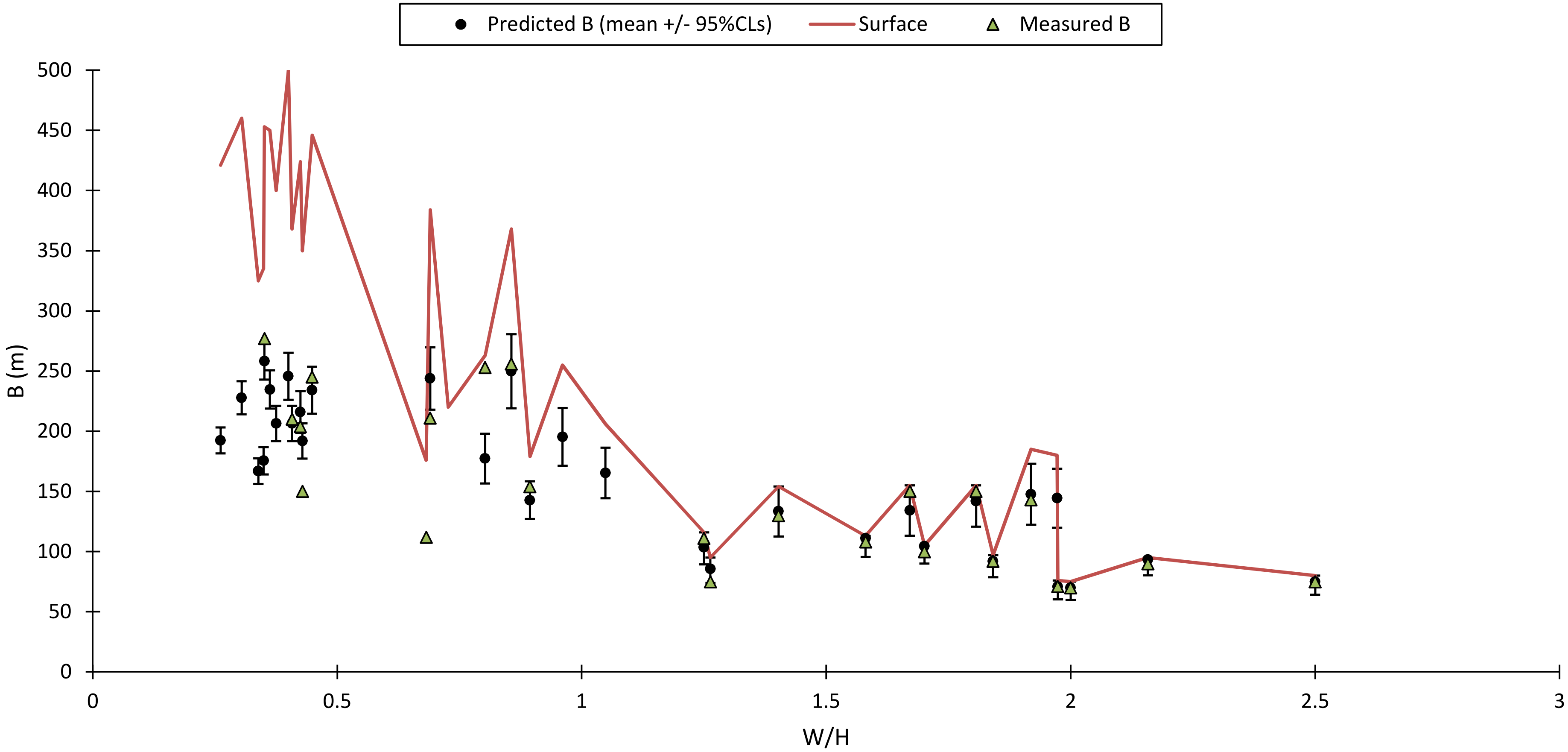
D	0.107
p-value	0.866
alpha	0.05

Test interpretation:
H0: The sample follows a Normal distribution
Ha: The sample does not follow a Normal distribution
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.
The risk to reject the null hypothesis H0 while it is true is 86.6%.

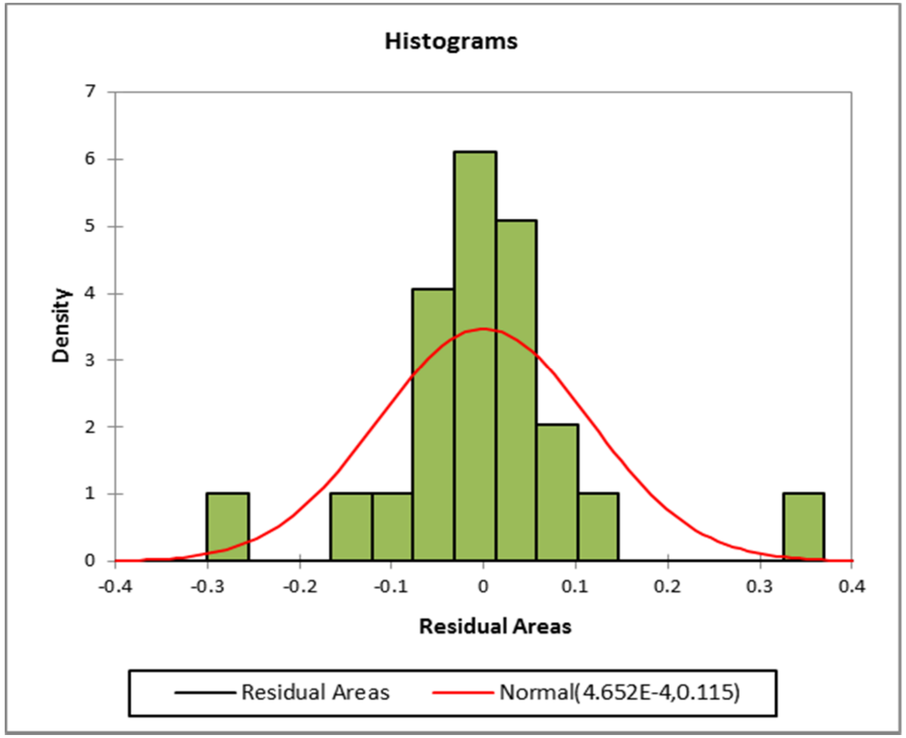
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn:	S.Ditton				
	Date:	01.05.14	Title:	Results of Non-Linear Regession Error analysis for Geology Pi-Term Height of A-Zone Prediction Model: Regression Error Normal Distribution Test		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42j

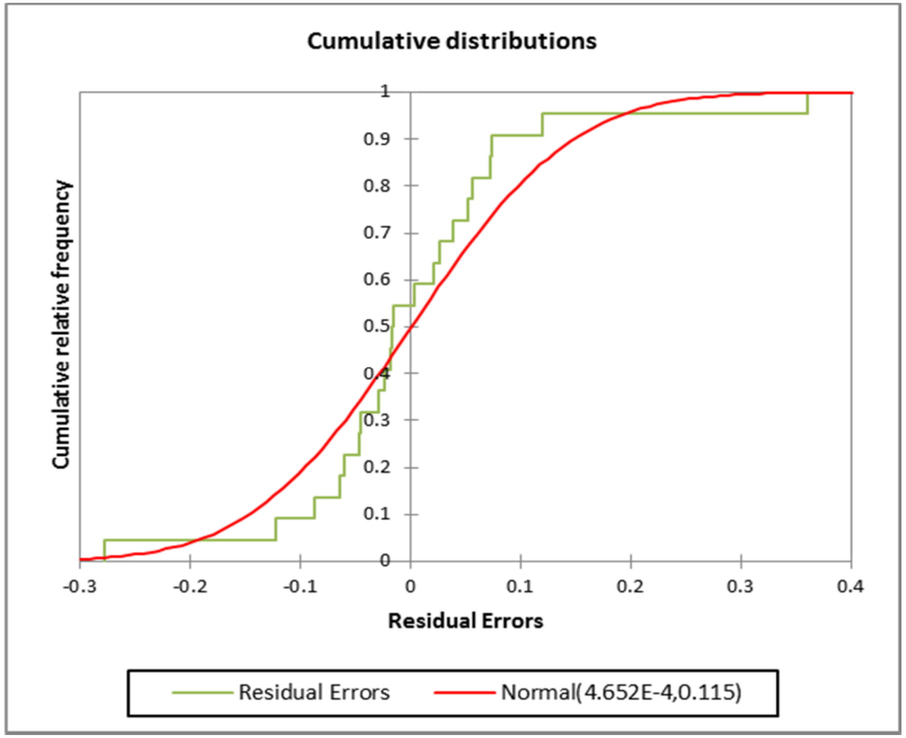


DgS	Engineer: S.Ditton	Client:	Review of Height of Fracturing Data		
	Drawn: S.Ditton				
	Date: 01.02.14	Title:	Results of Non-Linear Regession Error analysis for Height of B-Zone Predictions for Geometry Only Pi-Term Model		
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No:	A42k



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	01.02.14	Title:	Results of Non-Linear Regession Error analysis for Height of B-Zone Predictions for Geometry Only Pi-Term Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42l





Kolmogorov-Smirnov test:

D	0.173
p-value	0.487
alpha	0.05

Test interpretation:

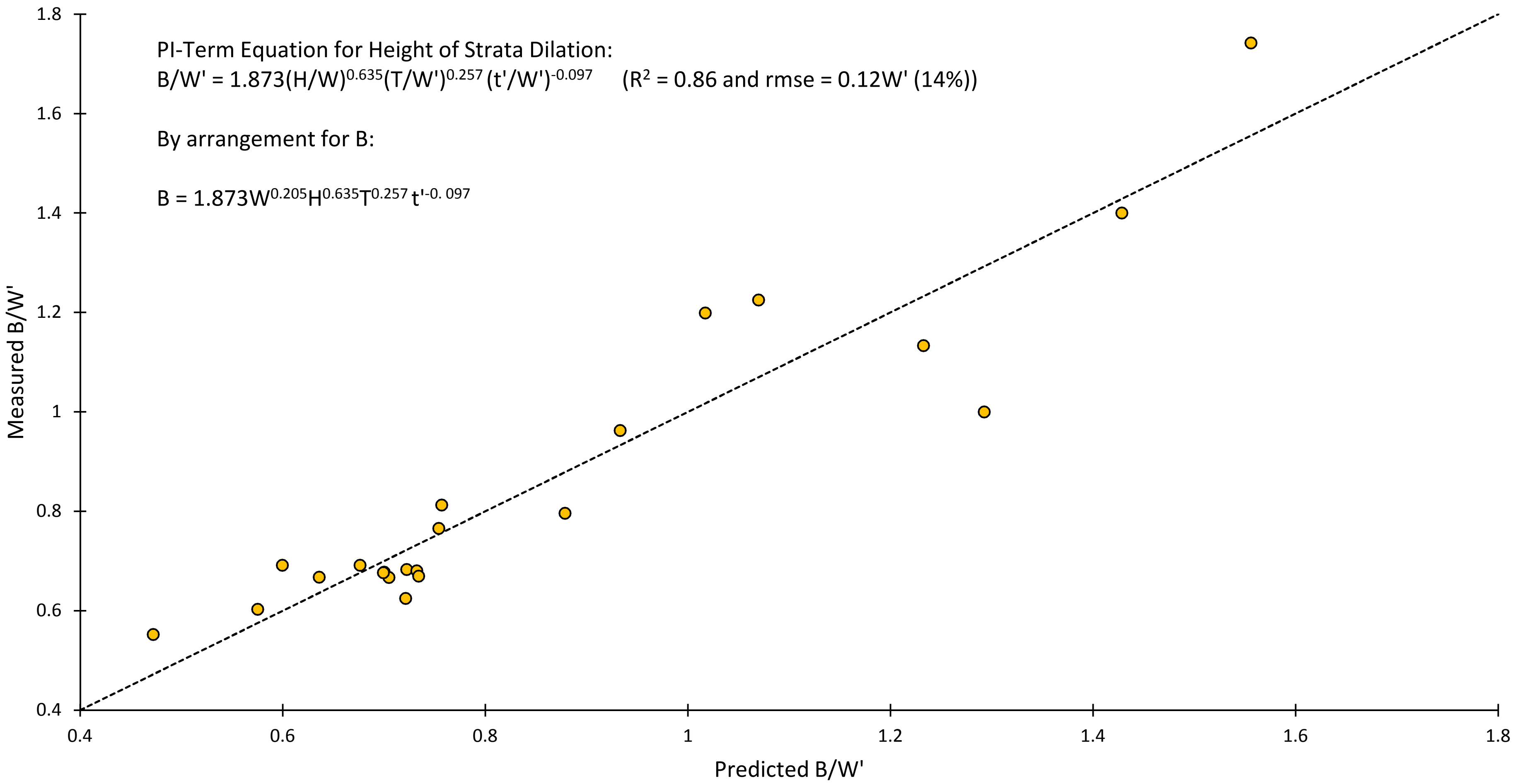
H0: The sample follows a Normal distribution

Ha: The sample does not follow a Normal distribution

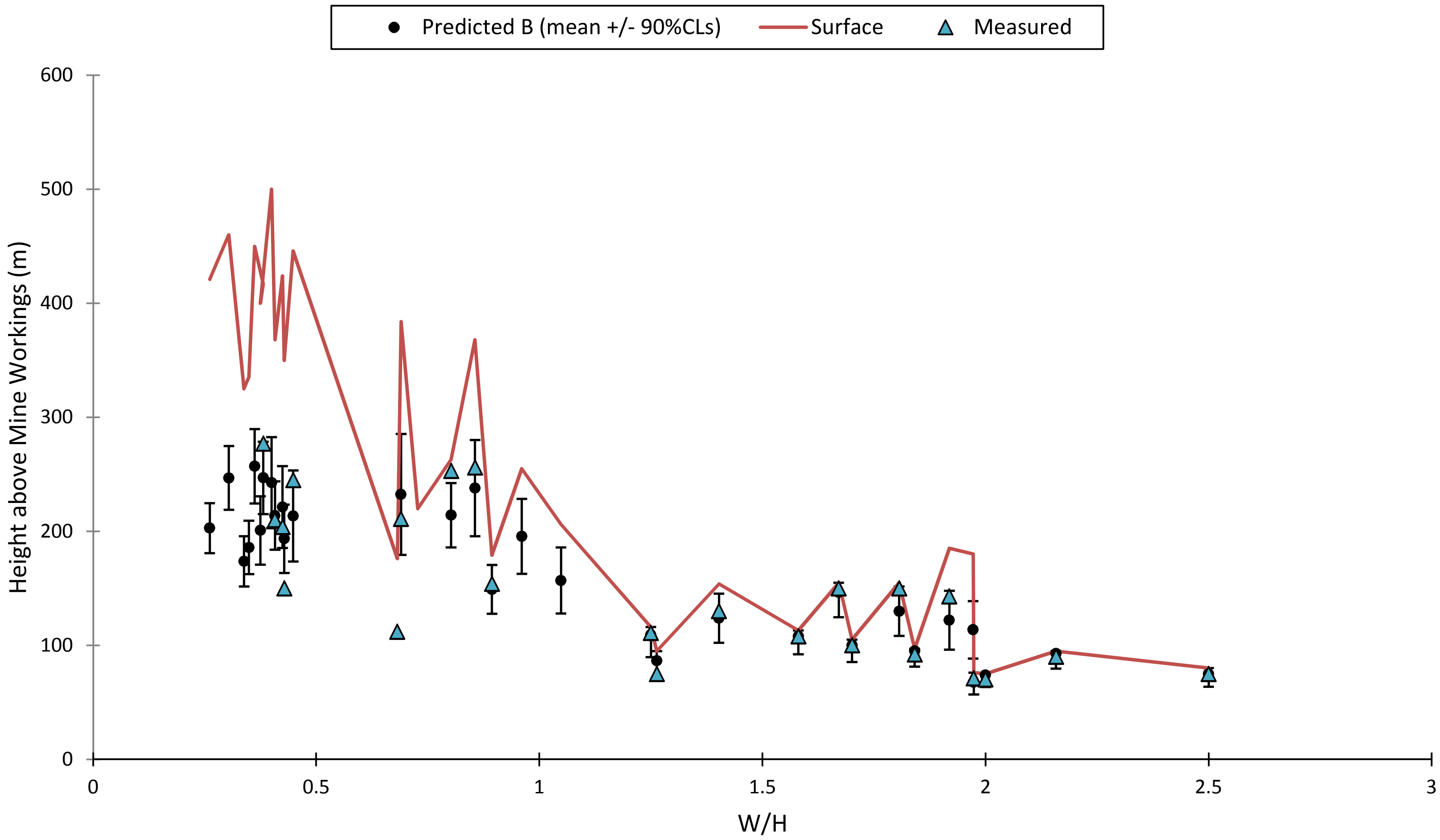
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

The risk to reject the null hypothesis H0 while it is true is 48.70%.

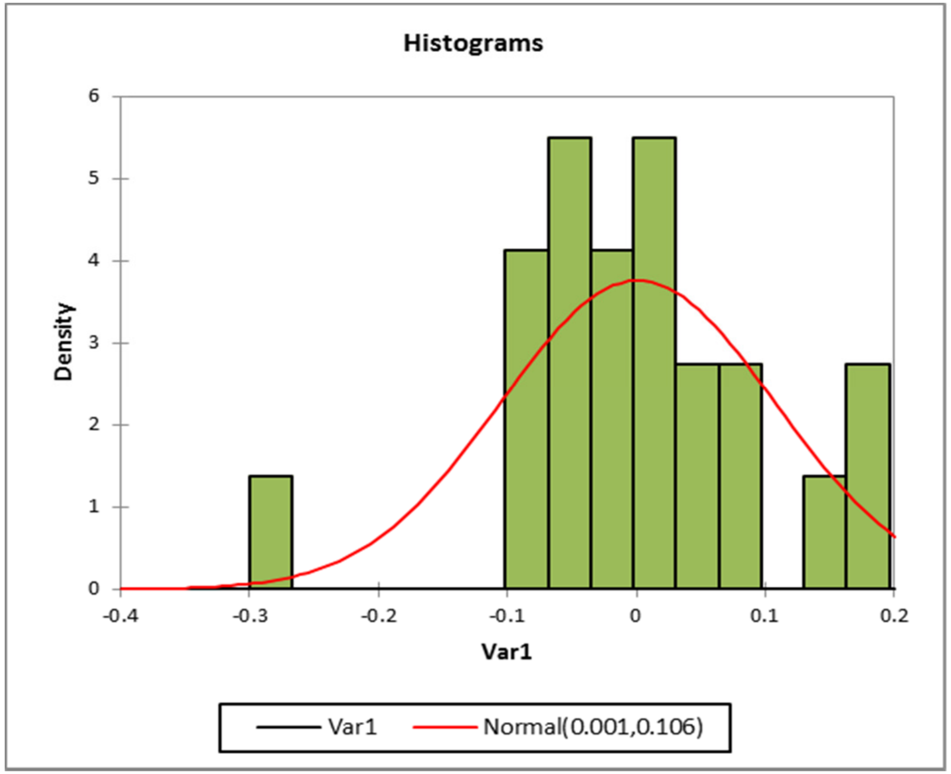
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data			
	Drawn:	S.Ditton					
	Date:	01.02.14	Title:	Results of Non-Linear Regession Error analysis for Height of B-Zone Predictions for Geometry Only Pi-Term Model			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42m	

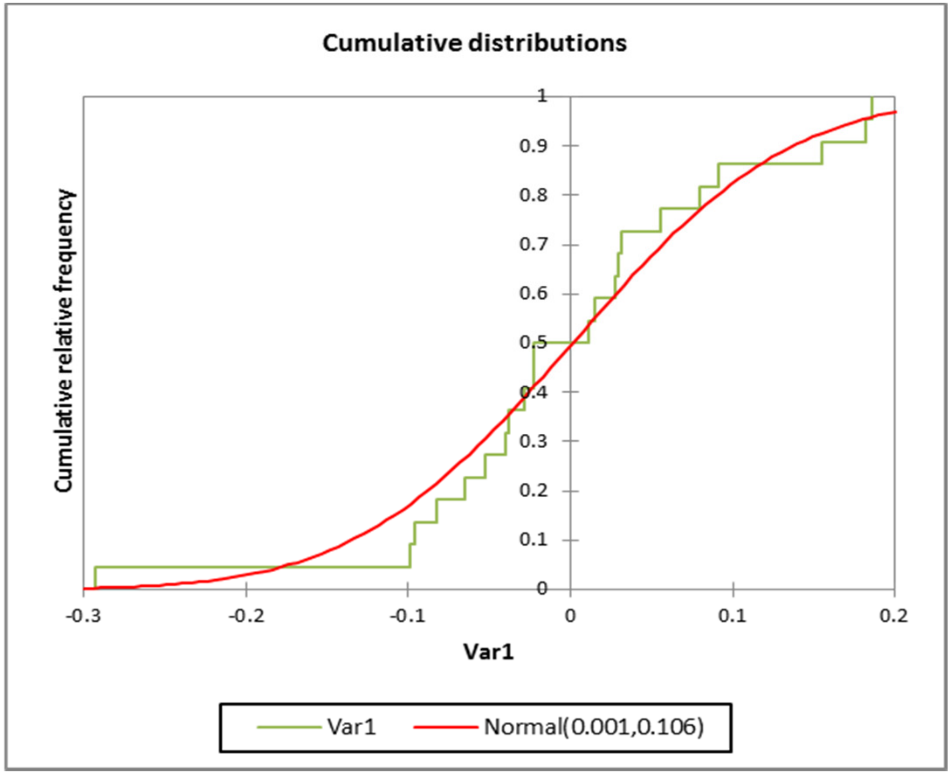


DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data
	Drawn:	S.Ditton		
	Date:	01.02.14	Title:	Results of Non-Linear Regession Error analysis for Height of B-Zone Predictions for Geology Pi-Term Model
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS
			Figure No:	A42n



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data			
	Drawn:	S.Ditton					
	Date:	01.02.14	Title:	Results of Non-Linear Regession Error analysis for Height of B-Zone Predictions for Geology Pi-Term Model			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A42o	





Kolmogorov-Smirnov test:

D	0.126
p-value	0.849
alpha	0.05

Test interpretation:

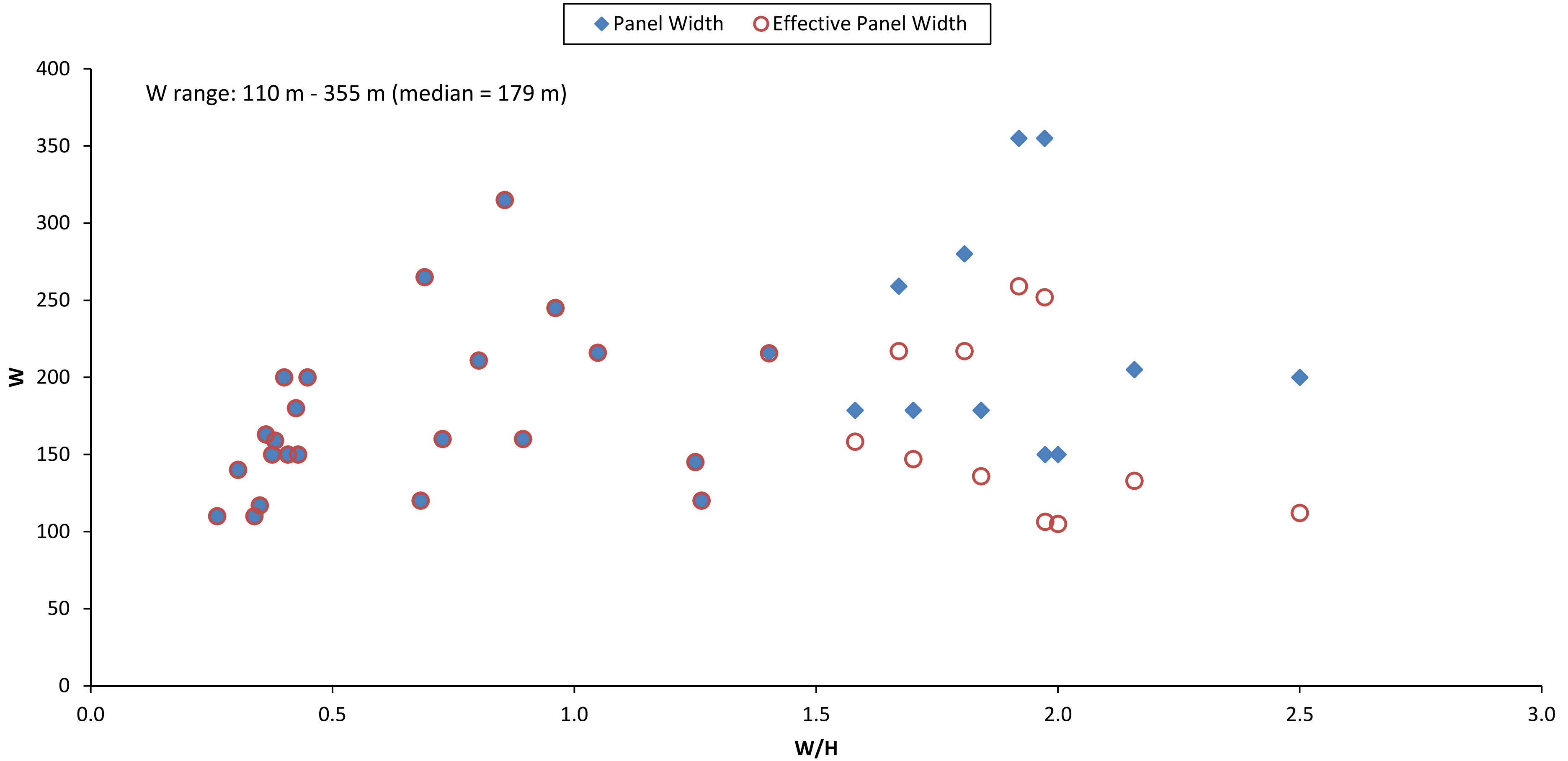
H0: The sample follows a Normal distribution

Ha: The sample does not follow a Normal distribution

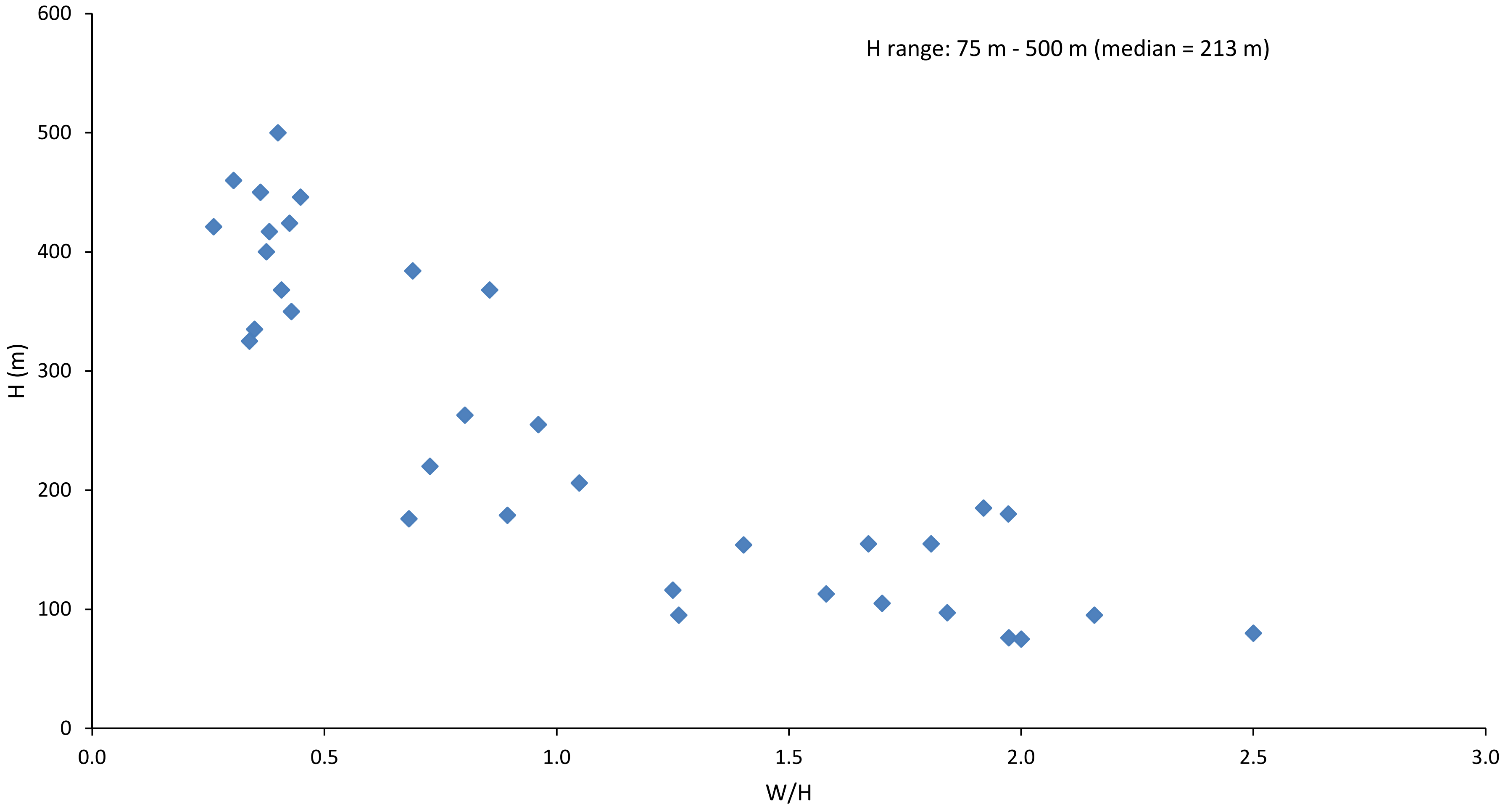
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

The risk to reject the null hypothesis H0 while it is true is 84.89%.

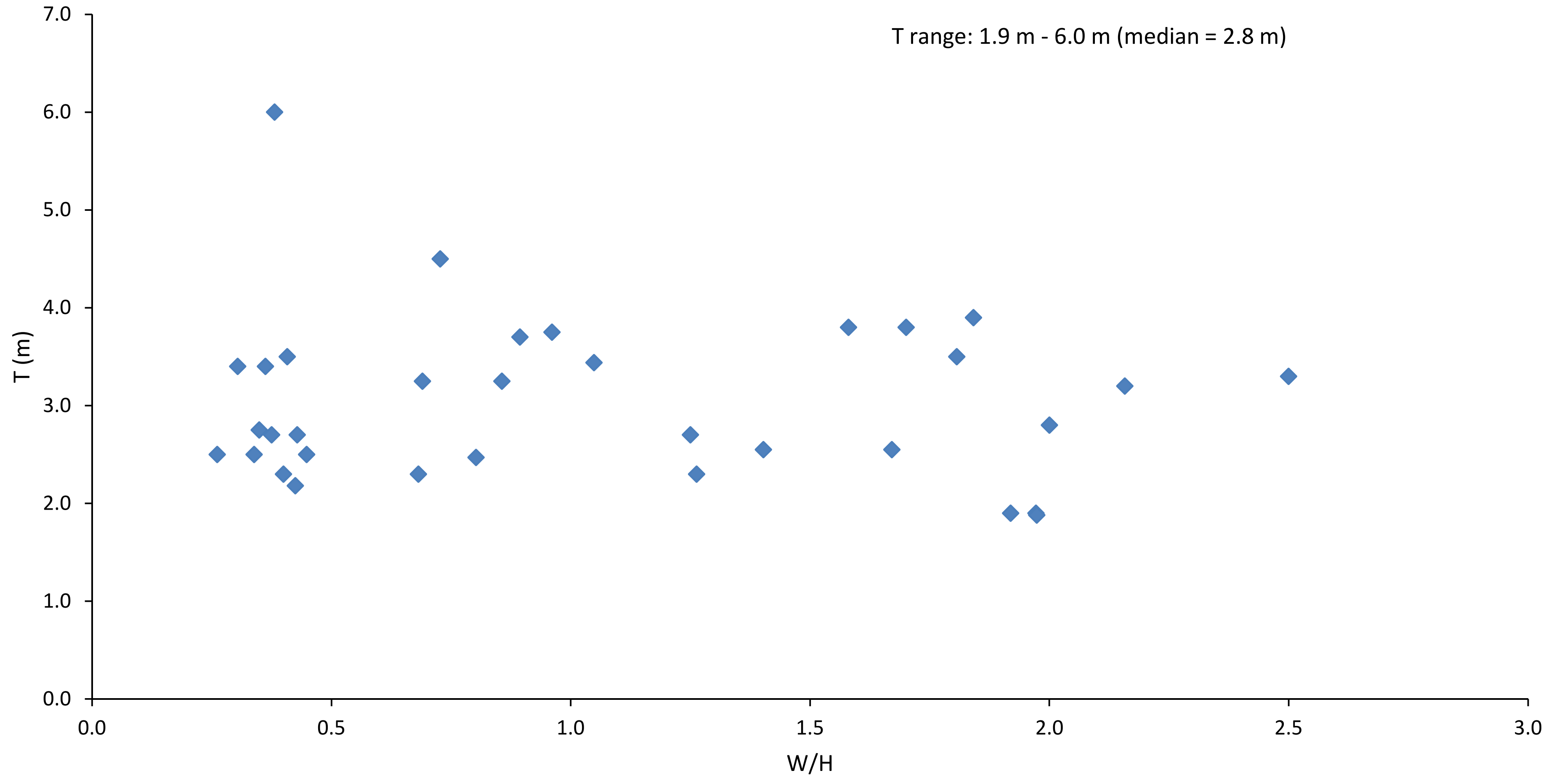
DgS	Engineer: S.Ditton		Client:	Review of Height of Fracturing Data
	Drawn: S.Ditton			
	Date: 01.02.14		Title:	Results of Non-Linear Regession Error analysis for Height of B-Zone Predictions for Geology Pi-Term Model
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS
			Figure No:	A42p



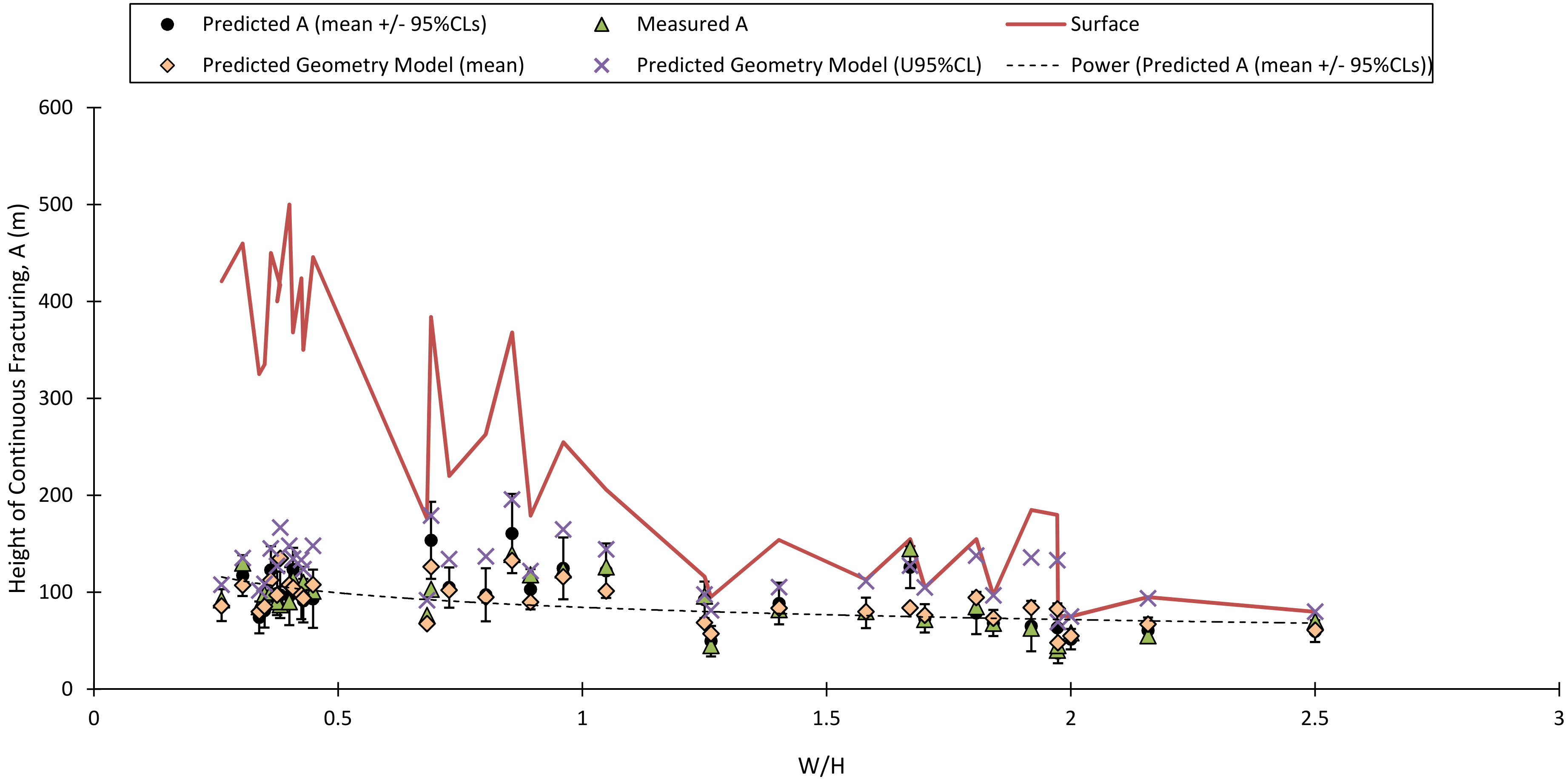
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	03.12.12	Title:	Panel Width v. W/H Database for Sub-surface Fracturing Model		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43a



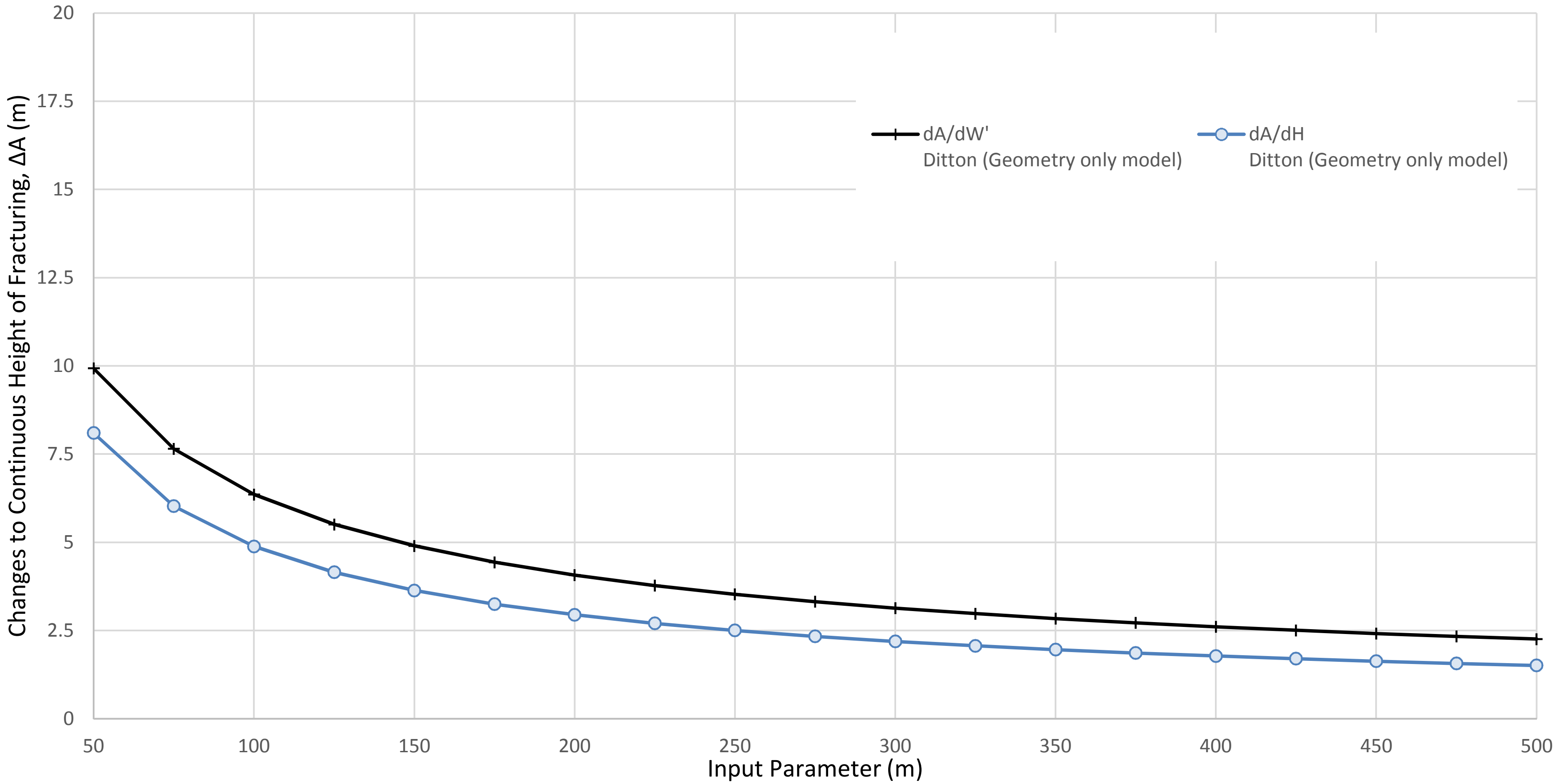
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003
	Drawn:	S.Ditton		
	Date:	03.12.12	Title:	Cover Depth v. W/H Database for Sub-surface Fracturing Model
	Ditton Geotechnical Services Pty Ltd			
			Scale:	NTS
			Figure No:	A43b



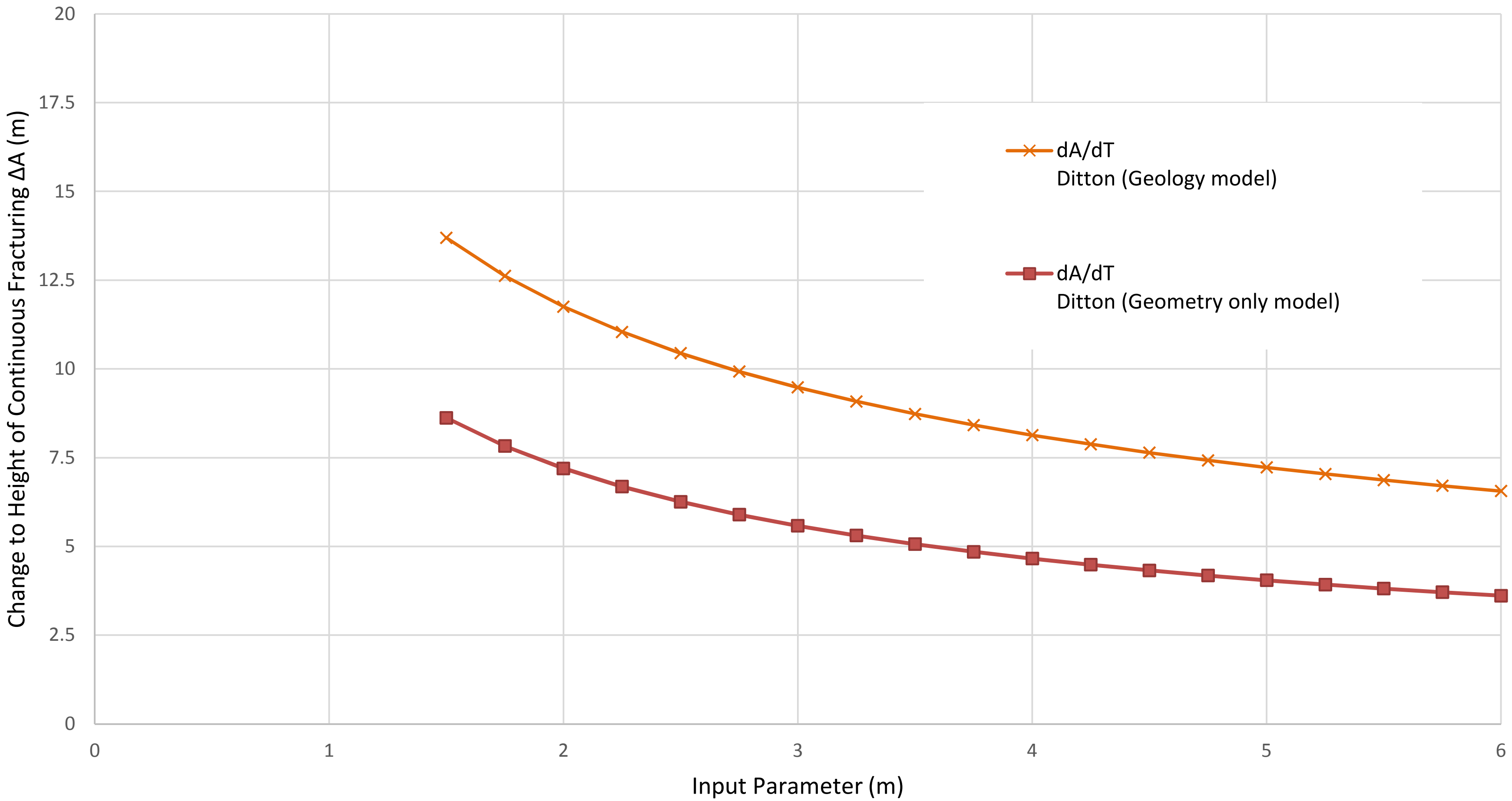
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	03.12.12	Title:	Mining Height v. W/H Database for Sub-surface Fracturing Model		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43c



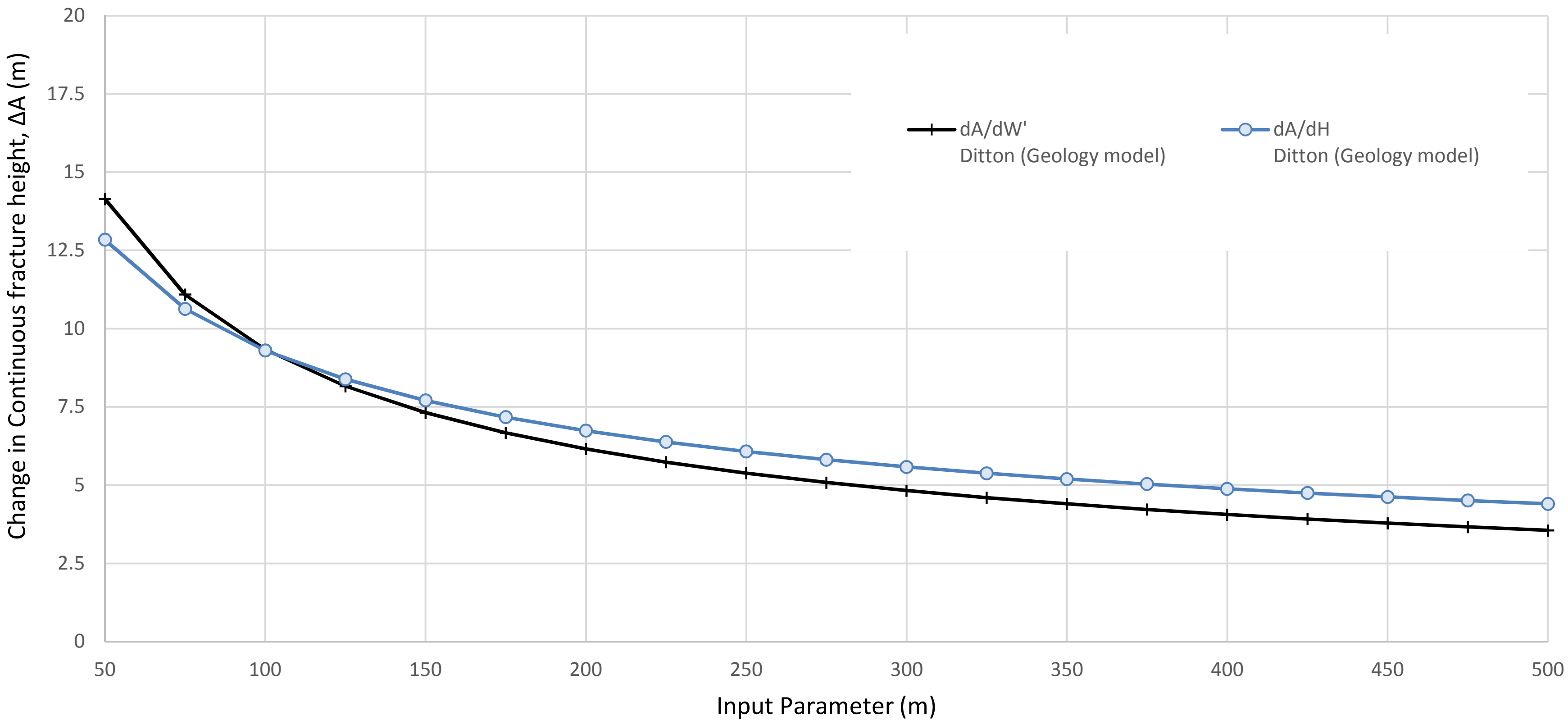
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data			
	Drawn:	S.Ditton					
	Date:	01.05.14	Title:	Heights of Continuous Fracturing Predictions for the Geometry and Geology Pi-Term Models			
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43d	



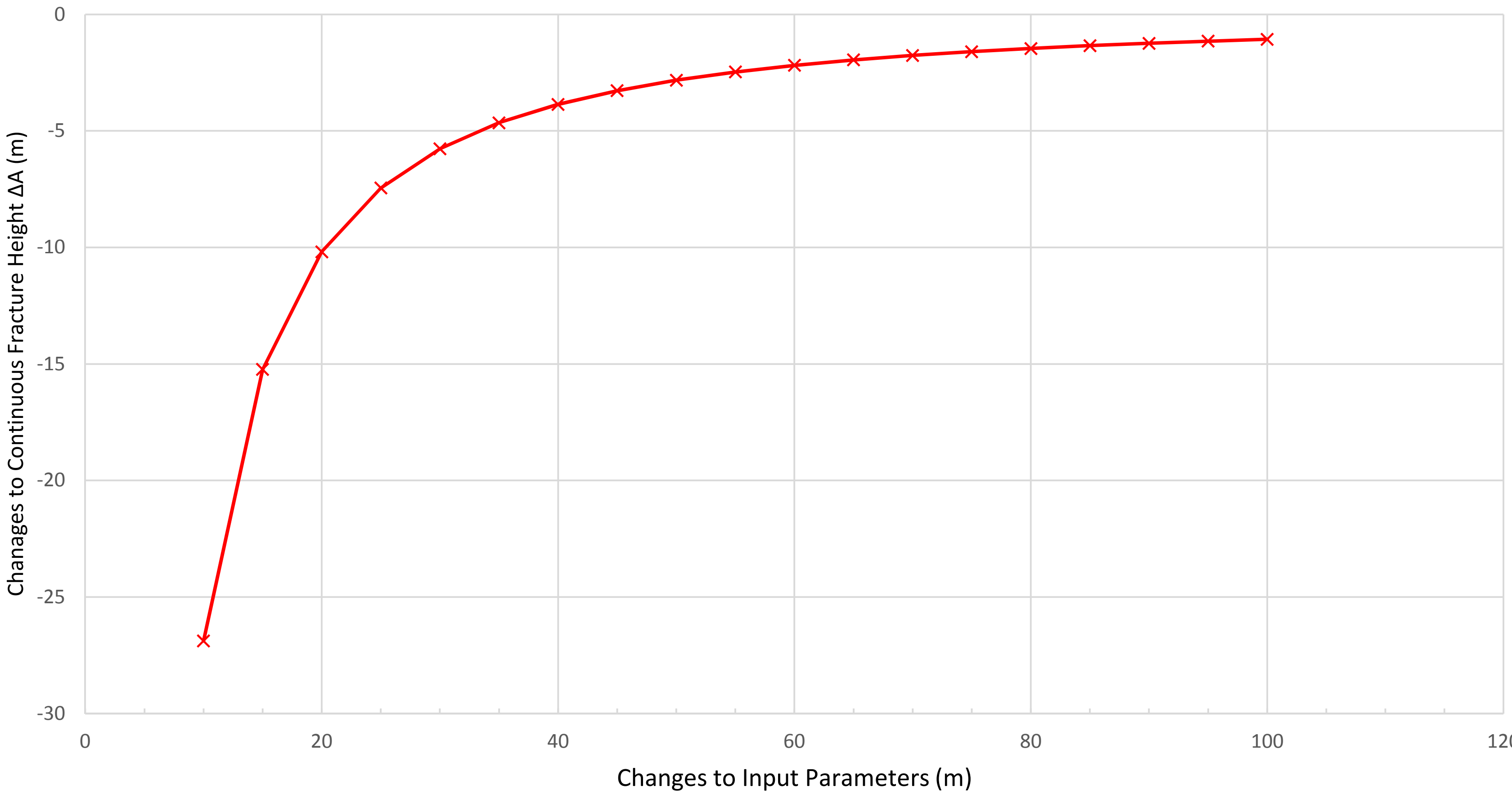
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	25.05.14	Title:	Sensitivity Analysis of Geometry Only Pi-Term Model Input Parameters on Predicted Height of Continuous Fracturing: W' and H (as per Merrick, 2014)		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43e



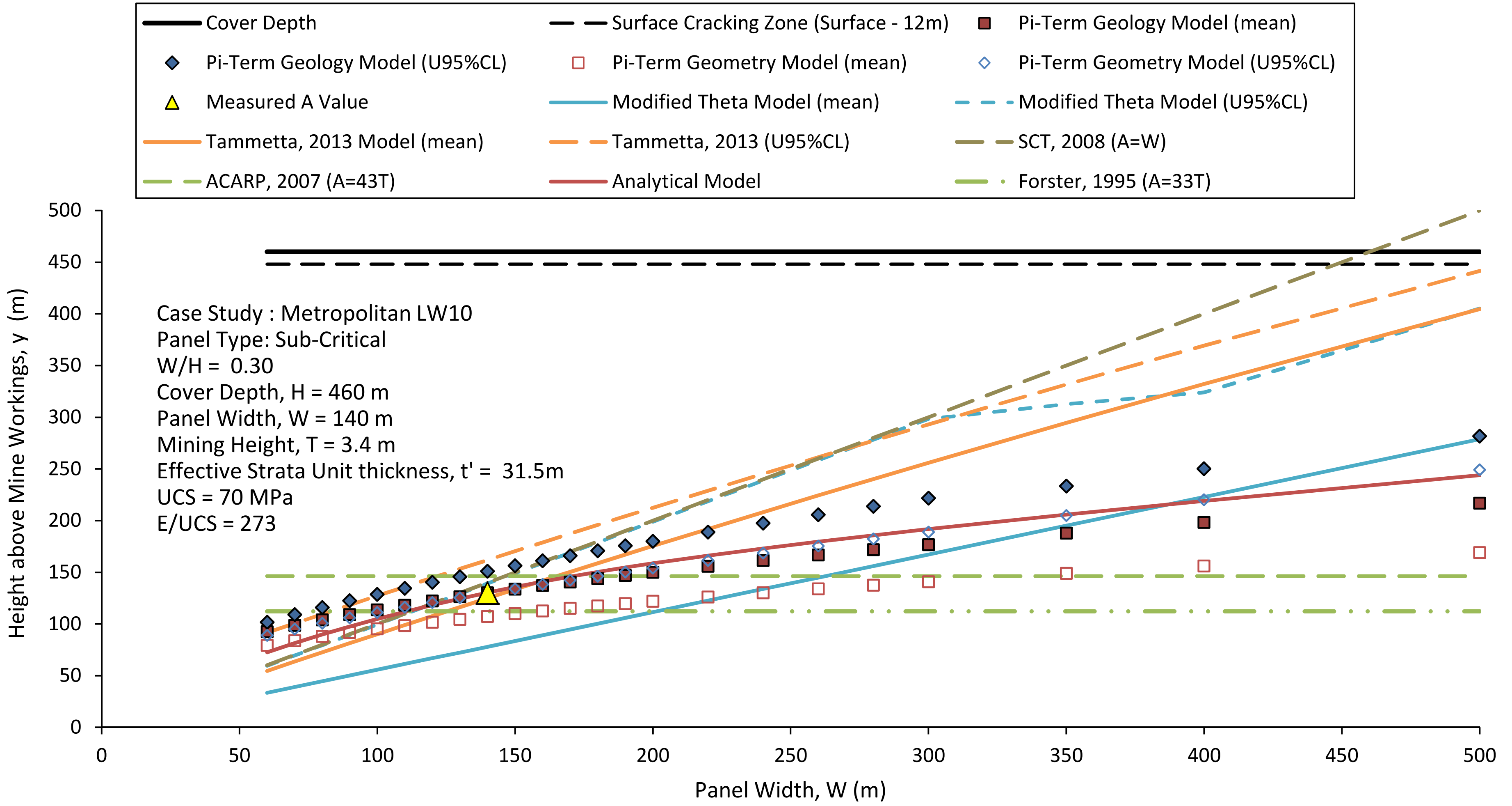
DgS	Engineer: S.Ditton		Client:	Modified from ACARP, 2003
	Drawn: S.Ditton			
	Date: 25.05.14		Title:	Sensitivity Analysis of Geology & Geometry Pi-Term Model Input Parameters on Predicted Height of Continuous Fracturing: T (as per Merrick, 2014)
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS; Figure No: A43f



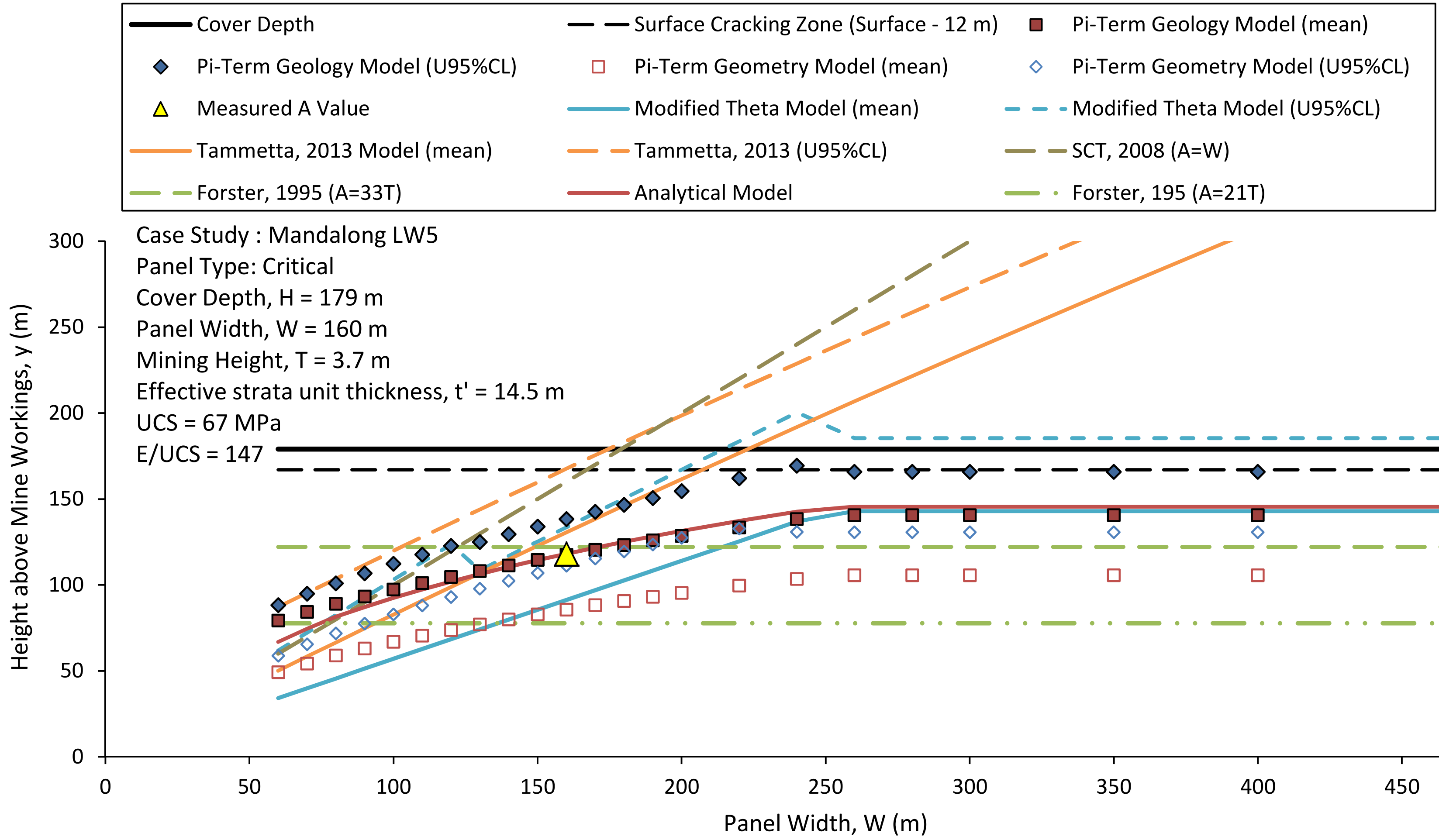
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	25.05.14	Title:	Sensitivity Analysis of Geology Pi-Term Model Input Parameters on Predicted Height of Continuous Fracturing: W' and H (as per Merrick, 2014)		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43g



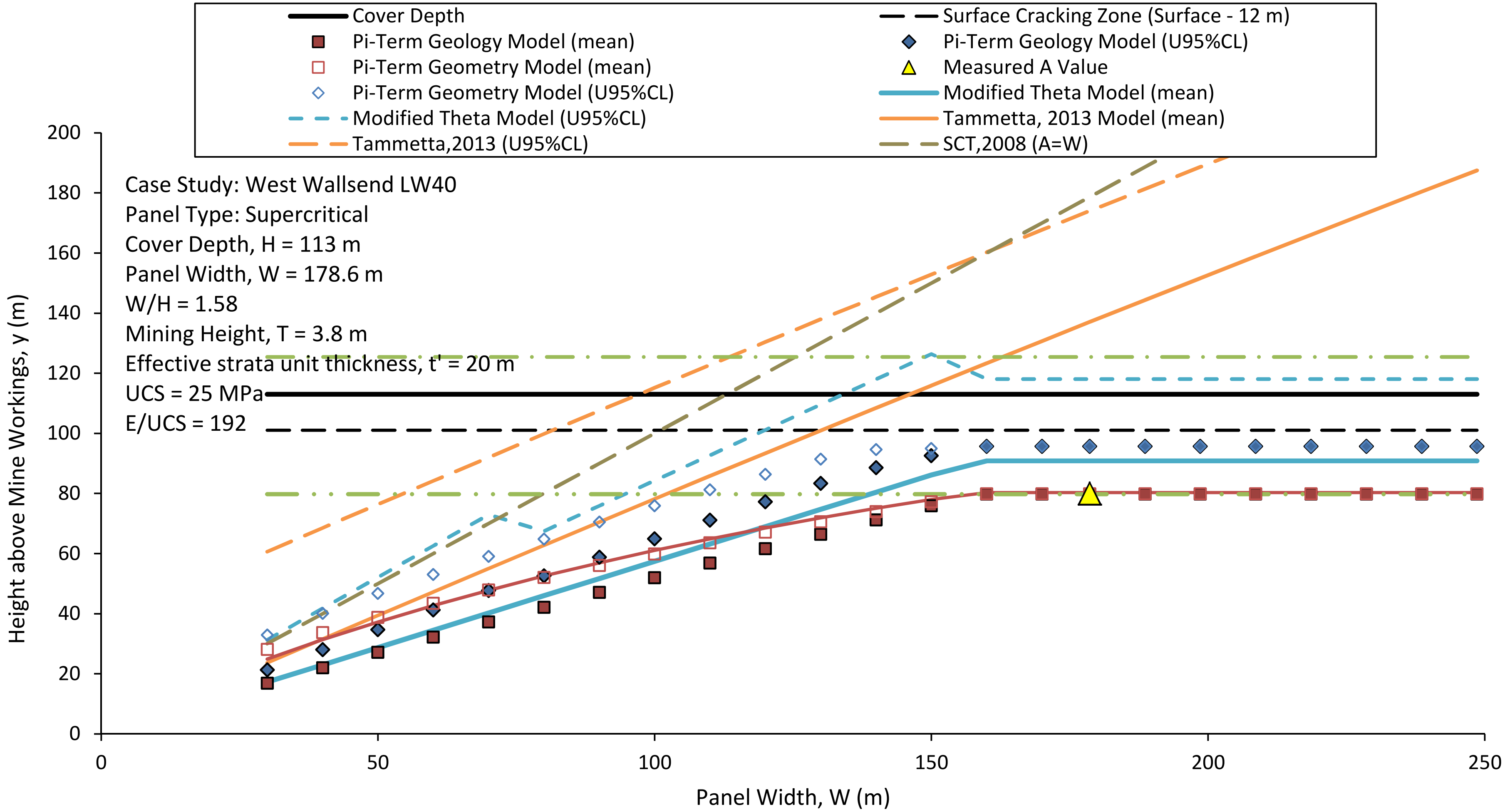
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	25.05.14	Title:	Sensitivity Analysis of Geology Pi-Term Model Input Parameters on Predicted Height of Continuous Fracturing: t' (as per Merrick, 2014)	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A43h



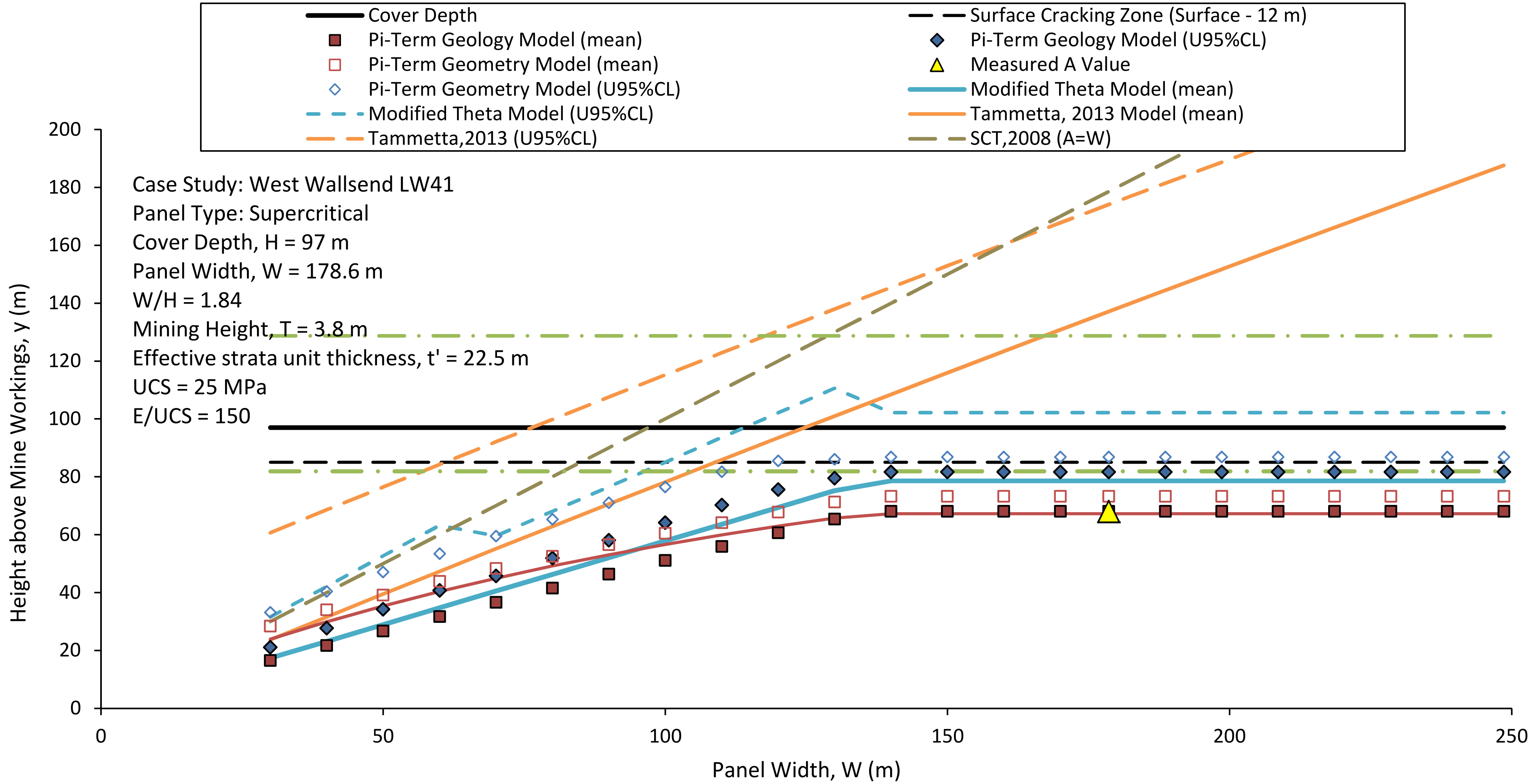
DgS	Engineer: S.Ditton		Client:	Modified from ACARP, 2003
	Drawn: S.Ditton			
	Date: 16.03.14		Title:	Predicted A-Zone Fracture Heights for Varying Panel Widths using Pi-Term Geometry and Geology Models and Current State of the Art Models
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS — Figure No: A43i



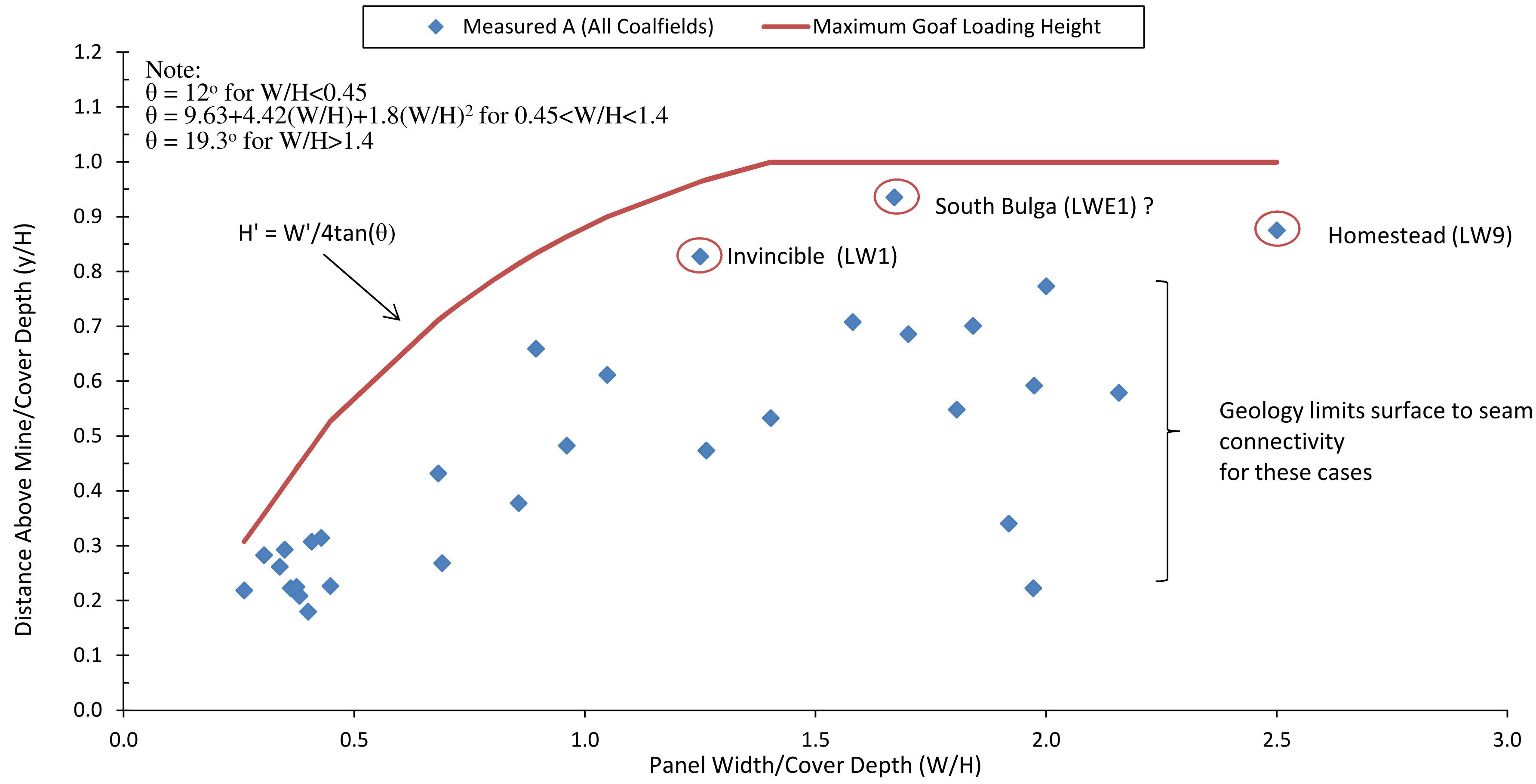
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003
	Drawn:	S.Ditton		
	Date:	16.03.14	Title:	Predicted A-Zone Fracture Heights for Varying Panel Widths using Pi-Term Geometry and Geology Models and Current State of the Art Models
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS
			Figure No:	A43j



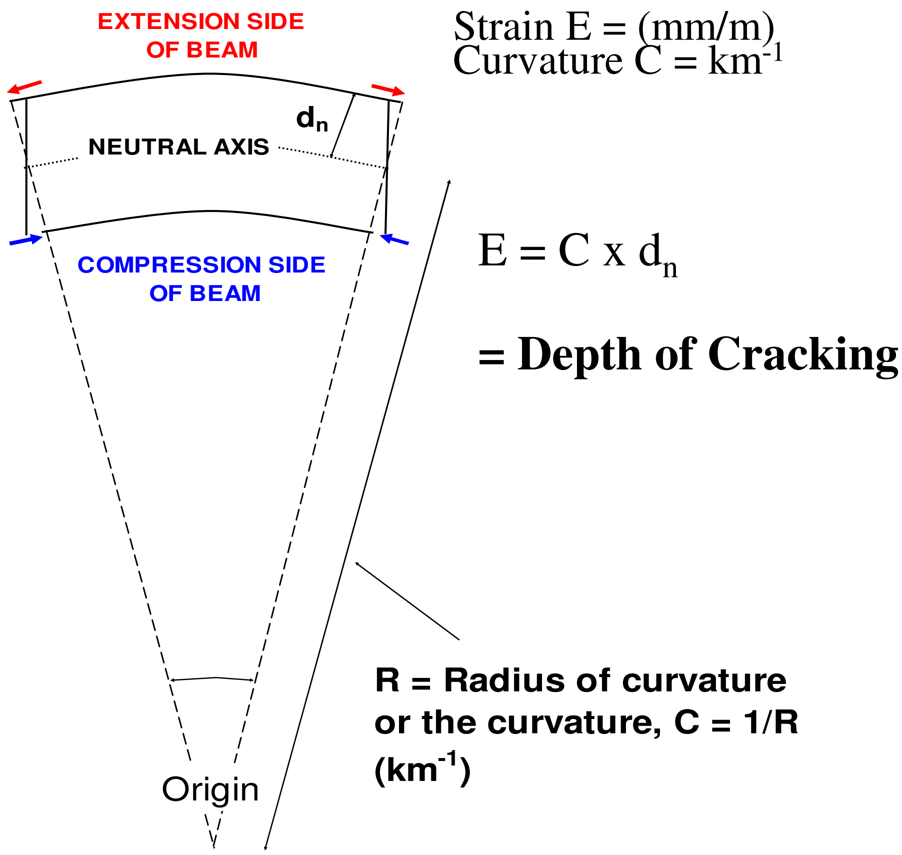
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	16.03.14	Title:	Predicted A-Zone Fracture Heights for Varying Panel Widths using Pi-Term Geometry and Geology Models and Current State of the Art Models		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43k



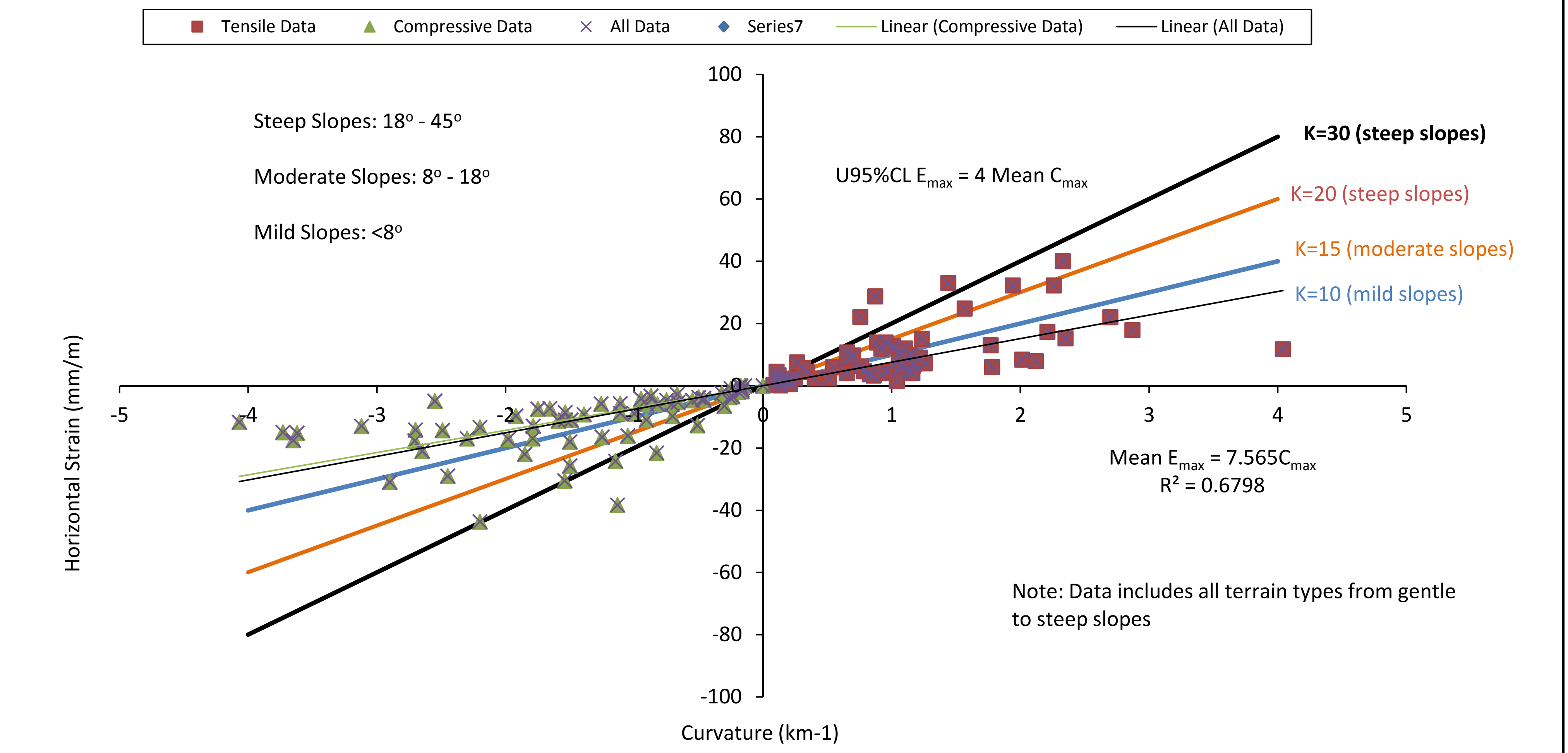
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	16.03.14	Title:	Predicted A-Zone Fracture Heights for Varying Panel Widths using Pi-Term Geometry and Geology Models and Current State of the Art Models		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43l



DgS	Engineer: S.Ditton		Client:	Review of Height of Fracturing Data
	Drawn: S.Ditton			
	Date: 01.05.14		Title:	Measured Heights of Continuous Fracturing in NSW and QLD Coalfields with Reported Surface to Seam Connectivity Cases and Theoretical Goaf Loading Height
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS — Figure No: A43m



DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003		
	Drawn:	S.Ditton				
	Date:	08.08.08	Title:	Bending Beam Theory for Strain Prediction from Curvature Measurements		
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No:	A43n



DgS	Engineer: S.Ditton		Client:	Extract from ACARP, 2003
	Drawn: S.Ditton			
	Date: 08.08.08		Title:	Empirical Model for Maximum Panel Strain Prediction Above Longwall Panels for Smooth and Cracked Profiles in the Newcastle Coalfield
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS
			Figure No:	A43o