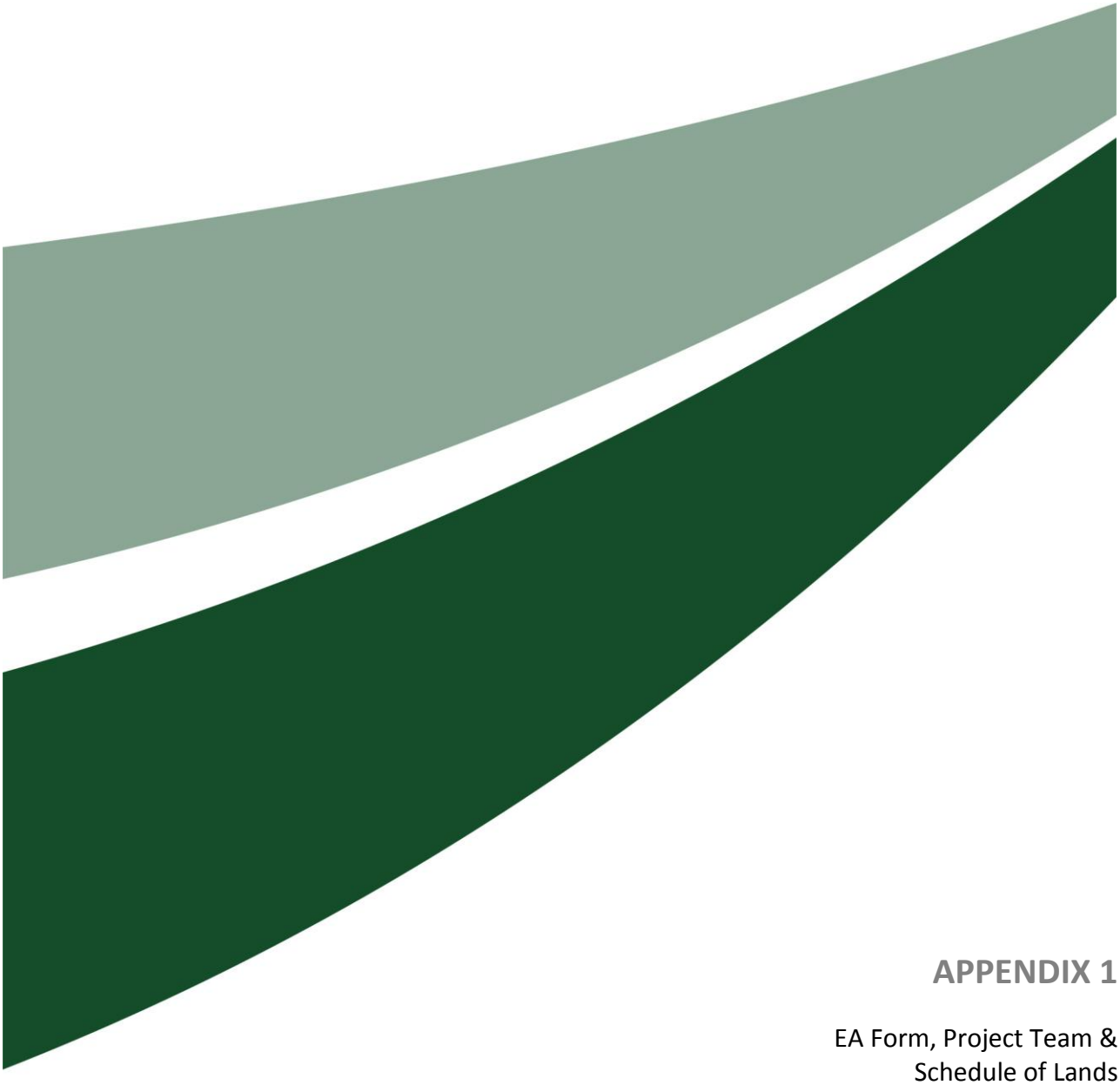


APPENDIX 1

EA Form, Project Team &
Schedule of Lands

STATEMENT OF AUTHORSHIP

EA prepared by	
Name:	John Merrell Group Manager, Environment and Community NSW
Qualifications:	Bachelor of Environmental Science University of Newcastle
Address:	Umwelt (Australia) Pty Limited 75 York Street Teralba NSW 2284
In respect of:	Proposed modification to mining area at West Wallsend Colliery as described in the accompanying Environmental Assessment
Applicant Name:	Oceanic Coal Australia Pty Ltd
Applicant Address:	The Broadway Killingworth NSW 2278
Land to be developed:	See Schedule of Lands attached.
Proposed Development:	West Wallsend Colliery Longwall 51 and Longwall 52 Project
Environmental Assessment	An Environmental Assessment is attached.
Certification	I declare that I have prepared the contents of this environmental assessment and to the best of my knowledge: • it is in accordance with the relevant provisions of the *Environmental Planning and Assessment Act 1979*; and • it contains all available information that is relevant to the environmental assessment of the development, activity or infrastructure to which the assessment relates; and • that the information contained in the environmental assessment is neither false nor misleading
Signature:	
Name:	John Merrell
Date:	23 December 2013

Project Team

Glencore Coal

The assistance of the following Glencore Coal personnel during the preparation of this EA is gratefully acknowledged. In addition, personnel from West Wallsend Colliery provided details regarding the project and participated in the consultation process.

Bret Jenkins	Approvals Manager NSW, Glencore Coal
Mark Robinson	Approvals Manager, Oceanic Coal
Wade Covey	Environment and Community Manager, Oceanic Coal

Umwelt (Australia) Pty Limited – EA Preparation

John Merrell, Group Manager, Environment & Community – NSW B Env Sc	Project Director, Strategic Direction, EA Review and Strategic Consultation
Luke Bettridge, Senior Environmental Scientist B Env Sc	Project Manager, Client and Agency Liaison, Environmental Assessment Reporting
Susan Shield, Technical Engineering Manager/Associate B E (Hons), M E (Water),	Surface Water Assessment
Dr Adam Wyatt, Senior Environmental Engineer/Hydrologist B Eng (Env); PhD	Surface Water Assessment
Janice Wilson, Manager Cultural Heritage/Associate B Arts (Hons)	Aboriginal Cultural Heritage and Archaeological Assessment
Amanda Reynolds, Archaeologist BA (Hons)	Aboriginal Cultural Heritage and Archaeological Assessment
Peter Saad, Senior Archaeologist B Arts (Arch)	Aboriginal Cultural Heritage and Archaeological Assessment
Travis Peake, Manager Ecology/Associate B Nat Res(Hons)	Ecological Impact Assessment
Alison Riley, Senior Ecologist B Sc	Ecological Impact Assessment
Shaun Corry, Ecologist B Sc (Biol)	Ecological Impact Assessment
Ian Kennedy, Design, Drafting and GIS Manager	Drafting and Graphic Design
Kerrie Hine	Report formatting, Quality Control and Compilation

Other Specialist Investigations

Ditton Geotechnical Services Pty Ltd Steve Ditton	Subsidence Assessment
Aurecon Australia Ian Forster	Groundwater Assessment

Schedule of Lands

Lot/Section	DP	Owner
1/F	2469	The Council of the Shire of Lake Macquarie
1/G	2469	Council of the City of Lake Macquarie
137	755207	The State of New South Wales
140	755207	The State of New South Wales
2/F	2469	The Council of the Shire of Lake Macquarie
2/G	2469	The Council of the Municipality of Lake Macquarie
20/G	2469	The Council of the Shire of Lake Macquarie
21/G	2469	The Council of the City of Lake Macquarie
24/F	2469	Council of the City of Lake Macquarie
25/F	2469	Council of the City of Lake Macquarie
26/F	2469	The Council of the City of Lake Macquarie
262	755207	The State of New South Wales
263	755207	The State of New South Wales
27/F	2469	Lake Macquarie City Council
28/F	2469	The Council of the Shire of Lake Macquarie
29/F	2469	The Council of the Shire of Lake Macquarie
3	788116	The State of New South Wales
3/F	2469	The Council of the Shire of Lake Macquarie
3/G	2469	The Council of the Shire of Lake Macquarie
30/F	2469	The Council of the Shire of Lake Macquarie
4	788116	The State of New South Wales
4/F	2469	The Council of the Shire of Lake Macquarie
5/F	2469	The Council of the Shire of Lake Macquarie
6/F	2469	The Council of the Shire of Lake Macquarie
7/E	2469	The Council of the Shire of Lake Macquarie
7/F	2469	The Council of the Shire of Lake Macquarie
8/E	2469	The Council of the Shire of Lake Macquarie
8/F	2469	The Council of the Shire of Lake Macquarie
Part M1 Motorway		
Part Wakefield Road		
Various Unnamed Crown Roads		

APPENDIX 2

Longwall 41 Subsidence Occurrence
Fact Sheets

GLENCORE

30 August 2013

West Wallsend Colliery Subsidence Management FAQ's Fact Sheet

Who is West Wallsend Colliery and what approval do they have to mine in the Sugarloaf State Conservation Area (SSCA)?

West Wallsend Colliery (WWC) (see Figure 1) is an underground coal mining operation that mines the West Borehole coal seam using longwall mining techniques. The majority of the coal from WWC is loaded onto trains and transported to Newcastle Port for export. WWC has been operating since 1969 and has been mining beneath the SSCA (a State Forest prior to 2007) for approximately 13 years.

WWC undertakes its mining operations in accordance with a Project Approval (PA09_0203) issued by the Minister for Planning and Infrastructure, as well as its Extraction / Subsidence Management Plans which are approved by the Department of Industry and Investment and the Department of Planning and Infrastructure.

Mining and related activities are permitted within State Conservation Areas which is managed by the National Parks and Wildlife Service.

Figure 1:



Private Mail Bag 8, Singleton, NSW 2330
567 Broke Road, Singleton, NSW 2330
T + 61 2 6570 2416 F + 61 2 6570 2520 www.glencore.com

Glencore Coal Assets Australia Pty Limited ACN 163 821 298

GLENCORE

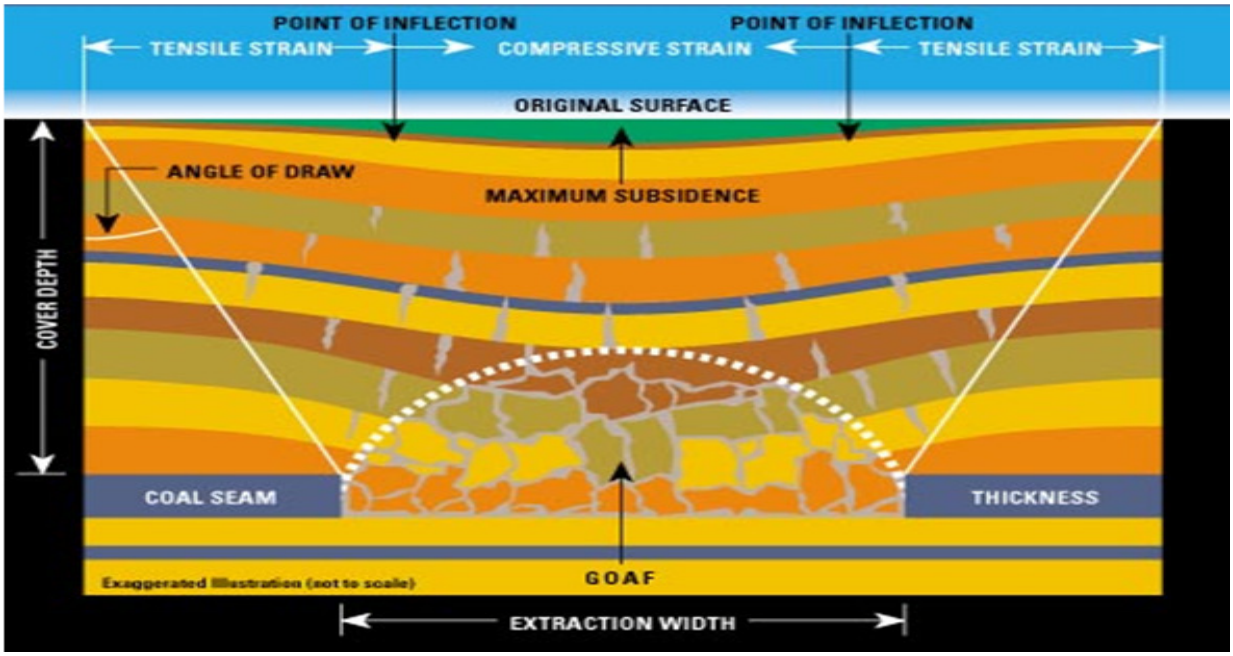
What is subsidence?

"Subsidence can be described as the lowering or settling down of the land's surface. When mining takes place, the earth's forces are redistributed and there is a tendency for the void to close. Some of this effect may be transferred to the surface as mine subsidence. The extent to which subsidence occurs in a particular location depends upon the width and height of the coal extracted, its depth from the surface, and the rock types found in the overlying strata" (Mine Subsidence Board, 2013).

In the mining process we extract a high percentage of the coal which results in the settling of the surrounding strata on the surface directly above the mining area.

Figure 2 shows how subsidence is caused by underground mining.

Figure 2:



Source : http://www.minesub.nsw.gov.au/templates/mine_subsidence_board.aspx?pageID=3797

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West Wallsend Colliery Greater than predicted subsidence incident FAQ's

What caused the "greater than predicted" subsidence impacts in the Sugarloaf State Conservation Area (SSCA)?

The impacts were confined to an isolated, remote area of the SSCA. It is believed that as subsidence began to impact the area from the mining of Longwall 41, it weakened the pre-existing anomalous geology in the area which resulted in unpredicted movement.

When did the incident occur?

The incident was first identified in early October 2012 during a weekly geotechnical inspection of the surface affected subsidence zones associated with Longwall 41.

Who was it reported to?

The incident was reported to the following agencies in accordance with the sites Project Approval (PA09_0203):

- NSW Department of Planning and Infrastructure
- NSW Department of Infrastructure and Investment
- NSW Office of Water
- Office of Environment and Heritage
- Mine Subsidence Board

What actions were taken by West Wallsend Colliery at the time of the incident?

The affected area was demarcated with safety mesh and barrier tape in accordance with the site's Public Safety Management Plan. A monitoring program was also initiated to monitor the affected area over time. A geotechnical investigation into the subsidence impacts was commenced in consultation with the relevant agencies and an assessment of potential remediation options was commenced.

Shouldn't these impacts have been predicted?

Industry experts were engaged to predict and assess subsidence impacts associated with WWC's underground operations. WWC's subsidence model is based on industry knowledge which has been built around extensive subsidence monitoring results obtained from previous underground mining at WWC.

The subsidence impacts that occurred in the area were as a result of anomalous subsurface fracturing which was unknown and resulted in unpredicted movement as mining progressed through the area.

How will the impacted area be remediated?

WWC is investigating potential remediation options for the site in consultation with the relevant stakeholders and remediation specialists. Due to the remote nature of the site, steep terrain, and a lack of formed access tracks in the area, the use of earthwork machinery is extremely difficult and potentially unsafe. WWC is investigating other remediation methods which have been used throughout the industry to achieve a sustainable long term outcome.

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What measures has the company taken to ensure public safety in the SSCA as a result of this incident?

The surface affected subsidence zones associated with Longwall 41 are clearly demarcated and signposted warning the public of the hazards associated with underground mining in the area. To assist with managing public safety and minimise risk, security is also posted on access points into the affected area to warn the public of the hazards and to stay outside of the demarcation zone. WWC requests that the public abide by all warning signs and not enter the demarcation zones.

Does the company plan to continue mining in the area?

In accordance with the site's Project Approval, WWC has approval to continue underground mining in the area till 2021.

Is this likely to happen again?

Whilst steps have been taken including increased subsidence modelling and monitoring to help predict anomalous geological events, the geology is complex.

WWC cannot guarantee that a similar event will not occur. However, after extensive consultation with subsidence specialists, WWC does not expect it will.

How does the company propose to manage subsidence impacts as mining continues in the SSCA?

A full review of the sites subsidence model has been undertaken by specialist subsidence consultants following the outcomes from the incident and the monitoring results obtained from Longwall 41. Based on this review WWC has modified the mine plan to reduce impacts on steep slopes and cliff lines within the SSCA as a result of subsidence.

Prior to the subsidence remediation incident reported on 4 June 2013, WWC had been remediating (through either minor earthworks or traditional grouting techniques) subsidence impacts within the SSCA in accordance with an agreed protocol and with the formal consent of the Office of Environment and Heritage – National Parks and Wildlife Service.

WWC proposes to continue remediation of subsidence impacts within the SSCA, using traditional grouting techniques and/or earthwork machinery. WWC is currently liaising with relevant government authorities regarding its remediation techniques within the SSCA for its future mining activities.

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West Wallsend Colliery Subsidence Remediation incident FAQ's

What was the incident?

During subsidence remediation activities above Longwall 41 on 4 June 2013, a leak of an approved foaming grouting product was identified.

The grout incident area extends approximately 250m down the slope of the work area and it is estimated that approximately 75 cubic meters of grout has travelled into the drainage channel.

Following the identification of the incident grouting activities ceased immediately.

Who was it reported to?

The incident was reported immediately in accordance with WWC's Pollution Incident Response Management Plan to the following agencies:

- Environmental Protection Authority
- Lake Macquarie City Council
- NSW Health
- NSW Workcover
- NSW Fire and Rescue
- NSW Department of Planning and Infrastructure
- Office of Environment and Heritage
- NSW Office of Water

Why is grout being used to repair surface cracking?

In accordance with the site's approved subsidence remediation methods detailed in its Environmental Assessment Report, remediation of surface cracking on gently sloping terrain with vehicular and equipment access is generally undertaken using small earthworks machinery. In areas where access is limited or where there is steeper terrain WWC has utilised a specialist grouting contractor to assist with filling surface cracking using traditional grouting techniques. The grouting process has proven to be a less intrusive method of remediation that requires limited disturbance to fill surface cracking to prevent surface water ingress and minimise the public safety risk associated with the exposed cracks.

Is it safe and has it been approved for use in the SSCA?

The grouting product used for surface remediation activities in the SSCA is a commercially available foaming grout that is used for cavity or void filling across the mining industry worldwide.

This product has been approved for use within the SSCA for surface cracking remediation by the Office of Environment and Heritage.

What is being done to remediate the grouting incident?

Following the incident and notification to the relevant agencies, WWC immediately began investigating remediation options in consultation with specialist contractors and the grouting contractor. WWC is currently developing a remediation strategy for the site in consultation with the Office of Environment and Heritage as per the remediation direction issued to WWC in August 2013.

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For further information, please call the OCAL Environment and Community Manager on +61 2 4941 2163 during business hours.

Alternatively, you can contact West Wallsend Colliery 24 hours a day on +61 2 4941 2100

SUGARLOAF STATE CONSERVATION AREA

A message from Glencore's West Wallsend operations

In recent weeks there have been a number of reports about West Wallsend Colliery's subsidence and remediation impacts within the Sugarloaf Conservation Area (SSCA) and, as a long standing member of this community, we are extremely disappointed by these events.

As there have been a number of inaccuracies in the media reporting of these events including allegations of a cover-up, we'd like to address them, provide an update on the situation and outline the remediation measures we are taking.

Our operations in the SSCA

The SSCA (formerly the Awaba and Heaton State Forest) was one of several State conservation areas created in 2007 as a category of reserve under the National Parks and Wildlife Act 1974.

It was formed as part of the implementation of the Lower Hunter Regional Strategy and Lower Hunter Regional Conservation Plan, which identifies that the area will be used for underground mining and also "recognises that mining may generate some surface impacts, including subsidence".

The West Wallsend Colliery has been mining under this area, now known as the SSCA, for the past 13 years.

Approval process

The rigorous approval process includes obtaining a Development Consent, a Mining Lease, the development of Extraction Plans and Subsidence Management Plans, all of which need to be approved before longwall mining can commence.

Project Approval to mine in this area was obtained only after comprehensive planning, assessment and consultation over likely subsidence impacts and their management. This process resulted in extensive modifications to the overall mine plan to reduce impacts on cliff lines, steep slopes, creek lines, Aboriginal sites, groundwater, roads, powerlines and other infrastructure and ecological communities.

Subsidence

Despite very careful and thorough planning for Longwall 41, our operations have intersected an abnormal geological formation on a steep slope in part of the SSCA, creating subsidence greater than predicted.

Reports that large sections of the SSCA have been affected are not accurate.

The area affected by this greater than predicted subsidence is approximately 120m long by 17m wide (or 0.2 hectares, about 25% of the area of a football field) within the SSCA, which covers 3937 hectares.

Remediation

In relation to the report around the grout leakage it should be noted that the grouting product is not concrete. It is a light, aerated cement-based material, easily broken up, that has been approved by regulators for use in the SSCA.

It flowed for approximately 250m along an ephemeral channel – that is, a normally dry channel that exists for short periods after rainfall – described by National Parks & Wildlife as a "drainage channel".

Reported estimates of 180 tonnes of grout are inaccurate. Site records indicate that at worst approximately 24 tonnes of the material may have flowed into the channel.

Reporting the incident

The subsidence incident was found during West Wallsend's routine weekly geotechnical inspections on the 2nd October 2012. We immediately demarcated the area and installed public safety controls. We notified all the relevant regulatory authorities.

After undertaking a geotechnical assessment, we then provided a detailed incident report to Department of Planning and Infrastructure (DP&I), NSW Office of Water (NOW), Office of Environment & Heritage (OEH), Mines Subsidence Board (MSB) and the NSW Division of Resources & Energy (DRE).

We have provided an overview and a subsequent update of the incident to two of the mine's Community Consultative Committee meetings.

On the 4th June 2013 the remediation activities being completed by a specialist grouting contractor resulted in the leakage of the approved grouting product. This incident was immediately reported in accordance with the West Wallsend Colliery's Pollution Incident Response Management Plan to the following agencies; Environment Protection Authority (EPA), Lake Macquarie City Council, NOW, OEH, DP&I, NSW Health, NSW Workcover and NSW Fire and Rescue.

The West Wallsend Colliery Environment and Community management team were progressing remediation plans for these affected areas in consultation with relevant stakeholders long before they became the subject of media attention.

Where are we now?

Since each of these events was discovered our primary focus has been development of the best possible remediation methods.

This week, we will submit our plan to remove the grout. It is proposed to be removed by hand and progress will be at a rate which will ensure the remediation is of a high standard, minimises further environmental impact, and provides for the safety of those involved.

Assessment of remediation options for the subsidence impacts is complicated by a number of factors.

First there are no "text book" solutions in an area of such challenging, steep terrain. Second, remediation cannot commence until specialists engaged to provide expert advice have confirmed the area is stable. Third, the remediation plan is to be reviewed by relevant specialists, then finally by relevant government authorities prior to the commencement of any work.



Part of the area affected by the subsidence incident.

Public Safety

As we undertake remediation activities, the area remains off-limits to the public to ensure safety and we urge everyone to observe the warnings sign-posted in the area. Since the subsidence incident in October 2012 we have approached the management of public safety as a priority. Last week members of the local broadcast media ignored those warnings and requests from security personnel and proceeded into the area of steep terrain. Regrettably, this resulted in one of the group being injured.

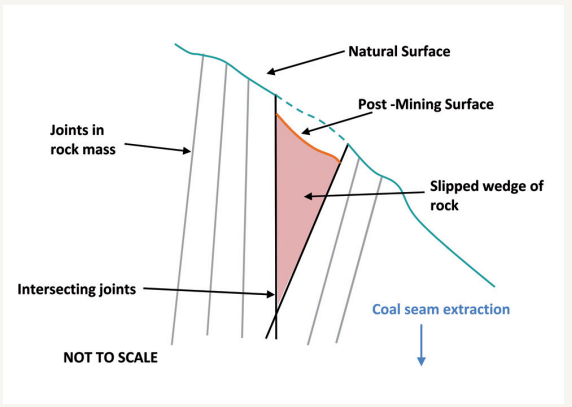
Moving Forward

We are steadfastly committed to working with all parties to return these areas to public use, and to ensure these events remain an exception in an otherwise strong record of responsible mining in this area over many years.

The West Wallsend Colliery has been operating for more than 40 years, today providing jobs for over 300 local people, and supporting many others across the wider Hunter community by sourcing goods and services from local companies. We also provide support for many local community initiatives and groups.

We again express our extreme disappointment that these incidents have occurred, not only because of the environmental impact but also because it does not accurately reflect on the efforts and attitudes of our Environment and Community management team as well as all employees at the West Wallsend Colliery.

Charlie Allan
Operations Manager, West Wallsend Colliery



How the subsidence incident occurred.

WEST WALLSEND

A GLENCORE MANAGED OPERATION

APPENDIX 3

Subsidence Assessment

Ditton Geotechnical Services Pty Ltd
82 Roslyn Avenue Charlestown NSW 2290
PO Box 5100 Kahibah NSW 2290

DgS
Ditton Geotechnical Services

West Wallsend Colliery

Subsidence Predictions and General Impact Assessment of the Proposed Southern Domain Longwalls 51 and 52, West Wallsend Colliery

DGS Report No. WWD-012/16

Date: 15 December 2013

ABN 43 113 858 910 ACN 124 206 962
Ph/Fax: 02 4920 9798 Mob: 0413 094074
Email: steve.dgs@westnet.com.au

15 December, 2013

Mr Mark Robinson
Approvals Manager
Oceanic Coal Continued Operations Project
West Wallsend Colliery
The Broadway
Killingworth NSW 2278

DGS Report No. WWD-012/16

Dear Mark,

Subject: Subsidence Predictions and General Impact Assessment of the Proposed Southern Domain Longwalls 51 and 52, West Wallsend Colliery

This report has been prepared in accordance with the brief provided on the above project.

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

Executive Summary

West Wallsend Colliery (WWC) is proposing to extract a further two longwall blocks (LWs 51 and 52) in the West Borehole (WBH) Seam. The proposed longwalls will be located in the Southern Domain to the south-west of LWs 44 to 46, with LW52 partially located within the current project area for LWs 38 to 50. The mining layout is considered conceptual at this stage.

The proposed mine workings have been assessed in accordance with Section 75W of the *Environmental Planning and Assessment Act* 1979 (EP&A Act) and the Project Approval Conditions for the current project area.

The proposed extension to the current project area is located predominantly in the Sugarloaf State Conservation Area (SSCA) that is dominated by several north-west orientated ridges and spurs between five broad valleys. The land is mainly undeveloped bush land with several fire trails and gravel access roads. A small portion of the project area is owned by Lake Macquarie City Council (LMCC) and is also undeveloped bushland.

The longwall panels 51 and 52 will be 178.8 m and 206.8 m wide (final void width) respectively. The cover depth ranges from 80 m to 140 m beneath undulating terrain with ground slopes varying between 5^{o} and 35^{o}. The mining height will range from approximately 4.2 m to 4.5 m.

The lithology above the longwall panels consists of shallow residual and alluvial soil profiles overlying near surface sandstone, conglomerate, siltstone and mudstones of the Permian Narrabeen Group and Upper Newcastle Coal Measures. Intermittent low-height conglomerate rock outcrops < 1.5 m in height exist along the mid to upper slopes of the ridges. One of the ridges extends from the north west corner of LW51 back to a large cutting made for the RMS M1 Motorway (formerly F3 Freeway) and has several shotcrete lined batter slopes and benches. A 5 m high embankment extends for 2 km from the cutting towards the north east, and includes the Wakefield Road carriageway.

There are approximately 5.4 ha and 2.9 ha of steep slopes with gradients that range from 18^{o} to 35^{o} above LWs 51 and 52 respectively. There are no cliffs, cliff terraces, minor cliffs or rock face features above LWs 51 and 52 as defined in the Project Approval Conditions (dated 25th January, 2012) for the current project area.

Five ephemeral creeks drain the majority of the proposed project area towards the south east and south west and include first order tributaries associated with Ryhope and Palmers Creeks. The majority of the creek beds are broad to incised with alluvial sediments that are actively eroding and transported and deposited downstream during storm events. The upper reaches of the creeks have sandstone and conglomerate exposures along the predominately dry channel bases.

Two Aboriginal heritage axe grinding groove sites of 'extremely high' cultural significance exist in adjacent valleys to the east of the proposed LW52. Table 1 in Schedule 3 of the current Project Approval Conditions requires that 'negligible' impact occurs to these features. The Project Approval Conditions for the current mining area also requires the following performance measures be met for the environment and built features:

- Palmers Creek (and alluvium) - 'negligible environmental consequences' and 'no connective cracking between the surface and the mine'.

- M1 Motorway, Services Easement (Caltex/Jemena Petroleum and natural gas pipelines, Nextgen/Optus/Telstra Fibre Optic Cables), Telstra Communications Tower, Transgrid 330kV Transmission Towers - 'always safe' with 'no loss of serviceability' and damage or losses 'fully compensated' or 'repaired'.

- Tracks and fences - 'serviceability should be maintained' and damage or losses 'fully compensated' or 'repaired'.

Other project area expectations include safe setback distances for the proposed panels from Newstan Colliery's mine workings and 'negligible additional' public safety risk.

The multiple-longwall panel subsidence predictions presented in this study have been based on several empirical models including overburden with massive sandstone and conglomerate strata and chain pillar subsidence behaviour. The models have been developed at WWC and applied successfully at other mines in the Newcastle Coalfield.

The potential worst-case impacts on surface and subsurface features have been assessed based on the predicted subsidence effects and previous experience gained from the WWC Northern and Western Domain longwalls.

The subsidence effect predictions are summarised below for LWs 51 and 52:

(i) Final Mean to U95%CL panel subsidence will range from 2.41 m to 2.61 m (57% to 58% of mining height).

(ii) Chain pillar subsidence after mining is estimated to range from 0.12 m to 0.15 m. The pillars will be 30 m wide and 97 m long generally. The subsidence will be due to compression of sandstone / siltstone / coal beds above and below the pillars and the pillars themselves. Some load will also be transferred to the goaf if pillars start to yield after mining is completed.

(iii) Mean to U95%CL tilts are estimated to range from 48 to 97 mm/m.

(iv) Mean to U95%CL concave curvatures are expected to range from 1.33 to 5.41 km^{-1} (or radii of 0.75 km to 0.18 km).

(v) Mean to U95%CL convex curvatures are expected to range from 1.05 to 3.77 km^{-1} (or radii of 0.95 km to 0.27 km).

(vi) The maximum tensile strains are predicted to range from 11 mm/m to 50 mm/m for continuous to discontinuous overburden behaviour.

(vii) The maximum compressive strains are predicted to range from 13 mm/m to 61 mm/m for continuous to discontinuous overburden behaviour.

Subsidence effect contours of principal tilt and horizontal strain have been prepared for surface and sub-surface impact assessment of the natural, archaeological and man-made features. The results of the subsidence prediction study indicate the following worst-case impacts and remediation strategies will be required for the natural and man-made features within the proposed project area:

General Surface Impacts:

- Based on a review of mining impacts above LWs 27 to 44 and the predicted range of transverse tensile strains of 11 to 25 mm/m for the proposed longwalls, surface cracks of between 110 mm and 250 mm wide are likely to occur within the limits of mining and in areas with moderately undulating terrain (i.e. slopes < 18^o).

- Cracks up to 833 mm wide are predicted near ridge crests due to rigid body rotation of a steep slope (i.e. > 26.5^o) by ~ 1 m. Similar size 'scarps' or vertical block movements (VBMs) could also develop as a result of subsiding a steep slope by the same order of magnitude.

- It is noted that cracking above Newstan LWs to the south near crests of steep slopes have ranged from 50 mm to 1400 mm where cover depths of 140 m exist. It is therefore possible that cracks of this order of magnitude could also develop along the slope crests above 51 and 52.

- Crack repairs should be considered as a public safety and erosion control management process.

Watercourses:

- An increase or decrease of surface gradients of up to 5^o (or 9%) will occur along ephemeral creeks and gullies that exist above the proposed longwall panels. A commensurate increase in erosion and sedimentation is expected to occur along creek beds after several storm events or until a new equilibrium is reached.

- Minor, localised, sub-surface flow re-routing could occur along creek beds due to the predicted surface cracking along exposed rock bar areas and re-surface downstream of the affected areas.

- It is expected that the high level sediment bed load that passes along the creeks during storm events is likely to infill surface cracking naturally.

- Repairs to some of the wider and deeper cracks along watercourses may be required where cracks are unable to infill through natural sedimentation processes. Some remediation of dry creek beds may therefore be necessary and should be done in consultation with stakeholders and government agencies.

Steep Slopes:

- The steep slopes above LW 51 and 52 will be tilted and cracked by subsidence of 2.44 m to 2.61 m respectively. The slopes above LW51 are likely to be increased towards the west by an average of 70 mm/m (4^o). The slopes above 52 will be tilted towards the east by 70 mm/m (4^o) on average.

- *En-masse* slip of hills or ridges on weakened bedded partings in thinly bedded siltstones / shale due to the predicted tilts is considered unlikely, provided cracking on steep slopes are repaired with the appropriate environmentally approved materials. It has also been assessed that there is no evidence that the steep slopes have been affected by previous instability or mine subsidence movements due to Newstan Mine longwalls to the south.

- Local instability and erosion could occur on the steep slopes due to mine subsidence deformation such as shear scarps and down slope cracking.

- Sealing of cracks on steep slopes will require the use of erosion resistant materials such as low strength sand-cement grout.

- It is noted that there have been several vertical block movement (VBM) events on the steep slopes above LWs 40 to 41 due to geological structure interactions, with displacements of between 0.5 m and 4 m (refer to **DgS, 2012**). It is considered that this type of impact requires the presence of persistent, sub-parallel geological structure with opposing hades beneath an unconfined ridge crest or spur. The zone between the structure will also probably be highly weathered and disturbed and therefore weaker than the surrounding rock mass.

  Underground and surface mapping work has not detected any significant structure of concern in the proposed project area, however if present, differential subsidence is unlikely to generate VBMs > 1 m deep based on the features observed on similar terrain to the north.

- There is a very low likelihood that rock fall rollout will occur from steep slope outcrops < 1.5 m high. It is considered that rock roll out is most likely to occur from the steep slopes above the starting end of LW51 and could impact the access track below.

  Any potential for roll-out occurrences represents a potential risk to the public and mining personnel. Appropriate management measures would be to provide appropriate warning

signage, removal of loose boulders from above the access tracks, repairing cracks promptly and controlling access to the area during mine subsidence development.

- The areal impact to the steep slopes due to the mining layout proposed is likely to be < 7% in regards to the current Project Approval Conditions.

- Further details on slope stability risks and their management are provided in **DP, 2013**.

Sub-Surface Impacts:

- Worst-case continuous fracture heights (A-Zone cracking) are predicted to range from 65 m to 116 m for cover depths between 80 m and 140 m and mining heights from 3.6 m to 4.5 m respectively.

- The Constrained Zone (B-Zone) thickness above the A-Zone cracks is estimated to range between 12 m and 44 m for the proposed mining geometries. The lowest value in the range is for the down slope side of LW51, where cover depth is 90 m above the panel goaf and 80 m above the chain pillars. It is recommended that the mining height be reduced to 3.8 m and 3.6 m below these areas to minimise connective cracking potential.

- Surface Cracking Zone (D-Zone) depths are typically < 15 m and estimated to range between 10 m and 12 m along the downslope side of the panels and 15 m to 20 m along the crests of steep slopes or below the base of subsided valleys. An average surface cracking depth of 12 m is considered reasonable above the panel goaf where the surface terrain is mildly undulated.

- It is assessed that decreasing the mining height to 3.6 m at LW51 tailgate, where the 80 m cover depth contour exists, and to 3.8 m below the 90 m cover depth contour, will make it 'unlikely' for the Continuous Fracture Zone (A-Zone) to connect with the Surface Cracking Zone.

- The presence of significant geological structure should also be assessed with regards to potential mine workings interaction with surface water courses and management strategies prepared to minimise impact. No significant faulting has been identified in adjacent first workings development or from exploration drilling which could cause higher than predicted cracking.

Aboriginal Heritage:

- The two axe grinding grooves sites (Palmers Creek No.s 38-4-1279 and 38-4-1007) of 'extremely high' cultural significance are located outside the angle of draw to LW52. The potential for cracking these sites is assessed to be 'very low' or < 5% probability, due to both valley closure and far-field displacement mechanisms.

- A scarred tree (Palmers Creek ST1) is located 16.5 m to the east of LW52 and has a 'low' to 'very low' probability of being impacted by mine subsidence cracking. The assessment

has been based on the probability that a tree with a diameter of 0.7 m in the potential crack development zone (which is likely to extend for 26 m outside the limits of the panel limits) will be impacted by cracking that may develop at a spacing of 10 m to 15 m due to predicted tensile strains of 2.5 mm/m.

- Two artefact sites (No. 38-4-1580 and Palmers Creek IF5) are situated directly above the proposed LW52. It is unlikely that the sites will be impacted by subsidence cracking or erosion.

Man Made Development Impacts:

- The unsealed gravel roads are likely to be subsided by up to 2.6 m. Cracking from 100 mm to 250 mm wide and/or shearing and uplift up to 300 mm across the roads are expected to occur where the tensile and compressive strain zones develop above each longwall panel.

- It is estimated that approximately 30 m to 50 m of the access roads or tracks above each longwall may require repairs to tensile cracking or compressive shear failures after mining of each panel is completed.

- The M1 Motorway pavements are all located outside the angle of draw to the nearest panel ends or corners and unlikely to be affected or impacted by subsidence due to LWs 51 and 52.

- Cracking or damage to the cuttings and embankments is considered very unlikely due to the proposed setback distance of 0.75H from the longwall panel ends and 0.5H from the panel corners. Early warning monitoring and impact management strategies may be required during the last 300 m of longwall retreat.

- The predicted far-field displacements at the crests of cuttings and toes of the embankments range from 2 mm and 43 mm, with principal tensile strains of 0.0 to 0.7 mm/m.

- Wakefield Road and the associated fill embankment are unlikely to be subsided with only minor far-field effects of 4 to 28 mm of horizontal displacement and 0.0 to 0.4 mm/m of tensile strain.

- Transgrid transmission towers are over 500 m away to the south of the proposed panels and located above the already extracted Newstan Colliery longwalls. The towers already have cruciform footings and have been subsided by 1.5 m to 1.8 m. Further impact is therefore unlikely.

- A Telstra communications tower (CT3) is 485 m or 4.4H from the finishing position of LW51 and will be outside the limits of subsidence and far-field effect.

- The services easement with buried Caltex/Jemena Pipelines and Tesltra/Optus/Nextgen fibre optic cables are also unlikely to be affected by the proposed longwall panels, which will be >400 m or >4H to the south east.

First Workings Pillar Stability:

The proposed first workings pillar dimensions beneath the M1 Motorway have been assessed for long-term stability in a separate report. It is assessed in **DgS, 2013d** that the pillars will have an FoS > 2.11 (< 1 in 1 million failure probability) and likely to have adequate load sharing capacity in the event of a pillar going into yield. The potential for measureable subsidence development beneath the M1 Motorway in the long-term is unlikely.

The above items will require further discussion with stakeholders to enable an effective Extraction Plan (EP) to be developed for LWs 51 and 52. A suggested program for monitoring subsidence, tilt and strain at the relevant locations has been provided for the purpose of implementing and reviewing the EP.

Table of Contents

Glossary of Terms

1.0 Introduction 1

2.0 Scope of Study 2

3.0 Available Information 3

4.0 Mining Geometry 4

5.0 Current Land Use 5

6.0 Surface Features 6

6.1 General 6

6.2 Steep Slopes 7

6.3 Ephemeral Creeks, Tributaries and Alluvium 9

6.4 Aboriginal Archaeological Sites 9

6.4.1 Axe Grinding Grooves 9

6.4.2 Scarred Tree Site 10

6.5 RMS M1 Motorway 10

6.5.1 Carriageways 11

6.5.2 Motorway Cutting No. 2 11

6.5.3 Motorway Cutting Design Details 24

6.5.4 Motorway Embankment No 1 24

6.5.5 Motorway Embankment No. 2 and 2a 24

6.5.6 Motorway Embankment Design Details 25

6.6 Wakefield Road 26

6.7 LMCC Land (Undeveloped) 26

7.0 Sub-Surface Conditions 29

7.1 Geological Setting 29

7.2 Overburden 29

7.3 Immediate Mine Workings Conditions 30

7.4 Joints 30

7.5 Bedding 31

7.6 Regional Structure 31

7.7 Groundwater 31

7.8 Horizontal Stress Regime 31
8.0 Description of Subsidence Development Mechanism 32
9.0 Subsidence Impact Parameter Profile and Contour Prediction Methodology 34
9.1 Model Background 34
9.2 Multiple-Panel Subsidence Impact Profile Prediction 35
9.3 Validation of Models 37
9.3.1 Northern Domain Subsidence Prediction and Impact Review Summary 38
9.3.2 Western Domain Subsidence Prediction and Impact Review Summary 39
10.0 Results of Longwall Panel Subsidence Assessment 41
10.1 General 41
10.2 Geological Model and Subsidence Reduction Potential of Massive Units 41
10.3 Predicted Single Panel Subsidence 42
10.4 Predicted Subsidence Above Chain Pillars 43
10.4.1 Empirical Model Development 43
10.4.2 Empirical Model Outcomes 44
10.5 Goaf Edge Subsidence Prediction 45
10.6 Multiple Panel Subsidence Prediction Results 45
10.7 Angle of Draw Prediction 47
10.8 Inflexion Point and Peak Strain Locations 48
10.10 Subsidence Profile Prediction Results 48
11.0 Prediction of Subsidence Impact Parameter Contours 49
11.1 Calibration of the SDPS® Model 49
11.2 Predicted Subsidence and Associated Impact Parameter Contours 50
12.0 Subsidence Impact Assessment and Management Strategies 51
12.1 General 51
12.2 Surface Cracking 53
12.2.1 Potential Impacts 53
12.2.2 General Impact Management Strategies 55
12.2.3 Impact Management Strategies on Ridges and Steep Slopes 56
12.2.4 Impact Management Strategies in Creeks and Watercourses 56
12.3 Sub-Surface Cracking 56
12.3.1 Sub-Surface Fracturing Zones 56

12.3.2 Impact on Rock Mass Permeability 58
12.3.3 Prediction Model 58
12.3.4 Predicted Sub-surface Fracture Zones for LWs 51 and 52 59
12.3.5 Discussion of Prediction Model Uncertainties 61
12.3.6 Impact Management Strategies 62
12.5 Slope Stability 62
12.5.1 Potential Impacts 62
12.5.2 General Stability 62
12.5.3 Shallow Soil Cover Instability 64
12.5.4 Local Instability and Erosion 66
12.7 Valley Closure and Uplift 66
12.7.1 Predictions and Potential Impacts 66
12.7.2 Impact Management Strategy 68
12.9 Aboriginal Archaeological Sites 69
12.9.1 Impact Potential Criteria 69
12.9.2 Potential Impacts to Grinding Groove Sites 69
12.9.3 Potential Impacts to Scarred Tree 70
12.9.4 Potential Impacts to Artefact Sites 70
12.9.5 Impact Management Strategies 71
12.10 Ryhope Lots (Undeveloped) 71
12.10.1 Potential Impacts 71
12.10.2 Impact Management Strategies 72
12.12 Access Roads 72
12.12.1 Potential Impacts 72
12.12.2 Impact Management Strategies 73
12.13 Wakefield Road 73
12.13.1 Potential Impacts 73
12.13.2 Impact Management Strategies 73
12.14 Far-Field Horizontal Displacements 74
12.14.1 Background to Prediction Model Development 74
12.14.2 Numerical Modelling 74
12.14.3 Potential Far Field Effects and Impacts at the M1 Motorway and Infrastructure 75

12.14.4 Potential Far Field Effects and Impacts at Buildings, Telstra Tower and Services Easement 77

12.14.5 Far-Field Displacement Impact Management Strategies 77

13.0 Suggested Monitoring Program 78

13.1 Surface Monitoring 78

13.2 Sub-surface Monitoring 79

14.0 Conclusions 80

15.0 References 81

Figures 1 to 30

Appendix A - Extract from ACARP, 2003 and SDPS User Manual

GLOSSARY OF TERMS

Angle of Draw	The angle (normally no greater than 26.5^{o} from the sides or ends of an extracted longwall block) from the vertical of the line drawn between the limits of extraction at seam level to the 20 mm subsidence contour at the surface. The 20 mm subsidence contour is an industry defined limit and represents the practical measurable limit of subsidence.
Chain Pillar	The pillar of coal left between adjacent longwall panels. This forms a barrier that allows the goaf to be sealed off and facilitates tailgate roof stability.
Compressive Strain	A decrease in the distance between two points on the surface. Compressive strains may cause shear cracking or steps at the surface if > 3 mm/m and are usually associated with concave curvatures near the middle of the panels.
Confidence Limits	A term used to define the level of confidence in a predicted subsidence impact parameter and based on a database of previously measured values above geometrically similar mining layouts.
Cover Depth	The depth from the surface to the mine workings.
Critical Longwall Panels	Longwall panels that are almost as deep (H) as they are wide (W) (ie 0.6 <W/H < 1.4) and is the point where complete failure of the overburden starts to occur and mid-panel subsidence is likely to increase if the panel widths are increased.
Curvature	The rate of change of tilt between three points (A, B and C), measured at set distances apart (usually 10 m). The curvature is plotted at the middle point or point B and is usually concave in the middle of the panel and convex near the panel edges. i.e. curvature = (tilt between points A and B - tilt between points B and C)/(average distance between points A to B and B to C) and usually expressed in 1/km. Radius of curvature is the reciprocal of the curvature is usually measured in km (i.e. radius = 1/curvature). The curvature is a measure of surface 'bending' and is generally associated with cracking.
CWC Values	The Credible Worst-Case (CWC) prediction for the predicted impact Parameter and normally based on the Upper 95% Confidence Limit line determined from measured data and the line of 'best fit' used to

	calculate the mean value. The CWC values for the tilt, curvature and strain are typically 1.5, 2.5 and 3 times the mean values respectively.
Development Height	The height at which the first workings (i.e. the main headings and gateroads) are driven; usually equal to or less than the extraction height on the longwall face.
Extraction Height	The height at which the seam is mined or extracted across a longwall face by the longwall shearer.
Factor of Safety	The ratio between the strength of a structure divided by the load applied to the structure. Commonly used to design underground coal mine pillars.
Far-Field Displacement	Horizontal displacement outside of the angle of draw, associated with movement are due to horizontal stress relief above an extracted panel of coal. The strains due to these movements are usually < 0.5 mm/m and do not cause damage directly. Such displacements have been associated with differential movement between bridge abutments and dam walls in the Southern Coalfield, but generally have not caused significant damage.
First Workings	The tunnels or roadways driven by a continuous mining machine to provide access to the longwall panels in a mine (i.e. main headings and gate roads). The roof of the roadways is generally supported by high strength steel rock bolts encapsulated in chemical resin. Subsidence above first workings pillars and roadways is generally < 20 mm.
Gate Roads	The tunnels or roadways driven down both sides of the longwall block (usually in pairs), to provide airways and access for men, materials, and the coal conveyor to the longwall face. The conveyor side of the block is called the 'maingate' and dust laden air and coal seam gases are exhausted on the opposite side (called the 'tailgate').
Goaf	The extracted area that the immediate roof or overburden collapses into, following the extraction of the coal. The overburden above the ‘goaf’ sags, resulting in a subsidence 'trough' at the surface.
Greenfields Site	Refers to a mining area where no local data of ground response to underground mining exists. Subsidence predictions must therefore be based on experience gained from mining in other areas with similar geological conditions and appropriate engineering models.
Horizontal Displacement	Horizontal displacement of a point after subsidence has occurred above an underground mining area within the angle of draw. It can be

	predicted by multiplying the tilt by a factor derived for the near surface lithology at a site (e.g. a factor of around 10 is normally applied in the Newcastle Coalfield).
Inbye	An underground coal mining term used to describe the relative position of some feature or location in the mine that is closer to the coal face than the reference location.
Inflexion Point	The point above a subsided area where tensile strain changes to compressive strain along the deflected surface. It is also the point where maximum panel tilt occurs above an extracted longwall panel. It is typically located between 0.25 and 0.4 x cover depth from the panel sides.
Longitudinal Subsidence Profile	Subsidence measured (or predicted) along a longwall panel or centre line.
Longwall	The method of extracting a wide block of coal using a coal shearer and armoured face conveyor. Hydraulic shields provide roof support across the face and protect the shearer and mine workers. The longwall equipment is installed along the full width of the block in an 8 to 10 m wide installation road at the start of the block before retreating back to the finishing end of the block. The shields are progressively advanced across the full width of the face, as shearing continues in a sequence of backwards and forwards motions across the face. Depending on the geological conditions and longwall performance, the longwall retreats at a typical rate of about 50 to 100 m/week.
Maingate	Refers to the tunnels or roadways down the side of a longwall block which provides access for mine operations personnel, power, materials and clean air to the longwall face. It is usually located on the side of the longwall panel adjacent to unmined panels or solid coal.
Mean Values	The average value of a given impact parameter value (i.e. of subsidence, tilt and strain) predicted using a line of 'best fit' through a set of measured data points against key independent variables (e.g. panel width, cover depth, extraction height). The mean values are typically two-thirds to half of the credible worst-case values.
Mining Height	Refers to the height or thickness of coal extracted along a longwall face.

Outbye	An underground coal mining term used to describe the relative position of some feature or location in the mine that is closer to the mine entry point than the reference location.
Outlier	A data point well outside the rest of the observations, representing an anomaly (e.g. a measurement related to a structural discontinuity or fault in the overburden that causes a compressive strain concentration at the surface, in an otherwise tensile strain field).
Panel Width	The width of an extracted area between chain pillars.
Primary Subsidence	The subsidence which occurs that is directly caused by longwall face retreat and the sagging of overburden or compression of chain pillars. Primary subsidence usually continues for three or four longwall panels at an exponential rate of decay after each longwall passes a given site.
Residual Subsidence	The last 5% to 10% of subsidence that occurs after primary subsidence is complete. It is not directly linked to the retreating longwall face and is associated with the re-consolidation or re-compaction of goaf and overburden. It is unlikely that any further impact to structures will occur due to residual subsidence.
Strain	The change in horizontal distance between two points at the surface after mining, divided by the pre-mining distance between the points. i.e. Strain = ((post-mining distance between A and B) - (pre-mining distance between A and B))/(pre-mining distance between A and B) and is usually expressed in mm/m. Strain can be estimated by multiplying the curvature by a factor derived for the near surface lithology at a site (e.g. a factor of around 10 is normally applied in the Newcastle Coalfield). However, discontinuous overburden behaviour can result in local strain and curvature concentrations at cracks, making accurate predictions difficult. A rule of thumb is normally applied to allow for these effects, which is to increase smooth profile strains (and curvatures) by 2 to 3 times. The increase in strain also usually develops at locations with shallow rock profiles, as opposed to areas with deep soil alluvial soil profiles.

Sub-critical Longwall Panels	Longwall panels that are deeper than they are wide (W/H < 0.7) and cause lower magnitudes of subsidence than shallower panels due to natural arching of the overburden across the extracted coal seam.
Subsidence	The difference between the pre-mining surface level and the post-mining surface level at a point, after it settles above an underground mining area.
Subsidence Control	Reducing the impact of subsidence on a feature by modifying the mining layout and set back distances from the feature (normally applied to sensitive natural features that can't be protected by mitigation or amelioration works).
Subsidence Impact	The effect that subsidence has on natural or man-made surface and sub-surface features above a mining area.
Subsidence Management Plan Plan	Refers to the approval process for managing mine subsidence impacts, in accordance with the Department of Resources & Energy (DRE)Guidelines. The mine must prepare a Subsidence Management (SMP) to the satisfaction of the Director-General, before the commencement of operations that will potentially lead to subsidence of the land surface.
Subsidence Mitigation/ Amelioration	Modifying or reducing the impact of subsidence on a feature, so that the impact is within safe, serviceable, and repairable limits (normally applied to moderately sensitive man-made features that can tolerate a certain amount of subsidence).
Subsidence Reduction Potential	Refers to the potential reduction in subsidence due to massive strata in the overburden being able to either 'bridge' across an extracted 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.
Super-Critical Longwall Panels	Longwall panels that are not as deep (H) as they are wide (W) (ie W/H > 1.4) and will cause complete failure of the overburden and maximum panel subsidence that is proportional to the mining height (i.e 0.58T) occurs.
Tailgate	Refers to the tunnels or roadways down the side of a longwall block which provides a ventilation pathway for gassy or dusty air away from the longwall face. It is usually located on the side of the longwall panel adjacent to previously extracted panels or goaf.
Tilt	The rate of change of subsidence between two points (A and B), measured at set distances apart (usually 10 m). Tilt is plotted at the

	mid-point between the points and is a measure of the amount of differential subsidence. i.e. Tilt = (subsidence at point A - subsidence at point B)/(distance between the points) and is usually expressed in mm/m.
Tensile Strain	An increase in the distance between two points on the surface. Tensile strains are likely to cause cracking at the surface if > 2 mm/m and are usually associated with convex curvatures near the sides (or ends) of the panels. Tensile strain also usually develops above chain pillars.
Transverse Subsidence Profile	Subsidence measured (or predicted) across a longwall panel or cross line.
Valley Closure	The inward (or outward) movement of valley ridge crests due to subsidence trough deformations or changes to horizontal stress fields associated with longwall mining. Measured movements have ranged between 10 mm and 400 mm in the Southern NSW Coalfields and are usually visually imperceptible in the Newcastle Coalfield.
Valley Uplift	The phenomenon of upward movements along the valley floors due to **Valley Closure** and buckling of sedimentary rock units. Measured movements have ranged between 10 mm and 400 mm in the Southern NSW Coalfields and may cause surface cracking in exposed bedrock on the floor of the valley (or gorge).

1.0 Introduction

This report presents mine subsidence predictions for the proposed Longwalls 51 to 52 in the West Borehole Seam at West Wallsend Colliery, Killingworth. The proposed panels will be located to the west of the approved longwalls 44 to 46 in the Southern Domain. The mining layout is considered conceptual at this stage.

The scope of work for the project requires the following items to be included in a report for inclusion with a Section 75W application to the NSW Department of Planning & Infrastructure (DP&I):

(i) Subsidence effect predictions for the longwall panels.

(ii) A general impact assessment of natural and man-made surface and sub-surface features within the zone of potential subsidence effects.

This study has been based on information provided by West Wallsend Colliery and two empirically based mine subsidence prediction models developed for the Newcastle and US Coalfields (refer to **ACARP, 2003** and **SDPS, 2007**).

Several risk assessment and planning meetings to-date have been held between the stakeholders so as to identify and minimise or practically avoid impacts deemed to be 'high' risk. As a result of this process, the longwall panels have been located at conservative angle of draw distances from the M1 Motorway (formerly F3 Freeway), two culturally sensitive aboriginal archaeological sites and alluvium along Palmers Creek. The panels have also been located to minimise the potential for connective cracking from seam to surface based on insitu data measurements above LWs 39 to 41.

Other features of note within the likely area of subsidence effects include a Scarred Tree of 'moderate' cultural significance, steep slopes, ephemeral drainage gullies, unsealed access roads and undeveloped bushland owned by LMCC.

2.0 Scope of Study

The work program included the following activities:

(i) Surface inspections of the panels to identify and characterise existing surface features.

(ii) Development of a geotechnical model for the project area.

(iii) Prediction of subsidence effects and profiles using **ACARP, 2003** and completion of model validation/calibration studies using local and regional mine subsidence data and geological information.

(iv) Calibration of the **SDPS®** model to the subsidence profiles generated by the **ACARP, 2003** model.

(v) Generation of subsidence, tilt, strain and horizontal displacement contours for the proposed mining layout.

(vi) Assessment of the stability of first workings pillars below the M1 Motorway based on **ACARP, 1998b**.

(vii) Assessment of the potential impacts of the predicted subsidence effects (including far-field and valley closure movements) on the existing surface and subsurface features. The level of uncertainty in the predictions has also been discussed to allow effective risk management assessments to be completed.

(viii) Estimation of sub-surface fracturing heights above the panels for the assessment of the potential of hydraulic connection occurring to surface watercourses and sub-surface aquifers.

(ix) Recommendations for subsidence effect and impact monitoring and options for managing impacts to acceptable levels.

3.0 Available Information

The following information for the project area was provided by West Wallsend Colliery to prepare this report:

- The proposed longwall panel layout.
- Cover depth contours to the West Borehole (WBH) Seam and seam thickness isopachs.
- Surface to seam borehole logs.
- WBH seam geological structure (fault and dyke) locations.
- Surface topographic levels and existing drainage regime locations.
- Locations of surface developments and infrastructure.
- Surface photography.

A plan of the proposed longwalls 51 to 52 with surface features, geological structures, surface levels, cover depth contours and seam thickness isopachs are presented in **Figures 1** to **4** respectively.

A 3-D Terrain Map of the project area has been generated from Aerial Laser Scanning (Lidar) data using Surfer 11® software and is presented in **Figure 5**.

4.0 Mining Geometry

The following mine workings geometry has been assumed in this assessment:

(i) The longwall panels 51 & 52 are located at a depth of approximately 80 m to 140 m and will be 178.8 m and 206.8 m wide respectively (final void width).

(ii) The longwall panels will be mined from the southern ends and retreat towards north.

(iii) The longwall panels will have average face extraction heights ranging from 4.2 m to 4.5 m and ramped back down to a height of 3.6 m at LW51s tailgate beneath the 80 m cover depth contour.

(iv) Chain pillars will be formed between the panels and will be nominally 30 m wide by 97 m long (solid). The roadways will be nominally 5.5 m wide and 3.5 m high.

(v) The barrier pillar between LW52 and LW44 will be 168 m wide with cover depths ranging from 120 m to 140 m.

The panel W/H ratio will range from 1.4 to 2.0, indicating supercritical subsidence behaviour (see glossary for more term definition details). The chain pillars will have w/h ratios of 8.6 and expected to 'strain harden' and yield slowly if overloaded.

5.0 Current Land Use

The surface land of the mining area is mainly Sugarloaf State Conservation Area (SSCA) (formerly State Forest) and is now managed by National Parks and Wildlife Service (NPWS). A portion of land above LW51 is owned by LMCC and consists of approximately 1.5 ha of undeveloped bush land.

The majority of the project area is mainly undeveloped native woodland that has been used as a timber logging resource in the past. The land has several unsealed access roads, tracks and fire trails. The SSCA is currently used for recreational activities such as bushwalking, mountain bike and trail bike riding.

The M1 Motorway and associated infrastructure (i.e. bridge overpasses, cuttings, fill embankments and drainage structures) exist to the north west of the proposed mining area. A utilities easement with high pressure gas and petroleum pipelines and optic fibre cables is adjacent to the northern side of the motorway and is unlikely to be affected by the proposed panels.

6.0 Surface Features

6.1 General

Topographic relief above Longwalls 51 and 52 ranges from 30 m to 105 m AHD. The terrain is moderately undulated with a broad-crested ridge extending across the panels from the north west to the south east. The site has gentle to steep slopes ranging from 5^{o} to 35^{o}; see **Figure 2**.

The headwaters of several ephemeral creeks and tributaries / gullies drain the site towards Diega Creek to the south-east and Ryhope and Palmers Creek to the south and south-west.

Vegetation in the project area consists of dense stands of dry schlerophyll forest with shrubs, ferns and grasses. Small riparian zones exist along the water courses and have sparse to dense stands of melaleucas.

The man-made developments and archaeological features of significance within the project area are located as shown in **Figure 1** and include:

- Aboriginal cultural heritage features that are present in the project area include two axe grinding groove sites (No.s 38-4-1279 and 38-4-1007) of 'extremely high' cultural significance, a scarred tree (Palmers Creek ST1) of 'moderate' cultural significance, and two artefact sites (No. 38-4-1580 and Palmers Creek IF5).

  The axe grinding groove sites are located 67 m and 116 m from the rib side of LW52 and have been inspected, catalogued and registered with OEH in liaison with the registered Aboriginal stakeholders. The scarred tree is located 16.5 m to the east of LW52 and the artefact sites are situated directly above the proposed LW52.

- RMS M1 Motorway and associated cuttings (Cutting No. 2), embankments (Fill No.s 1 and 2) and drainage infrastructure are located 95 m and 137 m to the north of the proposed Longwalls 51 and 52. Fill No. 1 and Cutting No. 2 are 80 m and 63 m from the corners of LWs 51 and 52 respectively.

- LMCC's Wakefield Road is located 130 m to 230 m north of LW 51 in Cutting No. 2 and 158 m to 296 m north of LW 52 on Fill Embankment No. 2.

- Telstra, Nextgen, Optus Optic Fibre Cables, Caltex Petroleum and Jemena Natural Gas Pipelines exist in a services easement along the northern side of the M1 Motorway. The easement is 412 to 527 m from the proposed finishing positions of LWs 51 and 52 and unlikely to be affected by their subsidence effects.

- A Telstra communications tower is located 485 m and 560 m to the south west of the proposed finishing positions of LW51 and LW52 respectively. The cover depth at the tower is 140 m and 110 m at the ends of the panels. It is very unlikely the tower will be affected by subsidence due to LWs 51 and 52.

- Transgrid transmission towers are located over 500 m away to the south of the proposed panels and located above the already extracted Newstan Colliery longwalls. The towers already have cruciform footings and have been subsided by 1.5 m to 1.8 m.

- Two rural residential lots are located 172 m and 321 m to the south and south west of the proposed starting position of LW52. The cover depth at the houses and panel ends is 100 m, giving effective angles of draw of 60° and 73° to the structures. There are several ancillary buildings (metal clad sheds) and a swimming pool also present on one of the sites.

Further details of the features that are likely to be affected by the proposed panels are provided in the following sections.

6.2 Steep Slopes

The proposed longwall panels 51 and 52 in the Southern Domain are overlain by approximately 8.3 ha of steep, rocky slopes with gradients ranging from 18° to 35° and shallow residual soil cover (< 1 m thick) - see **Photos 1** and **2**. The height of the slopes ranges from 30 m to 40 m above the valleys. The WBH Seam cover depth below the steep slopes ranges from about 100 m to 130 m.

The slopes have south eastern to western aspects with grey brown sandstone and conglomerate outcrops up to 1.5 m high at mid-slope. Fine to coarse grained, grey brown to yellow orange conglomerate and sandstone beds were also observed in cuttings along the fire trails and intermittent sections of incised drainage gullies.

The bedrock exposures have bedding dips of 3° to 5° towards the SW (195° dip direction) with persistent sub-vertical joint-sets that are parallel and perpendicular to the rock faces, striking SW, SE and N/S. The joints are generally open and widely spaced from 0.5 m to 5 m.

Photos 1 & 2 - Steep Slopes



6.3 Ephemeral Creeks, Tributaries and Alluvium

There are several broad first order, ephemeral drainage gullies within the proposed project area that have incised erosion channels and slope wash deposits. The gradients along the creek beds are typically <5^{o} with side slopes up to 15^{o}.

The gullies are covered with dense stands of mature to semi-mature eucalypts, melaleucas, ferns and shrubs. The cover depths to the proposed mine workings range from 110 m to 130 m beneath the gullies.

6.4 Aboriginal Archaeological Sites

A total of 4 Aboriginal heritage sites exist within the project area. The sites include:

- Two axe grinding grooves (Palmers Creek Site No.s 38-7-1279 and 38-4-1007) with 'extremely high' Aboriginal cultural significance.
- One scarred tree (Palmers Creek ST1) with 'extremely high' Aboriginal cultural significance; and
- One individual Isolated Find (Palmers Creek IF5) with 'extremely high' Aboriginal cultural significance.

The current project approval conditions require that the proposed mining activities will have negligible impact on the two axe grinding groove sites. The scarred tree and artefact sites have been identified in recent field surveys.

6.4.1 Axe Grinding Grooves

Site No. 38-4-1007 has a set of thirty four axe grinding grooves on the first order tributary of Palmers Creek, see **Photo 3**. The site is located within the watercourse on a sandstone outcrop that is approximately 5 to 10 m square.

Photo 3 - Axe Grinding Groove Site No. 38-4-1007



Site No. 38-4-1279 is smaller than Site No. 38-4-100727 and is also located in a similar rock bar along an ephemeral water course. To minimize the potential for subsidence impact to the groove sites, the existing longwall LW44 and the proposed LW52 have been positioned outside the angle of draw (to the 20 mm subsidence limit) from the heritage sites.

6.4.2 Scarred Tree Site

According to the AHIMS Register, the scarred tree (Palmers Creek ST1) is still standing. It has an oval shaped scar between 0.4 m and 2.5 m above its base. The tree has a diameter of 0.7 m and is located on the upper slopes of a steep slope where cover depth is approximately 130 m. The tree is currently in a fair condition with white ant and bushfire damage noted on the register.

6.5 RMS M1 Motorway

The RMS M1 Motorway is one of the most significant surface features traversing the colliery holding of West Wallsend Colliery; see **Photo 4**. The current project approval conditions require the motorway to "always remain safe and serviceable" and "must be fully repaired" in consultation with the stakeholder if mine subsidence impact occurs.

The mine layout has been developed to minimise subsidence impact on the M1 Motorway by aligning the main access roadways directly under limited sections of the motorway. The pillars of coal between the roadways have been designed to be long-term stable with negligible subsidence impacts. An additional protective barrier of coal has also been left between the longwalls and the main development headings to protect the headings pillars from additional abutment loads.

Photo 4 - The M1 Motorway's South-Bound Carriageway in Cutting 2



The motorway consists of separate north-bound and south-bound carriageways with two lanes each. The carriageways are 7.25 m wide and separated by a 22 m wide nature strip/open drainage reserve. The motorway passes through two cuttings (No.s 2 and 3) and across two earth-fill embankments (No.s 1 to 4) in the vicinity of the current project area. The cuttings are 10 m to 40 m deep and the fill embankments are about 5 to 10 m high. Details of the cuttings and embankments are presented in the following subs-sections.

6.5.1 Carriageways

The north bound and south bound carriageways are located 160 m to 360 m away from the proposed finishing positions of LWs 51 and 52. The cover depth along the carriageways range from 80 m to 130 m; see **Figure 3**. The main underground access headings pass underneath the carriageways at a cover depth of 100 m.

The carriageways are rigid pavements with a 230 mm thick continuously reinforced concrete (CRC) base and 150 mm thick lean-mix concrete (LMC) sub-base with integrally cast concrete shoulders. A 300 mm thick select fill material forms the sub-grade on the cutting floor, which was ripped to a depth of about 300 mm and re-compacted to RMS specifications. Concrete lined V-drains exist between the pavements and batters along both sides of the cuttings.

It is understood that the carriageways were required by the Mine Subsidence Board to be designed to tolerate surface deformations of up to 150 mm due to mine subsidence.

6.5.2 Motorway Cutting No. 2

Cutting No. 2 is a 330 m long, double-sided cutting and is located 95 m to the north of LW51 where the cover depth is 110 m. The cover depth at the cutting ranges from 90 m to 125 m on the eastern side; see **Figure 3**.

The cutting is approximately 25 m deep on the eastern batter and 40 m deep on the western batter. The distance between the cutting crests is 250 m. The cutting has four benches on the eastern batter that are 3 m to 8 m high and 2.5 to 16 m wide (see **Section 6.5.3** for design details).

Wakefield Road has been formed on the first bench of the eastern side of Cutting No. 2. The bench is located about 8 m above the M1 Motorway carriageway and 17 m below the crest of the cutting. Wakefield Road continues to the north on a 1 km earth fill embankment (Fill No. 2) and crosses LW 45.

The 17 m deep section of cutting above Wakefield Road is situated within medium to thickly bedded fine to medium grained sandstone, which is grey-brown in colour with honey-comb type weathering evident in the exposed rock; see **Photo 5**. The batter slopes in the cutting range from 40^{o} to 60^{o}.

Sections of the cutting between the top three benches has been shotcrete lined with PVC drainage tubes (of 20 mm in diameter) installed through the shotcrete on a 10 m grid spacing.

An inspection of the exposed rock slope behind the cutting indicates that the shotcrete lined section consists of extremely weathered siltstone and claystone (tuff) or a gravelly sandy clay.

The shotcrete has been applied to control long-term erosion damage to theses sections of the cutting. The shotcrete was in a good condition with minor hairline cracking (horizontal and vertical) due to shrinkage noted.

Photo 5 - Wakefield Road in Motorway Cutting No. 2



The southern side of the eastern cutting has exposed, distinctly to extremely weathered siltstone, sandstone and tuffaceous claystone. Heavy rill erosion has developed since the formation of this section of the cutting; see **Photo 6**.

Photo 6 - Motorway Cutting No. 2 (southern end) Erosion Damage above Wakefield Road



The surface to the east of the cutting crest rises at 10^o for 20 m and levels off along a broad ridge line with side slopes ranging from 15^o to 20^o towards the north and south. A cleared track extends along the ridge to the east for 120 m through dense vegetation.

6.5.3 Motorway Cutting Design Details

Based on reference to **Leventhal and Stone, 1995**, the cuttings were designed for the worst case scenarios of (i) rock wedge sliding on weak tuffaceous claystone beds (due to groundwater level increases of approximately 3 m above the toe of the embankment), and (ii) earthquake acceleration of 0.1g. For case (i), a design factor of safety (FoS) of 1.2 was adopted for lower bound peak material strengths with 1.5 assumed for average peak material strength conditions.

A minimum FoS of 1.0 was adopted for residual material strength conditions in case (i) and average peak material strength conditions for case (ii). The possible de-stabilizing effects of future mine subsidence impacts was noted in **Leventhal and Stone, 1995** but not formally included in the stability analysis.

6.5.4 Motorway Embankment No 1

The No.1 Fill is approximately 350 m long and is located across Ryhope Creek. The embankment forms the abutments and access ramps onto and off Palmers Road to the motorway; see **Figure 1**. The embankment is approximately 110 m wide at the base, 55 m wide at the top and 5 m high (see **Section 6.5.6** for design details).

The north eastern toe of the embankment is approximately 80 m from the corner of LW51 where the cover depth is 90 m. The cover depth ranges from 60 m to 80 m at the embankment; see **Figure 3**.

6.5.5 Motorway Embankment No. 2 and 2a

The No.2 Embankment is approximately 780 m long and located immediately to the north of Cutting 2, see **Figure 1** and **Photo 7**. The embankment is approximately 130 m wide at the base, 55 m wide at the top and 5 m high (see **Section 6.5.6** for design details). The cover depth at the embankment is about 100 m; see **Figure 3**.

The eastern toe of the embankment is approximately 137 m to 274 m north of the proposed finishing end of LW52 where the cover depth is 110 m.

Embankment 2a exists 115 m to the north east of Fill 2 and turns away from the motorway and forms the section of Wakefield Road which passes over LW45. The embankment is about 48 m wide at the base, 16 m wide at the top and 5 m high (see **Section 6.6** for further details on Wakefield Road).

Photo 7 - Embankment No. 2 and Wakefield Road



6.5.6 Motorway Embankment Design Details

The embankments are multi-zoned with a predominately low strength claystone core and granular select outer shell. Sandstone boulder rip-rap provide erosion protection to the batters; see **Photo 8**. The batters slope at about 26.5° (i.e. 2H:1V).

Photo 8 - Embankment No. 2 Sandstone Rip Rap on Batters



The embankments consist of engineered earth fill (i.e. compacted to 95% Standard Compaction in **AS3798**) with sandstone rip-rap boulders placed on the batters, refer to **Leventhal and Stone, 1995**.

The earth fill is a very low strength claystone 'core' with higher strength select sandstone 'shell' that was designed to meet stringent slope stability criteria (i.e. they have a minimum and average long term Factor of Safety of 1.2 and 1.5 respectively to allow for material shear strength variations).

The possible de-stabilizing effects of future mine subsidence impacts was noted in **Leventhal and Stone, 1995** but not formally included in the design analysis.

6.6 Wakefield Road

The road is a flexible gravel pavement with two-coat bitumen seal; see **Photo 7**. As previously mentioned, approximately 1 km of the road has been formed on Embankment No. 2 and 2a, with another 250 m in cut (Cutting No. 2) and 250 m on grade above LW46. The road appeared to be in good condition with no significant cracking or rutting.

The road surface is approximately 130 m to 230 m north of the proposed finishing end of LW51, where the cover depth is 115 m, and 158 m to 296 m north of the proposed finishing end of LW52, where the cover depth is 100 m, see **Figure 1**.

6.7 LMCC Land (Undeveloped)

Approximately 15 vacant lots are located within the area of potential subsidence effect above LW51. The lots are undeveloped and situated in bushland on south western facing slopes. Surface levels on the lots range from RL70 m to RL40 m (AHD) with gradients ranging from 10^{o} to 20^{o}.

7.0 Sub-Surface Conditions

7.1 Geological Setting

West Wallsend Colliery is situated within the western portion of the Newcastle Coalfield. The proposed longwalls are located within the WBH Seam (i.e. coalesced Nobbys, Dudley, Yard and Borehole Seams), which represents the geological base of the Newcastle Coal Measures (**Hawley and Bunton, 1995**).

Reference to the 1:100,000 Newcastle Coalfield Geology Sheet (**DMR, 1995**) the surface terrain in the panels are situated within the Narrabeen, Moon Island Beach and Boolaroo Sub-Groups of the Newcastle Coal Measures.

Sandstone and conglomerate of the Munmorah and Teralba Conglomerate Formations dominate the ridges within the project area. Tuffaceous claystone (Awaba Tuff), siltstone and coal seams (Fassifern Seam) generally underlie the near surface conglomerate units.

Relatively low-lying terrain with slope wash and alluvium filled gullies exist to the south, north and east of the proposed longwalls.

7.2 Overburden

The WBH Seam in the project area is overlain by several massive conglomerate and sandstone channel units that are summarised in **Table 1**.

Table 1 - Summary of Massive Sandstone/Conglomerate Units Above Longwalls 51 and 52

Massive Channel Unit No.	Sandstone/Conglomerate Channel Units*	Strata Unit Thickness Range (m)	Distance above Extraction Horizon, y (m)	Workings Cover Depth, H (m)	y/H
1	Victoria Tunnel	N/M	N/M	N/M	N/M
2	Fern Valley	20 - 45	10 - 20	80 - 140	0.07 - 0.15
3	Montrose	6 - 24	30 - 60	80 - 140	0.38 - 0.43
4	Lower and Upper Pilot	4 - 14	85 - 120	80 - 140	0.85 - 0.95
5	Teralba Conglomerate	N/M	N/M	N/M	N/M

* - The channels are named by WWC after the coal seam that they overly (except the Teralba Conglomerate, which immediately overlies the Great Northern Seam). N/M - Not measured or present.

The interpreted channel thicknesses above the longwalls have been determined from exploration boreholes located as shown in **Figure 6**. Interpreted long section plots are presented in **Figures 7a** and **7b**, with contours of the individual channel unit thicknesses and their distance above the workings shown in **Figures 8a,b** to **10a,b** for Channels 2 to 4 respectively.

The above information was used to assess the Subsidence Reduction Potential (SRP) and maximum sag or panel subsidence above the proposed longwalls (see **Section 9**) and estimate heights of subsurface fracturing (see **Section 10**).

7.3 Immediate Mine Workings Conditions

The thickness of the WBH Seam in the Western Domain ranges in thickness from 4.1 m to 4.4 m above LW51, and from 4.3 m to 4.6 m above LW52; see **Figure 4**.

WWC will drive 3.5 m high by 5.5 m wide development headings in the lower part of the WBH Seam, which consists of coalesced Borehole, Yard, Dudley and Nobbys Seams (in ascending order).

The immediate roof (i.e. the first 8 m above the gate road roof horizon) within the project area generally consists of low strength Nobbys Seam, Nobbys Tuff and shale with minor mudstone, Fern Valley coal, sandstone and siltstone (UCS ranges from 10 to 25 MPa with an average of 15 MPa).

The immediate mine roof is then overlain by moderate to high strength massive sandstone and conglomerate channels up to 45 m thick (UCS ranges from 30 to 60 MPa). The distance to the first channel above the mine roof will range between 10 m to 20 m.

The floor of the development roadways will comprise 0.3 m of moderate strength carbonaceous siltstone / mudstone and sandstone (UCS ranges from 30 to 40 MPa) with low slaking potential. High strength (UCS ranges from 50 to 60 MPa) Waratah Sandstone underlies the immediate floor strata.

Based on the UCS results, the Young's Modulus for the immediate roof and floor strata is estimated to range between 3 to 15 GPa. The Young's Modulus for coal is normally assumed to range from 2 to 4 GPa.

7.4 Joints

The joints noted in the borehole logs are generally planar, rough and clean with dip angles ranging from 20^o to 80^o. The joint spacing ranges between 0.1 and 3 m, with some crush zones and fault breccia noted. The main joint sets strike at SW (220^o to 240^o) and SE (130^o to 165^o) and generally define the low-level rock outcrops in the project area.

Three sub-vertical joint sets were measured in natural rock exposures and cuttings within the project area as follows:

Set 1: SE Strike, 70^o - 85^o dip, 200^o to 235^o dip direction
Set 2: SW Strike, 75^o - 85^o dip, 300^o dip direction
Set 3: S Strike, 75^o - 85^o dip, 270^o dip direction

The joints were moderately to widely spaced (0.5 m to 5 m) and their surface conditions ranged from open with clayey sand infill to closed, planar to wavy, smooth to rough.

7.5 Bedding

The coal seam dips at 2^{o} to 4^{o} towards the SE across the project area. Surface bedding dips towards the south-east at 2^{o} to 4^{o} along the eastern slopes and south-west along the western slopes (i.e. anticlinal ridge structure).

7.6 Regional Structure

Regional geological structure in the project area consists of minor to major normal faulting and igneous dyke intrusions. The structures are sub-vertical and strike at NNW:SSE; see **Figure 1**.

7.7 Groundwater

Groundwater inflows into the mine workings in the current project area have been low with typical or average conditions described as dry to damp by OCAL geologists. The source of the groundwater is most likely to be from the Nobbys Coal Unit, which means that it is unlikely to be percolating through the Nobbys Tuff horizon or affecting this potentially moisture sensitive unit.

A review of mine water discharges in June, 2013 indicated that they were lagging by ~10 months behind annual rainfall levels. This indicates that direct hydraulic connection to the mine workings has not occurred above longwalls in the current project area where the minimum cover depth was 95 m above LW39.

7.8 Horizontal Stress Regime

The horizontal stress can affect subsidence trough symmetry and far-field horizontal displacement direction.

In regards to longwalls 51 and 52, the major horizontal stress is likely to be parallel to the NW:SE ridge orientation, as the stress perpendicular to the ridge is likely to have been relieved due to loss of lateral confinement in the valleys.

Similar horizontal stress orientations have been mapped underground along MGs 41, 42 and 43.

8.0 Description of Subsidence Development Mechanism

After the extraction of a single longwall panel, the immediate mine roof usually collapses into the void left in the seam (i.e. the caving zone). The overlying strata or overburden then sags down onto the collapsed material, resulting in a subsidence trough developing at the surface. Further fracturing and bedding shear failures may also develop in the overburden above the caved zone, the extent and severity of the fracturing will depend upon the mine geometry and geology (see **Section 12** for further discussion on sub-surface fracturing).

The maximum subsidence usually occurs in the middle of the extracted panel and is dependent on the mining height, panel width, cover depth, overburden strata strength and stiffness, and bulking characteristics of the collapsed strata in the caving and fractured zones.

For the case of single seam mining in the Newcastle Coalfields, the maximum subsidence does not usually exceed 60% of the mining height, and may be lower than this value due to the spanning or bridging capability of the strata above the collapsed ground (or the goaf).

The Panel W/H ratio indicates whether a panel is likely to be *sub-critical, critical or supercritical*.

In the Australian coalfields, *sub-critical* behaviour generally occurs above the caving zone when the panel width (W) is <0.7 times the cover depth (H). Sub-critical are likely to have low levels of subsidence due to natural compressive or catenary arching within the overburden.

Critical panels generally have W/H > 0.7 and are too wide for a natural arch to develop, thus resulting in 'bending' action in the overburden strata. The magnitude of subsidence depends upon the span and characteristics of the overburden. If massive conglomerate or sandstone channel units exist in the strata then subsidence magnitudes may still remain relatively low if they continue to span above critical panel geometries.

Supercritical panels have W/H > 1.4 and unlikely to have spanning strata, with subsidence magnitudes controlled by the mining height and bulking characteristics of the goaf.

If relatively thick and strong massive strata exist in the *critical* width range, then Voussoir spanning behaviour can occur for panel W/H ratios of up to 0.9 in the Newcastle Coalfield, see **Figures 11a** and **11b**. The mid-panel subsidence for this scenario is usually significantly < 60% of the longwall extraction height and could range between 10% and 30%.

In the case of *super-critical* panels, mid-panel subsidence does not continue to increase significantly with increasing panel width. The mid-panel subsidence however, will be strongly influenced by the depth of cover and the magnitude of vertical stress acting on the collapsed roof material in the caved zone.

A summary of the range of overburden behaviours is shown in **Figures 11b** to **11d**.
The surface effect of extracting several adjacent longwall panels is dependent on the stiffness of the overburden and the chain pillars left between the panels. Usually, additional subsidence

occurs above a previously extracted panel and is caused primarily by the compression of the chain pillars and adjacent strata between the extracted longwall panels, see **Figure 12a**.

A longwall chain pillar undergoes the majority of life-cycle compression when subject to double abutment loading (i.e. the formation of goaf on either side, after two adjacent panels have been extracted). Surface survey data indicates that an extracted panel can affect the chain pillars between three or four previously extracted panels.

The stiffness of the overburden and chain pillar system will determine the extent of load transfer to the preceding chain pillars. The load on the chain pillars will be mitigated to some extent by load transfer to adjacent fallen roof material or goaf. The proportion of load that is transferred to the goaf from the overburden and chain pillar system is also reflected in the measured final subsidence profiles above a series of extracted panels.

After the development of subsidence above a longwall panel, the surface subsidence trough extends outside the limits of extraction for a distance assumed to be equal to half the depth of cover (or an angle of draw to the vertical of 26.5^{o}) in the Newcastle and QLD Coalfields, see **Figure 12b**.

The development of a subsidence trough also causes differential movements which may result in surface gradient changes (from tilt) and cracking (from curvature or bending and horizontal strain). The magnitude of tilt, curvature and strain can be estimated from the 'smooth' subsidence trough profile as shown in **Figure 12b**; however, all of these parameters can be strongly affected by discontinuous movements caused by the influence of surface topography and near surface geology.

The subsidence prediction models used in this study consider the abovementioned processes and will be further described in **Section 9**.

9.0 Subsidence Impact Parameter Profile and Contour Prediction Methodology

9.1 Model Background

Two empirically based prediction models (**ACARP, 2003** and **SDPS®**) have been used to generate subsidence impact parameter profiles and contours above the proposed longwall panels after mining is completed.

The subsidence predictions models used in this study are summarised below:

- **ACARP, 2003 -** An empirical model that was originally developed for predicting maximum single and multiple longwall panel subsidence, tilt, curvature and strain in the Newcastle Coalfield. The model database included measured subsidence parameters and overburden geology data which have been back analysed to predict the subsidence reduction potential (SRP) of massive lithology in terms of 'Low', 'Moderate' and 'High' SRP categories.

  The model database also includes chain pillar subsidence, inflexion point distance / subsidence, goaf edge subsidence and angle of draw prediction models, which allow subsidence profiles to be generated for any number of panels and a range of appropriate confidence limits. The Upper 95% Confidence Limit (U95%CL) has been adopted in this study for predictions of the Credible Worst-Case values.

  Sigmaplot® cubic-spline software is then used to generate the subsidence, tilt, horizontal displacement and strain profiles above the panels from the **ACARP, 2003** output.

  The **ACARP, 2003** model has been updated by DgS recently to allow the original model to be applied to other Australian Coalfields (see further below and **Appendix A** for details).

- **SDPS® -** A US developed (Virginia Polytechnical Institute) influence function model for subsidence predictions above longwalls or pillar extraction panels. The model requires calibration to measured subsidence profiles to reliably predict the subsidence and differential subsidence profiles for the assessment of impact to surface features. **Surfer 8®** graphics software is then used to generate the contours of subsidence, tilt, horizontal displacement and strain contours above the panels from the **SDPS®** output files.

  The **SDPS®** model also includes a database of percentage of hard rock (i.e. massive sandstone / conglomerate) that effectively reduces subsidence above super-critical and sub-critical panels, due to either bridging or bulking of collapsed material. An extract from the **SDPS®** User Manual that defines the parameters and terms used, is presented in **Appendix A**.

The modifications to the **ACARP, 2003** model included adjustment to the following key subsidence prediction parameters to improve compatibility with **SDPS®**:

- Chain pillar subsidence prediction is now based on pillar subsidence/extraction height (S_p/T) v. pillar stress (under double abutment loading conditions).

- Distance of the inflexion point from rib sides and inter-panel pillars in similar terms to **SDPS®** software (i.e. d/H v. W/H).

- The horizontal strain coefficient (β_s) is the linear constant used to estimate strain based on predicted curvature and is equivalent to the reciprocal of the neutral axis of bending, d_n used in **ACARP, 2003**. Based on NSW coalfield data, a value of $d_n = 7.3$ m or a $\beta_s = 0.136$ m^{-1} has been applied to predict 'smooth' profile strains using the calibrated **SDPS®** model.

9.2 Multiple-Panel Subsidence Impact Profile Prediction

Representative subsidence profiles for multiple longwall panels have been derived from the following seven key subsidence profile points and cubic spline curve fitting techniques:

(i) maximum subsidence above a longwall panel;

(ii) chain pillar subsidence between adjacent longwall panels;

(iii) inflexion point or maximum tilt location;

(iv) maximum tensile strain or convex curvature location;

(v) maximum compressive strain or concave curvature location;

(vi) goaf edge subsidence;

(vii) angle of draw to the 20 mm subsidence contour.

Multiple-panel effects are determined by adding a proportion of the chain pillar subsidence to the predicted single panel subsidence. Estimates of first and final subsidence above a given set of longwalls use this general approach. The definition of First and Final S_{max} is as follows:

First S_{max} = the first mid-panel subsidence after the extraction of a longwall panel, including the effects of previously extracted longwall panels adjacent to the subject panel;

Final S_{max} = the final mid-panel subsidence over an extracted longwall panel, after at least three more panels have been extracted, or when mining is completed.

In the Newcastle Coalfield, First and Final S_{max} for a panel are predicted by adding 50% and 100% of the predicted subsidence over the respective chain pillars (i.e. between the previous and current panel), less the goaf edge subsidence above the maingate.

The subsidence above chain pillars has been defined in this study as follows:

First S_p = subsidence over chain pillars after longwall panels have been extracted on both sides of the pillar;

Final S_p = the subsidence over a chain pillar, after at least another three more panels have been extracted, or when mining is completed.

Residual subsidence above chain pillars and longwall panels tend to occur after extraction and caving of the immediate roof due to (i) increased overburden loading on the pillars and (ii) on-going goaf consolidation or creep. The residual movements can increase subsidence by a further 10 to 30% above chain pillars. A subsidence increase of 20% after double abutment loading occurs (i.e. First S_p) has been assumed in this study to allow for long-term loading effects (i.e. Final S_p). Residual subsidence above longwall panels will decrease exponentially as mining moves further away from a given panel.

Tilts and curvatures have been assessed using the empirical techniques presented in **ACARP, 2003** and by also assessing the first and second derivatives of the predicted subsidence profiles with **Sigmaplot®** for comparative purposes.

Predictions of strain and horizontal displacement were made based on the relationship between the measured curvatures and tilt respectively as discussed in **ACARP, 1993** and **ACARP, 2003**.

Structural and geometrical analysis theories indicate that strain is linearly proportional to the curvature of an elastic, isotropic bending 'beam'. This proportionality actually represents the depth to the neutral axis of the beam, or in other words, half the beam thickness. **ACARP, 1993** studies returned average strain over curvature ratios ranging between 6 and 11 m for NSW and Queensland Coalfields. Near surface lithology strata unit thickness and jointing therefore dictate the magnitude of the proportionality constant between curvature and strain. Similar outcomes are found for tilt and horizontal displacement.

ACARP, 2003 continued with this approach and introduced the concept of secondary curvature and strain concentration factors due to cracking. The mean peak strain / curvature ratio for the Newcastle Coalfield was assessed to equal 5.2 m with strain concentration effects increasing the 'smooth-profile' strains by 2 to 3 times. The median value for the database was 7.3, indicating the database is 'skewed' towards the higher value end.

On-going review of the database has led to a value of 10 being adopted as a more appropriate value for making reliable, 'smooth' profile strain prediction. The U95%CL value for 'smooth' profile strains is 1.5 times the mean value (i.e. K=15).

A strain concentration factor of 2 may then applied to the U95%CL value for 'smooth profile' values for estimating U95%CL values caused by discontinuous behaviour or 'cracking' (i.e. K = 30).

Cracking is only expected to occur in zones of peak tensile (or compressive) strains or when strain exceeds 1 to 2 mm/m where surface rock exposures are present within 2 m to 3 m of the surface. The average depth of cracking may be assumed to equal the depth to the neutral axis of bending or 5 m to 11 m based on the above assessment of strain and curvature. Deeper cracking has developed in steep terrain above the Western Domain longwalls due to rigid body rotation effects, with depths of up to 20 m measured with tape measure dipping above LW41 in the Western Domain. A K factor of 30 m suggests a theoretical cracking depth of 30 m, however, what should be understood is that the factor is a theoretical relationship between maximum curvature and maximum strain measurements that rarely coincide at the same location above a longwall panel. A maximum cracking depth of 20 m is considered to be the U95% Confidence Limit for steep slopes in the West Wallsend Colliery terrain.

Colluvial/slopewash soils within the project area are likely to reduce the potential for strain concentration, resulting in strain profiles close to the predicted 'smooth' subsidence profile strains presented herein.

Surface crack widths (in mm) may be estimated by multiplying the predicted strains by an empirical factor of 10 m, which also corresponds with the distance between the pegs and observed crack widths and strains in the field. The estimation of crack widths along steep slopes that may be subject to rigid body rotations may be estimated as follows:

Steep Slope crack widths = U95%CL Strain (discontinuous) x 10 m + ΔS. Slope Height/Slope Width

ΔS = Differential subsidence between crest and toe of slope.

9.3 Validation of Models

Validation of the empirical subsidence prediction models used in this assessment was completed during the EA presented in **DgS, 2010** for the Northern Domain LWs 27 to 37 with additional checking in subsequent end of panel review reports for LWs 38 to 41 (**DgS, 2011**; **DgS, 2012**; **DgS 2013a** and **DgS, 2013c**).

The validation assessment included the following:

(i) The development of simple analytical models of overburden spanning mechanics and roof-chain pillar-floor system compression to sag subsidence over longwall panels due to spanning strata and chain pillar subsidence. The bearing capacity of the roof and floor strata was also estimated using established shallow footing design theories.

(ii) Comparison of subsidence data with model predictions.

A summary of the subsidence prediction model reviews are presented in **Sections 9.3.1** and **9.3.2**.

9.3.1 Northern Domain Subsidence Prediction and Impact Review Summary

The results of the validation studies for LWs 27 to 37 in the Northern Domain demonstrated the following:

- All of the measured values of First and Final S_{max} were between the predicted mean and Upper 95% Confidence Limits (U95%CLs) and equal to 0.86 times the U95%CL values on average.

- The measured chain pillar values on average were equal to 39% of the predicted U95%CL and 60% of the predicted mean values respectively.

- The outcomes of the SRP assessment indicated that the Young Wallsend Channel (Unit 1) and Fern Valley Channel (Unit 2) had 'Moderate' to ‘High’ SRP, while the other channels (Units 3 and 4) were assessed to have a ‘Low’ SRP. Unit 5 Teralba Conglomerate did not exist in the Northern Domain.

- Seventy-nine percent (79%) of the measured maximum tilts were <U95% CLs for the predicted tilts. The remaining 21% of measured tilt exceeded the U95%CL values by 1.20 to 1.35 times (average of 1.26) and likely to be due to ‘discontinuous’ overburden behaviour. The regression equation and U95%CLs were subsequently updated so that 95% of the data would be within the limits of the new U95%CL curve (see **Figure 13a**).

- Seventy percent (70%) of the measured maximum curvatures were <U95%CLs for the predicted curvatures. The remaining 30% of measured maximum panel curvatures exceeded the U95%CL values by 1.12 to 2.53 times (average of 1.70). The regression equation and U95%CLs were subsequently updated so that 95% of the data would be within the limits of the new U95%CL curve (see **Figures 13b** and **13c**).

- Seventy-seven percent (77%) of the measured maximum strains were within the mean and U95%CLs for the predicted. The remaining 23% of measured maximum panel strains exceeded the U95%CL values by 1.17 to 3.33 times (average of 1.83) and likely to be due to discontinuous overburden behaviour. The regression equation and U95%CLs were subsequently updated so that 95% of the data would be within the limits of the new U95%CL curve (see **Figure 13d**).

- The concentration of curvatures and associated horizontal strains generally started to occur when longwall panels were in the critical to supercritical W/H ratio range of 1 to 2 and in zones where the radius of curvature is less than 5 km (i.e. curvatures 0.2 km^{-1}). The phenomenon is thought to be caused by secondary curvature effects or surface 'hump' development in the compressive zones due to buckling or shear failure of surface strata; or crack development/opening of pre-existing jointing in the tensile regions of the subsidence profile.

- The surface topography and geology (i.e. lithology and defects) are also governing factors with regard to the distribution of curvature and strain over the subsiding area.

- The 'K' ratio between the maximum measured strain and curvature for each panel in the Northern Domain has also been determined. Regression analysis on the data indicates the mean 'K' values ranged between 4.7 and 10.8, giving an average ratio of 7.4. When all subsidence data for LWs 27 to 44 have been included, an average ratio of 7.5 is determined through linear regression analysis; see **Figure 14d**. A K factor of 30 is required to 95% of the data to be exceeded by the predicted values; see **Figure 14d** also.

  Based on the above analyses, an assumed 'K' value of 10 has and 15 have been adopted for making reliable mean and U95%CL predictions of strain from 'smooth curvature' profiles above LWs 51 & 52. A K of 30 (i.e. 2 x U95%CL for 'smooth profiles' has been assumed to estimate the U95%CL when discontinuous overburden behaviour is included.

9.3.2 Western Domain Subsidence Prediction and Impact Review Summary

The results of the validation studies for LWs 38 to 41 in the Western Domain demonstrated the following:

- The modified **ACARP, 2003** models discussed in **Section 9.3.2** are reliable for worst case subsidence effect prediction and impact assessment purposes for 95% of the time in the Western Domain (LWs 38 to 41). Two maximum subsidence prediction exceedances of up to 0.6 m occurred above LW40 that were probably due to lower than expected SRP for the units thicknesses estimated from the available borehole logs. The 1.6 m to 4.0 m of vertical subsidence that was measured outside the limits LW41extraction represents an unprecedented event at West Wallsend Colliery and for longwall mining in Australia generally.

- The impacts due to the measured mid-panel subsidence of 2.2 m above LW40 were still within the expected range for the predicted value of 1.6 m and did not result in additional remediation works being required. The difference in subsidence was due to High SRP being assessed in an area of Low SRP.

- The large vertical block movement (VBM) above solid coal adjacent to LW41 at a cover depth of 180 m was not anticipated, and therefore considered to be an unprecedented impact. Several smaller vertical block movements of between 0.6 m and 0.9 m above unconfined ridges above LWs 40 and 41, were also not expected, however the impacts of these are not considered to be outside the definitions of expected impact described in the project approval conditions for steep slopes.

- It is considered that the VBMs have developed on unconfined ridges above persistent geological structure associated with NW/SE striking shear zones and atypical of the conditions above LWs 51 and 52.

- Several tilt and strain prediction exceedances (as occurred for the Northern Domain cases) were measured where discontinuous strata behaviour from cracking and the vertical strata block movements (VBMs) occurred.

- Worst-case crack widths on cliff terraces have been significantly wider above LWs 40 and 41 than the worst-case values that were predicted for the steep slopes (e.g. 2.5 m v. 0.7 m). Adjustment of the crack width prediction model for LW51 to 52 crack width predictions was not considered necessary as the crack width exceedances were < 5% of the measured crack widths.

Further discussion of some of the prediction model exceedances and consequences of these in regards to environmental impact are discussed in **DgS, 2011**, **DgS, 2012** and **DgS, 2013a**.

It is considered that the prediction v. measured impact outcomes for the Northern Domain are more likely to reflect the performances of the panels in the Southern Domain than the Western Domain panels.

10.0 Results of Longwall Panel Subsidence Assessment

10.1 General

Cumulative subsidence effect predictions have been assessed across the project area after (i) each longwall block has been extracted, and (ii) after mining of all of the proposed longwall panels 51 to 52 is complete. The assessment required consideration of the following:

- The SRP of the overburden and the influence of proposed mining geometry on single panel subsidence development (i.e. whether the panels are likely to be *sub-critical, critical* or *super-critical*);

- The behaviour of the chain pillars and immediate roof and floor system under double - abutment loading conditions when longwalls have been extracted along both sides of the pillars; and

- The combined effects of single panel and chain pillar subsidence to estimate final subsidence profiles and subsidence contours for subsequent environmental impact assessment.

As mentioned previously, it is considered that the development of subsidence will be affected by the spanning potential of the massive sandstone and conglomerate units and the subsidence above the chain pillars between the panels. The outcomes of the subsidence assessment are presented in the following sections.

10.2 Geological Model and Subsidence Reduction Potential of Massive Units

The SRP refers to the subsidence reducing effect that massive conglomerate / sandstone units have above longwall panels due to inherent spanning or arching behaviour. The SRP is a function of the cover depth; the width of the panel (or span); the thickness of the massive unit; and the distance of the unit above the workings.

A conceptual model of the spanning potential of a massive strata unit and key parameters used in the assessment are presented in **Figure 14**.

The thickness and location of the three massive strata units present above the proposed workings have been plotted with the SRP threshold limit lines for the 100 m +/- 50 m cover depth category shown in **Figure 15**.

The outcomes of the assessment are summarised in **Table 2** and indicate that the massive units will all have ‘low’ SRP above the proposed 178.6 m and 206.8 m wide panels.

10.3 Predicted Single Panel Subsidence

The mid-panel subsidence above a single longwall panel will depend upon its width, cover depth, seam thickness, and the SRP of the overburden.

Based on reference to the **ACARP, 2003** model, the SRP categories are then used to select the appropriate subsidence prediction lines from the appropriate cover depth categories. The predictions for single panels in the project area are shown in **Figure 16**.

The depth categories were developed in the **ACARP, 2003** study to cater for the influence of scale on the spanning behaviour of the massive lithological units above panels of a given geometry.

The mid-panel subsidence (S_{max}) for single 178.6 m and 208.6 m wide longwall panels at 80 to 140 m depth with 'low' SRP overburden for the assumed maximum face extraction height range from 4.2 to 4.5 m is summarised in **Table 2**.

The values for each longwall panel were estimated along three representative cross lines (XL14 to 16), see **Figures 3** and **4** for their location.

Table 2 - Predicted Single Mid-Panel Subsidence in the Southern Domain

Panel No.	Cross Line No.	Panel Width W (m)	Cover Depth, H (m)	W/H	Unit t (m)	Unit Location Above Workings y (m)	Unit Location Factor y/H	SRP	Mining Height (m)	Single S_{max}* (m)	
										Mean	U95%CL
51	14	178.8	130	1.38	10	105	0.81	Low	4.2	2.35	2.44
51	15	178.8	110	1.63	6	100	0.91	Low	4.3	2.45	2.49
52	14	206.8	115	1.80	13	105	0.91	Low	4.5	2.45	2.49
52	15	206.8	140	1.48	8	117	0.84	Low	4.5	2.56	2.61
52	16	206.8	130	1.59	5	105	0.81	Low	4.5	2.56	2.61

Note:
SRP = refers to Subsidence Reduction Potential of the assumed strata unit for the purposes of subsidence prediction.
Single S_{max}= mid-panel subsidence predicted for a single, isolated longwall panel.
Italics - Maximum subsidence limited to 58% of mining height (refer to **ACARP, 2003**).

The results of the above assessment indicate that the single panel subsidence is likely to range between 2.35 and 2.49 m (56% to 58% of the mining height) above LW51, and between 2.45 and 2.61 m (57% to 58% of the mining height) above LW52.

The single panel subsidence predictions will be used with the chain pillar and goaf edge subsidence to estimate the multi-panel subsidence in **Section 10.6**.

10.4 Predicted Subsidence Above Chain Pillars

10.4.1 Empirical Model Development

The predicted subsidence values above the chain pillars have been estimated based on an empirical model and an analytical model of the roof-pillar-floor system.

The empirical model has been developed from measured subsidence data over chain pillars (S_p) divided by the mining height (T) v. the total pillar stress after longwall panel extraction on both sides.

The estimate of the total stress acting on the chain pillars on each side of the panel under double abutment loading conditions is based on the abutment angle concept described in **ACARP, 1998a**. The total stress acting on each pillar of a chain pillar pair after mining was estimated as follows:

σ = pillar load/area = $(P+A_1+A_2)/wl$

where:

P = full tributary area load of column of rock above each pillar;

= $(l+ r)(w + r).\rho.g.H$;

$A_{1,2}$ = total abutment load from each side of pillar in MN/m, and

= $(l+r)\rho g(0.5W'H - W'^2/8\tan\phi)$ (for sub-critical panel widths) or

= $(l+r)(\rho g H^2\tan\phi)/2$ (for super-critical panel widths);

w = pillar width (solid);

l = pillar length;

r = roadway width;

H = depth of cover;

ϕ = abutment angle (normally 21° adopted for cover depths < 360 m at West Wallsend);

W' = effective panel width (rib to rib distance minus the roadway width).

A panel is deemed sub-critical when $W'/2 < H\tan\phi$.

As presented in **ACARP, 1998b** the FoS of the chain pillars were based on the strength formula for 'squat' pillars with w/h ratios > 5 as follows:

$$S = 27.63\Theta^{0.51}(0.29((w/5h)^{2.5} - 1) + 1)/(w^{0.22}h^{0.11})$$

where:

h = pillar height;

Θ = a dimensionless 'aspect ratio' factor or w/h ratio in this case.

The FoS was calculated by dividing the pillar strength, S, with the pillar stress, σ.

10.4.2 Empirical Model Outcomes

The mean and U95%CL values for the proposed chain pillar subsidence with solid widths of 30 m and 168 m under double abutment loading conditions after mining is completed in LWs 51 and 52, are summarised in **Table 3**.

The predicted first subsidence over the chain pillars (S_p) between the first and next extracted panels is estimated to range from 0.10 m to 0.13 m for the range of pillar sizes and geometries proposed. The final subsidence over the chain pillars after mining is completed has been estimated by increasing the first chain pillar subsidence by 20% or 0.13 m to 0.15 m; see **Figure 17**.

It is also apparent from the measured data **Figure 17** that the subsidence above the pillars is a function of the strength and stiffness of the coal and surrounding rock mass (i.e. higher subsidence is measured above weak shale roof compared to a strong sandstone one).

Table 3 - Predicted Chain Pillar Subsidence (based on Modified ACARP, 2003 Empirical Model)

LW #	XL #	Pillar Width (m)	Cover Depth H (m)	Pillar Stress (MPa)	Pillar FoS under DA Loading	S_p First (mean)	Sp First (U95%CL)	Sp Final (mean)	Sp Final (U95%CL)
51	14	29.8	130	9.2	2.79	0.11	0.13	0.13	0.15
51	15	29.8	110	8.8	2.90	0.11	0.13	0.13	0.15
52	14	168	140	3.5	157	0.00	0.00	0.00	0.02
52	15	168	130	4.4	126	0.00	0.00	0.00	0.02
52	16	168	130	4.1	137	0.00	0.00	0.00	0.02

DA = Double abutment.

The observed behaviour of the chain pillars and roof / floor system has also been used to develop a simple analytical model that includes elastic and post-yielded pillar responses to estimate subsidence based on laboratory testing data and reference to **ACARP, 2005**.

10.5 Goaf Edge Subsidence Prediction

The mean and U95%CL goaf edge subsidence predictions for the proposed panels and cover depths of 80 m to 140 m are range from 0.08 to 0.22 m.

The goaf edge predictions are based on the prediction curves shown in **Figure 18** and the Maximum Subsidence predictions given in **Section 10.6**.

10.6 Multiple Panel Subsidence Prediction Results

Based on the predicted single panel, chain pillar and goaf edge subsidence values derived from the **ACARP, 2003** model, the empirically derived mean and U95%CL values of first and final panel subsidence effects are presented in **Table 4** (mean and U95%CL values) for LWs 51 and 52. The predictions include continuous and discontinuous overburden behaviour effects based on a comprehensive review of WWC's subsidence data for LWs 27 to 44.

Table 4 - Predicted First and Final Subsidence Parameters (Mean - U95%CL Values) for LWs 51 to 52

LW #	XL #	Panel Width W (m)	Cover Depth H (m)	Face Height T (m)	Panel Width/ Cover Ratio W/H	Chain Pillar Width w_{cp} (m)	Panel First S_{max} (m)		Panel Final S_{max} (m)		Pillar Final S_p (m)		Max# Tilt T_{max} (mm/m)		Max Comp Strain* $-E_{max}$ (mm/m)		Max Tensile Strain* $+E_{max}$ (mm/m)	
							mean	U95%	mean	U95%	mean	U95%	mean	U95%	mean	U95%	mean	U95%
51	14	178.8	130	4.2	1.38	30	2.35	2.44	2.41	2.44	0.12	0.15	49	74	15	22 (44)	12	18 (36)
51	15	178.8	110	4.3	1.63	30	2.45	2.49	2.49	2.49	0.13	0.15	65	97	21	31 (62)	16	25 (50)
52	14	206.8	115	4.3	1.80	168	2.47	2.49	2.48	2.49	0.00	0.02	60	90	19	28 (56)	15	22 (44)
52	15	206.8	140	4.5	1.48	168	2.58	2.61	2.59	2.61	0.00	0.02	48	72	13	20 (40)	11	16 (32)
52	16	206.8	130	4.5	1.59	168	2.57	2.61	2.59	2.61	0.00	0.02	53	80	15	36 (72)	12	18 (36)

XL # - Refer to **Figure 3**.
First S_{max}= first panel subsidence for a given panel (including chain pillar compression effects from previously extracted panel).
Final S_{max}= final panel subsidence for a given panel (including chain pillar compression effects after all longwall panels have been extracted).
Italics - Final S_{max} does not exceed 0.58 x Extraction Height (T).
Final Pillar S_p = final subsidence above a chain pillar after all longwalls have been extracted.
- Predicted U95%CL tilts include the effect of discontinuous overburden movement behaviour.
* - Predicted U95%CL strains include the effect of discontinuous overburden movement behaviour. The mean values consider a surface with a deep soil cover and likely to have 'smooth' profile strains.
(brackets) - Near surface rock and bedrock exposures are likely to cause strain concentrations such as cracking, and can result in U95%CL strains = 2 x 'smooth profile' U95%CL strains.

The outcomes of the subsidence effect predictions for LWs 51 and 52 are summarised below:

- The predicted mean and U95%CL values for the **first panel subsidence** ranges from 2.35 m to 2.61 m (i.e. 56% to 58% of proposed panel extraction height).

Note: the mean and U95%CL values are assumed to almost converge for supercritical panel geometries.

- The predicted mean and U95%CL values for the **final panel subsidence** ranges from 2.41 m to 2.61 m (i.e. 57% to 58% of proposed extraction heights).

- The predicted mean and U95%CL values for the **final chain pillar subsidence** between LWs 51 and 52, ranges from 0.12 m to 0.15 m (i.e. 3% to 4% of the proposed extraction heights).

- The predicted mean and U95%CL values for the **final tilt** ranges from 48 to 97 mm/m.

- The predicted mean and U95%CL values for the **final compressive strain** ranges from 13 to 31 mm/m for *continuous* overburden behaviour. For *discontinuous* overburden behaviour, the compressive strains range from 40 mm/m to 61 mm/m.

- The predicted mean and U95%CL values for the **final tensile strain** ranges from 11 to 25 mm/m. for *continuous* overburden behaviour. For *discontinuous* overburden behaviour, the tensile strains range from 36 mm/m to 50 mm/m.

- The predicted mean and U95%CL values for the **final concave curvatures** associated with the compressive strain zones ranges from 1.33 to 5.41 km^{-1} respectively (i.e. curvature radii of 0.75 to 0.18 km).

- The predicted mean and U95%CL values for the **final convex curvatures** associated with the tensile strain zones ranges from 1.05 to 3.77 km^{-1} (i.e. curvature radii of 0.95 to 0.27 km).

Note: the U95%CL tilt, strain and curvature predictions include discontinuous overburden movement effects, which can increase continuous or 'smooth profile' values by 2 to 4 times.

10.7 Angle of Draw Prediction

Reference to the **ACARP, 2003** longwall panel angle of draw predictions have been derived from the mean goaf edge subsidence predictions. The AoD to the 20 mm subsidence contour is estimated to range from 9^o to 22^o for the proposed LWs 51 and 52 and based on the empirical model presented in **Figure 19**.

An AoD of 26.5^o however, is considered to be an appropriate value for mine planning and impact management purposes near sensitive surface features.

10.8 Inflexion Point and Peak Strain Locations

The subsidence development process causes tensile and compressive strains to develop above an extracted longwall panel, due to the sagging and bending of the overburden strata.

Tensile strains are generally located in the outer third zone above an extracted longwall panel and the compressive strains will occur above the central or middle third area. The point where the tensile strains become compressive is called the inflexion point.

The Newcastle Coalfield database of longwall inflexion point and tensile/compressive strain or convex/concave curvature peak locations are shown in **Figure 20**.

The predicted locations of the above points for the proposed panels are given in **Table 5**.

Table 5 - Predicted Inflexion and Strain Peak Location Summary

Panel Width W (m)	Cover Depth H (m)	Panel W/H*	Inflexion Point Location Factor d/H	Inflexion Point Location from Panel Rib-side d	Tensile Strain Peak Location Factor d_t/H	Tensile Strain Peak Location From Panel Rib Side d_t	Compressive Strain Peak Location Factor d_c/H	Compressive Strain Peak Location from Panel Rib-Side d_c
178.8	130	1.38	0.39	50	0.27	35	0.51	66
178.8	110	1.63	0.39	43	0.28	30	0.51	57
206.8	115	1.80	0.39	45	0.28	32	0.51	59
206.8	140	1.48	0.39	55	0.28	39	0.51	72
206.8	130	1.59	0.39	51	0.28	36	0.51	67

* - $W/H_{max} = 1.4$

10.10 Subsidence Profile Prediction Results

Based on the modified **ACARP, 2003** empirical model and **Sigmaplot®** cubic-spline curves, predictions of the subsidence, tilt, curvature, horizontal displacement and strain profiles along cross lines XL 14 to 16 above LWs 51 and 52 are shown in **Figures 21a** to **21c**.

The profiles show the predicted subsidence effects after each panel is extracted and at the completion of mining.

11.0 Prediction of Subsidence Impact Parameter Contours

11.1 Calibration of the SDPS® Model

The **SDPS®** model was then calibrated to the ACARP model profiles to derive U95%CL subsidence contours. The outcome of the SDPS model calibration exercise is summarised in **Table 6**.

Table 6 - ACARP, 2003 & SDPS® Model Calibration Summary

Input Parameters	**Value**	**ACARP, 2003 Model Database**
Panel No.s (refer to **Figure 1**)	LWs 51 & 52	Includes LWs 11 to 41
Panel Void Width, W (m)	178.6 - 206.8	34 - 264
Cover Depth, H (m)	80 - 140	71 - 516
Mining Height, T (m)	4.2 - 4.5	1.05 - 4.9
W/H range	1.38 - 1.80	0.2 - 2.0
Massive Strata Unit Thickness, t (m)	4 - 45	<5 - 80
Strata Unit Distance Above Workings, y (m)	7 - 120	1 - 350
SRP for Mining Area	Low	Low to High
Strata Unit Location Ratio (y/H)	0.05 - 0.95	0.0 - 0.9
Final Panel Subsidence Range, S_{max} (m)	2.44 - 2.61	0.02 - 2.5
S_{max}/T Range for Panels	0.56 - 0.58	0.01 - 0.58
Chain Pillar Width (m)*	30	18 - 49
Chain Pillar Lengths (m)	97	60 - 110
Development Road or Chain Pillar Height (m)	3.5	1.8 - 3.5
Gate road Heading and Cut-through Widths (m)	5.5	4.8 - 6.0
Chain Pillar Subsidence (m)	0.02 - 0.17	0.03 - 1.00
Theoretical Chain Pillar Stress (MPa)*	8.8 - 9.2	4.8 - 81
Chain Pillar FoS*	2.7 – 2.9	0.56 - 9.40
Chain Pillar Width/Development Height	8.5	7.4 - 15.8
Modified ACARP, 2003 Inflection Point Location (d) from Rib-side/Cover Depth (H): d/H	0.39	0.03 - 0.50
Modified ACARP, 2003 Inflection Point Location from Rib-side, d (m)	43 - 55	5 - 99
Goaf Edge Subsidence (m)	0.08 - 0.23	0.02 - 0.38
Angle of Draw (degrees)	9 - 22	0 - 33
Calibration Results for Best Fit Solution to the Modified ACARP, 2003 Model Predictions^	**Optimum Value***	
Influence Angle (Tan(beta))	1.8	
Influence Angle (degrees)	61	
Supercritical Subsidence Factor for Panels and Pillars (S_{max}/T)	0.53 - 0.64	
Distance to Influence Inflexion Point from Internal Chain Pillar or Solid Rib-Sides (m)	40	

Notes:
^ - See SDPS manual extract in **Appendix A** for explanation of methodology and terms used.
* - Stress for 30 m pillar only considered here. Barrier pillar between LW44 and 52 is 168 m wide.

Based on reference to **Table 6** the geometry and geology of the proposed longwall panels (LWs 51 to 52) are generally within the limits of the current database.

The modified **ACARP, 2003** model and calibrated **SDPS®** model subsidence effect profiles have been compared along XL14 in **Figures 22a** to **22c**; XL15 in in **Figures 22d** to **22f**; and XL16 in **Figures 22g** to **22i**.

The predicted **SDPS®** subsidence and tilt profiles were generally located within +/- 10 to 20% of the predicted modified **ACARP, 2003** models Upper 95% Confidence Limits. This outcome is considered a reasonable fit considering that the **ACARP, 2003** profiles represent measured tilt profiles that are invariably affected by 'skewed' or kinked subsidence profiles.

The results of the analysis indicate that the majority of the predicted convex curvature (and tensile strain) and concave curvature (and compressive strains) predicted by the **SDPS®** model would fall within +/- 50% of the modified **ACARP, 2003** model predictions. This result is also considered reasonable in the context that the **ACARP, 2003** model represents measured profile data that includes strain concentration effects such as cracking and shearing. As mentioned earlier, this 'discontinuous' type of overburden behaviour can increase 'smooth' profile strains by 2 to 3 times locally.

11.2 Predicted Subsidence and Associated Impact Parameter Contours

Based on the calibrated SDPS® model, predictions of final, worst-case subsidence contours for LWs 51 and 52 are shown in **Figure 23a**.

Associated subsidence impact parameter contours of principal tilt and horizontal strain have been subsequently derived using the calculus module provided in **Surfer8®** and the worst-case subsidence contours. The outcomes are shown in **Figures 23b** and **23c** respectively.

The pre and post mining topography have been generated from the aerial survey and the predicted subsidence contours. The results are given in **Figure 24**.

12.0 Subsidence Impact Assessment and Management Strategies

12.1 General

DoP, 2008 provides a comprehensive summary of the range of potential mine subsidence effects on the environment and impact management techniques that have been considered in this document.

DoP, 2008 recommends that subsidence Risk Management Zones (RMZs) be defined around sensitive features within a mining lease before subsidence occurs. The RMZs are intended to provide focus for future impact management of sensitive features such as:

- 3rd and higher order streams, creeks and alluvium;
- significant rock bars;
- significant cliff lines and overhangs;
- ground dependant eco-systems;
- valley infill swamps;
- significant Aboriginal heritage sites (that may be associated with the above features);
- sensitive man-made developments (i.e. motorways, cuttings, embankments and infrastructure).

The location of an RMZ is considered to be the first step in managing prediction uncertainties and the potential impacts associated with subsidence, valley uplift and closure, and far-field displacements. It will then be necessary to determine what constraints on mining may be required within the RMZ to reduce subsidence effects to 'repairable' or ALARP (*'As Low As Reasonably Practicable')* levels. For longwall mining cases, the RMZs are deemed to be mining exclusion zones defined by a practical angle of draw (e.g. 26.5^o to 40^o) unless local data is available that allows the limits of mining to encroach inside the RMZ without significant impact on the feature.

Based on the current Project Approval conditions and consultation with stakeholders, the natural and man-made features within the proposed project area that will require an RMZ to be applied include:

- Aboriginal heritage sites of 'high' to 'extremely high' cultural significance;
- M1 Motorway, Cutting No. 2 and Fill No.s 1 and 2 and associated infrastructure;
- Utilities easement (high pressure gas and petroleum pipelines and several optic fibre cables);
- Telstra communications tower (CT3); and
- Palmers Creek and alluvium.

Based on available subsidence, strain and cracking data in similar terrain in the Northern and Southern domains of WWC, an RMZ defined by an AoD of 26.5^o to 37^o (0.5H to 0.75H) from the limits of proposed mining (depending on the feature and mining layout) is considered appropriate for the sensitive features listed above.

RMZs are not proposed for the following features that may be either repaired after mining impact or accepted as being likely to sustain cracking damage:

- Aboriginal archaeological sites of 'moderate' to 'low' cultural significance, although under mining 'moderate' culturally significant sites such as the scarred tree (ST1), has been avoided for LWs 51 and 52;
- first and second order creeks with cover depths > 80 m;
- steep slopes;
- Wakefield Road and embankment No. 2a (LMCC).

The following sub-sections provide an assessment of the worst-case subsidence impacts that could occur to the existing features within the proposed project area (with or without an appropriate RMZ applied) and suggested impact management strategies that will be required to minimise long-term impacts to the feature after mining is completed.

Due to the uncertainties associated with mine subsidence prediction and associated impacts for a given mining geometry and geology etc, a credible range of impact outcomes (based on probabilistic design methodologies) have been provided to assist with the development of effective subsidence management plans for the existing site features.

Discussions on the likelihood of impact occurrence are presented in the following sections and generally refer to the qualitative measures of likelihood described in **Table 7**, which are based on probabilistic terms used in **AGS, 2007** and event probability values suggested in **Vick, 2002** for the probabilistic terms.

The mean and U95%CL or credible worst-case values used in this report generally infer that the predictions will be exceeded by 50% and 5% of panels mined with similar geometry and geology etc. Using lower probability of exceedance values (i.e. <5% probability of exceedance) may result in potentially uneconomic or marginal mining layouts with a negligible gain to impact reduction.

The consequences of an exceedance will therefore need to be considered when selecting an appropriate probability of exceedance likelihood.

Table 7 - Qualitative Measures of Likelihood

Likelihood of Occurrence	**Event implication** *(ref AGS, 2007)*	**Indicative relative probability of a single event** *(ref Vick, 2002)*
Almost Certain	The event is expected to occur.	90-99%
Very Likely	The event is expected to occur, although not completely certain.	75-90%
Likely^{+}	The event will probably occur under normal conditions.	50-75%
Possible	The event may occur under normal conditions.	10-50%
Unlikely*	The event is conceivable, but only if adverse conditions are present.	5-10%
Very Unlikely	The event probably will not occur, even if adverse conditions are present.	1-5%
Not Credible	The event is inconceivable or practically impossible, regardless of the conditions.	<1%

Notes:
+ - Equivalent to the mean or line-of-best fit regression lines for a given impact parameter presented in **ACARP, 2003**.
* - Equivalent to the worst-case or U95%CL subsidence impact parameter in **ACARP, 2003**.

12.2 Surface Cracking

12.2.1 Potential Impacts

The development of surface cracking above a longwall panel is caused by the bending of the overburden strata as it sags down into the newly created void in the coal seam. The sagging strata is supported by collapsed roof material (goaf) that slowly compresses to final maximum subsidence. The stiffness and bulking characteristics of the overburden, and vertical stress acting on the goaf, will influence the final maximum subsidence magnitude.

Tensile fractures generally occur between the panel ribs and the point of inflexion where convex (i.e. hogging) curvatures and tensile strains develop above a longwall panel. The point of inflexion is assessed to be located 43 to 55 m from the panel ribs for the range of mining geometries proposed. Tensile fractures can also occur above chain pillars that are located between extracted panels.

The surface cracks in the tensile strain zones will probably be tapered and extend to depths ranging from 5 m to 10 m based on the measured strain to curvature ratios (K ratios) discussed earlier, and possibly deeper (~20 m) in near surface rock exposures and ridges based on tape measurements on steep slopes of up to 35^{o} above LWs 40 to 41.

As discussed in **Section 9.2**, the cracking width may be estimated by multiplying the predicted discontinuous tensile strain x 10 m (i.e. the distance between survey pegs).

Based on a review of the observed mining impacts above LWs 38 to 41, the predicted range of transverse tensile strains from 11 to 25 mm/m may cause surface cracking widths of between 220 mm and 500 mm within the limits of mining and in areas with moderately undulating terrain (i.e. slopes < 18^o).

Crack widths ranging from 500 mm to 833 mm wide have been estimated behind ridge crests above LWs 51 and 52 due to rigid body rotation of the steep slopes by 1 m. The crack widths (δ) were calculated as follows:

Steep slope crack width, δ = U95%CL Strain (dis-continuous).10 m + ΔS.Slope Height/Width

ΔS = Differential subsidence between crest and toe of slope = 1 m (see **Figure 23a**)

Slope Height = 20 m (see **Figure 24**)

Slope Width = 60 m (see **Figure 24**)

δ = 50 mm/m .10 m + 1000 mm. 20 m / 60 m = 500 + 333 = 833 mm

Similar size 'scarps' could also develop as a result of subsiding a steep slope by the same order of magnitude.

It is noted that cracking above Newstan LWs to the south near crests of steep slopes have ranged from 50 mm to 1400 mm where cover depths of 140 m exist. It is therefore possible that cracks of this order of magnitude could also develop along the slope crests above 51 and 52.

The location and frequency of surface cracking tends to occur within 10 m to 15 m from the tensile strain peaks and may consist of one to five cracks, depending on the strength properties near surface lithology. Undermining ridges can also result in surface cracks occurring up-slope and outside the limits of extraction for significant distances due to rigid block rotations.

This phenomenon has been previously observed up to 50 m outside the extraction limits of LW29 and 41, which are located to the northeast of LW52. The effective angle of draw to the cracks was 11^o or 0.2 x the cover depth. For the purposes of impact assessment for this study, cracks may therefore occur outside the limits of mining along the high sides of the proposed longwalls for distances of up to 26 m and 28 m for cover depths of 130 m and 140 m respectively.

Compressive shear fractures will generally develop in the central area above a longwall panel and between the inflexion point locations. This zone is where concave (i.e. sagging) curvatures and compressive strains will develop. Low-angle cracks and humps within compressive strain zones are generally caused by shear failure or buckling of near surface strata. Tensile cracks can also be present due to the uplift of near surface rock in the base of gullies or man-made cuttings (see section on valley closure also).

Based on reference to **ACARP, 2003**, the cracking described above will probably have developed by the time the longwall face has retreated for a distance equal to 1 to 2 times the cover depth past a given location.

Arcuate tensile cracks will also probably develop up to 20 or 30 m behind the advancing goaf edge of the longwall panels. The majority of these cracks will generally close in the central, compressive strain areas of the longwall panels after the subsidence trough has fully developed.

Cracking may also occur above the 30 m wide chain pillars. A database of surface cracking location has been compiled from LWs 22 to 36 for assessing the probability of crack development. Twenty two cracks have been observed above 30 m to 45 m wide chain pillars between LWs 22 to 36. The cracks were 10 mm to 100 mm wide and occurred within 16.5 m of the panel extraction limits.

In regards to the creeks and watercourses in the proposed project area, the following potential impacts are expected to occur due to mine subsidence:

- Transient surface cracking is likely to develop behind the retreating longwall face and along and across creek beds or watercourses that are undermined.

- Final surface crack width distribution will be influenced by the strain contours shown in **Figure 23c**.

- Cracks that occur within the drainage gullies or creek beds could result in sub-surface re-routing of surface flows during storm periods. The cracks in most cases should in fill naturally with sediment after several storm events.

- The depth of surface cracking in alluvial soils along creek beds will be affected by the depth to rock and width of cracking at rock head. Where shallow rock or bedrock is exposed, the maximum crack depth would be expected to range between 5 and 10 m.

- It is likely that there will be a short term increase of pre-mining erosion rates and head cuts along the creeks inside the up-stream ribs of the proposed longwall panels. The erosion rates are expected to reach a new equilibrium after several storm events have occurred, with sediment likely to accumulate where net surface gradients have been decreased after mining.

Cockle Creek has been previously undermined by Northern Domain longwall panels (LWs 27, 28, 31 and 32) with no significant impacts observed or measured to-date, after subsidence of up to 1.5 m and cover depths > 130 m (**Umwelt, 2004**).

12.2.2 General Impact Management Strategies

Surface crack repair works in accessible terrain may need to be implemented around the affected areas of the mining lease, and in particular, across any public (or private) access

roads or ephemeral watercourses that do not infill naturally with sediment due to natural geomorphic processes.

All remediation will be undertaken in consultation with the relevant stakeholders and may involve either the ripping / tilling of small to moderate sized cracks or pouring crushed rock, gravel, concrete or grout into larger sized cracks.

12.2.3 Impact Management Strategies on Ridges and Steep Slopes

Crack repairs on steep slopes may require the use of tracked equipment and erosion resistant materials such as sand-cement grout. Down-slope movements and grout flow should be monitored closely while remediation works are being undertaken.

The recent extraction of LW44 did not see any cracking develop on the slopes and valleys with gradients ranging from 5^{o} to 30^{o}; see **Figure 2**. Measured subsidence of 1.8 m resulted in horizontal strains ranging from -33 mm/m to 13 mm/m. The only visible impact to-date has been < 50 mm uplift across a track in the compressive strain zone above the panel. It is assessed that the lack of cracking to near surface strata is probably due to the greater depths of weathering present above the panel. It is assessed that the near surface conditions above LW51 and 52 will be similar to that above LW44.

12.2.4 Impact Management Strategies in Creeks and Watercourses

Remediation of subsidence impacts within creeks and watercourses will be undertaken in accordance with the existing subsidence management strategies that have been employed by WWC in the past. These strategies have been successfully developed in close consultation with the relevant stakeholders.

The previous management strategies implemented in regards to crack impacts on creeks and watercourses have been to undertake pre-mining and post-mining inspections and communicate the results of these inspections to the respective stakeholders. If a significant impact was identified during these inspections, an appropriate remediation strategy would have been developed.

Consultation with NOW and OEH has suggested that natural regeneration may be the favoured management strategy in most scenarios, due to the likely level of disturbance caused by other remediation strategies.

12.3 Sub-Surface Cracking

12.3.1 Sub-Surface Fracturing Zones

The caving and subsidence development processes above a longwall panel usually results in sub-surface fracturing and shearing of sedimentary strata in the overburden according to **Kendorski, 1993**; see **Figure 25**. The extent of fracturing and shearing up through the strata is dependent on the mining geometry and overburden geology.

The current project approval conditions require that no connective cracking occurs between the mine workings and the surface within the Cockle, Diega, Bangalow and Palmers Creek catchments.

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 and/or strata dilation as defined (in descending order) in **Table 8**.

Table 8 - 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 10 - 15 m depth. Surface waters may be diverted below affected area and resurface downstream.	<3
Elastic Deformation Zone (constrained & dilated bedding partings)	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 (constrained & dilated bedding partings)	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 Zoned (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

12.3.2 Impact on Rock Mass Permeability

In regards to changes to rock mass permeability, **Forster, 1995** indicates that horizontal permeability in the fractured A-Zone 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 could not be measured directly from the boreholes discussed in the **Forster, 1995** model, 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 however, that vertical flows (i.e. leakage) could occur from B-Zone into the A-Zone (and workings) as well, but at a significantly lower rate than in the A-Zone itself.
Overall, bedding parting separation would be expected to increase rock mass storage capacity and horizontal permeability without direct hydraulic connection to the workings in the B-Zone or Constrained Zone.

Rock mass hydraulic conductivity is unlikely to increase significantly outside the angle of draw from the extraction limits.

12.3.3 Prediction Model

The prediction model used to estimate heights of continuous fracturing above the proposed longwalls has been recently developed by DgS after a comprehensive review of published height of fracturing data in the NSW and Queensland Coalfields (see **Section A11** in **Appendix A** for details).

The PI-Term Model considers the influence of the panel width, mining height and strata unit thickness on the height of continuous fracturing above a longwall panel using a product and power rule derived using non-linear regression analysis of measured cases. The PI-Terms have been derived (by experiment) using Buckingham's PI theorem and refer to the dimensionless ratios of key independent variables with a repeating variable of influence (the panel width) as follows:

$$\underline{\text{Mean A/W'} = 1.565\,(H'/W')^{1.25}(T/W')^{0.37}(t'/W')^{-0.26}} \qquad R^2 = 0.66$$

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

where

a = 0.21W' for subcritical panels; 0.19W' m for critical panels and 0.1W' for supercritical panels with linear transition between error zones.

H' = Goaf Load Height = $W'/4\tan\theta$

Back analysis of the database indicated the angle of break varies as follows:

$\theta = 12^o$ for W/H <0.45;

$\theta = 9.63+4.42(W/H)+1.80(W/H)^2$ for 0.45< W/H <1.4;

$\theta = 19.29^o$ for W/H >1.4.

The goaf load height angles v. the W/H ratio are shown in **Figure A42b** of **Appendix A**.

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

T = Mining Height.

t' = Effective strata unit thickness

$= t_{min\ for\ non\text{-}spanning}$ if $t < t_{min\ for\ non\text{-}spanning}$

$= t$ if $t < t_{min\ for\ spanning}$

$= t_{min\ for\ spanning}$ if $t > t_{min\ for\ spanning}$

where $t_{min\ for\ non\text{-}spanning} = 10$ m; and $t_{min\ for\ spanning} = W'[0.20 - 0.075(y/H)]$

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

$$A = 0.273(1/\tan\theta)^{1.26} W'^{0.89} T^{0.37} t'^{-0.26} \quad +/- 0.1W'$$

The model indicates several key parameters are necessary to estimate the heights of fracturing reliably.

12.3.4 Predicted Sub-surface Fracture Zones for LWs 51 and 52

The assessment of the height of Continuous (A-Zone) and Discontinuous (B-Zone) Fracturing are summarised in **Table 9** for LWs 51 and 52 indicate:

LW51

- Worst-case A-Zone Fracture Heights if the full seam thickness is mined (i.e. 4.2 m to 4.4 m) are predicted to range from 71 m to 109 m for cover depths of 80 m to 130 m respectively.

- The minimum constrained or B-Zone thickness (above the A-Zone) is estimated to range between 9 m and 24 m. The lowest value in the range is for the low side of LW51, where cover depth is 80 m at the TG chain pillars. The mean B-Zone thickness values range from 20 m to 44 m.

- D-Zone surface cracking depths are estimated to range between 10 m and 12 m along the downslope side of a subsided steep slope and 15 m to 30 m along the crest of the slope.

- A-Zone fracture heights above LW51 are estimated to range 63 m to 75 m if the mining height is reduced to 3.8 m (from 4.2 m) where the cover depth is 90 m; and from 55 m to 66 m where mining height is reduced to 3.6 m where the cover depth is 80 m.

- The minimum B-Zone thickness due to the reduced mining heights is therefore estimated to range between 13 m and 15 m where maximum surface cracking may extend to depths of 10 m and 12 m along the downslope side of the panel. The mean B-Zone thickness values range from 21 m to 24 m for the reduced mining heights.

- It is considered 'unlikely' that A-Zone cracks will intersect with surface D-Zone cracks if the proposed reduction in mining heights are adopted.

LW52

- Worst-case A-Zone Fracture Heights if the full seam thickness is mined (i.e. 4.3 m to 4.5 m) are predicted to range from 91 m to 116 m for cover depths of 110 m to 140 m respectively.

- The minimum constrained or B-Zone thickness (above the A-Zone) is estimated to range between 19 m and 24 m above LW52. The lowest value in the range is for the low side of LW52 where cover depth is 110 m at the base of an ephemeral creek. The mean B-Zone thickness values range from 34 m to 44 m.

- D-Zone surface cracking depths above LW52 are estimated to range between 12 m and 15 m along the base of the valley and from 15 m to 20 m along the crest of the ridge slope.

- Worst case A-Zone fracture heights above LW52 are therefore 'unlikely' to intersect with worst case surface D-Zone cracks if the full seam height is extracted.

Table 9 - Sub-Surface Fracture Height Summary for LWs 51 to 52

LW	Panel Width W (m)	Cover Depth H (m)	Mining Height T (m)	Forster Model A-Zone Height^ (m)	Buckingham PI Term Model* A Zone Height (m)	Surface D-Zone Thickness# (m)	Constrained Zone Thickness& H-A (m)
Current Mining Heights							
51	178.8	130	4.3	77 - 90	91 - 109	20	21 - 39
51	178.8	120	4.3		85 - 101	15	19 - 35
51	178.8	110	4.3		78 - 94	15	16 - 32
51	178.8	100	4.2	76 - 88	71 - 85	12	15 - 29
51	*178.8*	*90*	*4.2*		*65 - 78*	*12*	*12 - 25*
51	*178.8*	*80*	*4.2*		*60 - 71*	*10*	*9 - 20*
52	206.8	140	4.5	81 - 95	99 - 118	20	22 - 41
52	206.8	125	4.5		89 - 107	15	18 - 36
52	206.8	110	4.3	77 - 90	78 - 94	15	16 - 32
Recommended Reduction to Mining Heights							
51	178.8	90	3.8	68 - 80	63 - 75	12	15 - 24
51	178.8	80	3.6	65 - 76	55 - 66	10	13 - 21

* - Predictions are mean and U95% Confidence Limit values based on the PI-Term Model and an effective strata unit thickness t' of 14 m;
^ - Forster model for supercritical panels ranges from 18T to 21T based on measured subsurface fracture heights above LWs 39 to 41.
Italics - mining height to be reduced from 4.2 m to minimise surface connectivity potential to mine workings.
- D-Zone cracking depth assumptions are 20 m on the crest of a steep slope; 10 m along toe of a steep slope; 15 m in base of valley and 12 m typically.
& - Constrained Zone thickness includes surface cracking depth and based on the PI-Term Model.

The predicted mean and U95%CL values for the heights of A-Zone fracturing are presented in **Figures 26a** and **26b** respectively. The measured heights of A-Zone fracturing above LWs 39 to 41 are also shown for comparative purposes. A strata unit thickness of 14 m has been back analysed to give the best fit to the measured results. It is considered appropriate to fit the model to the mean values to allow for measurement and surface cracking depth estimate error.

The results for the PI-Term Model indicates that the height of A-Zone fracturing for the recommended mining heights are 'unlikely' to intersect with the surface cracking zone for cover depths > 80 m. Further discussion on prediction model uncertainties are presented in **Section 12.3.5**.

Further details on the measurement of the heights of fracturing above LWs 39 to 41 are provided in **DgS, 2013b**.

12.3.5 Discussion of Prediction Model Uncertainties

The PI-Term model indicates that the height of fracturing is expected to increase with panel width, cover depth and mining height. This is because the cover depth drives the compression of the goaf and the subsequent bending and ultimately cracking of overlying strata units (see **DgS, 2013b**). For supercritical panels, the panel width is not as great an influence as for sub-

critical panels, and using the mining height only to predict heights of fracturing model is a valid if not more conservative method compared to the PI-Term model.

By reducing the mining height from 4.2 m to 3.8 m at a cover depth of 90 m, the PI-Term model predicts the mean and U95%CL A-Zone height of 63 m and 76 m respectively. This will put the A-Zone 14 m to 27 m below the surface and at a reasonable depth below the worst-case surface cracking depth of 10 m to 12 m along the toe of the steep slope.

It is also assessed that as the surface along the downslope side of the panel is also likely to be in compression due to surface topography the surface cracking depth will probably be < 12 m. The presence of weathered and/or tuffaceous materials near the surface will also reduce the potential for A-Zone and D-Zone crack interconnection in this area.

12.3.6 Impact Management Strategies

Based on discussions with the specialist groundwater consultant for the Project Area, there is an absence of surface alluvium along the ephemeral creeks and gullies in the proposed mining extension area.

The presence of geological structure however, should be viewed with caution in regards to potential interaction with surface water courses. Undermining significant faults may result in higher continuous fracture connectivity and water makes and should therefore be avoided if possible. At this stage, no significant geological structure has been detected above the panels.

12.5 Slope Stability

12.5.1 Potential Impacts

The following potential impact hazards due to subsidence of the steep slopes have been identified:

- General slope instability (translational / rotational sliding);
- Local instability due to cracking and erosion;
- Rock movements down steep slopes (falling, bouncing and rolling boulders) from rocky outcrops.

The likely impacts of the proposed mining layout have been assessed in the following sections. Options to manage these impacts appropriately have also been provided.

12.5.2 General Stability

The likelihood of *en-masse* sliding (i.e. a landslip) of the steep slopes or hills over basal siltstone and claystone beds that have been cracked and tilted by subsidence has been assessed

based on reference to **Das, 1996**, **Hoek 2000** and the landslide risk assessment terminology presented in **AGS, 2007**.

Based on field mapping and observation of aerial photographs (Google), there was no evidence of existing or past slope instability noted along the existing slope area.

It is considered that the stability of steep soil slopes will be dependent on the following key changes to the surface topography due to mine subsidence:

(i) existing slope magnitude and change in gradient due to tilt;

(ii) orientation and depth of cracking due to tensile strain;

(iii) presence of water in and on-going erosion of cracks;

(iv) depth of soil cover;

(v) stabilising effect of vegetation;

(vi) the completion of post-mining crack repair works.

Based on reference to **Fell et al, 1992,** any siltstone and mudstone units that may be present at the base of massive conglomerate units on the ridges on the site have been assumed to have a lower bound, drained angle of friction (Ø') of 15°. Saturated slopes with water filled joints or mining-induced cracks have been assumed representative of worst-case conditions.

The predicted tilts for the slopes above the proposed longwalls are expected to change existing gradients by between 3° and 4° (i.e. 40 to 70 mm/m tilt). This would indicate that any near-surface rock beds will have their dip increased from about 3° to a range of 6° to 7° on north and south facing slopes above LWs 51 and 52.

The predicted cracking widths of up to 833 mm along the high sides of the proposed panels suggests that surface water will be able to enter the slopes for depths of approximately 20 m and potentially affect their stability due to softening of mudstone or claystone beds and the development of perched water tables.

The stability of the 20^{o} to 35^{o} slopes (which have an average slope of 24.5^{o} based on **Figure 27a**) has been assessed for large-scale block sliding on claystone beds in wet (saturated) and dry conditions before and after the effects of longwall mining.

The factor of safety (FoS) for large scale block translational sliding of interbedded sandstone and shale strata units has been calculated using a simple force balance model defined in **Hoek, 2000**; see **Figure 27b**. The weight force of a unit width of a dry or wet, cracked slope with perched water present (in the cracks) acting down the slope versus the frictional resistance against sliding on claystone bedding planes has been calculated as follows:

$W = (d_r g)h^2 ((1-(z/h)^2)\cot(a) - \cot(b))$ = weight of rock slope block with density (d_r), gravity constant (g), depth (h), crack depth (z), bedding or failure plane slope (a) and surface slope (b).

$z = H (1-(\cot(b)\tan(a))$ = maximum tension crack depth for the minimum FoS of the given rock slope geometry.

$U_1 = d_w g z_w^2/2$ = driving force of water (with density d_w) filled crack of depth z_w on the slope block.

$U_2 = d_w g z_w X/2$ = driving force of water (with density d_w) filled crack of depth z_w along the base distance X the slope block.

$X = (H-z)/\sin(a)$ = base length of sliding rock block

$T = W\sin(a) + U_1\cos(a)$ = driving force of rock block (W) and a water filled crack (U_1)

$S = cX + [W\cos(a)-U_2-U_1\sin(a)]\tan(\phi)$ = rock block sliding resistance along a potential failure plane with drained cohesion, c' and drained friction angle, ϕ'.

FoS = S/T = factor of safety against sliding.

The slopes in their current condition are assessed to have a 'Low' sliding potential over an extreme range of climatic conditions (i.e. Dry to Saturated) with an FoS range of 2.79 to 5.1. This is confirmed by the absence of slope features that are indicative of existing or past slope instability.

If the slopes are subjected to cracking and an average tilt of 70 mm/m after mining, the FoS against sliding is estimated to range from 1.64 to 1.01 for wet conditions with water filled cracks.

Based on a recommended minimum short-term FoS of 1 (**Levanthal and Stone, 1995**) it is assessed that it is 'unlikely' that a large scale instability or landslip will occur provided groundwater levels do not rise above a level that is 8 m below the surface in a 23 m deep crack within the project area, and where average tilts of up to 70 mm/m have occurred. The stability of the slopes may become marginal unless surface cracking can be repaired or sealed in a timely manner.

Further details on slope stability risks and their management are provided in **DP, 2013**.

12.5.3 Shallow Soil Cover Instability

The stability of shallow clayey sands/sandy clay slopewash on the 20 to 35 degree slopes were assessed based on the infinite slope model presented in **Das, 1998**. The model assumes the soil slope above the slide plane is uniform; see **Figure 27c**.

The sandy clay soils on the slopes are likely to be subject to dry and wet (saturated) conditions before and after the effects of cracking due to longwall mining.

The factor of safety (FoS) for translational sliding of the sandy clay soils over the sandstone and claystone strata units has been calculated using the simple force balance equations below. The weight force of a unit width of soil and water (if present) acting down the slope and the frictional resistance against sliding has been calculated as follows:

$W = (d_s g)bh$ = weight of a 1 m wide soil block with density d_s, gravity constant, g, length b, and depth h.

$T = (W+U)\sin(a)$ = driving force along potential failure plane of slope, a.

$V = d_w gz/\cos(a)$ = uplift force of water (with density d_w) in a saturated soil of depth z on the slope.

$U = d_w gz^2/2$ = driving force of water (with density d_w) filled crack of depth z on the slope.

$S = c'b/\cos(a) + (W\cos(a)-V-U\sin(a))\tan(p')$ = sliding resistance along potential failure plane with drained cohesion, c' and drained friction angle, p'.

FoS = S/T = factor of safety against sliding.

The above theory indicates that the stability of the slopes will be most sensitive to (i) soil cover thickness and (ii) water filled cracks.
The drained soil strength parameters c' and p' were based on assumed conservative peak soil parameters of c' of 5 kPa and p' of 28^o for the stiff clayey sands/sandy clays and reference to **Lambe and Whitman, 1969** and **Leventhal and Stone, 1995**. The FoS for existing slopes were back calculated to before mining impacts of cracking and tilting. A conservative thickness of the soil profile on the steep slopes was assumed to be 0.75 m on the slopes < 26.5^o and 0.5 m on the slopes > 26.5^o. The soil /rock face interface soil thickness and strength assumptions were based on the observation that there have been no sliding failures on the slopes to-date.

The FoS for worst-case, pre-mining conditions with saturated, uncracked, 20^o to 35^o slopes ranged from 1.34 to 1.10.

Based on the predictions of principal tilt and strain on the slopes after mining, the steep slopes were considered likely to be subject to full soil profile cracking at some stage during or soon after mining. The stability assessment was therefore completed for the steep slopes for the range of climatic (i.e. dry or wet) and worst-case mine subsidence impacts. The FoS for worst-case, post-mining conditions with saturated, cracked, 24.5^o average slope ranges from 1.10 to 1.01.

Based on the above, it is considered that the proposed mining impacts on the slopes could result in marginally stable conditions developing in the soils at locations where tensile cracking has occurred and prolonged rainfall events have saturated the soil and filled the cracks to the surface (i.e. there will be 'High' potential for instability).

Remediation of slope cracks should therefore be undertaken as soon as practicable after mine subsidence has fully developed.

12.5.4 Local Instability and Erosion

Local instability refers to the following impacts due to subsidence:

(i) rock falls from outcrops;

(ii) erosion / deposition adjustment of watercourse channels.

The predicted impacts of the tilts are also considered 'very unlikely' to cause localised surface instability to soil slopes unless mining-induced cracking and increased erosion rates also affect them.

The rate of soil erosion is expected to increase significantly on crack affected slopes that have gradients > 10° and are subjected to cracking and the estimated tilt increases of 3^o to 4^o The long-term stability of the proposed first workings pillars in the main headings beneath the motorway (to provide access to LWs 51 and 52).

The presence of surface vegetation in the LW51/52 mining area will minimise the potential for increased erosion due to changes in surface gradients. Erosion impact is also likely to be exacerbated where cracking is orientated down the slopes.
Areas with slopes < 10° are expected to have low erosion rate increases, except for the creek channels, which would be expected to re-adjust to any changes in gradient.

The potential for rock-fall roll out from bedrock outcrops should also be considered in regards to the development of public safety management plans in areas where steep slopes are present. The trees present below the cliff lines will probably limit the distances at which boulders will be able to roll down slope.

Further discussion on surface water course impacts is discussed in the Environmental Assessment.

12.7 Valley Closure and Uplift

12.7.1 Predictions and Potential Impacts

As discussed in **ACARP, 2002**, when creeks and river valleys are subsided, the observed subsidence in the base of the creek or river is generally less than would normally be expected in flat terrain. This reduced subsidence is due to the floor rocks of a valley buckling upwards

when subject to compressive stresses generated by surface deformation. In most cases in the Newcastle and Southern NSW Coalfields, the observed uplift has extended outside steep sided valleys and included the ground beyond them.

The movements are strongly dependent on the level of 'locked-in' horizontal stress immediately below the floor of the gullies and more importantly the bedding thickness of the floor strata (i.e. thin to medium bedded sandstone is more likely to buckle than thicker, massive beds). The influence of the aspect ratio (i.e. valley width/ depth) is also recognised as an important factor, with deep, narrow valleys having greater upsidence than broad, rounded ones, due to higher stress concentrations.

Based on **Figures 2** and **3**, there are three valleys and one man made cutting (Cutting 2) that may be affected by closure and uplift movements due to subsidence from LWs 51 and 52. The valleys are located above or adjacent to LW52 and two of them have the Aboriginal grinding grooves of 'extremely high' cultural significance (No.s 38-4-1279 and 38-4-1007).

Predicted closure and uplift movements for the valleys and motorway cutting and proposed longwalls have been assessed using the Southern Coalfield model in **ACARP, 2007** and are summarised in **Table 10**.

Table 10 - Predicted Valley Closure and Uplift

Surface Feature	Longwall	Feature Location Relative to panel*		Valley Depth	S_{max} over LW (m)	Final Closure^ (mm)	Final Uplift (mm)	Final Comp. Strain (mm/m)
		Lateral Lx (m)	Longitudinal Ly (m)					
Cutting No. 2	51	0	-95	40	2.4	14	9	0.3
	52	-63	0		2.6	24	8	0.5
Valley 1	51	-133	240	35	2.4	180	73	0.5
	52	76	240		2.6	300	255	12
Valley 2 (No. 38-4-1007)	51	-352	300	30	2.4	42	30	0.0
	52	-116	300		2.6	140	60	0.75
Valley 3 (No. 38-4-1279)	51	-303	200	25	2.4	80	36	0.0
	52	-67	200		2.6	120	56	1.25

* - Distance from MG side of longwall panel (L_x) and nearest panel end (L_y). Negative values indicate site is located outside of extraction limits.
^ - Closure is assumed to occur across the steepest valley section.
+ - Final compressive strain (i.e. cumulative) due to longwall(s).

High horizontal stresses have been measured along the M1 Motorway cuttings (10 MPa at 27 m depth in Cutting 2) and uplift movements of 230 mm have occurred (Cutting 7A) after LW28 was extracted within the angle of draw. It was observed that cracking of the motorway and shotcrete batters did not occur until measured uplift movements > 80 mm had occurred.

Cutting 7A was up to 30 m deep and 50 m wide across the base, with massive conglomerate strata in the cutting walls and medium bedded sandstone beneath the cutting floor. The uplift movements damaged the reinforced concrete pavements and shotcrete lining on the batters.

As a result of the above impact, subsequent longwalls have only been extracted outside of the angle of draw to the motorway and its infrastructure. The panels were also re-orientated to retreat towards the motorway instead of sub-parallel to it. The changes have result in no further impact to cuttings or embankments.

To-date, closure and uplift measurements across several drainage gullies above extracted panels in the Northern and Eastern Domains (LWs 27 to 37) have not been significant, as measured movements have been similar to the available survey accuracy for total station observations (i.e. +/- 20 mm). Reference to **Metropolitan, 2010** indicates that surface cracking in rock bars may develop if closure movements > 200 mm occur across valleys or compressive strains are > 3 mm/m. The predicted closure and compressive results in **Table 10** therefore indicate that cracking is unlikely to develop in Valleys 2 and 3 but may occur in Valley 1 (see **Figures 2** and **3**).

The proposed longwalls have similar end-on orientation to the latter panels and will also finish further away from the motorway than previous panels. It is therefore considered 'very unlikely' that the motorway or its infrastructure will be impacted by valley closure or upsidence.
The development of upsidence > 80 mm or subsidence cracking above the panels may cause localised deviation of surface flows along rocky, ephemeral creek beds to sub-surface routes. The re-routed surface flows would be expected to re-surface downstream of the impacted area with no net loss to the hydrological system.

12.7.2 Impact Management Strategy

The impact of valley closure effects due to mine subsidence may be managed as follows:

(i) Install and monitor survey lines along ephemeral drainage gullies and along gully crests during and after longwall undermining. Combine with visual inspections to locate damage (cracking, uplift).

(ii) Review predictions of upsidence and valley crest movements after each longwall.

(iii) Assess whether repairs to cracking, as a result of upsidence or gully slope stabilisation works are required to minimise the likelihood of long-term degradation to the environment or risk to public safety.

(iv) Install and monitor early warning survey lines in consultation with stakeholders to provide sufficient time to respond to subsidence effect exceedances which may damage sensitive infrastructure or feature.

(v) Development a Management Plan with the relevant stakeholders.

12.9 Aboriginal Archaeological Sites

12.9.1 Impact Potential Criteria

The potential for impact to the Aboriginal heritage sites identified above and to the east of LW52 has been estimated based on the predicted final subsidence, tilt, and strain contours presented in **Figures 23a** to **23c** with reference to the risk ranking criteria in **Table11**.

Table 11 - Impact Potential Criteria for Aboriginal Heritage Sites

Key	**Cracking Potential**	**Indicative Probabilities of Occurrence**	**Predicted 'Smooth profile' Tensile Strain (mm/m)**
VL	Very Low	Very Unlikely (<5%)	<1
L	Low	Unlikely (5 - 10%)	1 - 1.5
M	Moderate	Possible (10 - 25%)	1.5 - 2.5
H	High	Likely (>25%)	>2.5
Key	**Erosion Damage Potential**	**Indicative Probabilities of Occurrence**	**Predicted Surface Gradient Change**
VL	Very Low	Very Unlikely (<5%)	<0.3%
L	Low	Unlikely (5 - 10%)	0.3-1%
M	Moderate	Possible (10 - 25%)	1-6%
H	High	Likely (>25%)	>6%

The ‘cracking potential’ is considered the primary impact indicator and the ‘erosion damage potential’ a secondary indicator of damage (i.e. the presence of erosion and sedimentation increases at a site may result in unacceptable long-term degradation of a site).

12.9.2 Potential Impacts to Grinding Groove Sites

The predicted worst-case subsidence parameters at the Palmers Creek Grinding Groove sites are presented in **Table 12**.

Table 12 - Predicted Worst-Case Subsidence Impacts at Grinding Groove Sites

Site No.	**LW #**	**Subsidence (m)**	**Tilt (mm/m)**	**Final Strain (mm/m)**	**Cracking Potential**
38-4-1279	52	0.00	0	*1.4*	Very Low
38-4-1007	52	0.00	0	*0.7*	Very Low

Note:
Bold - key sites requiring RMZ impact protection.
Predictions based on **Figures 23a** to **23c**.
* - negative crack widths indicate low-angle shearing.
^ - refers to transient tensile strains that may occur as subsidence develops at the site.
italics - far-field effect prediction.

Based on the review of chain pillar crack location data, it is assessed that the proposed mining layout controls instigated for the grinding groove sites are likely to provide adequate protection with 'very low' cracking potential assessed.

The erosion potential at the key sites is assessed as 'very low' (i.e. < 0.3% gradient increase) and ranges from 'very low' to 'moderate' for the other sites.

12.9.3 Potential Impacts to Scarred Tree

The predicted worst-case subsidence parameters at the Palmers Creek Scarred Tree 1 are presented in **Table 13**.

Table 13 - Predicted Worst-Case Subsidence Impacts at Scarred Tree

Site No	LW#	Subsidence (mm)	Tilt (mm/m)	Final Strain (mm/m)	Cracking Impact Potential
Palmers Creek Scarred Tree 1	52	100	5	5	Very Low to Low

Predictions are based on **Figures 23a** to **23c**;

Based on **Table 11** and earlier discussions regarding the potential for cracking outside of panel limits due to interaction with steep slopes, it is assessed that surface cracking up to 50 mm wide could develop somewhere within a distance of 0.2H or 26 m from the panel limits and at a frequency of approximately one crack every 10 m or 15 m (i.e. 2.6 to 1.7 cracks/0.2H).

The probability that a crack will develop at the tree site has been therefore been quantified by dividing the diameter of the tree with the distance and frequency in which cracking could develop outside the limits of extraction of LW52 to give 1.7 to 2.6 cracks times 0.7/26 = 4.6% to 7 %.

Table 11 indicates that a probability of cracking impacts occurring at the scarred tree is ‘very low’ to ‘low’.

12.9.4 Potential Impacts to Artefact Sites

The predicted worst-case subsidence parameters at the Palmers Creek artefact and individual find sites are presented in **Table 14**. The individual find site is located within the limits of LW52 extraction, whilst the artefact site is approximately 80 m east of LW52.

Table 14 - Predicted Worst-Case Subsidence Impacts at Artefact Sites

Site No	LW#	Subsidence (mm)	Tilt (mm/m)	Final Strain (mm/m)	Cracking Impact Potential
Palmers creek Individual Find IF5	52	2.2	20	+/- 10	Very Low
Artefact Site 38-4-1530	52	0.0	0.0	<0.5	Very Low

Predictions are based on **Figures 23a** to **23c**;

Table 11 indicates that the probability of cracking impacts occurring to the artefact and individual find site is 'very low'.

12.9.5 Impact Management Strategies

The impact management strategies for the two grinding groove sites are provided in the Project Approval Conditions. The scarred tree, artefact and individual find sites were discovered after the Project Approval Conditions were prepared.

In summary, WWC are required to prepare an Aboriginal Cultural Heritage Management Plan (ACHMP) that is consistent with Aboriginal cultural heritage values. The ACHMP developed has led to the current set back distances of the proposed panels to be implemented for the grinding groove sites and scarred tree site. The salvaging of the IF5 to a keeping place should be considered prior to the extraction of LW52.

12.10 Ryhope Lots (Undeveloped)

12.10.1 Potential Impacts

There are approximately 20 undeveloped lots on LMCC-owned land within the zone of subsidence above LW51. The predicted subsidence effects on the lots are summarised in **Table 15**.

Table 15 - Predicted Subsidence Impact Parameters for the Undeveloped Lots

Nearest XL	Cover Depth (m)	Mining Height (m)	Subsidence (m)	Tilt (m/m)	Strain (mm/m)	Crack Width* (mm)
14	85 - 120	4.2	2.44	62 - 94	-30 - 24	-300 - 240

Based on the predicted strains, it is estimated that cracks of up to 240 mm wide could develop on some of the lots. The predicted tilts are likely to decrease the existing gradients on the lots by up to 5^o (currently 10^o to 20^o) to leave a range of 5^o to 15^o after mining.

12.10.2 Impact Management Strategies

It will be necessary for the mine to ensure that the proposed mining does not diminish the capability of the site to be developed in the future for residential subdivision.

Appropriate impact management strategies for the lots would be:

- remediate surface cracks;
- restore natural drainage paths across the lots;
- remove unstable trees.

12.12 Access Roads

12.12.1 Potential Impacts

The predicted subsidence effects for the access roads are summarised in **Table 16**.

Table 16 - Predicted Subsidence Impact Parameters for the Access Roads

Longwall	Cover Depth (m)	Mining Height (m)	Subsidence (m)	Tilt (m/m)	Strain (mm/m)	Crack Width* (mm)
51	130	4.2	2.44	94	-30 - 24	-300 - 240
51	120	4.3	2.49	78	-23 - 18	-230 - 180
52	125	4.3	2.61	102	-32 - 25	-320 - 250
52	140	4.5	2.49	80	-24 - 19	-240 - 190
52	125	4.5	2.61	73	-20 - 16	-200 - 160

* - Negative strains and crack widths indicate compression and shearing displacements respectively.
Italics - No mining beneath this section of road.

Based on the predictions for tensile and compressive strain, the worst-case crack widths are estimated to range between 160 mm and 250 mm across the access roads where they pass through the tensile and compressive strain zones above each longwall panel. It is noted that crack widths above LW 44, which has similar cover depths to LW51 and 52, has been < 50 mm to-date.

It is estimated that approximately 30 to 50 m of the road above each longwall will require repairs to tensile cracking or compressive shear failures through the road after mining of each panel is completed.

Some erosion damage may also occur due to changes in drainage paths along the sides of the road and the installation of new table drains or possibly culverts across the road may be necessary. As the road is located along a ridge crest, no ponding impacts are expected to occur.

12.12.2 Impact Management Strategies

Appropriate impact management strategies would be:

(i) The development of a suitable monitoring and response plan, based on consultation with OEH and other regulatory authorities, to ensure the management of road impacts do not result in unsafe conditions during and after the effects of mining.

(ii) Management of impacts would include restricting access to the project area and visual inspections of the roads on a weekly basis just prior to and after undermining of the road until 90% of subsidence has developed (usually occurs when the longwall face has retreated 1.4 x the cover depth past the road). The inspections should be completed above each panel and any impacts repaired promptly in accordance with the Extraction Plans for the proposed panels.

(iii) Erection of signage along the affected area which cautions drivers / riders of vehicles / motorbikes / mountain bikes of the hazards associated with mine subsidence. A contact phone number should be provided if subsidence impacts are encountered.

12.13 Wakefield Road

12.13.1 Potential Impacts

Wakefield Road is located in Cutting 2 and Fill 2 in the vicinity of LWs 51 and 52 and beyond the predicted 20 mm subsidence limits from the corner and the ends of the panels. This section of Wakefield Road and embankment is therefore unlikely to be impacted by vertical subsidence. A far-field subsidence impact assessment has been completed in **Section 12.10** and indicates cracking is 'unlikely' to occur.

12.13.2 Impact Management Strategies

Appropriate impact management strategies would be:

(i) The development of a suitable monitoring and response plan, based on consultation with LMCC and regulatory authorities, to ensure the management of impacts on the road does not result in unsafe conditions during and after the effects of mining.

(ii) The stability of the embankment will also need to be monitored along the crests and toes, with cracks repaired as soon as possible to prevent excessive moisture ingress into the embankment.

(iii) It is recommended that the daily inspections of the road should be provided for the last 300 m of longwall retreat for LW51 and LW52.

12.14 Far-Field Horizontal Displacements

12.14.1 Background to Prediction Model Development

Horizontal movements due to longwall mining have been recorded at distances well outside of the angle of draw in the Newcastle, Southern and Western Coalfields (**Reid, 1998, Seedsman and Watson, 2001**). Horizontal movements recorded beyond the angle of draw are referred to as far-field horizontal displacements.

Far-field displacements (FFDs) generally only have the potential to damage long, linear features such as pipelines, bridges and dam walls.

For example, Cataract Dam in the Southern NSW Coalfield, **Reid, 1998**, reported horizontal movements of up to 25 mm when underground coal mining was about 1.5 km away. Seedsman reported movements in the Newcastle Coalfield of around 20 mm at distances of approximately 220 m, for a cover depth ranging from 70 to 100 m and a panel width of 193 m. However, the results may have been affected by GPS baseline accuracy limitations.

Based on a review of the above information, it is apparent that this phenomenon is dependent on (i) cover depth, (ii) distance from the goaf edges, (iii) the maximum subsidence over the extracted area, (iv) topographic relief and (v) the horizontal stress field characteristics.

An empirical model for predicting far-field displacement (FFDs) in the Newcastle Coalfield is presented in **Figure 28**. The model indicates that measurable FFD movements (i.e. 20 mm) generally occur in relatively flat terrain for distances up to 2 to 3 times the cover depth.

The direction of the FFD movement is generally towards the extracted area, but can vary due to the degree of regional horizontal stress adjustment around extracted area and the surface topography. The movements also appear to decrease around the corners of longwall panels.

Any sensitive surface feature, such as a bridge or culvert, within 3 times the cover depth (i.e. 300 m to 400 m from the proposed longwalls) should therefore be assessed and monitored for FFD movements during mining.

An empirical model for predicting far-field strains (FFSs) in the Newcastle Coalfield is presented in **Figures 29a** and **29b**. The model indicates that measureable (but diminishing) strains can also occur outside the limits of longwall extraction for distances up to 2 times the cover depth (based on the Upper 95% Confidence Limit curve). It should be noted that the model was based on steel tape measurements which did not extend further than a distance equal to the 1.5 times the cover depth from the extraction limits. Any FFS predictions that are >1.5 times the cover depth from the panels in this report are therefore an extrapolation of the regression lines for the database and likely to be conservative.

12.14.2 Numerical Modelling

Two far-field numerical modelling exercises were completed in **SEA, 2006** and **SEA, 2007** for the purpose of estimating the worst-case horizontal movements along the motorway, its

associated infrastructure and the services easement for the first five longwall panels in the Western Domain and five panels in the Southern Domain.

The Map-3D® model used was an elastic boundary-element program which was used to model the surface displacements and strains caused by horizontal stress relief into the caving zones above all of the longwall panels mined and proposed at West Wallsend Colliery. The model was calibrated to (i) measured far-field displacements at several surface features after several longwalls were extracted and (ii) horizontal stress measurements in investigation boreholes that were drilled in ridges proposed for the M1 Motorway cuttings.

The Map-3D® modelling was done to assess the cumulative impacts of mining on both sides of the motorway and possible divergences between the empirical model estimates. The numerical modelling also indicated that the horizontal stress tended to decrease in the overburden between the Western and Southern Domains due to stress relief effects in the caving zones above the panels.

One of the outcomes from the study was the assessment that the prediction of cumulative effects were considered too complex for single panel empirical models as the model was being used to predict the deflected profiles of the motorway pavement, pipelines and optic fibre cables and relative movements between bridge abutments. However, in regards to mine planning predictions, the use of superimposition techniques and the empirical models developed by DgS resulted in good agreement between the calibrated numerical model and empirical model values.

The issue of prediction model uncertainty can also be handled better by the empirical models, as the numerical model was calibrated to observed displacements to provide an 'expected' prediction response to mining. The uncertainty in the numerical model predictions then needs to refer to empirical models.

The empirical model's mean and U95%CL strain curves have been adopted to provide reasonably conservative outcomes when superimposition techniques are applied for multiple panel impact predictions. In some instances, the U99%CL curves have been used where additional conservatism is warranted (i.e. the services easement or steep slope interaction).

Discontinuous FFD response due to the presence of NW striking faults was also assessed in **DgS, 2009** study with Map-3D®. Very low shear strength and stiffness fault plane properties were assumed. The modelling results indicated that shearing at bridges between the longwall blocks was 'very unlikely' to damage these structures or render them 'unsafe'. A similar pair of bridges were also unaffected by the extraction of LW26 to the north of the project area.

The following sections discuss predicted impact and management strategies for infrastructure and utility features located within the limits of potential far-field horizontal displacements.

12.14.3 Potential Far Field Effects and Impacts at the M1 Motorway and Infrastructure

The nearest points of each proposed longwall panel to the motorway are the north-west corners of the panels (see **Figure 1**). The shortest distances from the motorway pavements

(north and south bound lanes) to the proposed longwall panel finishing ends range from 44° to 87°, which indicates that the motorway is 'likely' to be located outside the angle of draw limits to measurable vertical subsidence.

The predicted final far-field displacements and strains (U95%CLs) at the motorway pavements (north and south bound carriageways), cuttings and fills due to LWs 51 to 52 are summarised in **Table 17**.

The displacements and strains shown are located where the longwall panel centrelines have been projected out to intersect with the motorway. Principal displacements and strain directions were assumed to act towards the centre of the panel ends.

The principal movements were transformed into lateral (y-axis) and longitudinal (x-axis) components relative to the motorway axes at a given location. Positive lateral movement was assumed acting towards the Western Domain (i.e. NW to NNW) and positive longitudinal movement generally towards the NNE to NE along the motorway itself.

The worst-case impact to the motorway pavements after mining is assessed to be 'negligible'.

Table 17 - Predicted Far-Field Displacements and Strains (U95%CL Values) at the M1 Motorway Infrastructure

LW #	Location	Distance from Panel z (m)	Cover Depth H (m)	z/H	Angle of Draw (o)	Max Panel Subs. (m)	Predicted Cumulative Horizontal Displacement u (mm) 1=principle x=longitudinal y=lateral			Predicted Horizontal Strain, e (mm/m) x=longitudinal y=lateral	
							u_1	u_x	u_y	e_x	e_y
51	Fill 1	80 (cnr)	90	0.83	42	2.4	**19**	0	19	0.04	**0.13**
	Cut 2	95	115	0.89	40	2.4	**43**	0	43	0.24	**0.72**
	South BL	160	115	1.39	54	2.4	**20**	0	20	0.08	**0.24**
		258	115	2.24	66	2.4	**6**	-3	5	0.02	**0.05**
	North BL	220	110	1.97	62	2.4	**10**	0	10	0.03	**0.09**
		365	110	3.17	73	2.4	**2**	-1	1	0.00	**0.01**
	Wakefield	130	115	1.13	49	2.4	**28**	0	28	0.13	**0.40**
		230	115	2.00	63	2.4	**9**	-7	5	0.02	**0.08**
52	Cut 2	63 (cnr)	110	0.57	30	2.6	**32**	32	0	**0.37**	0.12
	Fill2	137	110	1.25	51	2.6	**26**	1	14	0.11	**0.35**
		274	110	2.49	68	2.6	**5**	-3	3	0.01	**0.03**
	South BL	187	110	1.70	60	2.6	**14**	1	9	0.05	**0.15**
		295	110	2.68	70	2.6	**4**	-2	1	0.01	**0.02**
	North BL	220	110	2.00	63	2.6	**9**	0	20	0.03	**0.08**
		365	110	3.32	73	2.6	**2**	-1	3	0.00	**0.01**
	Wakefield	158	110	1.44	55	2.6	**20**	1	26	0.08	**0.24**
		296	110	2.	70	2.6	**4**	-2	4	0.01	**0.02**

Bold - maximum value for location.

12.14.4 Potential Far Field Effects and Impacts at Buildings, Telstra Tower and Services Easement

Predictions of far-field effects have been completed for two buildings to the south of LW51, the Telstra communications tower and services easement to the north-west of LW51. The results are summarised in **Table 18**.

Table 18 - Summary of Predicted Far Field Effects for Various Structures

LW#	Location	Distance from Panel z (m)	Cover Depth H (m)	z/H	Angle of Draw (o)	Max Panel Subs. (m)	Predicted Cumulative Horizontal Displacement u (mm)	Predicted Horizontal Strain, e (mm/m)
51	Building 1	172	100	1.72	60	2.2	13	0.13
51	Building 2	321	100	3.21	75	2.2	2	0.01
51	Telstra Comms Tower (CT3)	485	100	4.85	78	2.2	<2	<0.01
52		560	100	5.60	80	2.6	<2	<0.01
51	Services Easement	412	100	4.12	76	2.2	<2	<0.01
52		527	100	5.27	79	2.6	<2	<0.01

It is assessed that the predicted far-field effects are unlikely to cause impact to the structures assessed.

12.14.5 Far-Field Displacement Impact Management Strategies

Based on the study, the maximum cumulative horizontal displacement and tensile strain of the motorway and utility infrastructure is likely to be < 50 mm and < 0.8 mm/m respectively after the completion of the proposed longwalls in the Western and Southern Domains (including any localised shear displacements along faults).

For effective management of far-field displacement impacts, it is important to have a good understanding of (i) the tolerable movements of the long or spanning structures present within the zone of influence and (ii) the accuracy of the survey or monitoring techniques that will be required to provide real-time management information.

It is understood that the monitoring of utility infrastructure signal loss or decay (i.e. optical fibre cable) is a more appropriate (and direct) indicator of system distress than standard survey measurement techniques. The accuracy of current survey techniques is discussed further in **Section 14**.

13.0 Suggested Monitoring Program

13.1 Surface Monitoring

The following subsidence and strain monitoring program is suggested for providing adequate information to monitor and implement appropriate subsidence impact management plans in the project area:

(i) Install a minimum of one cross line above LWs 51 and 52 to monitor subsidence and strain development across Valley No. 1 and near the Scarred Tree Site No. 1 (see XL14 in **Figure 3**). The line should also be used to monitor valley closure between ridge crests and floor uplift movements.

Consideration should also be given to a second cross line to measure movements on the steep slope above LW51 (see XL15 in **Figure 3**).

(ii) Install centre lines at the finishing ends of both panels to monitor subsidence and strain development over the panels and out to Cutting No. 2 and Fill 2 respectively.

A survey line extending out at 45^{o} from the corner of LW52 to Cutting No. 2 is also suggested.

(iii) Conduct visual inspections and surveys of surface cracking (width and depth), slope instability and significant erosion during and after longwall extraction.

(iv) Conduct low frequency subsidence monitoring of RTA Cuttings/ M1 Motorway pavements, the utility easement and the section of Wakefield Road along the motorway and subject to review after the completion of each longwall panel.

(v) Visual inspections of axe grinding groove sites before and after LW51 and 52 extraction is completed.

The above monitoring program proposed is intended to allow the comparison between predicted and measured subsidence parameters for the relevant features. The survey pegs should be spaced at a minimum of 10 m for reasonable tilt and curvature measurement accuracy. A minimum of one baseline survey is recommended before mine subsidence effects occur.

Survey frequency will be dependent upon mine management requirements for subsidence development data in order to implement subsidence and mine operation management plans.

Reference to **ACARP, 2003** indicates that measurable subsidence at a given location above the longwall panel centreline is likely to commence at a distance of about 50 to 100 m ahead of the retreating longwall face; accelerate up to rates from 50 to 300 mm/day when the face is 0.2 to 1 times the cover depth past the point; and decrease to < 0.020 m/week when the face is

> 1.5 times the cover depth past the point (see **Figure 30**). Further subsidence is likely to develop due to compression of chain pillars when adjacent panels are subsequently mined.

Subsidence and strains may be determined using total station techniques to determine 3-D coordinates, provided that the survey accuracy is suitable. Survey accuracy using EDM and traverse techniques from a terrestrial base line is normally expected to be +/- 2mm for level and +/- 10 to 20 mm for horizontal displacement (i.e. a strain measurement accuracy of +/- 1 to 2 mm/m over a 10 m bay-length).

Alternatively Aerial Laser Scanning (Lidar) techniques may allow a reduction in ground based monitoring and provide subsidence data to within +/- 0.15 m, based on published information. Surface vegetation density can affect the accuracy however, and the method cannot be used to measure angle of draw.

13.2 Sub-surface Monitoring

Sub-surface monitoring such as height of fracture measurement above the longwalls is only recommended for providing information required to manage surface and groundwater resource impacts in areas with shallow depth of cover of < 100 m.

As there are no environmental features of interest above the panels where cover depths are < 100 m, it is not considered necessary to implement a sub-surface monitoring program for the proposed panels.

14.0 Conclusions

It is concluded that the assessed range of potential subsidence and far-field displacement impacts after the mining of the proposed longwalls LW51 to 52 will be manageable for the site features.

Provided the proposed impact management strategies are acceptable to the relevant stakeholders, the proposed mining layout and monitoring program suggested is considered reasonable.

In regards to the current Project Approval Conditions, the following impacts are assessed:

- The areal impact to the steep slopes due to the mining layout proposed is likely to be < 7%. There are no other landscape features of note above the proposed panels.

- Several risk assessment and planning meetings to-date have been held between the stakeholders so as to identify and minimise impacts deemed to be 'high' risk. As a result of this process, the proposed longwall panels have been pulled back to conservative angle of draw distances from the motorway Cutting No. 2, the Palmers Creek alluvium, two culturally sensitive Aboriginal heritage sites (axe grinding groove sites) and an area of low depth of cover < 80 m to the south west of LW51.

- Reducing the mining height to 3.8 m below the 90 m cover depth contour and to 3.6 m in the tailgate will reduce the probability of connectivity to "unlikely" for LW51. The depth of surface cracking is also expected to be a lower at the 80 m depth of cover area due to the topography (tensile strains smaller at the toe of a slope than on the high side of the slope). There are also no known geological structures (faulting/jointing) which could cause higher than predicted cracking.

15.0 References

ACARP, 1993. **Improved Methods of Subsidence Engineering**, NERDDP Project No. 1311.Willey, P., Hornby P., Ditton S., Puckett, G. & McNally,P.

ACARP,1998a. **Chain Pillar Design (Calibration of ALPS)**. Colwell, M., Mark, C.ACARP Report No. C6036 (October).

ACARP, 2002. **Subsidence Impacts on River Valleys, Cliffs, Gorges and River Systems**. Project No. C9067, Waddington Kay & Associates, Report WKA110.

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

ACARP, 2005. **Systems Approach to Pillar Design**. Strata Control Technologies Pty Ltd, UNSW School of Mining, Coffey Geosciences Pty Ltd. ACARP Project No. C9018. (May).

ACARP, 2007. **General Discussion on Systematic and Non Systematic Mine Subsidence ground Movements**. MSEC Report (Rev A) August.

AGS, 2010. **Commentary on Practice Note Guidelines for Landslide Risk Management.** Australian Geomechanics Society Journal Vol 42 No.1.

AS3798. **Guidelines on Earthworks for Commercial and Residential Developments**. Australian Standard (2007).

Aurecon, 2013. **Groundwater Monitoring Results for LWs 39 to 41**. *Report pending.*

Brady and Brown, 1985. **Rock Mechanics for Underground Mining**. 2nd Edition, Brady, B.H.G and Brown, E.T..Chapman & Hall, London.

Das, 1998. **Principles of Geotechnical Engineering** (4th Edition), Das, B.M., PWS Publishing Company Inc.

DgS, 2009. **Review of Telstra Optic Fibre Subsidence Simulation for LW35 at West Wallsend Colliery.** Ditton Geotechnical Services Report No. WWD-012/2 (Dec).

DgS 2011. **Post Mining Subsidence Review for LW38**. DgS Report No. WWD-012/4 (21/12/11).

DgS, 2012. **Post Mining Subsidence Review for LW39**. DgS Report No. WWD-012/11 (28/03/12).

DgS, 2013a. **Post Mining Subsidence Review for LW40**. DgS Report No. WWD-12/15 (26/03/13).

DgS, 2013b. **Sub-Surface Fracture Height Review and Predictions for the Proposed Longwalls 42 to 47, 51 and 52 at West Wallsend Colliery, Killingworth**. DgS Report No. WWD-012/8 (12/08/13).

DgS, 2013c. **Post Mining Subsidence Review for LW41**. DgS Report No. WWD-12/18 (21/09/13).

DgS, 2013d. **Long-Term Stability Assessment of the Proposed Main Access Headings associated with LWs 51 and 52 below the M1 Motorway**. DgS Report No. WWD-12/16a (15/12/13).

DMR, 1995. **The Newcastle Coalfield**. Geological Sheet Series. NSW Department of Minerals Resources.

DoP, 2008. **Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield: Strategic Review**. NSW Department of Planning (July).

DP, 2013. **Report on Geotechnical Assessment of Slope Stability Impacts Due to Mine Subsidence and of a Steep Slope Monitoring Program Associated with Proposed Longwall Panels 42 and 43**. Douglas Partners Report No. 81324 (December).

Fell et al, 1992. **Geotechnical Engineering of Embankment Dams**. Fell, R., MacGregor, P., Stapledon, D. Balkema.

Forster, 1995.**Impact of Underground Coal Mining on the Hydrogeological Regime, Central Coast, NSW**. Forster, I. Published in Australian Geomechanics Society (AGS) Conference Proceedings (February), Engineering Geology of Newcastle – Gosford Region, University of Newcastle.

Hawley and Brunton, 1995. **The Newcastle Coalfield, Notes to Accompany the Newcastle Coldfield Geology Map**. Hawley, S.P. and Brunton, J.S., Coal and Petroleum Geology Branch, Department of Mineral Resources.

Hoek, 2000. **A Slope Stability Problem in Hong Kong**. Practical Rock Engineering. Chpt 7.

Hoek and Diederichs, 2006. **Empirical Estimation of Rock Mass Modulus**. Hoek, E. and Diederichs, M.S. International Journal of Rock Mechanics and Mining Science, 43 (2).

Kendorski, 1993. **Effect of High Extraction Coal Mining on Surface and Ground Water**. Kendorski, F.S. Proceedings of the 12th Conference on Ground Control in Mining, Morgantown, WV.p412-425.

Lambe and Whitman (1969). **Soil Mechanics**. Lambe,T.W. and Whitman, R.V. John Wiley and Sons.

Levanthal and Stone,1995. **Geotechnical Design Features - Deep cuttings and High Embankments on the western Margin of the Newcastle Coal Measures (F3-Sydney/Newcastle Freeway)**. Levanthal, A.R. and Stone, P.C. Published in Australian Geomechanics Society (AGS) Conference Proceedings (February), Engineering Geology of Newcastle – Gosford Region, University of Newcastle.

Luo and Peng, 1999. **Integrated Approach for Predicting Mining Subsidence in Hilly Terrain.** Luo. Y., Peng, S.S.. US Society of Mining Engineering Journal (June).

Metropolitan, 2010. **Annual Environmental Monitoring Report for Metropolitan Mine**. Peabody Energy.

Mark, 2007. **Multi-Seam Mining in the United States: Background**. Mark, C.M. NIOSH Information Circular 9495.

Pells *et al*, 1998. **Foundations on Sandstone and Shale in the Sydney Region**, Pells, P.J.N., Mostyn, G. and Walker, B.F..Australian Geomechanics Journal.

Reid,1998. **Horizontal Movements around Cataract Dam, Southern Coalfields**. Reid, P. Mine Subsidence Technological Society 4th Triennial Conference Proceedings. Newcastle, July 1998.

Seedsman and Watson, 2001. **Sensitive Infrastructure and Horizontal Ground Movement at Newstan Colliery**. Seedsman, R. W. and Watson, G. Mine Subsidence Technological Society 5th Triennial Conference Proceedings, Maitland, August 2001.

SDPS, 2007. **Subsidence Deformation Prediction System - Quick Reference Guide and Working Examples**. Agioutantis, Z., Karmis, M. Department of Mining and Minerals Engineering, Virginia Polytechnic Institute and State University, Virginia.

SEA, 2006. **Predictions of Far-Field Displacement due to Extraction of Longwalls in the Western and Southern Domains on the F3 Freeway and Utility Easement**. Strata Engineering Report No.05-001-WWD/2 (October).

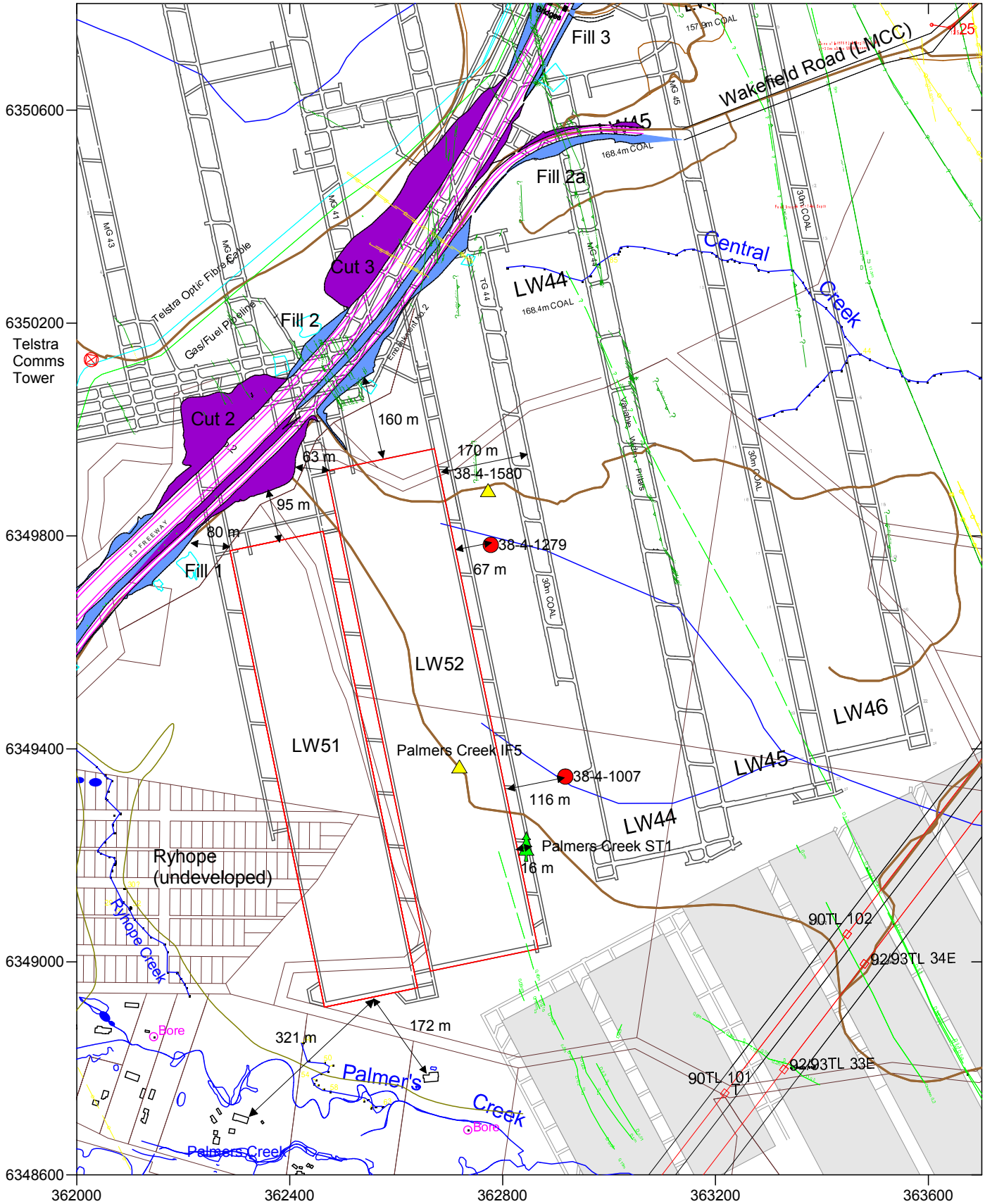
SEA, 2007. **Predictions of Far-Field Displacement and Strains for the RTA's F3 Freeway Bridges and Drainage Shaft due to the Proposed Longwalls in the Western and Southern Domains.** Strata Engineering Report No.05-001-WWD/4 (January).

Umwelt, 2004. **Review of Environmental Factors - Northern Domain Longwall Mining, West Wallsend Colliery**. Umwelt (Australia) Pty Limited.

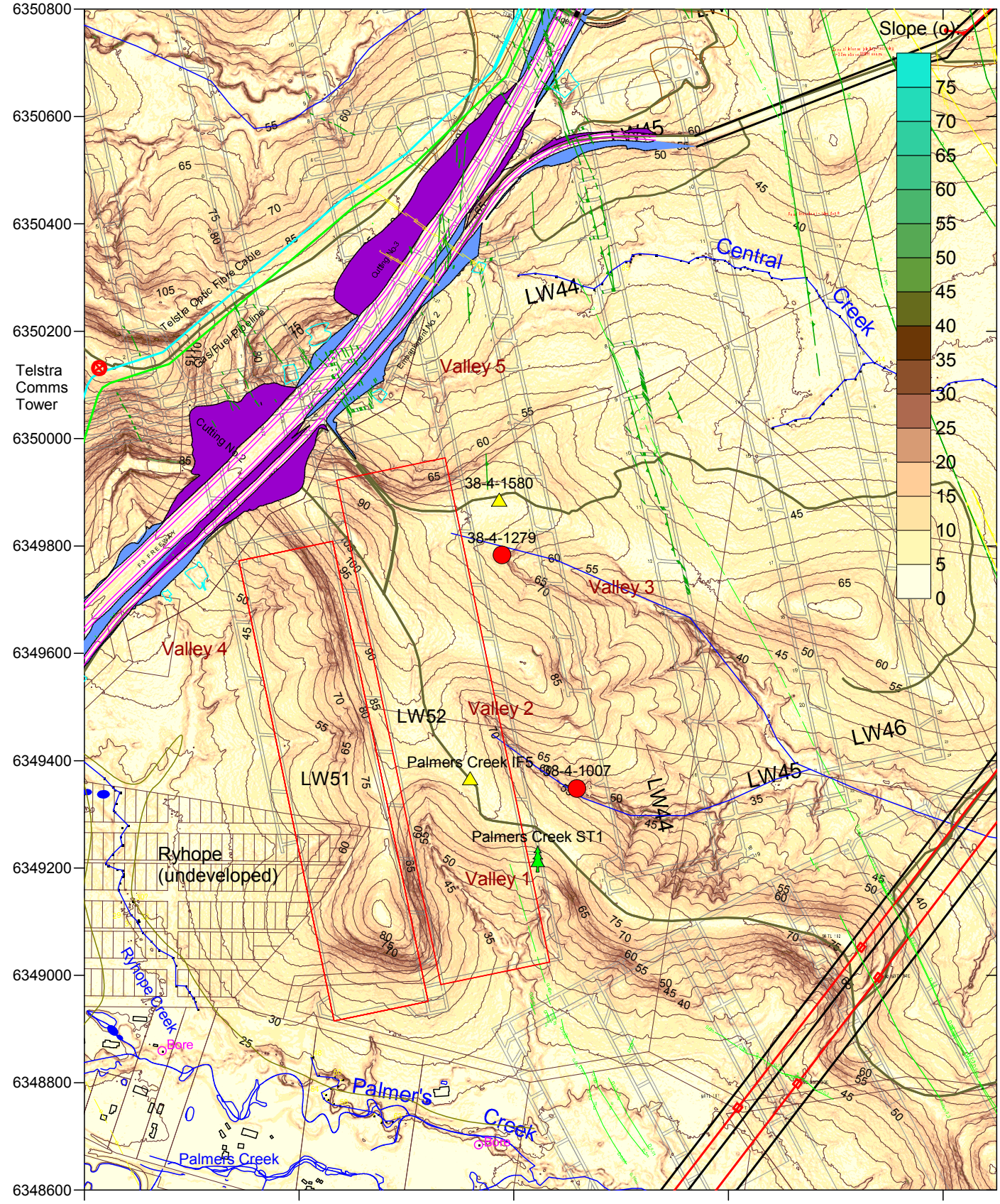
Vick, 2002. **Degrees of Belief: Subjective Probability and Engineering Judgement**. Vick, S.G. ASCE Press.

Whittaker and Reddish, 1989. **Subsidence Occurrence, Prediction and Control**. B.N. Whittaker and D.J. Reddish. Developments in Geotechnical Engineering, 56, Elsevier.

Worley Parsons, 2007. **OCAL-West Wallsend Colliery: Longwalls 38-45 & 47-48 Ground Movement Effects Pipeline Stress Analysis**. Worley Parsons Pty Ltd. Report No. 251/13215. (January).



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	Date:	06.08.13	Title:	Surface Features above the Proposed LWs 51 and 52	
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DgS

Ditton Geotechnical Services Pty Ltd

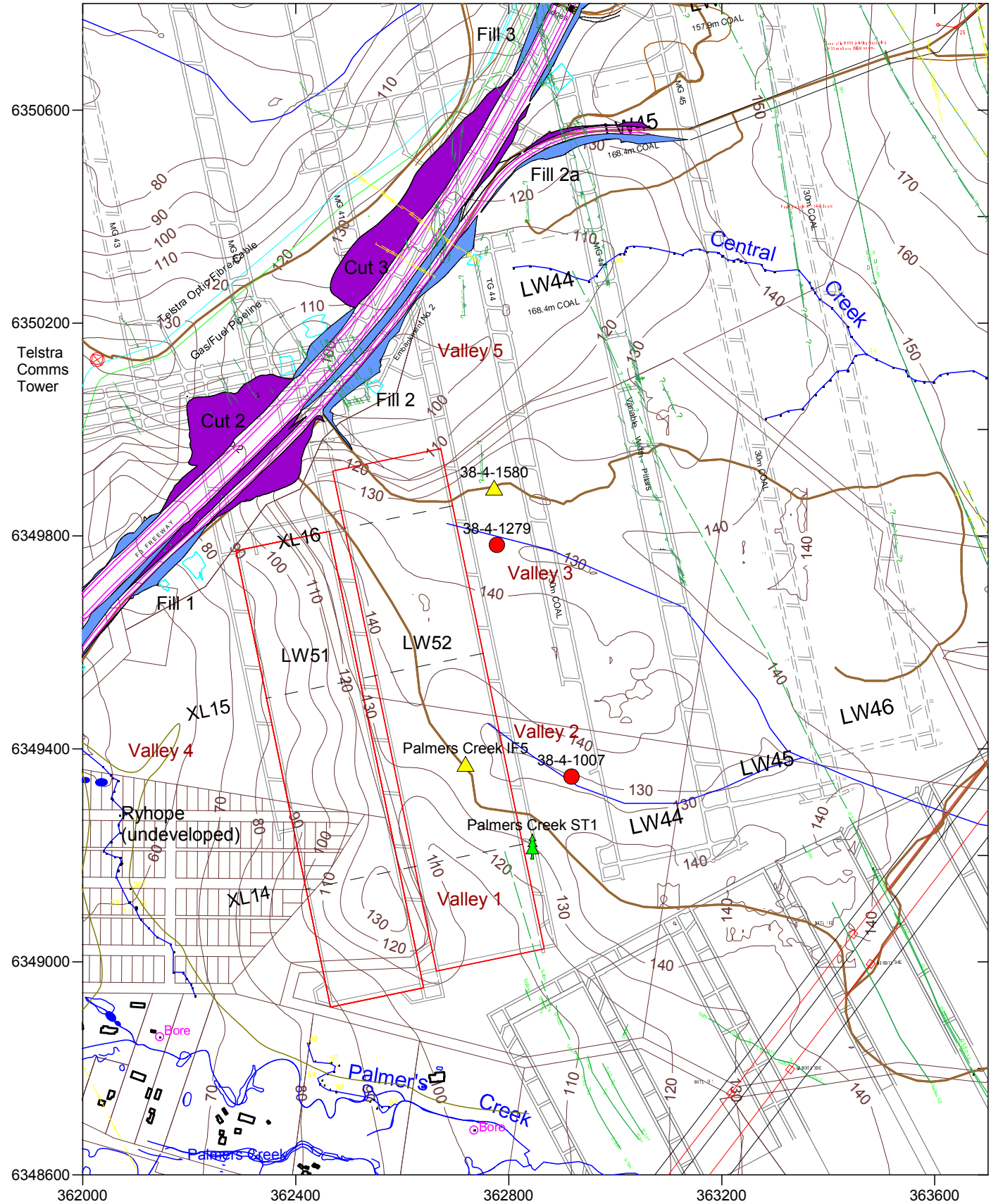
Engineer:	S.Ditton
Drawn:	S.Ditton
Date:	28.08.13

Client: West Wallsend Colliery
WWD-012/16

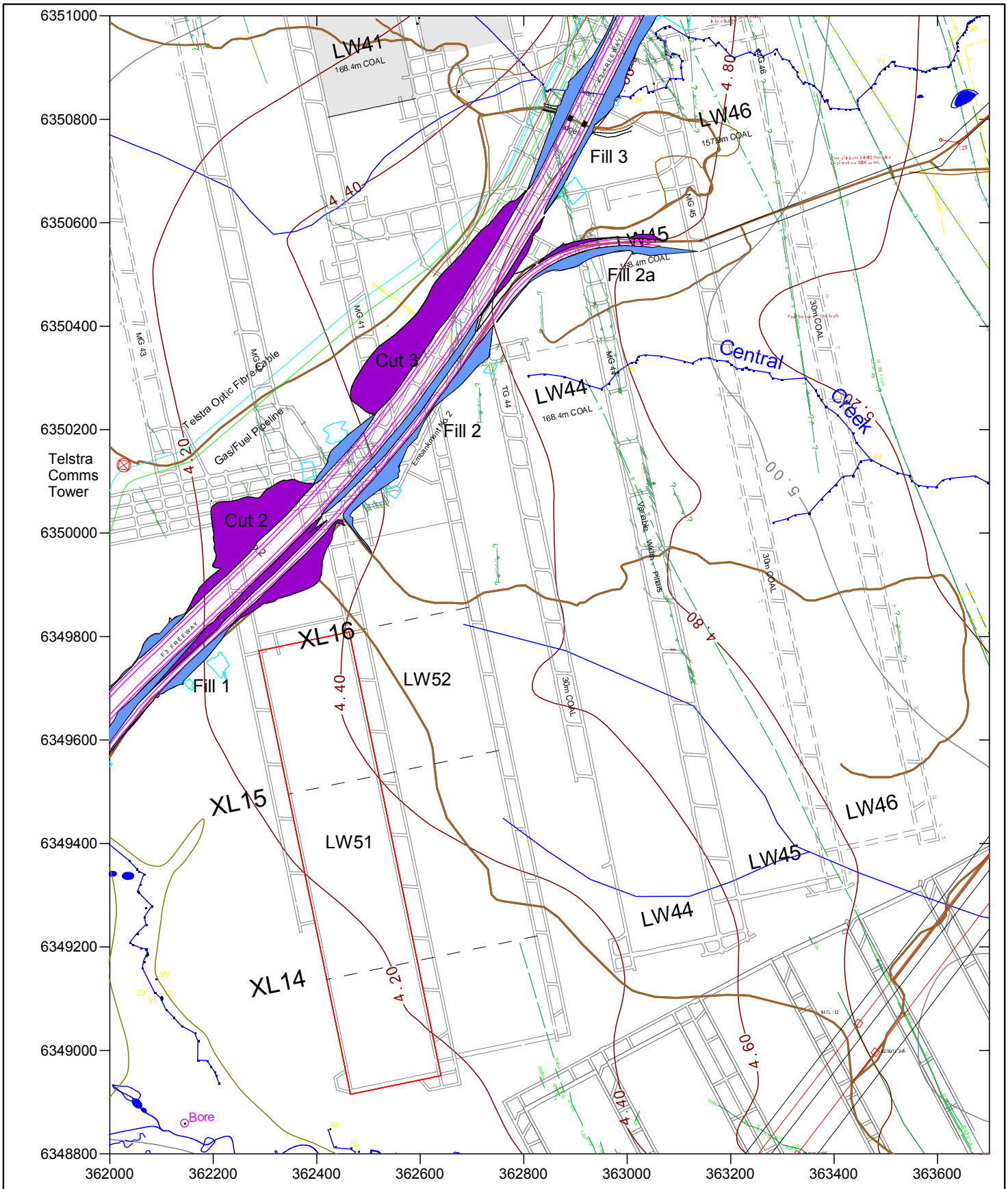
Title: Surface Level Contours and Surface Features above LWs 51 and 52

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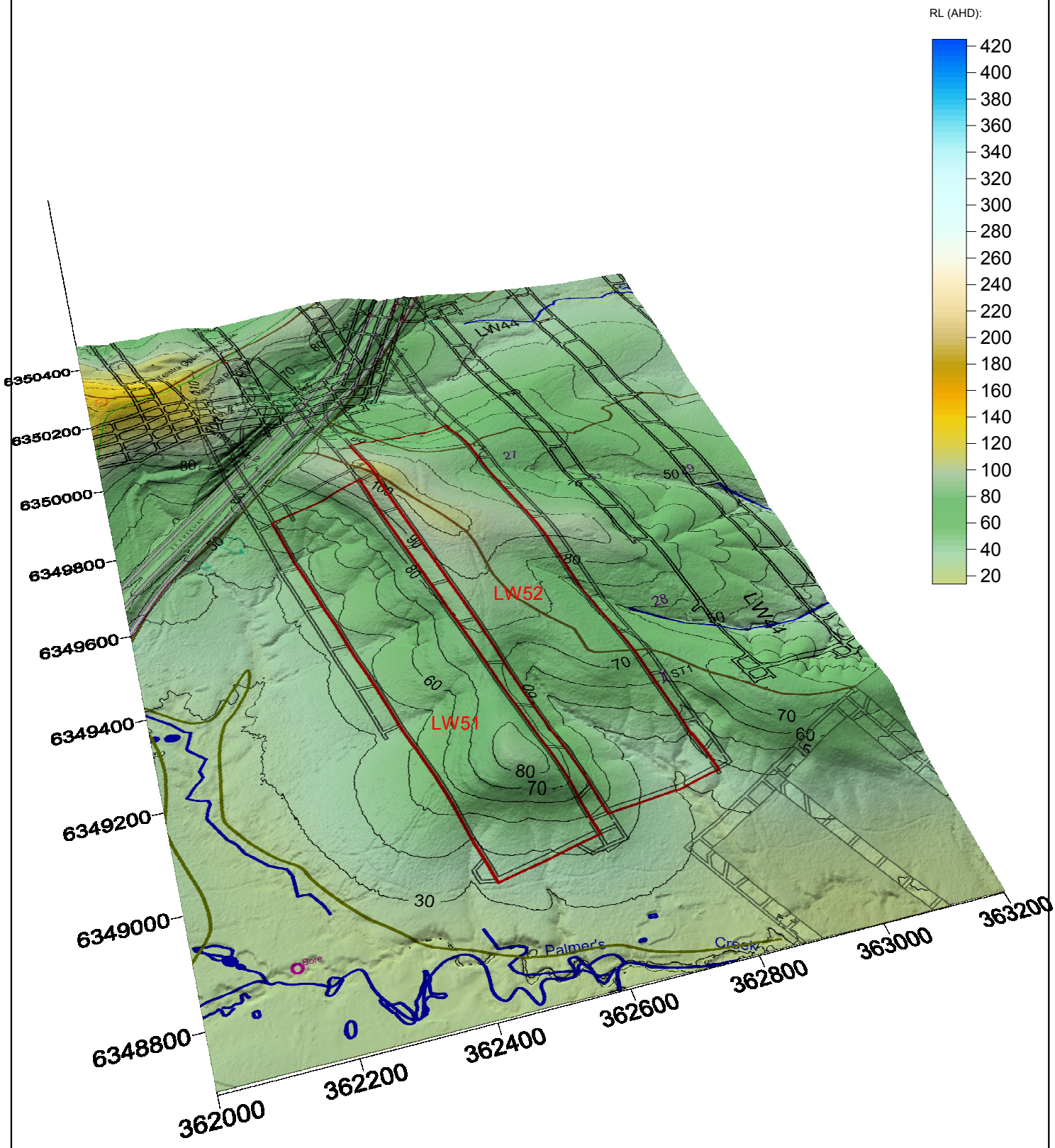
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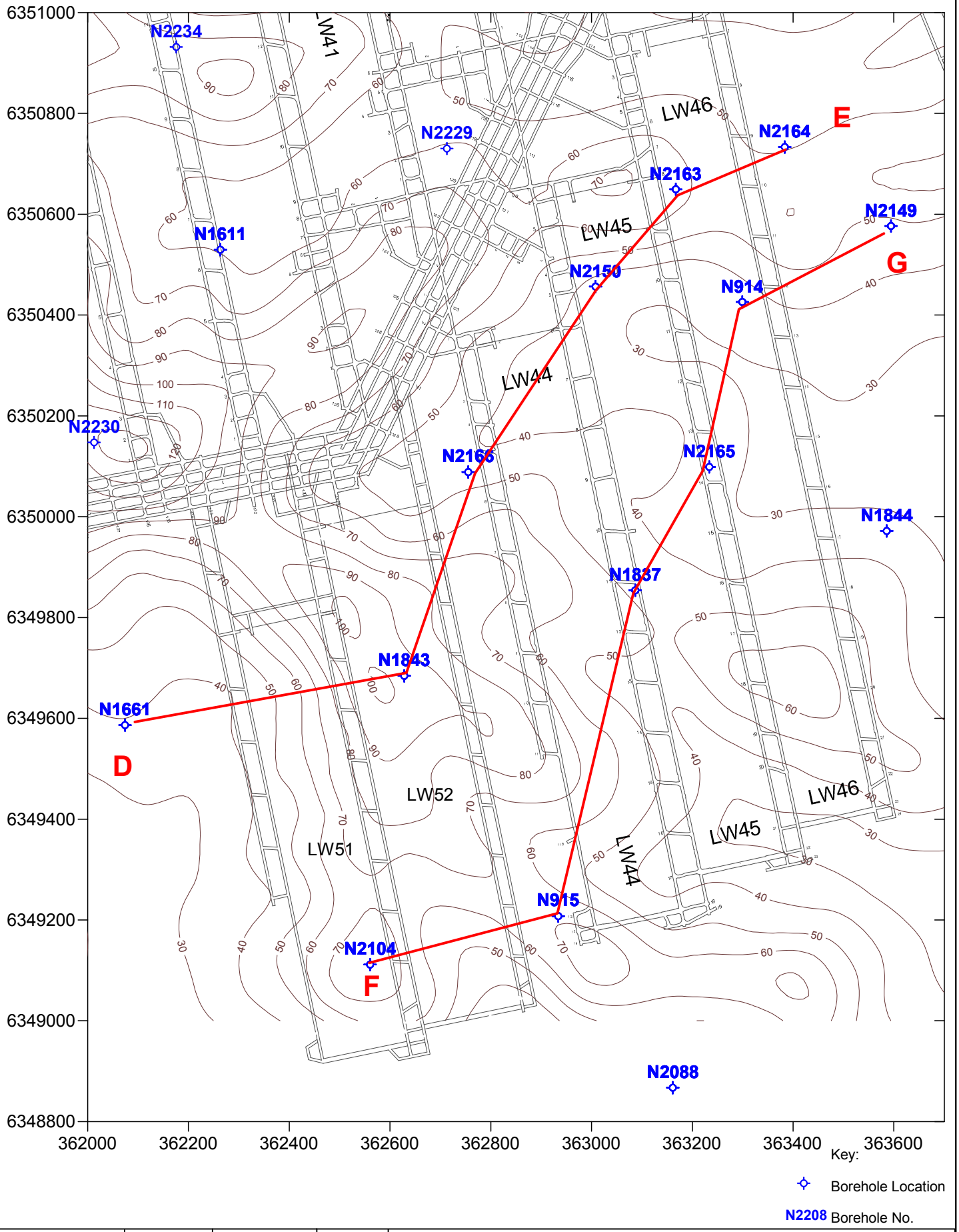
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	Drawn:	S.Ditton			
	Date:	06.08.13	Title:	Cover Depth and Surface Features above LWs 51 and 52	
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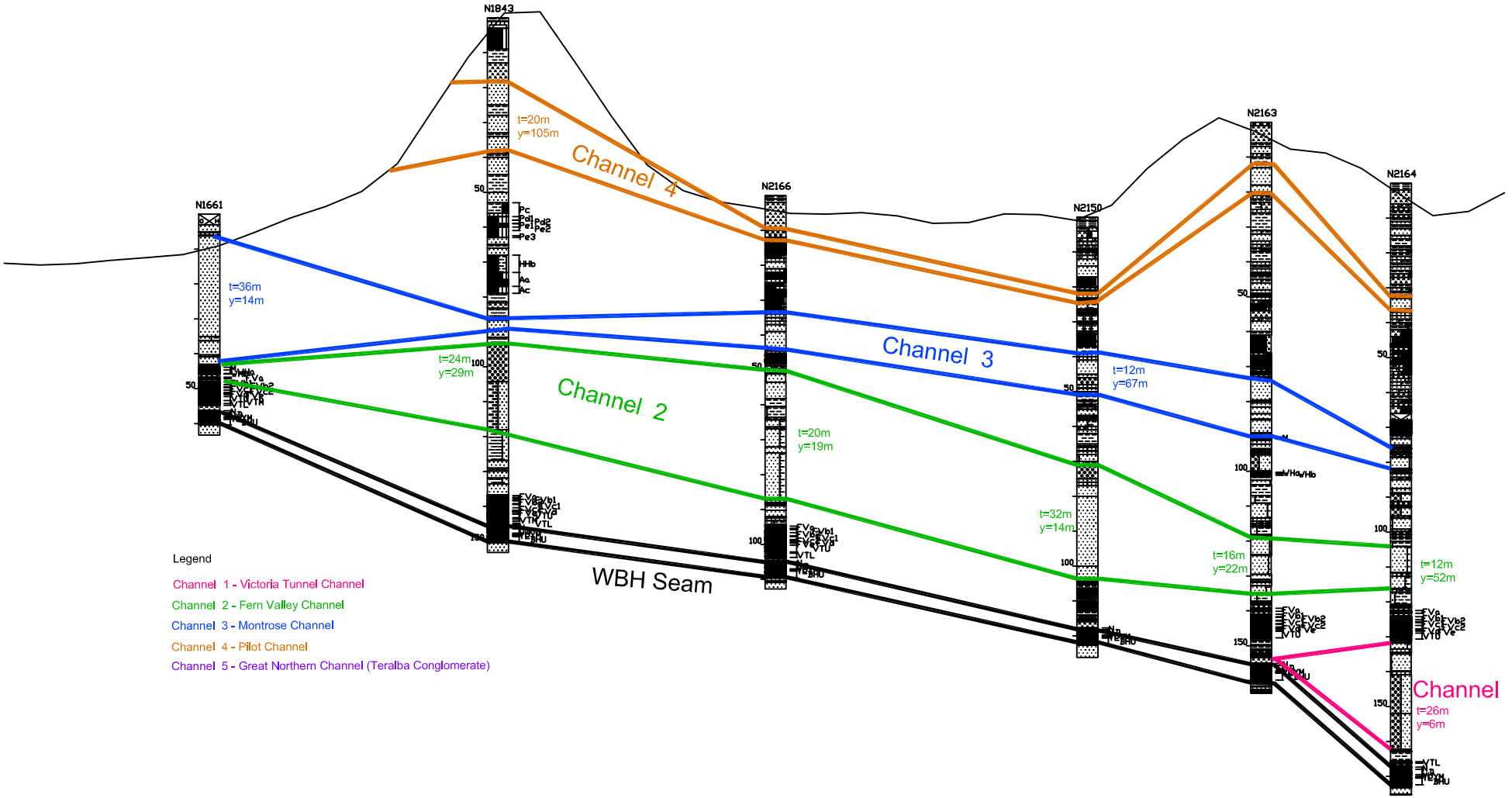
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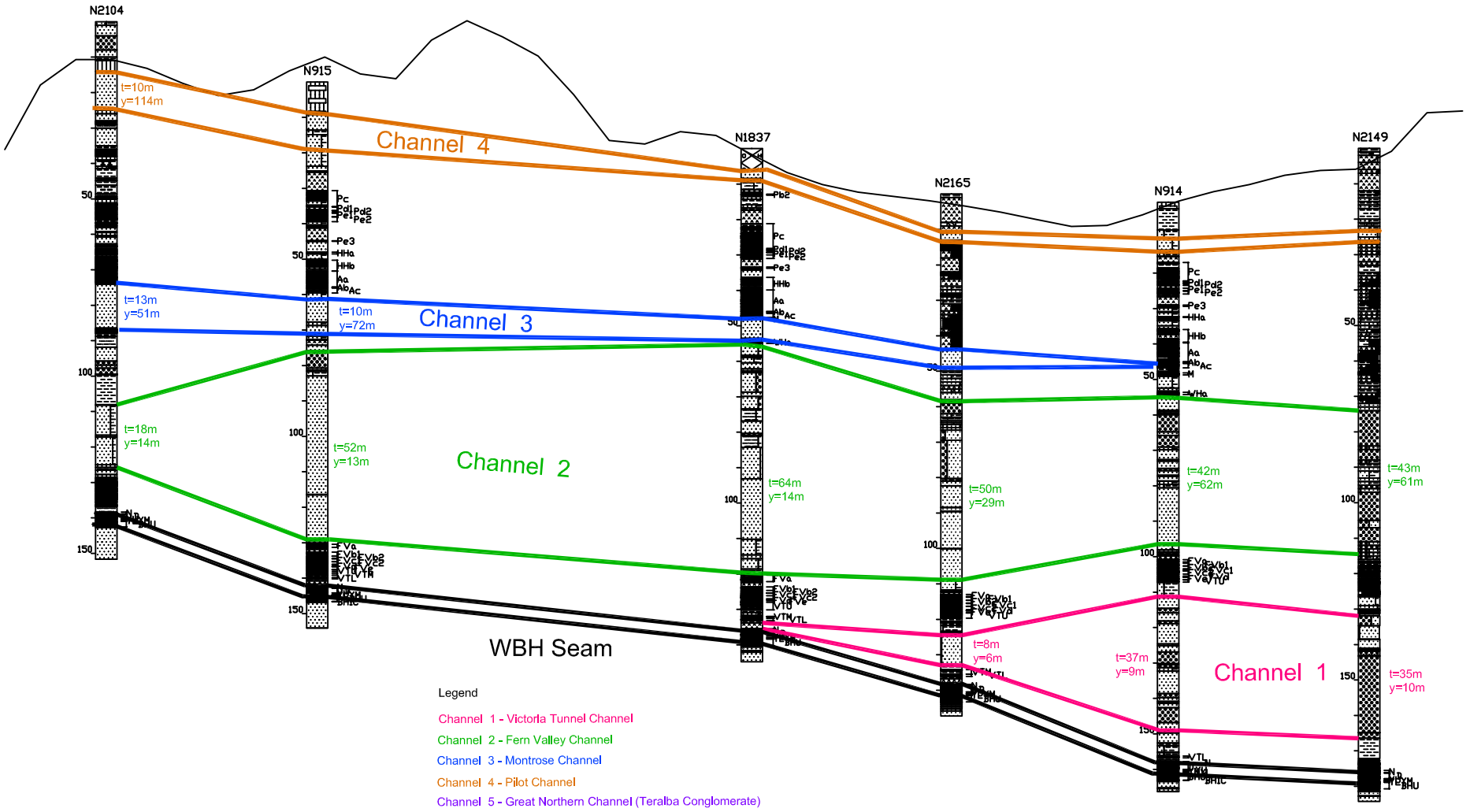
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	Drawn:	S.Ditton			
	Date:	21.07.13	Title:	3-D Terrain Model of Surface Features above LWs 51 and 52 (see Figure 1 for Symbol Key)	
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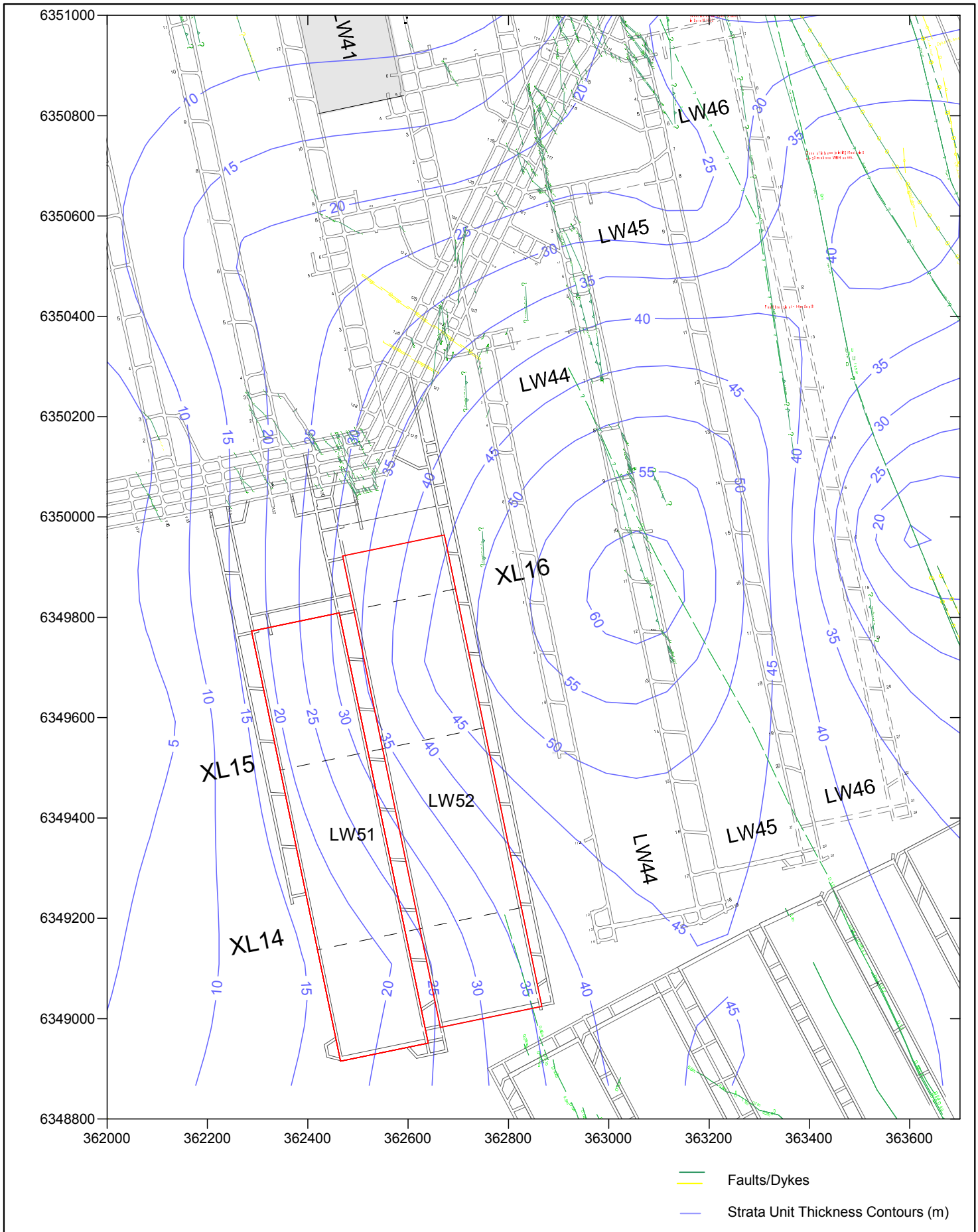
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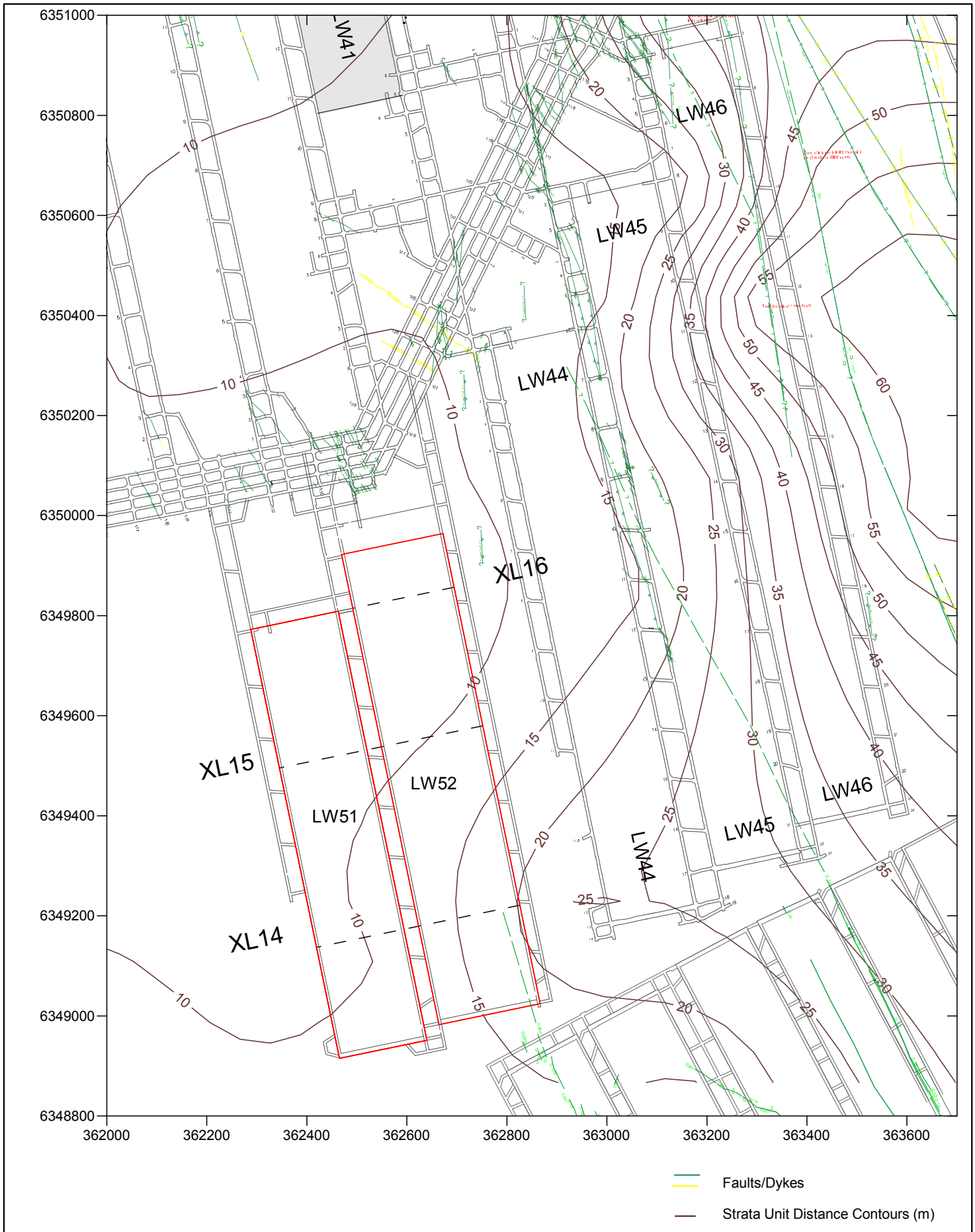
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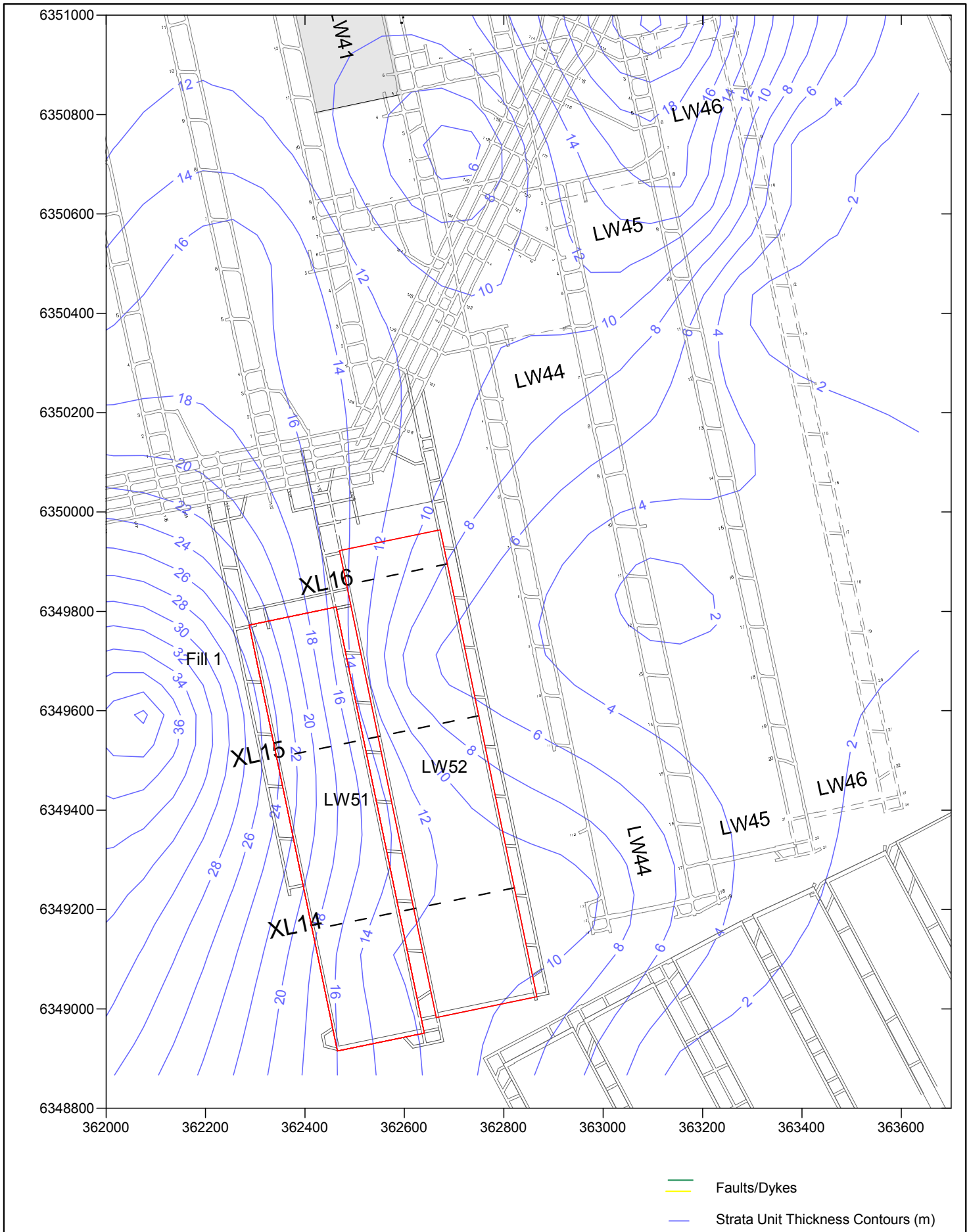
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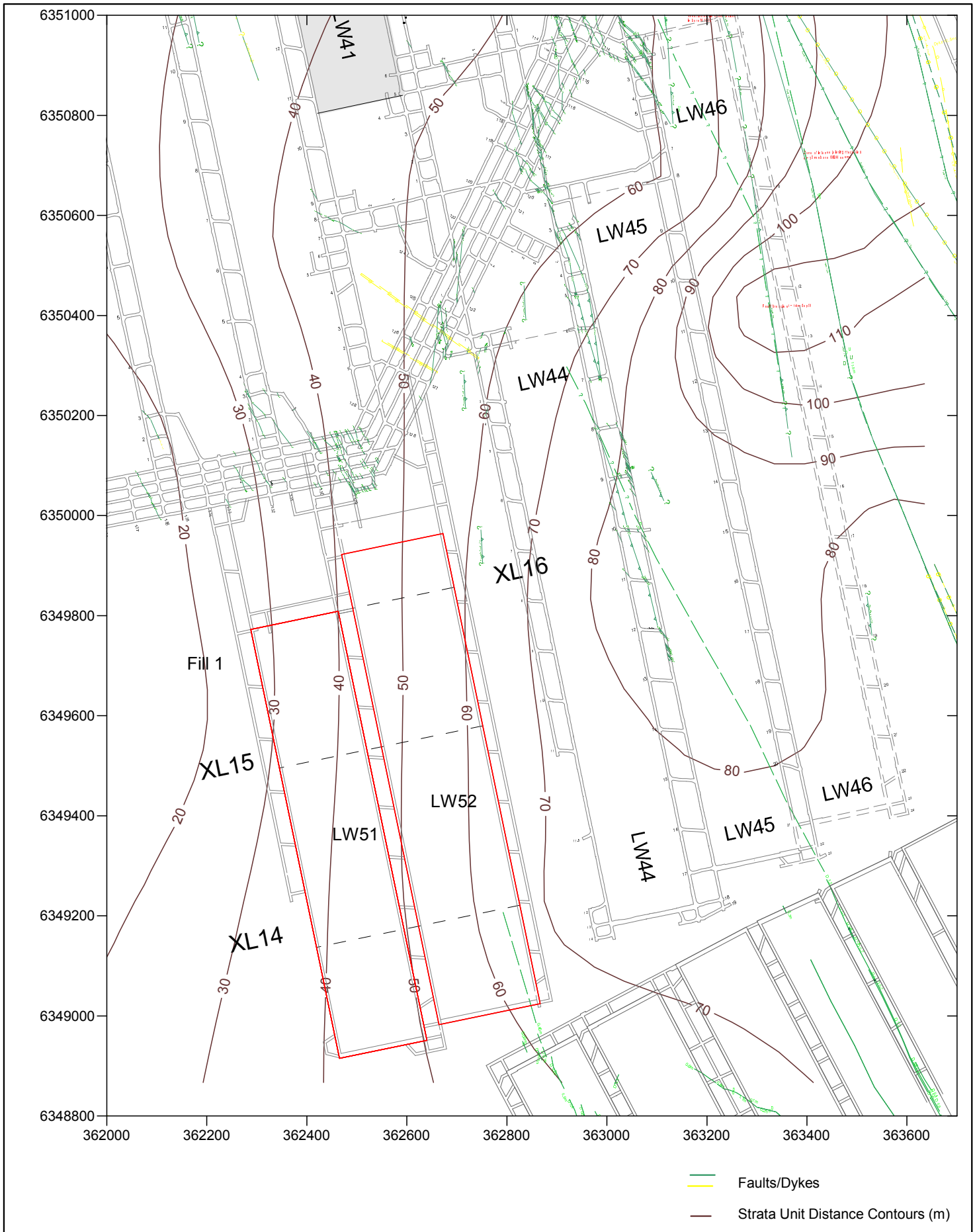
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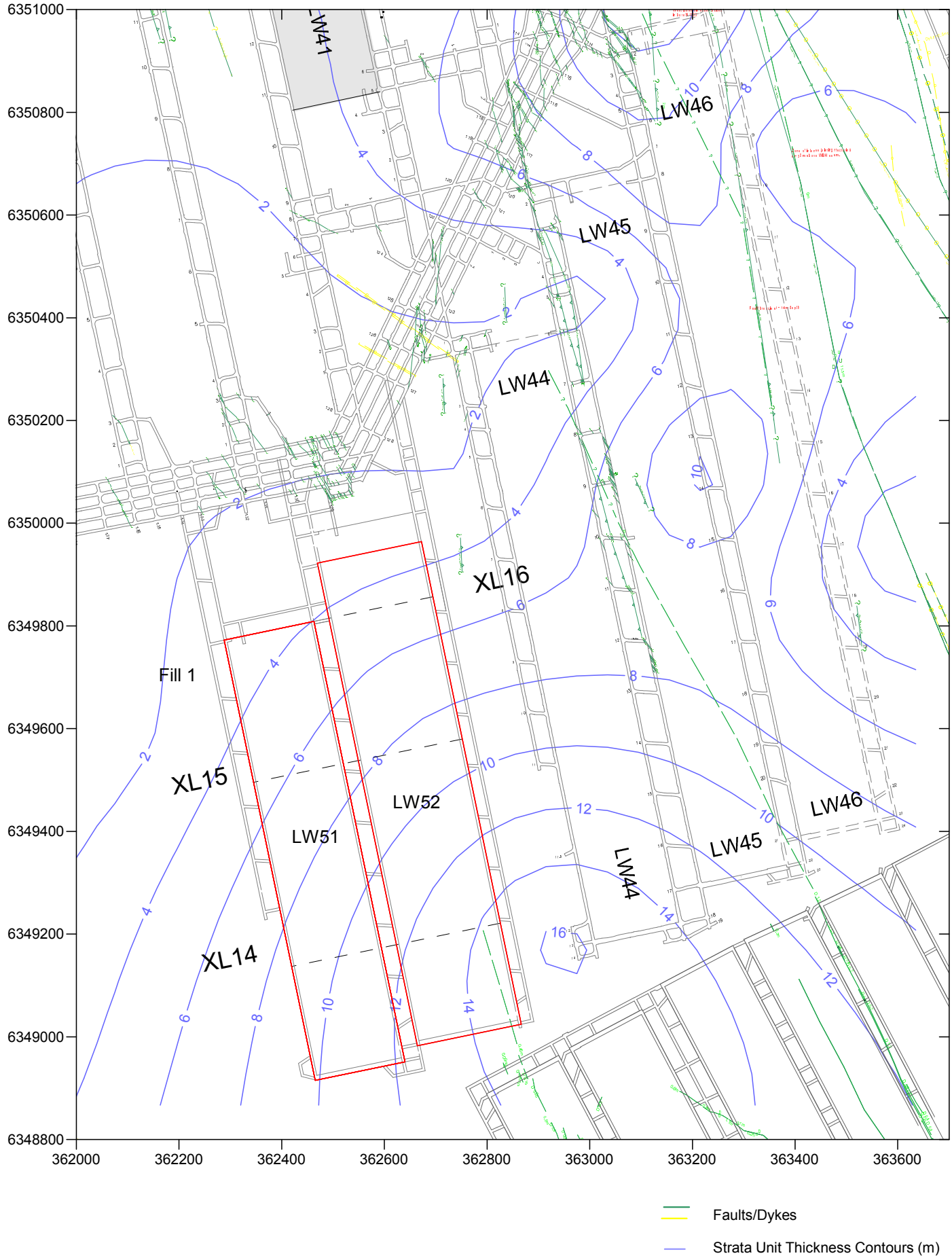
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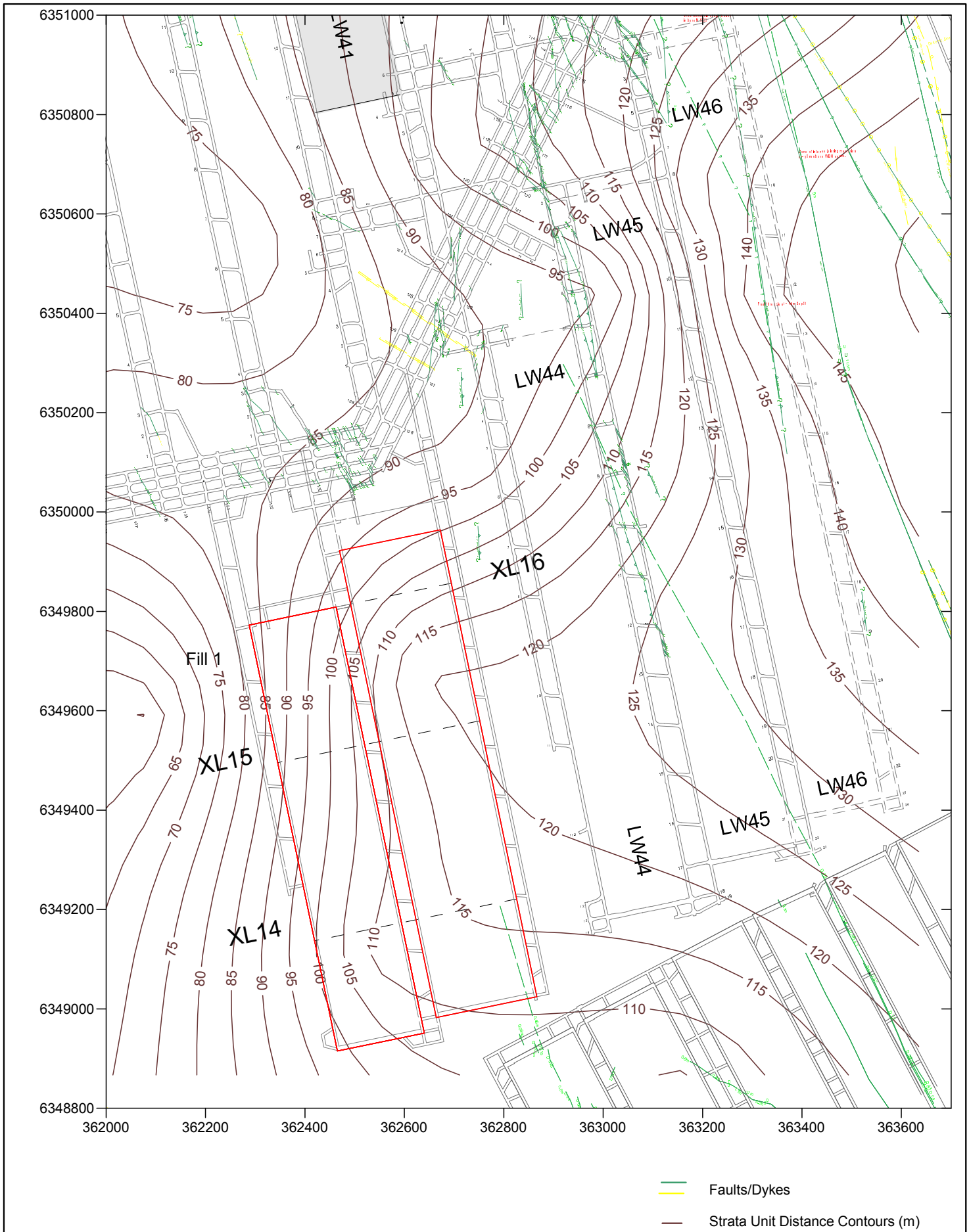
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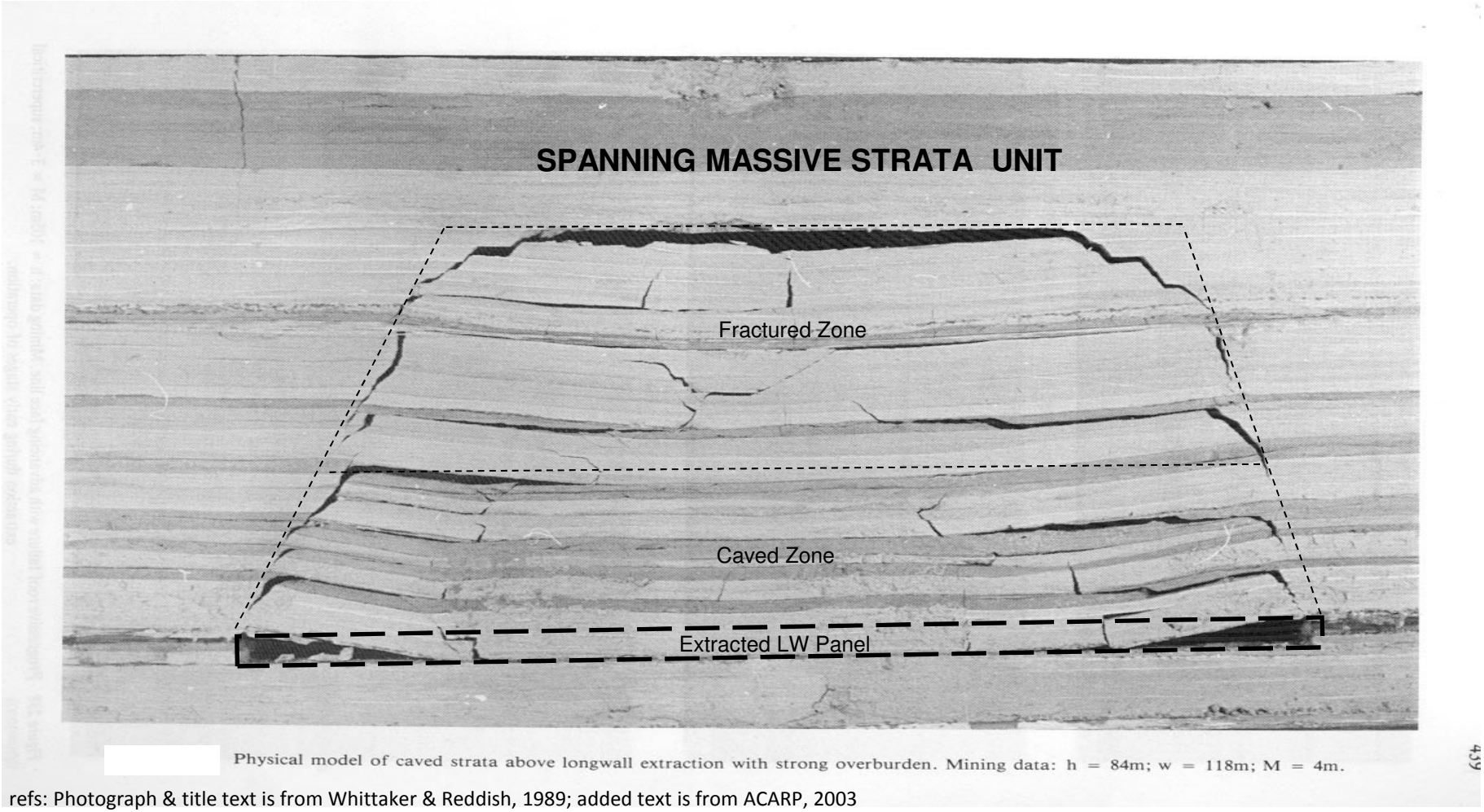
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Ditton Geotechnical Services Pty Ltd			Scale:	1:8,000	Figure No: 9b



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
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DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
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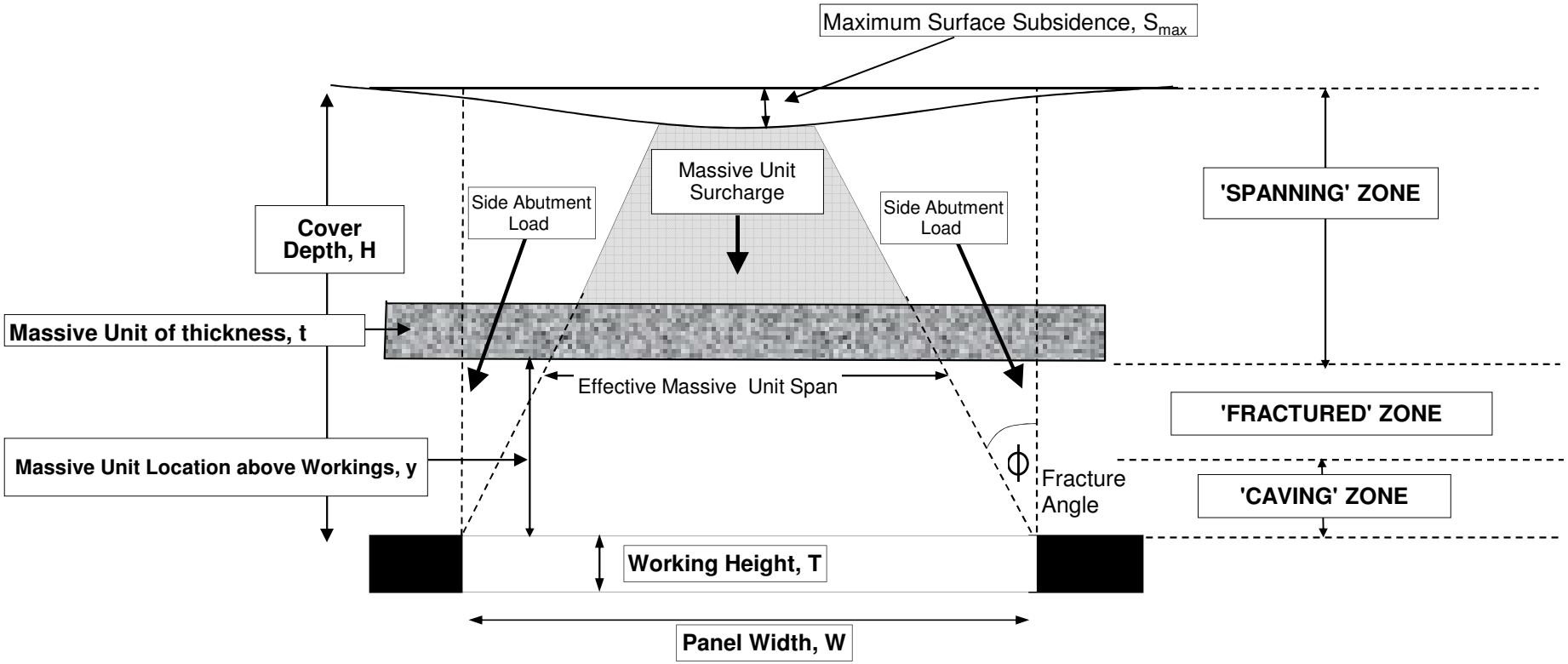


Physical model of caved strata above longwall extraction with strong overburden. Mining data: h = 84m; w = 118m; M = 4m.

459

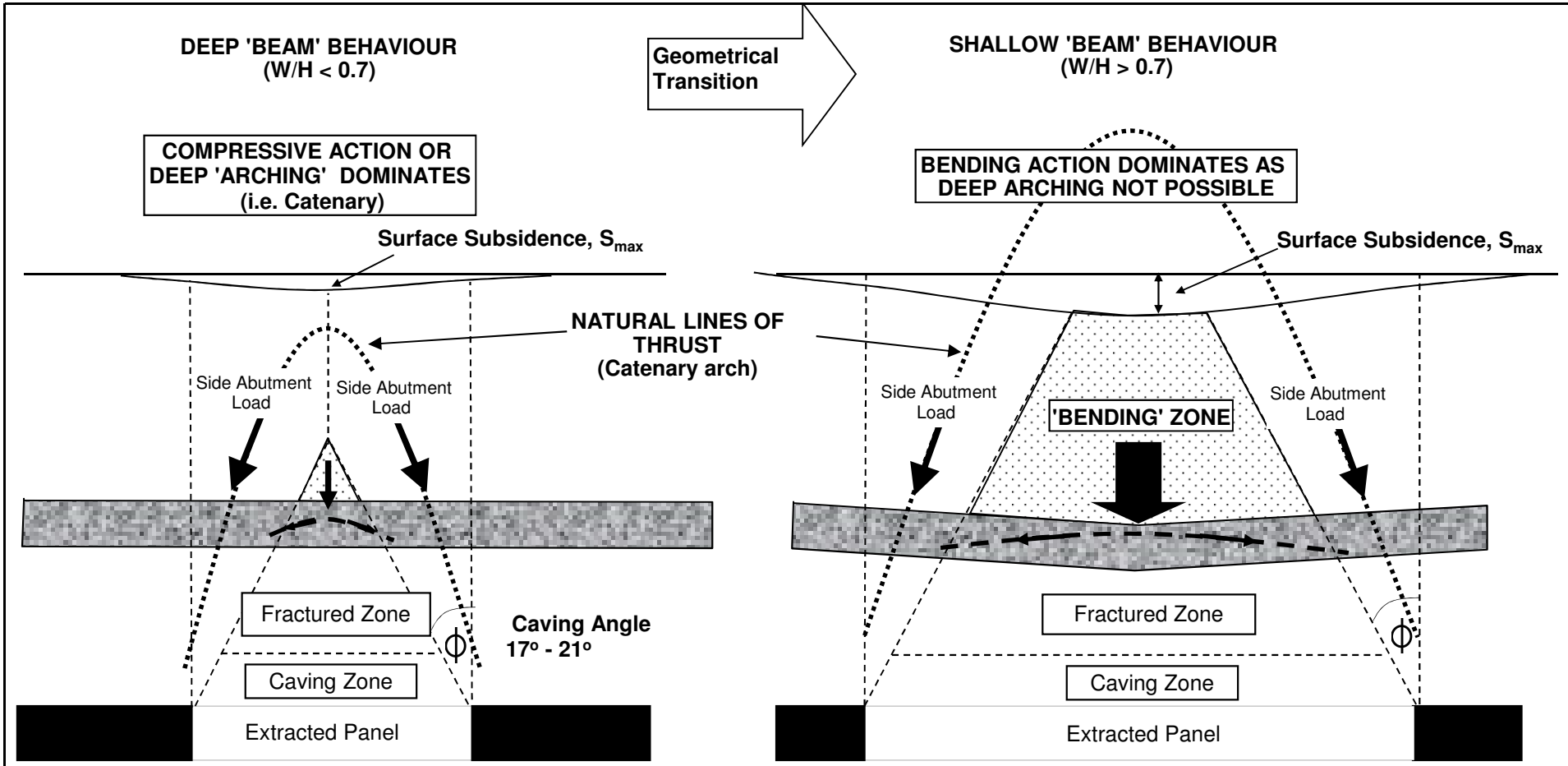
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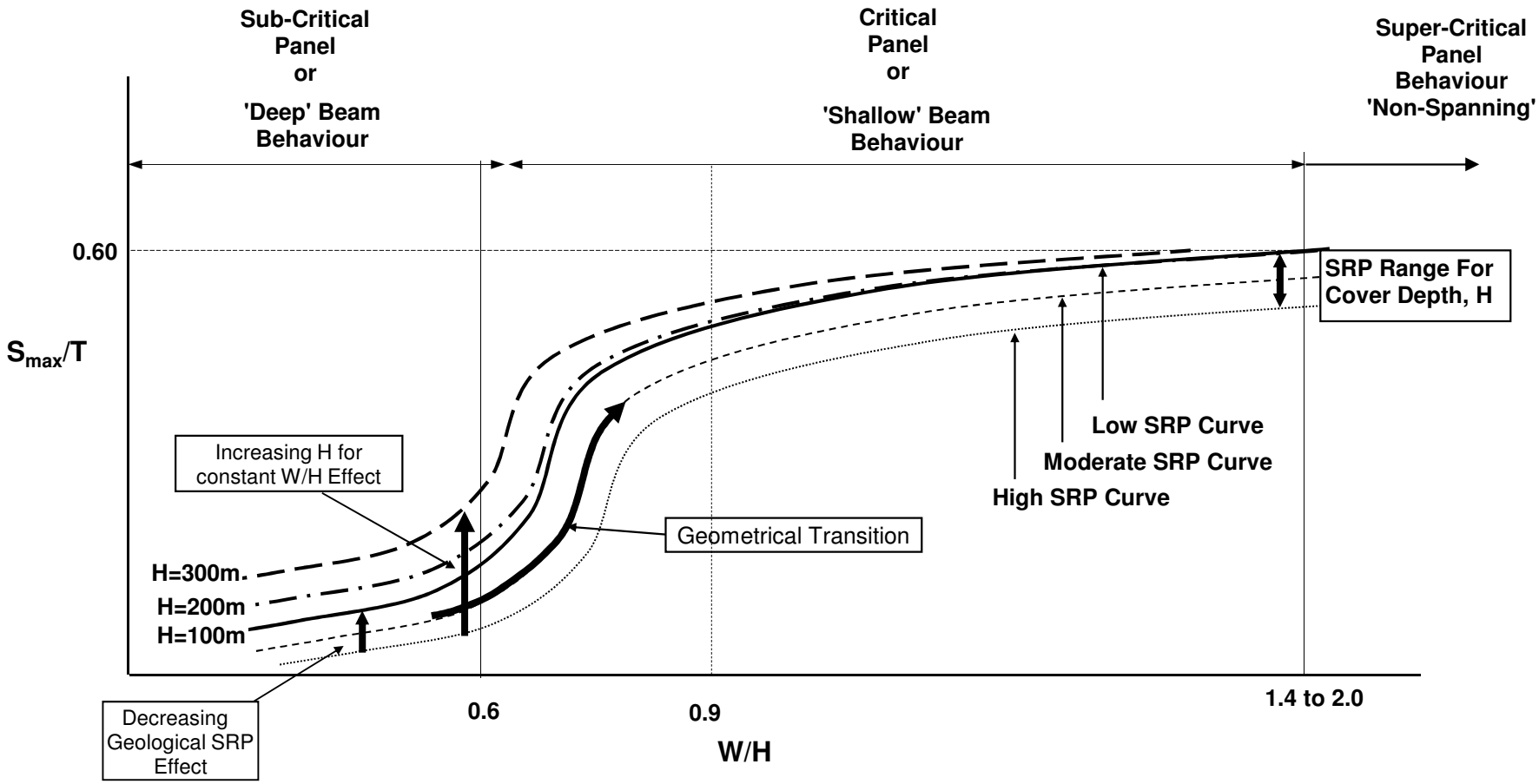
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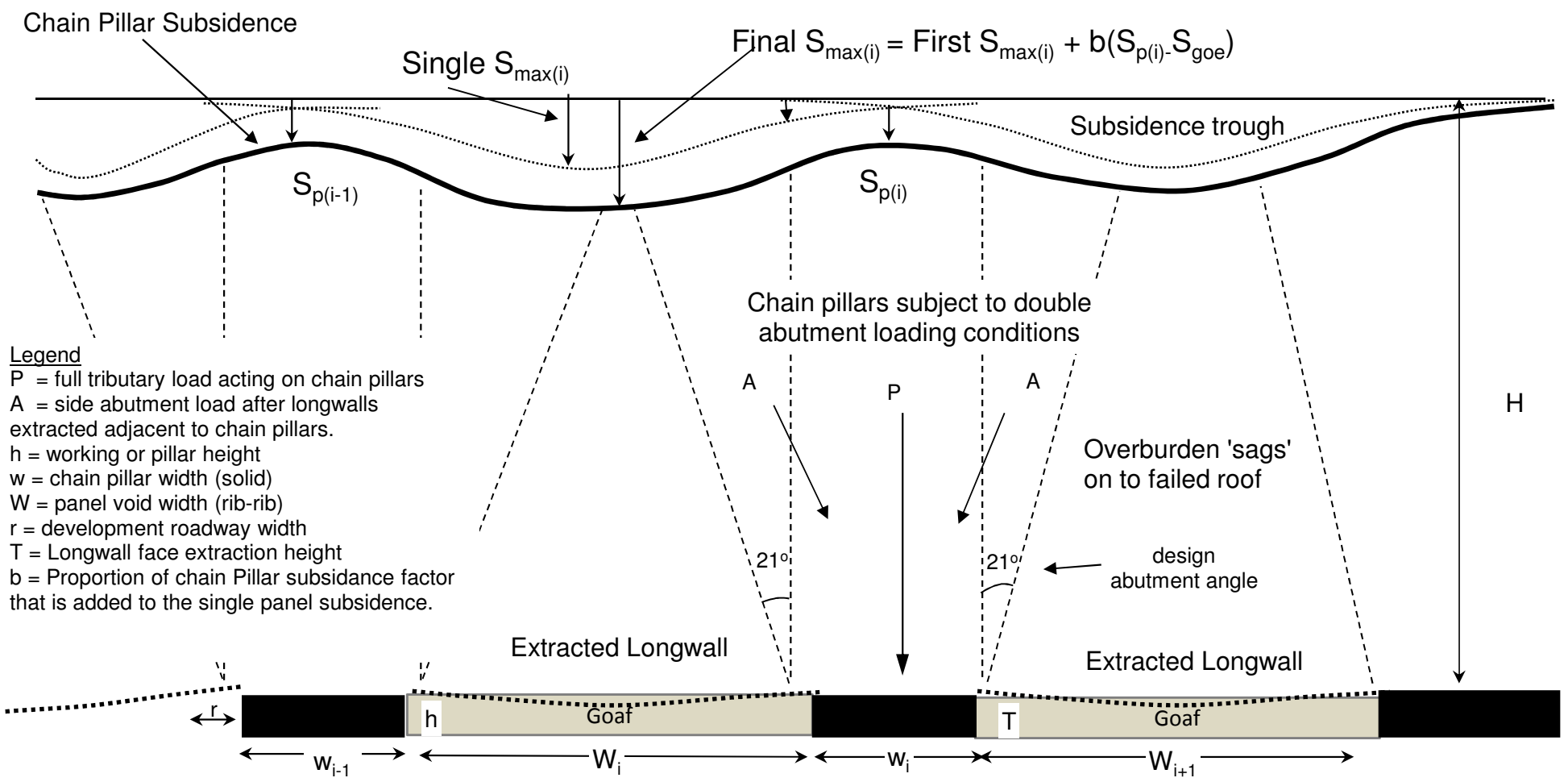
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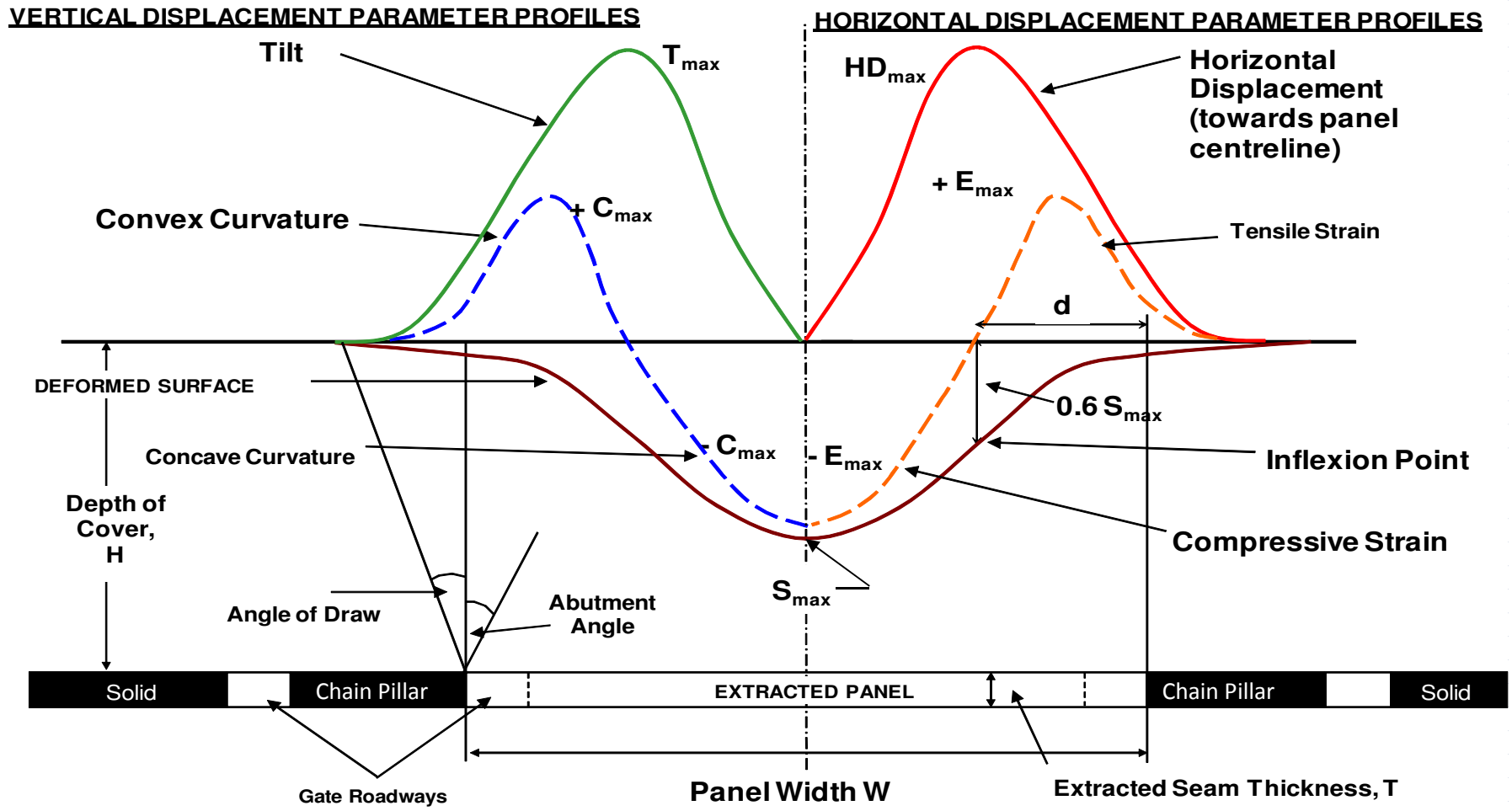
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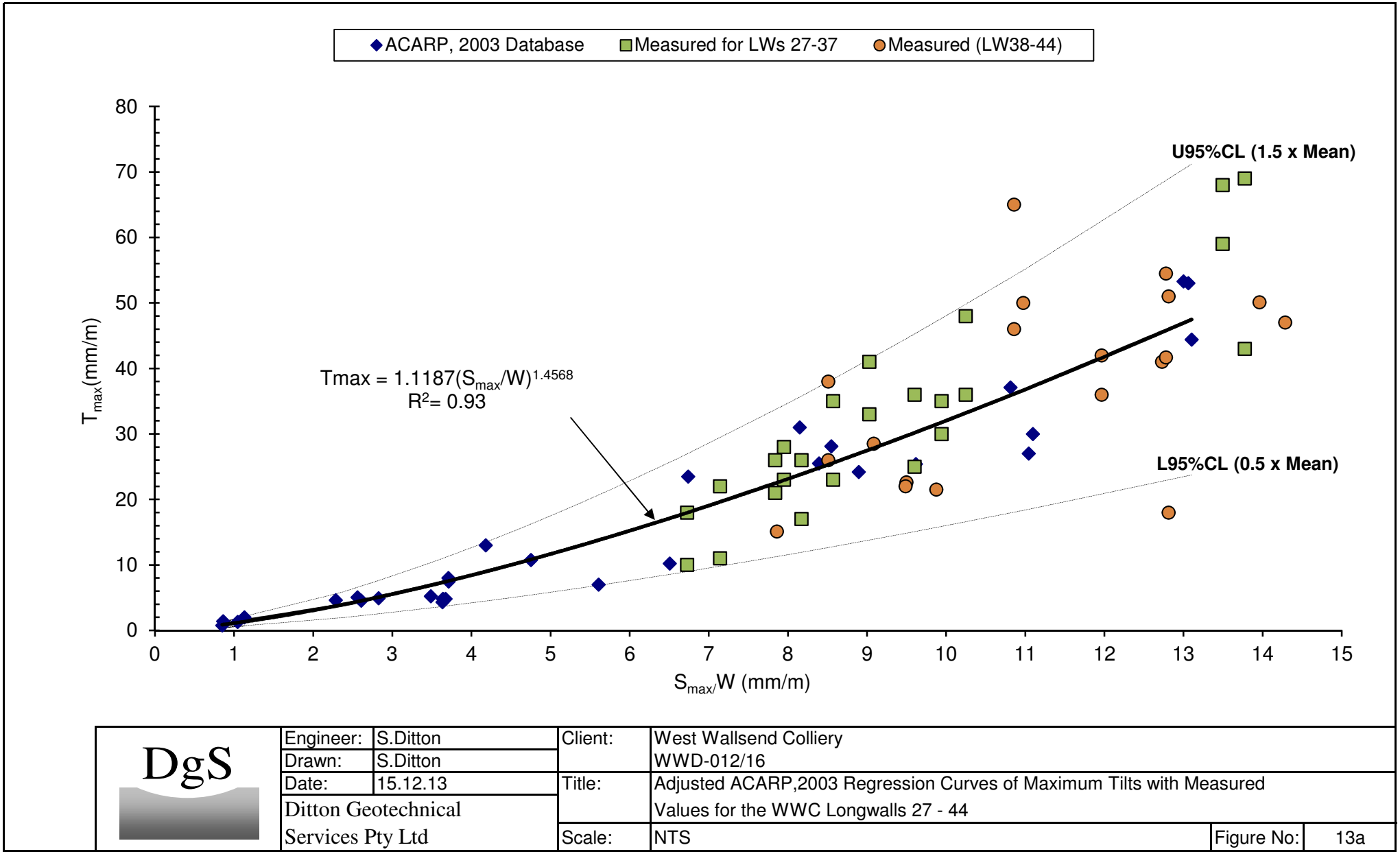


Legend
P = full tributary load acting on chain pillars
A = side abutment load after longwalls extracted adjacent to chain pillars.
h = working or pillar height
w = chain pillar width (solid)
W = panel void width (rib-rib)
r = development roadway width
T = Longwall face extraction height
b = Proportion of chain Pillar subsidance factor that is added to the single panel subsidence.

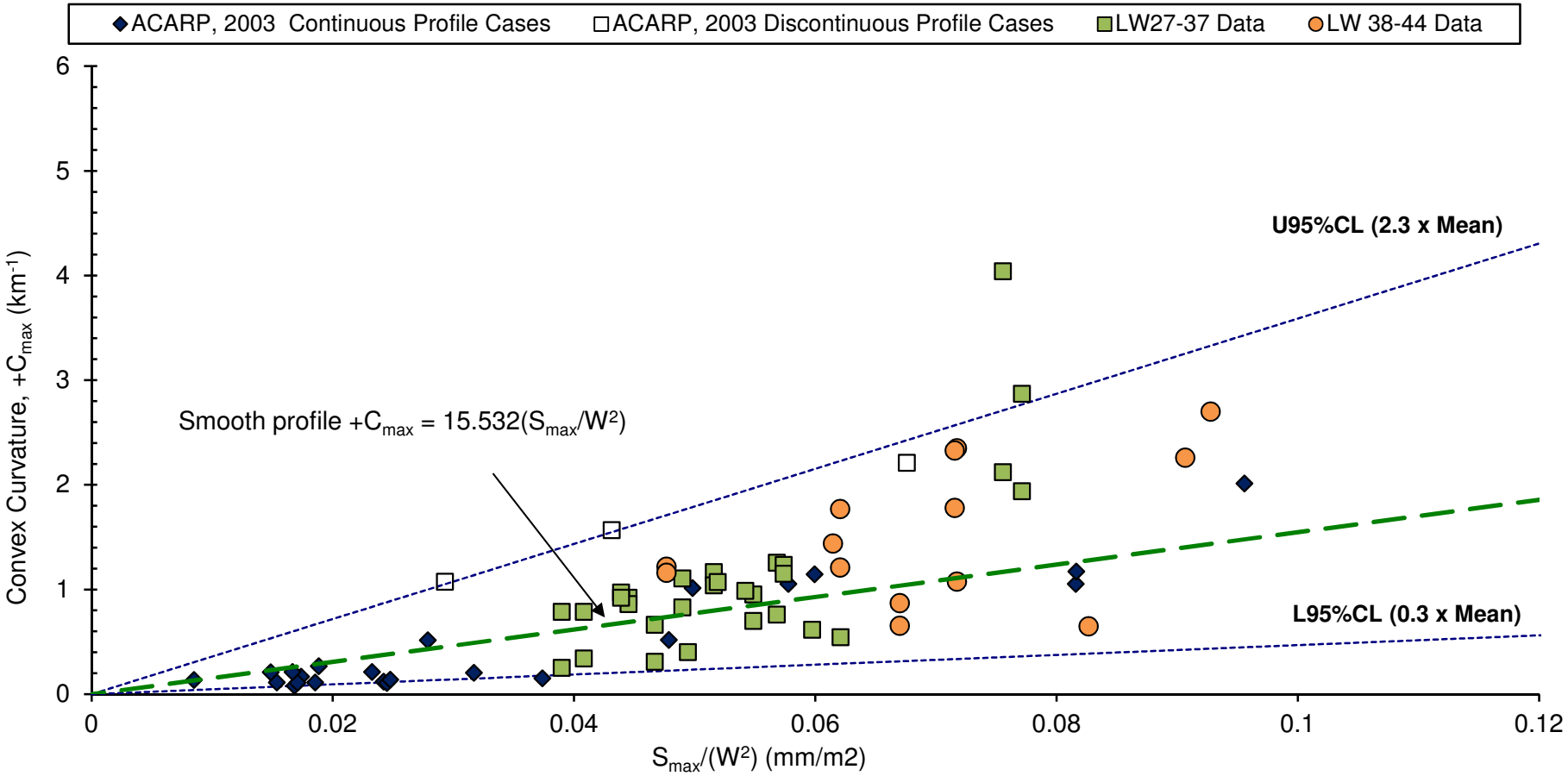
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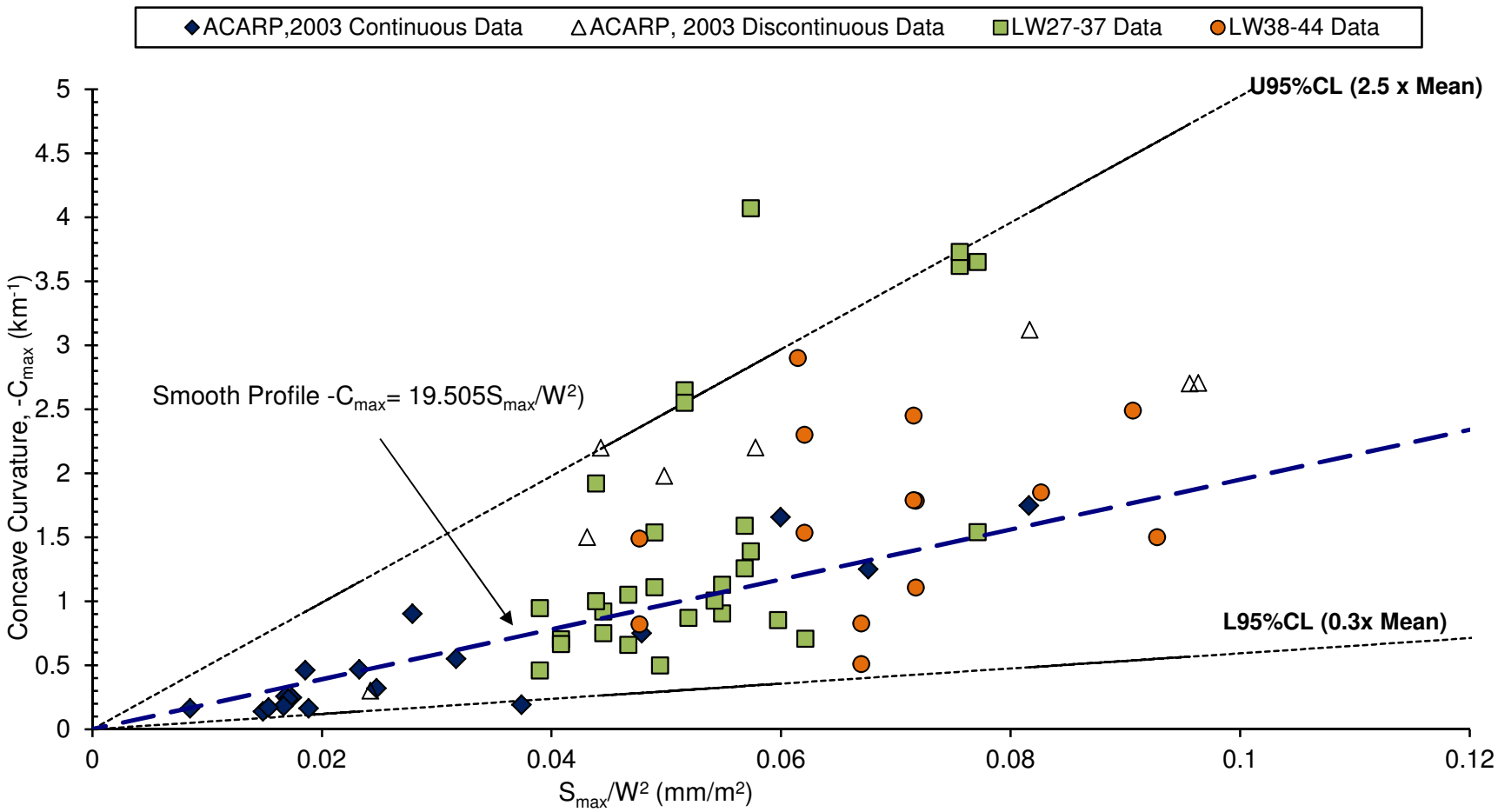
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	Date:	19.07.12	Title:	Mine Subsidence Trough Deformation Parameters (adapted from Holla, 1987)	
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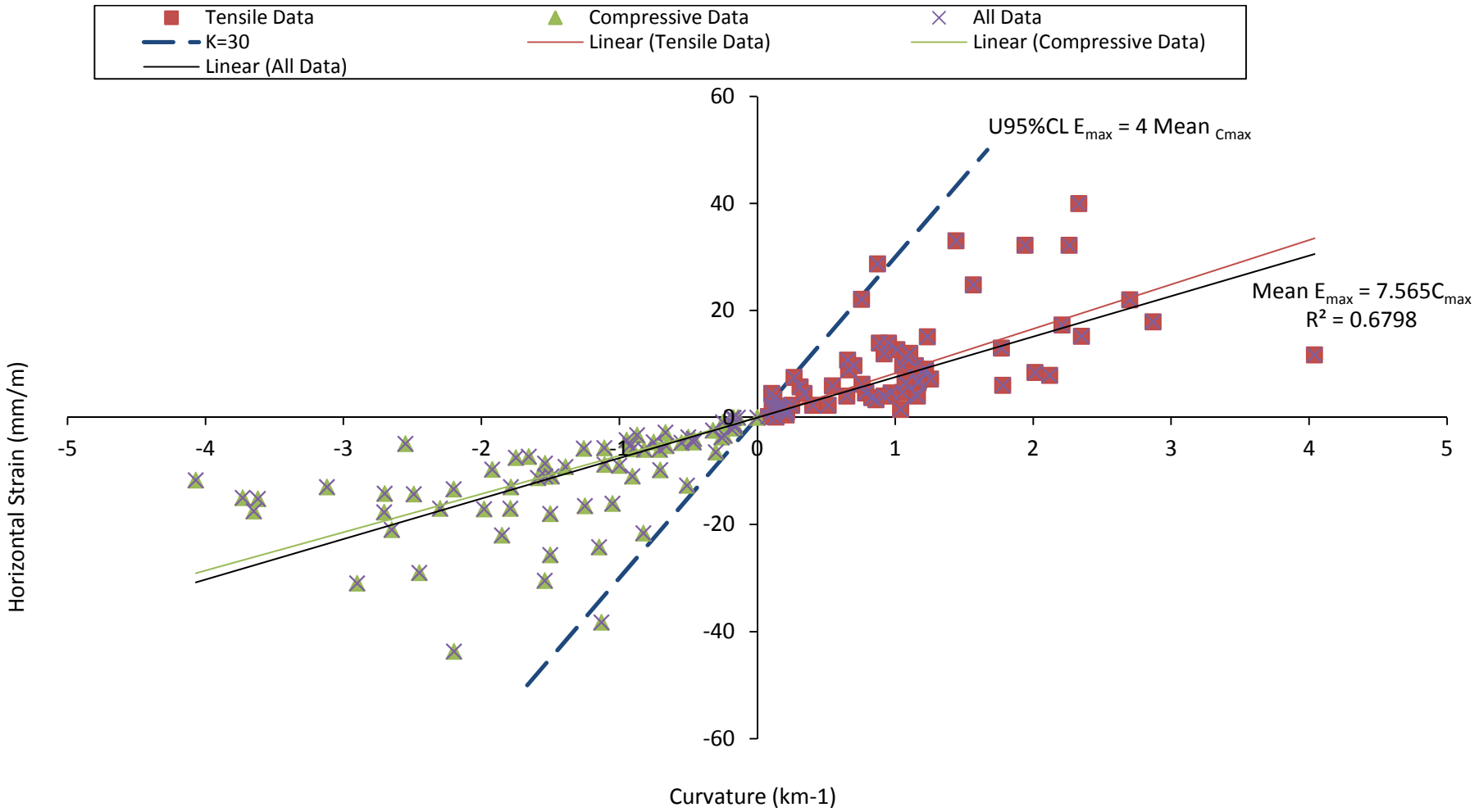
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	Date: 15.12.13	Title:	Adjusted ACARP,2003 Regression Curves of Maximum Tilts with Measured Values for the WWC Longwalls 27 - 44	
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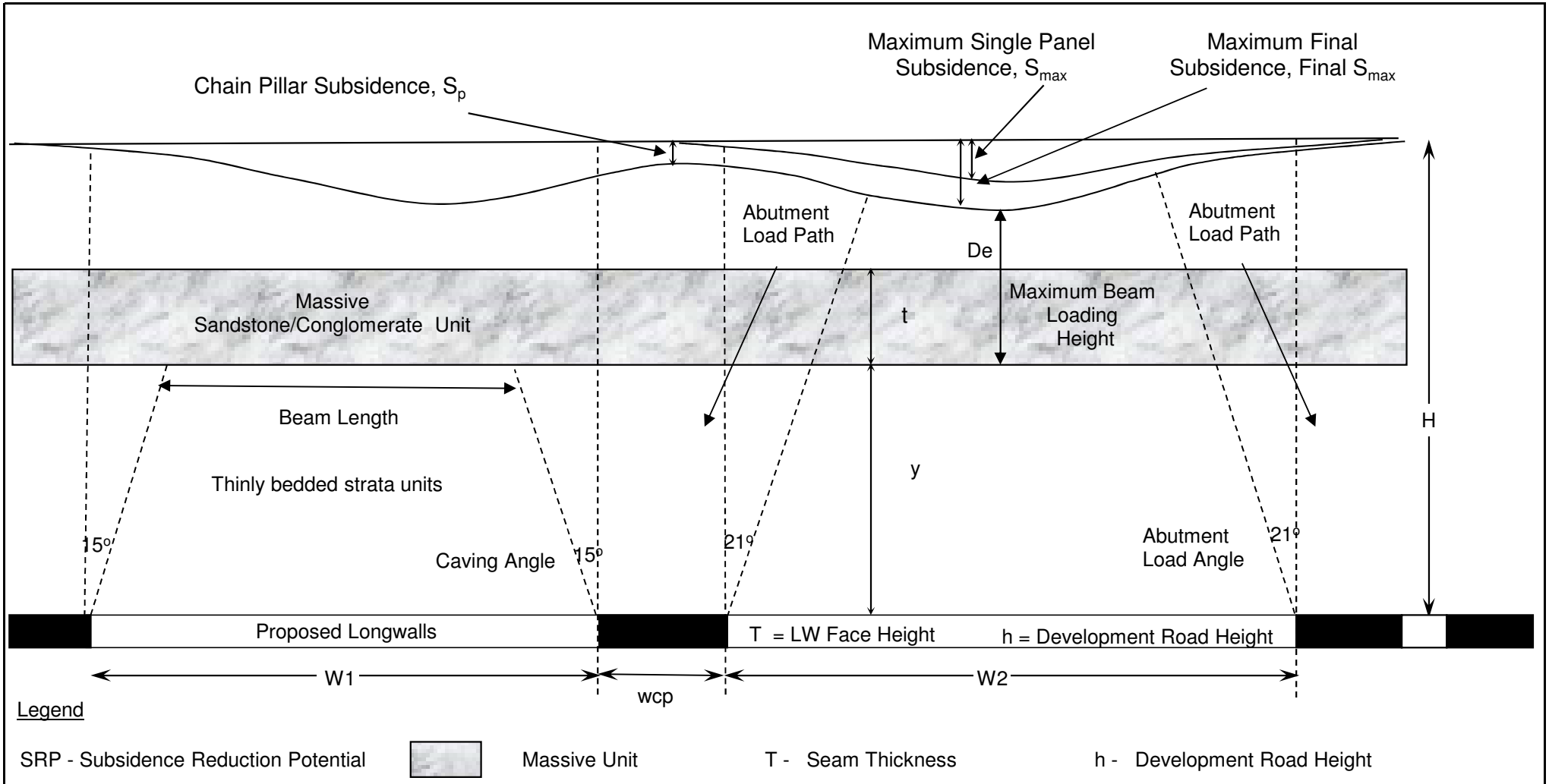
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	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 13b



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
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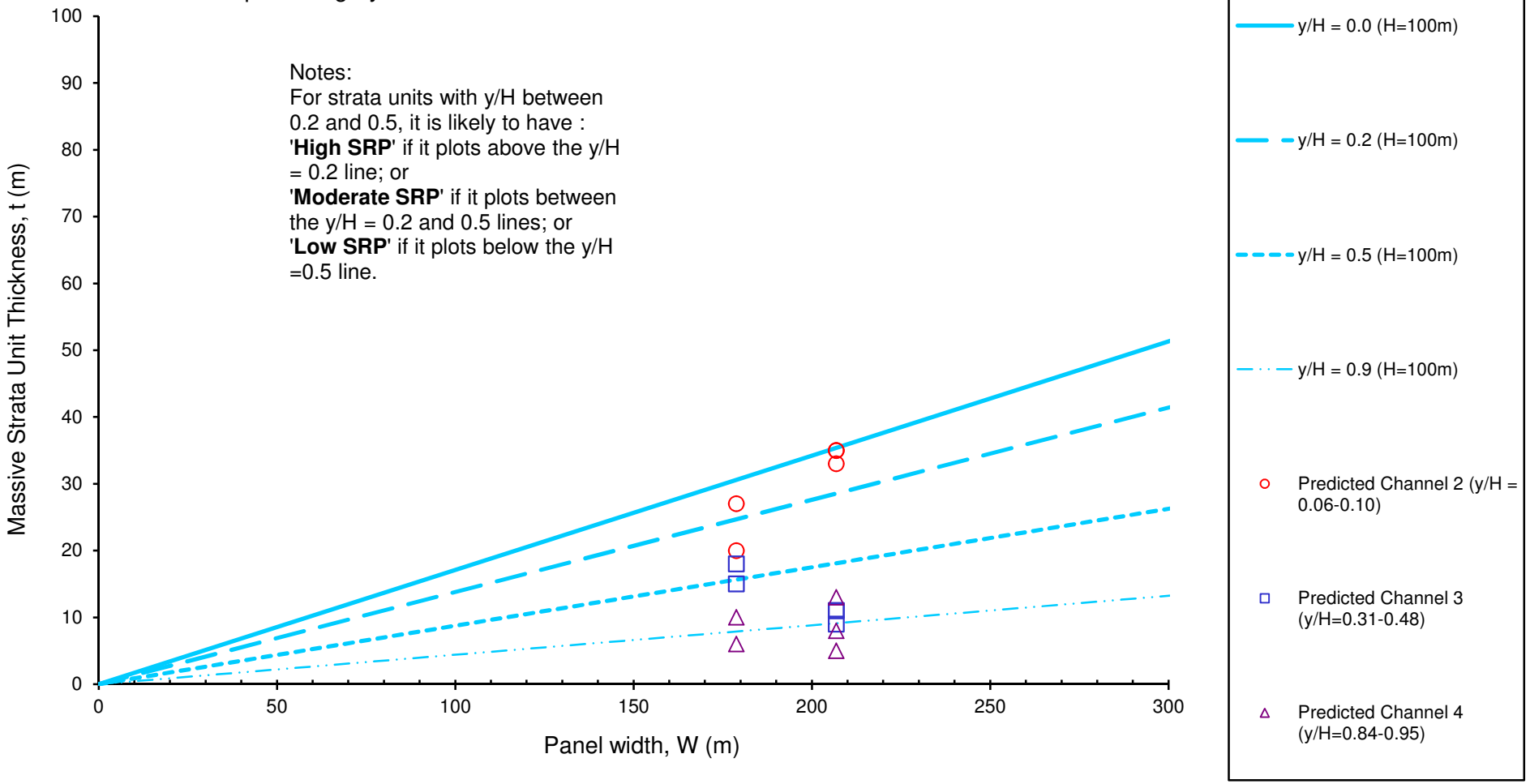
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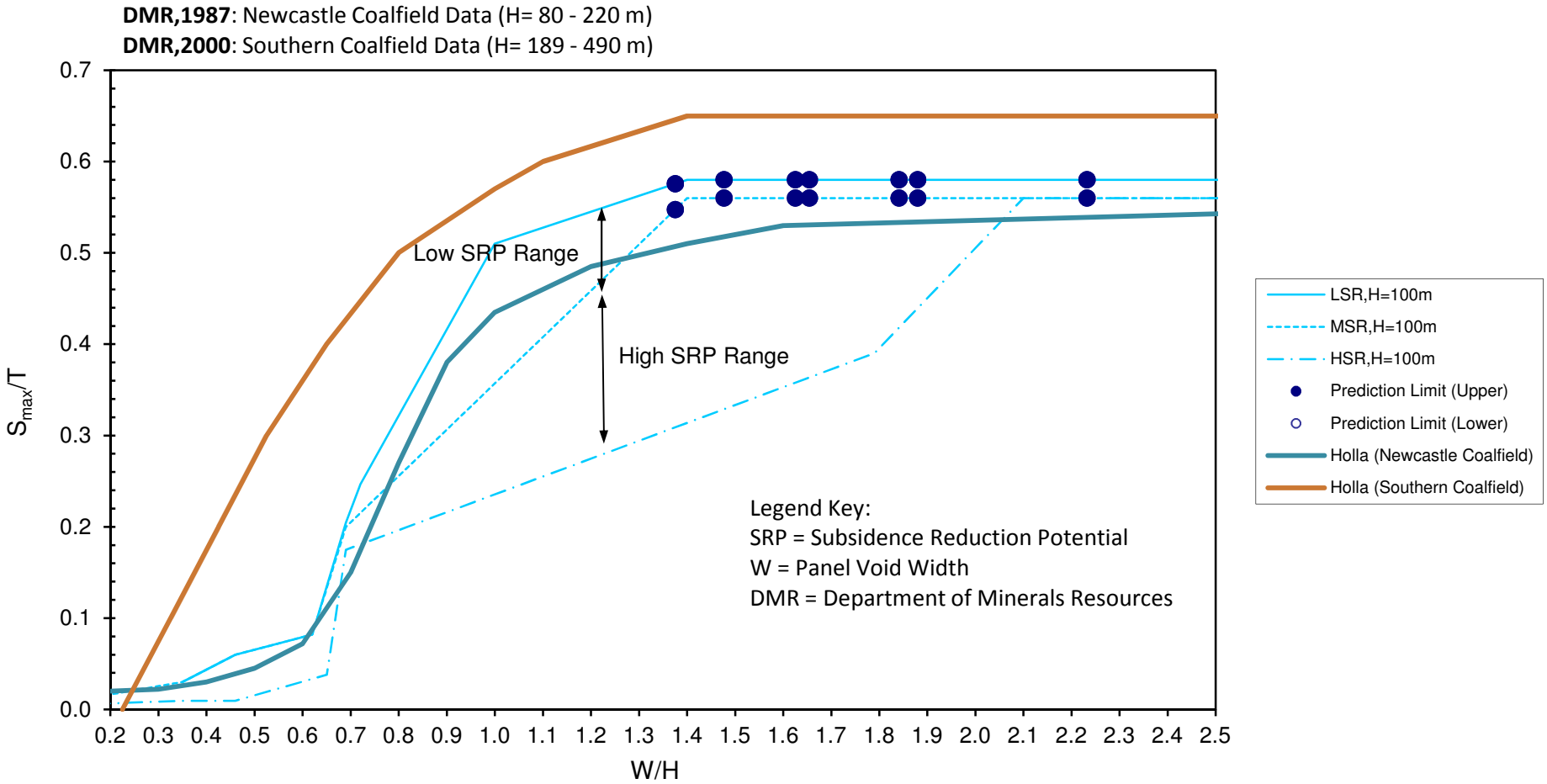
DgS	Engineer: S.Ditton	Client:	West Wallsend Colliery WWD-012/16
	Drawn: S.Ditton		
	Date: 08.08.13	Title:	Conceptual Model for Assessing Subsidence Reduction Potential of Massive Strata Units in Overburden
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS — Figure No: 14

Depth Category: H = 100 m +/- 50m

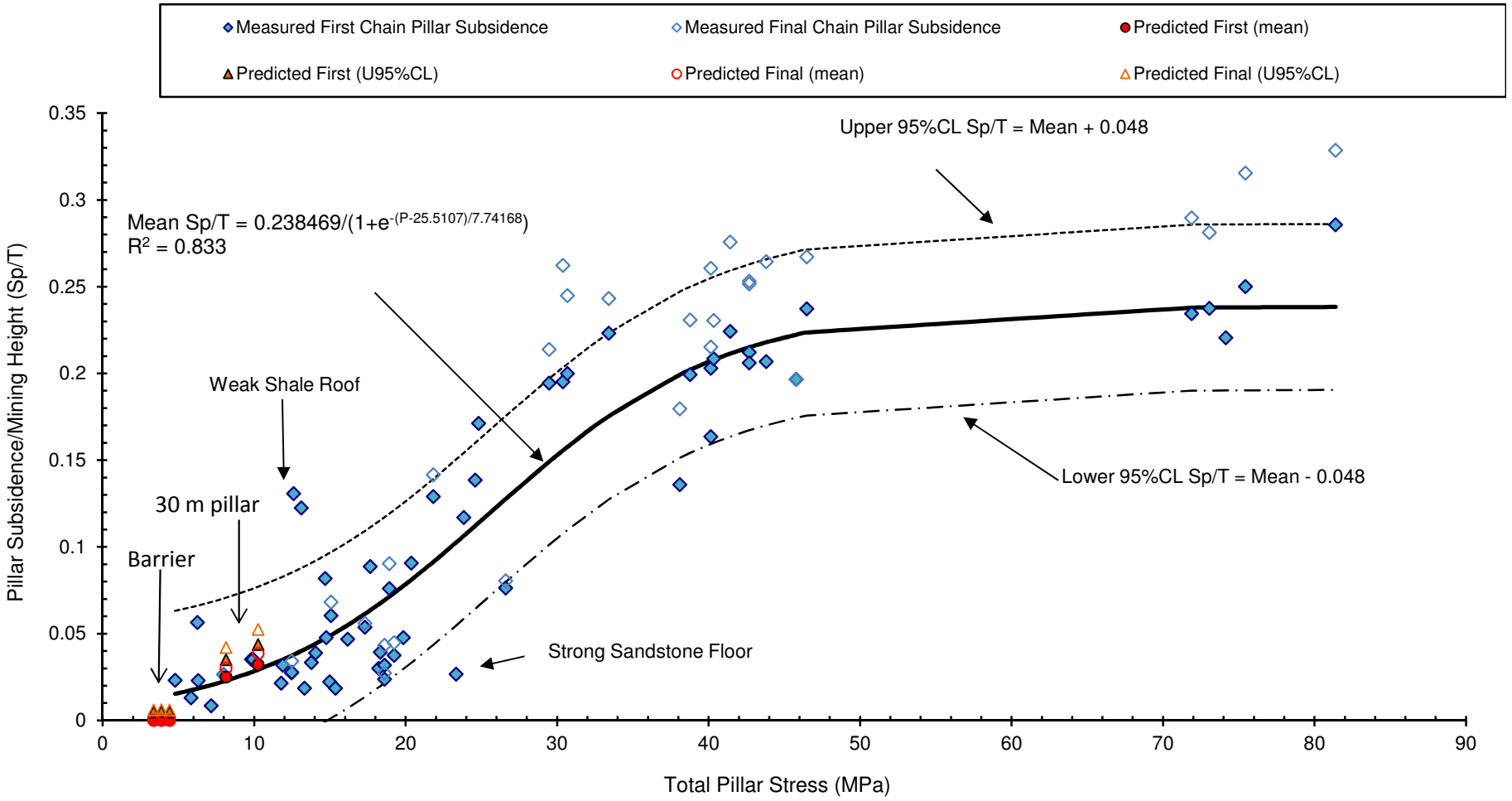
Notes:
For strata units with y/H between 0.2 and 0.5, it is likely to have :
'**High SRP**' if it plots above the y/H = 0.2 line; or
'**Moderate SRP**' if it plots between the y/H = 0.2 and 0.5 lines; or
'**Low SRP**' if it plots below the y/H =0.5 line.



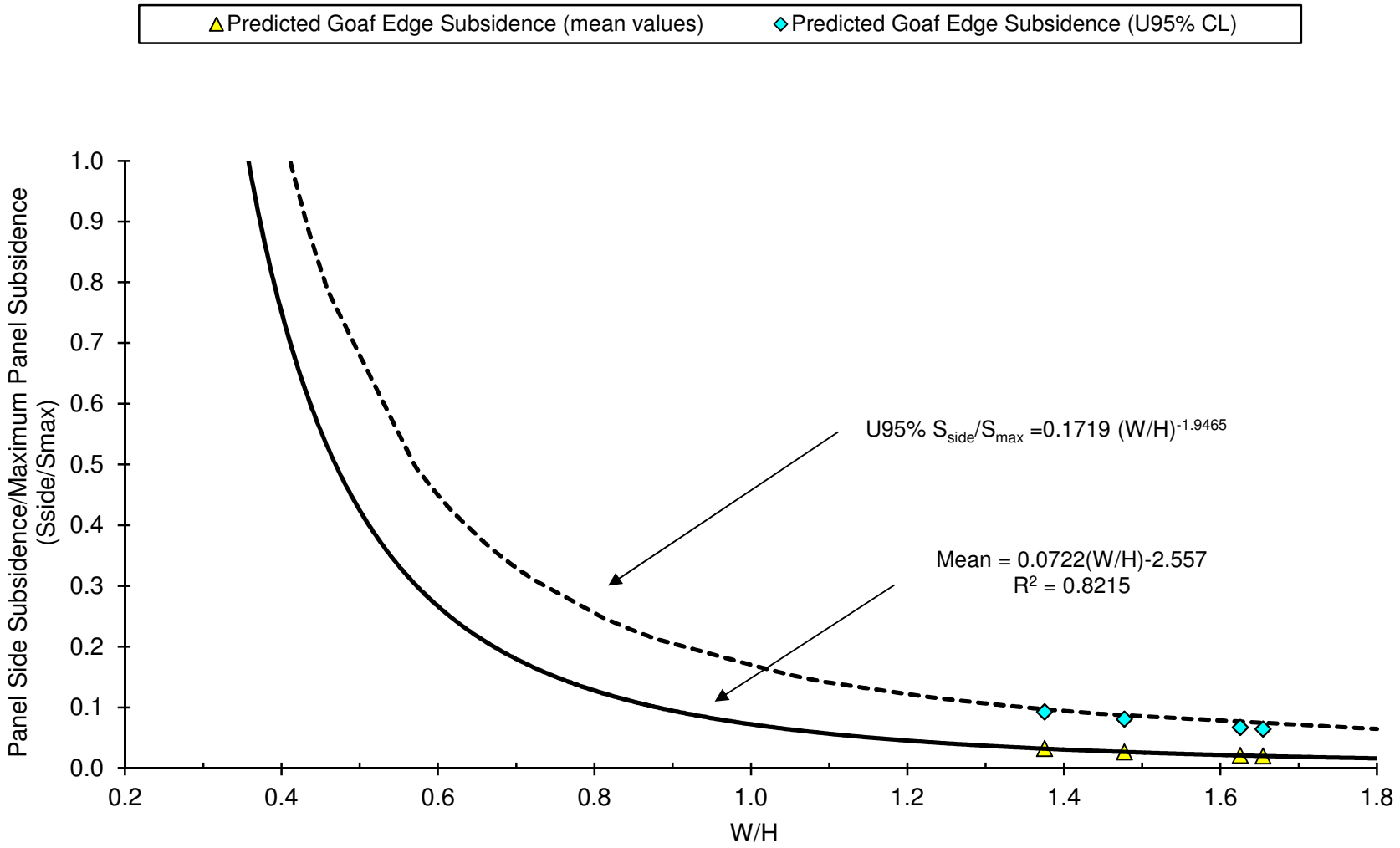
DgS	Engineer: S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn: S.Ditton			
	Date: 02.12.08	Title:	Subsidence Reduction Potential of Massive Units Above WBH Seam for Cover Depths from 50 to 150 m	
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No: 15



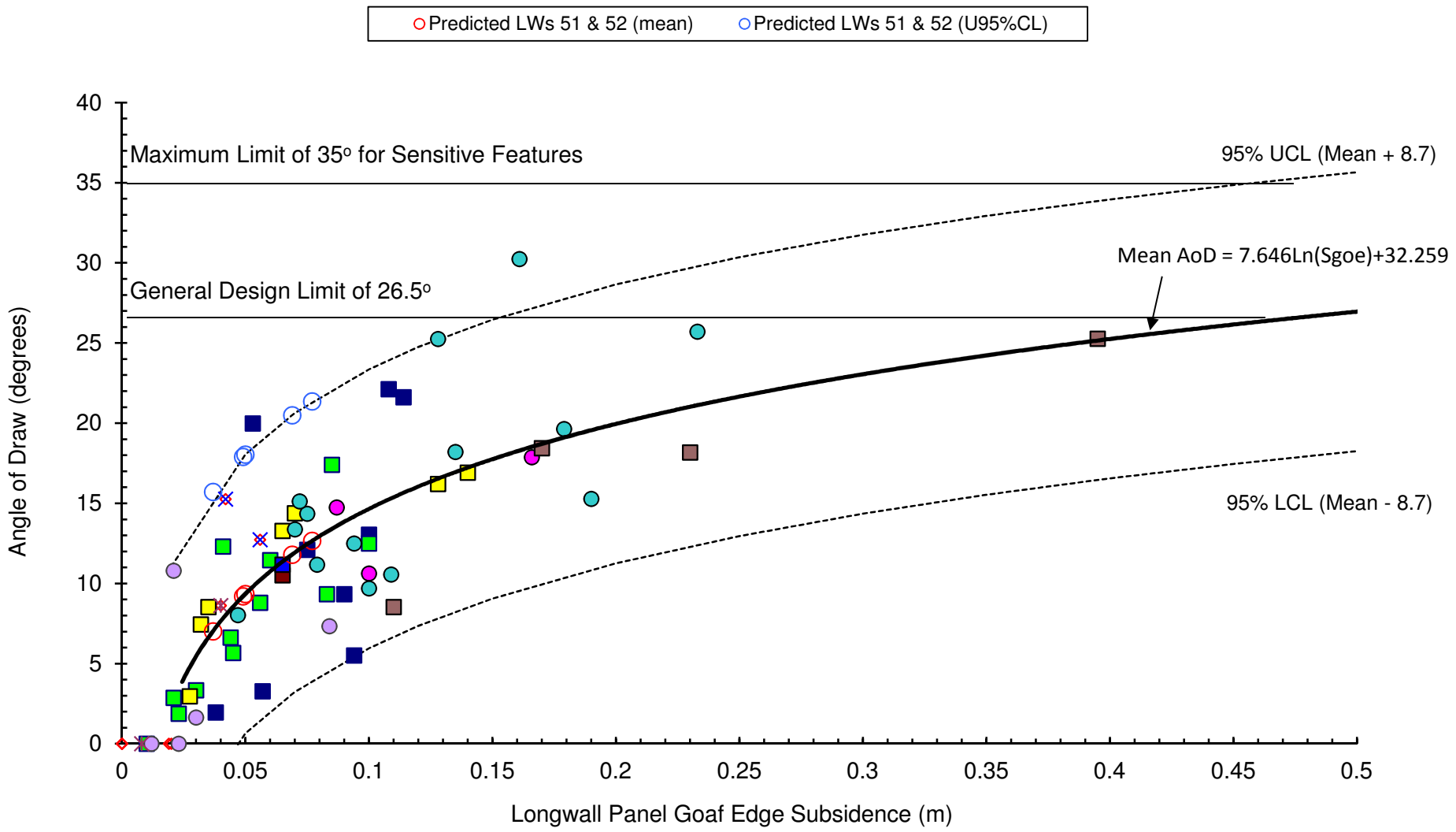
DgS	Engineer: S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn: S.Ditton			
	Date: 07.08.13	Title:	Predicted Maximum Single Panel Subsidence for Longwalls 51 to 52 with Cover Depths between 150 m and 250 m	
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No: 16



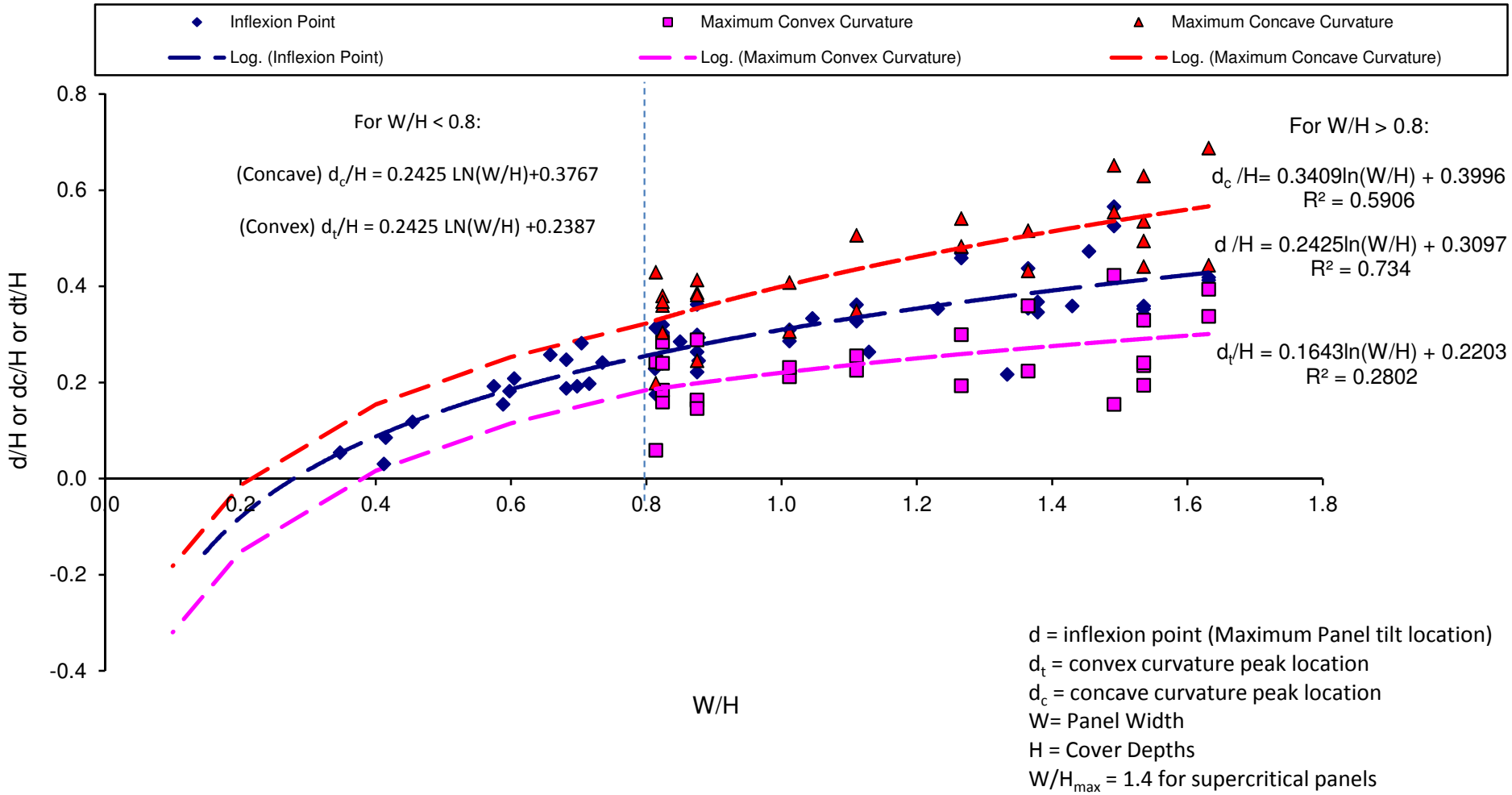
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	07.08.12	Title:	Chain Pillar Subsidence Prediction Model based on the ACARP, 2003 and the Predicted Outcomes for LWs 51-52	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 17



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery	
	Drawn:	S.Ditton		WWD-012/16	
	Date:	08.08.13	Title:	Empirical Model for Goaf Edge Subsidence Prediction Above Longwall Panels in the Newcastle Coalfield and Proposed LW 51 and 52 Outcomes	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 18

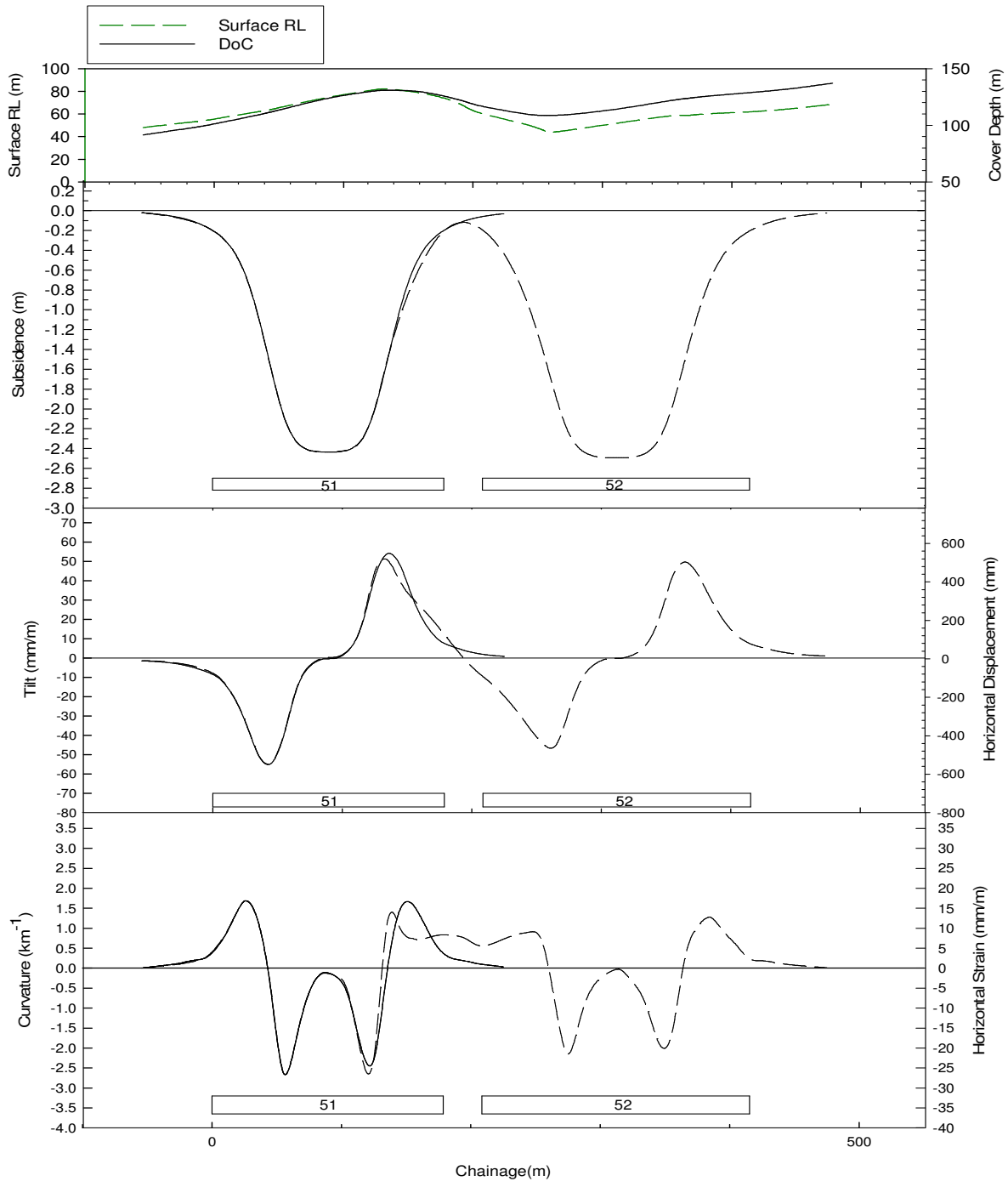


DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	15.08.13	Title:	Empirical Model for Predicting the Angle of Draw from Longwall Panel Limits in the Newcastle Coalfield (ACARP, 2003) and Proposed LW 51 - 52 Outcomes	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 19

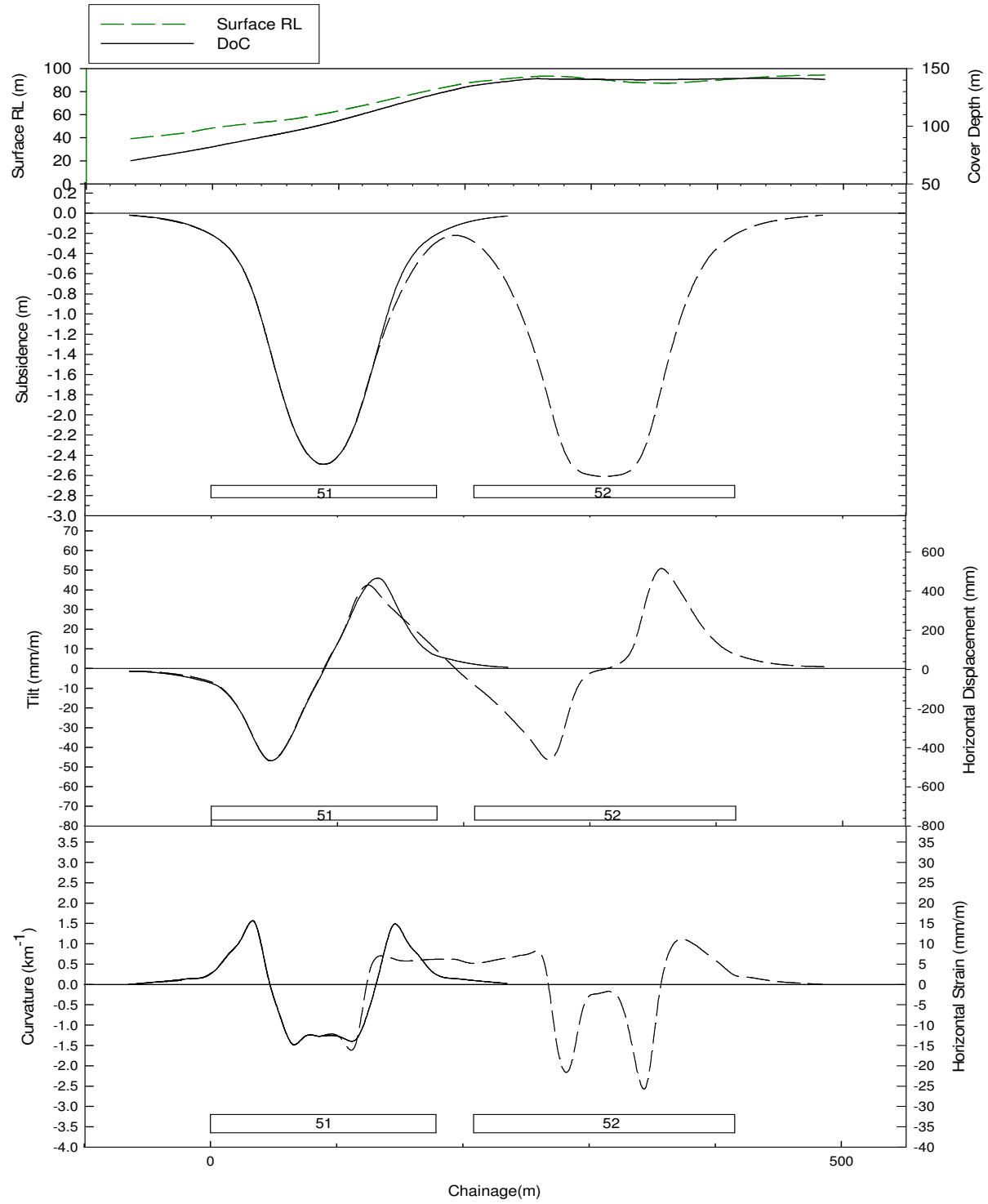


d = inflexion point (Maximum Panel tilt location)
d_t = convex curvature peak location
d_c = concave curvature peak location
W= Panel Width
H = Cover Depths
W/H_{max} = 1.4 for supercritical panels

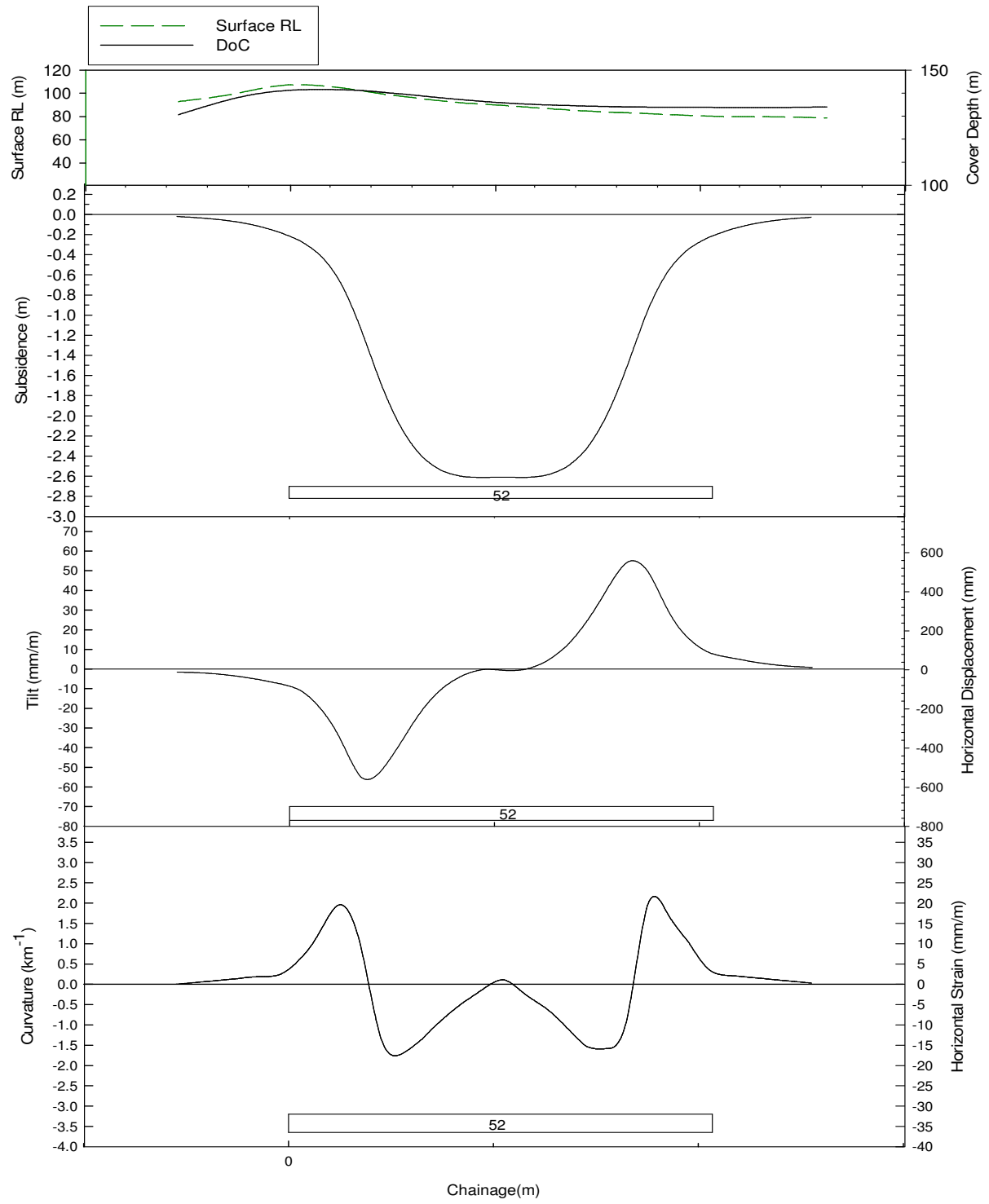
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	15.08.13	Title:	Empirical Model for Predicting the Location of Inflexion Points and Maximum Convex and Concave Curvature Peaks above Longwall Panels in the Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 20



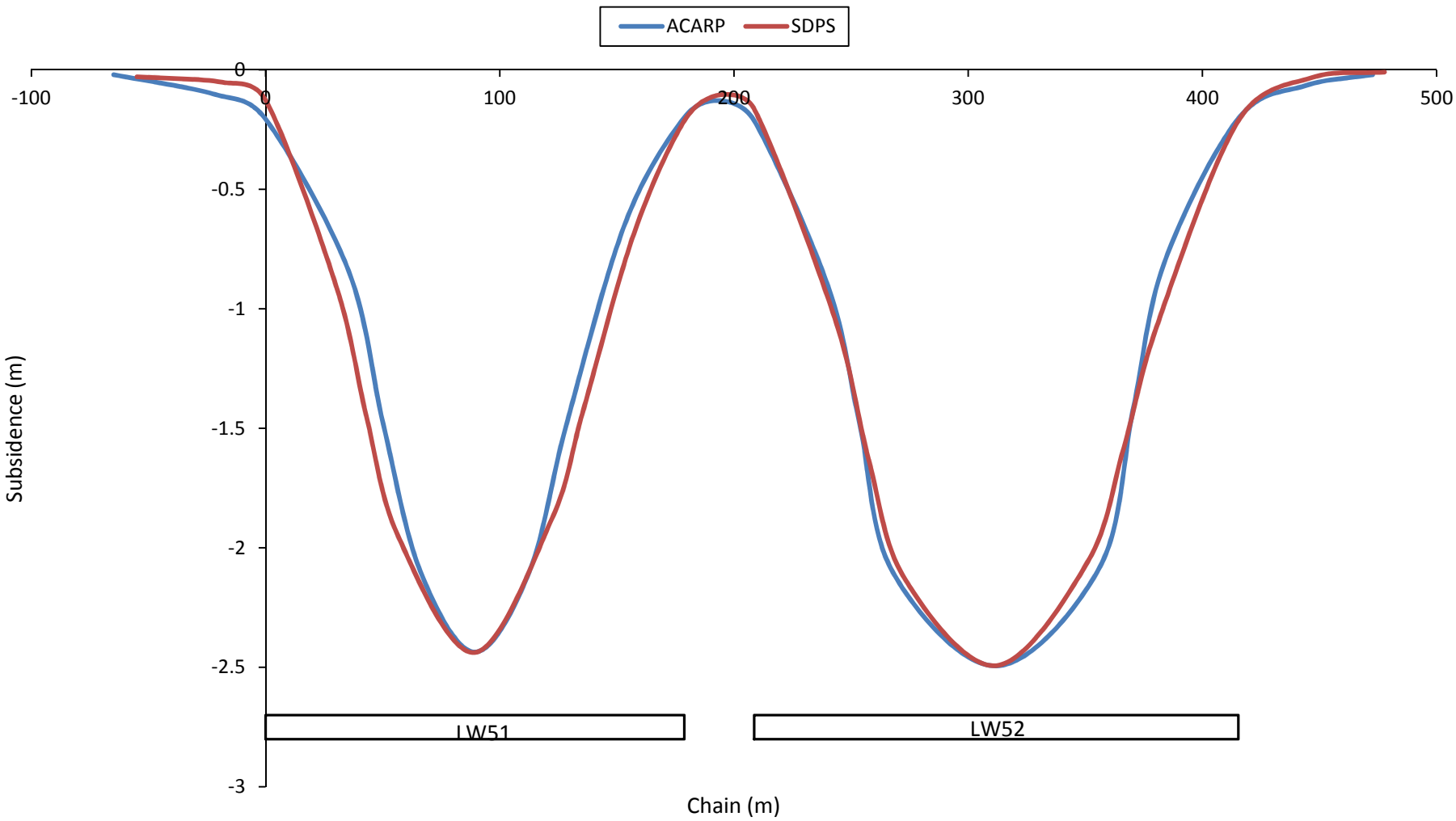
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery	
	Drawn:	S.Ditton		WWD-012/16	
	Date:	15.08.13	Title:	Predicted Subsidence Effect Profiles for XL14 above LWs 51 and 52	
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No: 21a



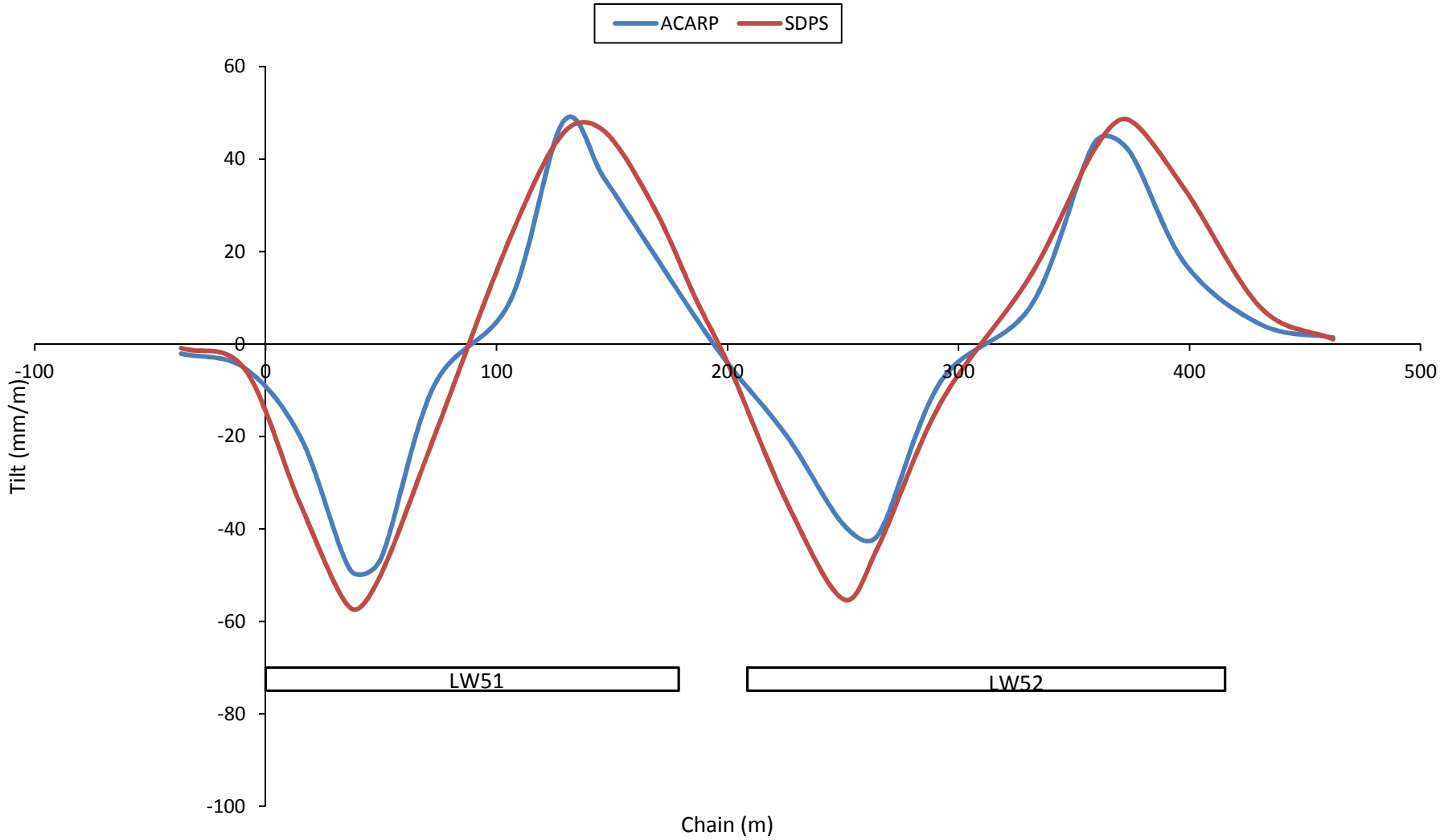
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery	
	Drawn:	S.Ditton		WWD-012/16	
	Date:	15.08.13	Title:	Predicted Subsidence Effect Profiles for XL15 above LWs 51 and 52	
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No: 21b



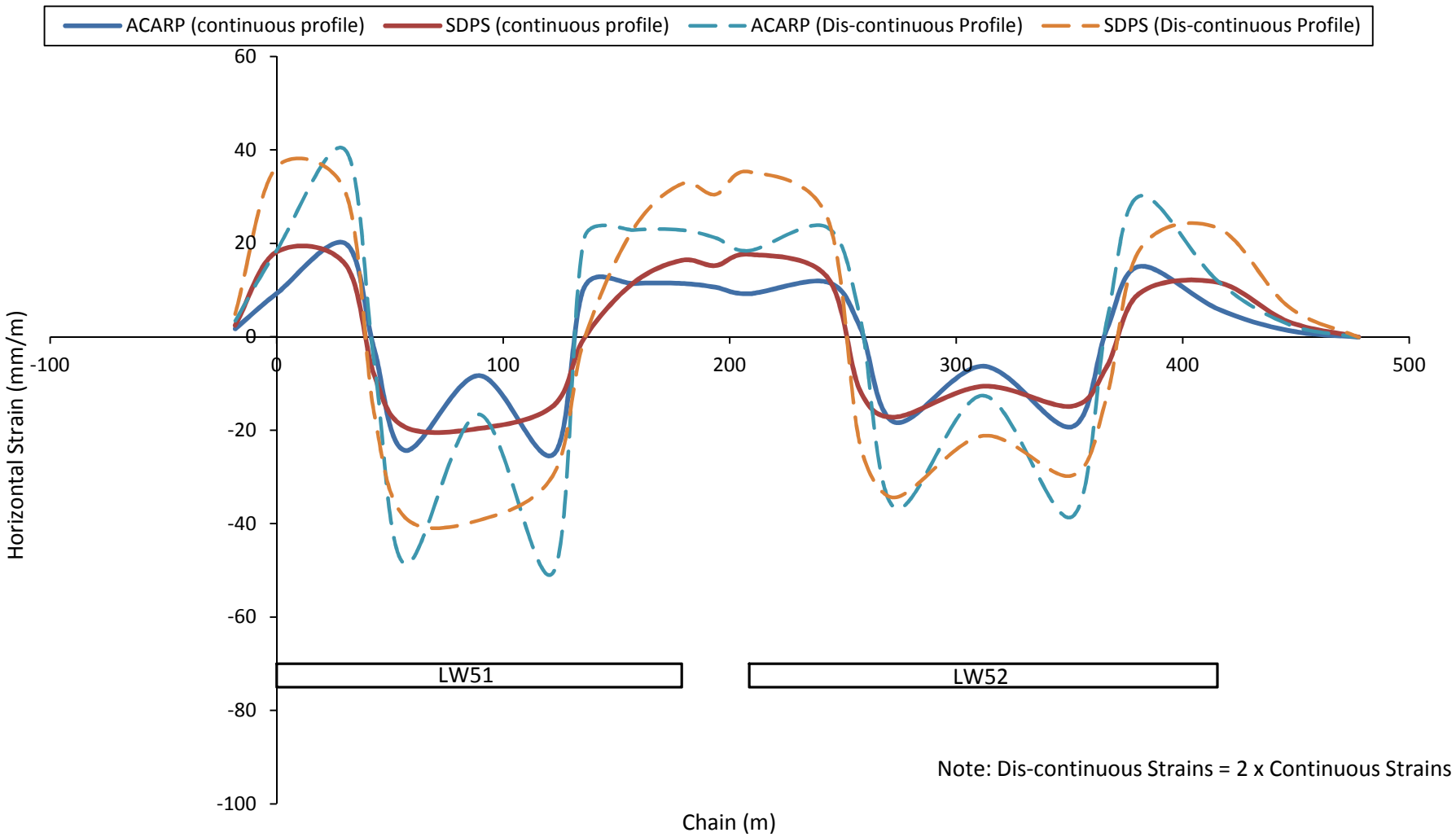
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery	
	Drawn:	S.Ditton		WWD-012/16	
	Date:	15.08.13	Title:	Predicted Subsidence Effect Profiles for XL16 above LWs 51 and 52	
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No: 21c



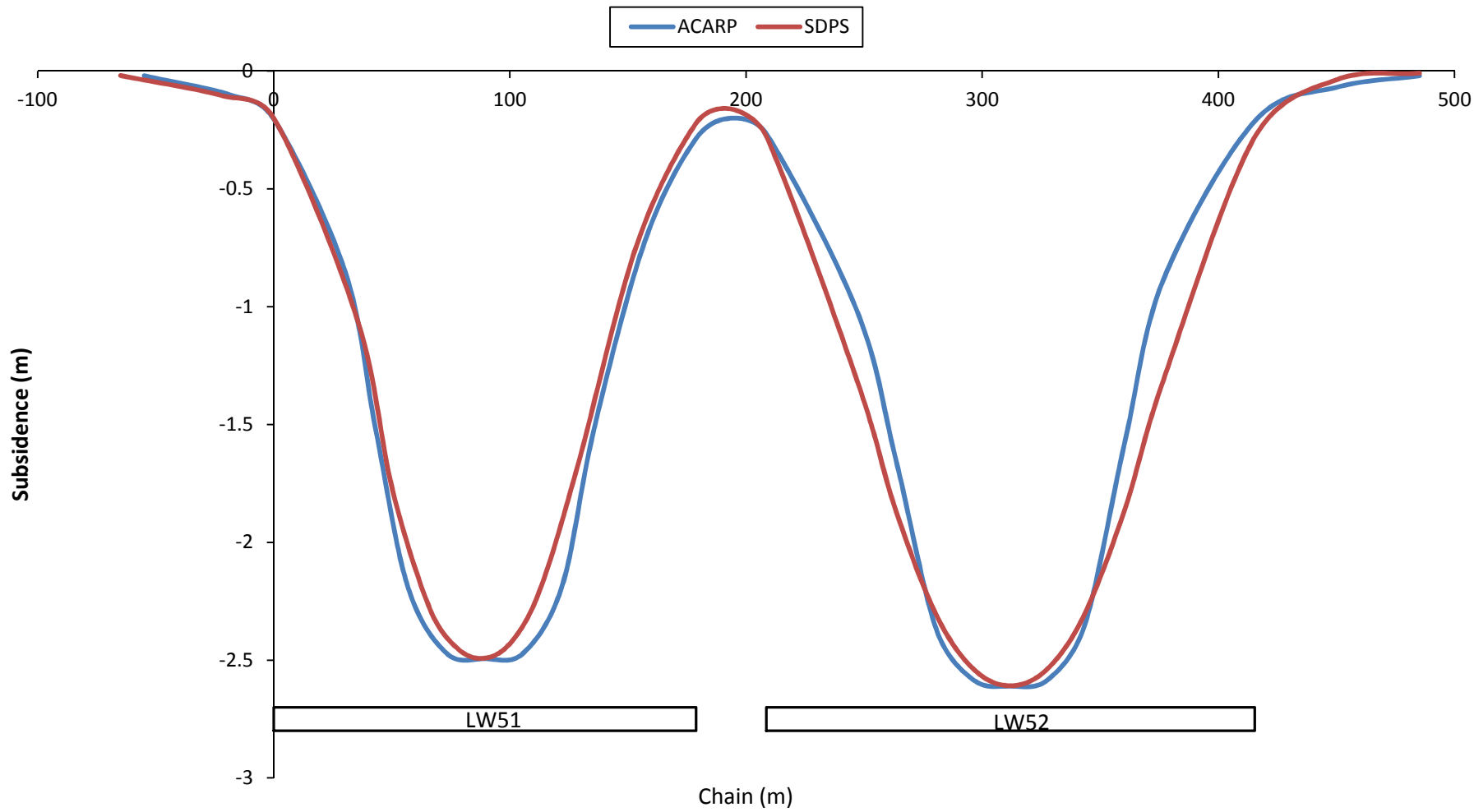
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS Model and ACARP Model for U95%CL Subsidence Profiles along XL14	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22a



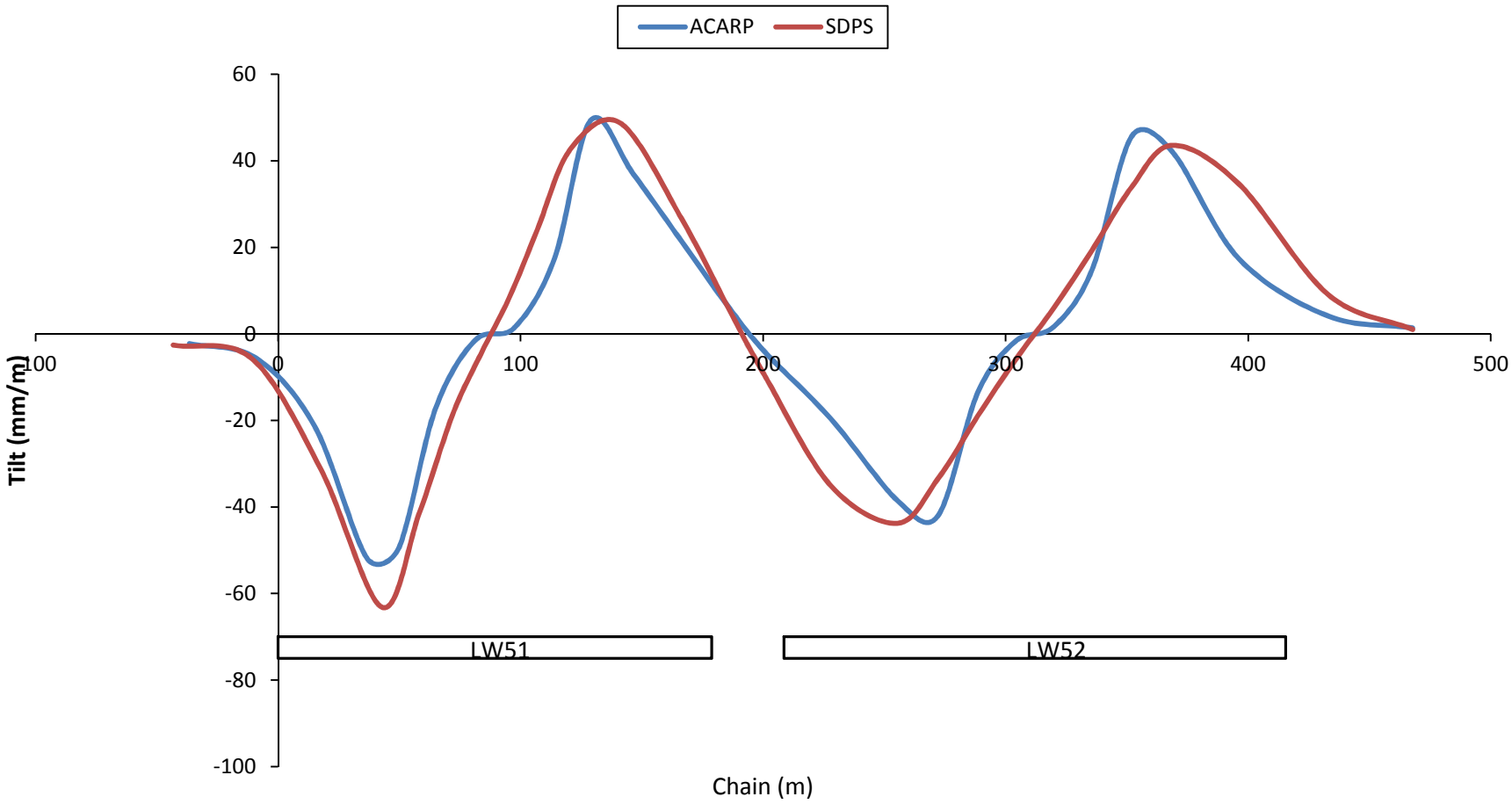
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS Model and ACARP Model Tilt Profiles for XL14	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22b



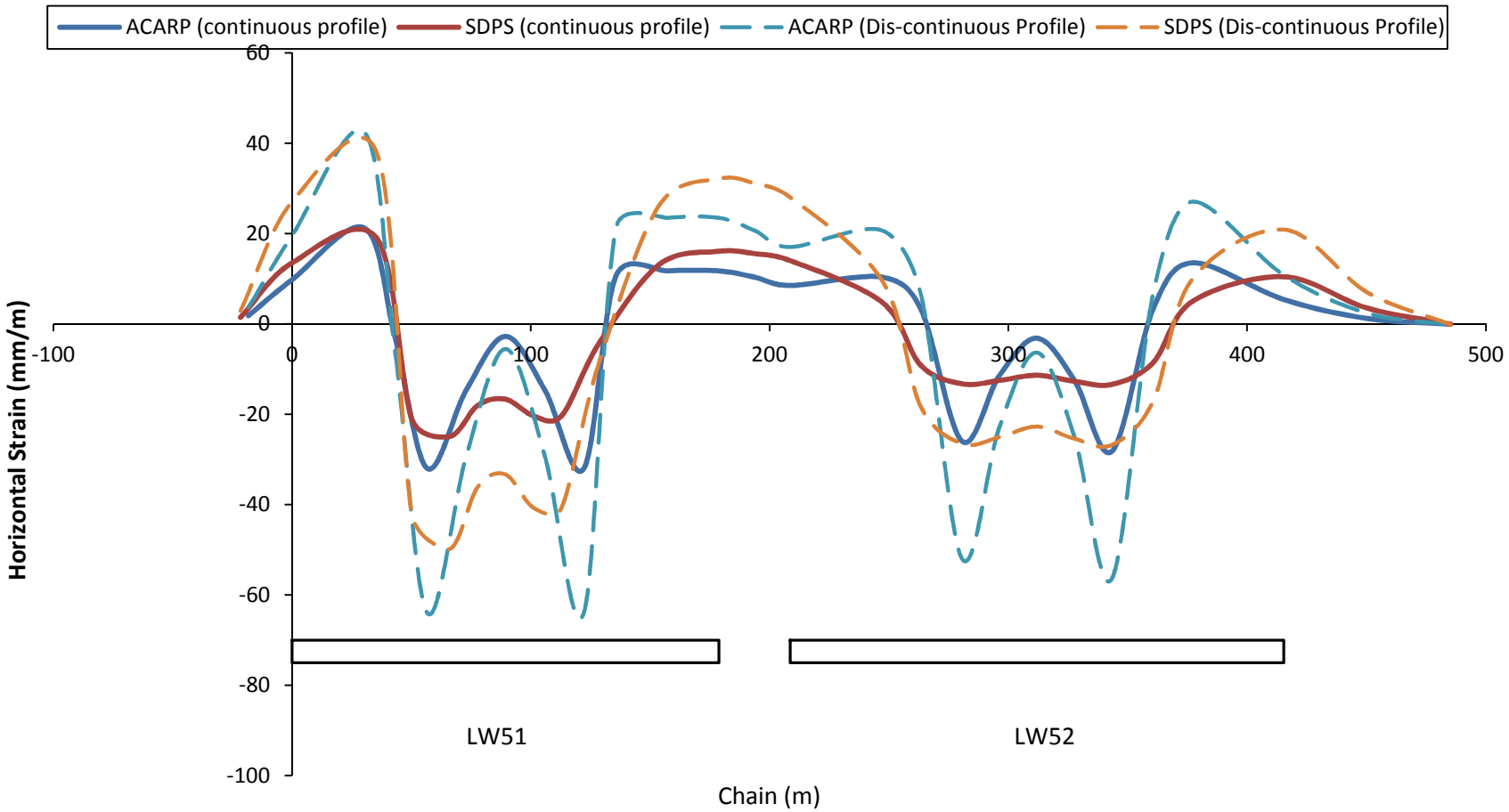
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS and ACARP Model U95%CL Horizontal Strain Profiles for XL14	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22c



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS and ACARP Model U95%CL Subsidence Profiles along XL15	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22d

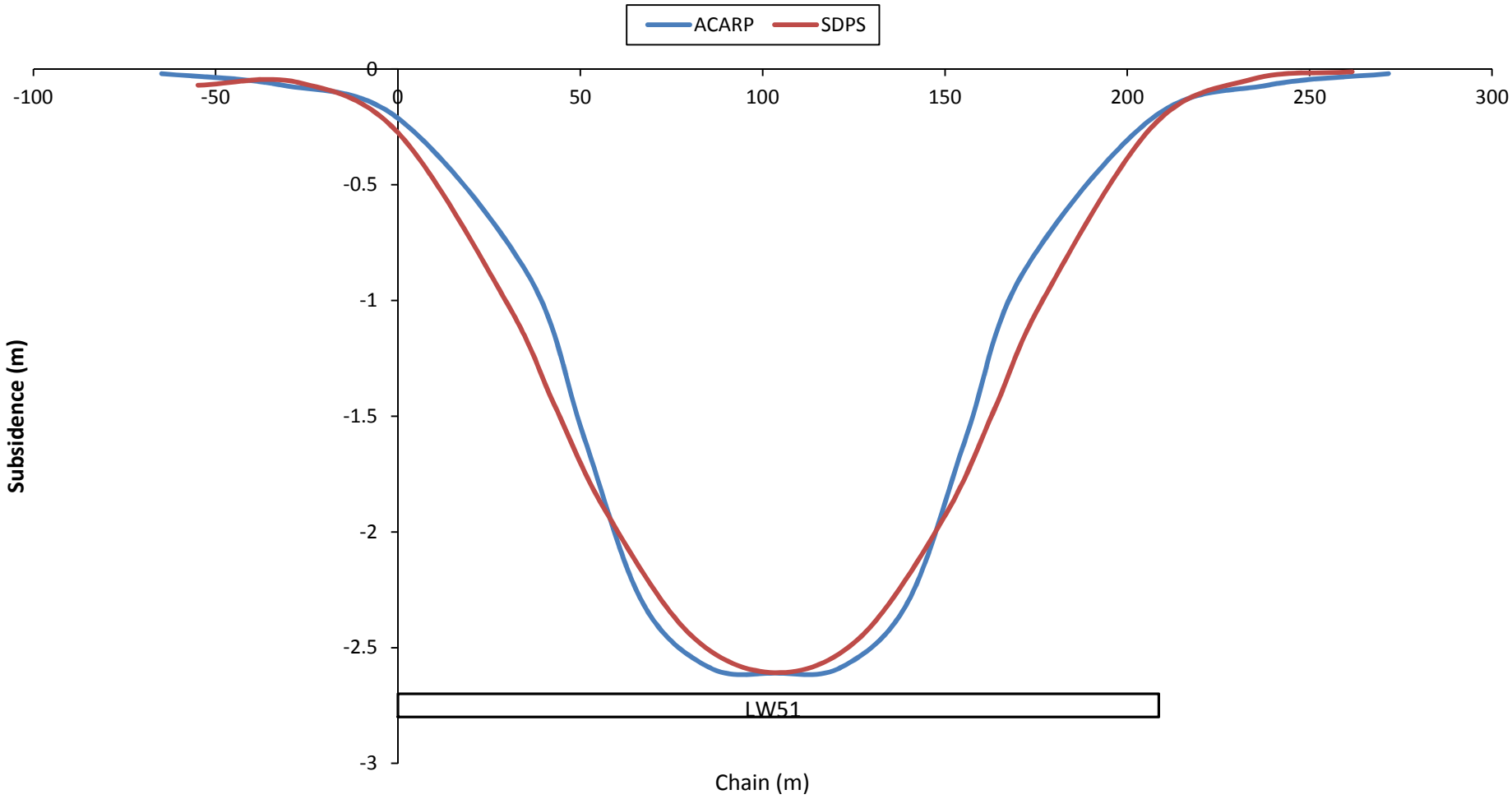


DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS and ACARP Model U95% Tilt Profiles for XL15	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22e

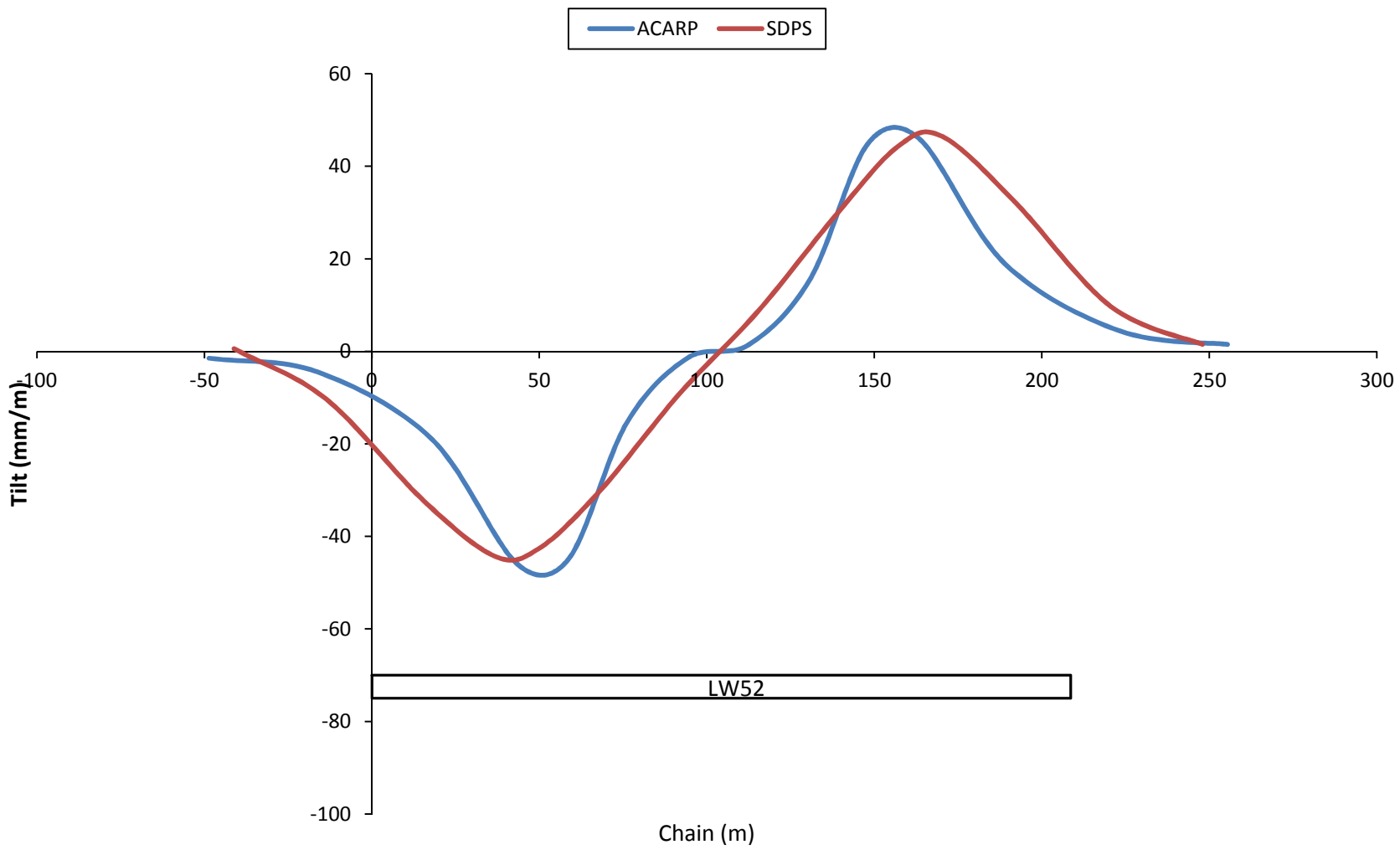


Note: Dis-continuous Strains = 2 x Continuous Strains

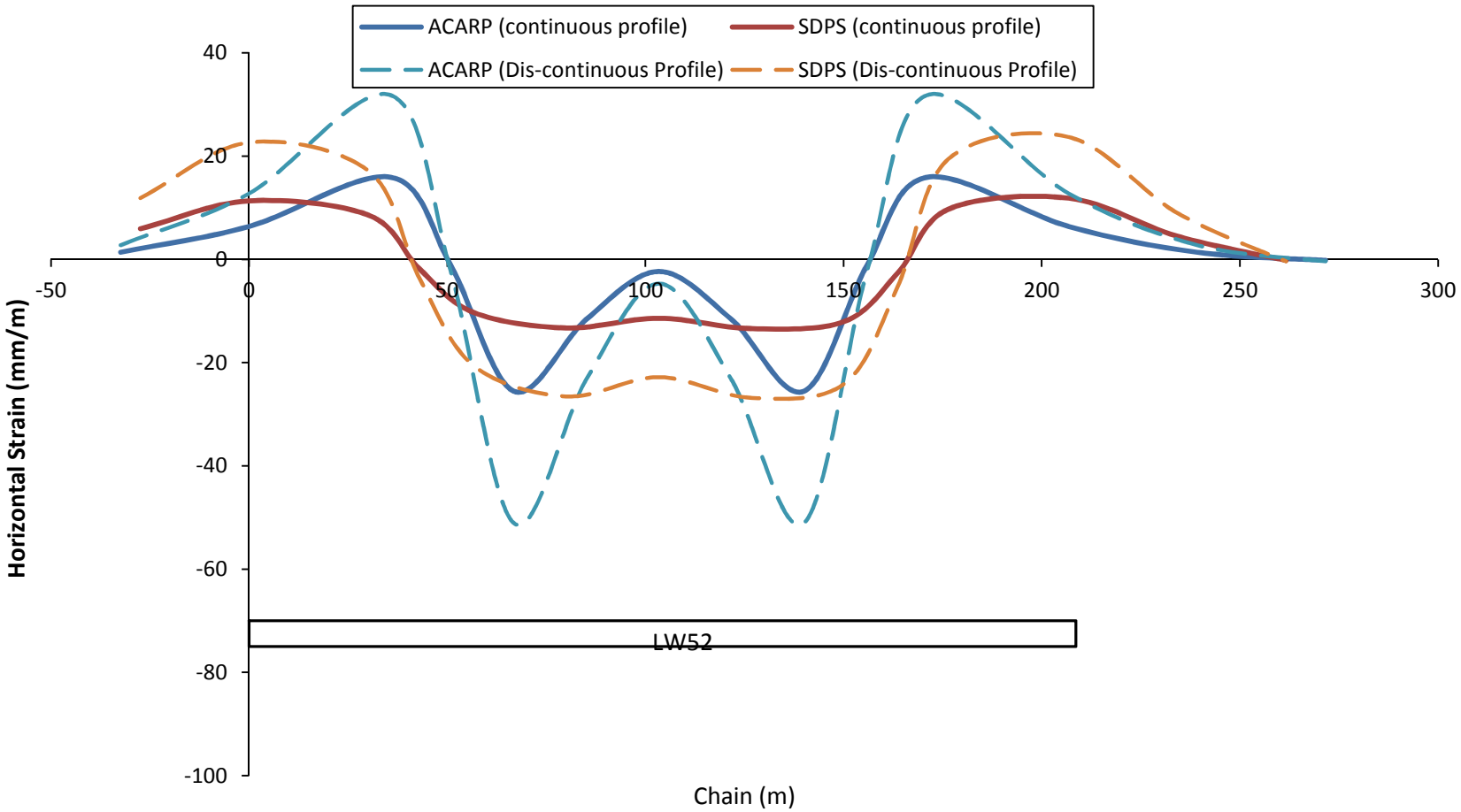
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS and ACARP Model U95%CL Horizontal Strain Profiles for XL15	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22f



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS and ACARP Model U95%CL Subsidence Profiles along XL16	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22g

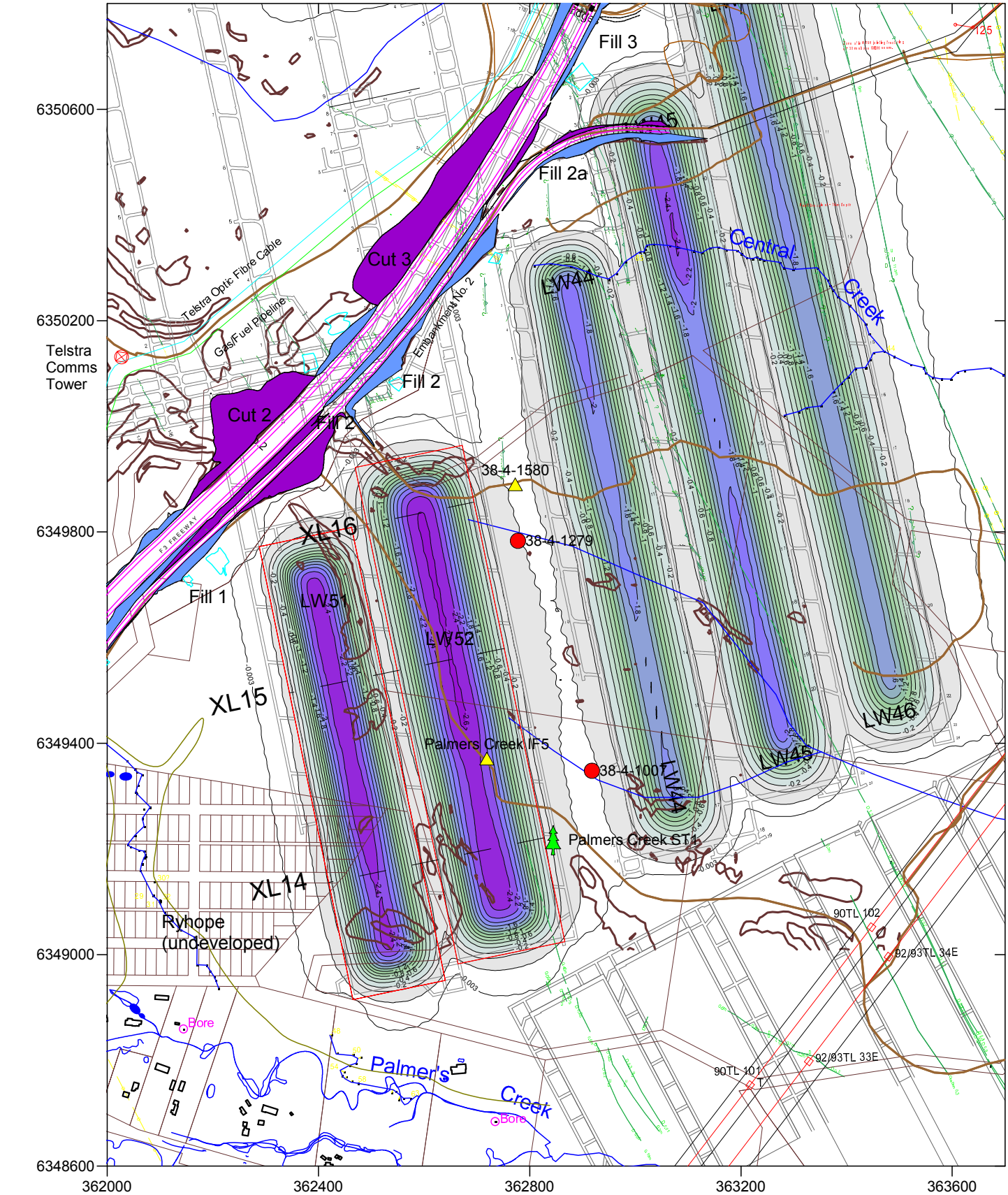


DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS and ACARP Model U95% Tilt Profiles for XL16	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22h

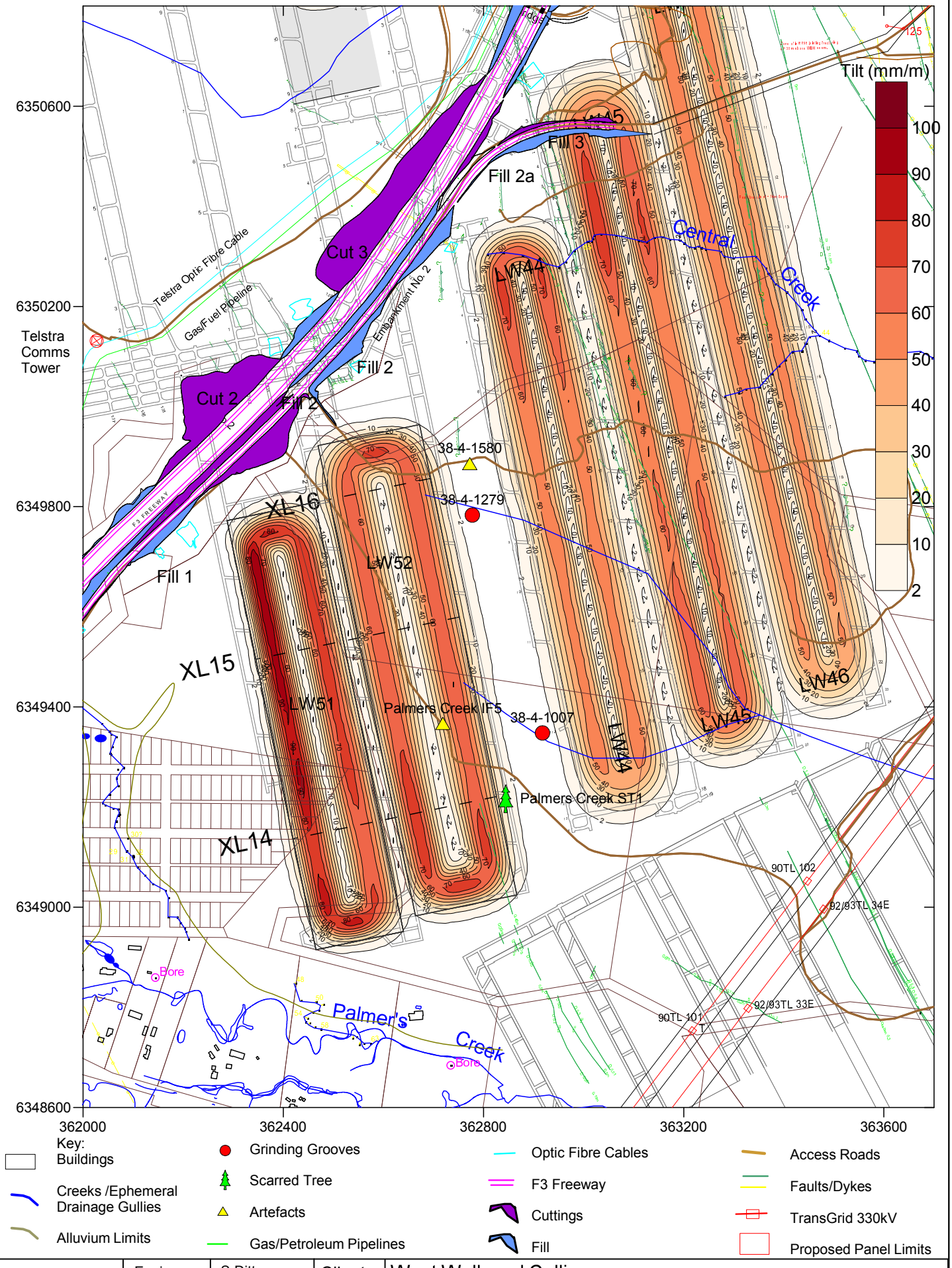


Note: Dis-continuous Strains = 2 x Continuous Strains

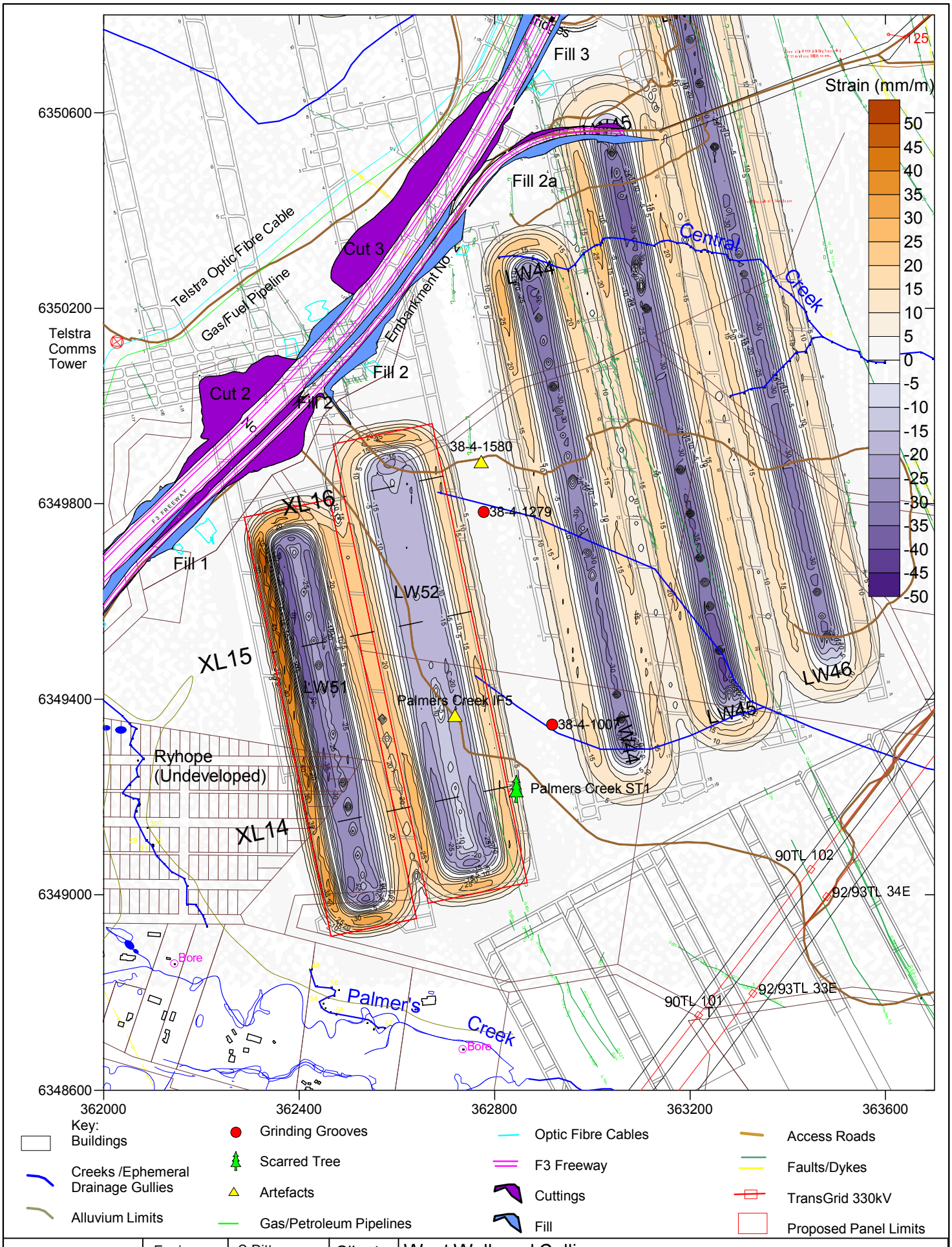
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	08.08.13	Title:	Calibrated SDPS and ACARP Model U95%CL Horizontal Strain Profiles for XL16	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 22i



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	06.08.13	Title:	Predicted Cumulative U95%CL Subsidence Contours above LWs 51/52 and LWs 44 to 46 in the Southern Domain	
Ditton Geotechnical Services Pty Ltd			Scale:	1:8,000	Figure No: 23a



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	06.08.13	Title:	Predicted U95%CL Principal Tilt Contours due to Cumulative Subsidence above LWs 51/52 and 44 to 46	
Ditton Geotechnical Services Pty Ltd			Scale:	1:8,000	Figure No: 23b



Key:

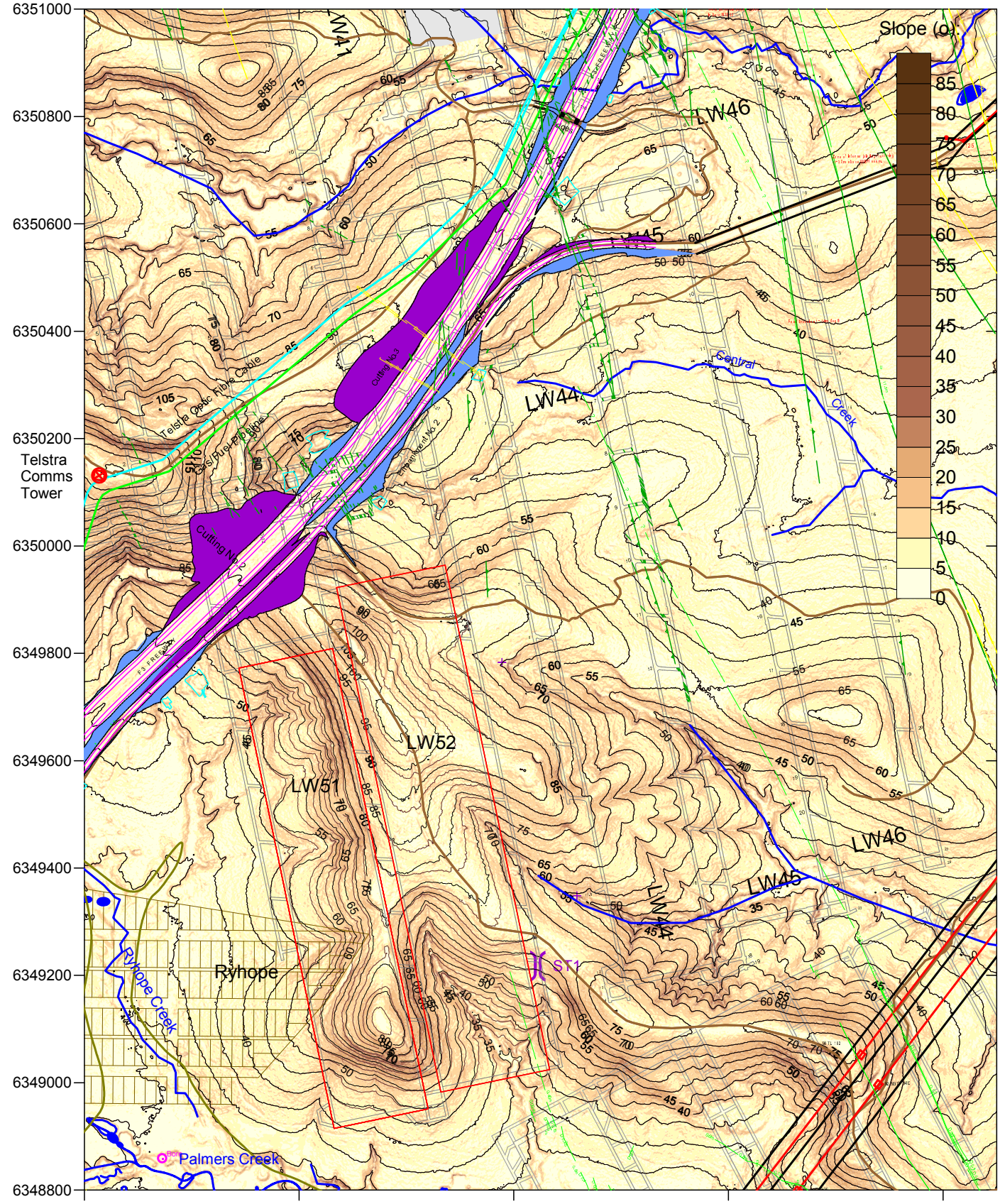
- Buildings
- Creeks /Ephemeral Drainage Gullies
- Alluvium Limits
- Grinding Grooves
- Scarred Tree
- Artefacts
- Gas/Petroleum Pipelines
- Optic Fibre Cables
- F3 Freeway
- Cuttings
- Fill
- Access Roads
- Faults/Dykes
- TransGrid 330kV
- Proposed Panel Limits

DgS

Ditton Geotechnical Services Pty Ltd

Engineer:	S.Ditton
Drawn:	S.Ditton
Date:	06.08.13

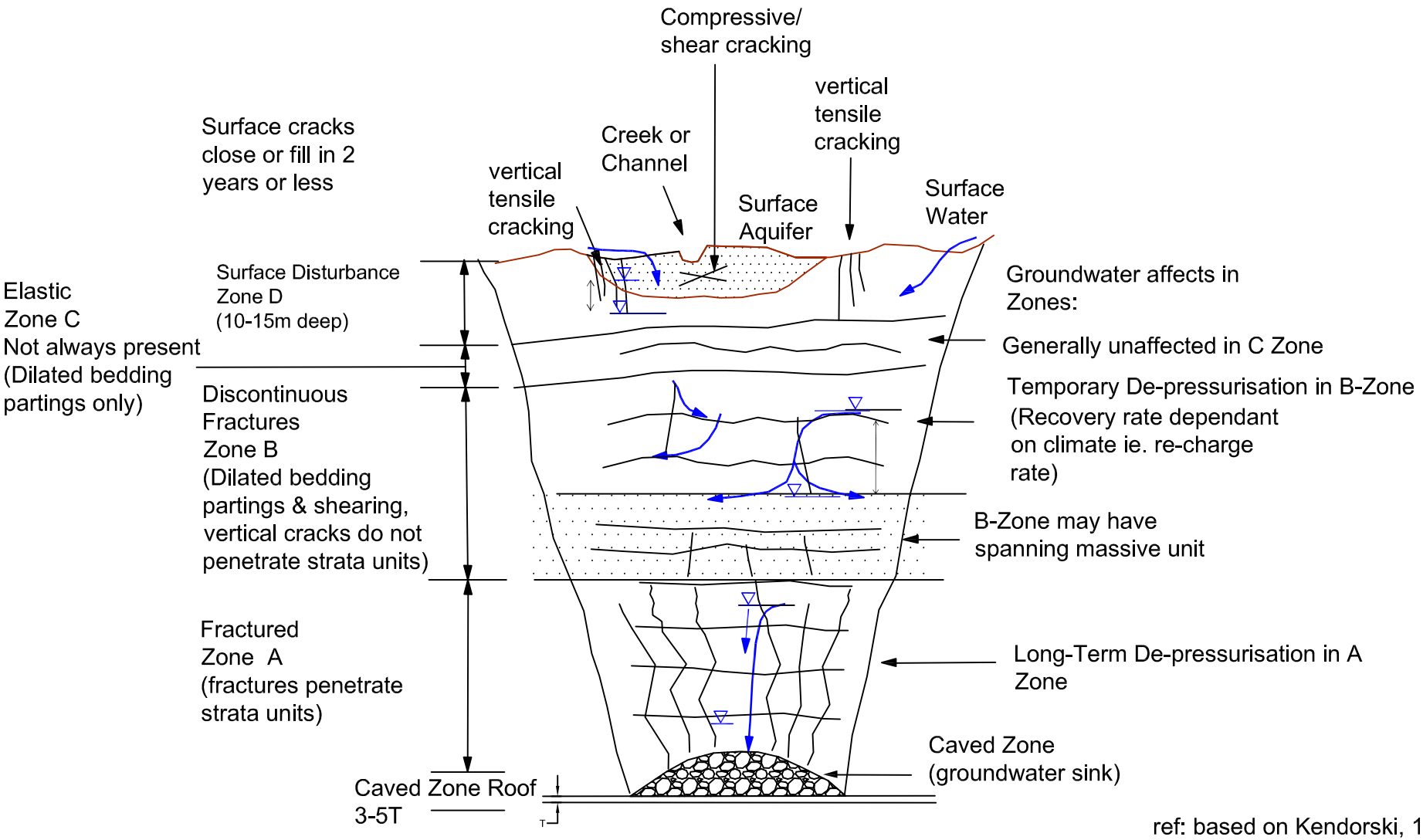
Client:	West Wallsend Colliery WWD-012/16
Title:	Predicted U95%CL Principal Horizontal Strain Contours due to Cumulative Subsidence above LWs 51/52 and 44 to 46 in the Southern Domain
Scale:	1:8,000
Figure No:	23c



Key:

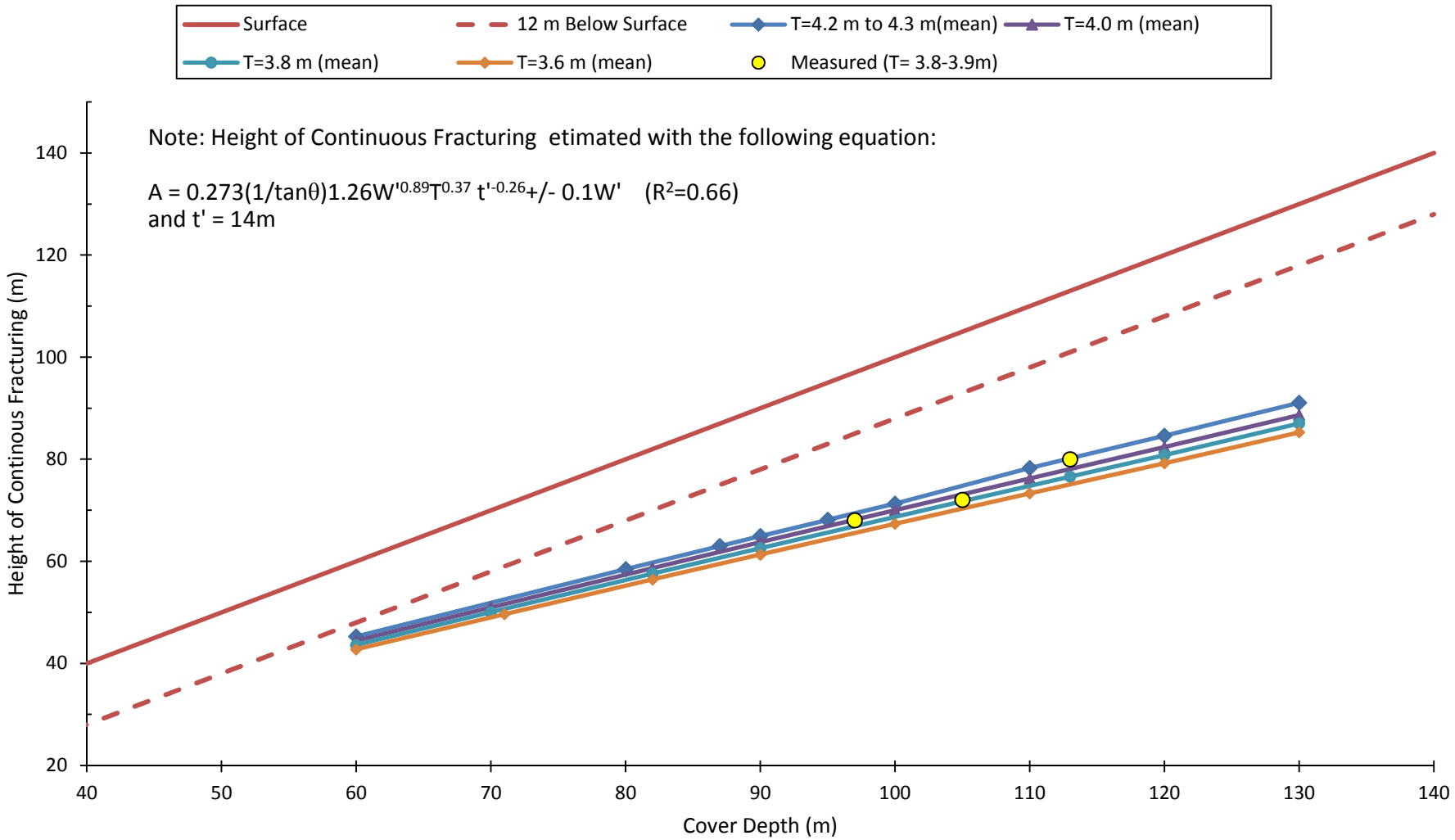
- Rock Face Features
- Creeks /Ephemeral Drainage Gullies
- Alluvium Limits
- Aboriginal Heritage
- Gravel Access Roads
- Gas/Petroleum Pipelines
- Optic Fibre Cables
- F3 Freeway
- Cuts
- Fill
- Faults/Dykes
- TransGrid 330kV
- Pre-Mining Surface Level Contours (m)
- Post-Mining Surface Level Contours (m)

DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	06.08.13	Title:	Post Mining Topography and Surface Features above LWs 51 and 52	
	Ditton Geotechnical Services Pty Ltd		Scale:	1:10,000	Figure No: 24

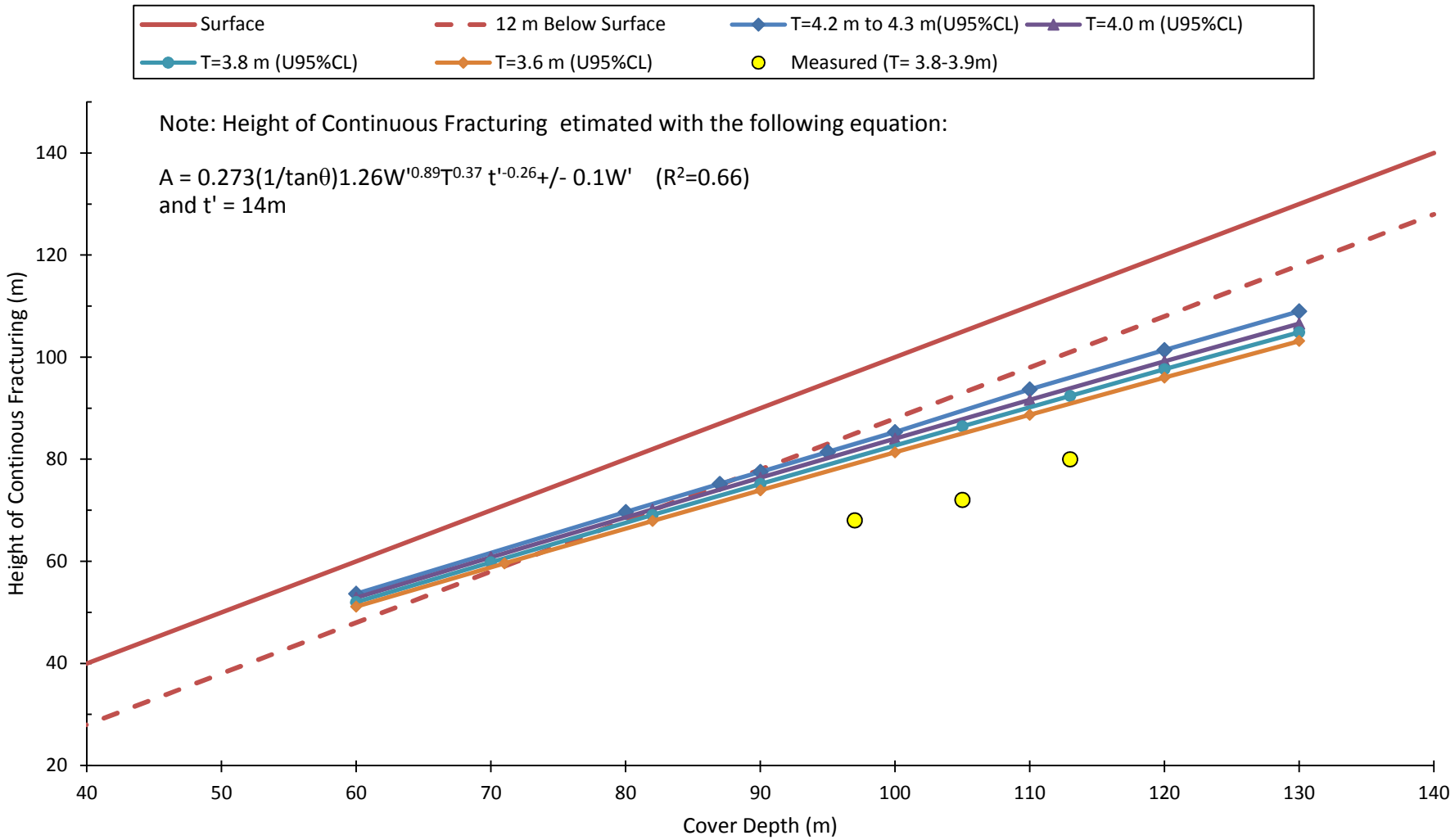


ref: based on Kendorski, 1993

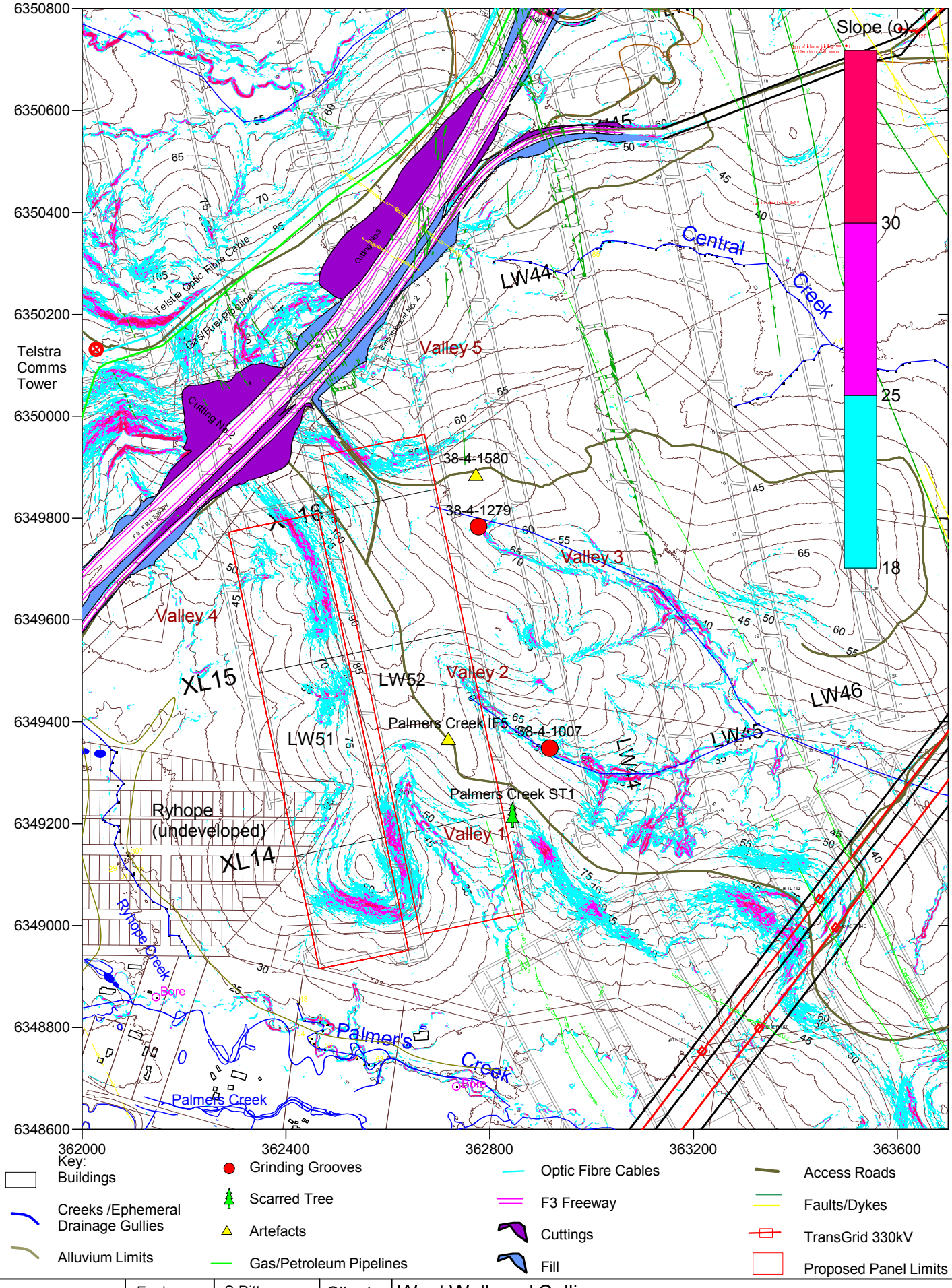
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16
	Drawn:	S.Ditton		
	Date:	13.05.13	Title:	Conceptual Model of Sub-surface Fracturing Above Longwall Panels
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS — Figure No: 25



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery	
	Drawn:	S.Ditton		WWD-012/16	
	Date:	23.08.13	Title:	Alternative PI-Term Model for Continuous Sub-Surface Fracture Height Prediction: Mean Values	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 26a



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16
	Drawn:	S.Ditton		
	Date:	23.08.13	Title:	Alternative PI-Term Model for Continuous Sub-Surface Fracture Height Prediction: U95%CL Values
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS — Figure No: 26b



Key:

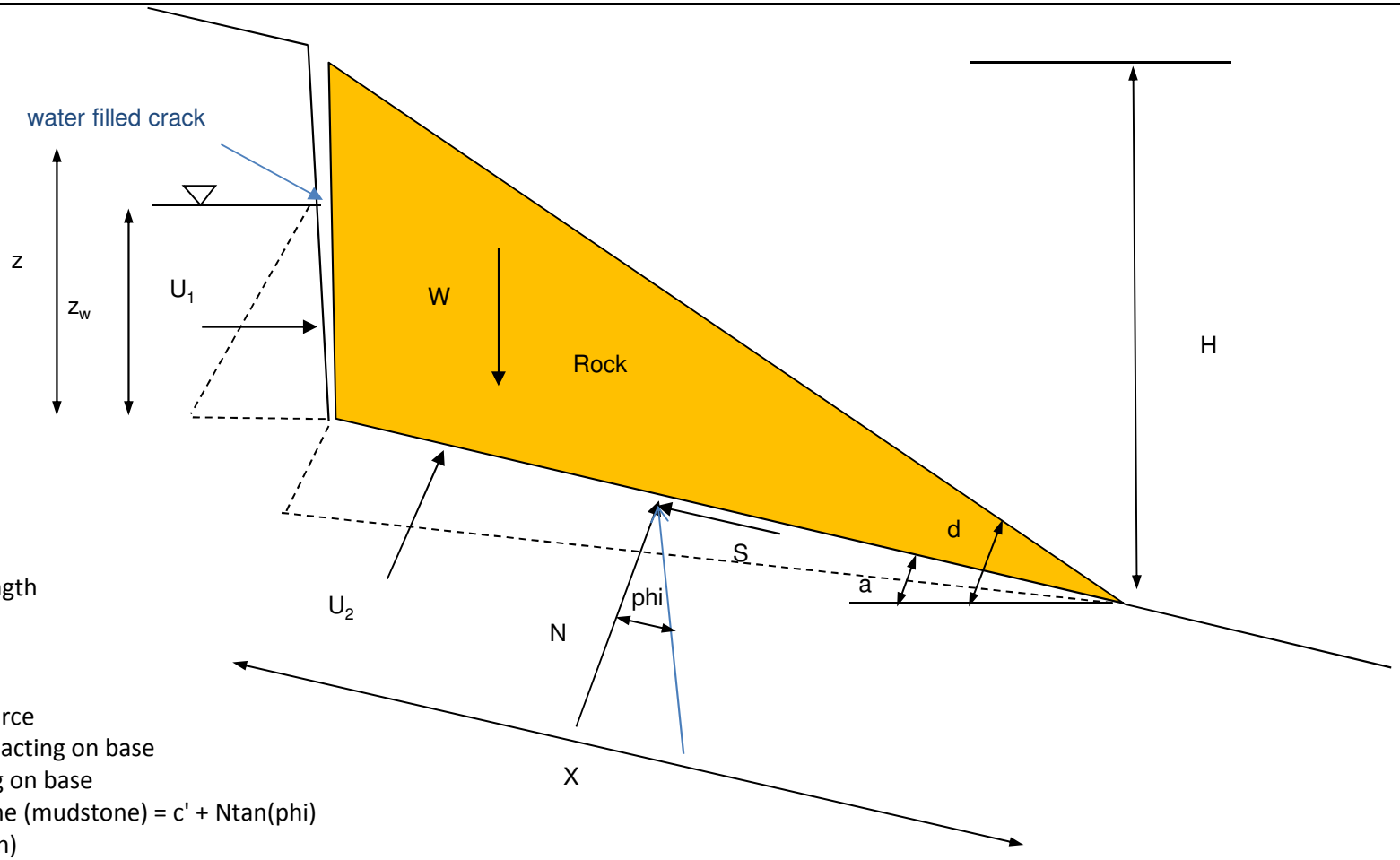
- Buildings
- Creeks /Ephemeral Drainage Gullies
- Alluvium Limits
- Grinding Grooves
- Scarred Tree
- Artefacts
- Gas/Petroleum Pipelines
- Optic Fibre Cables
- F3 Freeway
- Cuttings
- Fill
- Access Roads
- Faults/Dykes
- TransGrid 330kV
- Proposed Panel Limits

DgS

Ditton Geotechnical Services Pty Ltd

Engineer:	S.Ditton
Drawn:	S.Ditton
Date:	12.12.13

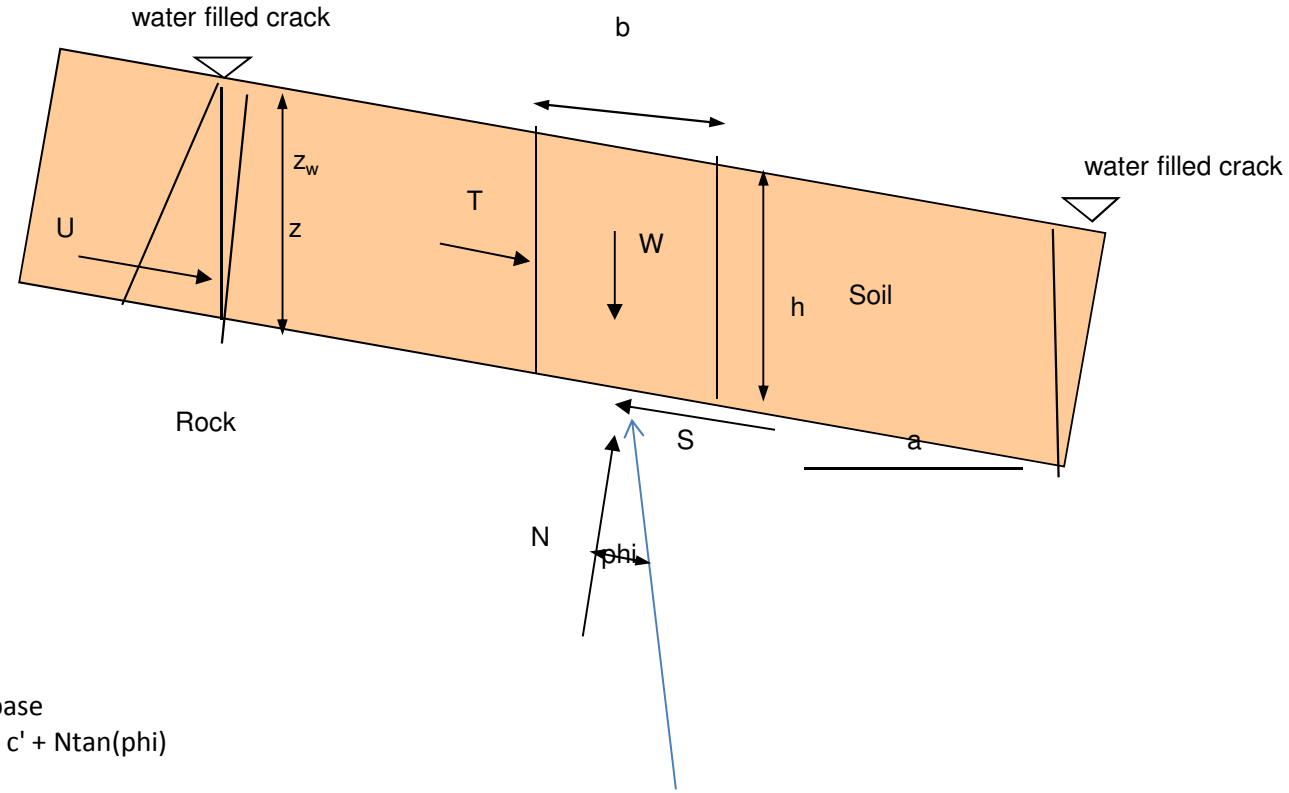
Client:	West Wallsend Colliery WWD-012/16
Title:	Steep Slope Gradients above LWs 51 and 52
Scale:	1:10,000
Figure No:	27a



Key:
H = Slope Height
b = distance crack behind crest
d = slope dip angle
a = bedding dip angle
X = Rock Wedge Basal Contact Length
W = Rock Wedge Weight
z = crack depth
z_w = water depth in crack
U_1 = Horizontal Water Pressure Force
U_2 = Normal water pressure force acting on base
N = Normal resistance force acting on base
S = Shear Strength of bedding plane (mudstone) = c' + Ntan(phi)
(see **Section 6.1** for FoS calculation)

Ref: Hoek, 2000

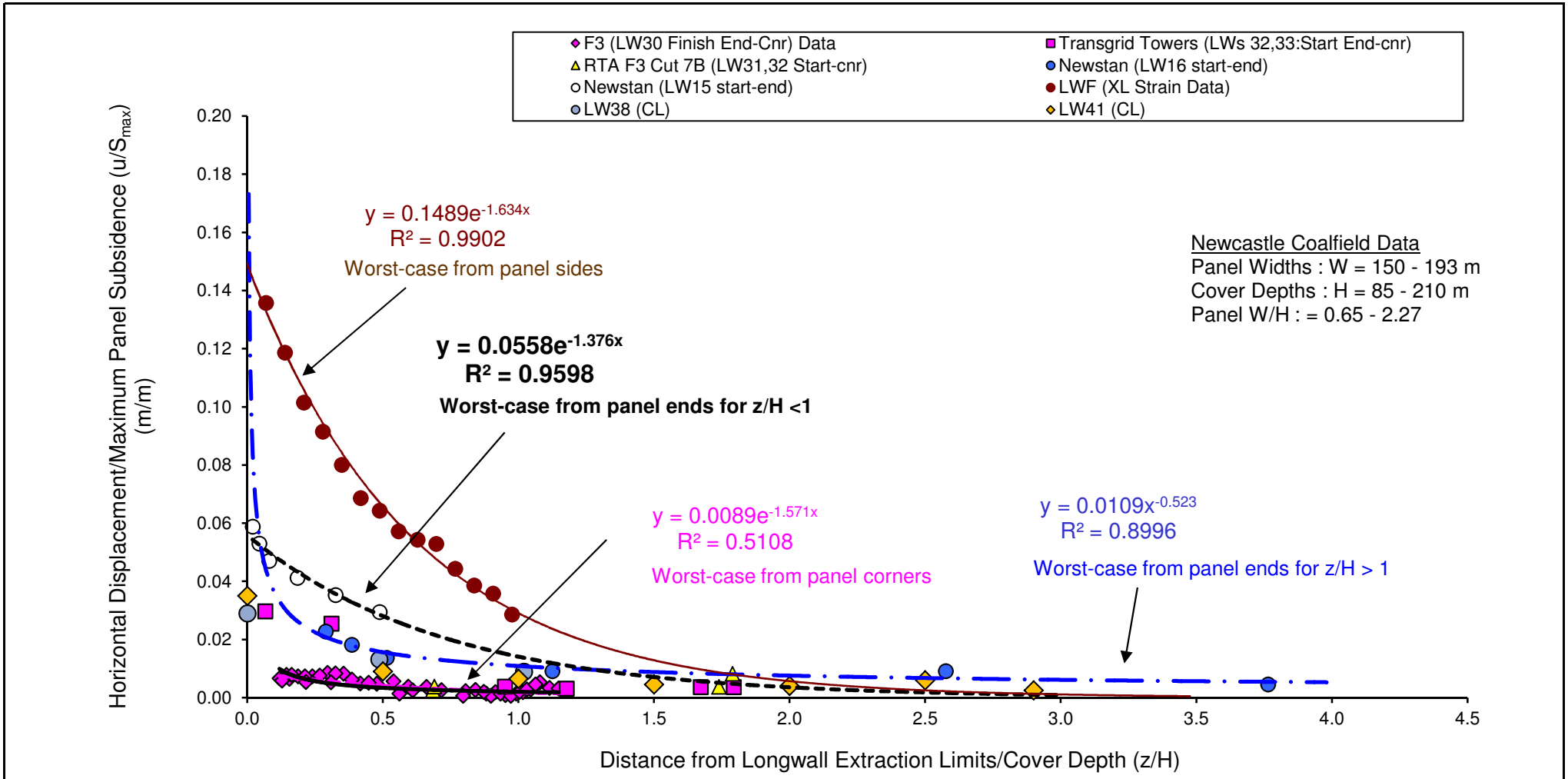
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	27.07.11	Title:	Force Balance Diagram for Assessing Deep-Seated Sliding Potential on Steep Slopes which have been Tilted and Cracked by Mine Subsidence	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 27b



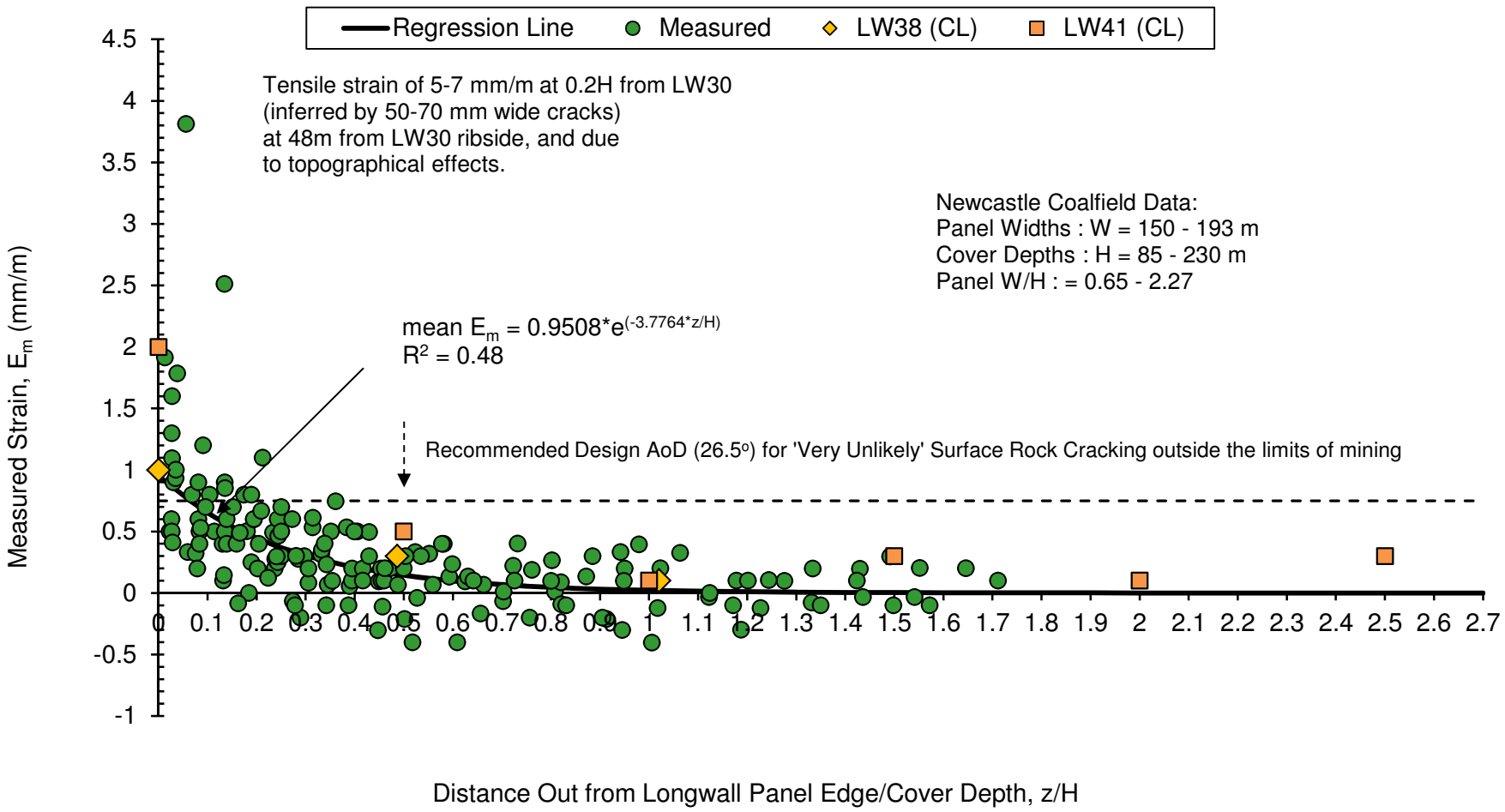
Key:
H = Slope Height
a = slope dip angle (o)
X = Rock Wedge Basal Contact Length
W = Rock Wedge Weight
z = crack depth
z_w = water depth in crack
N = Normal resistance force acting on base
S = Shear Strength of soil/rock plane = c' + Ntan(phi)

Ref: Das, 1998

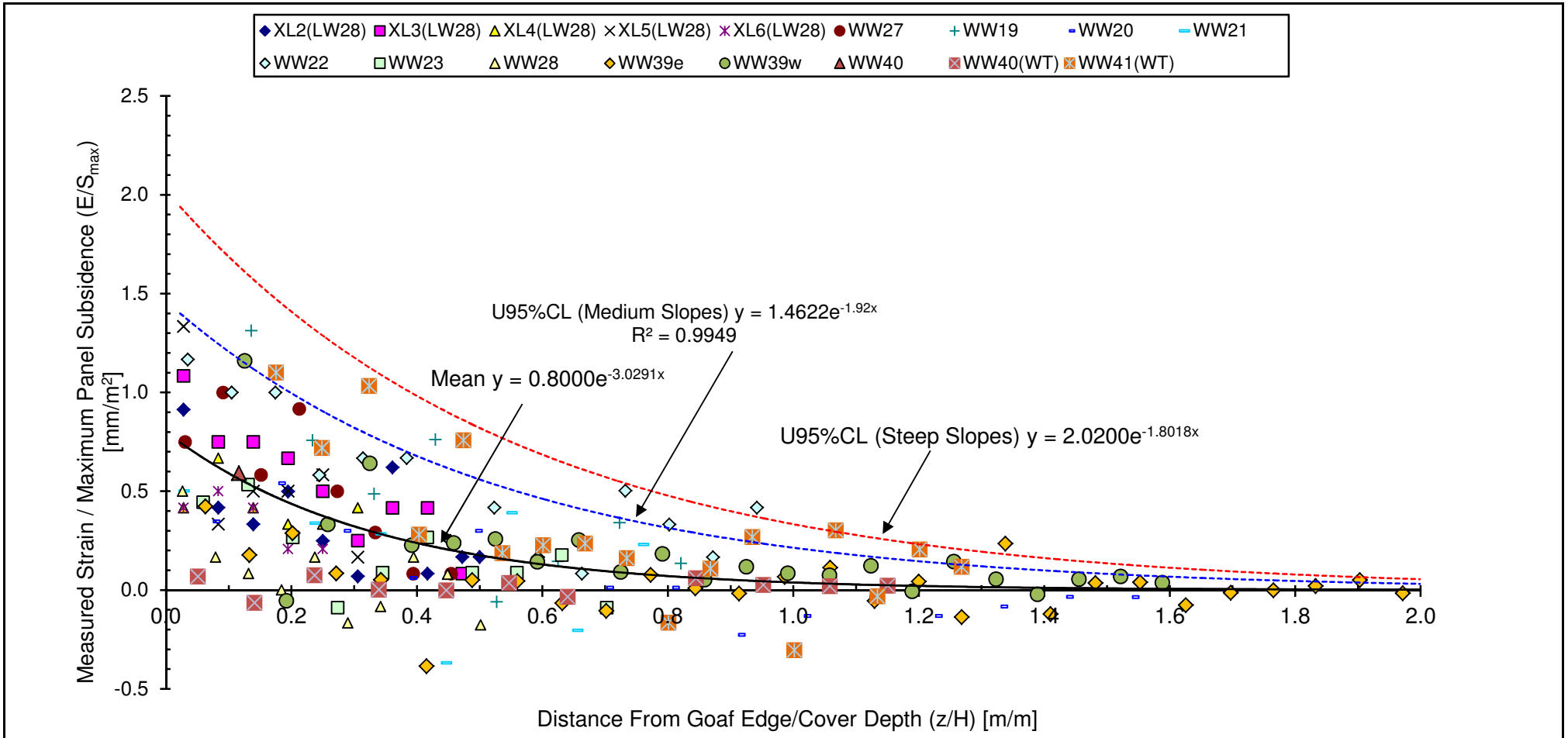
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	15.12.13	Title:	Force Balance Diagram for Assessing Sliding Potential on Steep Slopes which have been Tilted and Cracked by Mine Subsidence	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 27c



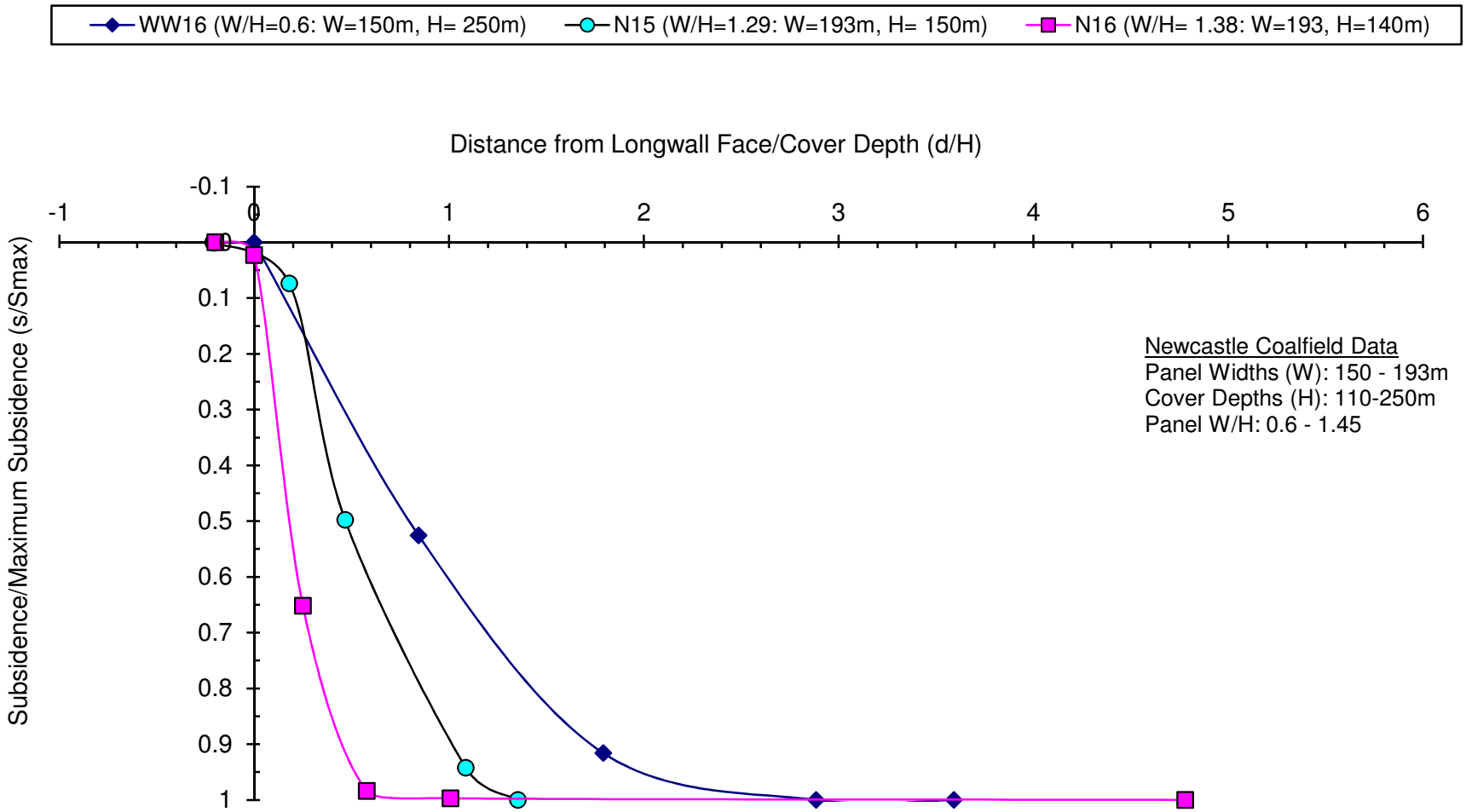
DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	02.04.13	Title:	Combined Empirical Far-Field Displacement Prediction Models for Longwall Panel Sides, Ends and Corners.	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 28



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	02.02.09	Title:	Measured Far-Field Strain Database Using Cummulative Steel Tape from Longwall Sides in the Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 29a



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	25/04/2013	Title:	Empirical Far-Field Strain Prediction Model from LW Sides at West Wallsend Colliery based on Measurements in Flat and Steep Terrain	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 29b



DgS	Engineer:	S.Ditton	Client:	West Wallsend Colliery WWD-012/16	
	Drawn:	S.Ditton			
	Date:	18.08.13	Title:	Empirical Single Longwall Centreline Subsidence Development Prediction Model (based on Newcastle Coalfield Measurements)	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 30

APPENDIX A - Extracts from ACARP, 2003 and SDPS® User Manual

ACARP, 2003 EMPIRICAL SUBSIDENCE PREDICTION MODEL

A1 Introduction

This appendix provides a description of how subsidence develops above longwall panels and provides a summary of the empirical subsidence prediction models used in this study: **ACARP, 2003** and SDPS (Surface Deformation Prediction System).

The **ACARP, 2003** model was originally developed by Strata Engineering (Australia) Pty Ltd under ACARP funding with the goal of providing the industry with a robust and reliable technique to utilise the significant amount of geological and testing information already gathered by mining companies.

Over the past six years the **ACARP, 2003** model has been used successfully by the model's author, Steven Ditton, at several longwall mines in the Newcastle, Hunter Valley, Western and Southern Coalfields of NSW and the Bowen Basin, Queensland.

Subsidence prediction work for Stage 1 of the Moolarben Coal Project in 2006 resulted in further external scrutinization of the model and the robustness of the methodology by an Independent Hearing and Assessment Panel (IHAP), which was set up to assess Environmental Impact Assessments for new coal mining projects by NSW Department of Planning (DoP).

The outcomes of the IHAP for Moolarben resulted in several refinements to the model, as requested by the independent subsidence expert, Emeritus Professor J M Galvin, UNSW School of Mining and Director of Galvin and Associates Pty Ltd.

The refinements generally included several technical adjustments and clarification of the terminology used, to enable a better understanding of the model by the wider technical community.

Over the past two years, Ditton Geotechnical Services Pty Ltd (DgS) has modified the **ACARP, 2003** model to be able to use it to calibrate an influence function model (SDPS®) that was developed by the Polytechnical Institute for the US Coalfields. The SDPS® program allows a wider range of topographic and complex mining layouts (including longwall and pillar extraction panels) to be assessed.

This appendix summarises the **ACARP, 2003** model in its current format and explains the refinements made to the original model. Details of the **SDPS®** model itself are provided at the back of this appendix and discussed further in the main body of the report.

A2 Description of Subsidence Development Mechanisms Above Longwalls

After the extraction of a single longwall panel, the immediate mine roof usually collapses into the void left in the seam. The overlying strata or overburden then sags down onto the collapsed material, resulting in settlement of the surface.

The maximum subsidence occurs in the middle of the extracted panel and is dependent on the mining height, panel width, cover depth, overburden strata strength and stiffness and bulking characteristics of the collapsed strata. For the case of single seam mining, maximum panel subsidence has not exceeded 60% of the mining height (T) in over 95% of the published cases for the Newcastle, and Southern Coalfields (refer **ACARP, 2003** and **Holla and Barclay, 2000**). For the 5% of cases, which did exceed 58%T, the maximum subsidence did not exceed 65%T (i.e. 2.7 m for a 4.2m mining height). The actual subsidence may also be lower than this value due to the spanning or bridging capability of the strata above the collapsed ground (or the goaf).

The combination of the above factors determines whether a single longwall panel will be sub-critical, critical, or supercritical in terms of maximum subsidence.

Sub-critical subsidence refers to panels that are narrow and deep enough for the overburden to bridge or 'arch' across the extracted panel regardless of geology. It is therefore termed 'geometrical' or 'deep beam arching'.

Beyond the sub-critical range, the overburden becomes critical, and is unable to arch without the presence of massive, competent strata. Failure of the strata starts to develop and it sags down onto the collapsed or caved roof strata immediately above the extracted seam. Critical panel geometries refer to panels where maximum possible subsidence starts to develop.

Supercritical panels refer to panel geometries that cause complete collapse of the overburden. In the case of super-critical panels, maximum panel subsidence does not usually continue to increase significantly with increasing panel width.

In the Newcastle Coalfields, sub-critical or (geometrical arching) behaviour generally occurs when the panel width (W) is <0.7 times the cover depth (H) and supercritical when W/H > 1.4. Critical behaviour usually occurs between W/H ratios of 0.7 and 1.4 and represents the transition from 'geometrical arching' to 'shallow beam bending' and then 'complete failure' of the overburden. In the Southern Coalfield, critical subsidence behaviour starts to occur when W/H is > 0.5. As the cover depth averages at about 250 m in the Newcastle Coalfield and 450 m in the Southern Coalfield and both areas have massive strata units in the overburden, this indicates that the cover depth is likely to be a key factor when assessing subsidence in this manner.

The transition point from sub-critical to critical behaviour in a particular coalfield is also influenced by the 'bridging' capability of the strata if it has 'strong' beams present within it. In the Newcastle Coalfield the 'tipping point' W/H ratio can vary from 0.6 to 0.8 with increasing massive strata unit thickness.

The maximum subsidence for sub-critical and critical panel widths is generally < 60% of the longwall extraction height (T) and could range between 5% and 40% T, depending on the thickness of massive sandstone or conglomerate strata.

The surface effect of extracting several adjacent longwall panels is dependent on the stiffness of the overburden and the chain pillars left between the panels. Invariably, 'extra' subsidence occurs above a previously extracted panel and is caused primarily by the compression of the chain pillars and adjacent strata between the extracted longwall panels.

A longwall chain pillar undergoes the majority of life-cycle compression when subject to double abutment loading (i.e. the formation of goaf on both sides of it, after two adjacent panels have been extracted). Surface survey data indicates that an extracted panel can affect the chain pillars between three or four previously extracted panels. The stiffness of the overburden and chain pillar system will determine the extent of load transfer to the preceding chain pillars. If the chain pillars go into yield, the load on the pillars will be mitigated to some extent by load transfer to adjacent fallen roof material or goaf.

The surface subsidence usually extends outside the limits of extraction for a certain distance (i.e. the angle of draw). The angle of draw distance is usually less than or equal to 0.5 to 0.7 times the depth of cover (or angles of draw to the vertical of 26.5^{o} to 35^{o}) in the NSW and QLD Coalfields.

A3 ACARP Project Overview

The original **ACARP, 2003** model was originally developed for the Newcastle Coalfield to deal with the issue of making reliable subsidence predictions over longwall panels by using both geometrical and geological information.

The project was initially focused on the behaviour of massive sandstone and conglomerate strata in the Newcastle Coalfield, but has now been successfully used in other coalfields since development over the past six years. This has occurred naturally due to the expansion of the model's database with data from other coalfields and has resulted in generic refinements to the model to deal with the wider range of geometrical and geological conditions.

In regards to geometry, the subsidence above a series of longwalls is strongly influenced by the panel width, the cover depth, the extraction height and the stiffness of the interpanel pillars (i.e. the chain pillars) and immediate roof and floor strata.
In regards to geology, the presence of massive strata units, such as conglomerate and sandstone channels above longwall panels, has resulted in reduced subsidence compared to that measured over longwall panels with similar geometry and thinner strata units.

Geological structure, such as faults and dykes, can cause increases in subsidence due to their potential to adversely affect the spanning capability of the overburden.

During the original development of the model, a database of maximum single and multi longwall panel subsidence and associated massive strata units was compiled for the

Newcastle Coalfield. The database draws on subsidence data from over fifty longwall panels and covers a panel width to cover depth (W/H) ratio from 0.2 to 2.0 (cover depth ranges between 70 m and 351 m), as shown in **Figure A1**.

The original project database includes single seam longwall mining data from eleven collieries within the Newcastle Coalfield, as presented in **Table A1**.

Table A1 - Empirical Database Sources from Newcastle Coalfield

Colliery	Colliery	Colliery
Cooranbong	Lambton	Wyee
New Wallsend No. 2 (Gretley)	Teralba	
Moonee	Burwood	
Stockton Borehole	West Wallsend	
Newstan	John Darling	

The wide range of single longwall panel W/H ratios in the database was considered unique compared to the other Australian coalfields and enabled the study to focus on overburden and chain pillar behaviour effects separately.

Pillar extraction or multiple seam data was not used to produce the subsidence prediction curves, as it invariably makes the assessment of geological influences more difficult. Other NSW and QLD longwall and high pillar extraction mine data that have been added to the model database over the past seven years as shown in **Table A2**.

Table A2 - Empirical Longwall Database from Other Mines

Coalfield	Colliery	Colliery
Newcastle	West Wallsend	Newstan
	Mandalong	Chain Valley
Hunter Valley	United	Wollemi
	Austar	North Wambo
Southern	Berrima	Appin
	Elouera	Dendrobium
	Metropolitan	
Western	Springvale	Angus Place
	Ulan	
Queensland	Cook	Oaky Creek
	Moranbah North	

In summary, the key features of the **ACARP, 2003** model are that it:

- Is derived from a comprehensive database of measured subsidence, strain, tilt and curvature above longwalls in the Newcastle, Hunter Valley, Western and Southern Coalfields.

- Has been validated with measured subsidence profile data.

- Adds to the **DMR, 1987** model for the Newcastle Coalfield, as it addresses multiple panels and contains a significantly larger data base.

- Includes the effects of massive sandstone/conglomerate lithology on subsidence.

- Allows reliable predictions of maximum single panel subsidence, chain pillar subsidence, tilt, curvature, strain and the angle of draw within a 95% Confidence Limit.

- Enables 'greenfield' sites (i.e. where there is no subsidence data) to be assessed rapidly and accurately.

- Provides maximum subsidence predictions based on Upper 95% Confidence Limits (or 5% Probability of Exceedence limits), which in practice have rarely been exceeded.

- The confidence limits have been derived by the application of central limit theory and the likely normal distribution of residuals about lines of best fit or regression lines determined for the model database.

- Utilises historical information directly - predictions are based on actual data.

- Enables prediction of secondary tilt, curvature and strain magnitudes. Effects such as 'skewing' due to rapid surface terrain variations, surface 'hump' or step development and cracking can result in tilt, curvature and strain magnitudes significantly greater than predicted 'smooth' profile values.

  This issue has been addressed empirically by linking measured impact parameters with key mining geometry variables. Strain concentration factors and database confidence limits have been developed to estimate the likely range of subsidence impact parameters.

- Is amenable to subsidence contouring and allows the impacts on surface features to be assessed, including post-mining topography levels for watercourse impact assessment.

- Predictions of subsidence at specific locations can be done to provide an indication of likely subsidence magnitude; however, depending on the sensitivity of the feature, it may be prudent to adopt maximum predicted subsidence for a given panel.

- Incorporates an empirical model of sub-surface fracturing and far-field displacements.

  Note: Recent far-field horizontal displacement model work in the Newcastle Coalfield indicates the empirical model is conservative.

The following key input parameters are required to make subsidence predictions using the model:

- Panel Width (W)
- Cover Depth (H)
- Seam Working Height (T)
- Overburden lithology details, specifically the thickness and location of massive strata units (t, y).
- Chain Pillar Height (h), Width (w_{cp}) and Length (l) [solid dimensions]
- Roadway width (r)

The statistical inferences and estimates of the model uncertainty associated with the prediction methodology are presented in the following sections.

A4 Single Panel Subsidence Predictions

A4.1 Geometrical Factors

The major finding of the **ACARP, 2003** project in regards to mining geometry was that the historical relationship between subsidence and panel width to cover depth ratio (W/H) is not a constant for the range of cover depths (H) involved.

Figure A2.1 shows the range of maximum subsidence that can occur above longwall panels with similar mining geometries and a range of cover depths. The apparent differences between the DMR's Southern NSW and Newcastle Coalfield curves and laminated overburden theory (**Heasley, 2000**) also support the above finding.

For an overburden consisting of sedimentary rock layers or plates, **Heasley, 2000** applied laminated beam theory by **Salamon, 1989** to form the basis of the pseudo-numerical subsidence prediction program LAMODEL ("LAyered MODEL" of overburden) that has been found to have reasonable success in the US Coalfields.

According to LAMODEL theory, the maximum seam roof convergence (C_{max}) above a longwall panel of mining height (T), width (W) and cover depth (H), with an idealised overburden of uniform lamination thickness (t), Youngs Modulus (E), unit weight (γ) and Poisson's Ratio (v) is:

$C_{max} = [\sqrt{12(1-v^2)}]/t\ (\gamma H/E)\ (W^2/4)$ or T (whichever gives the lower value)

Several points can be made about this equation:

- The γH term represents the vertical stress acting on the plates at seam level and assumes spanning strata (i.e. sub-critical to critical panels).

- For completely collapsed strata, C_{max} may be assumed to equal T at seam level.

- The surface subsidence may then be estimated as the minimum of $0.5C_{max}$ and 0.6T for sub-critical/critical and supercritical panel geometries.

- In terms of traditional empirical models of estimating subsidence, the above equation indicates that the maximum single panel subsidence is a function of W^2/t and γH/E for sub-critical W/H ratios < 0.7 or T for super-critical W/H ratios >1.4. The influence of the panel width and mining height will therefore change with W/H.

Clamped elastic beam theory indicates that strata beam deflections, that are located at a distance y above the mine workings, are a function of γ(H-y)/E and W^4/t^3 before cracking at the abutments and mid-span. The deflection of the beam will generate higher tensile stresses in the top of the beam at the abutments than in the bottom of the beam at mid-span. The cracking results in a transition from continuous elastic beam behaviour to a cracked beam of separate blocks or 'voussoirs' under simply supported loading conditions.

The Voussoir beam supports the load through the formation of a compressive arch, which develops as the individual blocks or Voussoirs rotate towards the goaf below it (i.e. the voussoirs cannot sustain tensile stresses, however, the deformed beam will span if the blocks have sufficient strength, stiffness and geometry. The elastic and Voussoir beam cases are shown in **Figure A2.2**.

If the rotated blocks are able to support the load, then the deflection of the cracked Voussoir beam is a function of γ(H-y)/E and W^2/t, which is consistent with the laminated beam model theory; see **Figure A2.3**.

The **ACARP, 2003** model surmised that single panel subsidence normalised by mining height T, was a function of W/H, γH/E or H, W/t and y/H in accordance with Buckingham's Pi theory.

The first three parameters above are related to panel geometry (i.e. the panel width, W, cover depth, H, and mining height, T, whilst the last two parameters (strata unit thickness, t, and distance, y, to the unit above the workings) infer geological influences of massive strata units.

Based on the above equations, surface subsidence is expected to increase with increasing cover depth (H) for the same W/H ratio, and is primarily a function of the increasing panel width (W) as $S_{max} = f(W^2/H)$ according to beam theory. For constant single panel width (W), subsidence will therefore decrease with increasing cover depth (H). The subsidence data was subsequently separated into three cover depth categories of H = 100, 200 and 300 m +/-50 m and is presented in **Figures A3** to **A5**.

The influence of overburden lithology was found to be readily apparent once the database was filtered using the above cover depth ranges.

A4.2 Geological Factors

Once the first stage in the development of the subsidence prediction model had addressed the influence of cover depth the effect of "significant" overburden lithology above single longwall / miniwall panels could be addressed. **Figure A6** illustrates a physical model, showing the subsidence reducing effects of a massive strata unit.

Borehole data was used to derive the thickness and location of massive strata units considered to be critically important for surface subsidence prediction, for a given panel width and depth. The methodology takes into account the maximum massive strata unit thickness (t) at each location and the height to the base of the unit above the longwall panel (y).

The subsidence above a panel, given cover depth (H) and panel width (W) decreases significantly when a massive strata unit is thicker than a certain minimum limit value. The thickness is also reduced when the unit is closer to the surface. The strata unit is considered to have a 'high' subsidence reduction potential (SRP) when it exceeds a minimum thickness for a given y/H ratio, as shown in **Figures A7.1** to **A7.3** for each cover depth category.

For a thin strata unit located relatively close to a panel, the 'Subsidence Reduction Potential (SRP) will be 'low'. However, there is also an intermediate zone, where a single strata unit (or several thinner units) below the 'high' subsidence reduction thickness can result in a 'moderate' reduction in subsidence. A second limit line can therefore be drawn, which represents the threshold between 'moderate' and 'low' SRP.

It is considered that the 'high' SRP limit line represents the point between elastic and yielding behaviour of a spanning beam. The 'moderate' SRP limit line represents the point between yielding behaviour and collapse or failure of a spanning beam (which has been yielding).

The limit lines have been determined for the strata units located at various heights (y) above the workings in each depth category, as shown in **Figures A8** to **A10**.

A4.3 Summary of Model Concepts

The **ACARP, 2003** model introduces several new parameters, to improve the definition of various types of overburden behaviour and the associated mechanics.

As outlined in **Section A4.2**, the 'Subsidence Reduction Potential' (SRP) of massive or thickly bedded geological units above single longwall panels for the Newcastle Coalfield has been introduced to describe the influence that a geological unit may have on subsidence magnitudes. The massive geological units are defined in terms of 'high', 'moderate' or 'low' SRP.

Massive unit thickness, panel width, depth of cover and height of unit above the workings are considered to be key parameters for assessing overburden stiffness and spanning capability over a given panel width, controlling surface subsidence. A conceptual model for overburden behaviour is illustrated in **Figure A11**.

Variation in subsidence along the length of a panel may therefore be due to the geometry and / or SRP variation of geological units within the overburden.

For W/H ratios <0.7, the overburden spans across the extracted panel like a 'deep' beam or linear arch, whereby the mechanics of load transfer to the abutments is governed by axial compression along an approximately parabolic shaped line of thrust, see **Figure A12**.

For W/H ratios >0.7 the overburden geometry no longer allows axially compressive structural behaviour to dominate, as the natural line of thrust now lies outside of the overburden. Bending action due to subsequent block rotation occurs. Provided that the abutments are able to resist this rotation, flatter lines of thrust still develop within the overburden, but the structural action is now dominated by bending action. This type of overburden behaviour has been defined as 'shallow' beam behaviour, which in structural terms is fundamentally less stiff than 'deep' beam behaviour. This results in a significant increase in subsidence or sag across an extracted longwall panel (all other factors being equal), as shown **Figure A12**.

"Voussoir beam" or "fractured linear arch" theory can be used to explain both types of overburden behaviour, as deep seated or flatter arches develop in the strata in an attempt to balance the disturbing forces.

The database also indicates the presence of a 'Geometrical Transition Zone', whereby subsidence increases significantly, regardless of the SRP of the geological units, as shown in **Figure A13**. This behaviour occurs when panel width to cover height ratio (W/H) ranges from 0.6 to 0.9. This phenomenon can be simply explained as a point of significant shift in structural behaviour and the commencement of overburden breakdown.

The model therefore allows the user to determine the range of expected subsidence magnitudes and the location of geology related SRP and/or 'geometrical transition zones' along a panel. Identification of the transition zones is an important factor in assessing potential damage risks of differential subsidence to important infrastructure, buildings and natural surface features, such as rivers, lakes and cliff lines etc.

The 'strata unit location factor' (y/H) was developed to assist in assessing the behaviour of massive strata units above the workings. The y/H factor is a simple way to include the influence of the unit location above the workings in terms of the effective span of the unit and the stresses acting upon it.

The key elements of this factor and their influence on the behaviour of the strata unit are:

- y, the height of the beam above the workings, which determines the effective span of the beam, and

- H, cover depth over the workings, which exerts a strong influence on the stress environment and, hence, the propensity for buckling or compressive failure of the beam.

Essentially beam failure due to the action of increasing horizontal stress (i.e. crushing or buckling) appears more likely as y decreases and H increases. The ratio of y/H may therefore be used to differentiate between the SRP of a beam of similar thickness, but at varying heights above the workings. The model also demonstrates that as the depth of cover increases, a thicker beam is required to produce the same SRP above a given panel width. This phenomenon may also be simply due to greater vertical load acting upon the massive strata 'beam'.

A5 Multiple Longwall Panel Subsidence Prediction

A5.1 General

The effect of extracting several adjacent longwall panels is governed by the stiffness of the overburden and the chain pillars left between the panels. Invariably, 'extra' subsidence occurs above a previously extracted panel and is caused primarily by cracking of the overburden and the compression of the chain pillars and adjacent strata between the extracted longwall panels.

A conceptual model of subsidence mechanisms above adjacent longwall panels in a single seam is shown in **Figure A14**.

A5.2 Predicting Subsidence above Chain Pillars (ACARP, 2003 Model)

A chain pillar undergoes the majority of life-cycle compression when subject to double abutment loading (i.e. the formation of goaf on either side, after two adjacent panels have been extracted). Surface survey data indicates that an extracted panel can affect the chain pillars of up to three or four previously extracted panels. The stiffness of the overburden and chain pillar system will determine the extent of load transfer to preceding chain pillars.

Multiple-panel effects have therefore been included in the model by adding empirical estimates of surface subsidence over chain pillars to the maximum subsidence predictions for single panels.

The empirical model presented in **ACARP, 2003** for estimating the subsidence above a chain pillar, was based on the regression equation presented in **Figure A15**. The model compares the ratio of chain pillar subsidence (Sp) over the extraction height (T), to the width of the chain pillar divided by the cover depth multiplied by the total extracted width (1000w/W'H).

A regression analysis on the data indicates a strong exponential relationship for 1000wcp/W'H values up to 0.543. For values > 0.543, the relationship becomes constant.

$S_p/T = 7.4044e–10.329F$ ($R^2 = 0.92$) for $F< 0.543$, and

$S_p/T = 0.023$ for $F > 0.543$

where

$F = 1000w/W'H$

W' = The total extracted width which includes the width of the panels extracted on both sides of the subject chain pillar, and the width of the chain pillar itself (i.e. $W' = W_i + w_i + W_{i+1}$).

Note that the final subsidence for a longwall panel with several subsequent extracted panels was then determined empirically by adding 50% of the predicted chain pillar subsidence (S_p) to the single panel S_{max} estimate.
This approach however, did not include an abutment angle to estimate pillar loads, which are likely to vary significantly between sub-critical and supercritical panel layouts.

*The chain pillar model has now been amended to include better predictions of chain pillar load that are consistent with ALTS methodology (refer **ACARP, 1998a**) and has resulted in the modified version presented in Section A5.2.*

A5.2 Predicting Subsidence above Chain Pillars (DgS, 2008 Model)

After the **ACARP, 2003** model was published; further studies on chain pillar subsidence measurements were undertaken at several mine sites in the Western (Springvale, Angus Place and Ulan) and Southern Coalfields (Appin and Elouera). The measured subsidence above the chain pillars was significantly greater than the Newcastle Coalfield pillars and considered to be linked to the stress acting on the pillars and the longwall mining height.

Maximum subsidence above the chain pillars invariably occurred after the pillars were subject to double abutment loading conditions (i.e. goaf on both sides).

The **ACARP, 2003** model for estimating chain pillar subsidence was subsequently superseded by the pillar stress v. strain type approach presented in **Figure A16**. The chain pillar stress was estimated by assuming a design abutment angle of 21^o for the pillar load, according to the methodology presented in **ACARP, 1998a** for sub-critical and supercritical longwall panels.

Prediction of subsidence above the chain pillars (S_p) was determined based on the following regression equation using the mining height, T and pillar stress, σ:

$$S_p/T = 0.238469/(1+e^{-[(\sigma-25.5107)/7.74168]}) \qquad (R^2 = 0.833)$$

The uncertainty of the predictions was estimated by calculating the variance of the residuals about the regression lines and calculating 90% Confidence Limits for the database as follows:

90% CL S_p error = 0.048T

It was also considered necessary to test if the above stress v. strain type approach was adequate for reliable predictions, by comparing the subsidence outcomes with the pillar Factor of Safety; see **Figure A17**.

The strength of the chain pillars was estimated using the rectangular pillar strength formulae presented in **ACARP, 1998b**. The FoS was derived by dividing the pillar strength by the pillar load (i.e. stress).

Generally it has been found that significant surface subsidence above the chain pillar (i.e. 10 - 30% of pillar height) starts to occur when the pillar FoS is < 2. For FoS values greater than 2, subsidence above the pillars is virtually independent of FoS and the pillars generally perform elastically under load.

The database indicates that when the FoS is < 2, the stiffness of the pillar starts to decrease, due to the development of load induced fracturing within the pillar and surrounding strata. FoS values of < 2 represent pillar stresses that exceed 50% of the pillar strength. Laboratory testing of coal and sandstone samples also show sample 'softening' as the ultimate load carrying capacity of the sample is approached.

For pillars with FoS values < 1, the subsidence above the chain pillars tend to a maximum limit of approximately 25 to 30% of the mining height. This type of behaviour is expected for chain pillars that have width to height ratios w/h > 5, which is the point where 'strain hardening' deformation starts to develop with increased confinement of the 'pillar core'.

A5.3 Calculation of First and Final Subsidence for Multiple Longwall Panels

Multiple panel predictions can be made by adding the predicted single panel subsidence to a proportion of the chain pillar subsidence (including the residual subsidence) to estimate first and final subsidence above a given longwall panel.

The definition of first and final S_{max} is as follows:

First S_{max} = the first maximum subsidence after the extraction of a longwall panel, including the effects of previously extracted longwall panels adjacent to the subject panel.

Final S_{max} = the final maximum subsidence over an extracted longwall panel, after at least three more panels have been extracted, or when mining is completed.

In the Newcastle Coalfield, First and Final S_{max} values for a panel are predicted by adding 50% and 100% of the predicted subsidence over the chain pillars respectively (i.e. between the previous and current panel) less the goaf edge subsidence (see **Section A5**).

Residual subsidence above chain pillars and longwall blocks tends to occur after extraction due to (i) increased overburden loading on pillars and (ii) on-going goaf consolidation or creep effects. Based on the final chain pillar subsidence measurements presented in **Figure A16**, the residual movements can increase subsidence by a further 10 to 30%.

An example of measured multiple longwall subsidence behaviour is presented in **Figure A18**.

Final subsidence is normally estimated by assuming a further 20% of the chain pillar subsidence will occur. However, this may be increased or decreased, depending on local experience.

The prediction of first and final subsidence originally presented in **ACARP, 2003** involved the use of several empirical coefficients, which have proven to be difficult to apply in practice. The interested reader may refer to this methodology, however, the above method is considered easier to apply and likely to result in a similar outcome.

In summary, the mean values of the First S_{max} and Final S_{max} are calculated as:

$$\text{First } S_{max} = \text{Single } S_{max} + 0.5(S_{p(i-1)} - S_{goe(i-1)})$$

$$\text{Final } S_{max} = \text{First } S_{max} + 1.0(\text{Final } S_{p(i)} - \text{First } S_{goe(i)})$$

The U95% Confidence Limits or Credible Worst Case Values are then:

$$\text{U95\% First } S_{max} = \text{mean First } S_{max} + 1.64\ (\text{U95\% } S_{max} \text{ error} + \text{U95\% } S_p \text{ error})^{1/2}.$$

$$\text{U95\% Final } S_{max} = \text{mean Final } S_{max} + 1.64\ (\text{U95\% } S_{max} \text{ error} + \text{U95\% } S_p \text{ error})^{1/2}.$$

It should also be understood that the terms ‘mean' and ‘Upper 95% Confidence Limit’ used in the model generally infer that the predicted maximum values will be exceeded by 50% and 5% respectively of the panels mined with similar geometry and geology etc.

Using lower probability of exceedence values (e.g. U99%CL) may be justified for particularly sensitive features, however, the magnitude of the maximum values does not usually increase significantly above the U95%CL values.

When local subsidence data is available for multiple longwall panels, the relationship between the multiple and single panel subsidence predictions can be determined as follows:

$$\text{First } S_{max} = \text{Single } S_{max} + 0.5b(S_{p(i-1)} - S_{goe(i-1)})$$

$$\text{Final } S_{max} = \text{First } S_{max} + b(\text{Final } S_{p(i)} - \text{First } S_{goe(i)})$$

The ‘b’ factor may be estimated from measured subsidence profiles, and allows the load transfer effect between the goaf and the chain pillars to be included in the model if necessary.

It has been observed at deeper NSW Coalfield Mines (i.e. the Western and Southern Coalfields) where the proportion of subsidence over the chain pillars to be added to the single panel subsidence decreased when the cover depth exceeded 350 m.

A6 Subsidence Profile and Impact Parameter Predictions

Part of the **ACARP, 2003** project included the development of several models to predict the maximum panel deformation parameters and surface profiles associated with subsidence. The following models were developed:

- panel goaf edge or rib subsidence,
- angle of draw,
- maximum transverse and longitudinal tilt, curvature and strain,
- the locations of the above parameters over the longwall panel for the purposes of subsidence profile development, and
- heights of continuous and discontinuous fracturing above the longwall, based on measured surface tensile strains and fracture limit horizons over extracted panels (see **Section A7** for details).

A conceptual model of surface deformation profiles that develop above longwall panels is given in **Figure A19**.

All of the above subsidence parameters have been statistically linked to key geometrical parameters such as the cover depth (H), panel width (W), working height (T) and chain pillar width (w_{cp}) and shown in **Figures A20** to **A27**.

A summary of all the empirical model relationships between the key subsidence profile parameters that were developed in **ACARP, 2003** and DgS are presented in **Table A3**.

Table A3 - Summary of Subsidence Impact Parameter Prediction Models Developed from ACARP, 2003

Parameter	Regression Equation and +/- 90% Confidence Limits or Upper95% CL	Coefficient of Determination (R^2)	Figure No.
Subsidence Reduction Potential (SRP) of Strata Unit in Overburden with thickness t, panel width, W and location factor, y/H above workings for Cover Depth Category	**High** SRP t for a given panel W plots above line for given strata unit y/H. **Moderate** SRP t plots between High SRP line and next y/H line below it. **Low** SRP t plots below Moderate SRP limit line.	N/A - curve location determined by successful re-prediction of >90% of cases I databases	**Figure A8** for H<150m; **Figure A9** for H< 250m; **Figure A10** for H< 350m
Single Maximum Longwall Panel Subsidence (Single S_{max}) for Assessed Strata Unit SRP of Low, Moderate or High	Upper and Lower bound prediction lines for a given SRP are used to estimate range of S_{max}/T for a given Panel W/H. Average of limit lines value is mean Single S_{max} value +/- 0.03T for W/H < 0.6; +/- 0.1T for 0.6<W/H<0.9; +/-0.05T for W/H>0.9	N/A - curve location determined by successful re-prediction of >90% of cases I databases	**Figure A3** for H<150m; **Figure A4** for H< 250m; **Figure A5** for H< 350m
Chain Pillar Subsidence, S_p (m)	Mean $S_p/T = 0.238469/(1+e^{-[(\sigma DAL-25.5107)/7.74168]})$ +/- 0.048T	$R^2 = 0.833$	**Figure A16**
Goaf Edge Subsidence	Mean $S_{goe}/S_{max} = 0.0722(W/H)^{-2.557}$ U95%CL $S_{goe}/S_{max} = 0.0719(W/H)^{-1.9465}$	$R^2 = 0.82$	**Figure A20**
Angle of Draw	Mean AoD = $7.646Ln(S_{goe})+32.259$ U95%CL = Mean AoD + 8.7^o	$R^2 = 0.56$	**Figure A21**
Maximum Tilt T_{max} (mm/m)	$T_{max} = 1.1925(S_{max}/W')^{1.3955}$ +/- $0.4T_{max}$ (W' = lesser of W and 1.4H)	$R^2 = 0.94$	**Figure A22**
Maximum Convex Curvature C_{max} (km^{-1})	Mean $C_{max} = 15.60(S_{max}/W'^2)$ +/- 0.5Mean	$R^2 = 0.79$	**Figure A23**
Maximum Concave Curvature C_{min} (km^{-1})	Mean $C_{min} = 19.79(S_{max}/W'^2)$ +/- 0.5Mean	$R^2 = 0.79$	**Figure A24**
Maximum Tensile Strain E_{max} (mm/m)	Mean 'smooth' $E_{max} = 5.2C_{max}$ +/- 0.5 Mean Mean 'Cracked' $E_{max} = 14.4C_{max}$	$R^2 = 0.72$ $R^2 = 0.32$	**Figure A25**
Maximum Compressive E_{min} (mm/m)	Mean $E_{max} = 5.2(C_{min})$ +/- 0.5 Mean Mean 'Cracked' $E_{min} = 14.4C_{min}$	$R^2 = 0.72$ $R^2 = 0.32$	**Figure A25**
Critical Panel Width	W_{crit} = 1.4H where H = cover depth	N/A	**ACARP, 2003**

Table A3 (Continued) - Summary of Subsidence Impact Parameter Prediction Models Developed from ACARP, 2003

Subsidence at Inflexion Point or Maximum Tilt S_{Tmax}	Mean S_{Tmax}/S_{max} = -0.0925(W/H)+0.7356 +/- 0.2	R^2 = 0.5	**ACARP, 2003**
Distance to Inflexion Point, d/H	d/H = 0.2425Ln(W/H) + 0.3097	R^2 = 0.73	**Figure A27**
Distance to Peak Tensile Strain (mm/m)	d_t/H = 0.1643Ln(W/H) + 0.2203 for W/H >0.6; d_t/H = 0.2425Ln(W/H) + 0.2387 for W/H <0.6;	R^2 = 0.28	**Figure A27**
Distance to Peak Compressive Strain (mm/m)	d_c/H = 0.3409Ln(W/H) + 0.3996 for W/H >0.6; d_c/H = 0.2425Ln(W/H) + 0.3767 for W/H <0.6	R^2 = 0.59	**Figure A27**

* - If H within 25 m of depth category boundary, then average result with overlying or underlying depth category value.
- Centreline profile parameters are not presented here (refer to **ACARP, 2003**).

A7 Subsidence Profile Predictions above Longwall Panels

Predicted 'smooth' subsidence profiles above single and multiple longwall panels have been determined based on cubic spline curve interpolation through seven key points along the subsidence trough (i.e. maximum in-panel subsidence, inflexion point, maximum tensile and compressive strain, goaf edge subsidence, subsidence over chain pillars and 20 mm subsidence or angle of draw limit).

The locations of these points have been determined empirically, based on regression relationships between the variables and the geometry of the panels (see **Table A3**). Both transverse and longitudinal profiles have been derived in this manner.

First and second derivatives of the fitted spline curves provide 'smooth' or continuous subsidence profiles and values for tilt and curvature. Horizontal displacement and strain profiles were derived by multiplying the tilt and curvature profiles by an empirically derived constant associated with the bending surface beam thickness (based on the linear regression relationship between the variables, as discussed in **ACARP, 2003**).

An allowance for the possible horizontal shift in the location of the inflexion point (within the 95% Confidence Limits of the database) has also been considered, for predictions ofsubsidence at features located over the goaf or extracted area.

A8 Subsidence Contour Predictions above Longwall Panels

Subsidence contours can be derived with geostatistical kriging techniques over a 10 m square grid using Surfer 10® software and the empirically derived subsidence profiles along cross lines, centre lines and corner lines around the ends of the longwall panels. Vertical 'slices' may taken through the contours to (i) determine subsidence profiles along creeks or infrastructure, and (ii) assess the likely impacts on the relevant surface features.

A8.1 Subsidence Contours

Subsidence contour predictions have been made in this study using SPDS®, which is an influence function based model that firstly calculates seam convergence and pillar displacements empirically around the workings. The influence of an extracted element of coal is transmitted to the surface via a 3-D influence function, which also takes varying topography into account.

The model is usually calibrated to measured maximum subsidence values by adjusting key parameters such as influence angles and inflexion point location from extracted panel sides.

A8.2 Tilt and Curvature Contours

The predicted principal tilt and curvature contours were derived using the calculus module of the Surfer10® program and the predicted subsidence contours from the SPDS® runs. The subsidence contours were based on a 10 m grid.

Principal tilts (i.e. surface gradient or slope) were calculated by taking the first derivative of the subsidence contours in x and y directions as follows:

$$T_p = [(\partial s/\partial x)^2 + (\partial s/\partial y)^2]^{0.5}$$

where ∂s = subsidence increment over distances ∂x and ∂y along x and y axes.

Principal curvatures (i.e. rate of change in slope or surface bending) were calculated by taking the second derivative of the subsidence contours in x and y directions as follows:

$$C_p = [(\partial^2 s/\partial x^2)(\partial s/\partial x)^2 + 2(\partial^2 s/\partial x \partial y)(\partial s/\partial x)(\partial s/\partial y) + (\partial^2 s/\partial y^2)(\partial s/\partial y)^2]/pq^{2/3}$$

where $p = (\partial s/\partial x)^2 + (\partial s/\partial y)^2$ and $q = 1+p$

A8.3 Strain

Before predictions of strain can be made, the relationship between the measured curvatures and strain must be understood. As discussed in **NERDDP, 1993b** and **ACARP, 2003**, structural and geometrical analysis theories indicate that strain is linearly proportional to the curvature of an elastic, isotropic bending 'beam'; see **Figure A28**. This proportionality actually represents the depth to the neutral axis of the beam, or in other words, half the beam

thickness. **NERDDP, 1993b** studies returned strain over curvature ratios ranging between 6 and 11 m for NSW and Queensland Coalfields. Near surface lithology strata unit thickness and jointing therefore dictate the magnitude of the proportionality constant between curvature and strain.

ACARP, 2003 continued with this approach and introduced the concept of secondary curvature and strain concentration factors due to cracking. The peak strain / curvature ratio for 'smooth' subsidence profiles in the Newcastle Coalfield was assessed to equal 5.2 m (mean) and 7.8 m (U95%CL) with the possibility that surface cracking could increasing the 'smooth-profile' strains to 10 or 15 times the curvature. The above values may also be affected by the thickness of near surface geology.

Reference to **DMR, 1987** also suggests a curvature to strain multiplier of 10 for high pillar extraction and longwall panels in the Newcastle Coalfield.

Attempts by others to reduce the variability in strain and curvature data by introducing additional parameters, such as the radius of influence, r, by **Karmis et al, 1987** and cover depth, H, by **Holla and Barclay, 2000**, appear to have achieved moderate success in the coalfields in which they were applied. However, when these models were applied to the Newcastle Coalfield data presented in **ACARP, 2003**, the results did not appear to improve things unfortunately; see **Figures A29.1** and **A29.2**.

It is therefore considered that the variability in behaviour is probably due to other parameters, which are very difficult to measure (such as the thickness and flexural, buckling and shear strengths of the near surface strata).

Provided that the likelihood of cracking can be ascertained from the strain predictions, then appropriate subsidence management plans can still be implemented.

A9 Prediction Of Subsidence Impact Parameters And Uncertainty Using Regression Analysis Techniques

A9.1 Regression Analysis

Key impact parameters have been predicted using normalised longwall subsidence data from the Newcastle Coalfield. This approach allows a reasonable assessment of the uncertainty involved using statistical regression techniques. A linear or non-linear regression line has been fitted to the database for each impact parameter, normalised to easily measured parameters, such as maximum subsidence, panel width and cover depth. The quality or significance of the regression line is influenced by the following parameters:

(i) the size of the database,

(ii) the presence of outliers, and

(iii) the physical relationship between the key parameters.

The regression curves were reviewed carefully, as such curves can be (i) affected by outliers, and (ii) misleading, in that by adopting a mathematical relationship which gives the best fit (i.e. R^2) the curves are controlled by the database and may not reflect the true underlying physical dependencies or mechanisms that the data represents.

These issues are inherent in all prediction modelling techniques because, for example, all models must be calibrated to field observations to validate their use for prediction or back analysis purposes.

The regression techniques presented in the **ACARP, 2003** was done by firstly assessing conceptual models of the mechanics and key parameter dependencies (based on established solid mechanics and structural analysis theories), before generating the regression equations.

Several outliers in the model databases were excluded in the final regression equations, but only when a reasonable explanation could be given for each anomaly (i.e. multiple seam subsidence, geological faults / dykes and surface cracking effects).

The regression equations in **ACARP, 2003** have R^2 (i.e. Coefficients of Determination) values generally greater than 50%; indicating that the relationships between the variables are significant. For cases where the R^2 values are < 50%, the regression lines are almost horizontal (i.e. the parameter doesn't change significantly over the range of the database), and the use of the regression line will be close to the mean of the database anyway.

A9.2 Prediction Model Uncertainty

The level of uncertainty in the model predictions has been assessed using statistical analysis of the residuals or differences between the measured data and regression lines (i.e. lines of best fit). The *Standard Error* of the prediction has been derived from the residuals, which has then been multiplied by the appropriate 'z' or 't' statistic for the assumed normal probability distribution to define Upper (and Lower) Confidence Limits.

The residual population errors for the single panel subsidence model are shown in **Figure A30**.

The empirical database therefore allows an assessment of variance and standard error such that the required subsidence parameter's mean and upper 95% Confidence Limit (Credible Worst Case) values can be determined for a given mining geometry and geology.

Provided there are (i) more than 10 data points in the data sets covering the range of the prediction cases, and (ii) the impact parameter and independent variables have an established physical relationship based on solid or structural mechanics theories, then it is considered unlikely that the regression lines will be significantly biased away from the underlying physical relationship between the variables by any limitations of the data set.

On-going review of each of the regression equations over the past six years by DgS has not required significant adjustment of the equations to include new measured data points. The

regression equations derived are also amenable to spreadsheet calculation and program automation.

It is also important to make the distinction between the terms confidence *limit* and confidence *interval*. The Credible Worst Case terminology used in the model is **not** the upper limit of the 95% Confidence **Interval** - which would encompass 95% of the data. Since the lower 95% Confidence Limit is rarely used in practice, it was considered appropriate to adopt the 5% Probability of Exceedence values instead (this by definition represents the upper limit of the **90% Confidence Interval**).

Further, the term *Upper 95% Confidence Limit* used in the **ACARP, 2003** model is considered acceptable in the context of 'one-tailed' probability distribution limits (i.e. the Lower 95% Confidence Limit is generally of little practical interest).

A10 Subsidence Model Validation Studies

A10.1 Model Development

The **ACARP, 2003** model was developed so that it could re-predict > 90% of the database on which it is based. Validation studies also included comparison of measured and predicted subsidence, tilt and strain profiles above several longwall panel crosslines and centrelines. Examples of predicted and measured profiles above multiple panels for the Newcastle Coalfield are shown in **Figures A31** to **A34** using the **ACARP, 2003** model. Subsequent predictions v. measured subsidence profiles are presented in **Figures A35** to **A38** using the updated version of the model discussed herein.

DgS is usually required to review predicted v. measured subsidence profiles after the completion of a longwall panel and report the results to mines and government departments. Over the past nine years, the model has usually over predicted measured subsidence, with the data falling somewhere between the mean and U95%CL values. Prediction exceedances have occurred less than 5% of the time and where the assessment of the overburden SRP was found to be incorrect.

The predictions of curvature and strain, however, are generally problematic due to the common effects of discontinuous or cracking behaviour (i.e. lithological variation and cracking), resulting in measured strains that can be two to four times greater than predicted 'smooth' profile strains. This issue is discussed further in **Section A10.2**.

A10.2 Field Testing of Strain Predictions

Strain and curvature concentrations can increase 'smooth' profile strains by 2 to 4 times in the Newcastle Coalfield, when the panel width to cover depth ratio (W/H) exceeds 0.8 or radius of curvature is less than 2 km, see **ACARP, 2003**.

Where cracking occurs, measured strains will be highly dependent on the bay-length. Rock exposures with widely spaced or adversely orientated jointing can also result in much larger crack widths than for a location with deep soil profiles.

For example, a measured strain of 3 to 6 mm/m along a cross line above a longwall panel in the Newcastle Coalfield caused several cracks in soil that ranged in width from 10 mm to 30 mm and a single 100 mm wide crack in a sandstone rock exposure with medium strength and widely spaced jointing, see **Figure A39**.

At the moment, it is not possible to predict the magnitude of strains from 'smooth profile' models confidently, however, it is possible to make reasonable predictions that strains > 2 mm/m will cause cracking within the tensile strain zones. Shearing and buckling is also likely to occur within the compressive zones above a longwall with shallow surface rock.

Overall, strains and cracking can be managed effectively by assuming cracks will occur within the limits of a longwall panel and may need to be repaired after each panel is completed.

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 **Discontinuous Fracture 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 dilated’ strata zone with low connectivity potential to the mine workings. The B-Zone therefore represents a sub-surface fracturing zone that causes only minor groundwater system disturbance.

The **Elastic Deformation Zone (C-Zone)** is where the strata may have suffered minor bed separations (due to vertical tensile strains between 1 and 2 mm/m) and horizontal shearing, with cracking and jointing unlikely to cause a major change in vertical hydraulic conductivity. The bedding separations of up to 30 mm will allow minor increases to horizontal hydraulic conductivity, but they are more likely to act as additional groundwater storage ‘reservoirs’ with only minor groundwater system losses expected.

The development of the Elastic Deformation Zone (C-Zone) will depend on the cover depth above the workings, 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.

As for the B-Zone, the Elastic Deformation Zone is also likely to be predominately in compression due to natural arch formation above sub-critical and critical panels and will also act as barrier to vertical drainage of groundwater. Groundwater will still able to 'leak' downwards through the C-Zone due the presence of naturally occurring vertical joints in the rock mass. However, the presence of low permeability strata such as claystone, tuff and mudstone and zones of compressive strain in the spanning region of the overburden will limit rock mass 'gaps' and further retard vertical flow rates.

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 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, however, both zones are considered to be 'constrained dilated' zones that 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):

- Subcritical refers to panels with W/H < 0.7;
- Critical refers to panels with W/H > 0.7 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.

A11.2.1 Wardell, 1975, Reynolds, 1977 and Singh and Kendorski, 1981

Wardell, 1975 recommended that 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.

A11.2.2 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. massive units and / or 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 layers of coloured sand and plaster with sawdust bond breakers placed between each successive layer. 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 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 strains were calculated using the method provided in the UK Subsidence Engineers Handbook, 1975.

- The fracturing path progressed up at an inward angle of approximately 18^{o} 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.

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

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

A11.2.3 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.

A11.2.4 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.

A11.2.5 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 A40g**.

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 A40g** and **Section 11.3** 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 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 (or to within 10 m of it). DgS has requested a copy of the Angus Place and South Bulga reports for review before the results of these studies are confirmed.

A11.2.6 Bulli Seam PAC, 2010

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

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

- The panel width only-based models do not seem to distinguish between continuous and discontinuous fracture heights, so it is probably the case that the data on which they are based are likely to include both A and B type fracturing zones.

- The mining height models do not include the influence of panel width, which is believed to be a key parameter as well.

- 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.

- The height of fracturing is also 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.

A11.2.7 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 from 43T to 60T 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 includes 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 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 of the strata units 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 semi-impermeable strata units such as mudstone and claystone in the B-Zone.

- For the case of sub-critical panels, the maximum non-spanning strata height and load acting on the goaf will probably be limited by the 'natural' or catenary arch that can form across the mined void width.

- For super-critical panels on the other hand, the height of fracturing could theoretically reach the surface and the maximum load acting on the goaf will probably equal the cover depth.

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 (strata unit thicknesses and its mechanical properties).

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

A11.3 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 A5.1** 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 data from the Southern and Western NSW coalfields presented in **MSEC, 2011** (see **Figure A40g)** and additional Newcastle Coalfield cases based on extensometer and piezometric data from Abel, West Wallsend and Mandalong Mines.

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 B-Zone and three cases whereby the 'height of fracturing' is claimed to reach the surface a distance above the workings of 43T (Invincible Colliery, LW1), 57T (South Bulga LWE1) and 105T (Angus Place, LW11); see **Figure A40g**. A fourth surface to seam connective cracking case (Homestead, LW9) was also added to the database.

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

(ii) 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.

The results of the database review and re-assignment of A to B Zones are shown in **Figure A40h**.

At this stage the height of fracturing claimed for Angus Place LW11 is well above established ranges and based on extensometer data only. The point has been removed from the database at this stage and assumed to be an outlier until confirmation of its validity can be obtained. The

remaining two points are just within the quoted ranges in the literature and have been left in the data base for further analysis as follows:

- The height of fracturing for LW1 at Invincible Colliery was assessed to extend to within 10 m of the surface, with the B-Zone extending to the surface.

- The height of fracturing for LWE1, South Bulga has been assumed to have reached 10 m below the Surface as the extensometer data is not available to review at this stage.

It has also been decided to remove two case study points (Central and Southern German Creek Mines) from the original **ACARP, 2003** data base due to the uncertainty associated with using drilling data only above old goaves to assess the height of fracturing.

A summary of the extensometer results for the amended A-Zone to B-Zone cases is presented in **Table A5.2**.

The expanded database presented in **Table A5.1** has subsequently been used to update the strain and curvature index-based models presented in **ACARP, 2003** in the following sections.

Table A5.1 - Updated HoF Model Database for Australian Coalfields

Site	Panels	Mine	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	LW10	Metropolitan	140	460	0.30	3.4	**130**	-	38	50	130	High	0.29	3
2	LW1 to 4	South Coast	110	325	0.34	2.5	**85**	-	34	50	85	High	0.24	3
3	LW6	Kemira	117	335	0.35	1.7	**98**	-	58	50	98	High	0.16	2
4	LWA1	Austar	159	453	0.35	6.0	**113**	**313**	21	50	113	High	0.56	4
5	LW20	Metropolitan	163	450	0.36	3.4	**100**	-	29	50	100	High	0.34	2
6	LW514	Bellambi West	150	400	0.38	2.7	**90**	-	33	50	90	High	0.29	2
7	LW28	Appin	200	500	0.40	2.3	**90**	-	39	50	90	High	0.27	1
8	LW2	Ellalong	150	368	0.41	3.5	**113**	**210**	*32*	50	113	High	0.40	3
9	LW3	Tahmoor	180	424	0.42	2.2		**204**		50	100	High	0.29	2
10	LW9	Teralba	150	350	0.43	2.7	**110**	**150**	41	37	110	High	0.32	2
11	TE	West Cliff	200	446	0.45	2.5	**101**	***245***	*40*	50	101	High	0.30	1
12	LW11	Angus Place	211	263	0.80	2.5	**253**	***253***	*102*	10	210	Low	1.11	5
13	LW5	Mandalong	160	179	0.89	3.7	**116**	**162**	32	25	82	High	0.68	5
14	411	Springvale	315	350	0.90	3.3	**132**	**256**	*43*	73	132	High	1.38	3
15	LW5	Dendrobium	245	255	0.96	3.8	**123**	-	33	50	123	High	1.25	5
16	LW1	Wyee	216	206	1.05	3.4	**126**	-	37	25	126	High	1.09	5
17	LW1	Invincible	145	116	1.25	2.7	**102**	***111***	36	13	63	Low	1.62	16
18	Panel1	Abel 1	120	95	1.26	2.6	**45**	***75***	18	10	41	Low	1.51	22
19	LW40	WWD	179	113	1.58	3.8	**80**	***108***	21	20	45	Low	2.28	21
20	LWE1	Sth Bulga	259	155	1.67	2.6	**145**	**150**	57	10	124	Low	1.53	8
21	LW41	WWD	179	105	1.70	3.8	**72**	**100**	19	14	36	Low	2.28	24
22	LW9	Crinum	280	155	1.81	3.5	**85**	***150***	24	35	105	High	1.82	8
23	LW39	WWD	179	97	1.84	3.9	**68**	**92**	17	14	34	High	2.18	25
24	TE	Wyee North 3D	355	185	1.92	1.9	**63**	***143***	33	40	63	Moderate	1.14	4
25	355	Wyee North (LW4)	355	180	1.97	1.9	**40**	-	21	40	40	Low	1.14	4
26	Panel2	Abel 2	150	76	1.97	1.9	**45**	**71**	24	10	33	Low	1.13	23
27	TE	Cooranbong North B	150	75	2.00	2.8	**58**	***70***	21	10	58	High	1.68	33
28	LW1	Oaky Creek	205	95	2.16	3.2	**55**	***90***	17	12	55	Low	1.92	25
29	LW9/9a	Homestead	200	80	2.50	3.3	**70**	**75**	21	10	62	Low	1.98	29

- = not available;
bold - surface to seam fracturing assessed by others. DgS unable to review these assessments and currently considered to be outliers compared to rest of data base;
italics - Continuous Fracture Zone heights (A-Zone) assessed by others may have included the Constrained Discontinuous Fracture and Dilated Zone (B-Zone) and have been assumed at this stage to equal the height of the B-Zone based on data review of measured vertical strains by DgS (see **Figure A40h**);
No shade - Sub-critical panels; Light grey shade - Critical panels; Grey shade - Supercritical panels.
* - 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 (despite whether its spanning or not).
^ - maximum likely values assumed from borehole data.

Table A5.2 - Summary of Measured A, B, C & D Zone Strains in Extensometers*

Parameter	**Underground Coal Mines**									
	Springvale		**West Wallsend**				**Abel^**			
Panel No.	LW411		LW39		LW40		Panel 1		Panel 2	
Cover Depth H (m)	368		97		113		95		76	
Panel Width W (m)	315		179		179		120		150	
W/H	0.90		1.84		1.58		1.26		2.0	
Mining Height, T	3.25		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***	-	***25***	-	***24***	-	***24***	-	***23***
C-Zone	<90	**<5**	-	**-**	-	**-**	-	**-**	-	**-**
B-Zone	31 - 410	**4 - 17**	8 - 17	**1 - 2**	25 - 50	**5 - 8**	14 - 19	**1 - 2**	<20	**-1 - 0**
A-Zone	194 - 1441	**14 - 42**	234 - 957	**115 - 139**	236 - 1833	**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**	411 - 1820	**11 - 59**	**>10**		**10 - 75**		**N/A**	

* - A, B & C-Zone strains are vertical.
italics - D-Zone strains are horizontal.
- strains are positive. Negative strains or compression develop after full subsidence develops.
^ - Effective mining height for total pillar extraction (Te = 0.85T).

A11.3.1 Updated Tensile Strain Model

The tensile strain model presented in **ACARP, 2003** was found to have a much stronger fit to the new database for the A-Zone, with only a slight improvement for the B-Zone horizon apparent. The R^2 value for the logarithmic regression curve fitted to the 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 results of the review of the strain based model are presented in **Figure A41a** and summarized below:

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

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

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

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

* - 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 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 height of 'continuous' and 'discontinuous' fracturing are again higher for a given tensile strain at the surface, and is probably due to geological structure and strata bedding thickness differences in the rock mass compared those used 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 dependent on surface crack width development and should therefore not be used to assess surface to seam connectivity without considering near surface and B-Zone lithology.

Considering the potential difficulties with predicting strains after the onset of cracking, **ACARP, 2003** attempted to modify the strain model to a curvature-based approach. The curvature model has now also been updated (see **Section A11.3.2**).

A11.3.2 Updated Overburden Curvature Index Model

It should be understood that the tensile strain model is reliant on a non-robust parameter (i.e. tensile strain) that has been noted for its high variability if cracking develops. It was therefore decided to re-plot the database again using the previously derived Overburden Curvature Index or S_{max}/W'^2 term to provide a readily measurable field parameter that would not be compromised by surface strain concentration effects (i.e. cracking). Logarithmic regression lines were re-derived to give predictions of mean and U95%CL values for both A and B-Zones.

The revised regression results are shown in **Figure A41b** and summarised below:

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

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

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

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

* - 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 same apparent differences still remain between the Australian height of fracturing database and the UK physical modelling results. The differences between the model and measured values indicate that there are further parameters that need to be included in one or both of the models, or the scaling of the physical model did not match the range of real-world conditions likely to be present.

One obvious difference is that the UK physical model represents a case study where the panel width and cover depth was constant (i.e. W/H = 1.34) and within the critical to supercritical range. The Australian database however, has a significant range of sub-critical, critical and super-critical panel geometries and further investigation of this issue is therefore required (see **Section A11.3.4**).

A11.3.3 Influence of Lithology on Sub-Surface Fracture Heights

An assessment was also made on whether the lithology had the potential to control or limit the height of fracturing above a longwall panel. Reference to the database presented in **ACARP, 2003**, indicates that 15 of the 29 case studies were assessed to have 'High' SRP and had A-Horizons that coincided with the base of the massive strata units. The other data points had 'Low' SRP with no massive units present. 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 could control the height of direct hydraulic fracturing. Due to the complex nature of this problem, it is 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.

A11.3.4 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 (theta A) as follows:

- Continuous Fracture Zone Height, $A = W'/(4\tan(\text{theta}_A))$
- Discontinuous Fracture Zone Height, $B = W'/(4\tan(\text{theta}_B))$

where,

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

theta_A = abutment angle to estimate height of A-Zone

theta_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 fracture height angle model proposed by DgS in 2012 could also be further divided into sub-critical, critical and supercritical panel geometries (see **Figure A41e**). 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 was considered 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.

A11.4 Alternative Sub-surface Fracture Model Development

Starting with the influence of mining height on the height of 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 A41f**. 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.

If the fracture heights are plotted against panel width (W) only, a similar 'scattered' outcome results as shown in **Figure A41g**. A slightly improved regression analysis results if A is plotted against W/H in **Figure A41h** or when normalized to the panel width (A/W) and is plotted against T in **Figure A41i** for sub-critical, critical and super-critical panel geometries.

Based on these plots, it is clear that consideration also 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.

A11.4.1 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 A41j**:

Macro-Scale Mechanisms:

- 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:

Micro-scale Mechanisms:

- 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.

- 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 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 will be dependent on the height to the underside of the spanning catenary arch above sub-critical panels, which increases to the full cover depth once supercritical panel geometries are reached.

A11.4.2 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 relationships between the mining geometry and overburden behaviour described in the previous section.

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 = $\gamma DW_i^2/12 = \gamma(H-y)\ W_i^2/12$

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 are likely (θ) to range between 12^o and 19^o according to the literature and underground observations.

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 angle discussed in **Section A11.3.4**, as the latter is back-calculated from measured heights of continuous fracturing and an assumed parabolic fracture limit profile.

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:

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

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.

$$W_i = W - 2y\tan\theta$$

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:

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

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.

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

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

It is noted that Equation (1) ignores the presence of collapsed and fractured material within the A-Zone itself. The formation of a compressible 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 beams (p) may be estimated as follows:

$$p_i = 2\Delta/(L_i)^2 = 2\,(\varepsilon_g\,6T)/L_i^2 = 12\,(\sigma_g/E_g)T/L_i^2 = 12\,(\gamma H'/E_g)T/L_i^2$$

where

Δ = mid-span deflection of beam with an effective span, L_i.
ε_g = vertical strain of goaf with thickness of 6T (T+5T).
σ_g = maximum vertical stress acting on the goaf = $\gamma H'$.
θ_b = angle subtended to vertical from the rib side to the point of maximum concave curvature along a beam or maximum subsidence.
L_i = effective span distance to estimate curvature = y ($\tan\theta_b$) = 0.5 y.
H' = effective goaf load height = W'/4tanθ where
θ = goaf loading height angle.

The goaf loading height angle is similar to the angle of break or caving angle, θ, but also represents the angle subtended to the vertical for the assumed parabolic profile or catenary arch above sub-critical panels. The goaf height angle is expected to increase for critical and supercritical panel geometries as the spans increase and cover depth decreases.

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

$$\sigma_c = 2M/(Znt) = 2p_i E't^3/[(n\, t^2\, (1-0.667n))] = 8(\gamma H')T(E'/E_g)t/[y^2 n(1-0.667n)]$$

where

E' = rock mass Young's Modulus = 150UCS
n = 0.5 for beam at yield point

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

$$\sigma_c = UCS = 24(\gamma H')TEt/[E_g A^2]$$

which gives by re-arrangement,

$$A = 4.9((\gamma H')^{0.5} T^{0.5} t^{0.5} E^{0.5}/(UCS^{0.5}\, E_g^{\,0.5}) \qquad (2)$$

and if H' is substituted with W'/4tanθ for subcritical panel geometries then (2) becomes

$$A = 2.45((\gamma W')^{0.5} T^{0.5} t^{0.5} E^{0.5}/(UCS^{0.5}\, E_g^{\,0.5}\, \tan\theta_c^{\,0.5}) \qquad (3)$$

For supercritical panel geometries, W' may then be substituted with 1.4H, and (3) becomes

$$A = 2.9((\gamma H)^{0.5} T^{0.5} t^{0.5} E^{0.5}/(UCS^{0.5}\, E_g^{\,0.5} \tan\theta_c^{\,0.5}) \qquad (4)$$

Overall, the equations represent the physical relationships for either spanning strata (Equation (1)) or yielded strata (Equations (2) to (4) that are thick enough to limit fracture continuation through it. The equations indicate a very complex system with a significant number of variables that will influence the height of fracturing outcomes.

Considering the complexity of the above equations and uncertainty in the assumptions made, the physical relationship between the variables may also be assessed practically with Dimensional Analysis, a commonly used tool in hydraulics (see **Section A11.4.3**).

A11.4.3 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 heights of continuous fracturing (A) and discontinuous fracturing (B) respectively. 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 A11.4.2**, 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.

Note:

1. The y term may be ignored as it corresponds with the dependent variable (A or B).

2. The beam thickness, t refers to the thickness likely to exist just above the fracture height location (which is probably going to be unknown before mining commences and will be discussed further later).

3. The caving angle or angle of break, tanθ is considered to be dependent on the W and H terms, so it may be ignored at this point. It has been included later indirectly to estimate the goaf load height, H' = W/4tanθ.

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 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)

π_6: $E_g \cdot M^{-1} L^1 T^2 = E_g/UCS$ (Goaf Stiffness Term)

which gives:

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

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 two π terms representing the ratios of rock mass and goaf stiffness to strength for all cases in the database will be constant, 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 further 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 height of continuous fracturing beyond this point would then be controlled by the mining height and geological conditions.

A11.4.4 Identifying Strata Units Likely to Limit the Height of Fracturing

The likelihoods that a strata unit will span the fractured zone have been determined by plotting the 'spanning' and 'non-spanning' strata unit thicknesses as π_4 terms (i.e. t is normalised to the effective panel width, W') against the unit location factor y/H.

For ease of expression, the significant strata units that are likely to limit heights of continuous fracturing have been termed 'spanning' units. Strata units that did not stop the height of fracturing in the A-Zone are described as 'non-spanning'.

The strata unit thickness t and it's distance y above the workings may also not be able to be practically measured in the field without extensometry and borehole data. In the absence of extensometry data, conservative estimates of spanning unit thicknesses based on subsidence data were assumed.

Logistic regression analysis was subsequently used to define probabilistic straight line equations that indicate the 50%, 90% and 95% probabilities of whether a strata unit has spanned and/or limited the development of the height of fracturing; see **Figure A42a**.

Given that i= 1 or 0 for a spanning or non-spanning case study and P(i=1)=95% for t_{min} refers to a 95% probability that a beam of a minimum thickness will span the fractured zone at a given location in the overburden, then:

$$P(i=1)=50\% \text{ for } t_{min} = W'[0.17 - 0.075(y/H)]$$

$$P(i=1)= 90\% \text{ for } t_{min} = W'[0.19 - 0.075(y/H)]$$

$$P(i=1)= 95\% \text{ for } t_{min} = W'[0.20 - 0.075(y/H)]$$

A summary of spanning and non-spanning cases are presented in **Table A5.3**.

Table A5.3 - Spanning and Non-Spanning Case Studies in HoF Model Database for Australian Coalfields

Site	Panels	Mine	W (m)	H (m)	W/H	T (m)	A (m)	A/H	Strata Unit Spanning Analysis Results						
									t^ (m)	y (m)	t/W'	y/H	t_{min} P(i=1, 50%)	t_{min} P(i=1, 95%)	Success/ Failure i (1/0)
1	LW10	Metropolitan	140	460	0.30	3.4	130	0.28	50	130	0.36	0.28	21	25	1
2	LW1 to 4	South Coast	110	325	0.34	2.5	85	0.26	50	85	0.45	0.26	16	20	1
3	LW6	Kemira	117	335	0.35	1.7	98	0.29	50	98	0.43	0.29	17	21	1
4	LWA1	Austar	159	453	0.35	6.0	113	0.28	50	113	0.31	0.28	23	28	1
5	LW20	Metropolitan	163	450	0.36	3.4	100	0.22	50	100	0.31	0.22	25	30	1
6	LW514	Bellambi West	150	400	0.38	2.7	90	0.23	50	90	0.33	0.23	23	27	1
7	LW28	Appin	200	500	0.40	2.3	90	0.18	50	90	0.25	0.18	31	37	1
8	LW2	Ellalong	150	368	0.41	3.5	113	0.31	50	113	0.33	0.31	22	27	1
9	LW3	Tahmoor	180	424	0.42	2.2		-	50	100	0.28	0.24	27	33	1
10	LW9	Teralba	150	350	0.43	2.7	110	0.31	37	110	0.25	0.31	22	26	1
11	TE	West Cliff	200	446	0.45	2.5	101	0.23	50	101	0.25	0.23	30	37	1
12	LW11	Angus Place	211	263	0.80	2.5	253	***0.96***	10	210	0.05	0.96	20	27	0
13	LW5	Mandalong	160	179	0.89	3.7	116	0.66	25	82	0.16	0.67	19	24	1
14	411	Springvale	315	350	0.90	3.3	132	0.40	73	132	0.23	0.40	44	54	1
15	LW5	Dendrobium	245	255	0.96	3.8	123	0.48	50	123	0.20	0.48	32	40	1
16	LW1	Wyee	216	206	1.05	3.4	126	0.61	25	126	0.12	0.61	26	33	0
17	LW1	Invincible	145	116	1.25	2.7	102	0.83	13	63	0.09	0.83	15	20	0
18	Panel1	Abel 1	120	95	1.26	2.6	45	*0.47*	10	41	0.08	0.43	16	20	0
19	LW40	WWD	179	113	1.58	3.8	80	0.71	20	45	0.13	0.35	22	27	0
20	LWE1	Sth Bulga	259	155	1.67	2.6	145	***0.94***	10	124	0.05	0.80	23	30	0
21	LW41	WWD	179	105	1.70	3.8	72	0.69	14	36	0.14	0.30	21	26	0
22	LW9	Crinum	280	155	1.81	3.5	85	0.55	35	105	0.16	0.68	25	32	1
23	LW39	WWD	179	97	1.84	3.9	68	0.70	14	34	0.15	0.19	21	25	0
24	TE	Wyee North 3D	355	185	1.92	1.9	63	0.34	40	63	0.15	0.34	37	45	1
25	355	Wyee North (LW4)	355	180	1.97	1.9	40	0.22	40	40	0.16	0.22	38	46	1
26	Panel2	Abel 2	150	76	1.97	1.9	45	0.59	10	33	0.09	0.43	14	18	0
27	TE	Cooranbong North B	150	75	2.00	2.8	58	0.77	10	58	0.10	0.77	12	15	0
28	LW1	Oaky Creek	205	95	2.16	3.2	55	0.58	12	55	0.10	0.58	17	21	0
29	LW9/9a	Homestead	200	80	2.50	3.3	70	0.88	10	62	0.09	0.78	12	16	0

W' = minimum(W, 1.4H); t^ - maximum likely values from borehole data.

$t_{min\ for\ spanning}$ P(i=1, 50%) = W'[0.17 - 0.075(y/H)]

$t_{min\ for\ spanning}$ P(i=1, 95%) = W'[0.20 - 0.075(y/H)]

For the purposes of making robust predictions, the 95% logistic regression lines were used to determine maximum beam thickness for cases where the borehole logs indicated that the overburden units were significantly thicker (and therefore likely to span).

For cases where non-spanning strata were likely to be present a minimum beam thickness of 10 m or the actual strata thickness (whichever was the greater) was adopted.

A11.4.5 PI-Term Model for Predicting Height of Continuous Fracturing (A) above Longwalls

Based on the empirical database presented in **Table A5.1**, the statistics software XLSTAT® was used to complete a multi-nonlinear regression analyses on the first four PI terms defined earlier as follows:

$$\underline{\text{Mean } A/W' = 1.565\,(H'/W')^{1.256}(T/W')^{0.371}(t'/W')^{-0.261}} \qquad R^2 = 0.66$$

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

where

a = 0.21 for subcritical; 0.19 for critical panels and 0.1 for supercritical panels (with linear transition between error zones).

H' = Goaf Load Height = $W'/4\tan\theta$

Back analysis of the database indicated the angle of break varies as follows:

$\theta = 12^o$ for W/H <0.45;

$\theta = 9.63+4.42(W/H)+1.80(W/H)^2$ 0.45< W/H <1.4;

$\theta = 19.29^o$ for W/H >1.4.

The goaf load height angles v. the W/H ratio are shown in **Figure A42b**.

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

T = Mining Height.

t' = Effective strata unit thickness

$= t_{\text{min for non-spanning}}$ if $t < t_{\text{min for non-spanning}}$

$= t$ if $t < t_{\text{min for spanning}}$

$= t_{\text{min for spanning}}$ if $t > t_{\text{min for spanning}}$

where $t_{\text{min for non-spanning}}$ = 10 m; and $t_{\text{min for spanning}}$ = see **Section A11.4.4**.

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

$$\underline{A = 0.273(1/\tan\theta)^{1.26}W'^{0.89}T^{0.37}\,t'^{-0.26} \qquad +/- aW'} \qquad R^2 = 0.66$$

The height of goaf loading is also considered to be the maximum height of continuous fracturing or A_{max}, which has been derived from the abutment angles and panel widths. The predicted A_{max} values are plotted with the measured A-Zone values in **Figure A42c**.

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

The predicted v. observed A/W' and A values for the proposed PI-Term model are presented in **Figures A42d** and **Figure A42e** respectively. The residual errors reasonably follow a normal probability distribution about the regression curve according to Central Limit Theory in statistics (see **Figure A42f**).

The regression results suggest that the height of continuous fracturing will increase with effective panel width, W', goaf load H' and mining height, T raised to powers ranging from to 0.4 to 0.8 and decrease with strata unit thickness raised to the power of -0.2.

The results are generally consistent with **Whittaker and Reddish, 1990**, **Singh & Kendorski, 1991** and the analytical models presented in **Section A11.3**.

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

- critical panel widths exceed 1.4H;
- the maximum possible arch height across sub-critical panels has been reached,
- Spanning strata exists that can bridge the fractured zone.

The presence of 'plastic' and 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 behaviours 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.

Ignoring the Angus Place result for the moment, 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) with a minimum t' value of 10 m assumed. Adopting a minimum beam thickness of 10 m will therefore generally indicate the maximum likely height of continuous fracturing for all cases in the database (see **Figures A42e** and **A42g**).

The presence of relatively thick strata units at a given distance y within the height of fracturing may truncate or reduce the result indicated. It is assessed from the database that the strata unit thickness would have to be at least 0.15 times the span, W', before a fracture height truncation would be considered possible (see **Figure A42a**).

A11.4.6 PI-Term Model for Predicting Heights of Discontinuous Fracturing (B) Above Longwalls

Based on the empirical database presented in **Table A5.1**, the statistics software XLSTAT® was used to complete a multi-nonlinear regression analysis as follows for estimating the height of the dilated B-Zone :

$$\underline{\text{Mean B/W'} = 2.529\ (H'/W')^{1.985}(T/W')^{0.354}(t'/W')^{-0.271}} \qquad R^2 = 0.87$$

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

where

b = 0.21 for subcritical; 0.15 for critical; and 0.11 supercritical panels (with linear transition between error zones)

H' = Goaf Load Height = W'/4tanθ

Back analysis of the database indicated the angle of break varies as follows:

$\theta = 12^o$ for W/H <0.45;

$\theta = 9.63+4.42(W/H)+1.80(W/H)^2$ 0.45< W/H <1.4;

$\theta = 19.29^o$ for W/H >1.4.

The goaf load height angles v. the W/H ratio are shown in **Figure A42b**.

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

T = Mining Height.

t' = Effective strata unit thickness

$= t_{\text{min for non-spanning}}$ if $t < t_{\text{min for non-spanning}}$

$= t$ if $t < t_{\text{min for spanning}}$

$= t_{\text{min for spanning}}$ if $t > t_{\text{min for spanning}}$

where $t_{\text{min for non-spanning}}$ = 10 m; and $t_{\text{min for spanning}}$ = see **Section A11.4.4**.

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

$$\underline{B = 0.161\ (1/\tan\theta)^{1.985}\ W'^{0.917}T^{0.354}\ t'^{\ -0.271} \quad +/-\ bW'} \qquad R^2 = 0.87$$

The predicted v. observed B/W' and B' values are presented in **Figure A42h** and **Figure A42i** respectively. The residual errors follow a normal probability distribution about the regression curve as expected according to Central Limit Theory in statistics (see **Figure A42j**). 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.

A11.4.7 PI-Term Model Validation

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

(i) A review of the database to check if the model is likely to be biased towards a particular parameter or mining geometry, and

(ii) Comparison of prediction v. measured database of A and B-Horizons

In regards to the data base, the following parameters from **Table A5.1** 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.

In regards to prediction model reliability, the distributions of model residual errors should follow central limit theory 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 results for the A-Zone model checks are summarised in **Table A5.4** and demonstrate the model errors satisfy normality tests with ~50% of the measured values above and below the predicted mean values with 95% of the measured values below the Upper 95%CL predictions.

Table A5.4 - Summary of Measured v. Predicted Height of Continuous Fracture A-Zones

Site	Panel	Mine	Panel Width W (m)	Cover Depth H (m)	W/H	Mining Height T (m)	t' (m)	Predicted A (m)		Measured A (m)	Pass = 1; Fail = 0	
								mean	U95%CL		m	U95
1	LW10	Metropolitan	140	460	0.30	3.4	25	106	135	**130**	0	1
2	LW1 to 4	South Coast	110	325	0.34	2.5	20	81	104	**85**	0	1
3	LW6	Kemira	117	335	0.35	1.7	21	73	98	**98**	0	1
4	LWA1	Austar	159	453	0.35	6.0	29	141	175	**113**	1	1
5	LW20	Metropolitan	163	450	0.36	3.4	30	116	150	**100**	1	1
6	LW514	Bellambi West	150	400	0.38	2.7	27	101	132	**90**	1	1
7	LW28	Appin	200	500	0.40	2.3	37	113	155	**90**	1	1
8	LW2	Ellalong	150	368	0.41	3.5	27	112	144	**113**	0	1
9	LW3	Tahmoor	180	424	0.42	2.2	33	105	143		0	
10	LW9	Teralba	150	350	0.43	2.7	26	102	133	**110**	0	1
11	TE	West Cliff	200	446	0.45	2.5	37	118	160	**101**	1	1
12	LW11	Angus Place	211	263	0.80	2.5	10	133	167	**253**	0	
13	LW5	Mandalong	160	179	0.89	3.7	25	91	116	**116**	0	1
14	411	Springvale	315	350	0.90	3.3	55	132	183	**132**	1	1
15	LW5	Dendrobium	245	255	0.96	3.8	40	113	153	**123**	0	1
16	LW1	Wyee	216	206	1.05	3.4	25	106	141	**126**	0	1
17	LW1	Invincible	145	116	1.25	2.7	10	78	102	**102**	0	1
18	Panel1	Abel 1	120	95	1.26	2.6	10	64	84	**45**	1	1
19	LW40	WWD	179	113	1.58	3.8	10	84	99	**80**	1	1
20	LWE1	Sth Bulga	259	155	1.67	2.6	10	96	117	**145**	0	0
21	LW41	WWD	179	105	1.70	3.8	10	78	93	**72**	1	1
22	LW9	Crinum	280	155	1.81	3.5	10	107	129	**85**	1	1
23	LW39	WWD	179	97	1.84	3.9	10	74	87	**68**	1	1
24	TE	Wyee North 3D	355	185	1.92	1.9	40	70	96	**63**	1	1
25	355	Wyee North (LW4)	355	180	1.97	1.9	40	68	93	**40**	1	1
26	Panel2	Abel 2	150	76	1.97	1.9	10	45	56	**45**	1	1
27	TE	Cooranbong North B	150	75	2.00	2.8	10	52	62	**58**	0	1
28	LW1	Oaky Creek	205	95	2.16	3.2	13	63	76	**55**	1	1
29	LW9/9a	Homestead	200	80	2.50	3.4	10	59	70	**70**	0	1
Reliability check for mean and U95% Predictions: % Pass											**52**	**96**

Ignoring the Angus Place result for LW11 until it can be confirmed, the proposed mean and U95%CL model satisfactorily over predicts 52% and 96% of the measured A-Zone data (i.e. expected values of 50% and 95%). The one model failure was indicated for Site 20 (South Bulga) which is not available for review at this stage.

It is therefore considered that the reliability of the new 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 model checks also indicate the model errors satisfy normality tests as shown in **Figure A42f** and are summarised in **Table A5.5**.

Table A5.5 - Summary of Measured v. Predicted Heights of Discontinuous Fracture B-Zones

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	LW10	Metropolitan	140	460	0.30	3.4	25	208	238	**-**	-	-
2	LW1 to 4	South Coast	110	325	0.34	2.5	20	159	182	**-**	-	-
3	LW6	Kemira	117	335	0.35	1.7	21	142	167	**-**	-	-
4	LWA1	Austar	159	453	0.35	6.0	29	280	313	**313**	0	1
5	LW20	Metropolitan	163	450	0.36	3.4	30	227	261	**-**	-	-
6	LW514	Bellambi West	150	400	0.38	2.7	27	197	229	**-**	-	-
7	LW28	Appin	200	500	0.40	2.3	37	219	261	**-**	-	-
8	LW2	Ellalong	150	368	0.41	3.5	27	220	252	**210**	1	1
9	LW3	Tahmoor	180	424	0.42	2.2	33	203	241	**204**	0	1
10	LW9	Teralba	150	350	0.43	2.7	26	199	231	**150**	1	1
11	TE	West Cliff	200	446	0.45	2.5	37	228	270	***245***	0	1
12	LW11	Angus Place	211	263	0.80	2.5	10	223	255	***253***	0	1
13	LW5	Mandalong	160	179	0.89	3.7	25	149	173	**162**	0	1
14	411	Springvale	315	350	0.90	3.3	55	225	272	**256**	0	1
15	LW5	Dendrobium	245	255	0.96	3.8	40	182	218	**-**	-	-
16	LW1	Wyee	216	206	1.05	3.4	25	166	198	**-**	-	-
17	LW1	Invincible	145	116	1.25	2.7	10	111	116	***111***	**1**	1
18	Panel1	Abel 1	120	95	1.26	2.6	10	90	95	***75***	1	1
19	LW40	WWD	179	113	1.58	3.8	10	108	113	***108***	**1**	1
20	LWE1	Sth Bulga	259	155	1.67	2.6	10	130	154	**150**	0	1
21	LW41	WWD	179	105	1.70	3.8	10	100	105	**100**	1	1
22	LW9	Crinum	280	155	1.81	3.5	10	147	155	***150***	0	1
23	LW39	WWD	179	97	1.84	3.9	10	92	97	**92**	1	1
24	TE	Wyee North 3D	355	185	1.92	1.9	40	94	122	***143***	0	0
25	355	Wyee North (LW4)	355	180	1.97	1.9	40	91	119	-	-	-
26	Panel2	Abel 2	150	76	1.97	1.9	10	62	74	**71**	0	1
27	TE	Cooranbong North B	150	75	2.00	2.8	10	71	75	***70***	1	1
28	LW1	Oaky Creek	205	95	2.16	3.2	13	86	95	***90***	0	1
29	LW9/9a	Homestead	200	80	2.50	3.3	10	75	80	**75**	**1**	1
Reliability check for mean and U95% Predictions: % Pass											**45**	**95**

The proposed mean and U95%CL model satisfactorily over predicts 45% and 95% of the measured B-Zone data (i.e. within 5% of the expected values).

It is considered that the reliability of the new model is acceptable for general estimates of B-Zone discontinuous fracture height assessments at new or existing coal mines in Australia and should be confirmed or re-calibrated with local measurement data.

The reliability test results also indicate that the proposed heights of fracturing models for estimating A and B Zones are likely to be conservative.

A11.4.8 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 A11.2** indicate that surface cracking depths above longwalls are likely to be <11 to <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 A43e** and **A43f**) 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 the minimum beam thicknesses determined for the PI-Term 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 A5.6** may be assumed when assessing surface to seam connectivity potential above longwalls in the Newcastle Coalfield beneath varying topography:

Table A5.6 - Recommended Maximum Cracking Depths

Location and Topography	Maximum Surface Cracking Depth (m)
Flat Terrain with Moderate Slopes up to 18^o	12
Bases of Valleys	15
Low side of panel beneath steep slopes > 18^o (not valley floor)	10
Crests or high side of panel beneath steep slopes > 18^o	20

A11.4.9 Summary

The new PI-Term models presented in **Section A11.4** 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 spanning or non-spanning capability of strata units in the overburden cannot be ignored 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 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 PI-Term model will allow the influence of strata unit thickness to be included directly in the predictions of 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. The thickness of 10 m also corresponds to the minimum beam thicknesses assessed from surface strain and curvature measurements in the Newcastle Coalfield.

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 two cases in the database that have been reported to have fractured through to the surface, which, if found to be correct, will require a beam thickness of < 10 m to calibrate the PI-Term Model.

At the other end of the scale, the maximum strata unit thickness for a given site has been limited to the minimum thickness required to span the fractured zone using logistic regression techniques. This has been done so that the database is not unduly biased by borehole log information and overconfidence in the assessment of actual beam thicknesses.

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.

A12 Far-Field Displacements and Strain Predictions

A12.1 Background

The term far-field displacements (FFD) generally refer to the horizontal surface movements that occur outside the vertical subsidence limit or angle of draw to an extracted pillar panel or longwall block. It is currently understood that FFDs are a phenomenon caused by the reduction of horizontal stress when collapse of overburden rock (i.e. goafing) occurs above an extracted area. There also appears to be a strong correlation between the FFDs and the surface subsidence magnitude (which is also an indicator of horizontal stress relief). A conceptual model of the mechanics of FFDs is presented in **Figure A44a**.

Horizontal stress in rock is normally greater than the vertical stress at a given depth of cover; it has been 'locked' into the strata by tectonic movements and over-consolidation pressures (i.e. stress). Over-consolidation stresses occur in sedimentary rock after uplift and erosion over millennia has gradually removed the overlying material since the time of formation. Tectonic induced stress usually results in strong directional bias between the major and minor principal stress magnitudes, with variation due to stiffness of the lithological units as well (refer to **Nemcik et al, 2005**, **Pells, 2004**, **McQueen, 2004, Enever, 1999** and **Walker, 2004**).

It is considered that both of the abovementioned horizontal stress development mechanisms are likely to be present in the near surface rocks in the western area of the Newcastle Coalfield.

FFD's have only recently become an issue in the Newcastle Coalfield because of adverse surface impact experiences in the Southern Coalfield (e.g. horizontal movements of around 25 mm have been measured over 1.5 km away from extracted longwall panels on a concrete dam wall. No cracking damage occurred to the dam wall because of these movements however).

The strains associated with FFDs are usually very low, however, there is one case in the Southern Coalfield where a bridge was subject to lateral shearing of approximately 50 mm along the river bed axis.

To-date, it is understood that there are no precedents in the Newcastle Coalfield where similar FFD effects (measured or inferred via damage) have occurred around longwalls or total extraction panels. Horizontal movements have been measured outside the angle of draw limits from mine workings however, albeit at smaller distances and magnitudes (eg. 20 mm of horizontal movement has been measured in undulating terrain at 250 m from one longwall block where the cover depth was 135 m).

The horizontal stress in the Newcastle Coal Measures has been measured at several locations along the F3 Freeway to the west of Wyong and Newcastle (**Lohe and Dean-Jones, 1995**). The magnitude of the measured horizontal stress indicates that it is relatively high, with magnitudes that are 1.5 to >5 times the vertical stress, in relatively flat or moderately undulated terrain.

The major principal horizontal stress is usually orientated N to NE in the Western Newcastle Coalfield, but it can be re-orientated parallel to the axis of a ridge due to natural weathering processes near the surface (which cause lateral unloading towards the gullies); refer to **Lohe and Dean Jones, 1995**.

A12.2 In-situ Stress Field

Reference to stress measurement data in **Lohe and Dean-Jones, 1995** indicates that the 'shallow' (ie < 100 m below the surface) regional stress field in the undulating terrain along the eastern and eastern sides of Lake Macquarie is likely to have its major principal horizontal stress > 5 x vertical stress (and assuming horizontal stress is zero at the surface). Deeper strata at depths > 150 m is likely to have its major principal horizontal stress <2 x vertical stress.

The stress data from the above reference was measured using over-coring / HI-Cell techniques and is presented in Table A4.

Table A6 - Horizontal Stress Field Measurements in Newcastle Coalfield Relevant to Tasman

Location	Depth (m)	In-situ Stress Measurements*			
		Major Sigma 1 (MPa)	Minor Sigma 2 (MPa)	Vertical Sigma 3 (MPa)	Sigma1+/ Sigma 3
Wakefield	24	10.4	0.42	0.6	17.3
Wallsend Borehole	100	13.3	9.7	2.5	5.3
West Wallsend No. 2	190	27.4	20.3	4.75	5.8
Kangy Angy	70	11.8	4.2	1.75	6.7
Moonee	90	11.7	8.3	2.25	5.2
West Wallsend	170	6.4	n/a	4.25	1.5
Ellalong	320	6.5	4.6	8.0	0.8

* - All measurements in medium strength sandstone.
+ - ratio assumes horizontal stress is zero at the surface (which is not always correct).

The shallow stress data is plotted in **Figure A44b** and indicates that the major principal horizontal stress could be as high as 6 MPa at the surface (unless weathered rock and soil is present) with the Major and Minor Principal Horizontal stresses equal to approximately 4 times the vertical stress for depths up to 250 m.

This high Sigma 1 reading, however, may be associated with a sandstone / conglomerate ridgeline and not typical for the areas away from ridgelines (although a residual 'surface' horizontal stress range from 1.5 to 6.5 MPa has also been assessed for the Sydney Metropolitan area in **McQueen, 1999** and **Pells, 2002**).

Another commonly used assumption in the NSW Coalfields is that the major principal horizontal stress is approximately 2 x the vertical stress and the minor principal horizontal stress is 1.4 ~ 1.5 x the vertical stress (or the Major Principal Horizontal Stress is 1.33~1.4 x the Minor Principal Horizontal Stress). It is also acknowledged that the horizontal stress in the

Newcastle and Sydney areas can be 4 to 5 times the vertical stress, based on shallow rock mass data at depths < 50 m; refer to **Lohe and Dean Jones, 1995**. The sources of this stress field imbalance has been explained in **Enever, 1999**, **Pells, 2002** and **Fell *et al*, 1992** as being due to:

(i) the 'over consolidation' ratio; where the vertical pressure due to ancient surface at the time of consolidation has since been eroded away, leaving a 'locked' in horizontal stress component in today's sedimentary rock mass. The OCR can be shown to decrease exponentially with depth and is equal in all directions at a given point.

(ii) Tectonic strain; where crustal plate movements apply a strain to the rock mass and the resultant stress is dependent on the stiffness of the individual beds and direction of movement.

(iii) Geological structure (faults/dykes); where discontinuities can change the magnitude and orientations of the regional stress field significantly.

(iv) Topographic relief (ridges/valleys/gorges); where the magnitude and direction of the regional stress field can vary due to geometric affects.

The influence of underground mining can also result in changes (both increases and decreases) in horizontal and vertical stress field magnitudes as the rock mass adjusts to a new equilibrium state.

Based on the measured stress conditions, the horizontal stress magnitudes may be estimated based on the equations presented in **Nemcik et al, 2005**:

$\sigma_H = K\sigma_v + E\varepsilon = \sigma_v [(\upsilon/1-\upsilon)OCR] + E\varepsilon$

$\sigma_h = f(\sigma_H)$ and $\sigma_v = 0.025H$ (MPa)

where,

σ_H = Major Horizontal Principal Stress;

σ_h = Minor Horizontal Principal Stress;

σ_v = Vertical Stress;

υ = Poisson's Ratio (normally ranges between 0.15 and 0.4 in coal measure rocks);

$(\upsilon/1-\upsilon)$ = Horizontal to vertical stress ratio factor (K_o) due to Poisson's Ratio effect on its own;

OCR = The over-consolidation ratio, which relates vertical pre-consolidation pressure (σ_{vo}) with current vertical pressure (σ_v) as follows, $OCR = \sigma_{vo}/\sigma_v = H_o/H$.

(*Note: This is an additional term that has been introduced by DgS, and has been mentioned (but not derived) in* **Pells, 2002** *and calculated in* **Fell et al, 1992**).

E = Young's Modulus for rock-mass unit;

ε = Tectonic Stress Factor (TSF) or Tectonic Strain.

Due to the wide range of horizontal stress values noted in the literature, it is recommended that the horizontal stress magnitudes be measured in-situ at several lithological horizons before high extraction mining commences.

Based on the apparent complexity and large variation between the interpretations of published stress field data, it was considered necessary to conduct a sensitivity analysis on the stress field profiles during the calibration of Map-3D® using the flat terrain data (see **Section A12.3** for details).

Total horizontal displacement measurements outside the ends and corners of several longwall panels in the Newcastle Coalfield (Newstan and West Wallsend Collieries), have been plotted against distance from the panel goaf edge / cover depth at the panel; refer to **Figure A45**.

Curves of best fit have been fitted to identify data trends from various locations from the ends and corners of the panels (note: the movements outside the corners of a longwall are typically smaller than the panel ends). The data has been obtained using GPS / EDM traverse techniques with quoted accuracy limits of +/- 7 to 10 mm.

The data in **Figure A45** has also been normalised to maximum measured subsidence (S_{max}) above a given panel and is presented in **Figure A46**. It is considered that presenting the data in this format allows all of the available data to be used appropriately to make subsequent FFD predictions.

The data presented in **Figures A47** was measured from the sides of several longwall panels using in-line, steel tape measurements. This method is considered more accurate than the EDM techniques, however, they do not capture all of the displacement. The measured values have subsequently been adjusted to absolute movements, based on the EDM measurements presented in **Figures A45** and **A46**.

A combined graph of normalised total displacement data from the ends and sides of the longwall panels is presented in **Figure A48** with worst-case design curves from ends, corners and sides of a longwall panel for flat terrain conditions.

The empirical models may be used for calibrating the numerical models input parameters when proposed mining layouts and topographical conditions are considered to be well outside the available database (see **DgS, 2007**).

A12.3 Numerical Far-Field Displacement Modelling

The numerical modelling program Map-3D® has been applied at several mines in the Newcastle Coalfield to-date for the purposes of estimating FFD movements. The model was chosen mainly due to its suitability for modelling large-scale rock masses.

The program is a 3-dimensional elastic, isotropic, boundary-element model, which essentially starts with an infinite solid space and calculates the effects of excavations, geological structure, varying material types, and free-surfaces on the regional stresses and strains. Further details about the software can be found at the Map-3D® web site.

The model is firstly calibrated to measured displacement data for a given mining geometry, regional horizontal stress field and surface topography. The Young's Modulus or stiffness of the overburden is then adjusted above an extracted panel (or panels) and assumed caving zone until a reasonable match is achieved.

Although the empirical models indicate that subsidence is a key parameter for predicting FFDs, numerical modelling of horizontal stress relief effects does not require the subsidence above the panels to be matched (by the model) because the extraction of coal and subsequent goafing behaviour can be calibrated to measured far-field displacements instead. Therefore, the modelling outcomes are not linked to the modelled subsidence directly.

Non-linearity can be introduced into the model to analyse the effects of fault planes and bedding using displacement-discontinuity elements with normal and shear stiffness and Mohr-Coulomb friction and cohesive strength properties.

Multiple mining stages and irregular topography can also be defined to enable mechanistic extrapolation of existing empirical databases with a reasonable degree of confidence.

An example of a predicted far-field displacement pattern around a high extraction pillar panel mine is presented in **Figure A49**.

A12.5 Empirical Strain Prediction Model

Strain measurements from the side of several longwall panels from West Wallsend and Newstan Collieries and were also normalised to maximum panel subsidence. The data are presented in **Figure A50**.

Several curves are shown with the data in the above figure, one is the best-fit or mean curve and two are upper limit confidence limit curves for the data (U95%CL and U99%CL). The confidence limit curves have been defined using weighted non-linear statistical techniques and the residual errors about the mean curve.

A13 References

ACARP, 1998a. **Chain Pillar Design (Calibration of ALPS)**. ACARP Project No. C6036, Colwell, M. Colwell Geotechnical Services.

ACARP, 1998b, **Project No. C5024, Establishing the Strength of Rectangular and Irregular Pillars**. J.M.Galvin, B.K. Hebblewhite, M.D.G. Salamon and B.B.Lin. School of Mining, UNSW.

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

ACARP, 2006. **Techniques to Predict and Measure Subsidence & its Impacts on the Groundwater Regime above Shallow Longwalls**. ACARP Project No. C23920 Report by Seedsman Geotechnics Pty Ltd and Geoterra Pty Ltd (March).

ACARP, 2007. **Hydrological Response to Longwall Mining**. CSIRO Exploration & Mining. H. Guo, D. Adhikary, D. Gaveva. Report No. C14033 (October).

Bulli Seam PAC, 2010. **Bulli Seam Operations Review Report**. NSW Government Planning Assessment Commission (10 July).

Colwell,1993. **Water Inflow Investigation for a Longwall Operation**. M. Colwell. Published in Queensland Coal Geology Groups Conference Proceedings, New Developments in Coal Geology, Brisbane.

Diedrichs and Kaiser, 1999. **Stability of Large Excavations in Laminated Hard Rock Masses: the Voussoir Analogue Revisited**. M.S. Diedrichs and P.K. Kaiser. International Journal of Rock Mechanics and Mining Sciences 36.

DgS, 2007. **Prediction of Far-Field Displacements Due to Pillar Extraction or Longwall Mining in Mountainous Terrain**. S. Ditton. Proceedings of the 7th Triennial MSTS Conference on Mine Subsidence, University of Wollongong (November 26-27)

DMR, 1987. **Mining Subsidence in NSW: 2. Surface Subsidence Prediction in the Newcastle Coalfield**. L. Holla. Department of Minerals Resources (June).

Enever, 1999. **Near Surface In-situ Stress and its Counterpart at Depth in the Sydney Metropolitan Area**. Enever, J.R. Published in Australian Geomechanics Society (AGS) Conference Proceedings of the 8th Annual Conference on Geomechanics, Hobart.

Fell *et al*, 1992. **Geotechnical Engineering of Embankment Dams**. Fell, R., MacGregor, P. and Stapledon, D.A.A. Balkema.

Forster and Enever, 1992. **Hydrogeological Response of Overburden Strata to Underground Mining, Central Coast, NSW**. I.R. Forster (Pacific Power) and J. Enever (CSIRO).

Forster, 1995. **Impact of Underground Coal Mining on the Hydrogeological Regime, Central Coast, NSW**. I.R. Forster. Published in Australian Geomechanics Society (AGS) Conference Proceedings (February), Engineering Geology of Newcastle – Gosford Region, University of Newcastle.

Frith, 2006. **Geotechnical Assessment of Overburden Fracturing Related to the Bulli Seam Extraction along the Line of the Proposed Endeavour Drift**. Frith Consulting Pty Ltd. Internal Report to BHP Billiton (October).

Holla, 1991. **Some Aspects of Strata Movement relating to Mining Under Water Bodies in NSW, Australia**. L. Holla. Published proceedings of 4th Int. Water Congress, Ljubljana, Slovenia, Yugoslavia (September).

Holla and Barclay, 2000. **Mine Subsidence in the Southern Coalfield**. L.Holla and E.Barclay. Department of Minerals Resources (June).

Karmis, et al, 1987. **Surface Deformation Characteristics Above Undermined Areas: Experiences from the Eastern United States Coalfields**. M. Karmis, A. Jarosz, P. Schilizzi & Z. Agioutantis. Published in Civil Engineering Transactions Journal, Institution of Engineers, Australia.

Kendorski, F.S., 1993. **Effect of High Extraction Coal Mining on Surface and Ground Water**. Proceedings of the 12th Conference on Ground Control in Mining, Morgantown, WV.

Li and Cairns, 2000. **Strata control experiences in longwall mining over old mine workings**. Li, G. and Cairns, R. AJM 3rd Annual Longwall Mining Summit, Yeppoon.

Lohe and Dean-Jones, 1995. **Structural Geology of the Newcastle-Gosford Region**. E.M. Lohe and G.L. Dean-Jones. Published in Australian Geomechanics Society (AGS) Conference Proceedings (February), Engineering Geology of Newcastle - Gosford Region, University of Newcastle.

McQueen, 2004. **In-situ Rock Stress and Its Effect in Tunnels and Deep Excavations in Sydney**. McQueen. L.B. Article presented in Australian Geomechnics Journal Vol 39. No. 3 (September).

MSEC, 2011. **Review of Under Surface and Groundwater Resources at Shallow Depths of Cover for the Proposed LWs 41 to 50, West Wallsend Colliery**. MSEC Report No. 519 (Rev A) - August.

Nemcik et al, 2005. **Statistical Analysis of Underground Stress Measurements in Australian Coal Mines**. Nemcik, J., Gale, W. and Mills, K. Published in proceedings of the Bowen Basin Geology Symposium.

Pells, 2002. **Developments in the Design of Tunnels and Caverns in the Triassic Rocks of the Sydney Region**. International Journal of Rock Mechanics and Mining Sciences No. 39. Pells, P.J.N.

Pells, 2004. **Substance and Mass Properties for the Design of Engineering Structures in the Hawkesbury Sandstone**. Article presented in Australian Geomechnics Journal Vol 39. No. 3 (September).

Peng and Chiang, 1984. **Longwall Mining**. S.S. Peng & H.S. Chiang. Wiley.

RCA, 2013. **End of Panel Longwall 41, Surface Subsidence Mapping Report, West Wallsend Colliery**. Robert Carr and Associates Pty Ltd. *Report Pending*.

Reynolds, 1977. **Coal Mining Under Stored Water**. Report on an Inquiry into Coal Mining Under or in the Vicinity of Stored Waters of the Nepean, Avon, Cordeaux, Cataract and Woronora Reservoirs, NSW for the NSW Government.

SCT, 2001. **Geotechnical Assessment for the Dendrobium Project**. SCT Operations Pty Ltd Report No. DEN1950 (5th June).

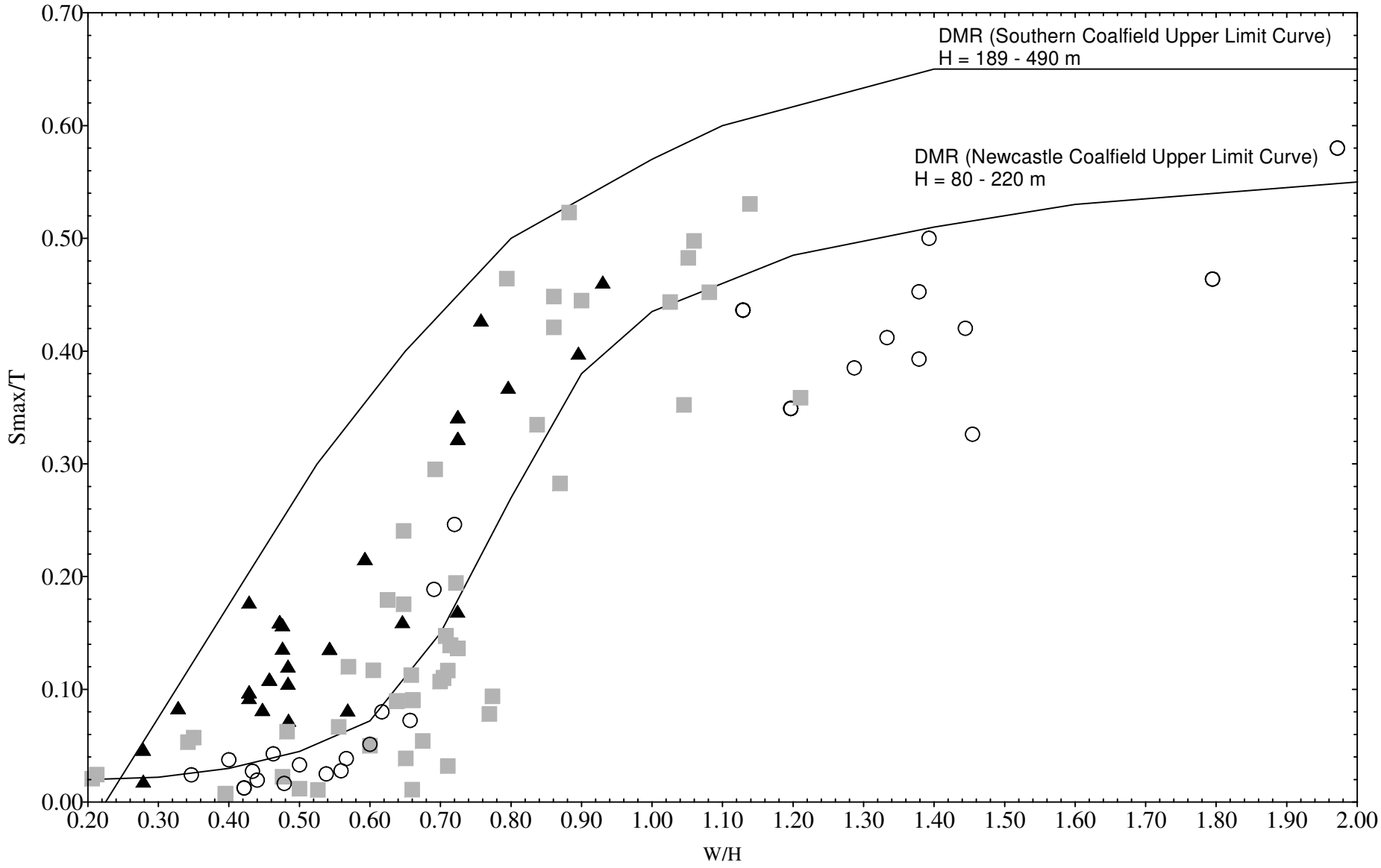
Seedsman, 2010. **Calibrated Parameters for the Prediction of Subsidence at Mandalong Mine**. R.W. Seedsman. Coal Operators' Conference, University of Wollongong (February).

Singh and Kendorski, 1981. **Strata Disturbance Prediction for Mining Beneath Surface Water and Waste Empoundments**. M.M. Singh and F.S Kendorski. First Conference in Ground Control in Mining, West Virginia University, 76-89.

Walker, 2004. **Stress Relief on Hillsides and Hillside Excavations**. Walker, B.F. Article presented in Australian Geomechnics Journal Vol 39. No. 3 (September).

Wardell, 1975. **Mining Under Tidal Waters**. Wardell and Partners Report prepared for NSW Government.

Whittaker & Reddish, 1989. **Subsidence, Occurrence, Prediction and Control**. B. N. Whittaker and D.J. Reddish. Department of Mining Engineering, University of Nottingham, UK.



LEGEND
Cover Depth, H (m)

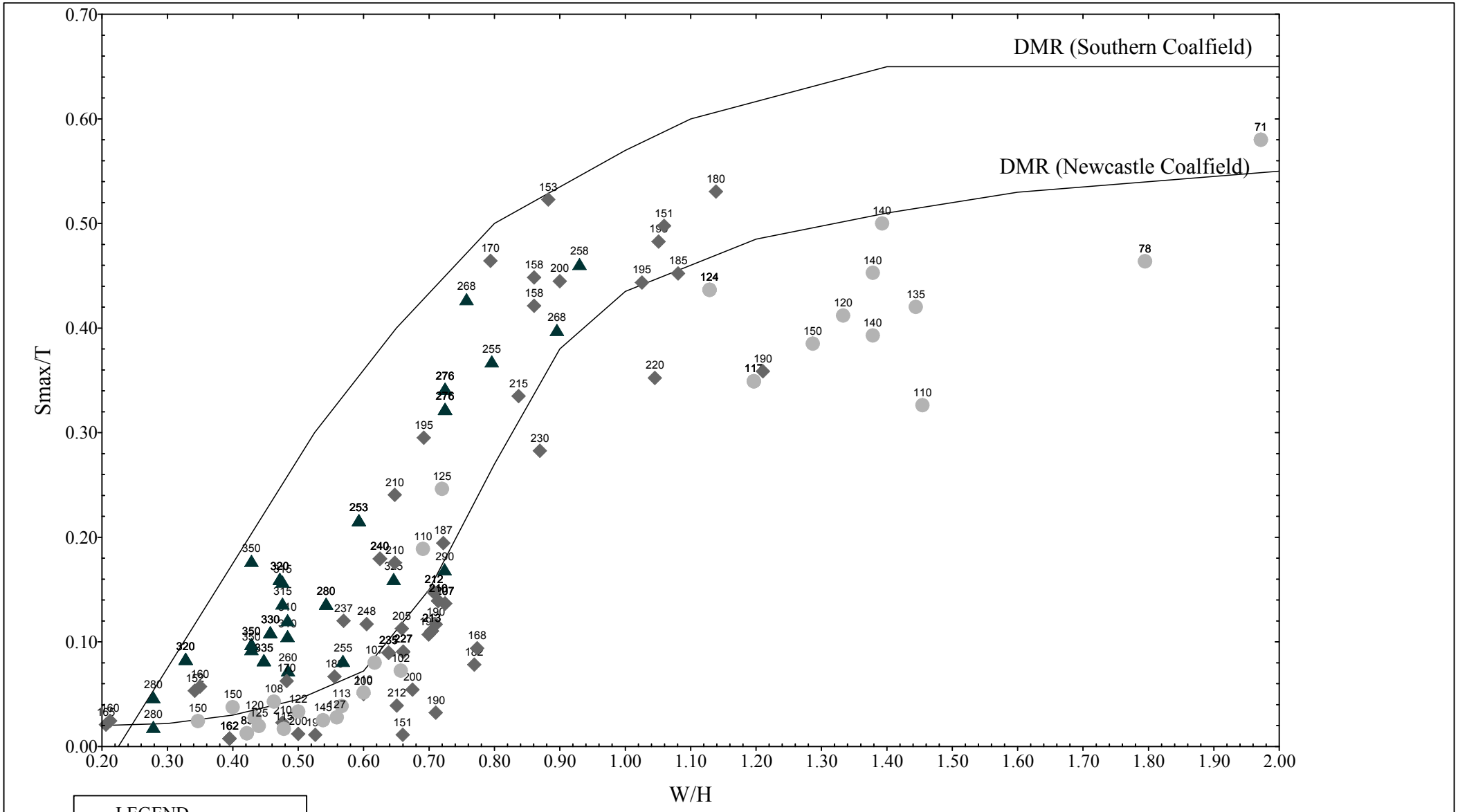
- ○ H = 70m to H = 151m
- ■ H = 151m to H = 251m
- ▲ H = 251m to H = 350m

DgS

Ditton Geotechnical Services Pty Ltd

Engineer:	S.Ditton
Drawn:	S.Ditton
Date:	08.06.08

Client:	Adapted from ACARP, 2003
Title:	Project Database and DMR Subsidence Prediction Curves for Single Longwall Panels in Newcastle Coalfield
Scale:	NTS
Figure No:	A1



LEGEND
Data Point
Cover Depth, H (m)

- H = 70m to H = 151m
- H = 151m to H = 251m
- H = 251m to H = 350m

DgS

Ditton Geotechnical Services Pty Ltd

Engineer:	S.Ditton
Drawn:	S.Ditton
Date:	08.06.08

Client:	Adapted from ACARP, 2003		
Title:	Project Database for Single Longwall Panels in Newcastle Coalfield showing Cover Depth for Each Point		
Scale:	NTS	Figure No:	A2.1

Continuous or clamped elastic beam in overburden with horizontal stress.

Simply supported beam analogy for cracked beam analysis

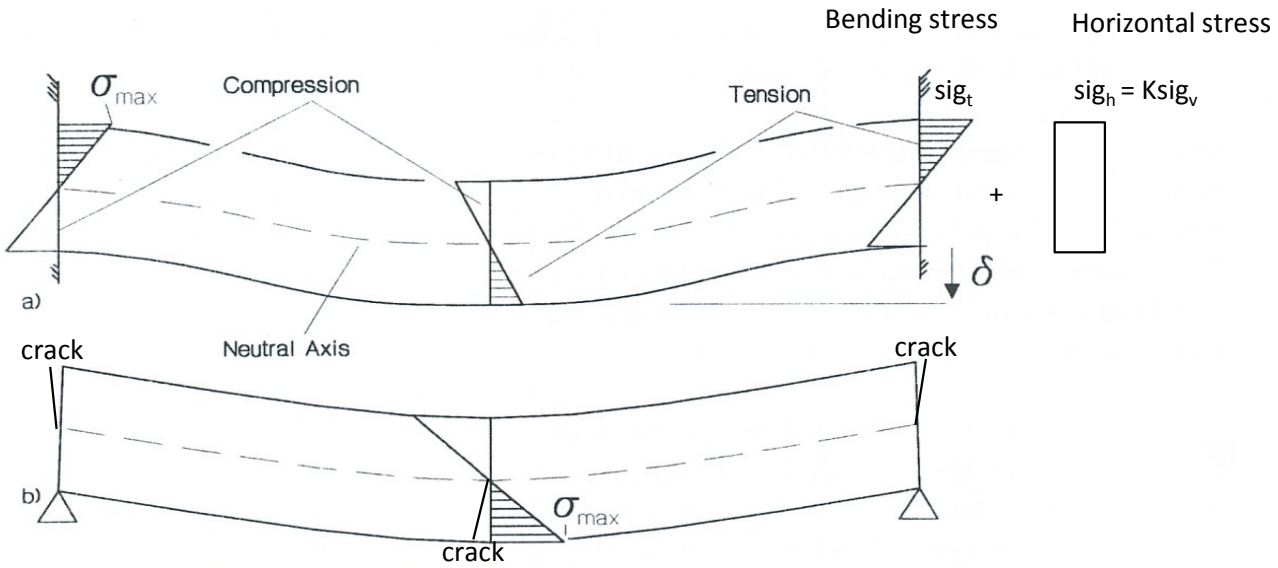


Fig. 4. Elastic beam with (a) fixed ends and (b) simple (pin) supports.

Note: Elastic beam cracks if $sig_t + sig_h > 0$, where tensile stress is positive.

Ref: Diedrichs & Kaiser, 1999

DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003	
	Drawn:	S.Ditton			
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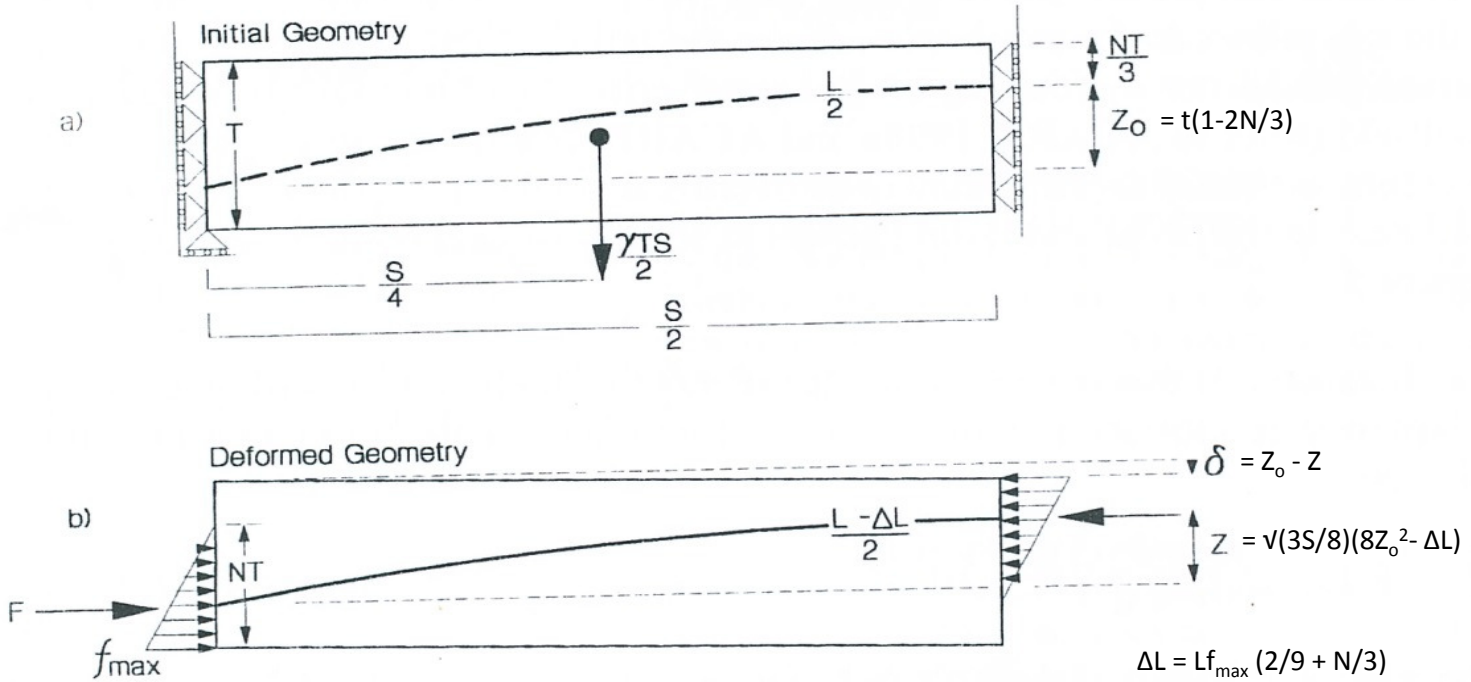
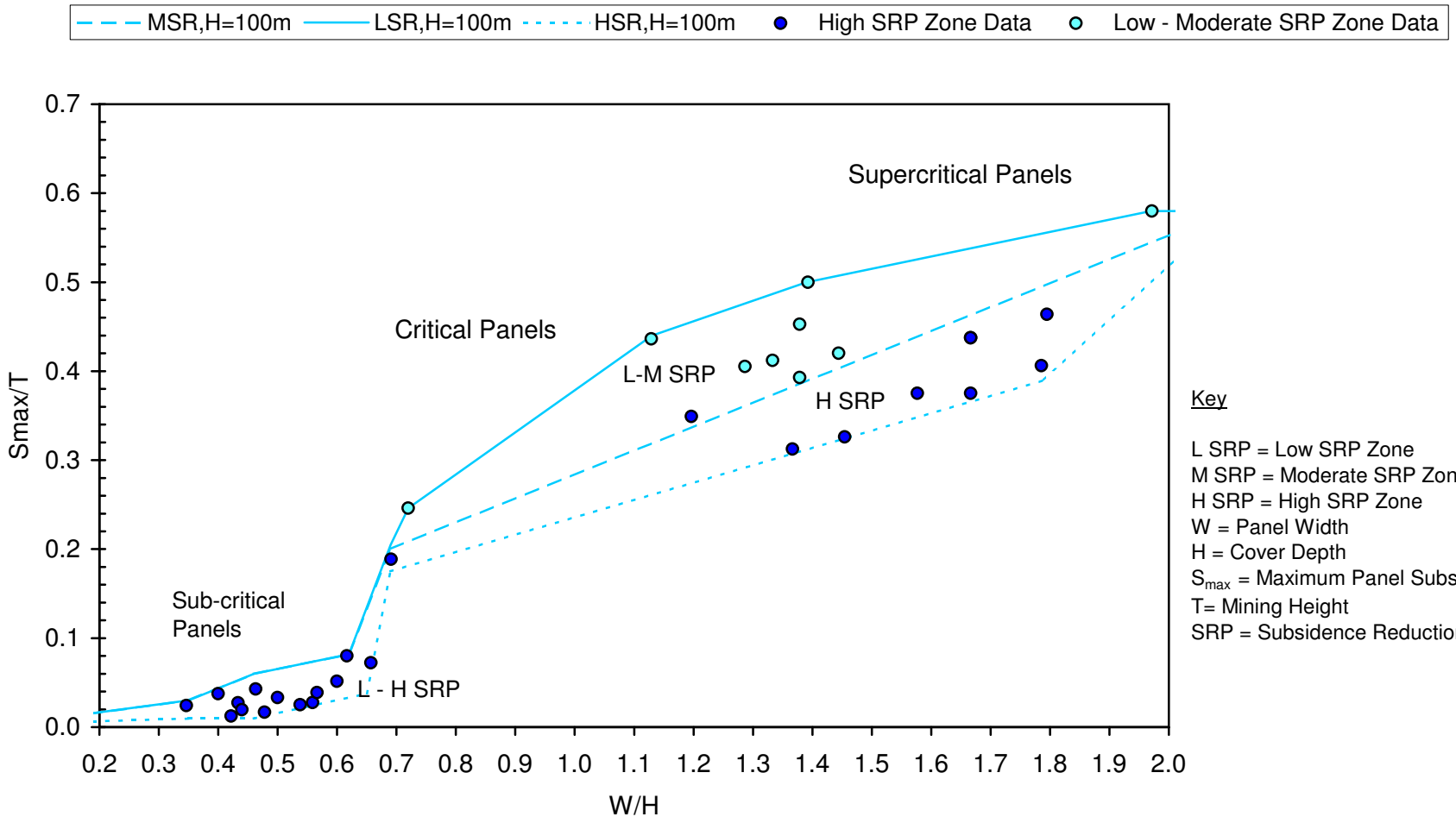


Fig. 5. Voussoir beam (half-span shown) and nomenclature.

Ref: Diedrichs & Kaiser, 1999

DgS	Engineer: S.Ditton	Client:	Adapted from ACARP, 2003		
	Drawn: S.Ditton				
	Date: 03.06.13	Title:	Internal Compressive Stress Arch Development in Simply Supported Beam (i.e. Voussoir Beam Analogy)		
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No:	A2.3

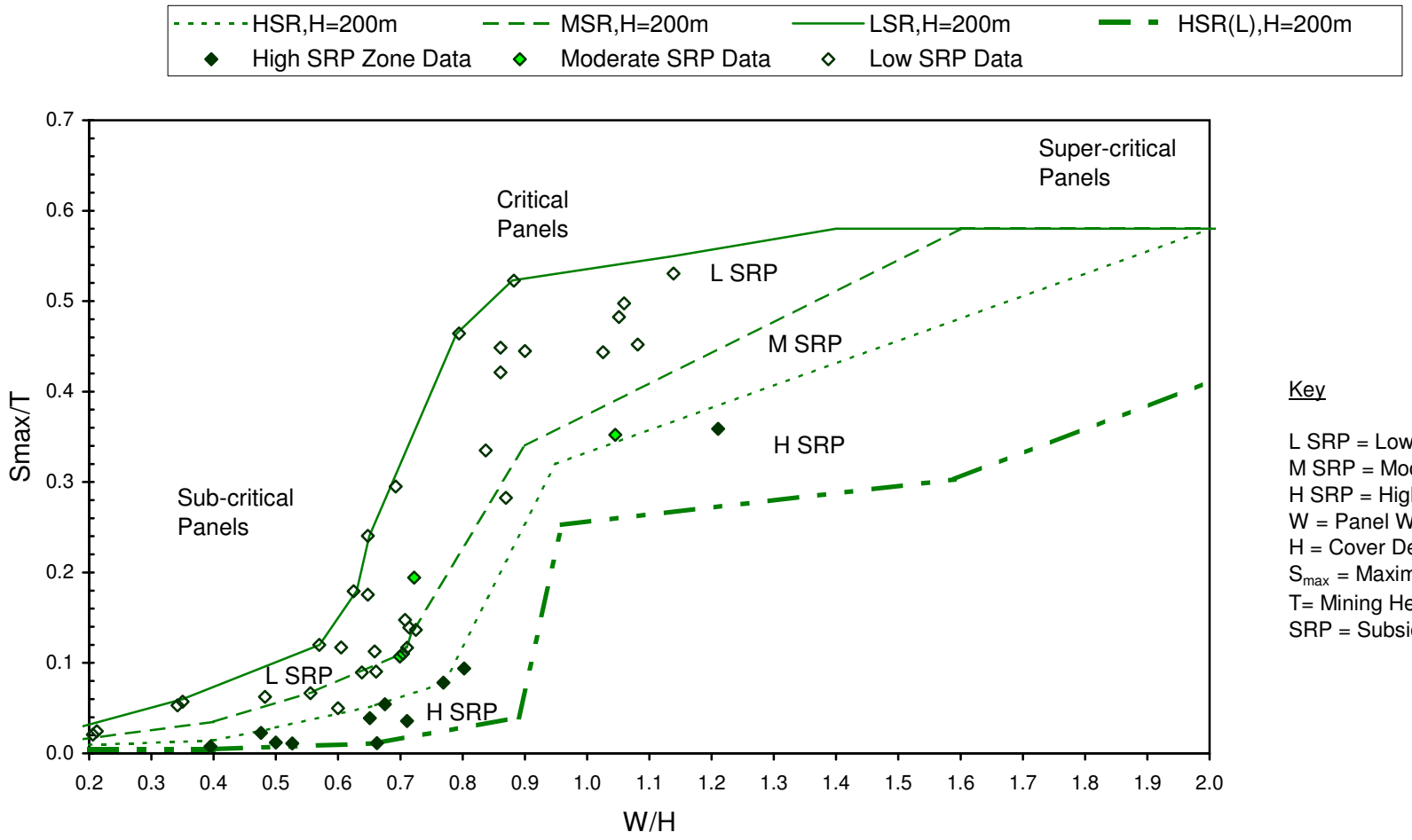


Key

L SRP = Low SRP Zone
M SRP = Moderate SRP Zone
H SRP = High SRP Zone
W = Panel Width
H = Cover Depth
S_{max} = Maximum Panel Subsidence
T= Mining Height
SRP = Subsidence Reduction Potential

Note: No SRP distinguishment for panels with W/H<0.65

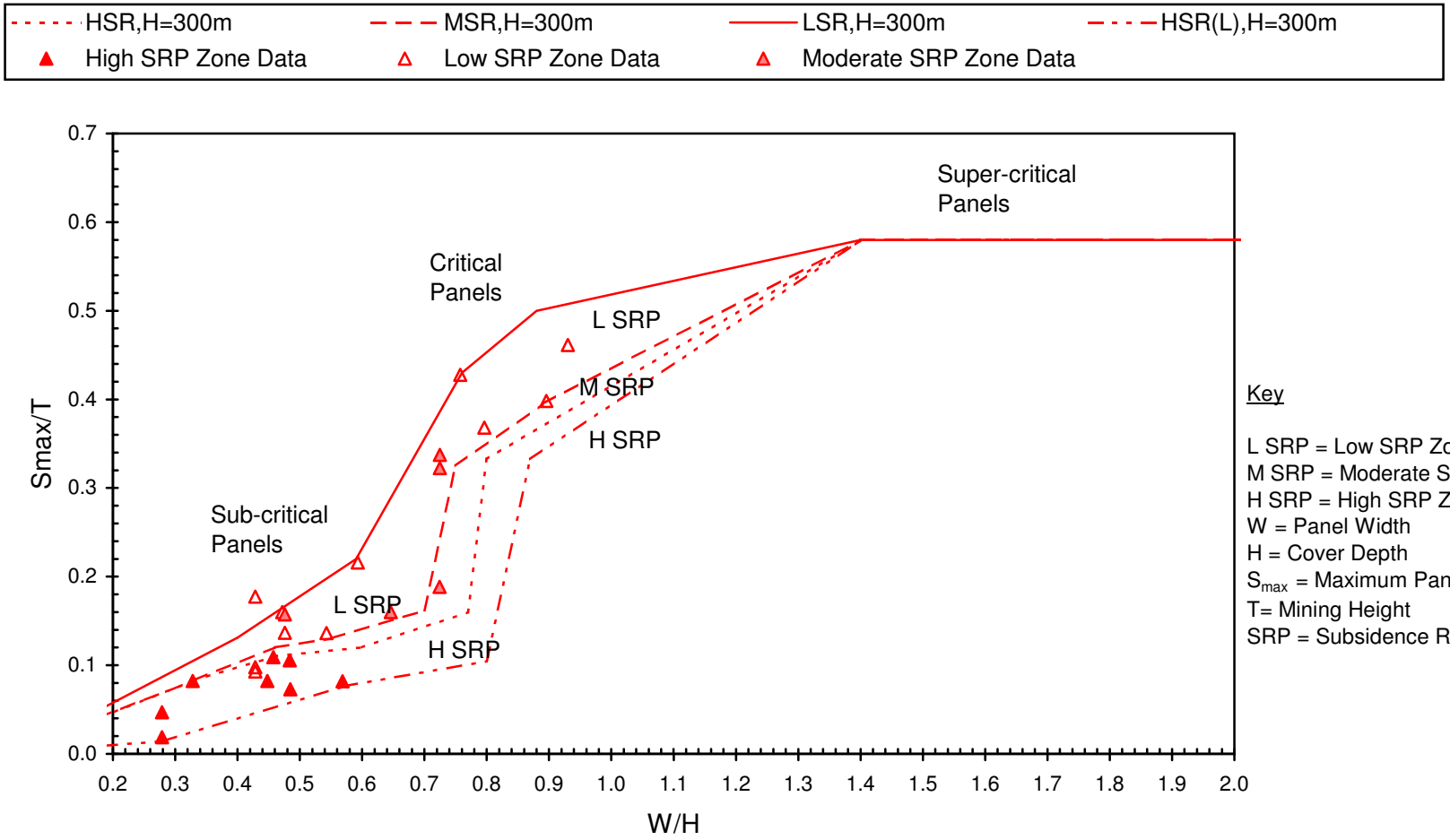
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	Drawn: S.Ditton			
	Date: 08.08.08	Title:	Empirical Model for Predicting Subsidence Above Panels with Cover Depths Between 50 and 150 m and Low to High SRP Zones	
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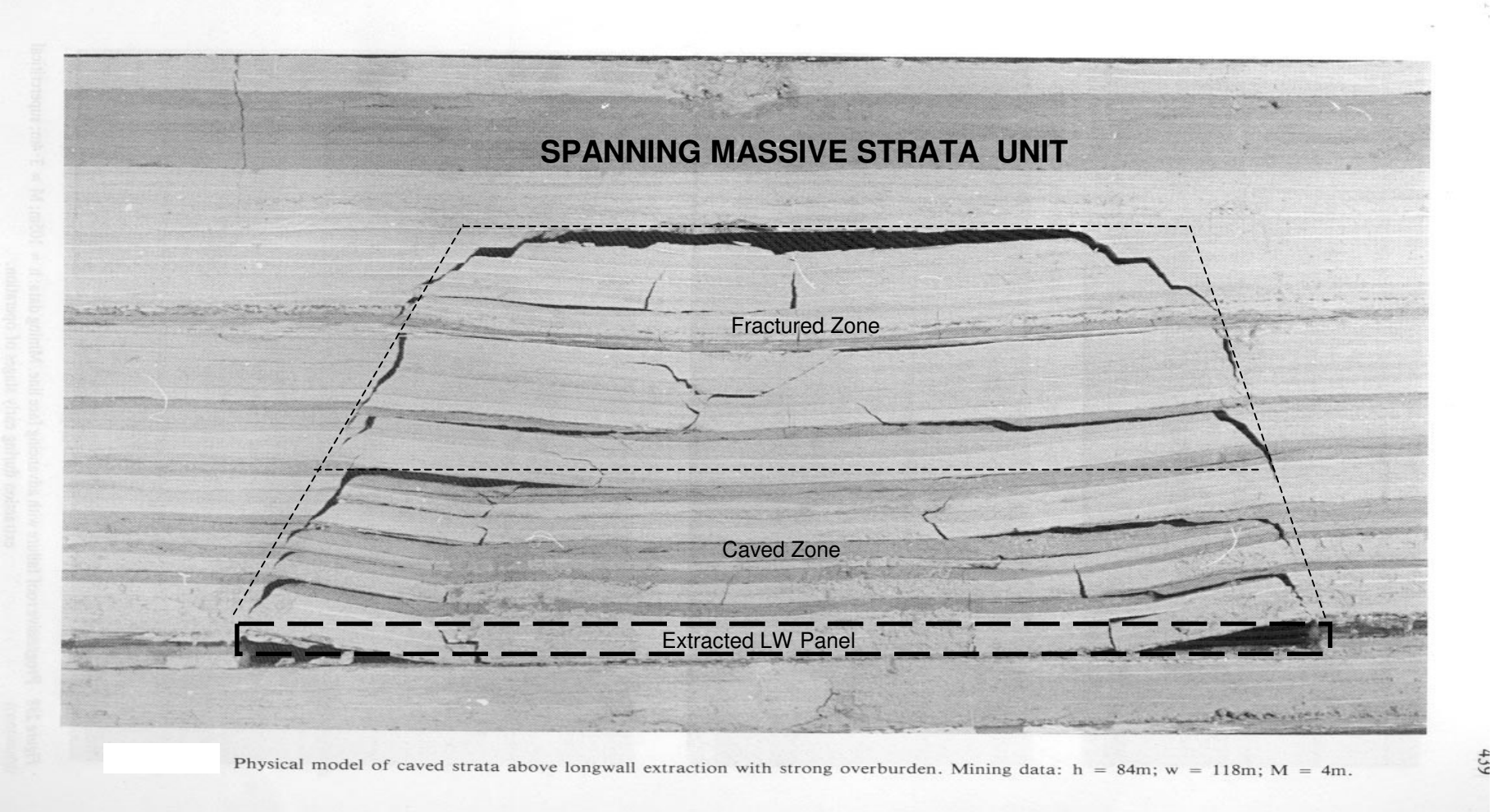
Key

L SRP = Low SRP Zone
M SRP = Moderate SRP Zone
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DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Predicting Subsidence Above Panels with Cover Depths Between 250 and 350 m and Low to High SRP Zones	
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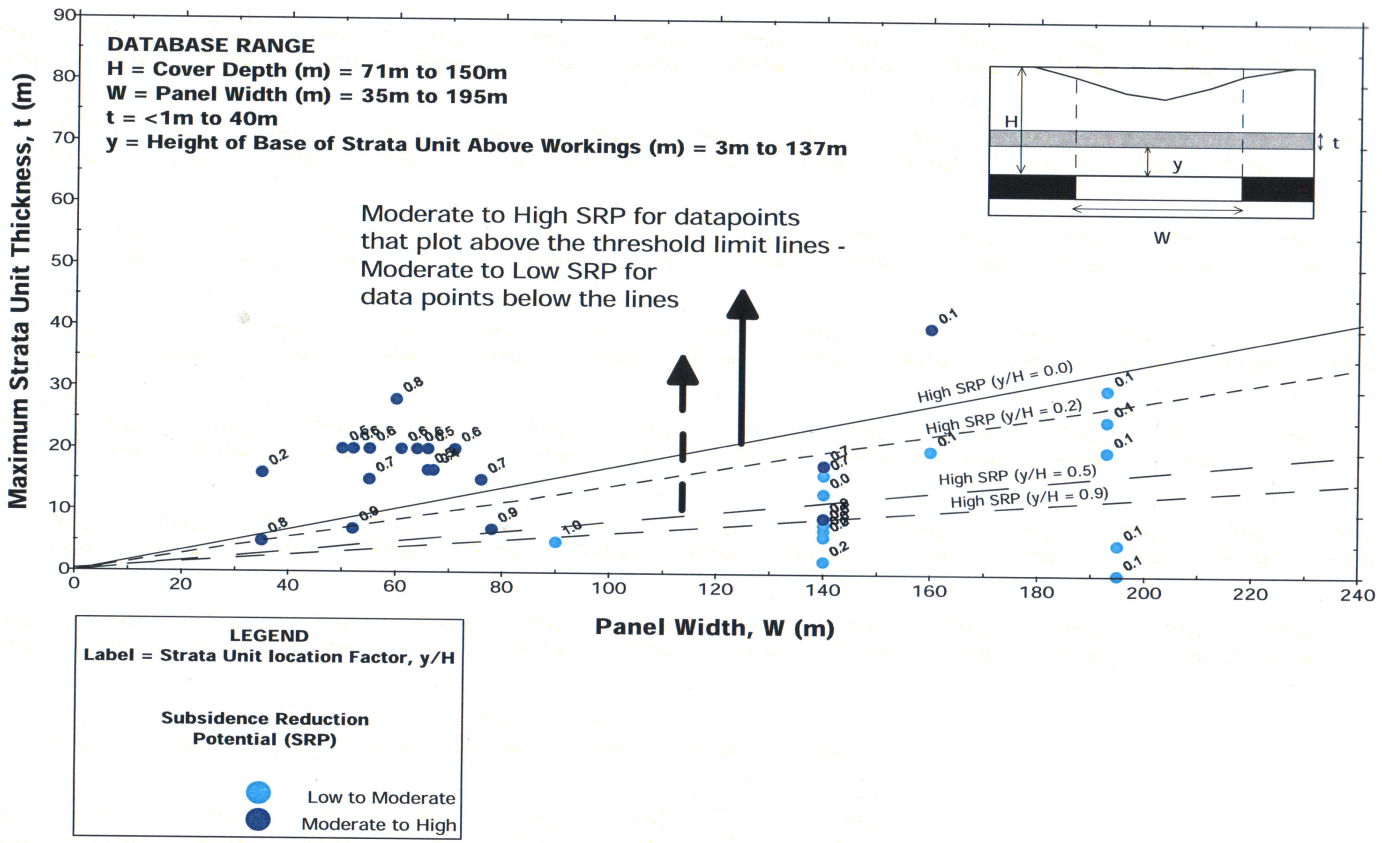
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	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Predicting Subsidence Above Panels with Cover Depths Between 250 and 350 m and Low to High SRP Zones	
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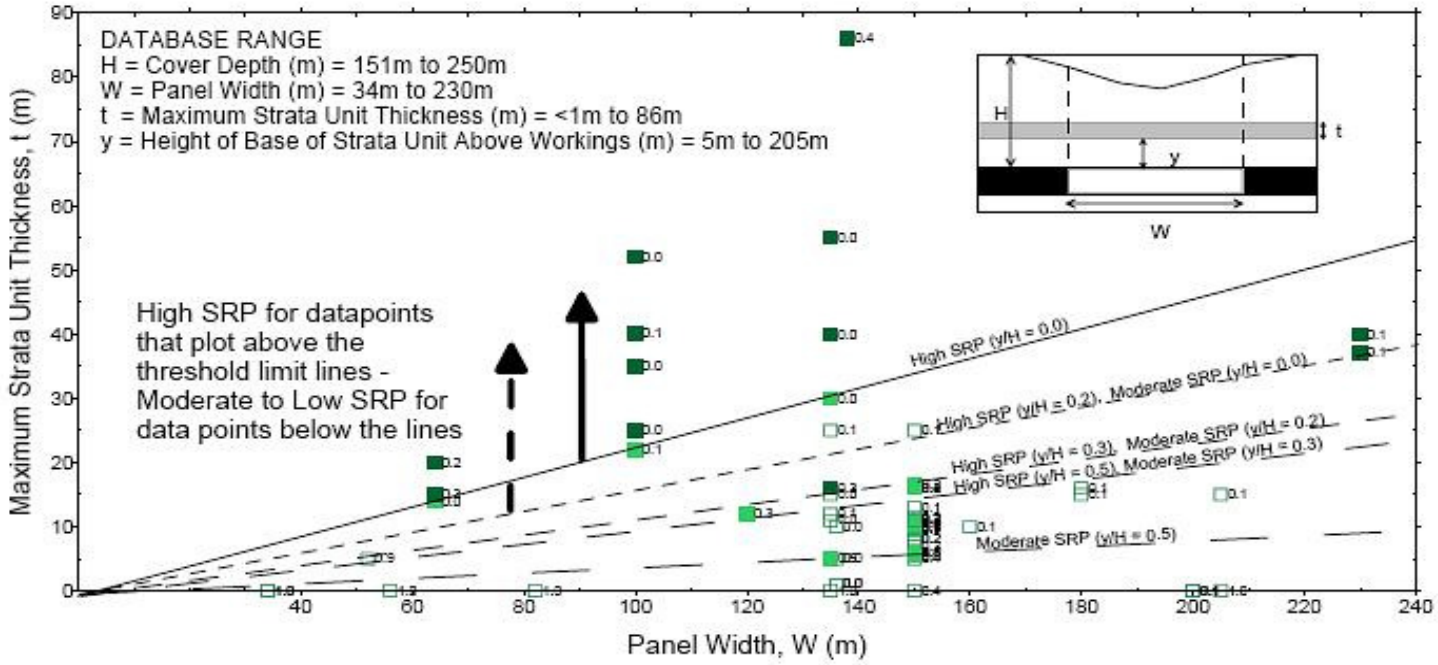
Physical model of caved strata above longwall extraction with strong overburden. Mining data: h = 84m; w = 118m; M = 4m.

439

DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003	
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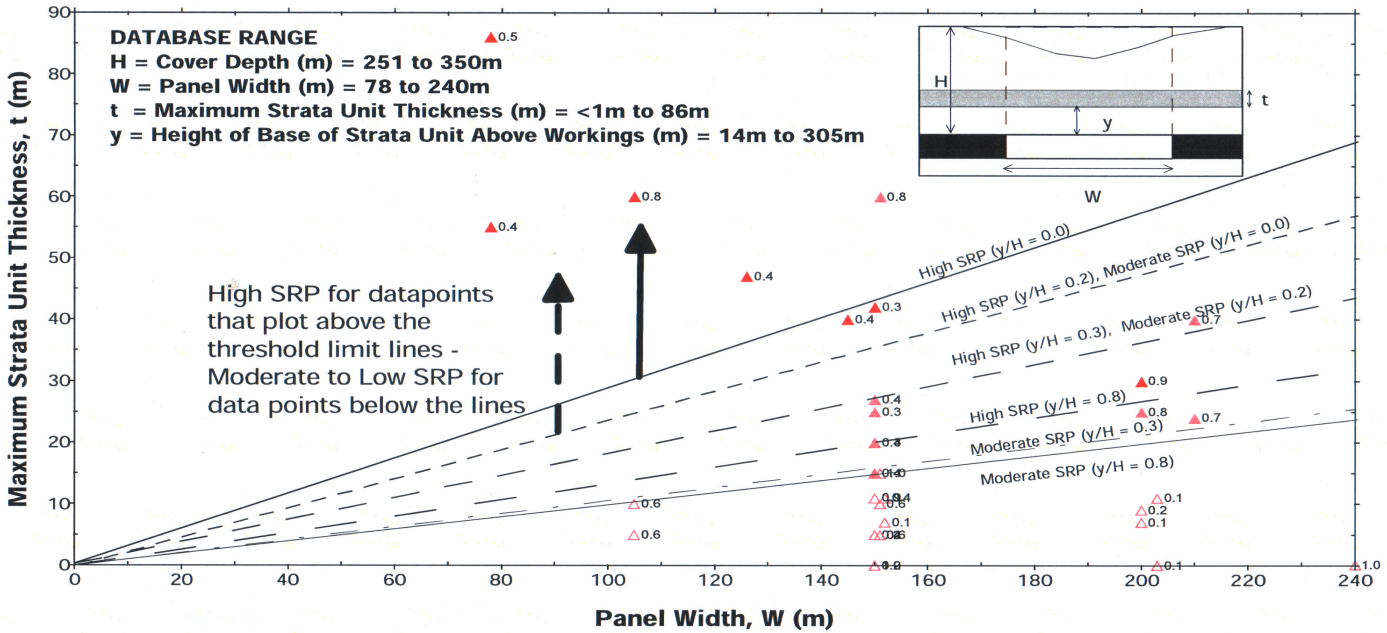


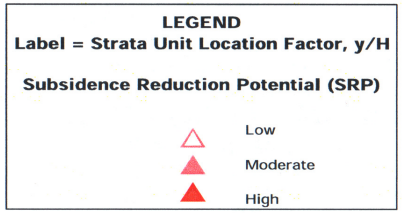
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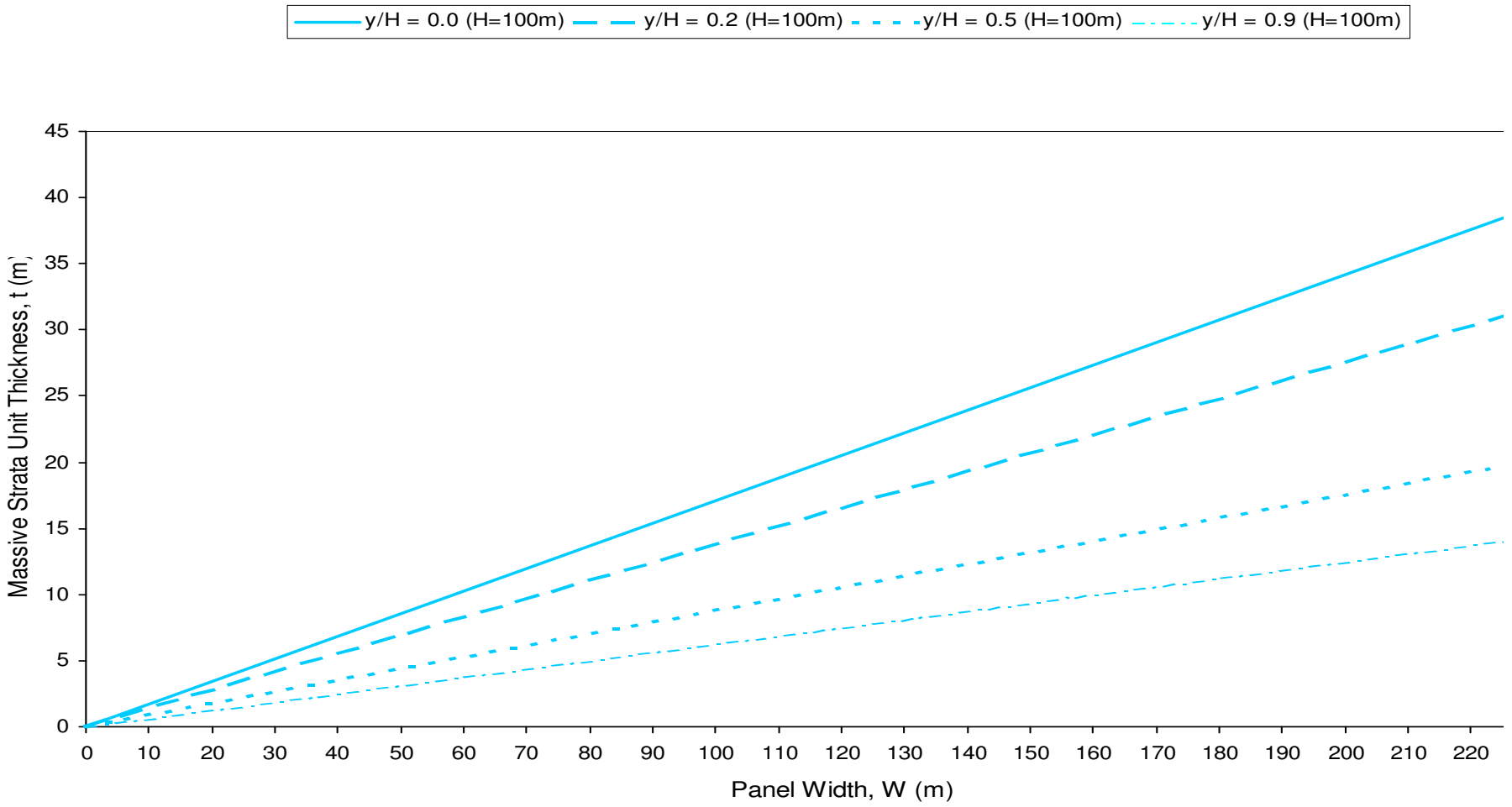


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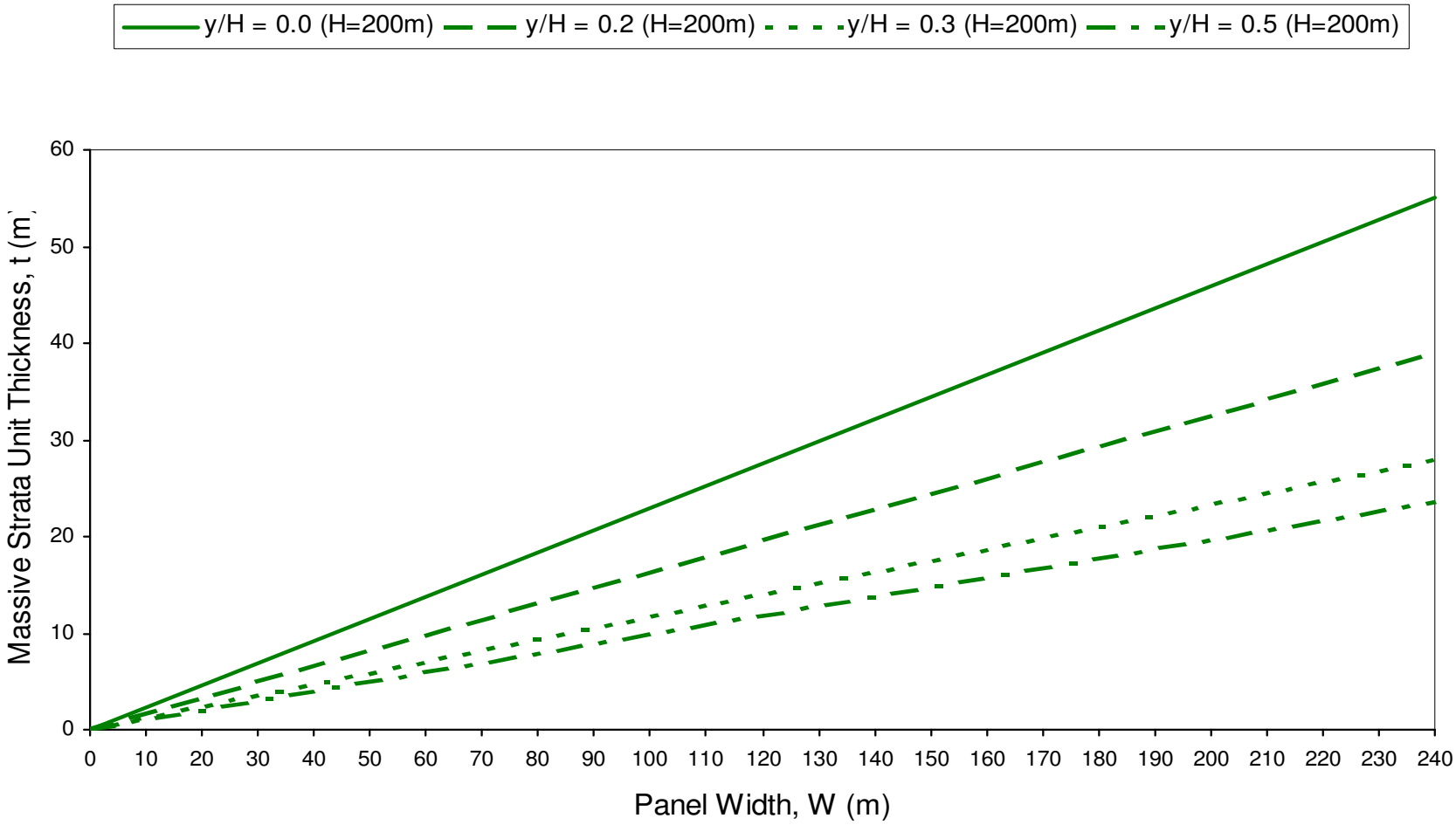




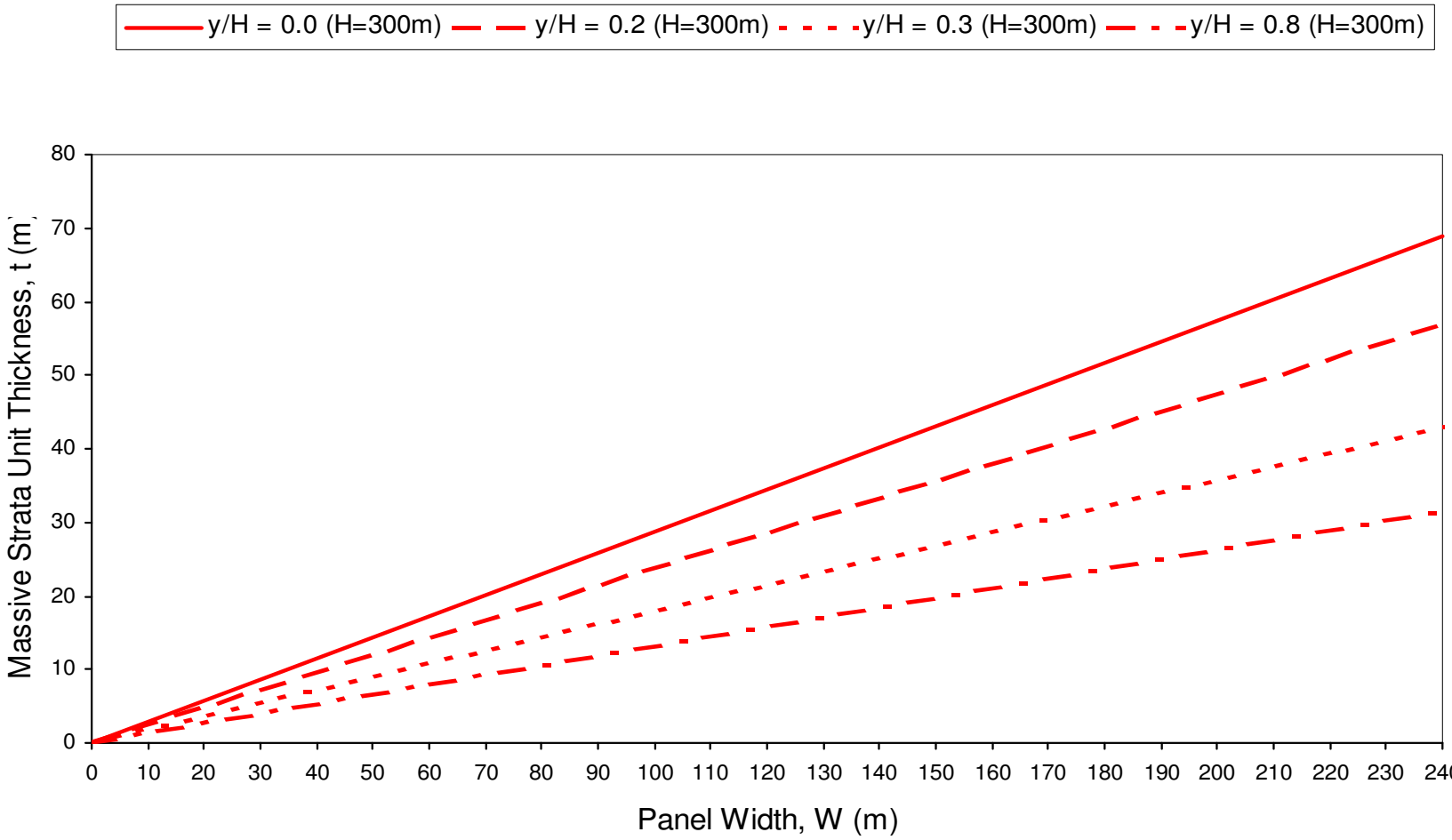
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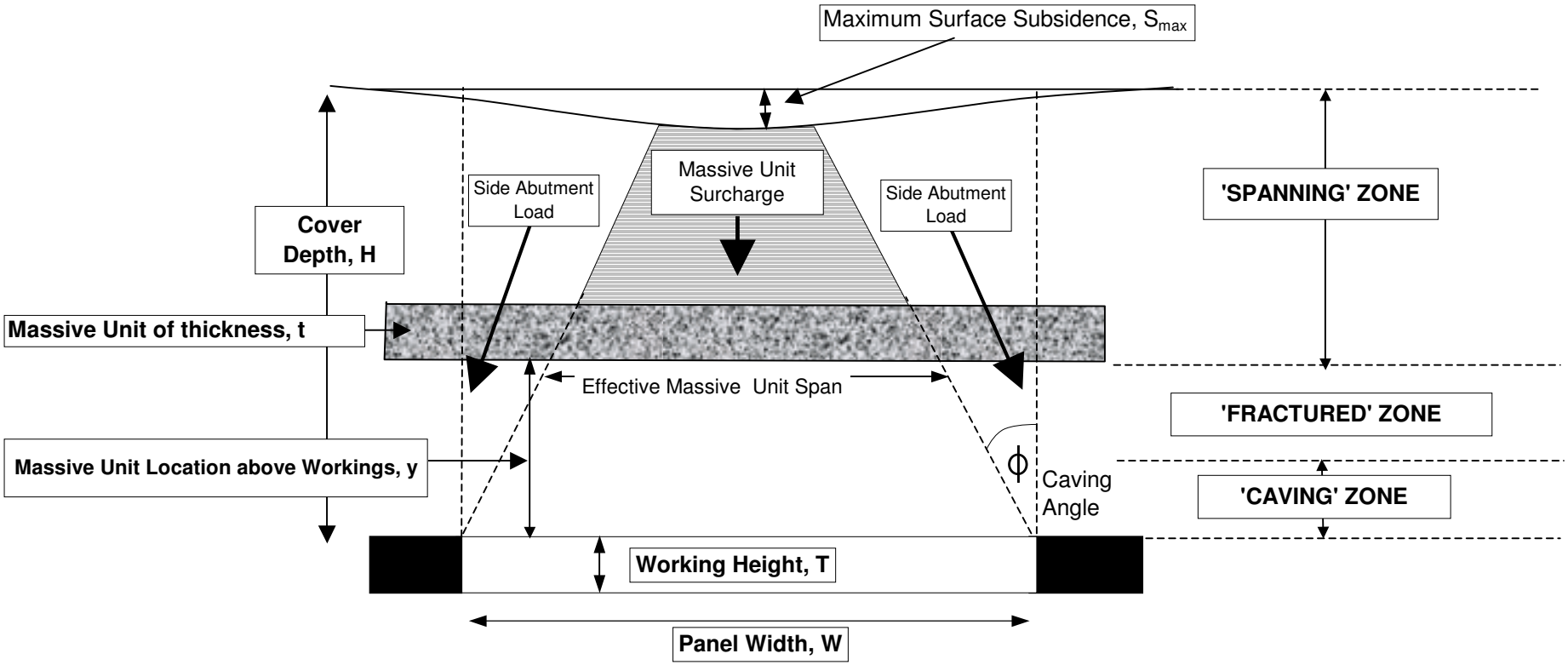
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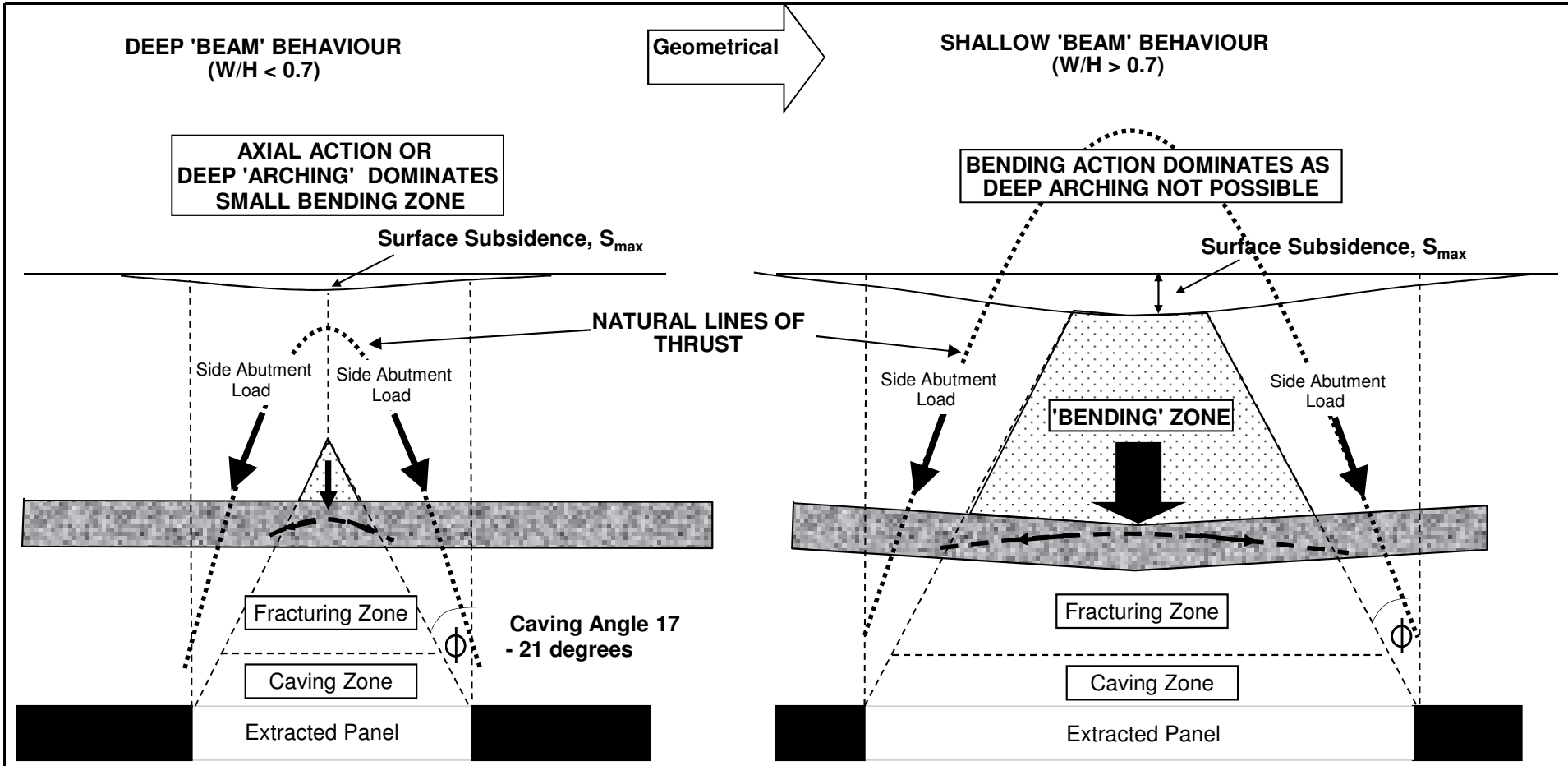
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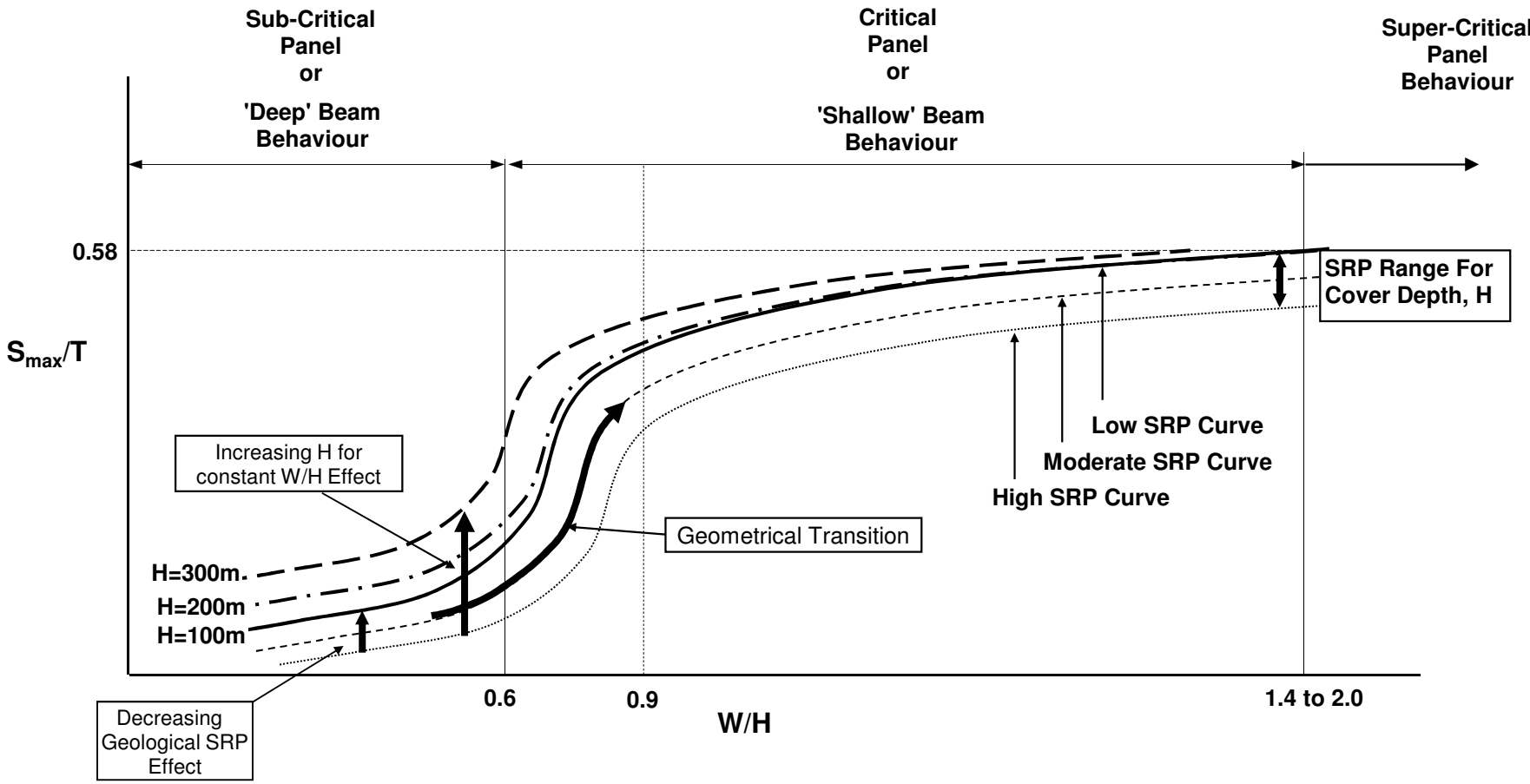
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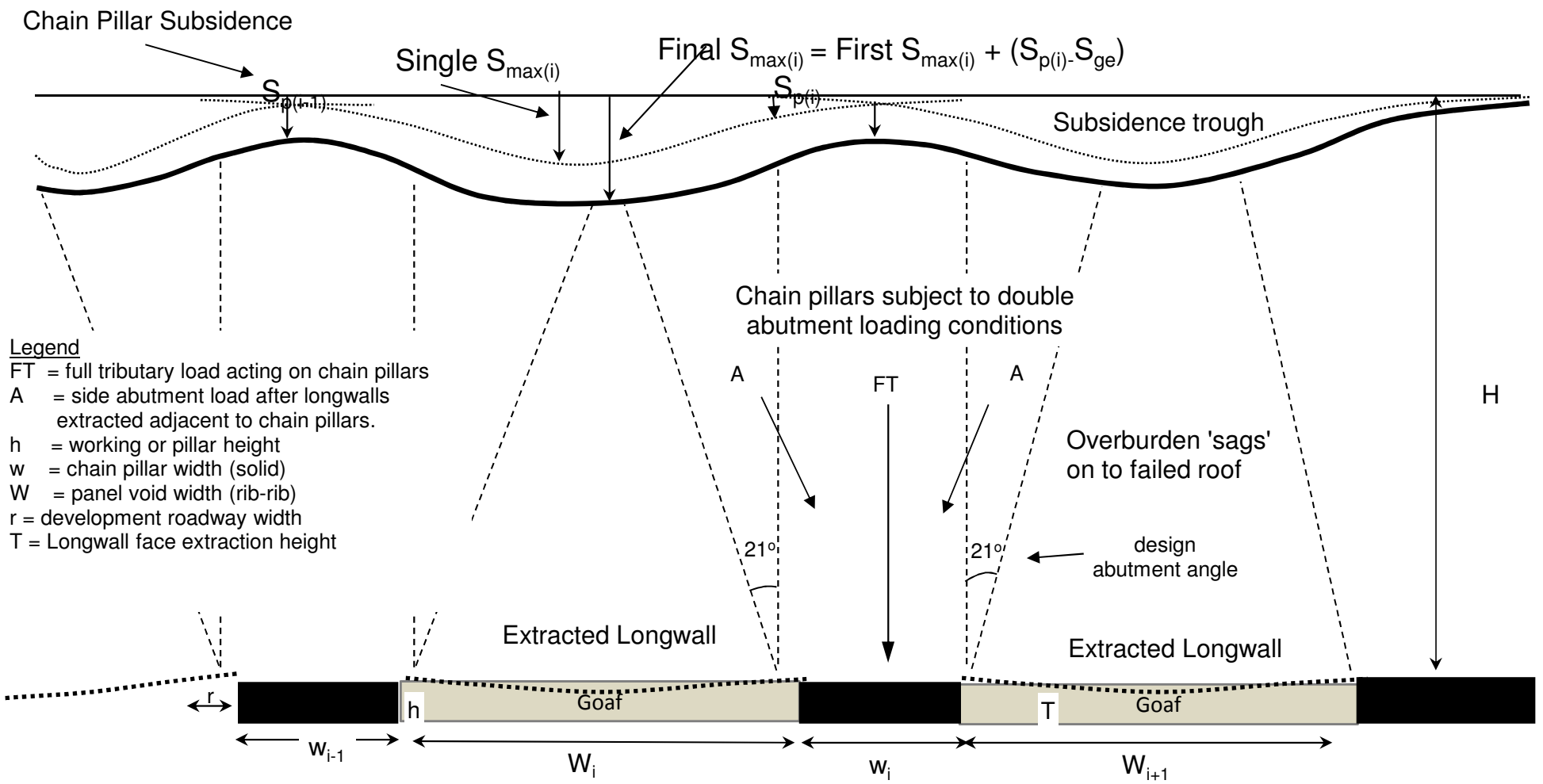
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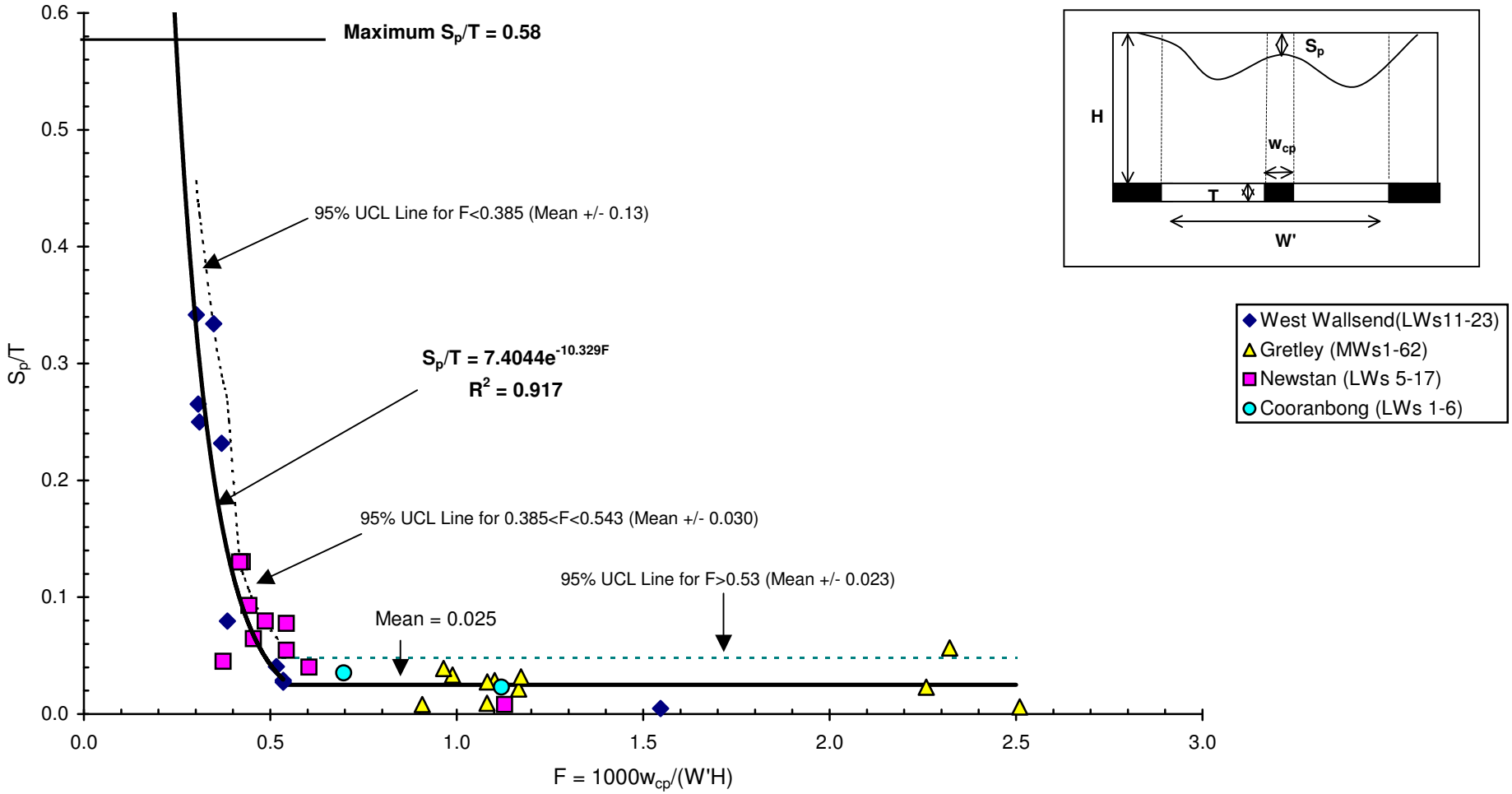
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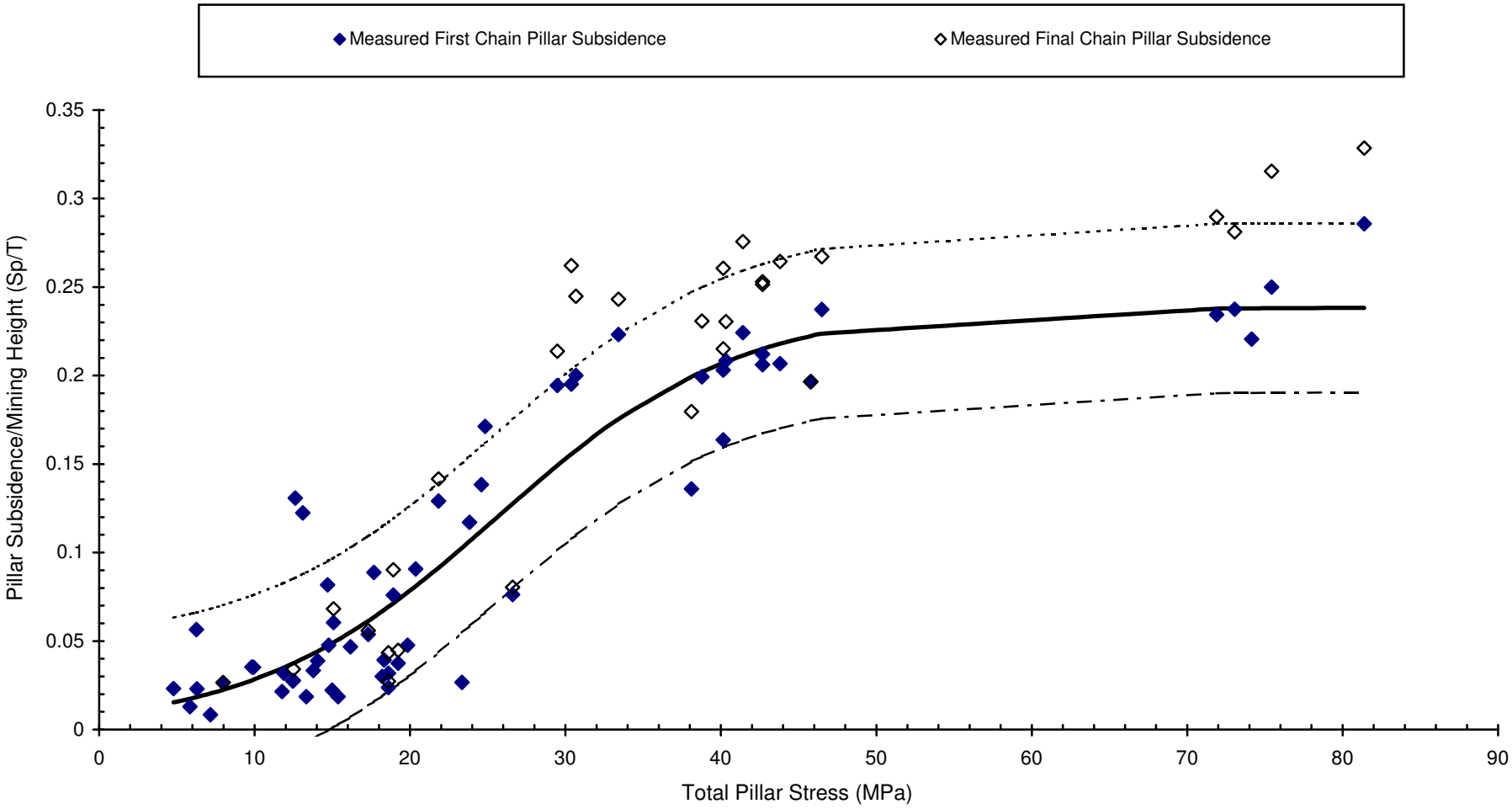
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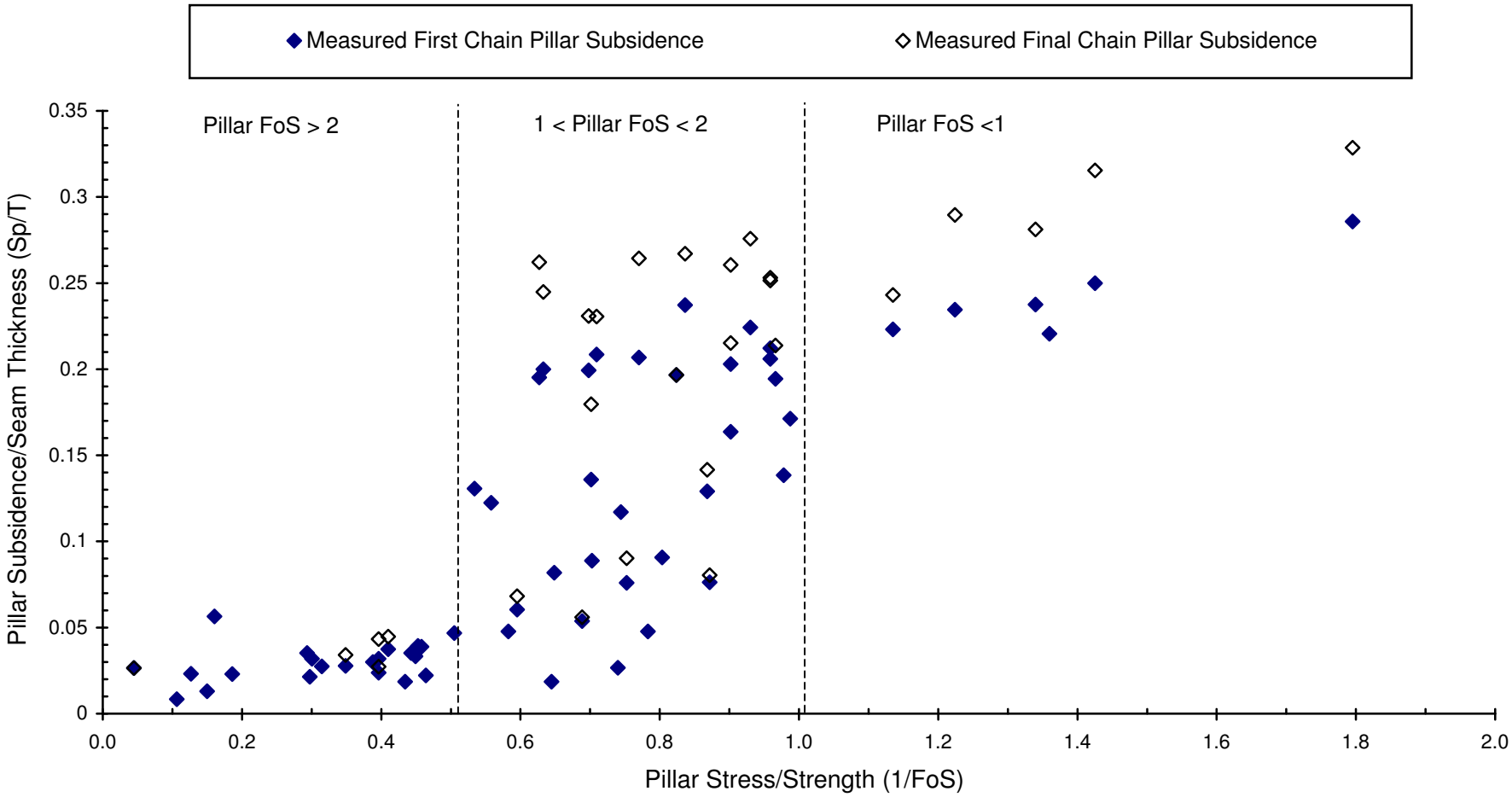
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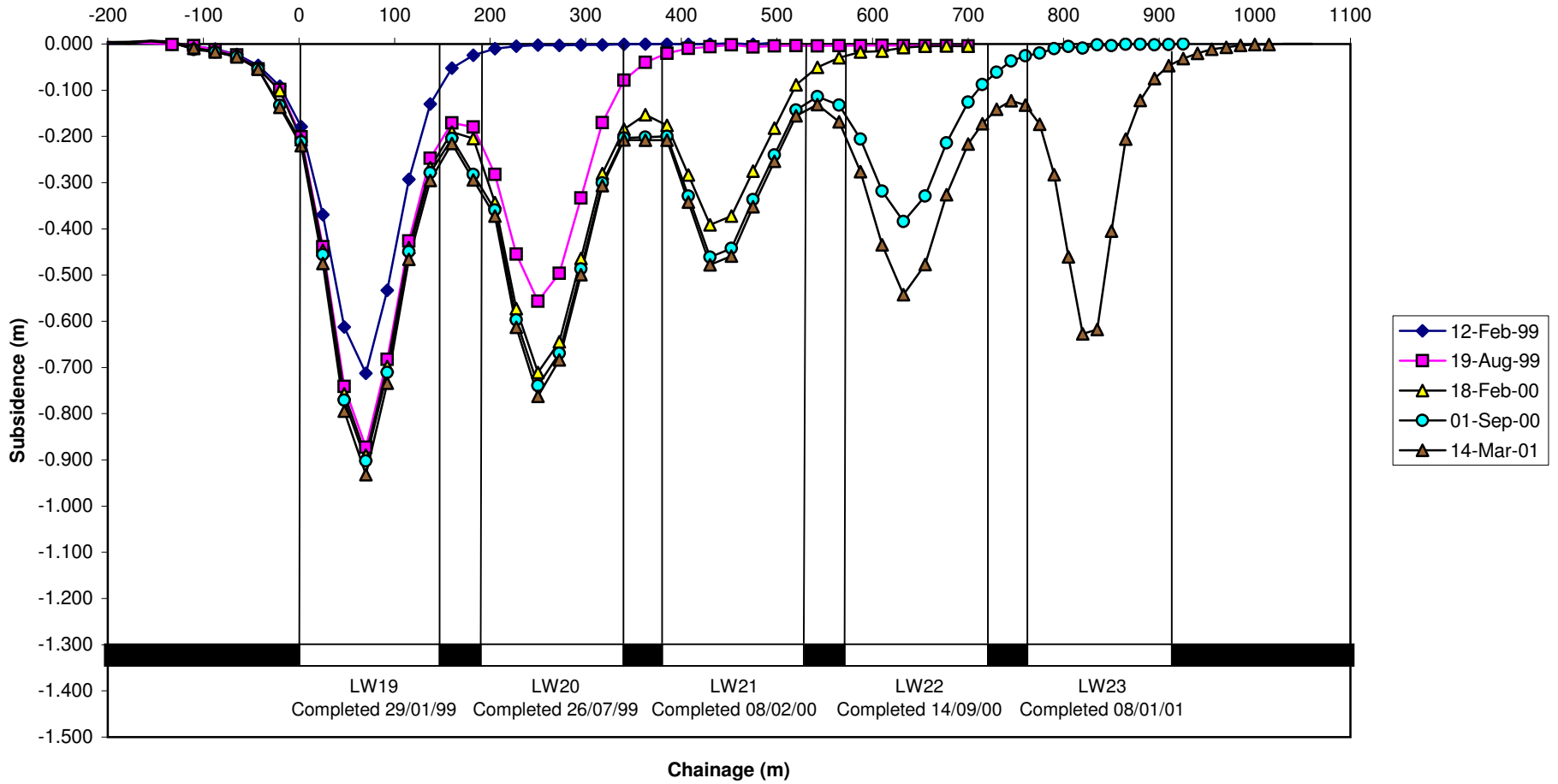
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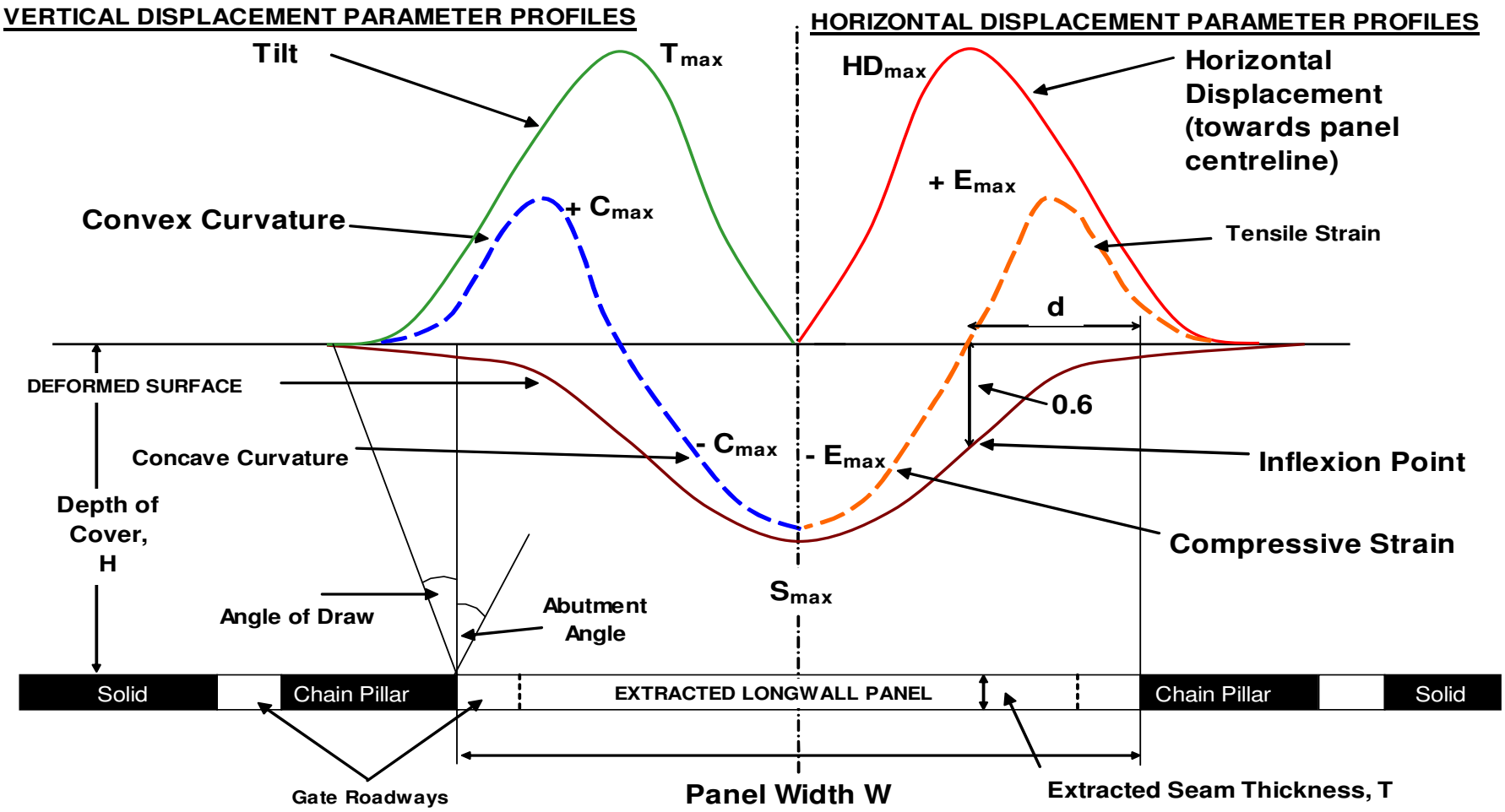
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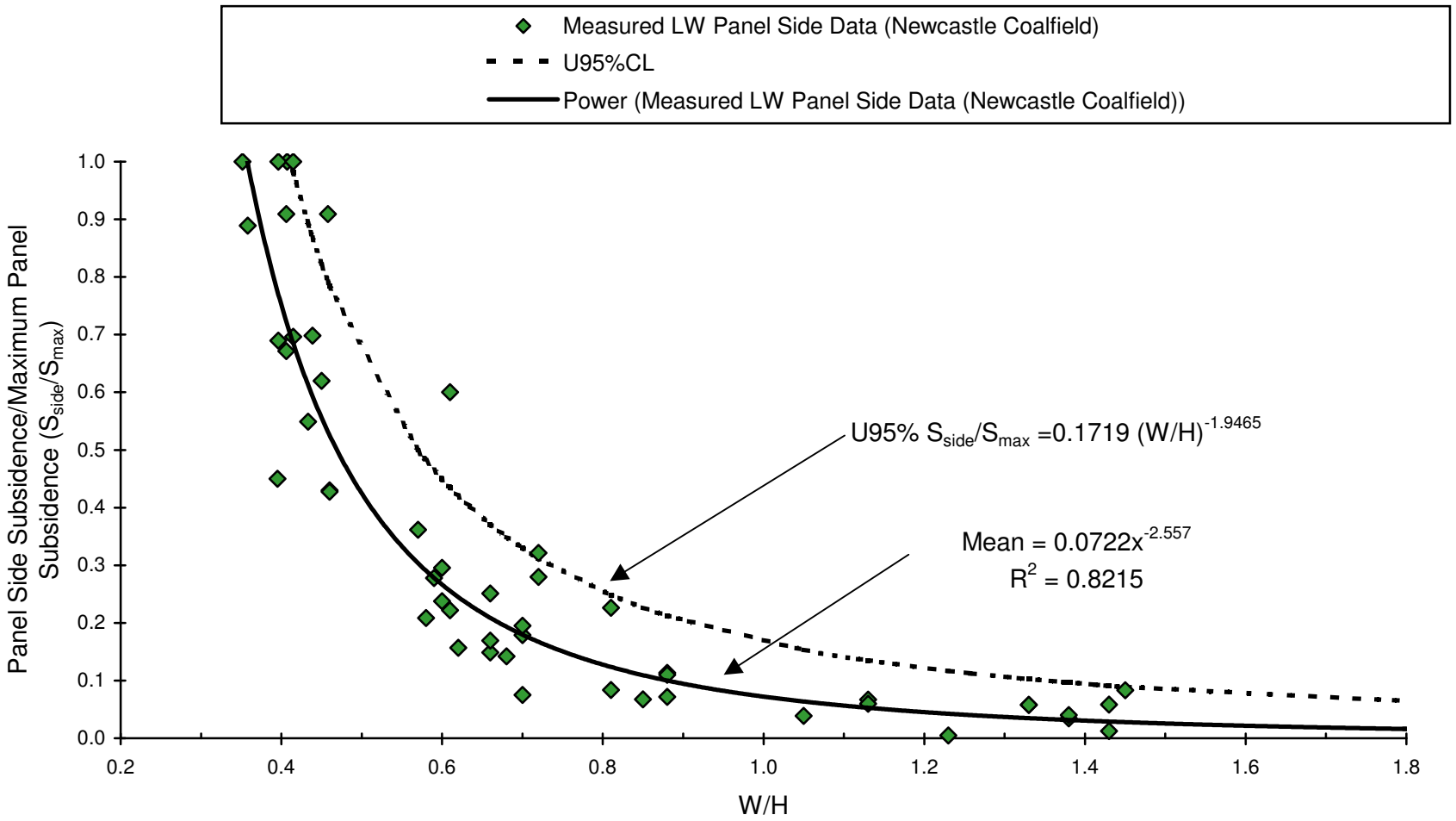
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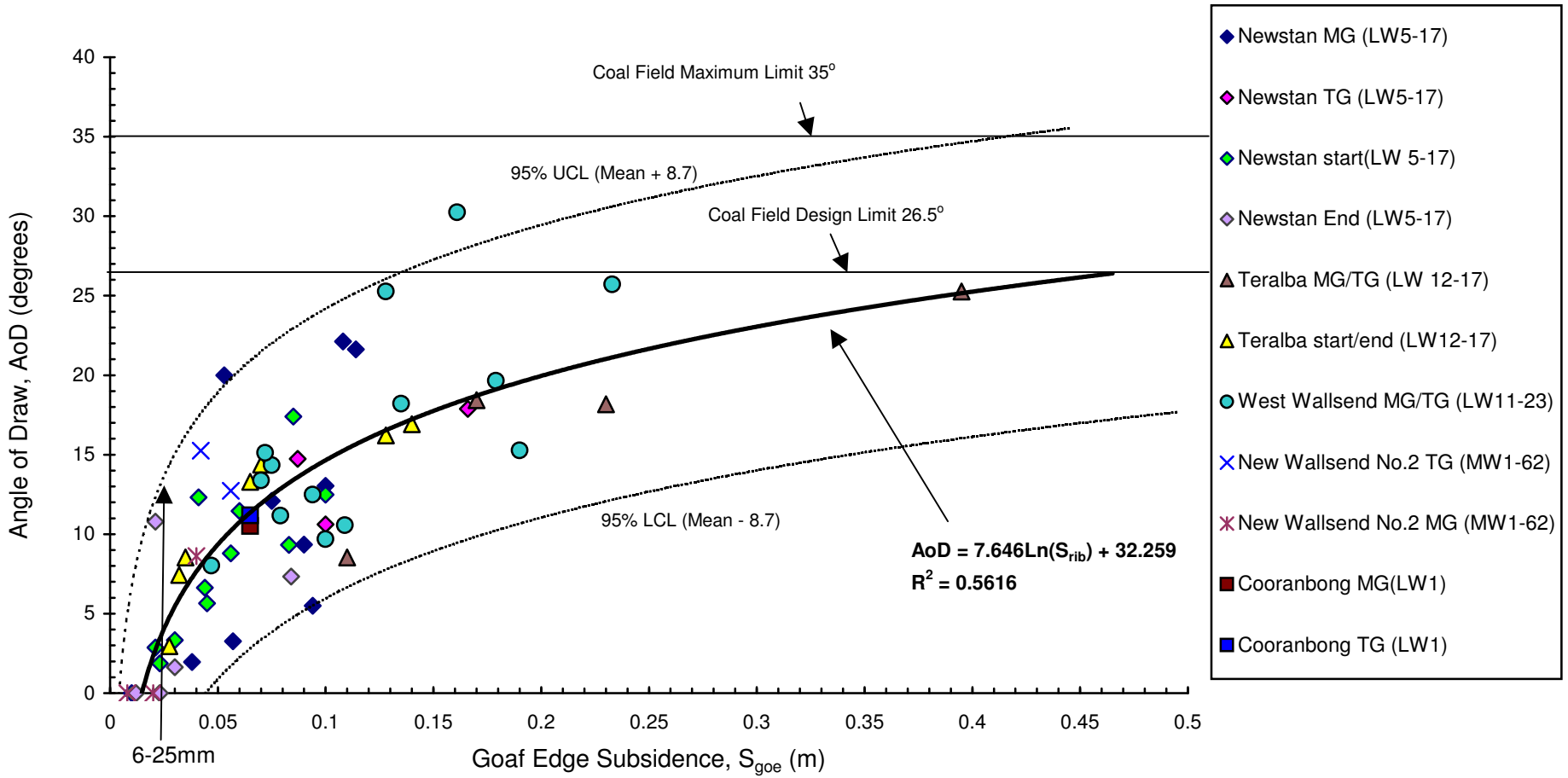
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	Date:	08.08.08	Title:	Measured Multiple Longwall Panel Subsidence in Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A18



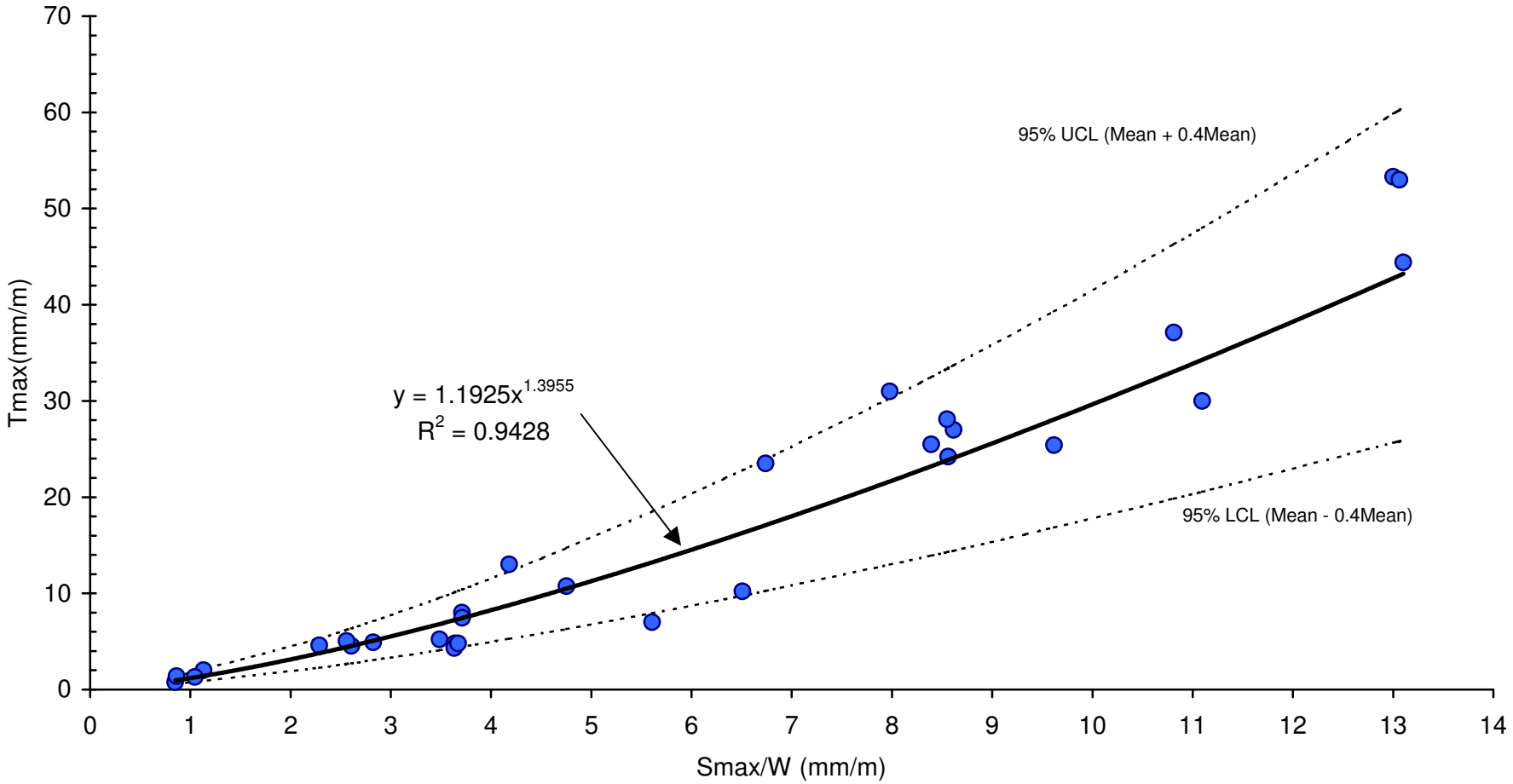
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Mine Subsidence Trough Deformation Parameters (adapted from Holla, 1987)	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A19



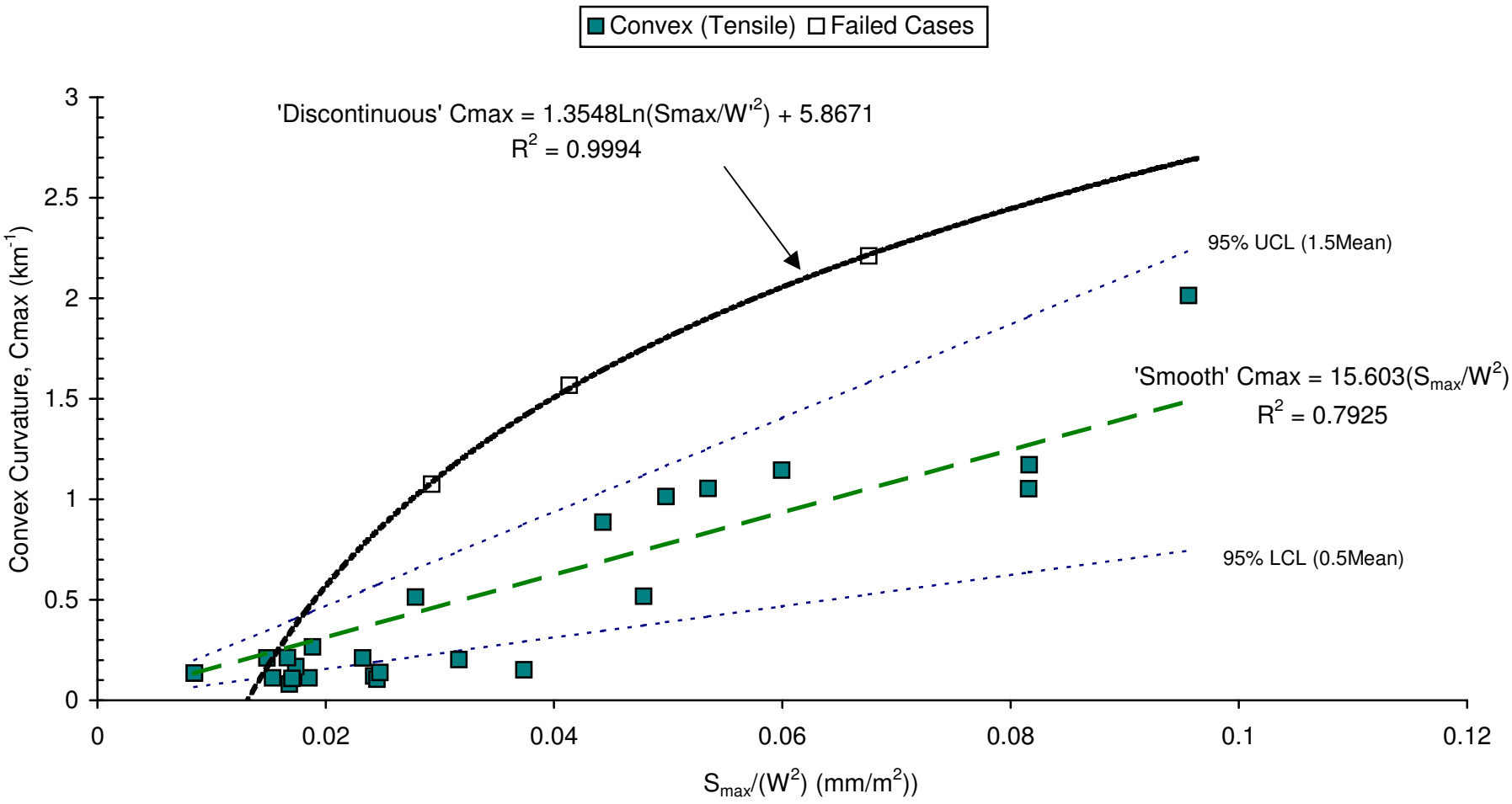
DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Goaf Edge Subsidence Prediction Above Longwall Panels	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A20



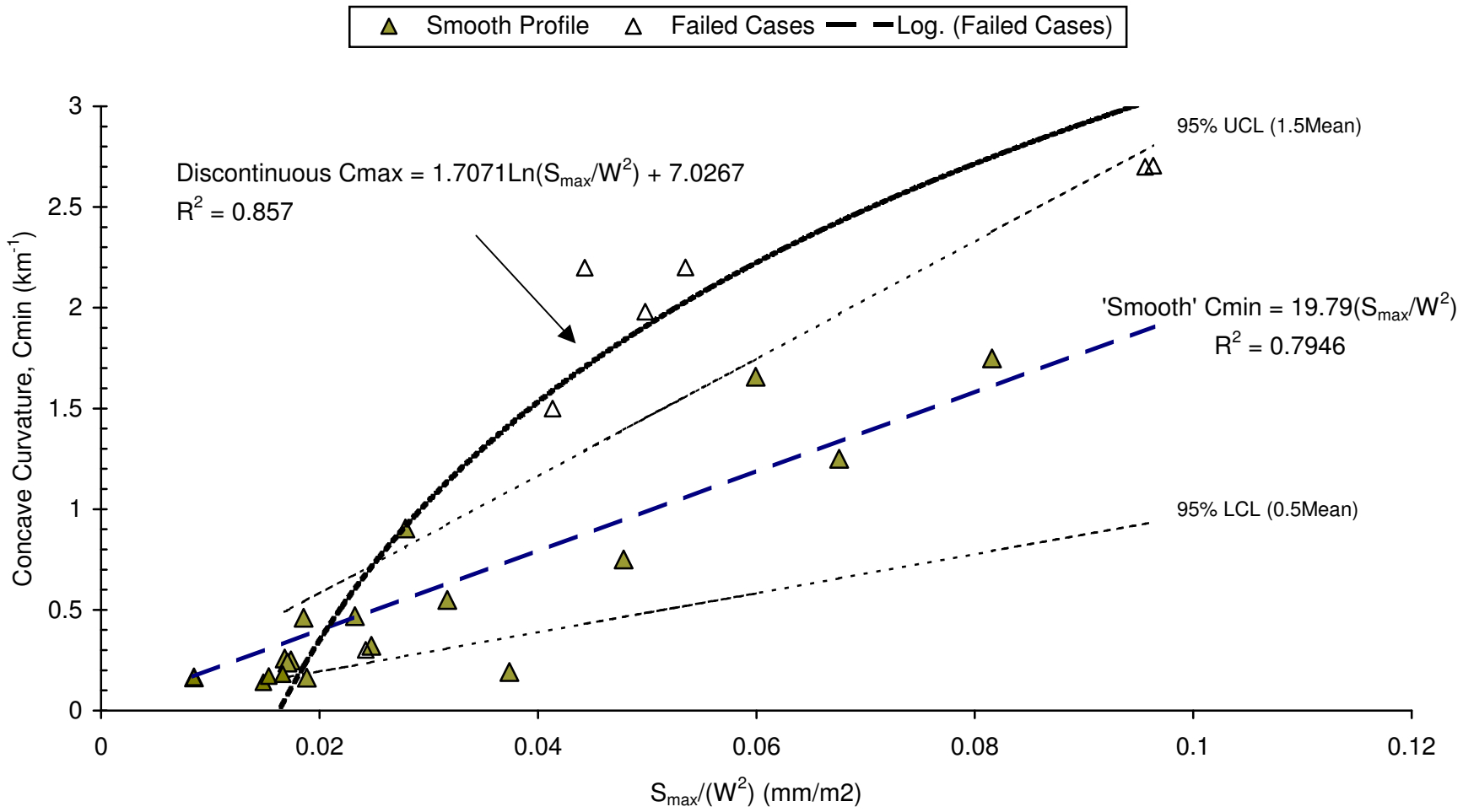
DgS	Engineer:	S.Ditton	Client:	Extracted from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Prediction Model for Longwall Panel Angle of Draw	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A21



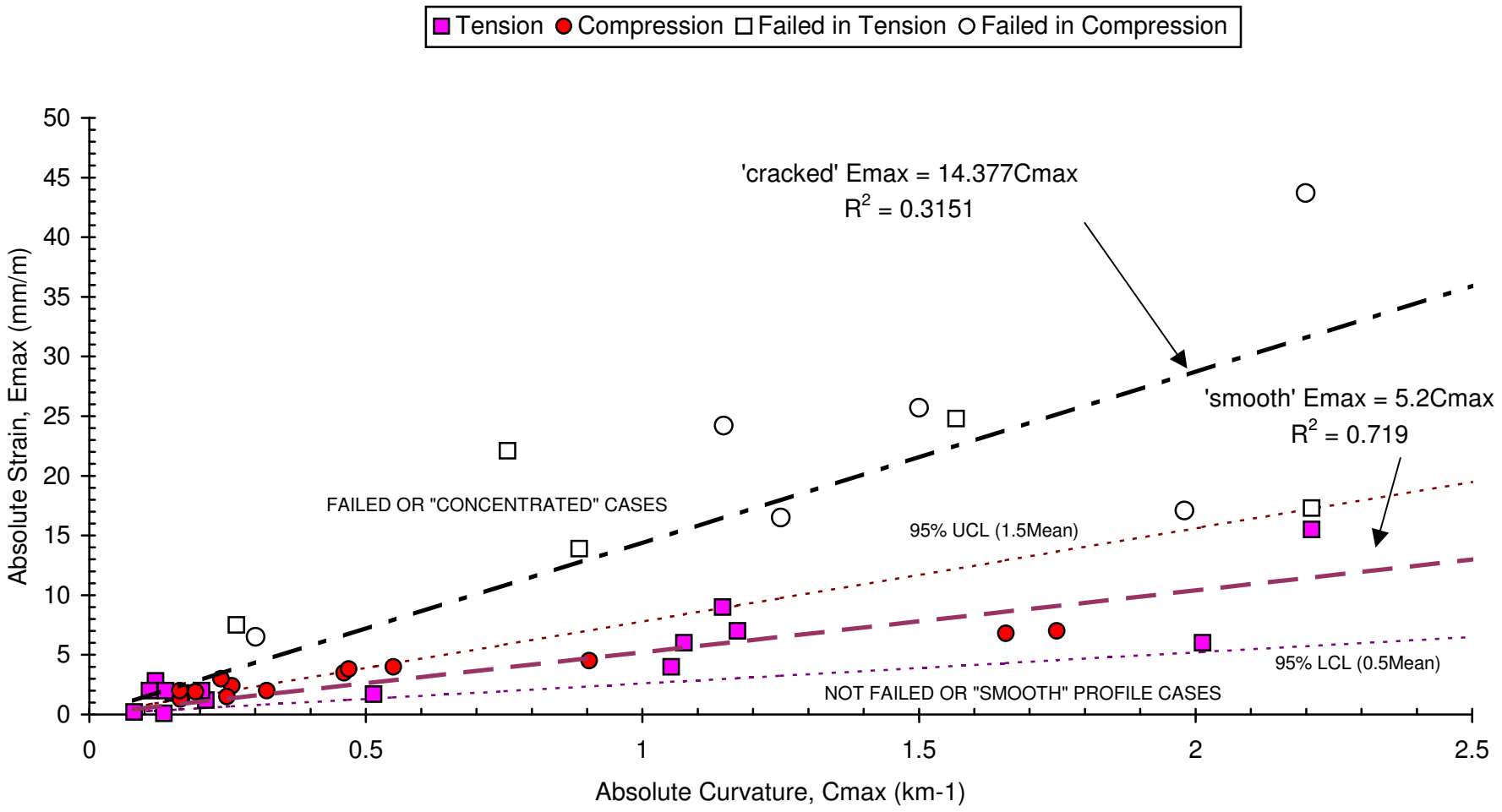
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Tilt Prediction Above Longwall Panels	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A22



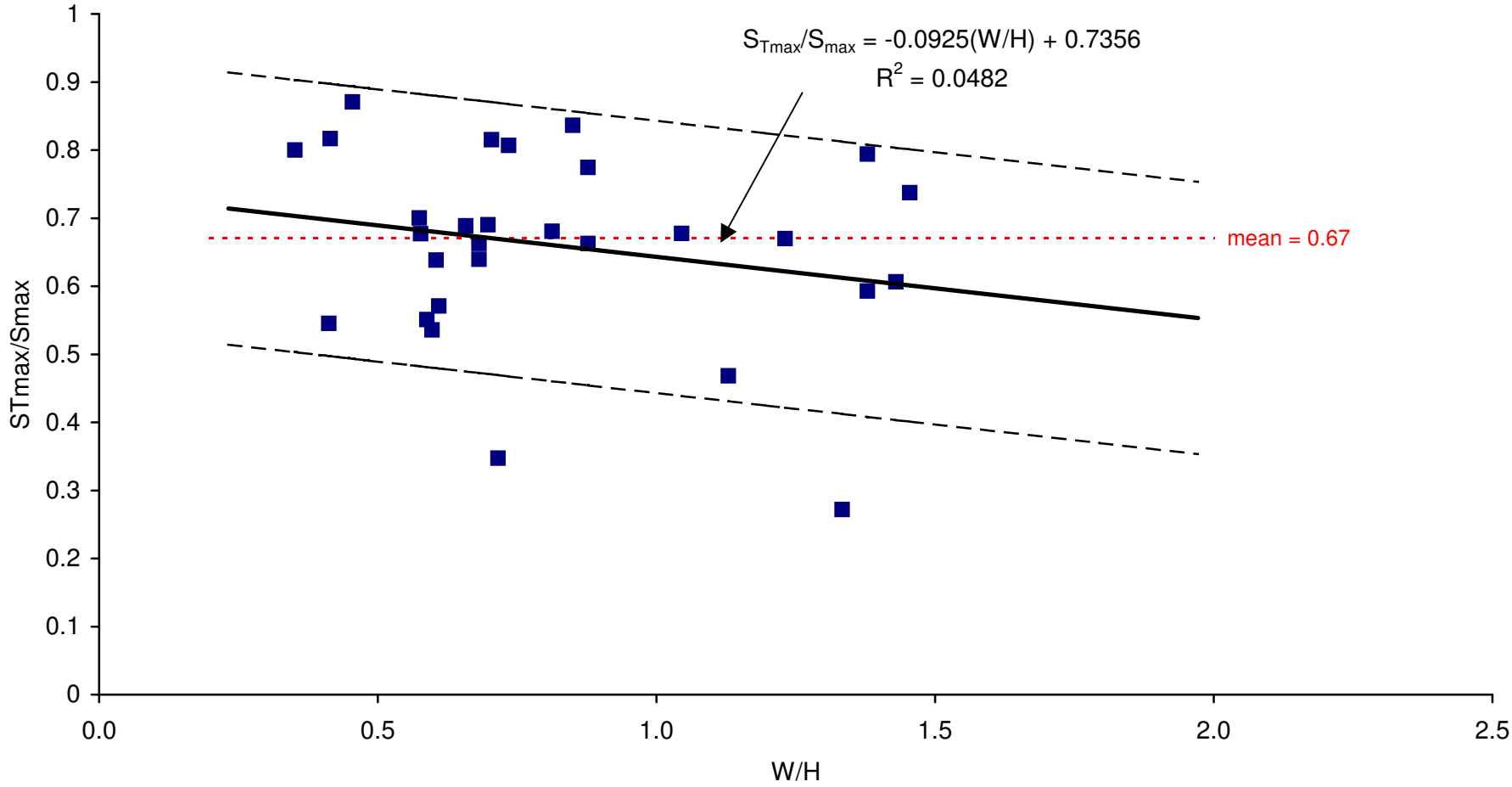
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Convex Curvature Prediction Above Longwall Panels for Smooth and Discontinuous Profiles	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A23



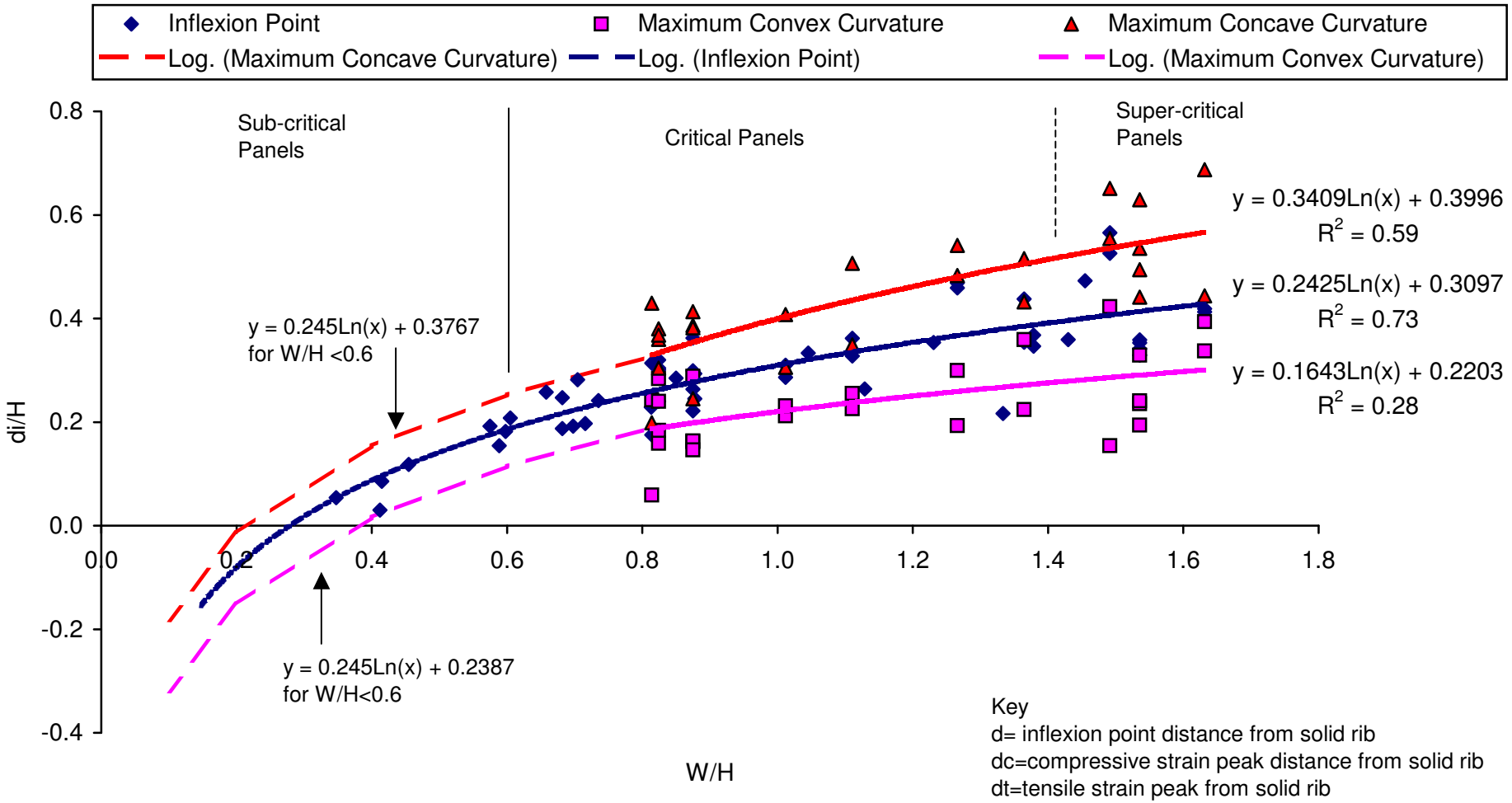
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Concave Curvature Prediction Above Longwall Panels for Smooth and Discontinuous Profiles	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A24



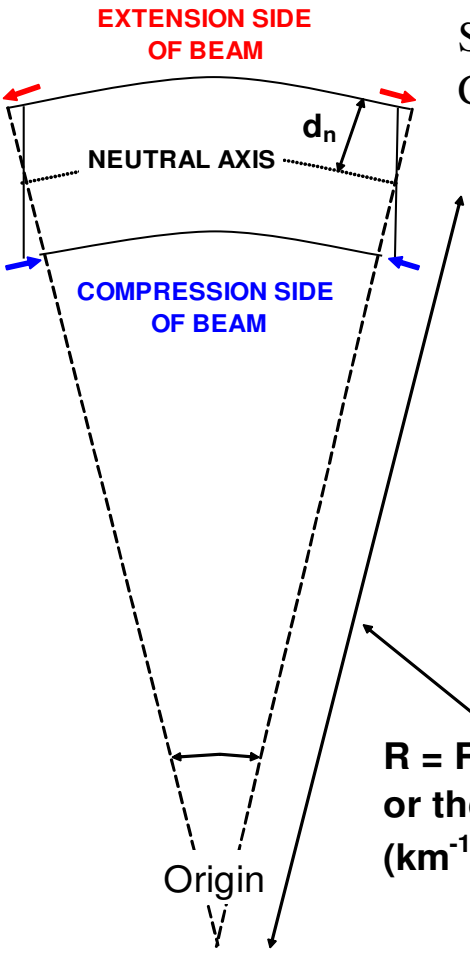
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Strain Prediction Above Longwall Panels for Smooth and Cracked Profiles	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A25



DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Subsidence at Maximum Tilt Above Longwall Panels	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A26



DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Predicting the Location of Inflexion Point, Maximum Tensile and Compressive Strain Peaks due to Longwall Panel Subsidence in the Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A27



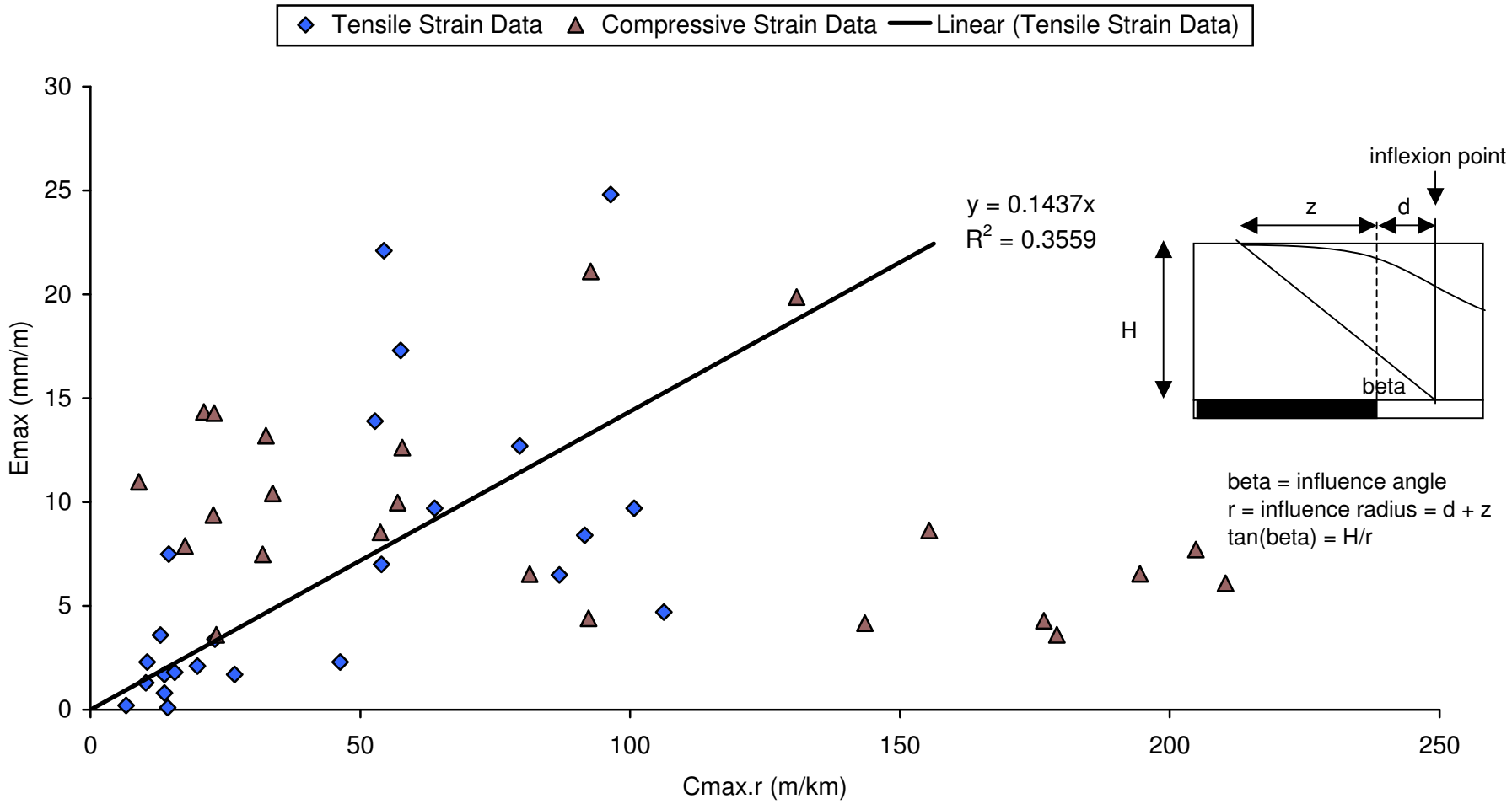
Strain E = (mm/m)
Curvature C = km-1

E = C x dn

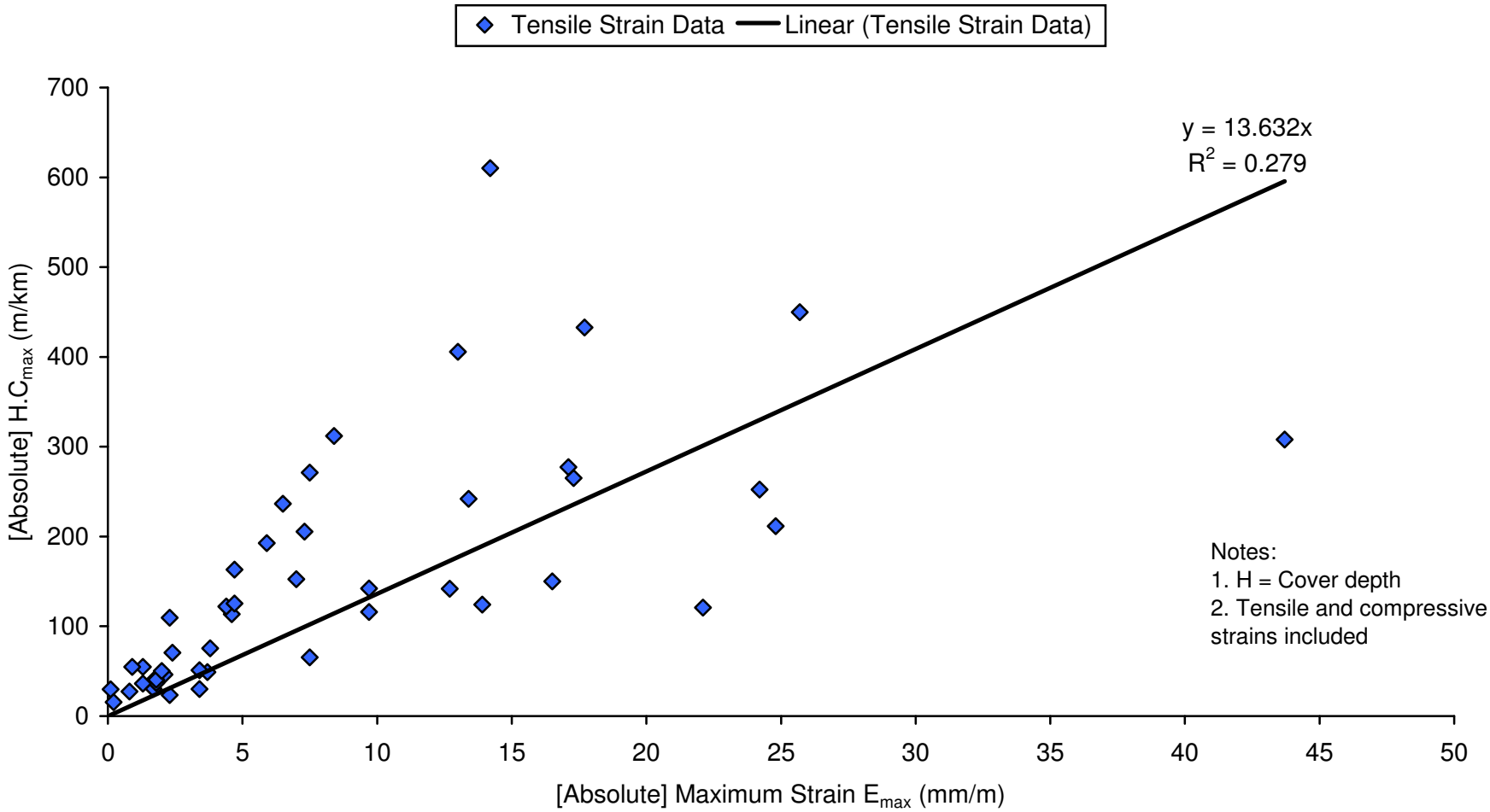
Average
dn = 5.2 m
for database

R = Radius of curvature or the curvature, C = 1/R (km^{-1})

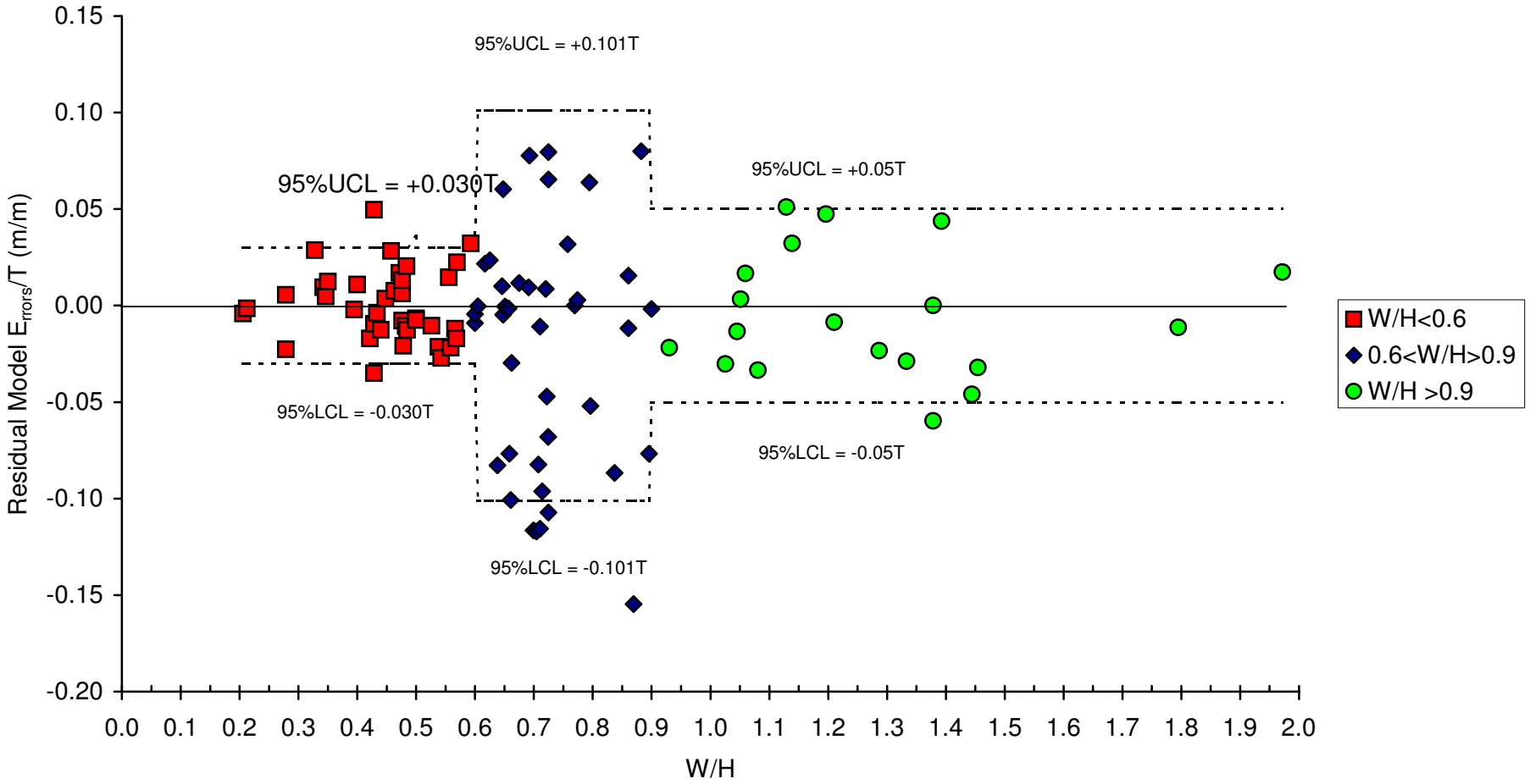
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Bending Beam Theory for Strain Prediction from Curvature Measurements	
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No: A28



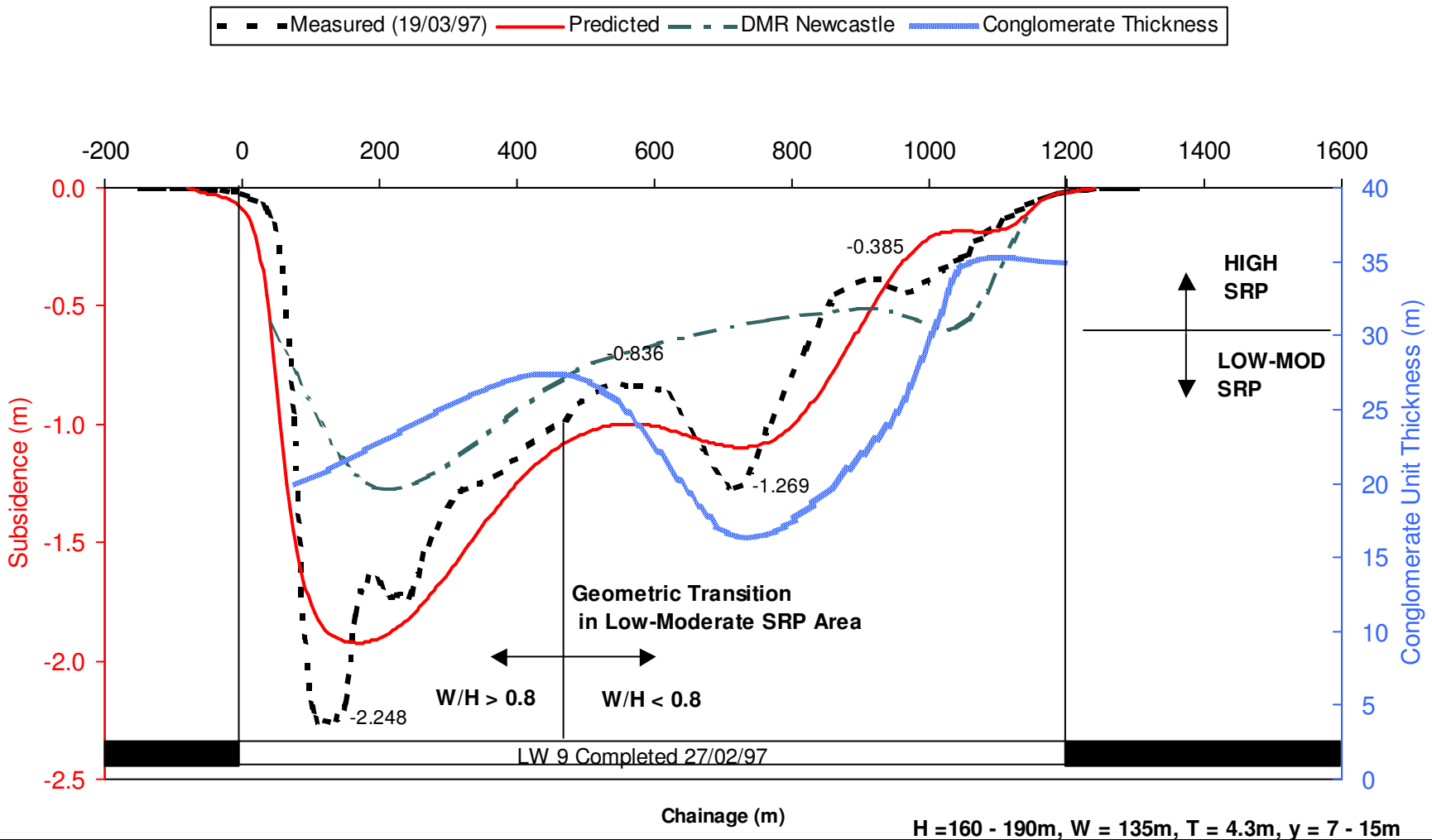
DgS	Engineer:	S.Ditton	Client:	Karmis, 1987 Adapted for ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model Recommended by Karmis et al, 1987 for Predicting Strain from Curvature Above Longwall Panels in Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A29.1



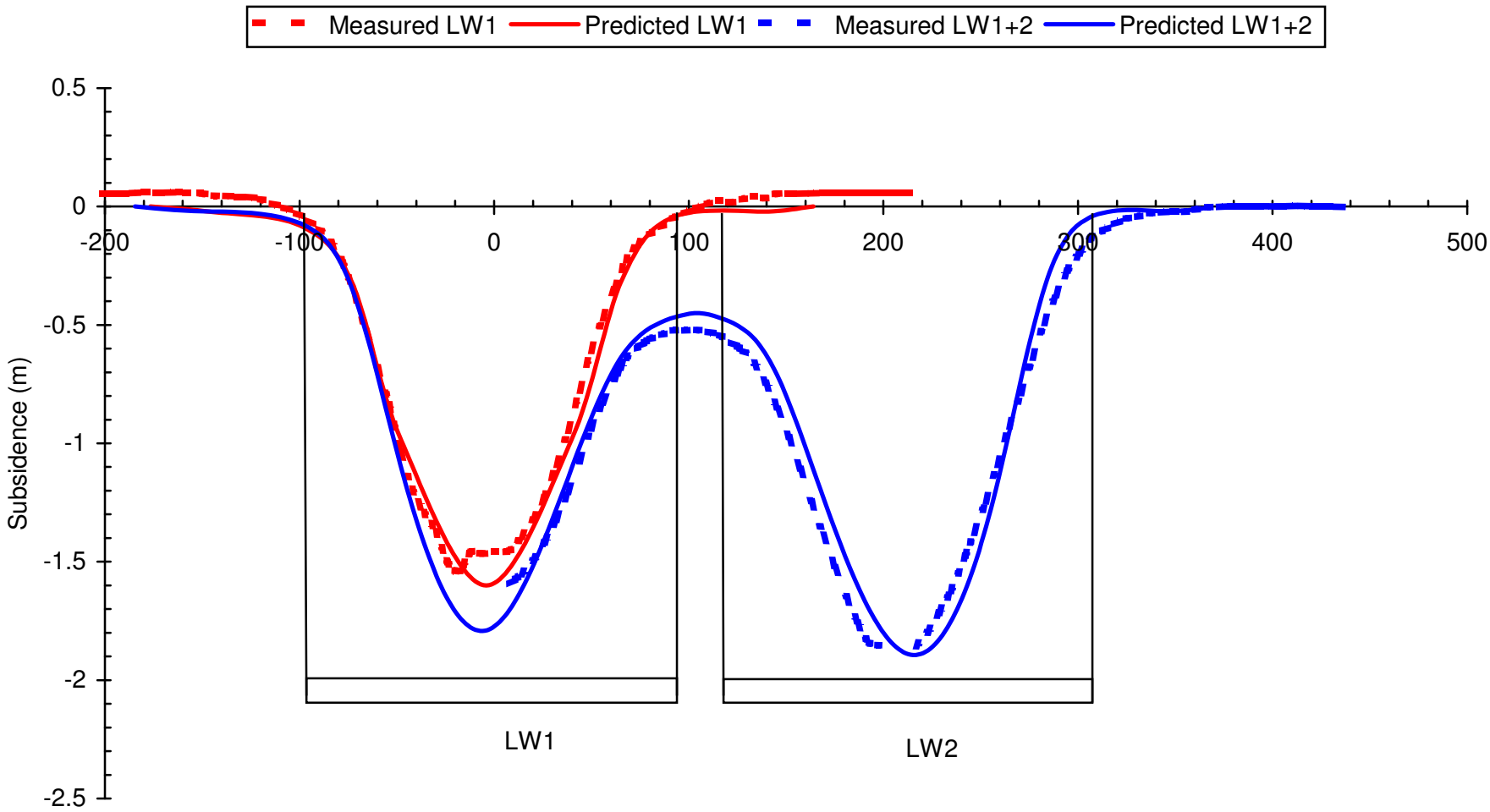
DgS	Engineer:	S.Ditton	Client:	Holla and Barclay, 2000 Adapted for ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model Recommended by Holla and Barclay, 2000 for Predicting Curvature from Maximum Strain Above Longwall Panels in the Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A29.2



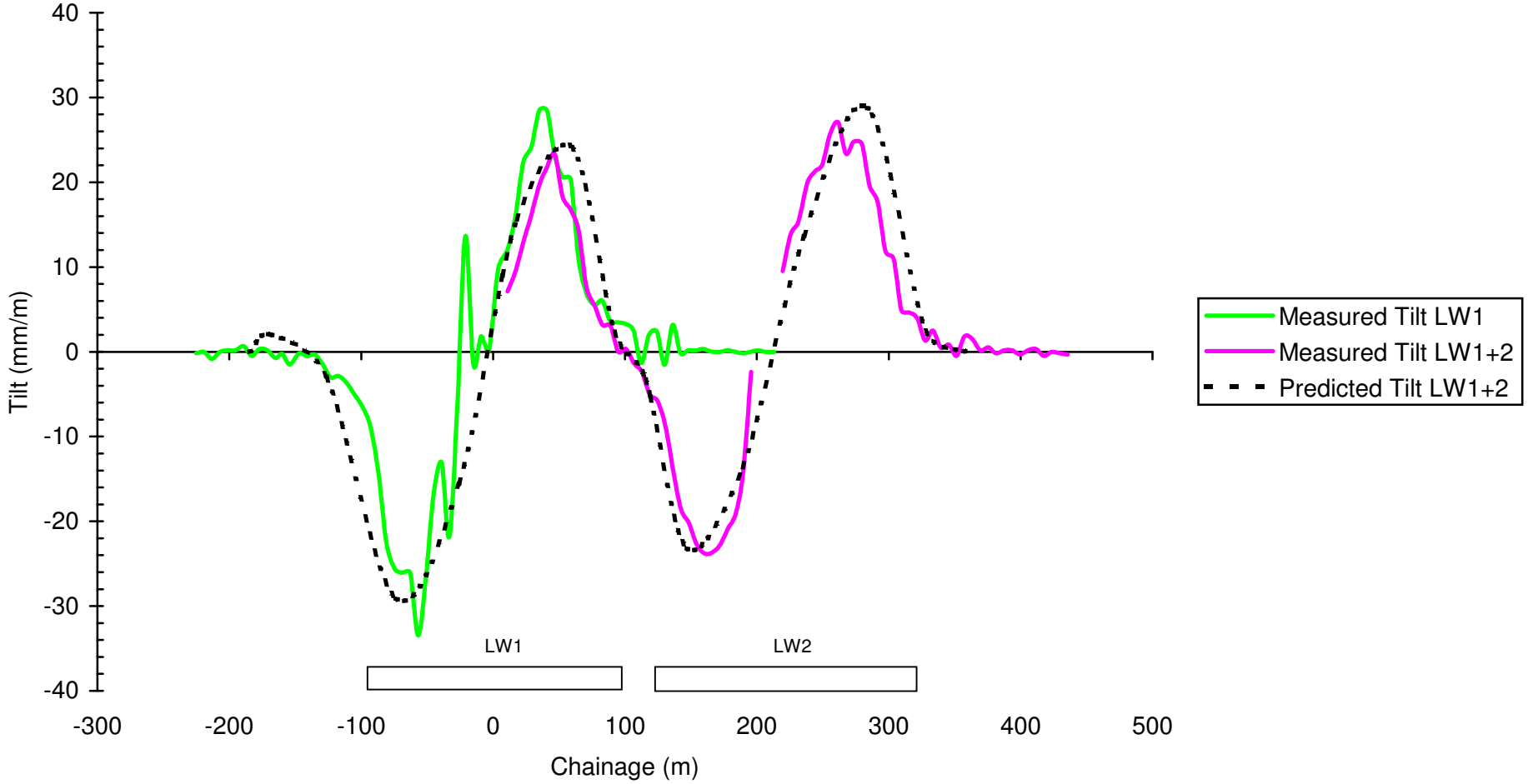
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Residual Errors of Database for Single Panel Prediction Model above Longwalls in the Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A30



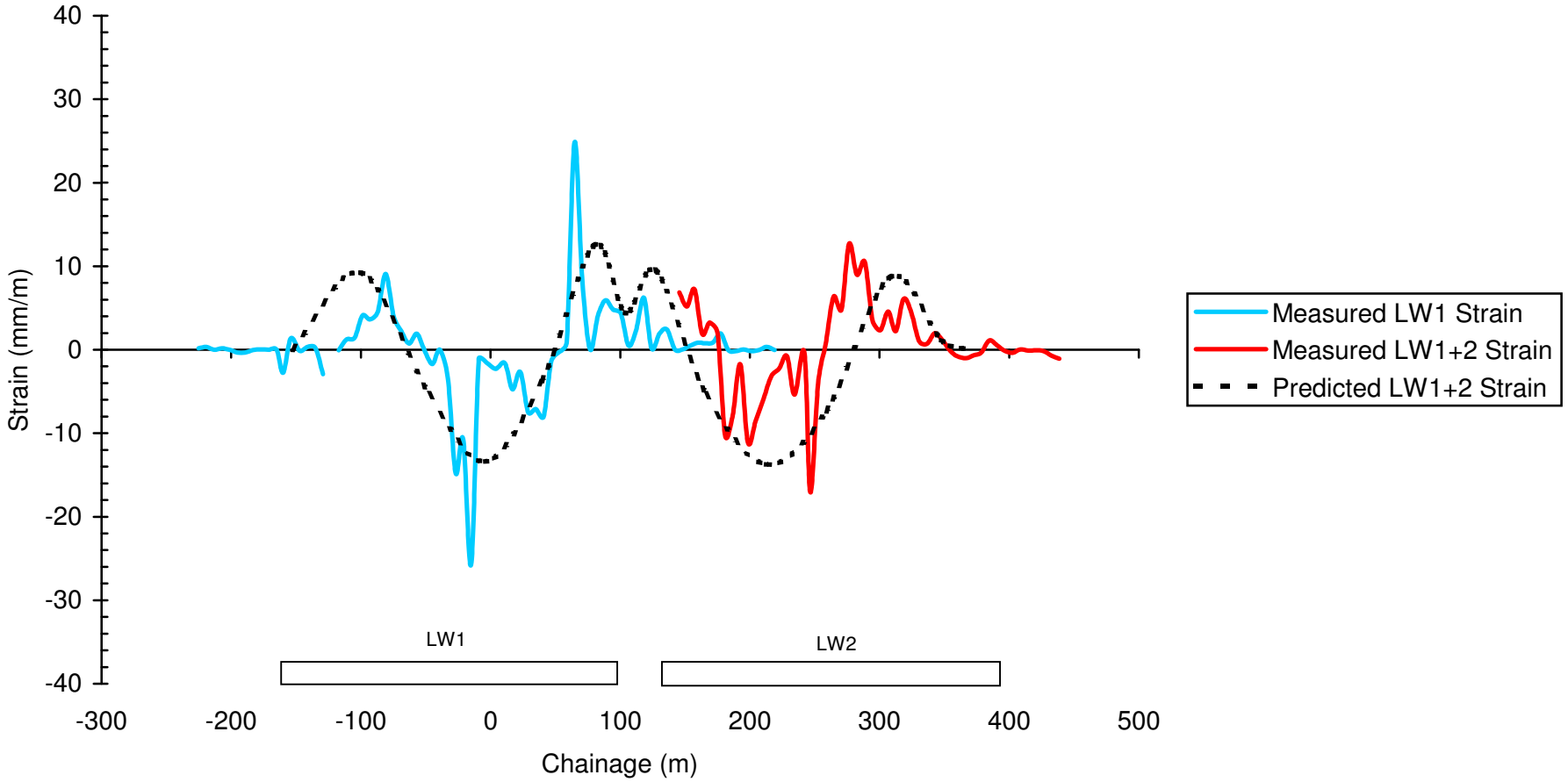
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Predicted v. Measured Centreline Subsidence Profiles for a Newcastle Coalfield Longwall with Massive Conglomerate Strata and Sub-Critical to Supercritical Transition	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A31



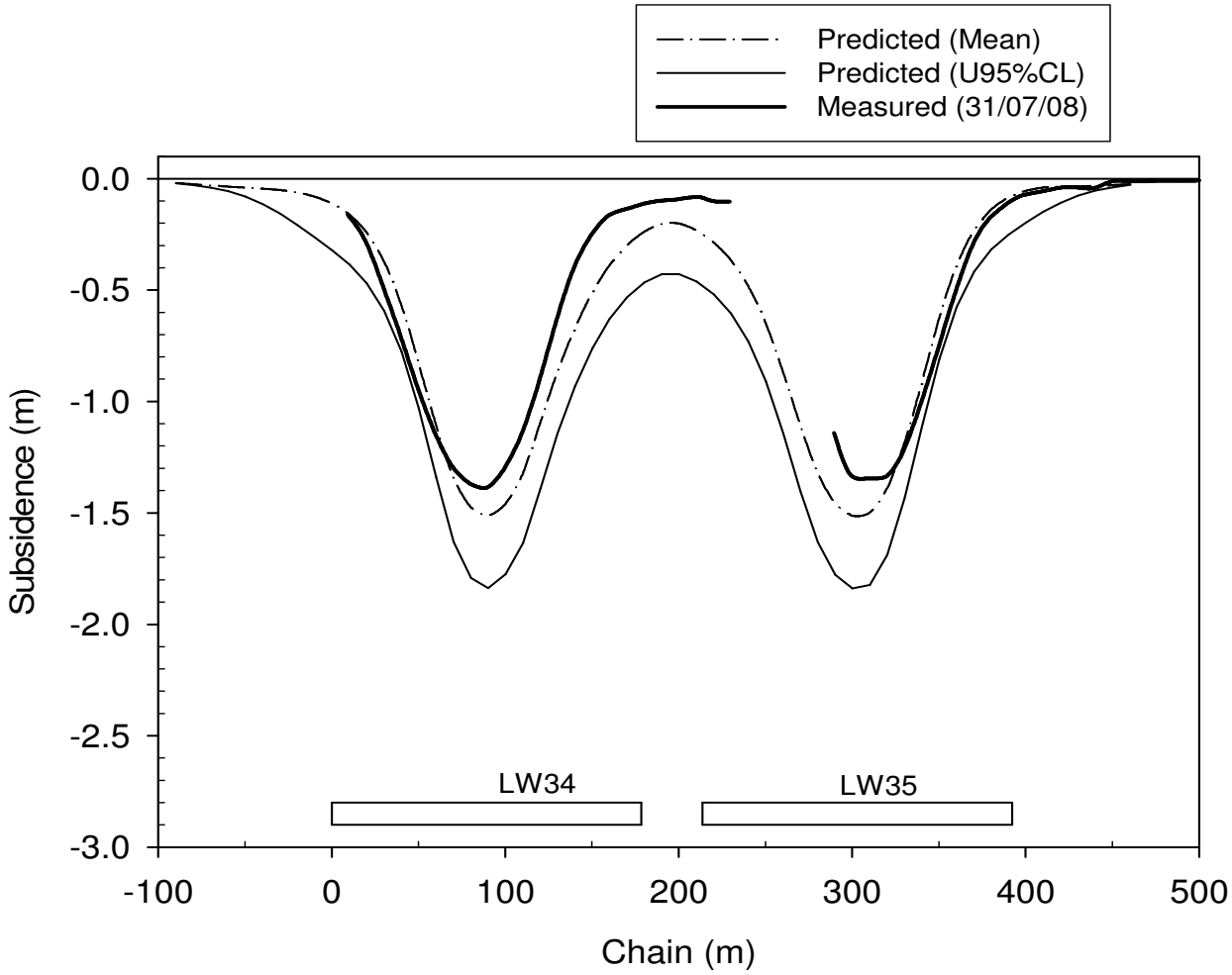
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Predicted v. Measured Crossline Subsidence Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A32



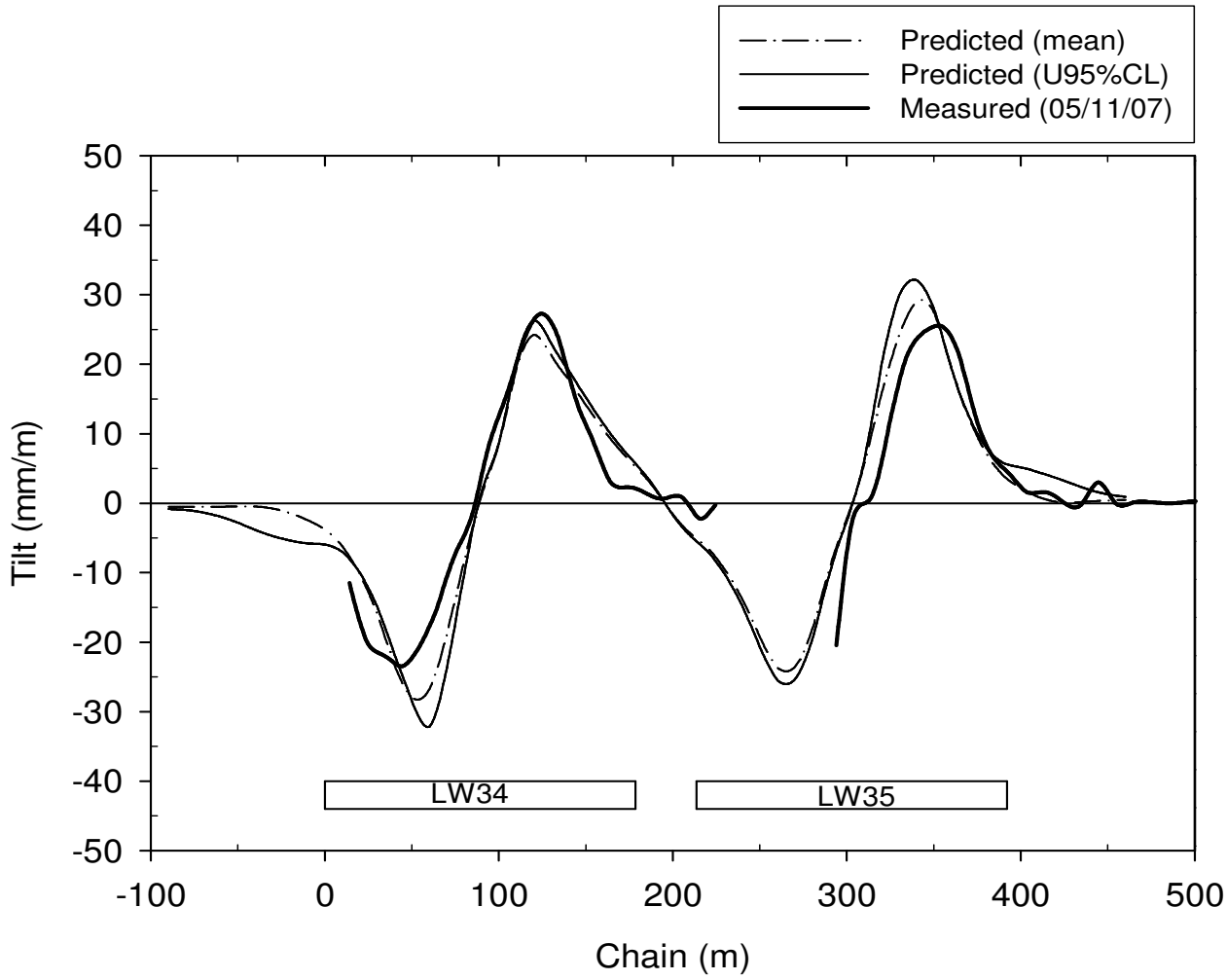
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Predicted v. Measured Crossline Tilt Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A33



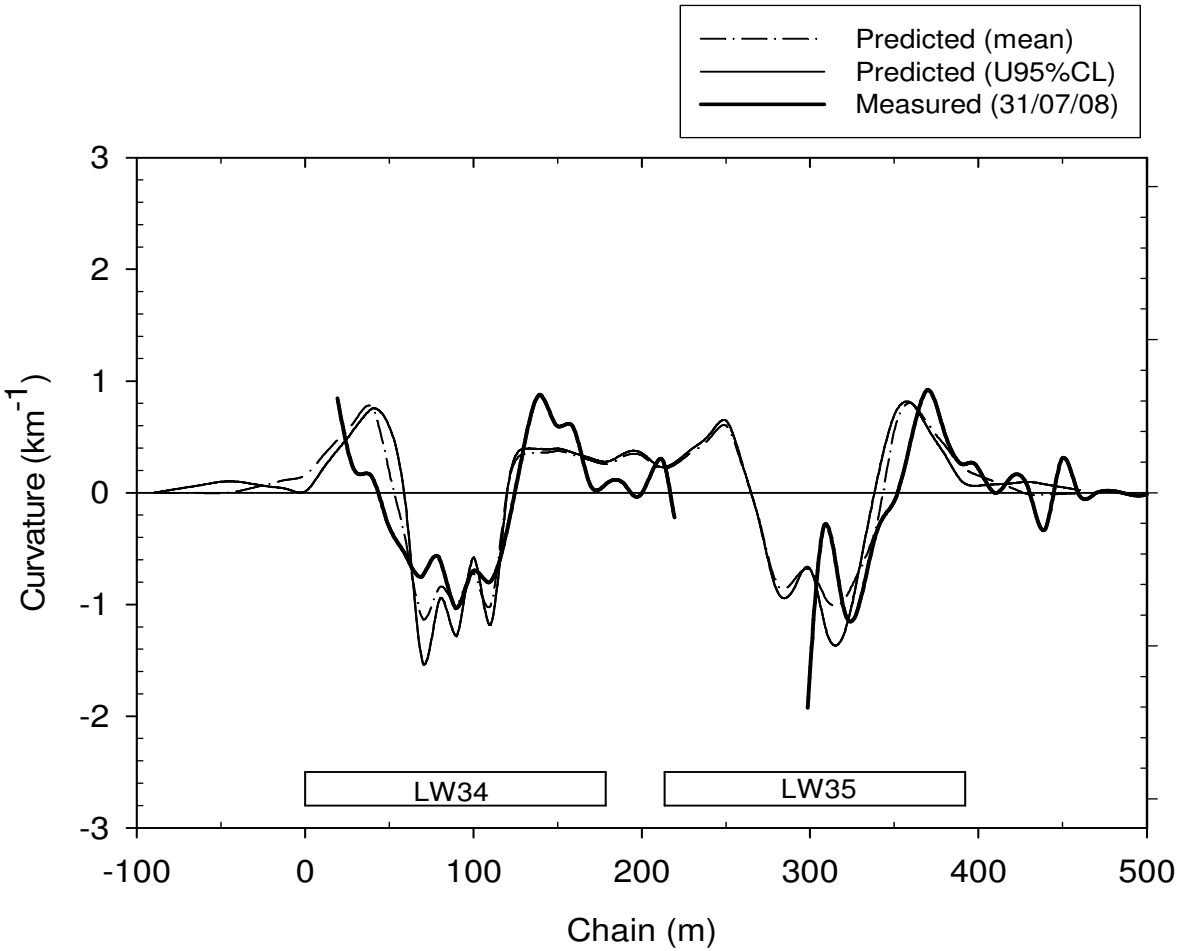
DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Predicted v. Measured Crossline Strain Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A34



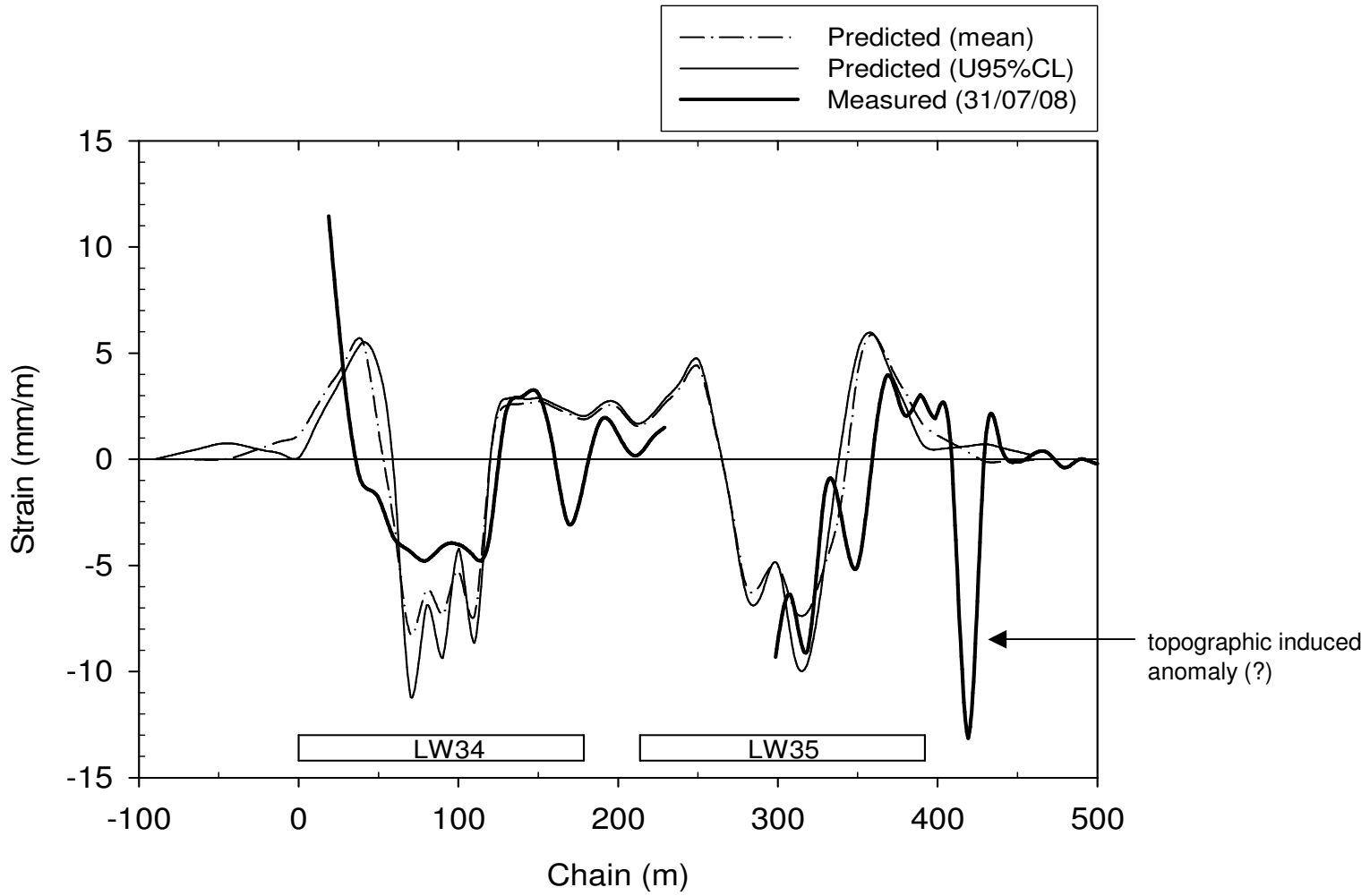
DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes	
	Drawn:	S.Ditton			
	Date:	07.09.08	Title:	Predicted v. Measured Crossline Subsidence Profiles for a Newcastle Coalfield Longwall Longwall Panel	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A35



DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes	
	Drawn:	S.Ditton			
	Date:	07.09.08	Title:	Predicted v. Measured Crossline Tilt Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A36



DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes	
	Drawn:	S.Ditton			
	Date:	07.09.08	Title:	Predicted v. Measured Crossline Curvature Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A37



DgS	Engineer:	S.Ditton	Client:	DgS, 2008 Modified ACARP, 2003 Model Outcomes	
	Drawn:	S.Ditton			
	Date:	08.09.08	Title:	Predicted v. Measured Crossline Strain Profiles for a Newcastle Coalfield Longwall Mine	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A38



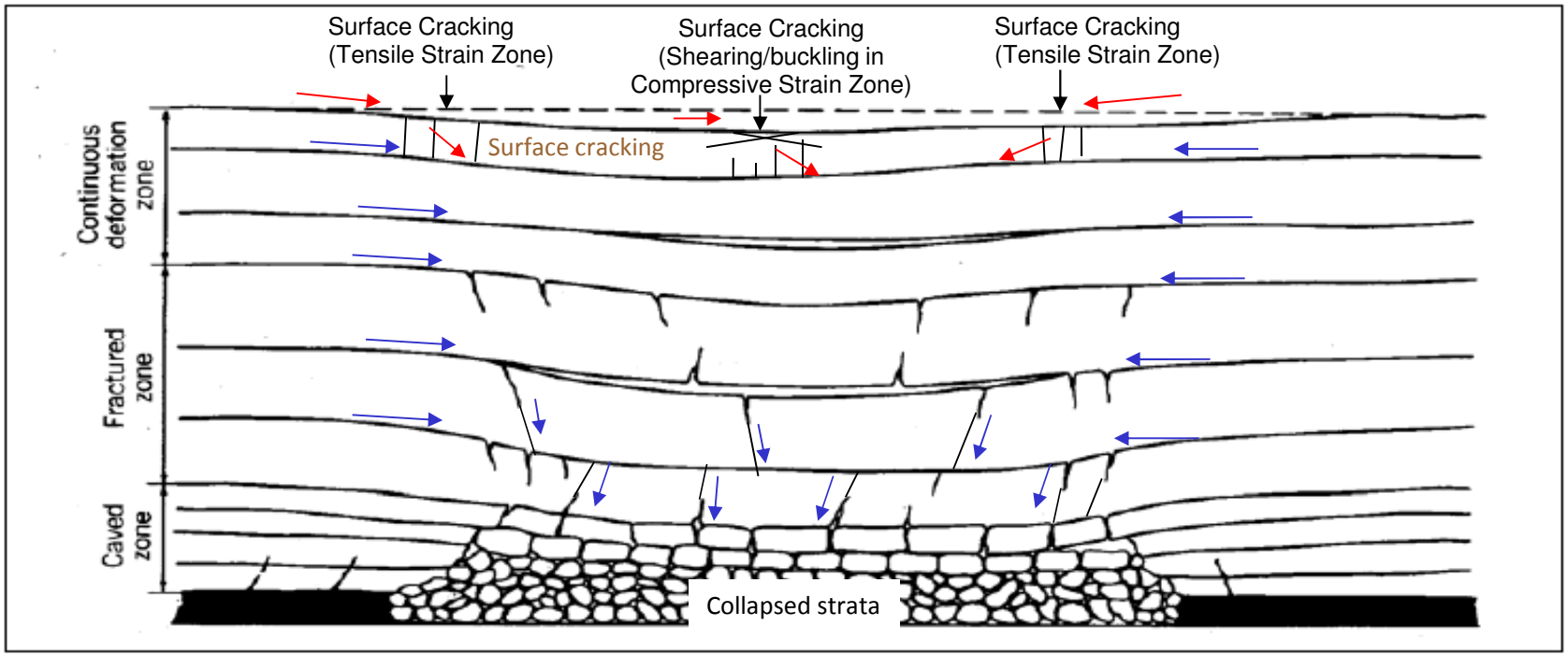
Strain Concentration Factor Calculation for 10 m Baylength^

- Measured crack width = 100 mm.
- Measured crack depth >5 m
- Location = 27 m from solid rib.
  Smax = 1.4 m.
- Cover depth, H = 180 m.
- LW panel width, W= 175 m.
  (W/H = 0.97)
- Measured curvature,
  C = 1.15 km-1
  (radius of 867 m)
- Measured strain over 10 m,
  E = 5.8 mm/m*
- Concentrated strain = crack width/bay-length = 100/10 = 10 mm/m.

Therefore, concentrated strain = 10/5.8 = 1.7 x uniform strain.

*- peak strains measured 10 m to south of crack at same distance from rib.
^ - It is likely that strain concentration includes strain from adjacent 'bays'.

DgS	Engineer:	S.Ditton	Client:	Adapted from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Example of Strain Concentration Effect Above Longwall with Shallow Surface Rock	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A39



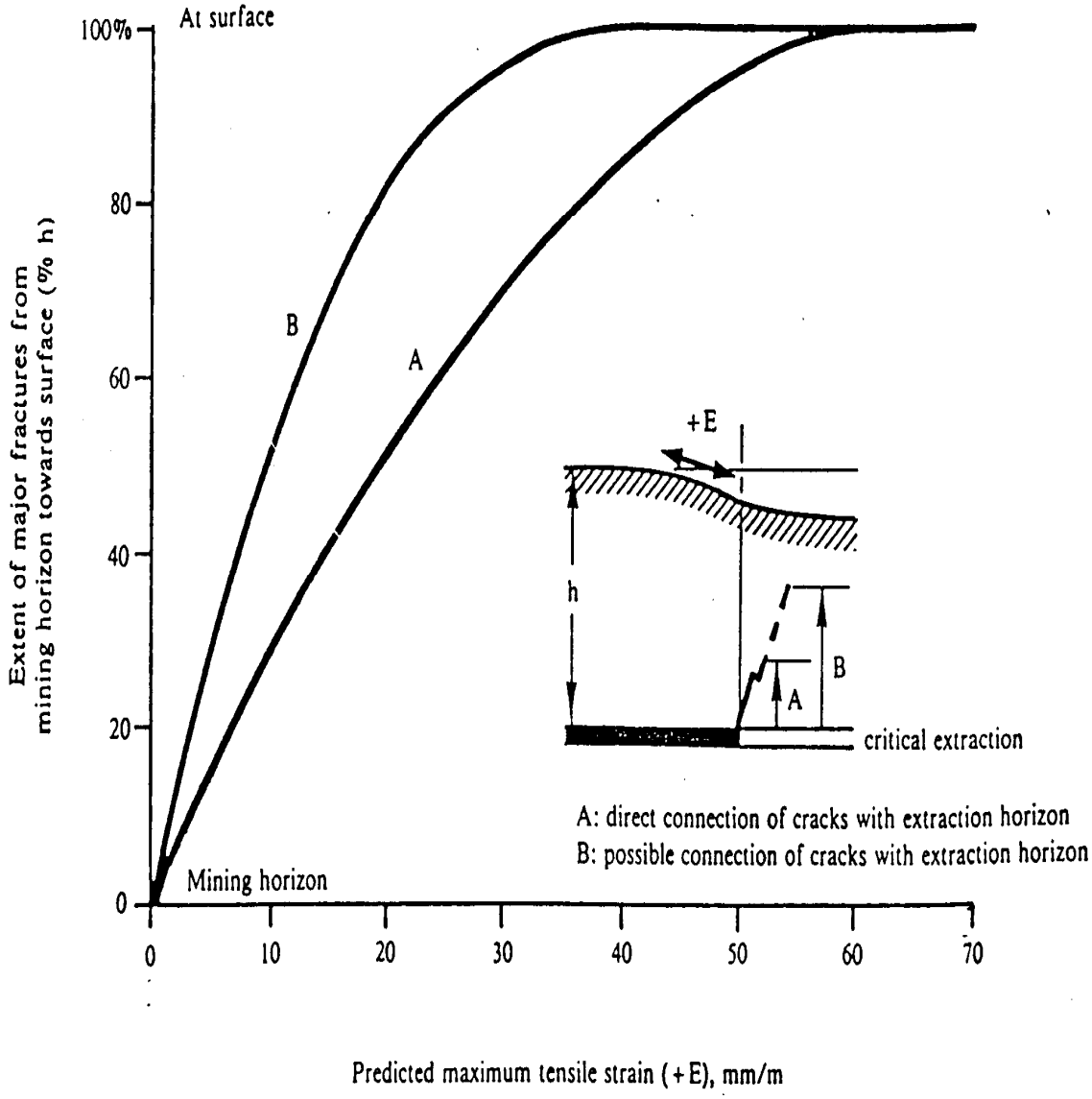
Zones in the Overburden According to Peng and Chiang (1984)

Key

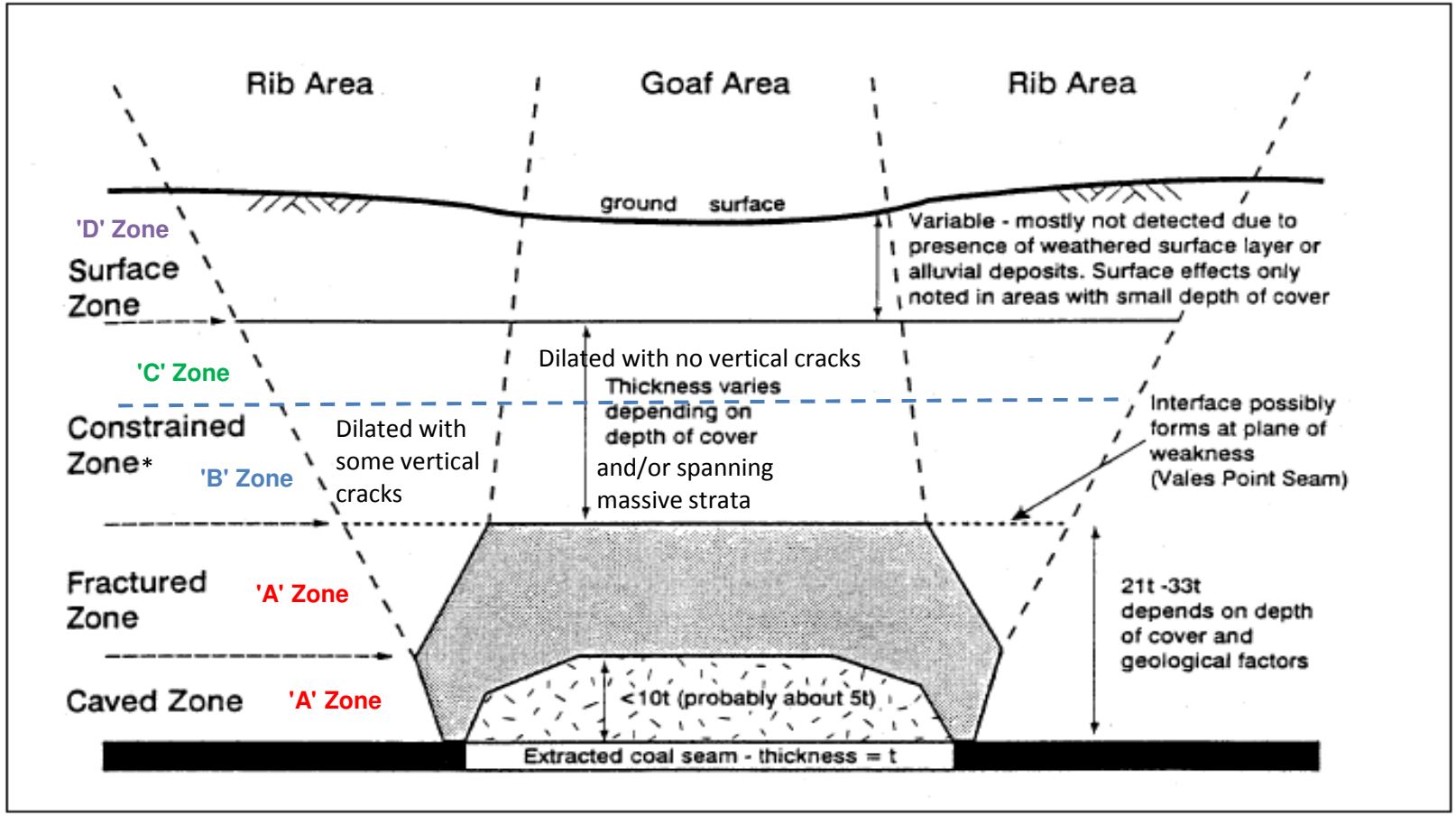
Surface water flow path

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

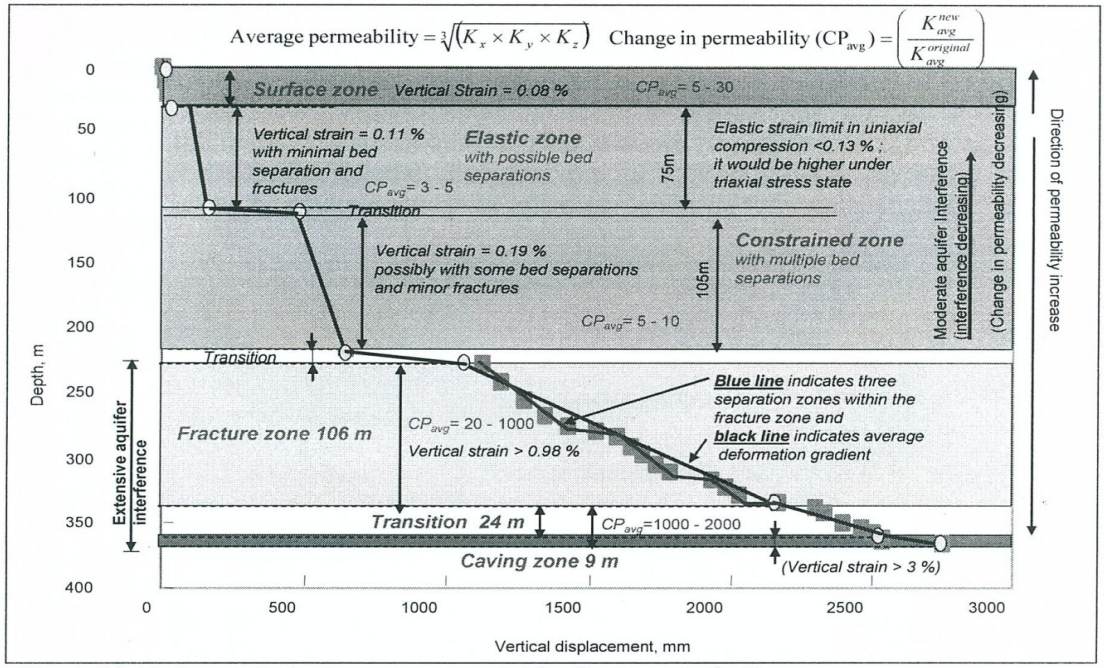


Figure H. Hydrogeological response model for Springvale Colliery

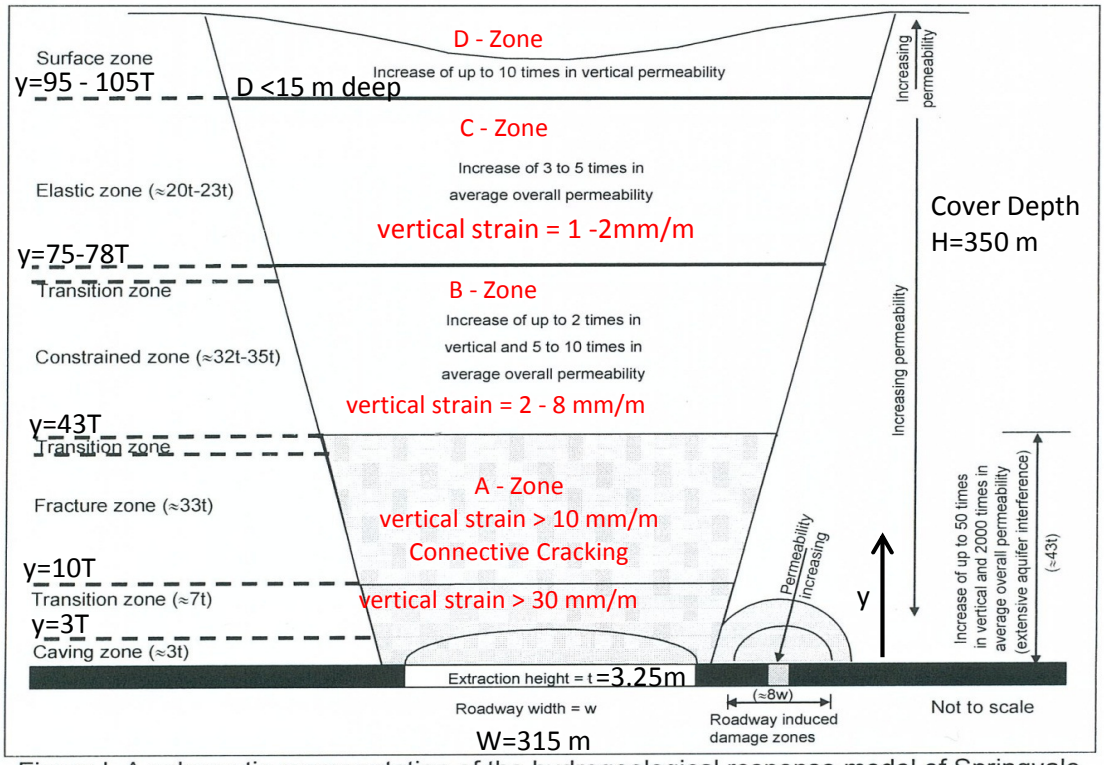


Figure I. A schematic representation of the hydrogeological response model of Springvale Colliery

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.

6. D - Zone (<15 m)

5. C - Zone

4. B - Zone

3. A - Zone

1, 2. A - Zone

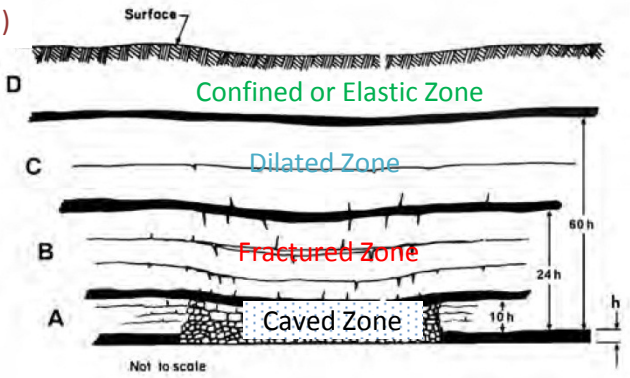


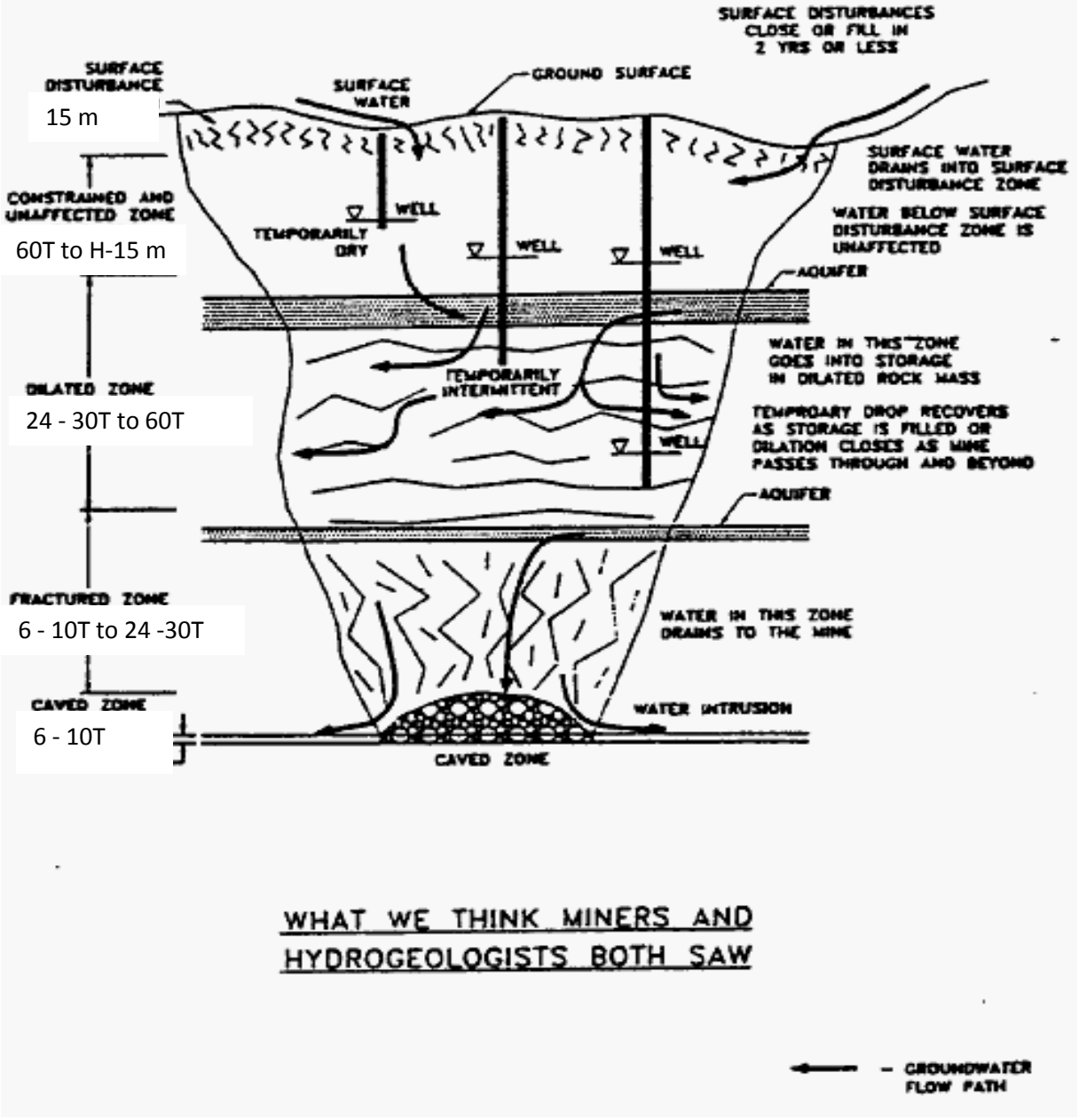
Figure 6.—Overburden response to full-extraction mining: (A) caving zones, (B) fracture zone, (C) dilated zone, and (D) confined zone.

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.

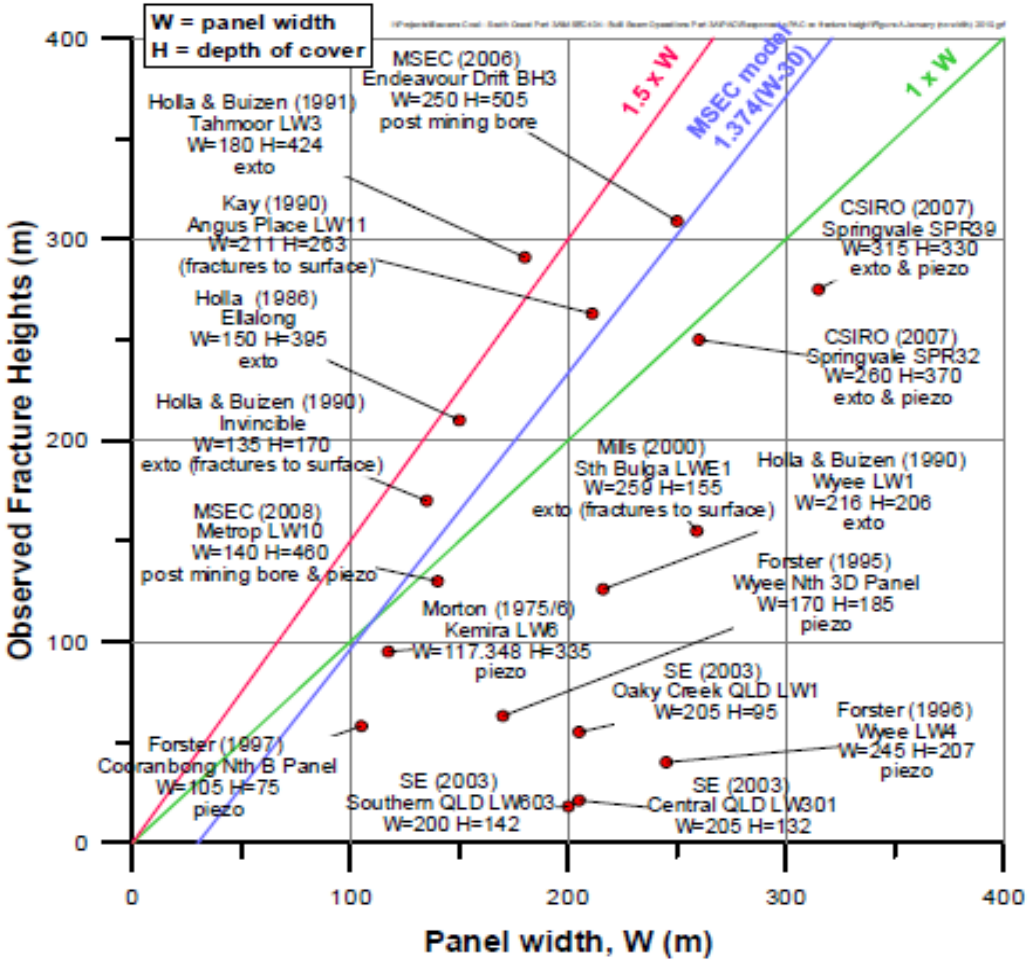
Note: Equivalent **ACARP, 2007** model zones A to D also shown down the left side.

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)

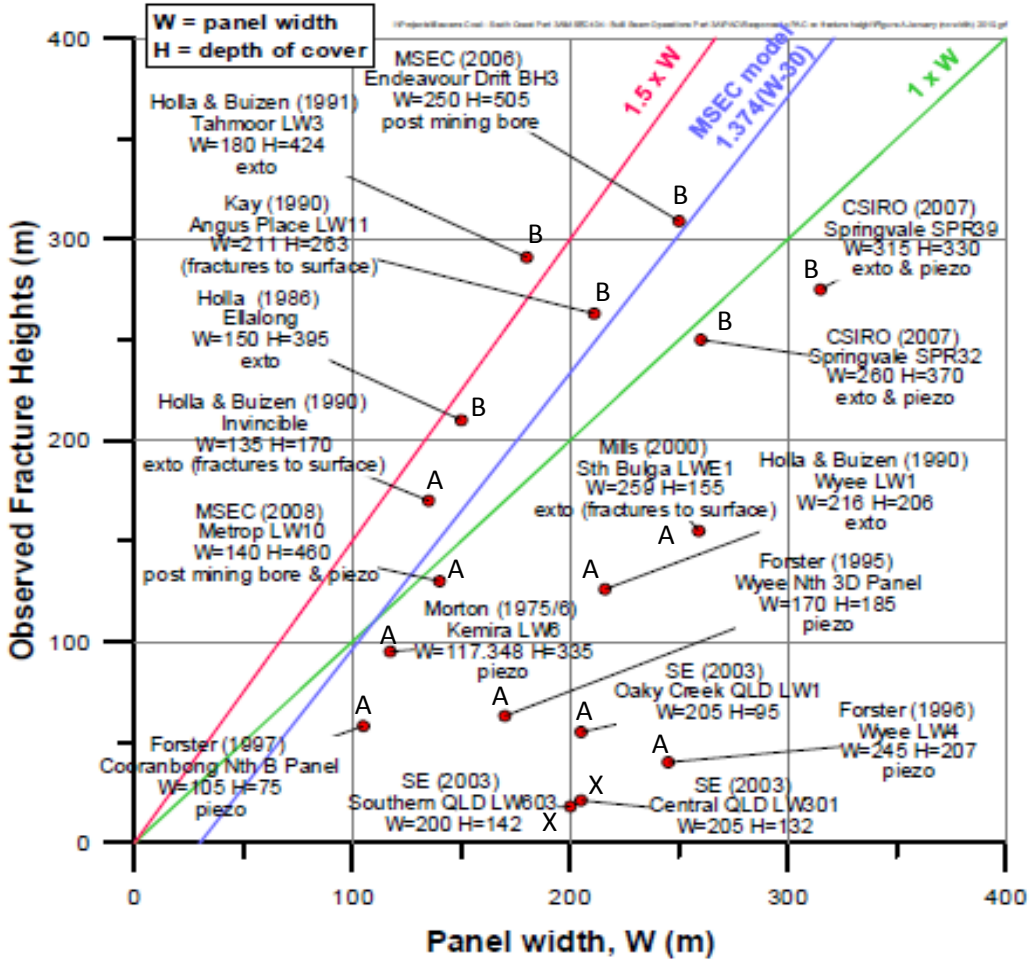


DgS	Engineer:	S.Ditton	Client:	Appendix A	
	Drawn:	S.Ditton			
	Date:	03.06.13	Title:	Model of Overburden Fracture Zones above UK Longwall Mines According to Kendorski, 1993	
	Ditton Geotechnical Services Pty Ltd		Scale:		Figure No: A40f



Ref: MSEC, 2011

DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	07.06.13	Title:	Observed Fracture Height Models presented by SCT and MSEC	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A40g



Key

A: A-Zone Horizon

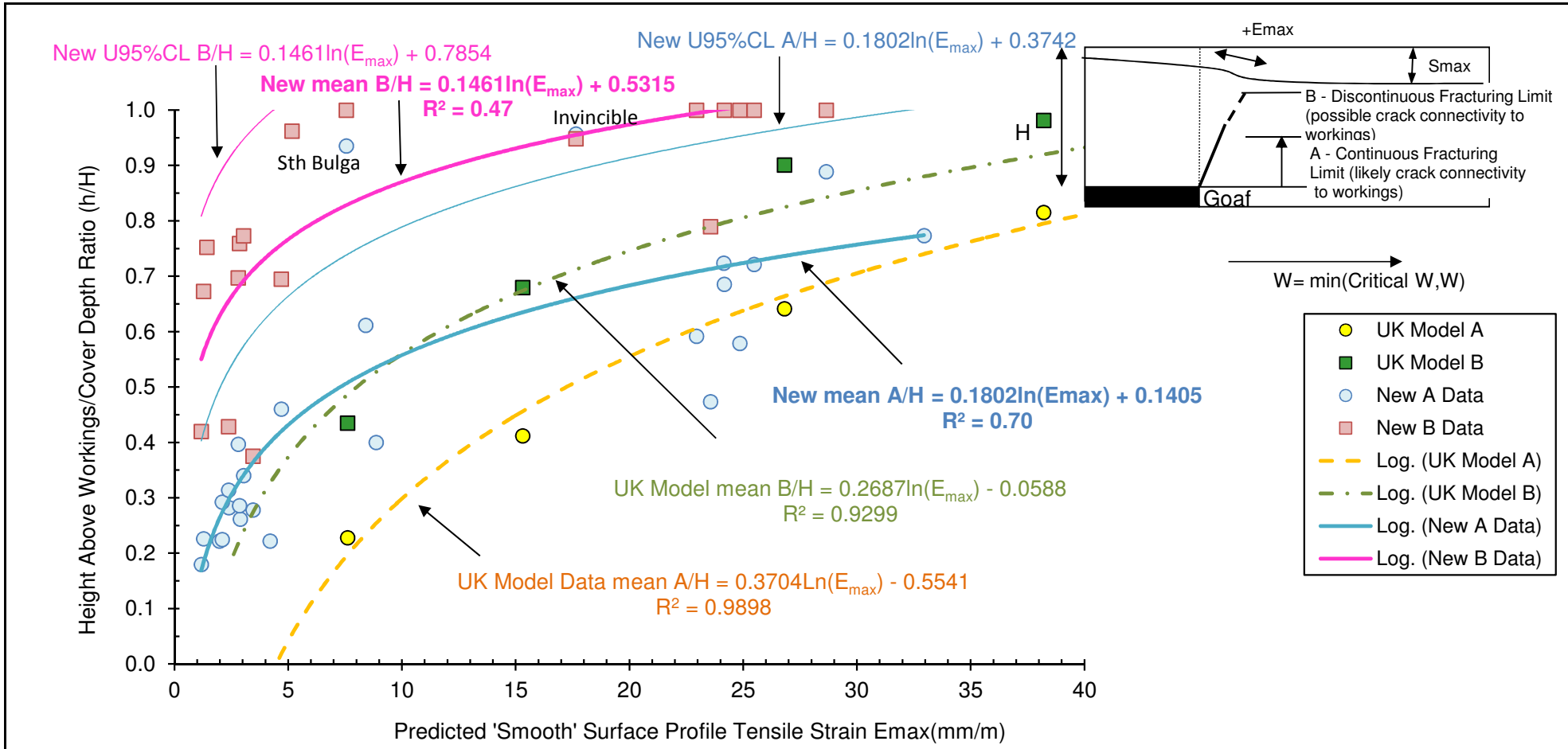
B: B-Zone Horizon

X: In-conclusive data

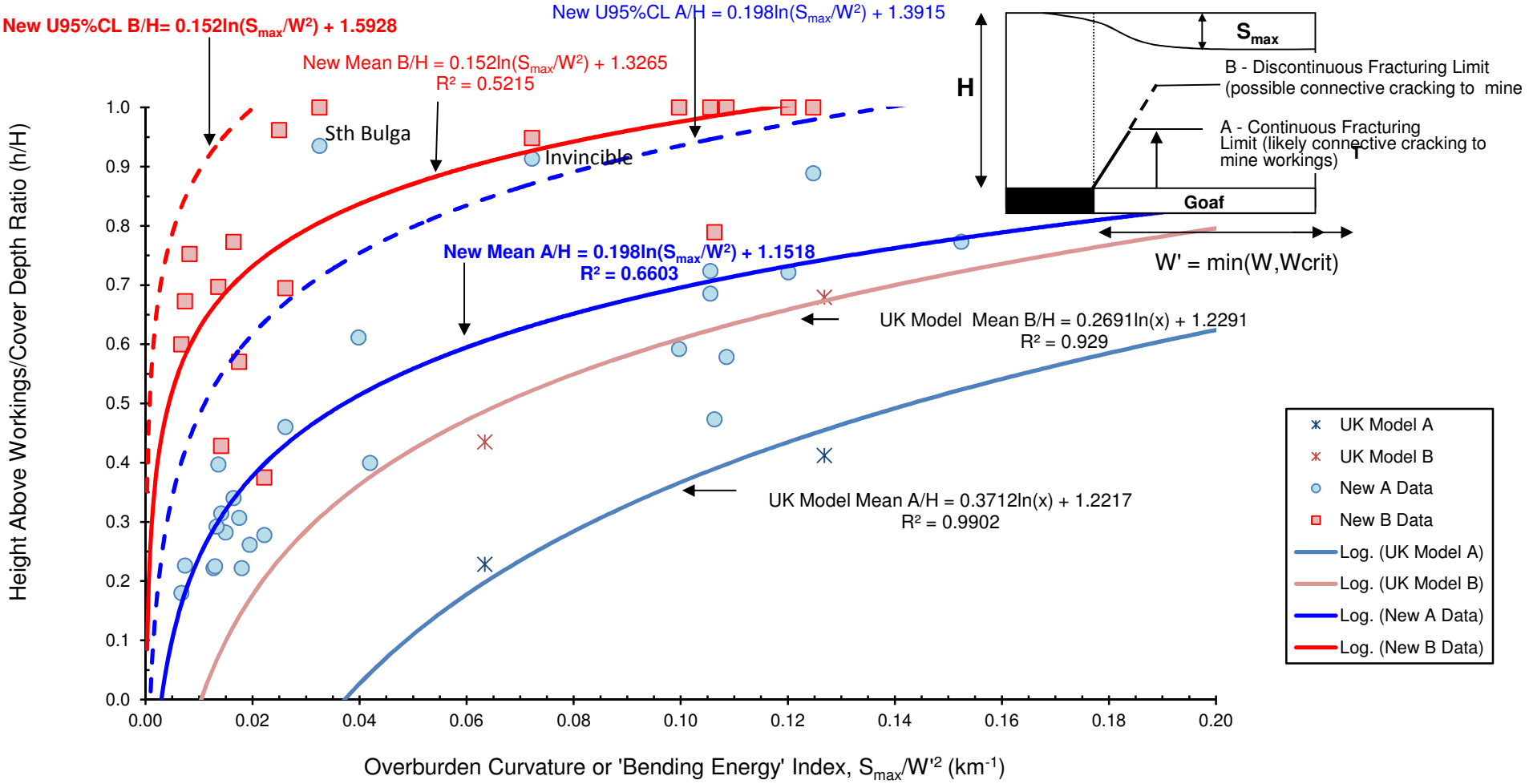
Note: amended zone horizons presented in Table A4

Ref: MSEC, 2011

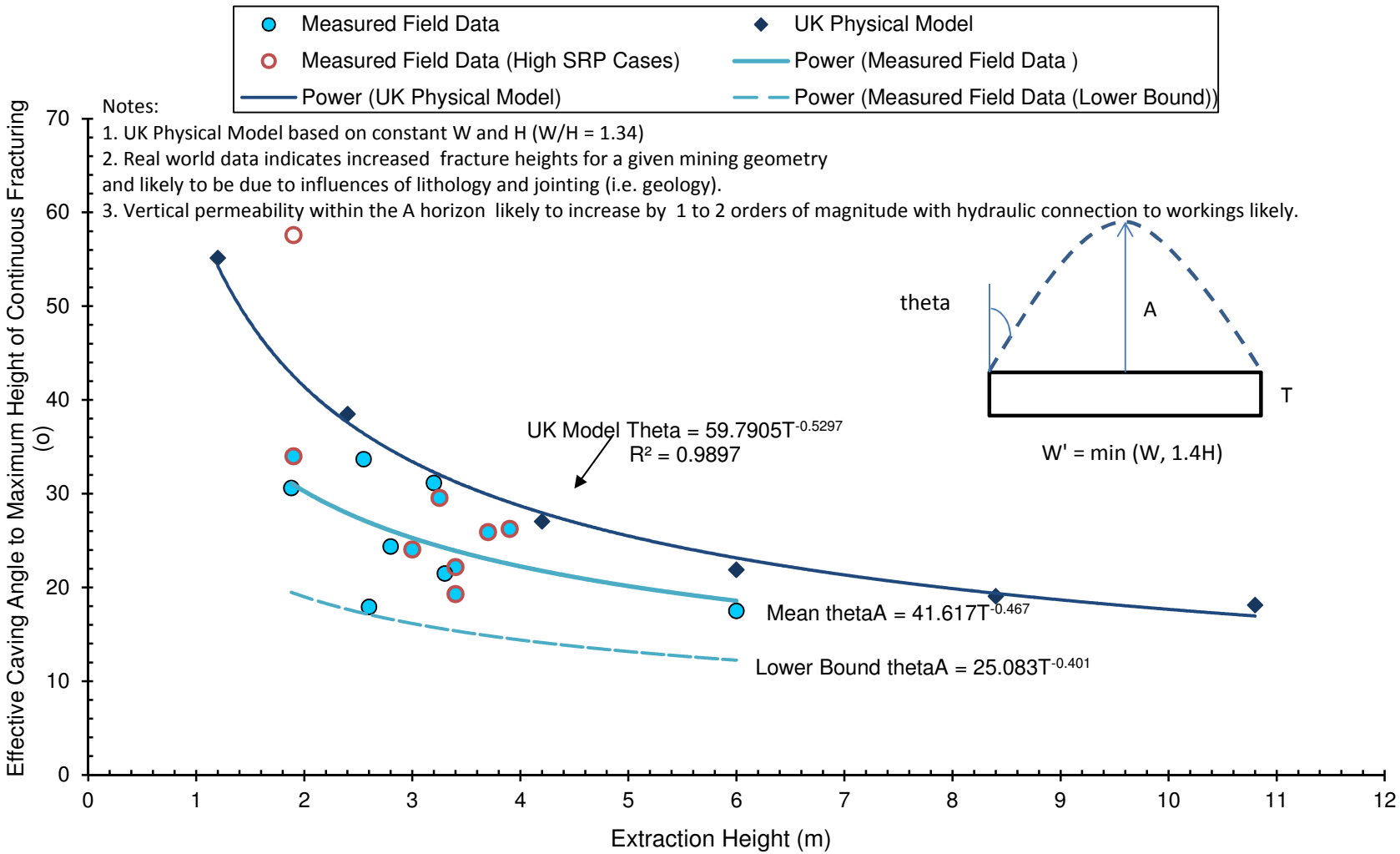
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	07.06.13	Title:	Review of Observed Fracture Height Models presented by SCT and MSEC v. Whittaker & Reddish Sub-Surface Fracture Model Zoning	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A40h



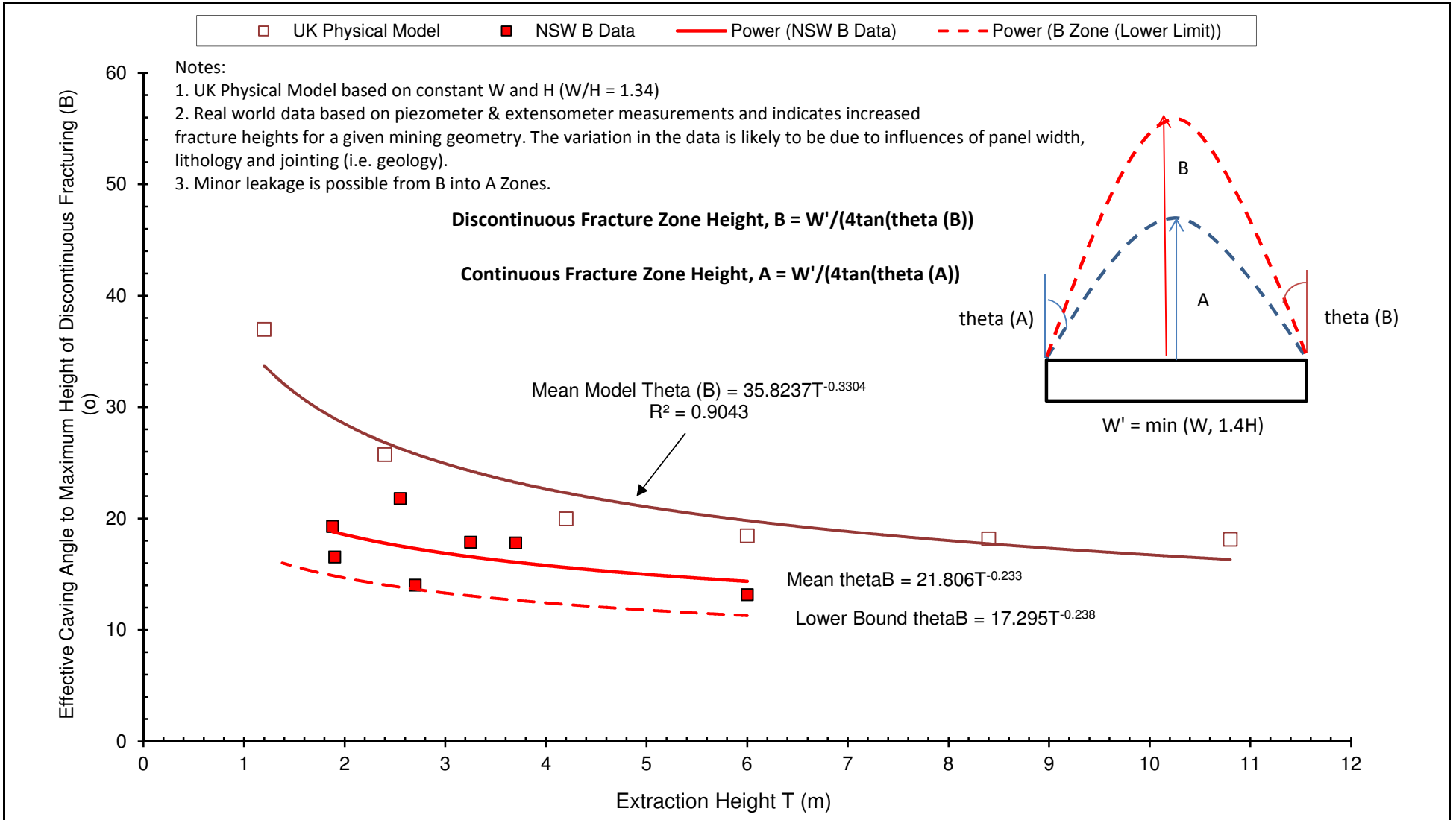
DgS	Engineer: S.Ditton	Client:	Updated Whittaker and Reddish Model presented in ACARP, 2003	
	Drawn: S.Ditton			
	Date: 18.11.12	Title:	Continuous and Discontinuous Sub-Surface Fracture Height Model above Longwalls using Surface Tensile Strains as the Key Indicator	
	Ditton Geotechnical Services Pty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



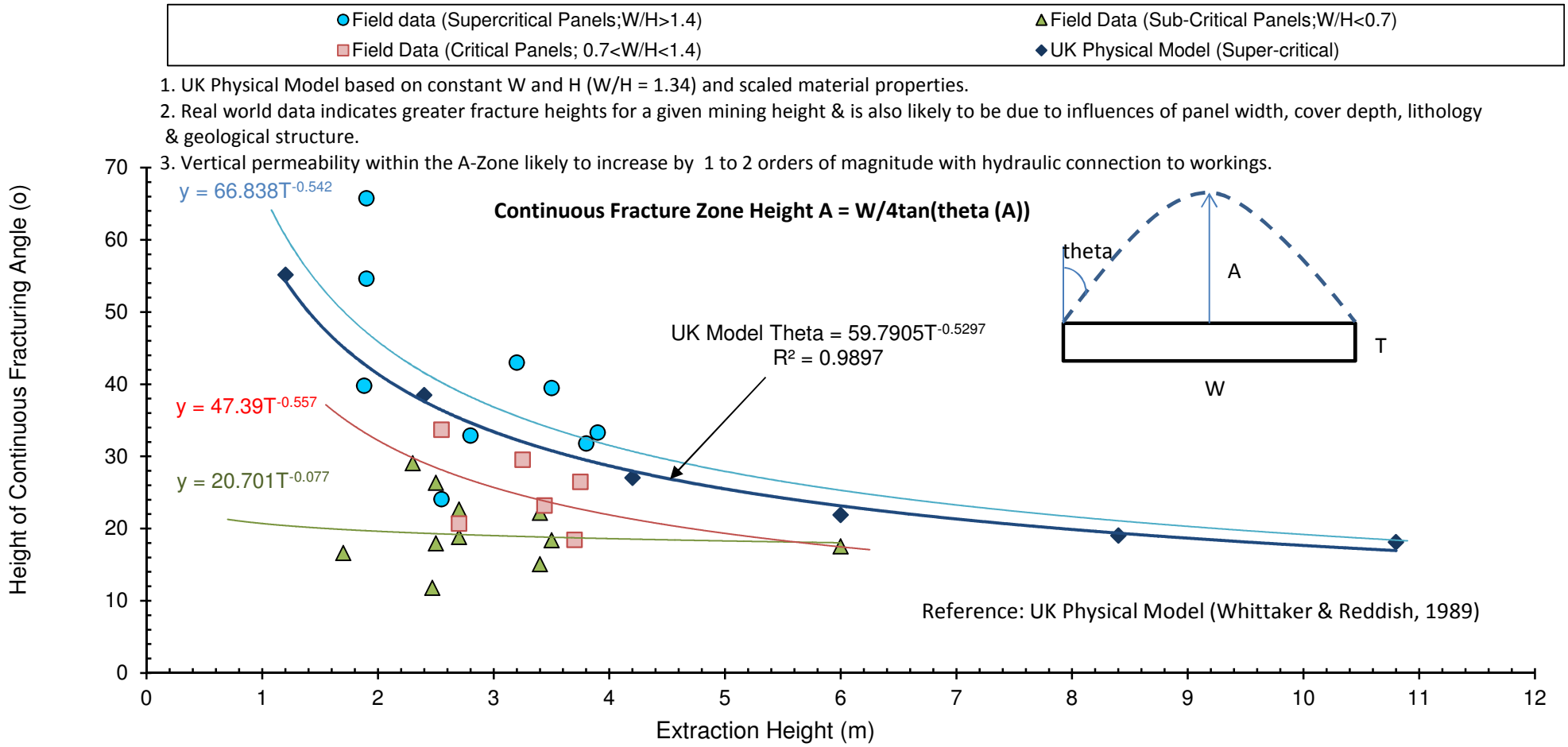
DgS	Engineer:	S.Ditton	Client:	Updated from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	03.12.12	Title:	Continuous and Discontinuous Sub-Surface Fracture Heights above Longwalls (based on ACARP, 2003)	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41b



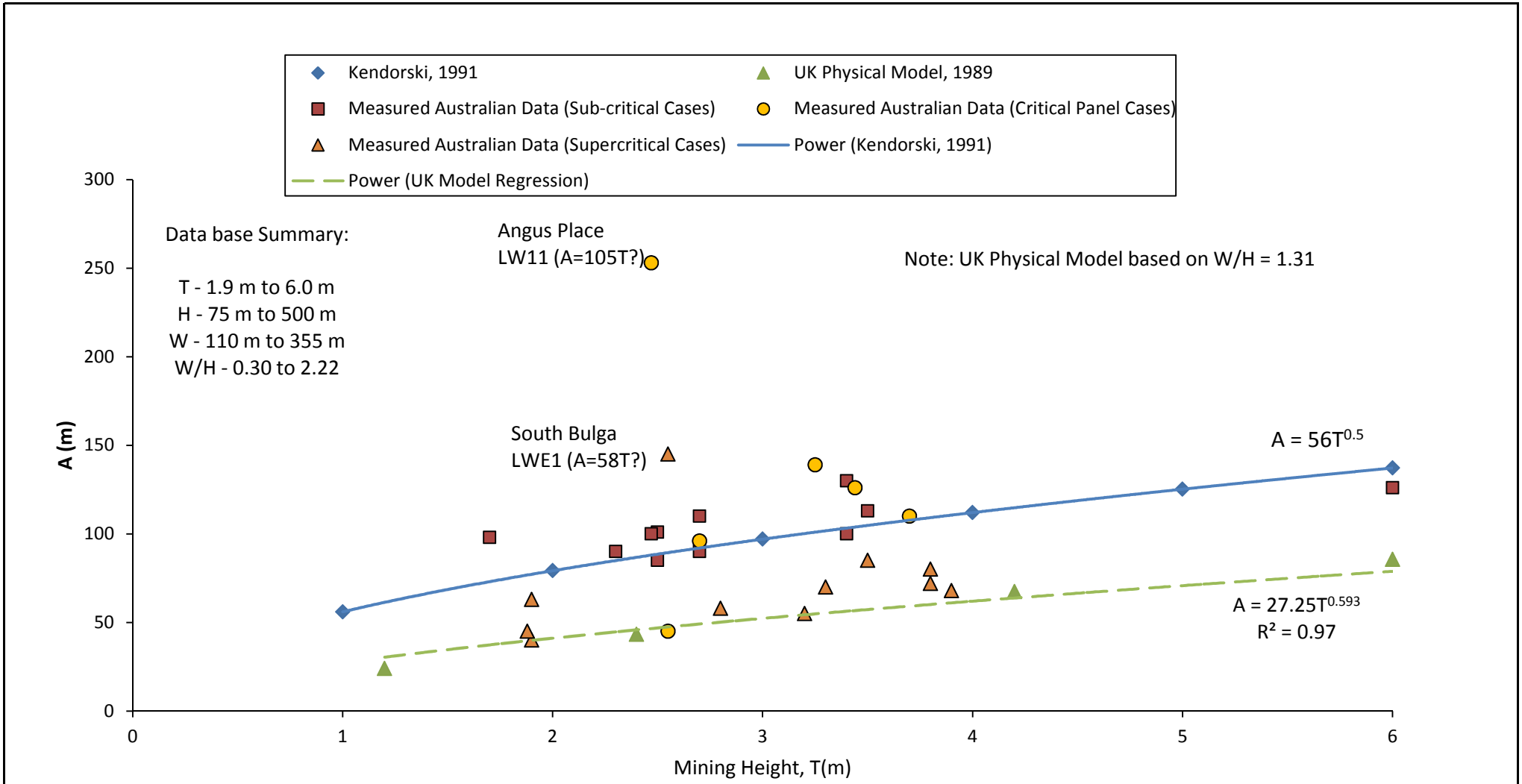
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003 (DgS,2012)	
	Drawn:	S.Ditton			
	Date:	15.11.12	Title:	Alternative ACARP, 2003 A-Zone Sub-Surface Fracture Height Model based on Panel Width and Mining Height as Key Parameters	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41c



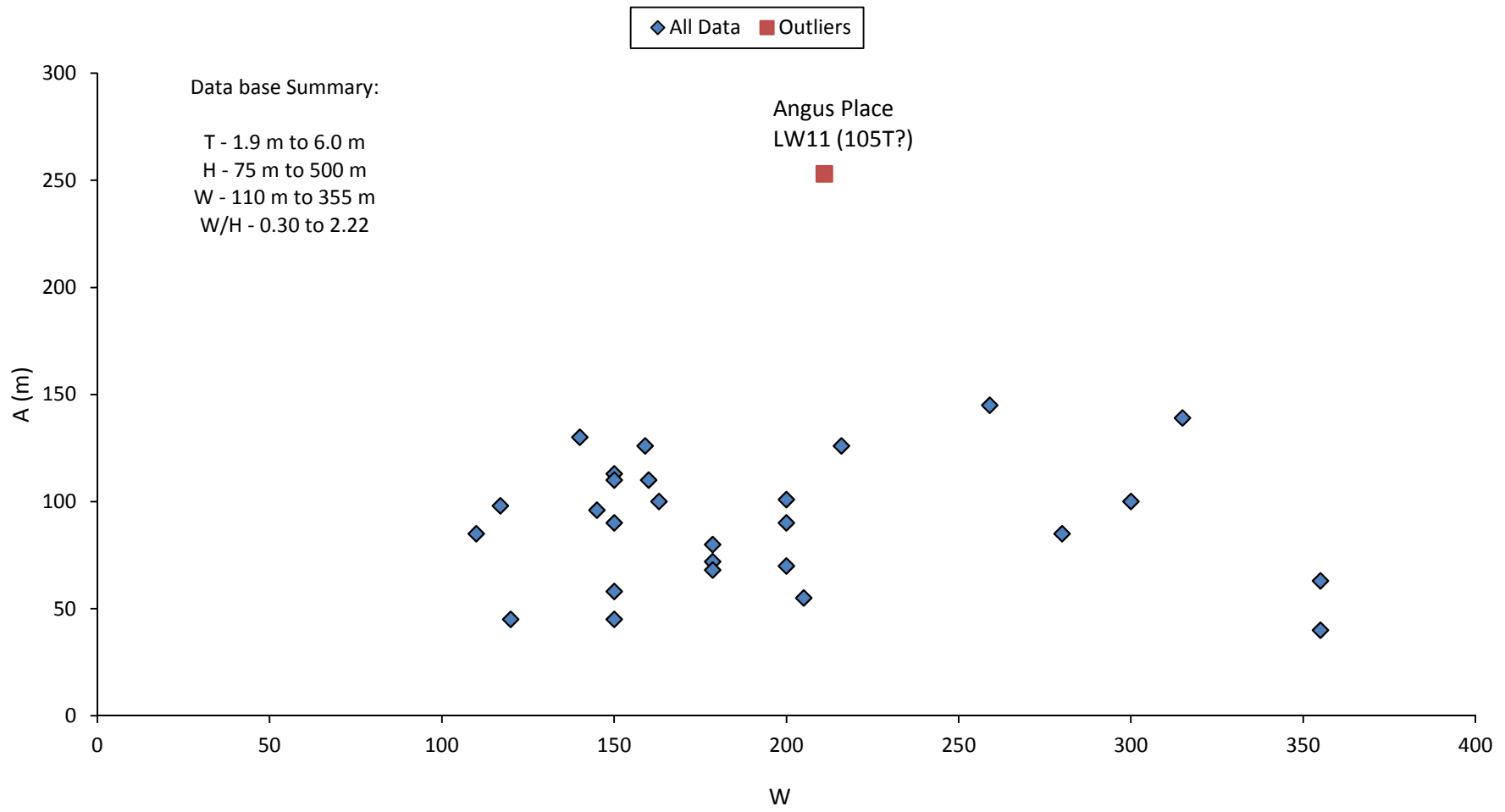
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003 (DgS,2012)	
	Drawn:	S.Ditton			
	Date:	15.11.12	Title:	Alternative ACARP, 2003 B-Zone Sub-Surface Fracture Height Model based on Panel Width and Mining Height as Key Parameters	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41d



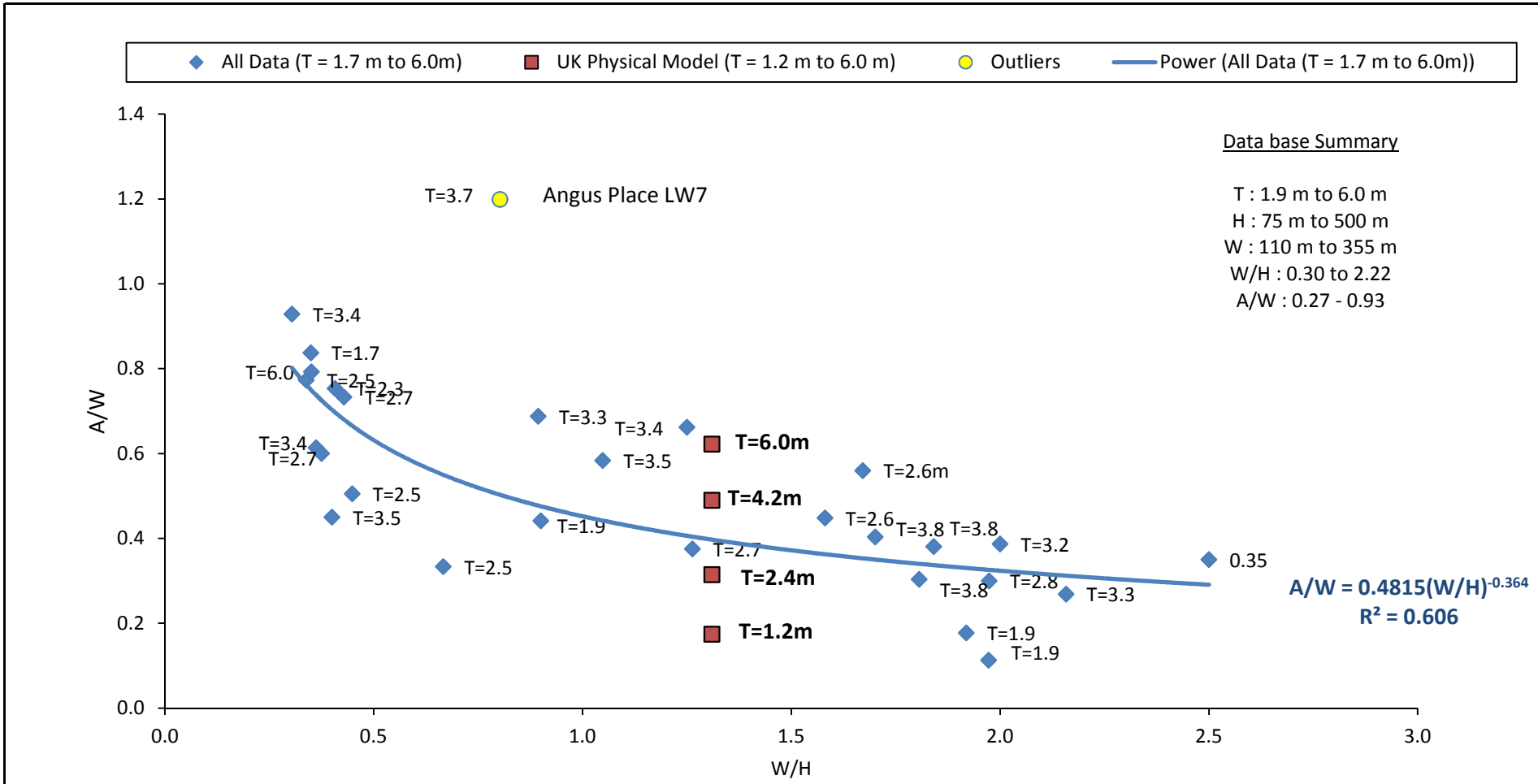
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	10.06.13	Title:	Predicted Height of Continuous Fracturing Based on HoF Angle and Mining Height	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41e



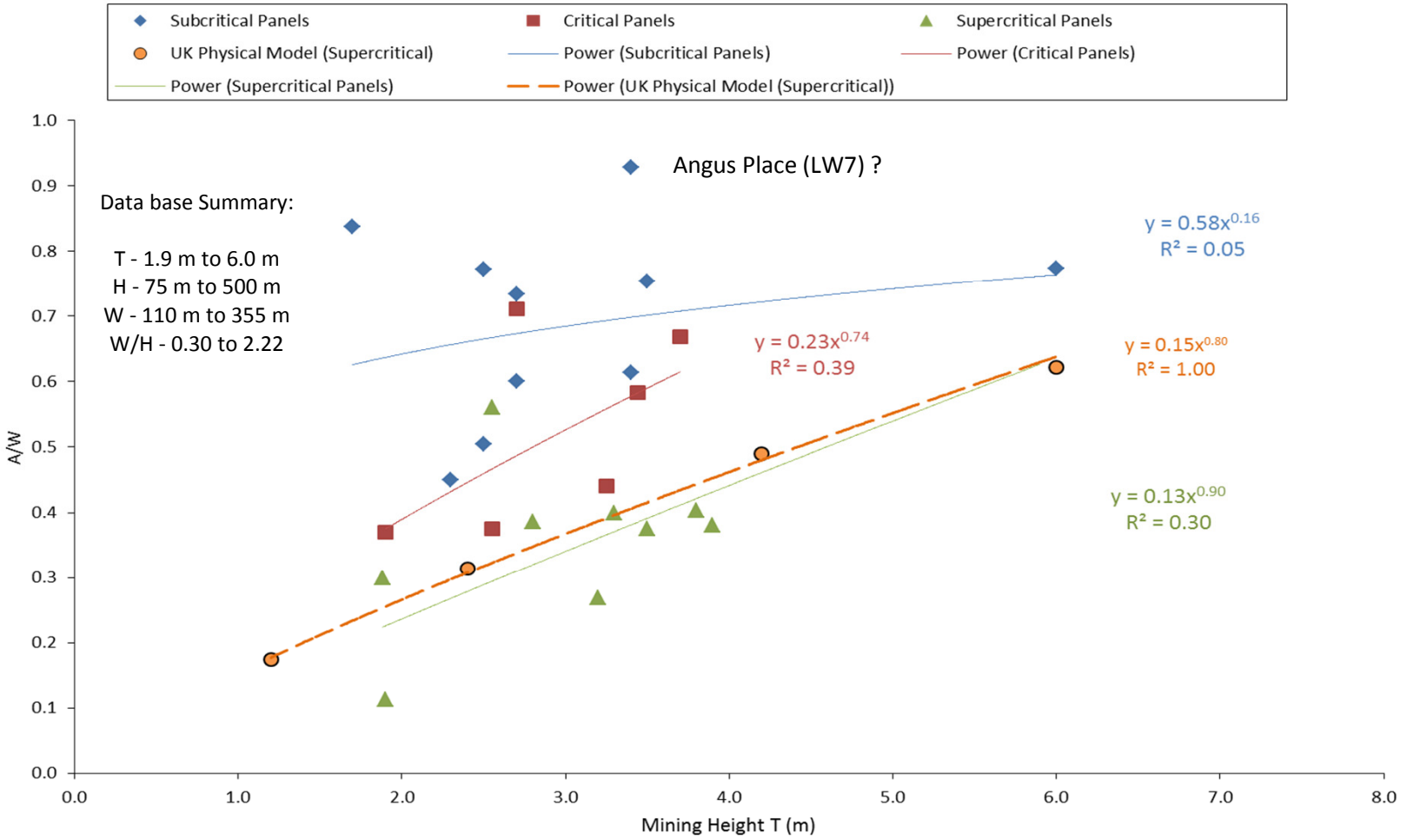
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	07.06.13	Title:	Continuous UK Fracture Height Models based on Mining Height Only v. Measured Australian Database	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41f



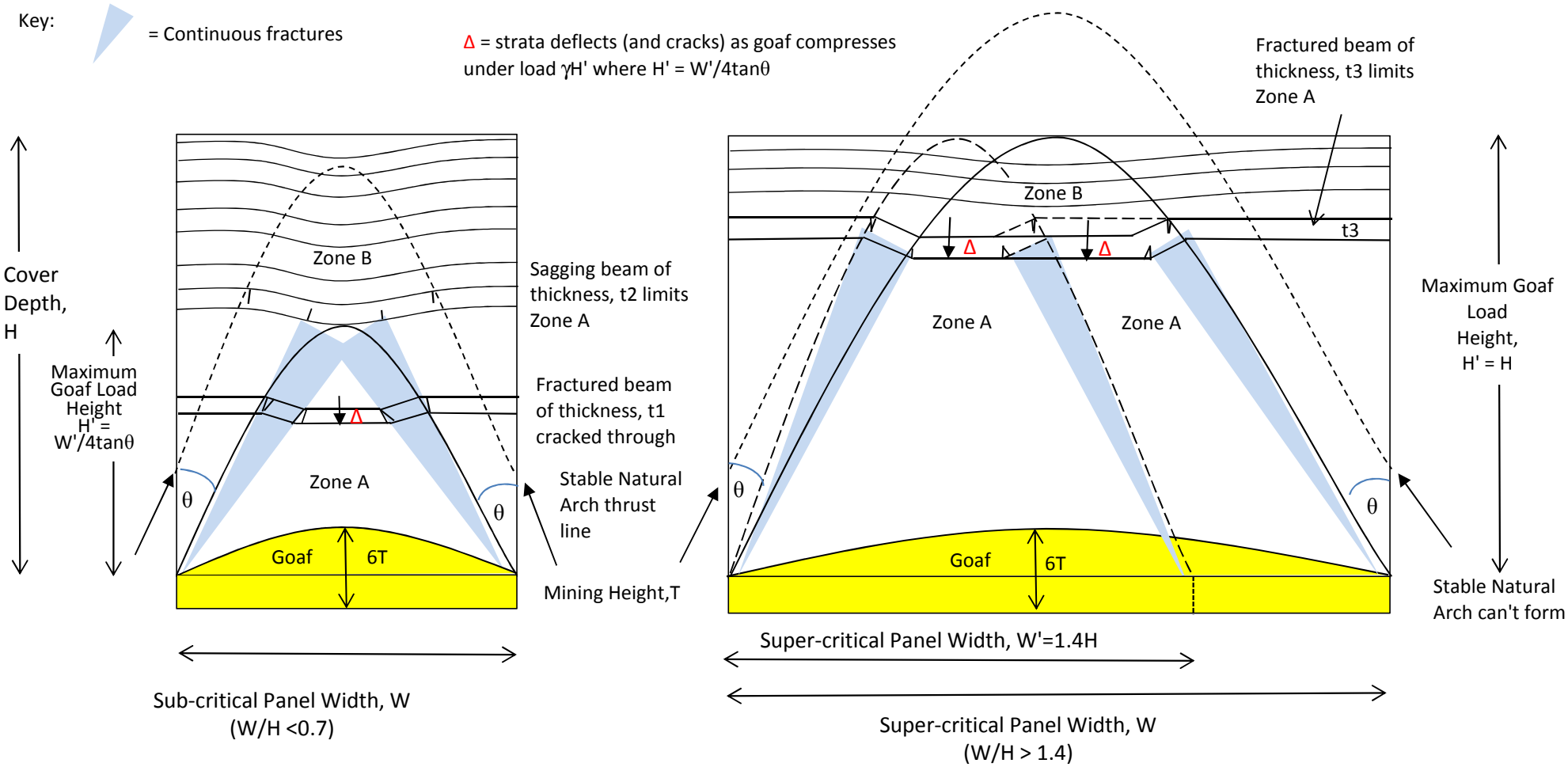
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	07.06.13	Title:	Continuous Australian Fracture Height Model based on Panel Width Only Database	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41g



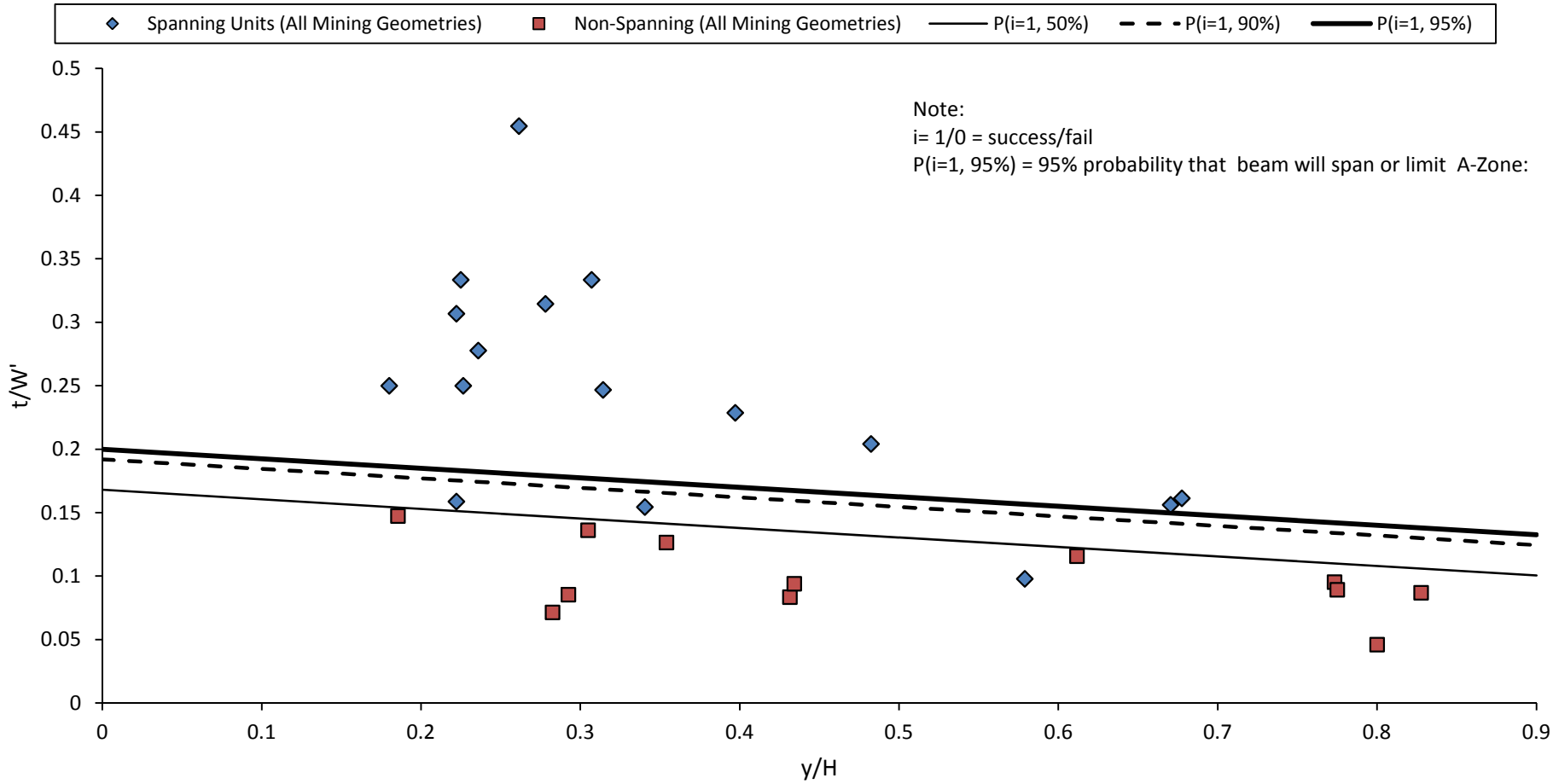
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	07.06.13	Title:	Continuous Australian Fracture Height Model based on A normalised to Panel Width with Influence of Mining Height Included	
Ditton Geotechnical Services Pty Ltd			Scale:	NTS	Figure No: A41h



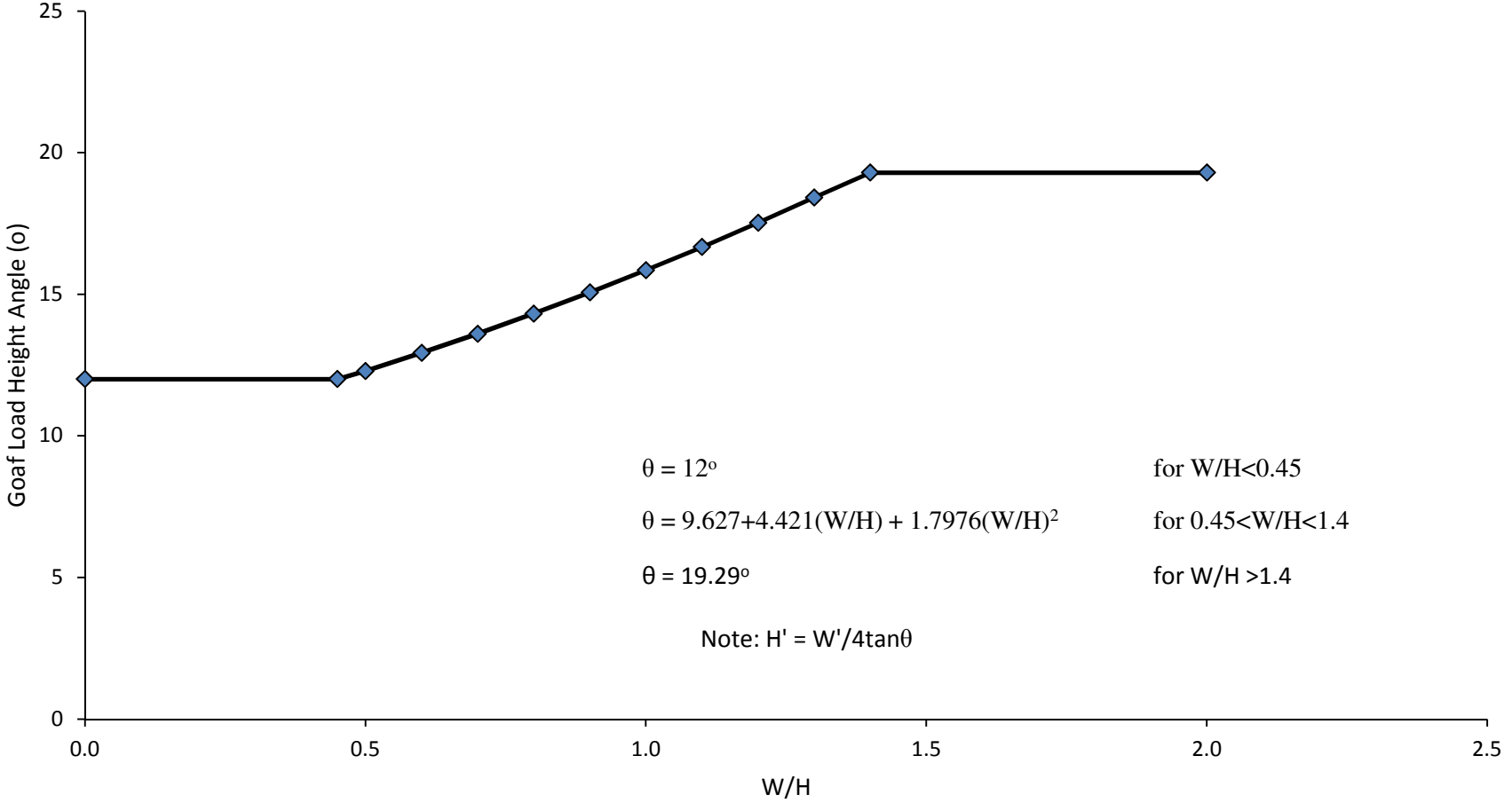
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	07.06.13	Title:	Continuous Australian Fracture Height Model based on A normalised to Panel Width v. Mining Height	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 41i



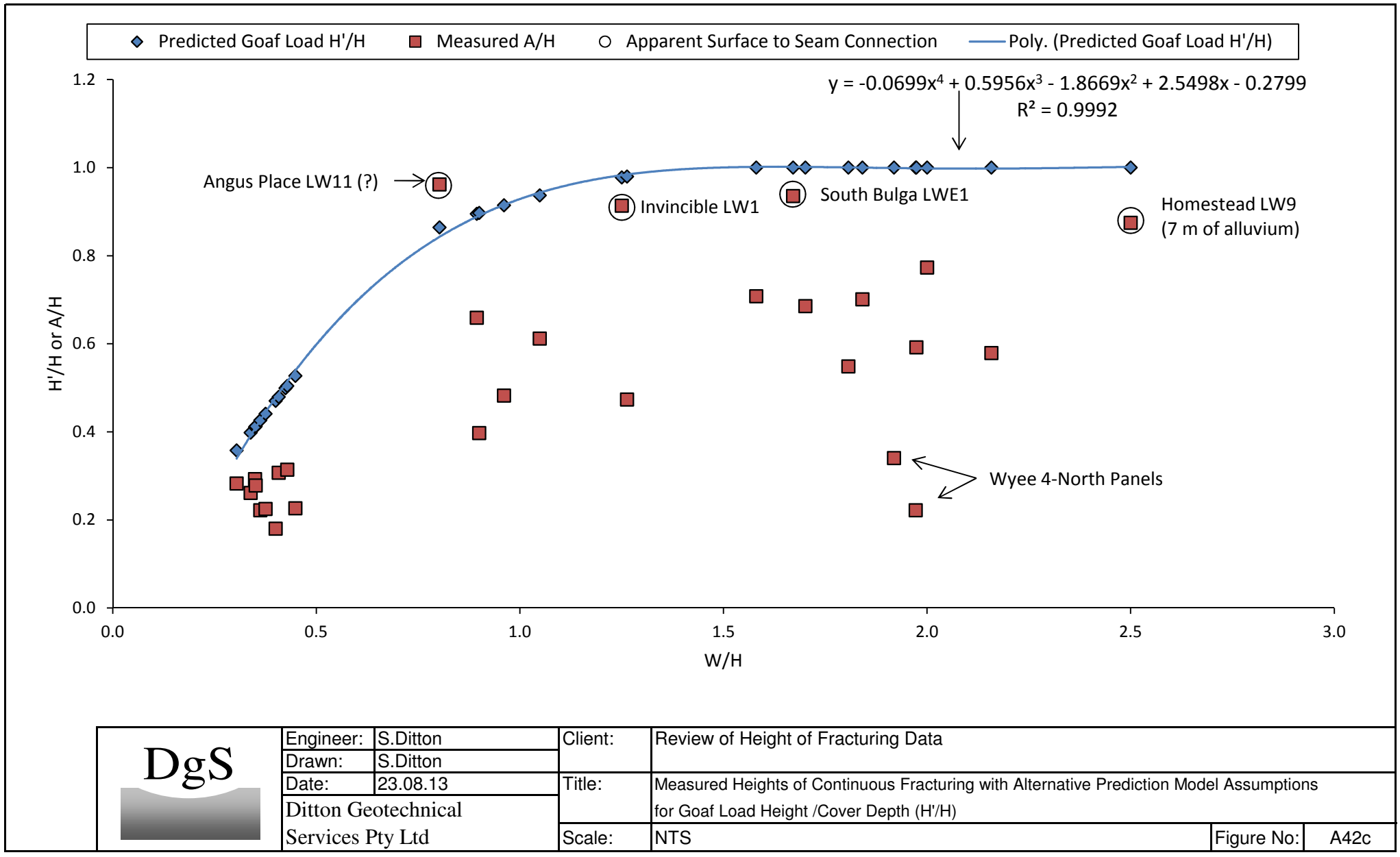
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	26.08.13	Title:	Conceptual Model for Development of Height of Continuous Fracturing Zone for a range of Longwall Panel Geometries	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A41j



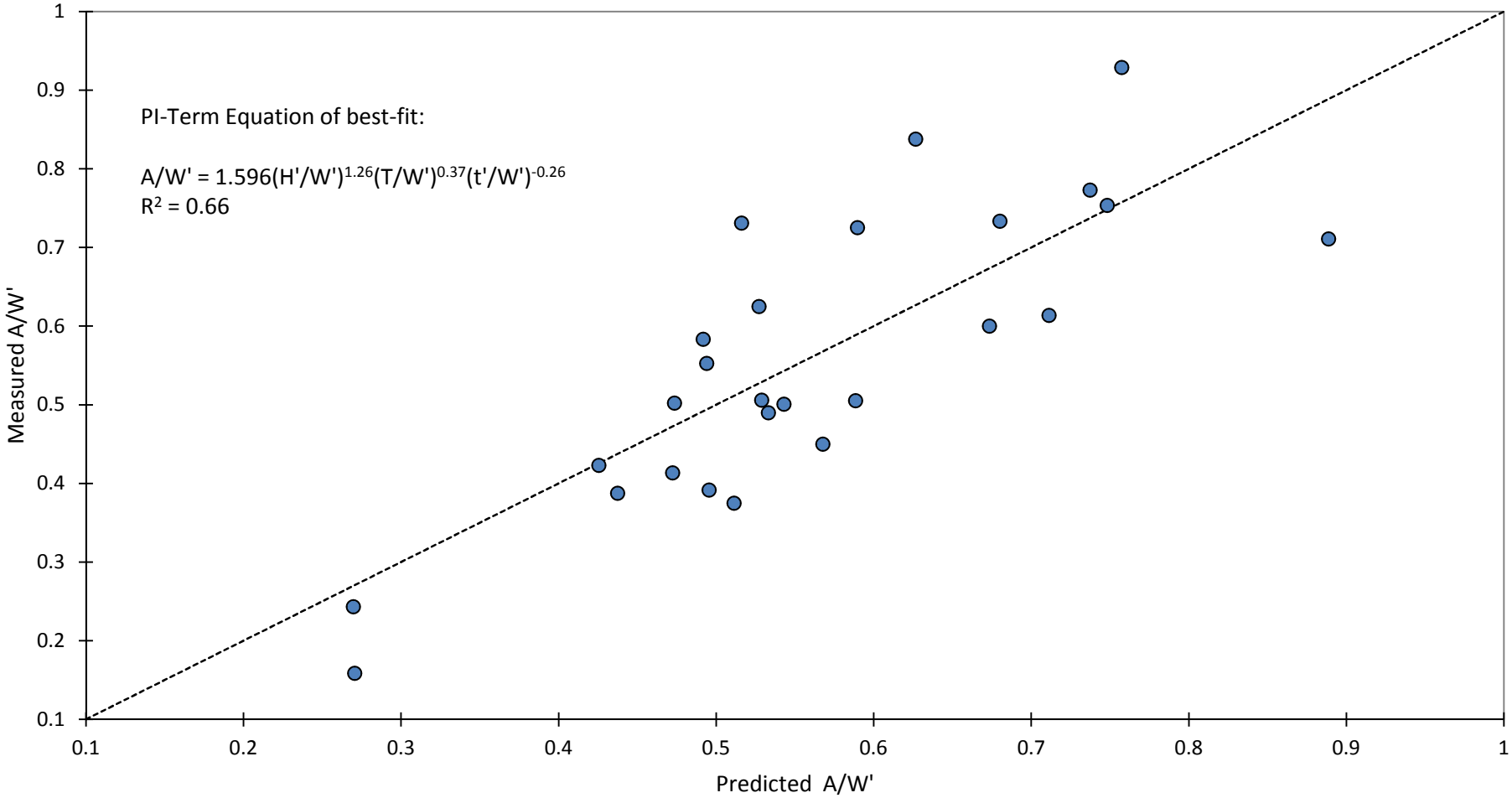
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	23.08.13	Title:	Results of Logistic Regession Analysis for Spanning and Non-Spanning Strata Units above Longwall Panels	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42a



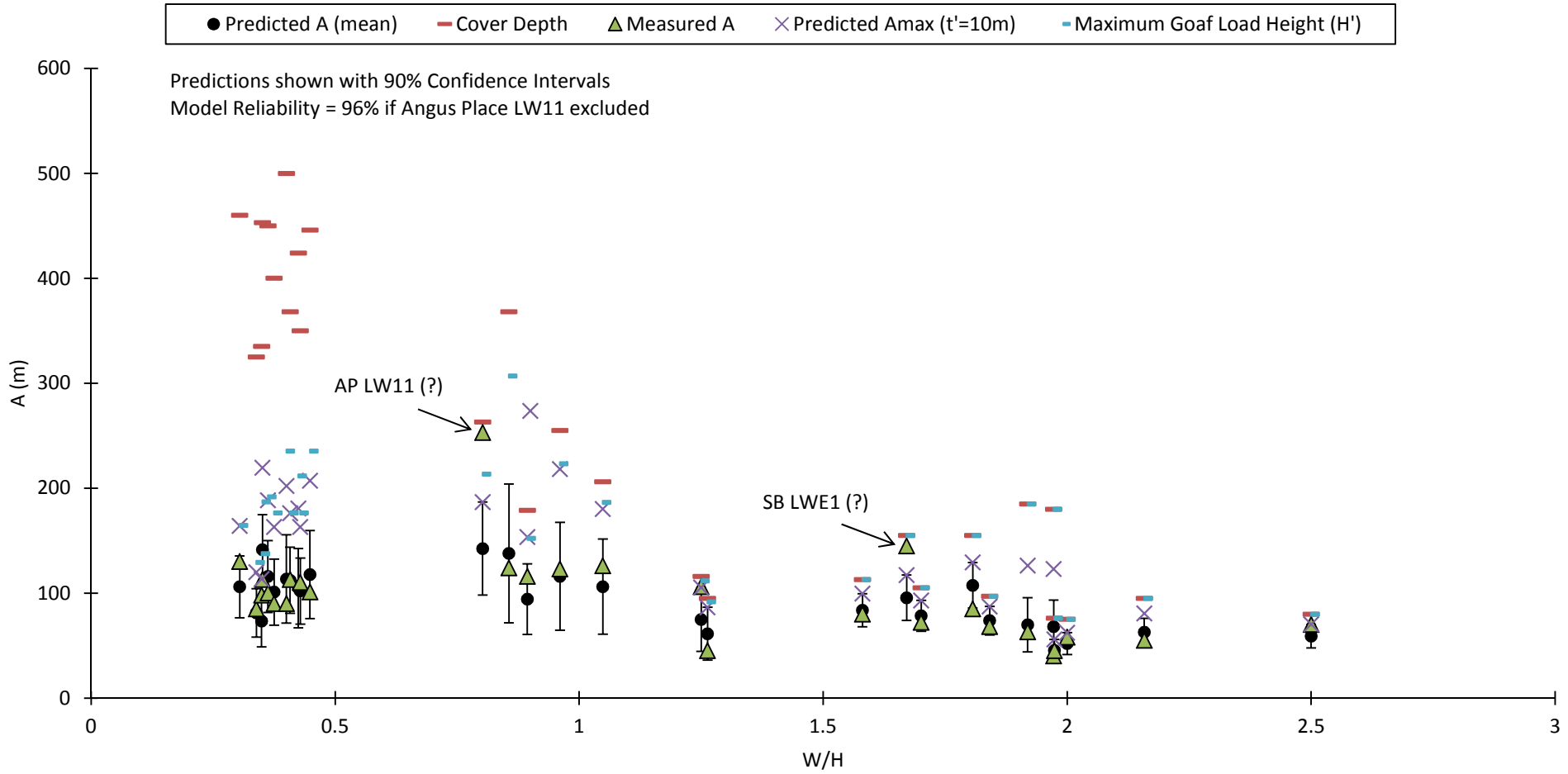
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	30.08.13	Title:	Height of Goaf Load Angle for PI-Term Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42b



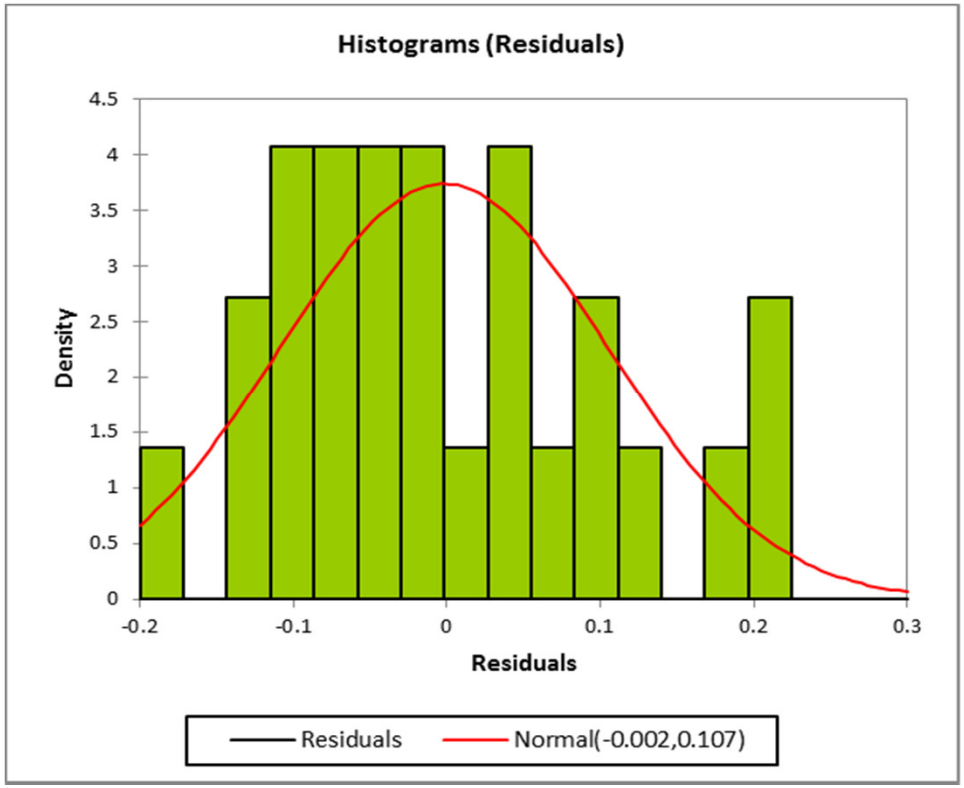
DgS	Engineer: S.Ditton	Client:	Review of Height of Fracturing Data
	Drawn: S.Ditton		
	Date: 23.08.13	Title:	Measured Heights of Continuous Fracturing with Alternative Prediction Model Assumptions for Goaf Load Height /Cover Depth (H'/H)
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS — Figure No: A42c

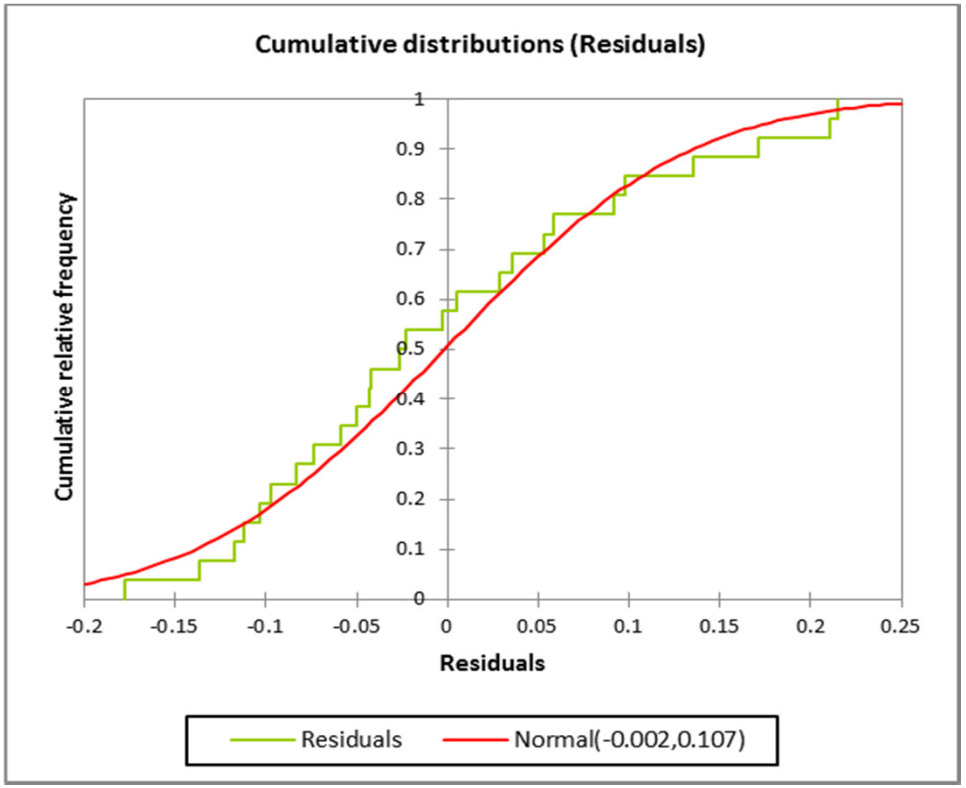


DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	30.08.13	Title:	Results of Non-Linear Regession Analysis: Predicted v. Measured Value Analysis for Height of A-Zone Fracturing	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42d



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	30.08.13	Title:	Results of Non-Linear Regession Error analysis for Height of A-Zone Prediction Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42e

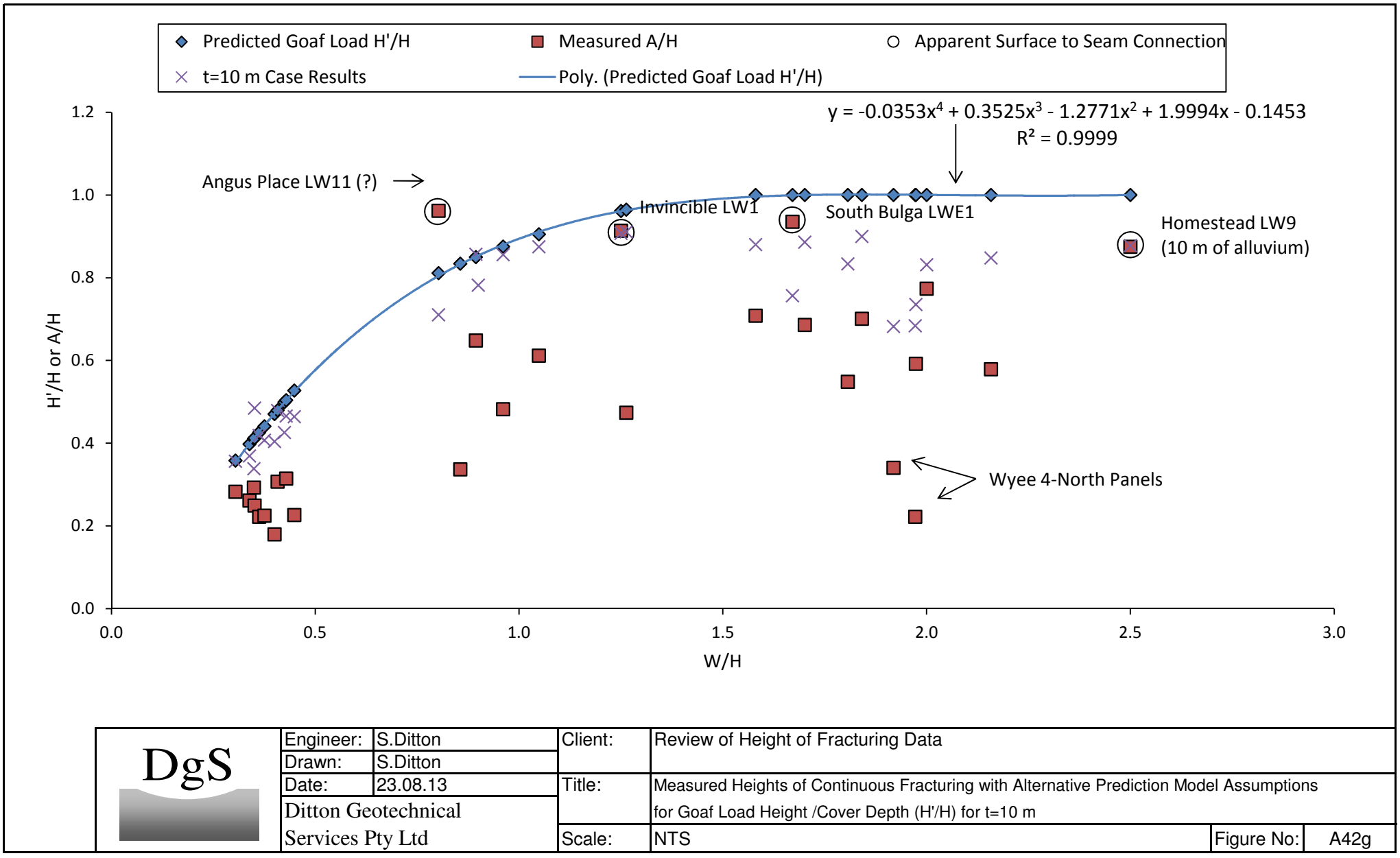




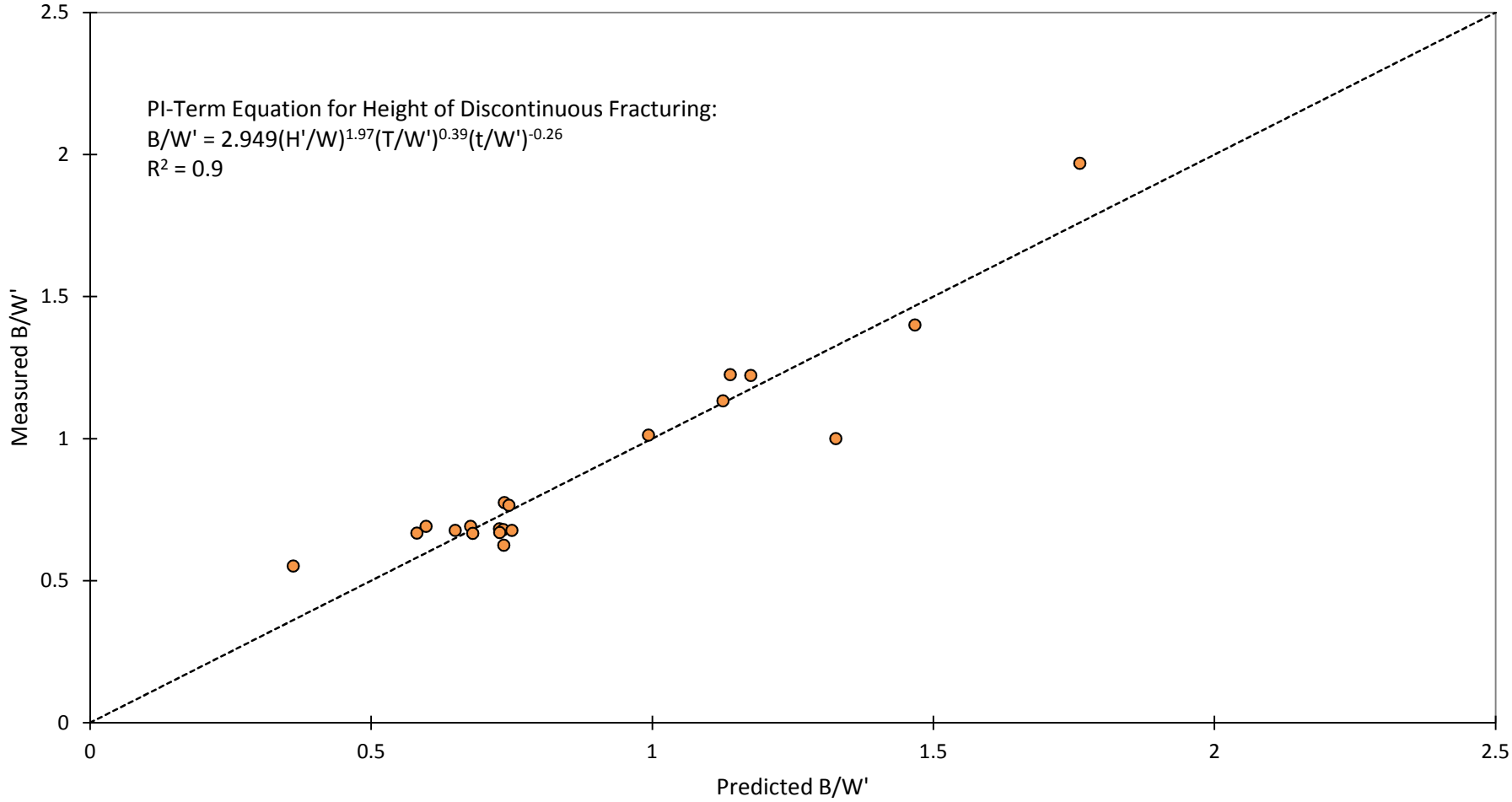
D	0.118
p-value	0.839
alpha	0.05

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 83.93%.

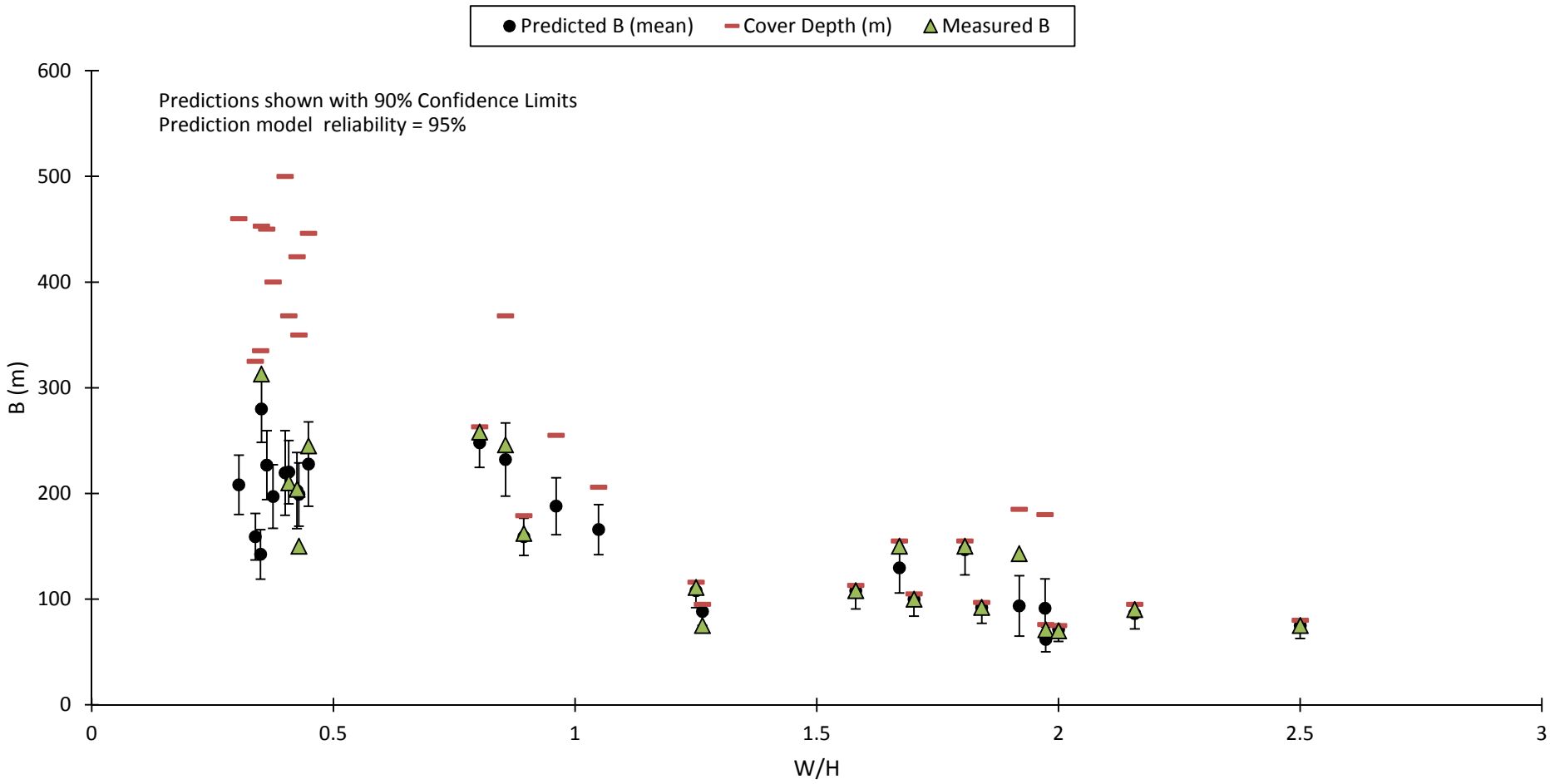
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	23.08.13	Title:	Results of Non-Linear Regession Error analysis for Height of A-Zone Prediction Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42f



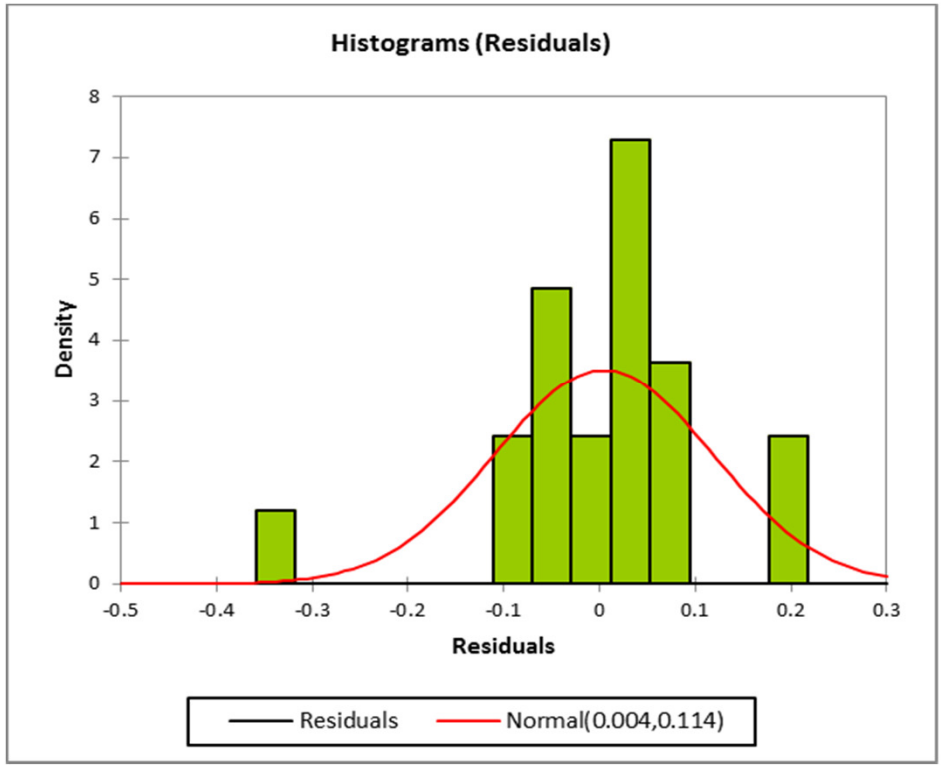
DgS	Engineer: S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn: S.Ditton			
	Date: 23.08.13	Title:	Measured Heights of Continuous Fracturing with Alternative Prediction Model Assumptions for Goaf Load Height /Cover Depth (H'/H) for t=10 m	
	Ditton Geotechnical Services Pty Ltd	Scale:	NTS	Figure No: A42g

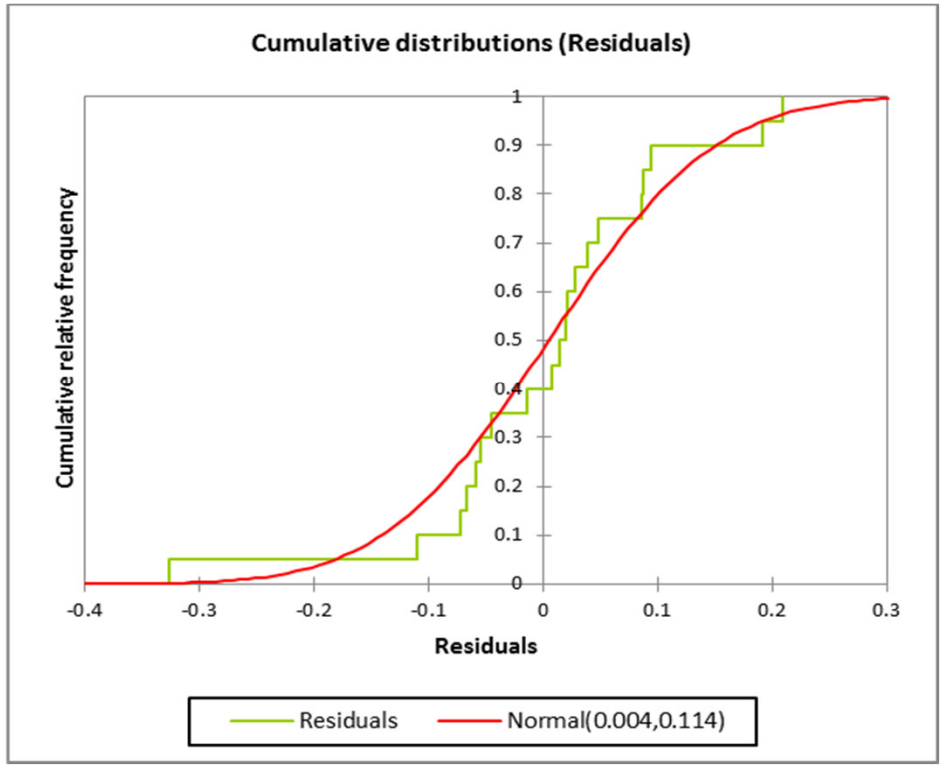


DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	30.08.13	Title:	Results of Non-Linear Regession: Predicted v. Measured Value Analysis for Height of B-Zone Prediction Model Normalised to Effective Panel Width	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42h



DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	26.08.13	Title:	Results of Non-Linear Regession: Predicted v. Measured Value Error Bar Analysis for Height of B-Zone Predictions v. W/H	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42i





Kolmogorov-Smirnov test:

D	0.149
p-value	0.731
alpha	0.05

Test interpretation:

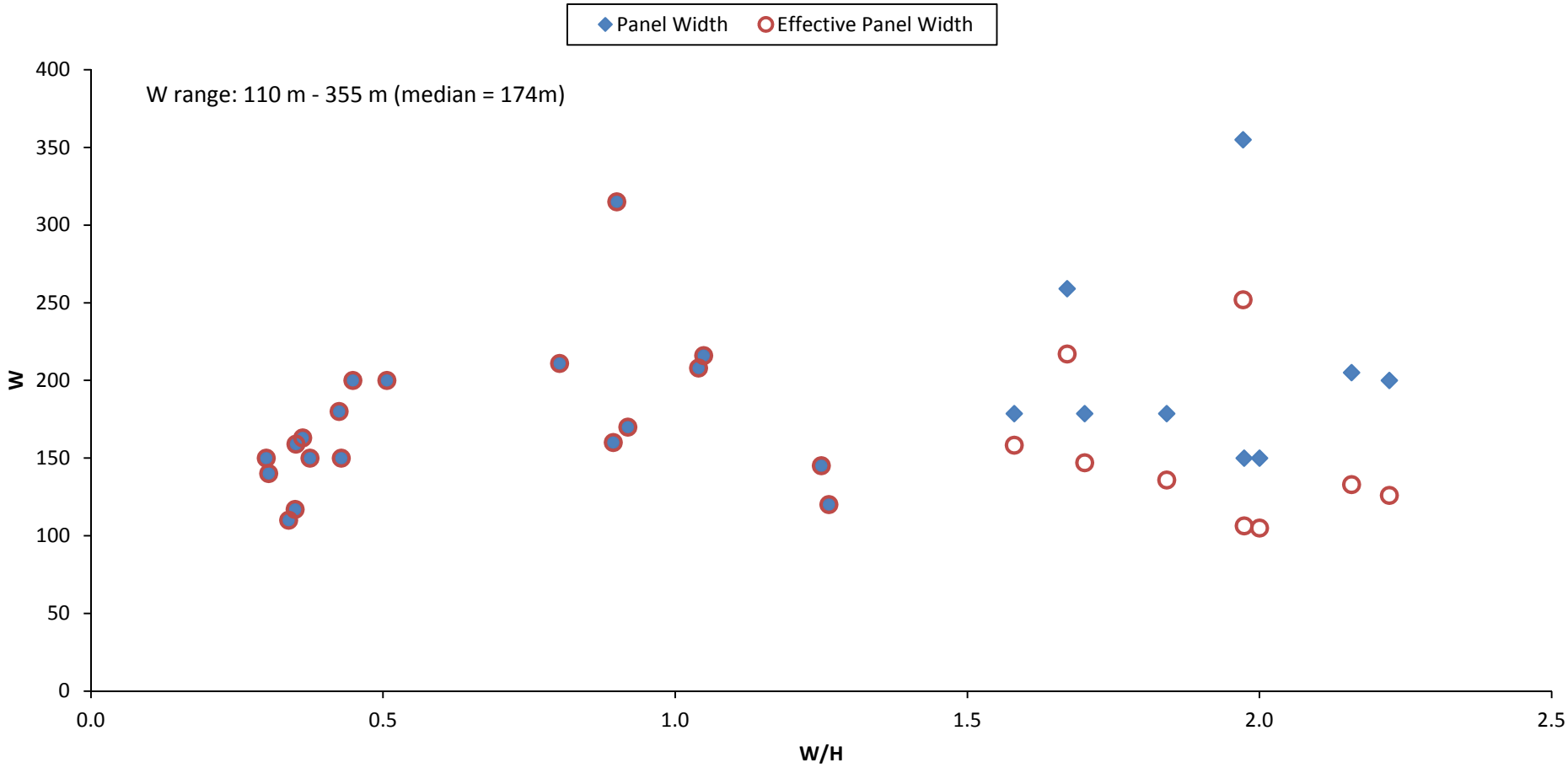
H0: The sample follows a Normal distribution

Ha: The sample does not follow a Normal distribution

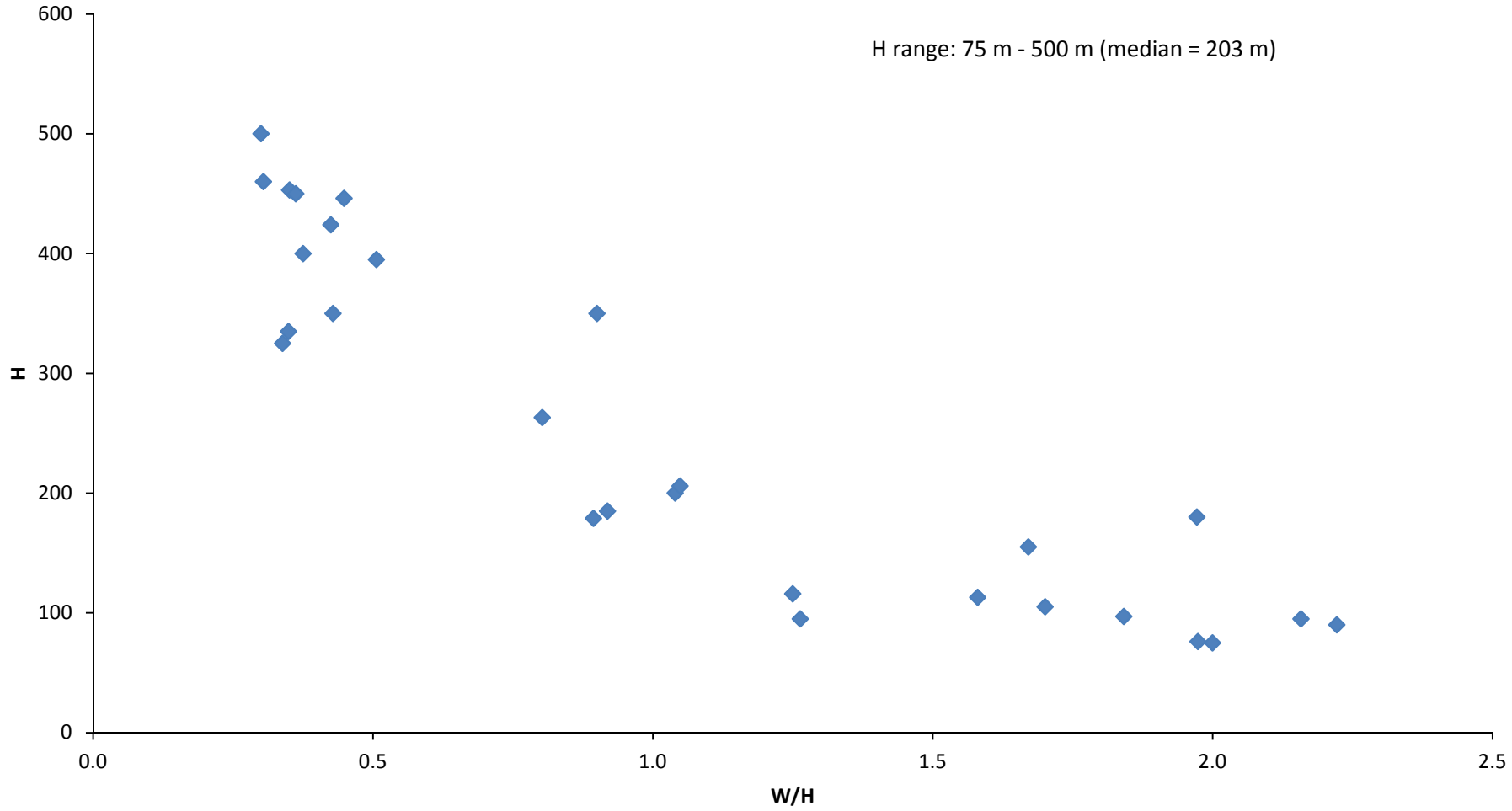
As the computed p-value is greater than the significance level alpha=0.05, one cannot reject the null hypothesis H0.

The risk to reject the null hypothesis H0 while it is true is 73.07%.

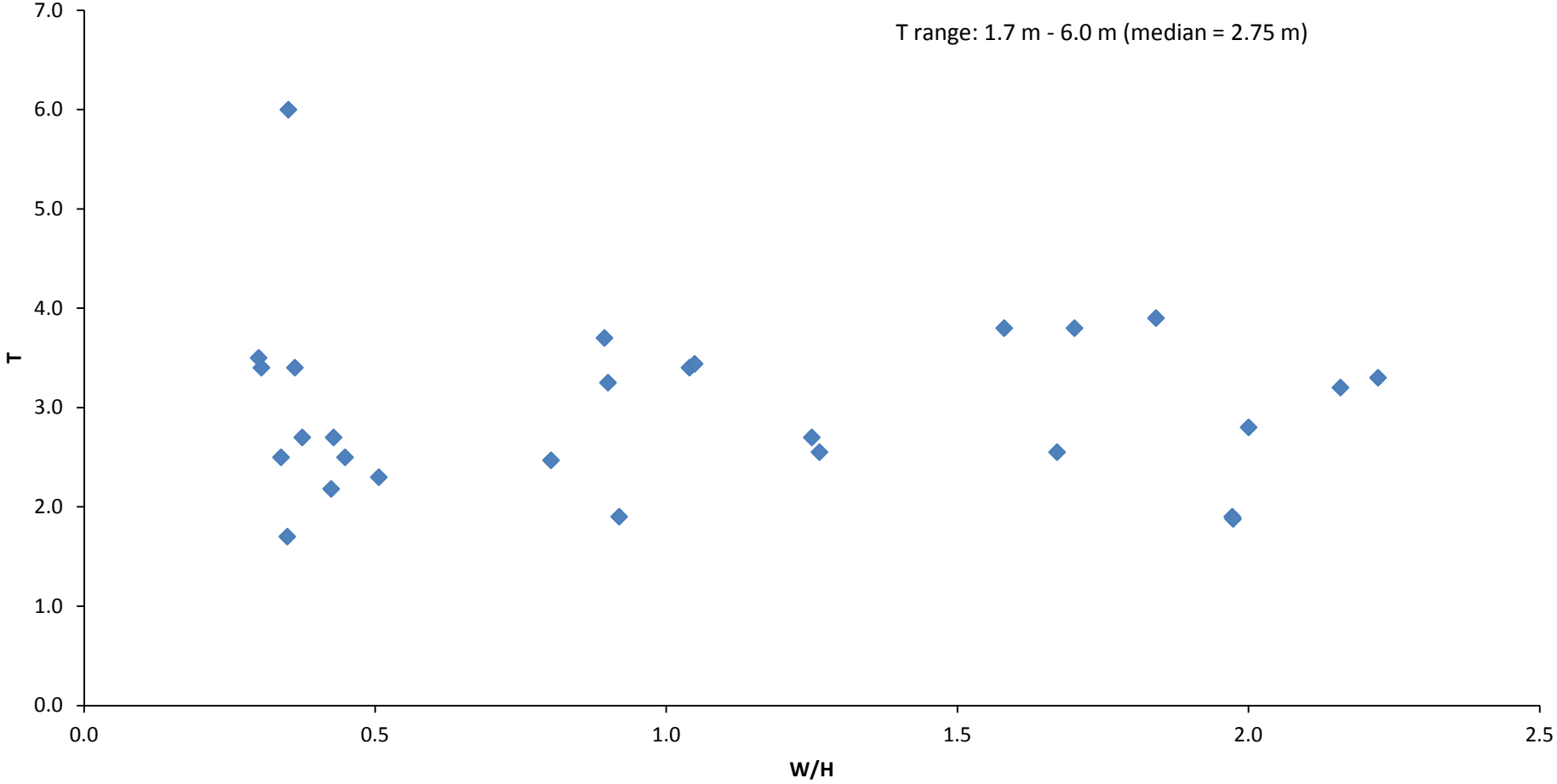
DgS	Engineer:	S.Ditton	Client:	Review of Height of Fracturing Data	
	Drawn:	S.Ditton			
	Date:	30.08.13	Title:	Results of Non-Linear Regession Error analysis for Height of B-Zone Prediction Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A42j



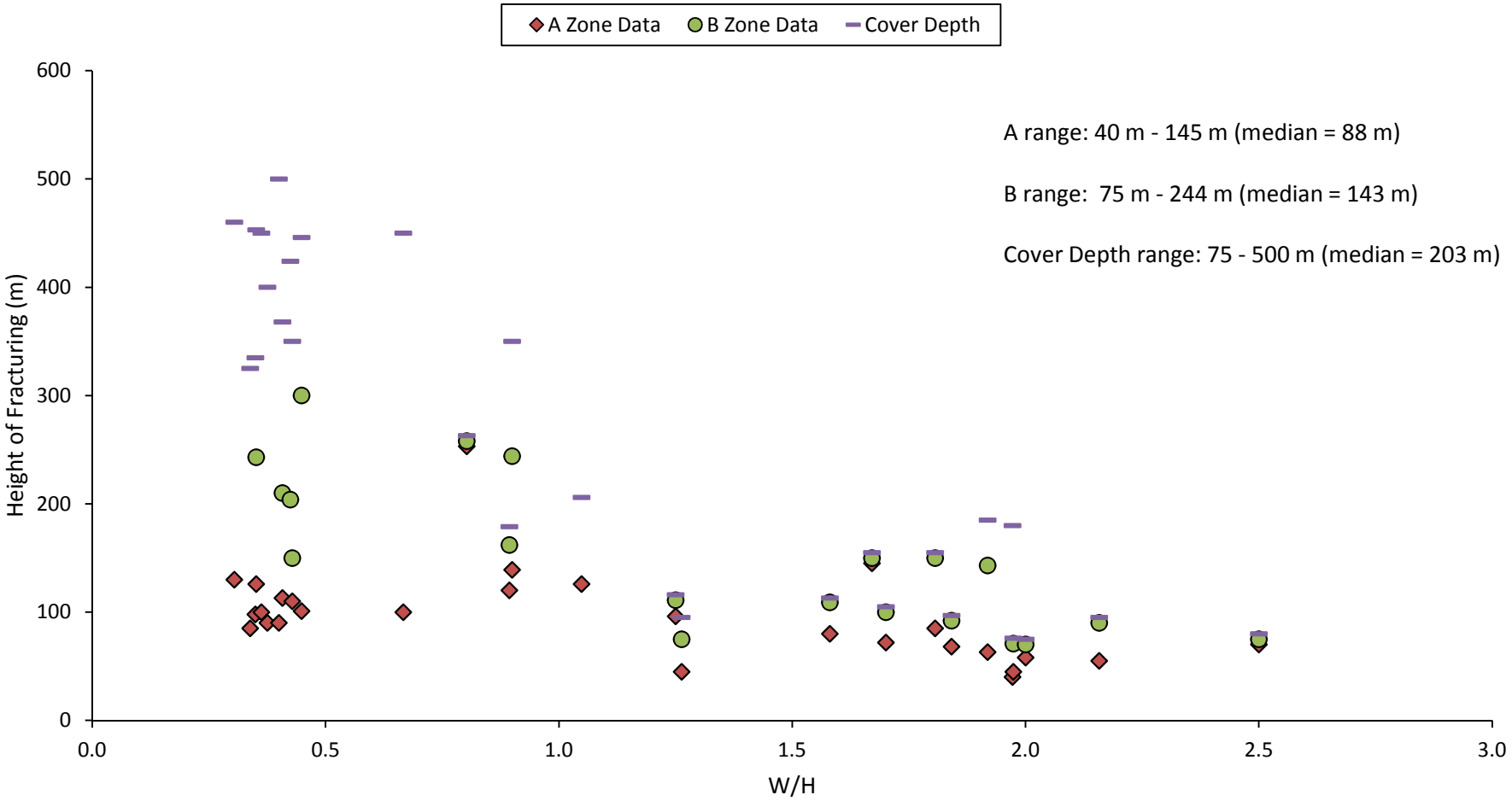
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	03.12.12	Title:	Panel Width v. W/H Database for Sub-surface Fracturing Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A43a



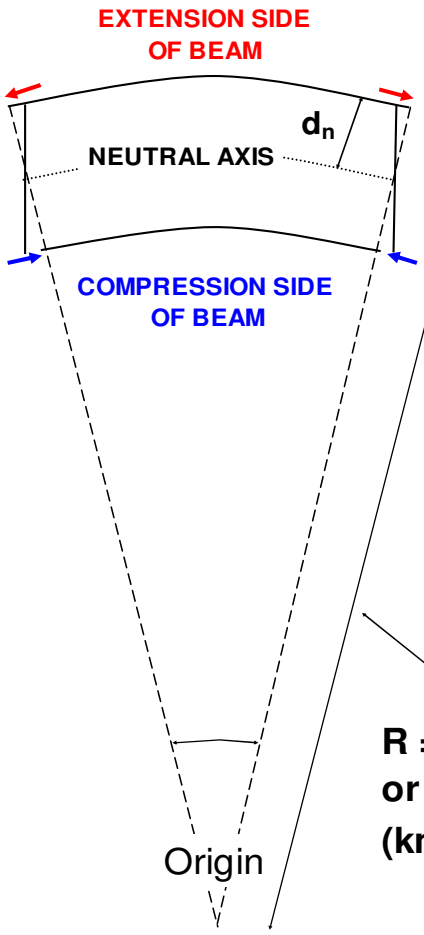
DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	03.12.12	Title:	Cover Depth v. W/H Database for Sub-surface Fracturing Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A43b



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: 43c



DgS	Engineer:	S.Ditton	Client:	Modified from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	03.12.12	Title:	Measured A-Zone and B-Zone Fracture Heights v. W/H Database for Sub-surface Fracturing Model	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: 43d



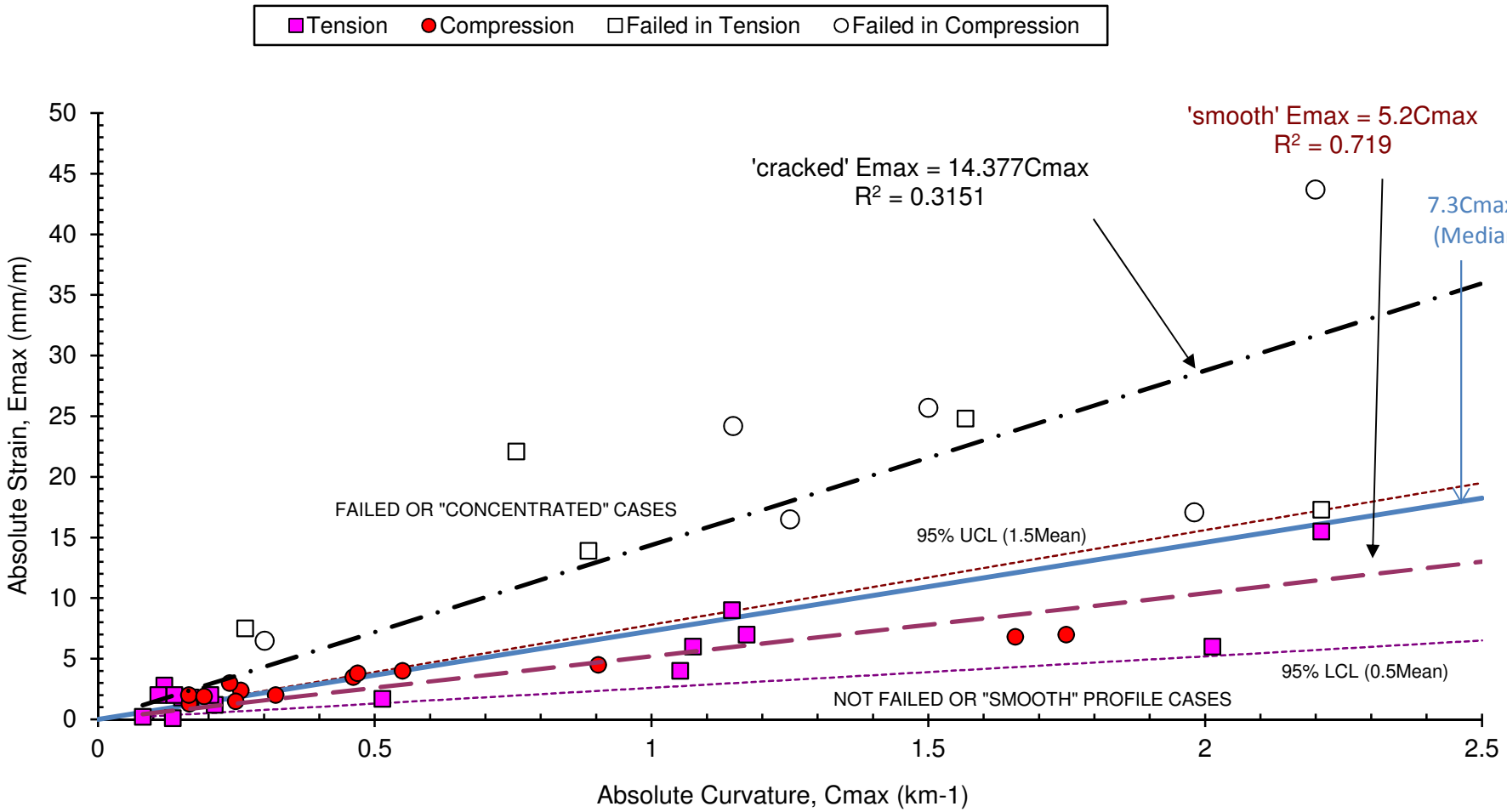
Strain E = (mm/m)
Curvature C = km^{-1}

$E = C \times d_n$

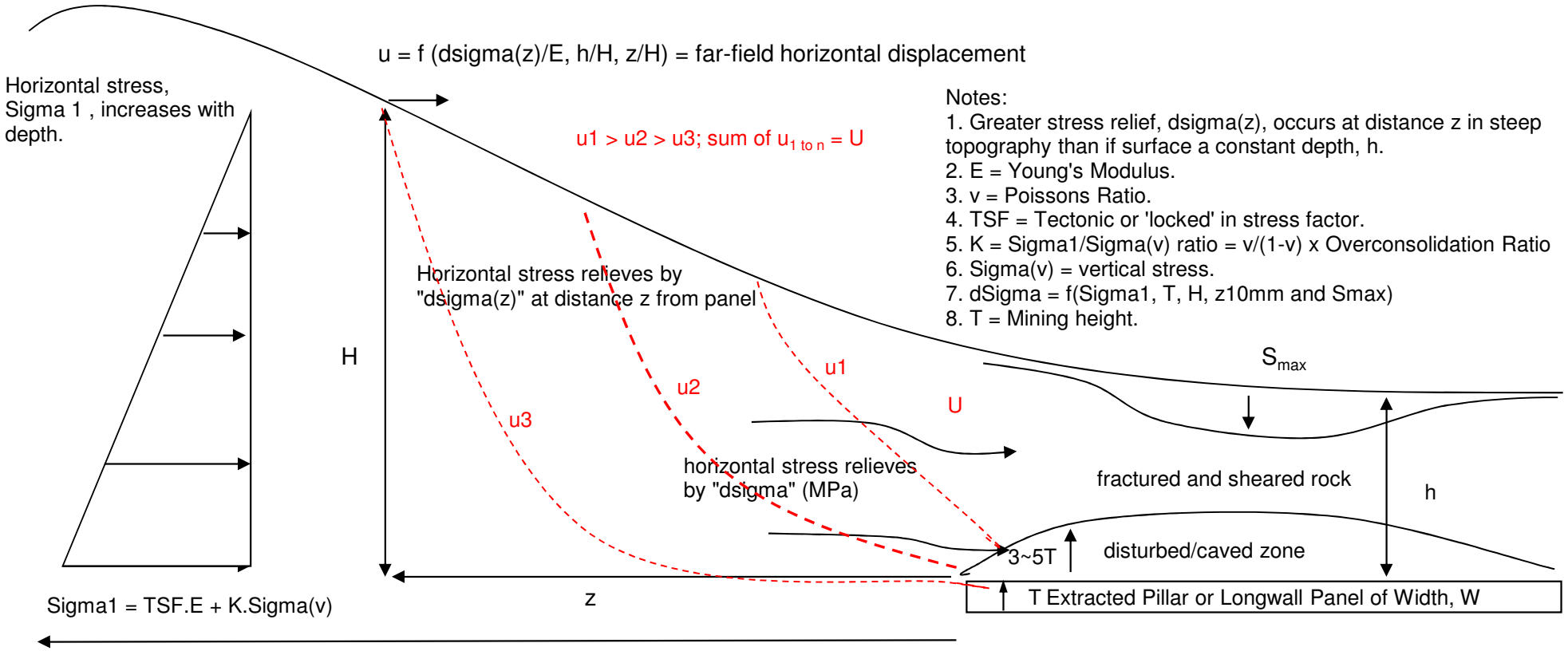
Mean - Median
d_n = 5.2 m
to 7.3 m
for database
= Depth of Cracking

R = Radius of curvature or the curvature, C = 1/R (km^{-1})

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: A43e

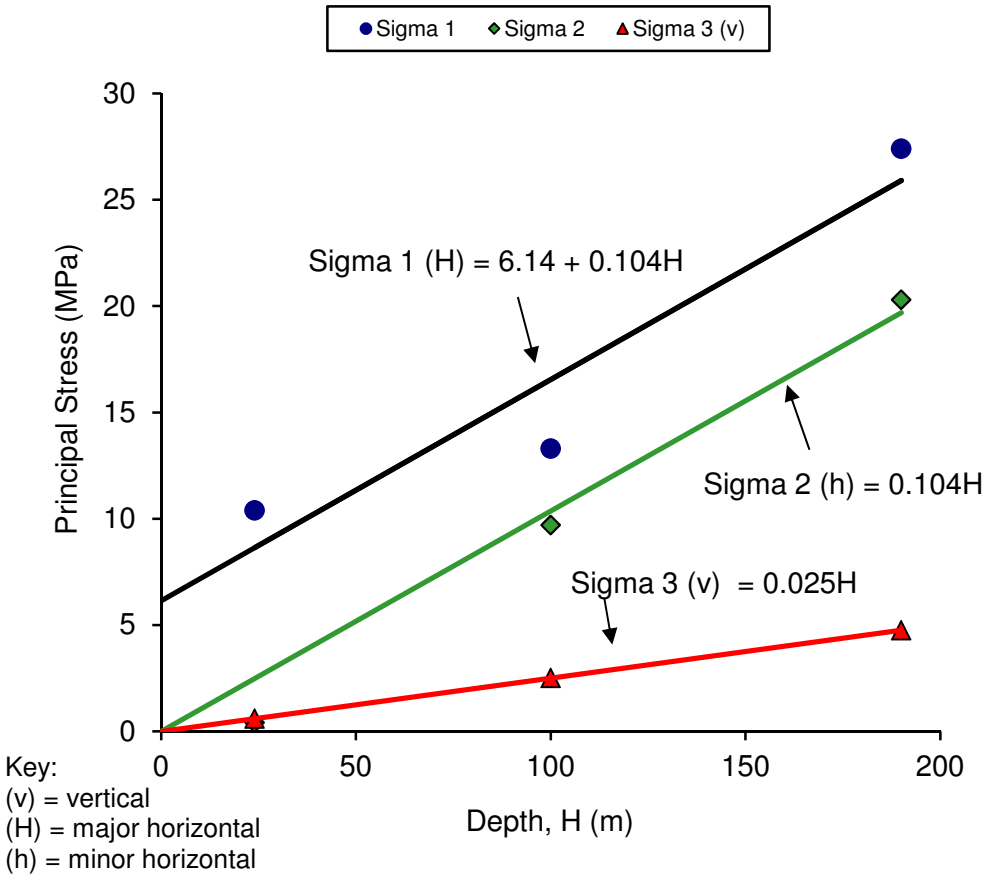


DgS	Engineer:	S.Ditton	Client:	Extract from ACARP, 2003	
	Drawn:	S.Ditton			
	Date:	08.08.08	Title:	Empirical Model for Maximum Panel Strain Prediction Above Longwall Panels for Smooth and Cracked Profiles in the Newcastle Coalfield	
Ditton Geotechnical Services Pty Ltd			Scale:	NTS	Figure No: A43f

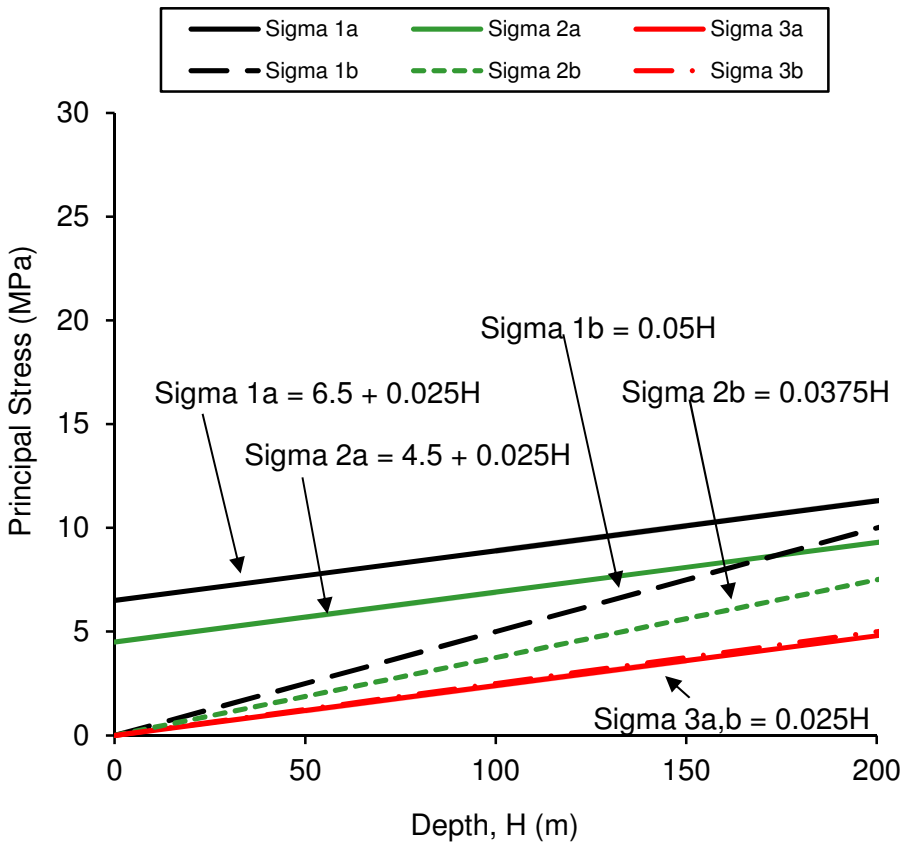


Simple Analytical Model for Predicting Total FFD : U = 0.5(Sigma1 x 12.3/2)z10mm/[E(H+h)/2] + 'tail' of 10mm + Smax component (refer to text)

DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Conceptual Model of Far-Field Displacement Outside Angle of Draw Limits from Pillar Extraction or Longwall Panels	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A44a

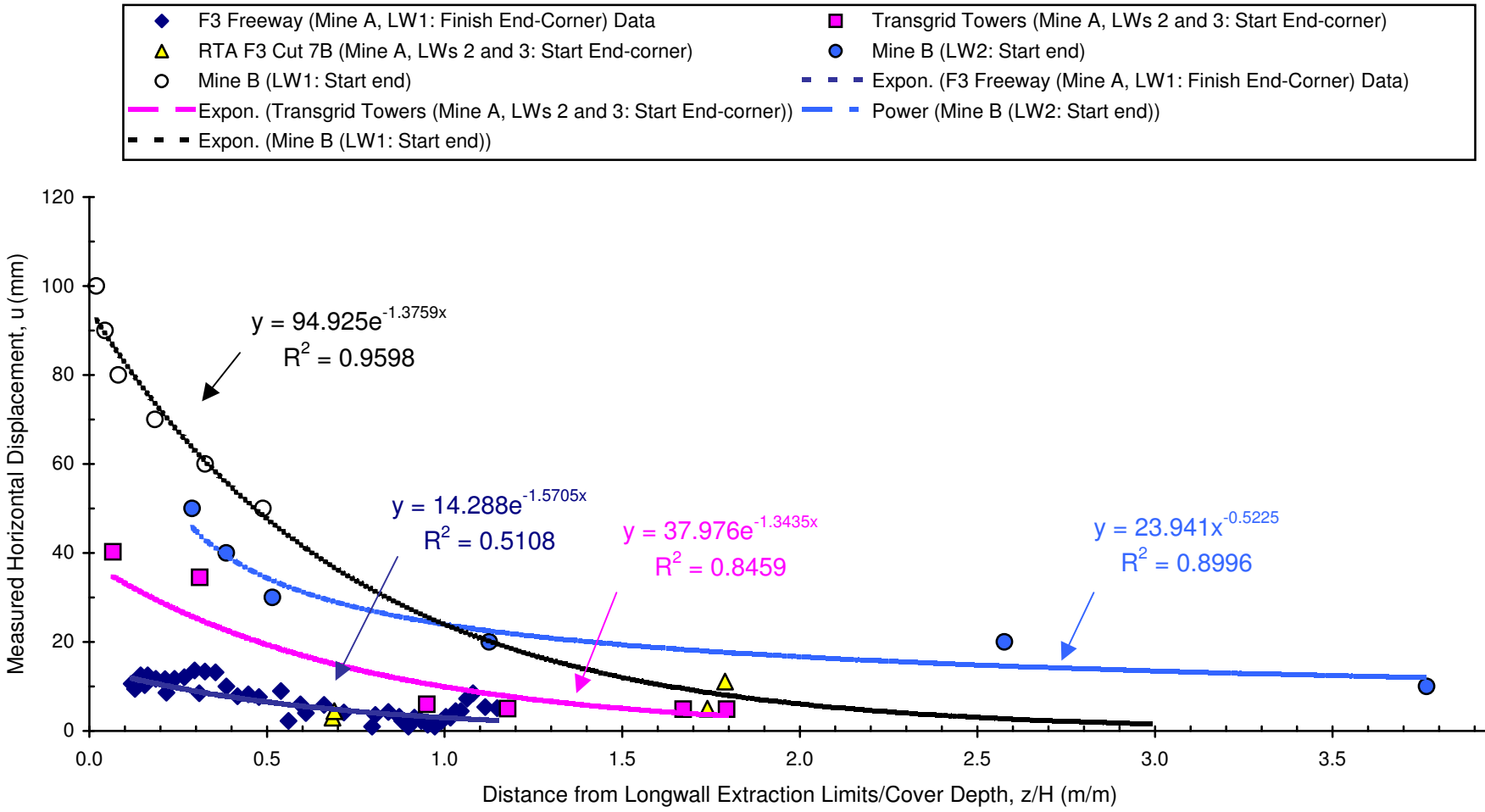


Measured Stress Field for F3 Freeway, West of Newcastle (Lohe & Dean Jones, 1995)

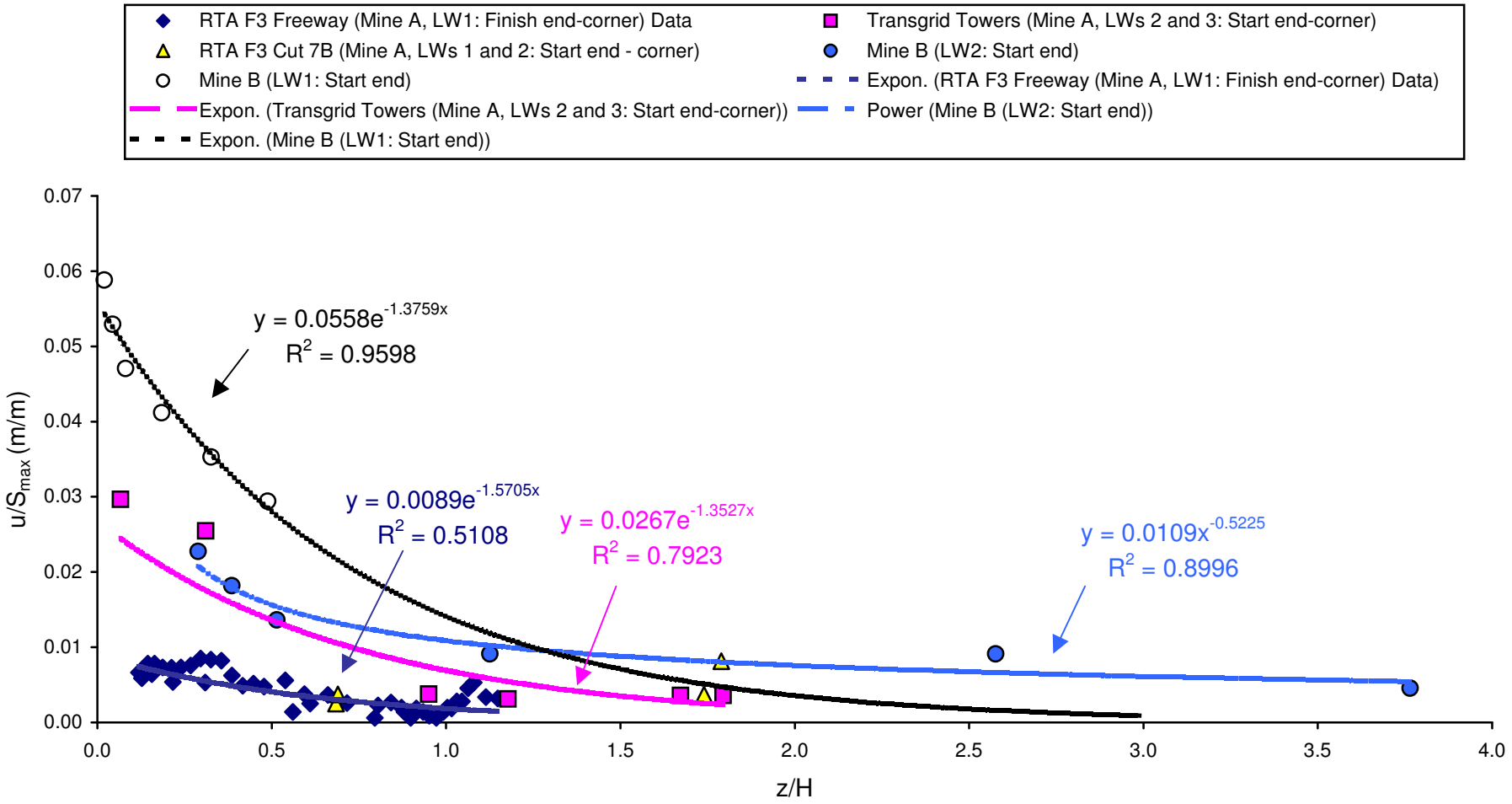


Typical Stress Field Models for Sydney Basin Overburden a) McQueen, 2004; b) Lohe & Dean Jones, 1995; c) Pells, 2002 not shown for clarity (refer to text).

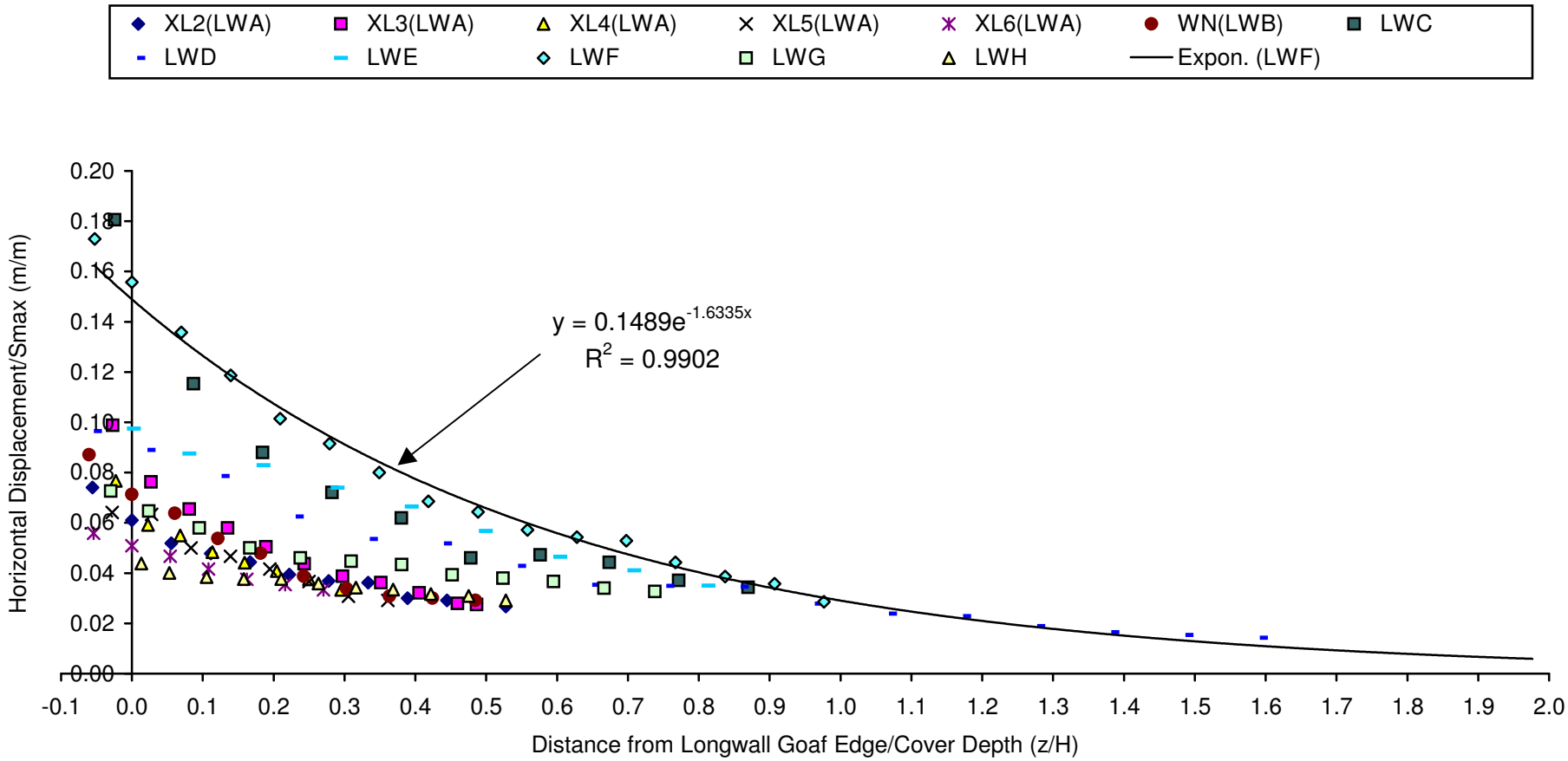
DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	12.07.07	Title:	Published Principal Stress Field Models for Sydney Basin and Western Area of Newcastle Coalfield	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A44b



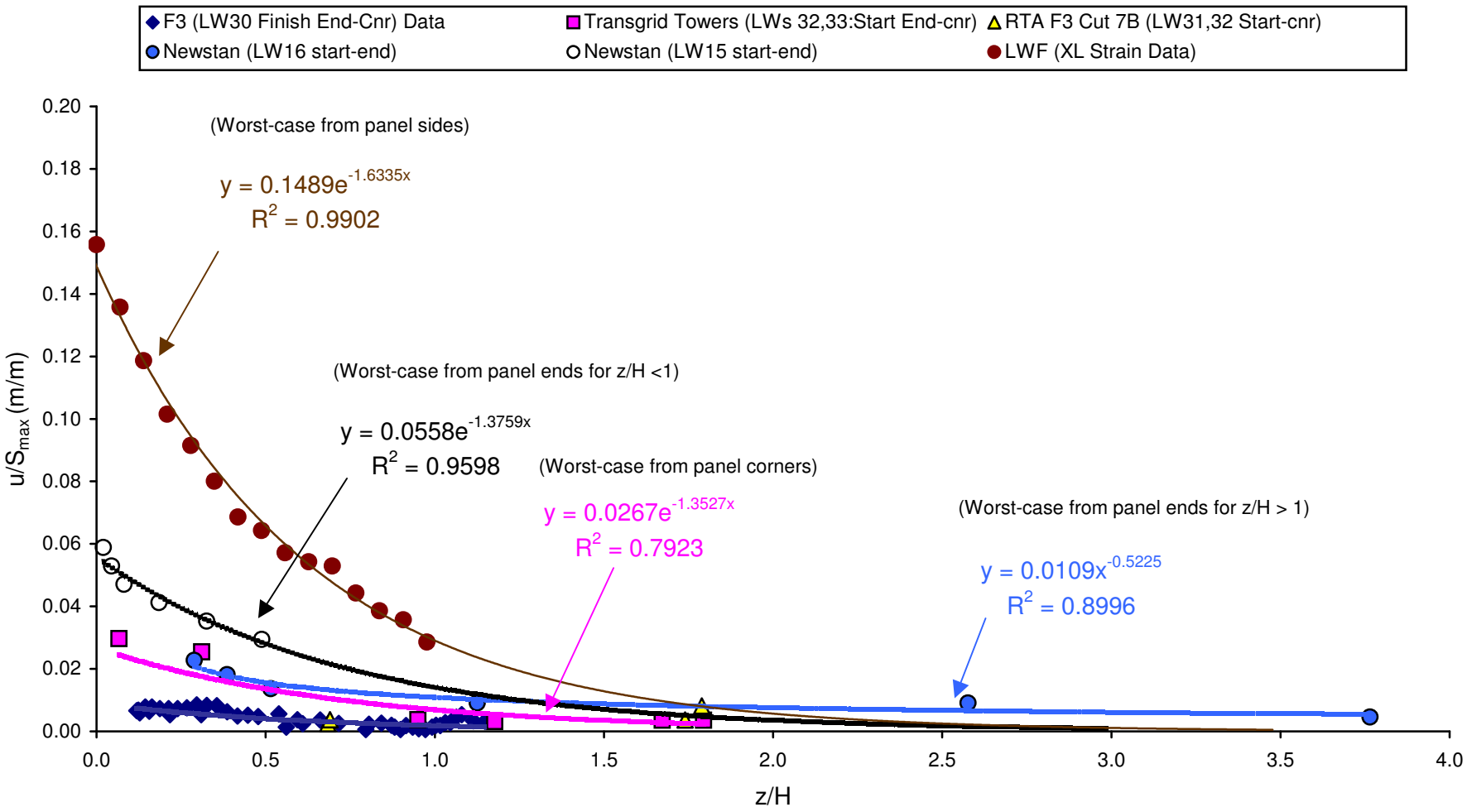
DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Empirical far-field displacement prediction model using total station electronic distance measurements from longwall panel ends	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A45



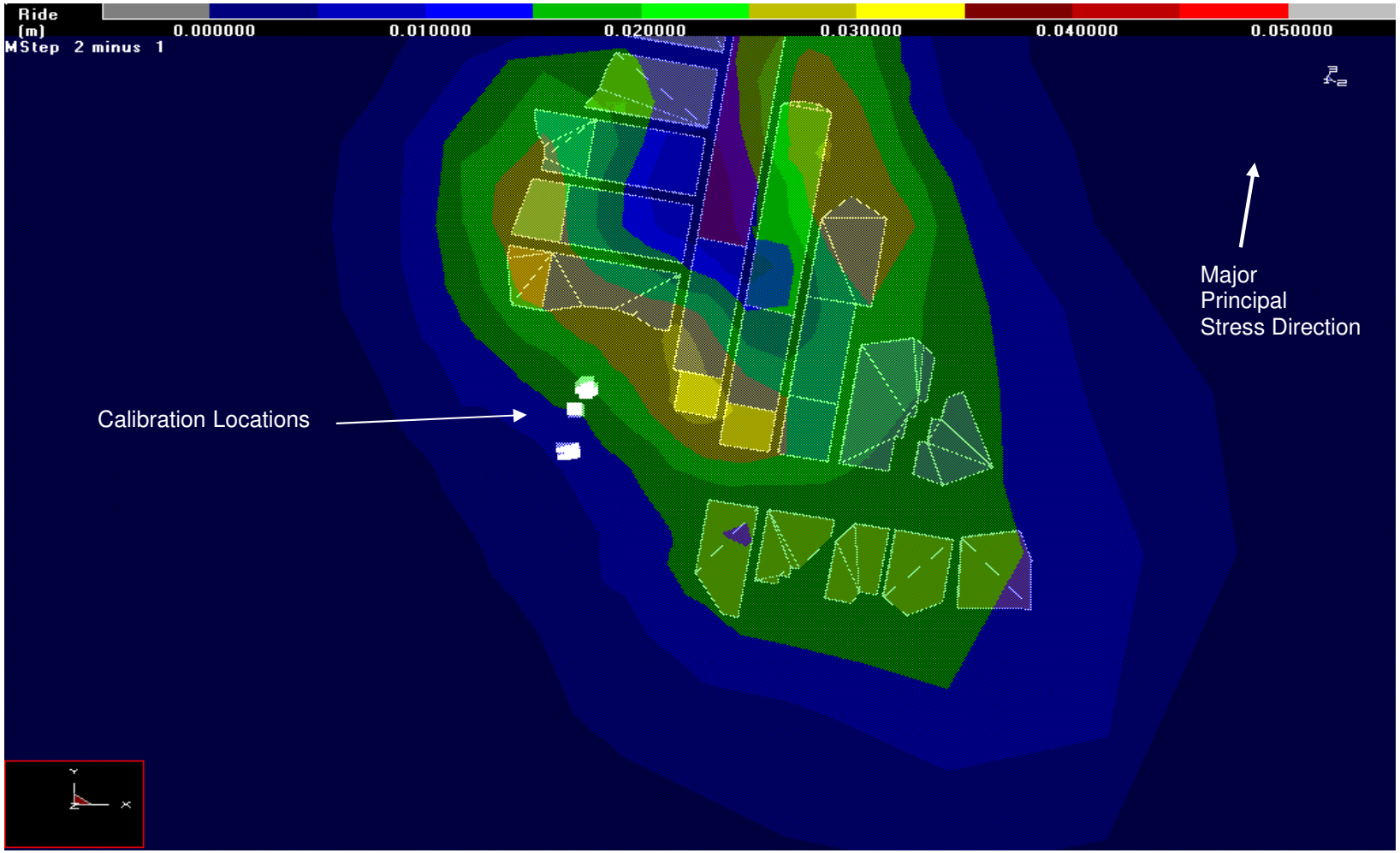
DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Empirical far-field displacement prediction model using total station electronic distance measurements from longwall panel ends and normalised to maximum panel subsidence	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A46



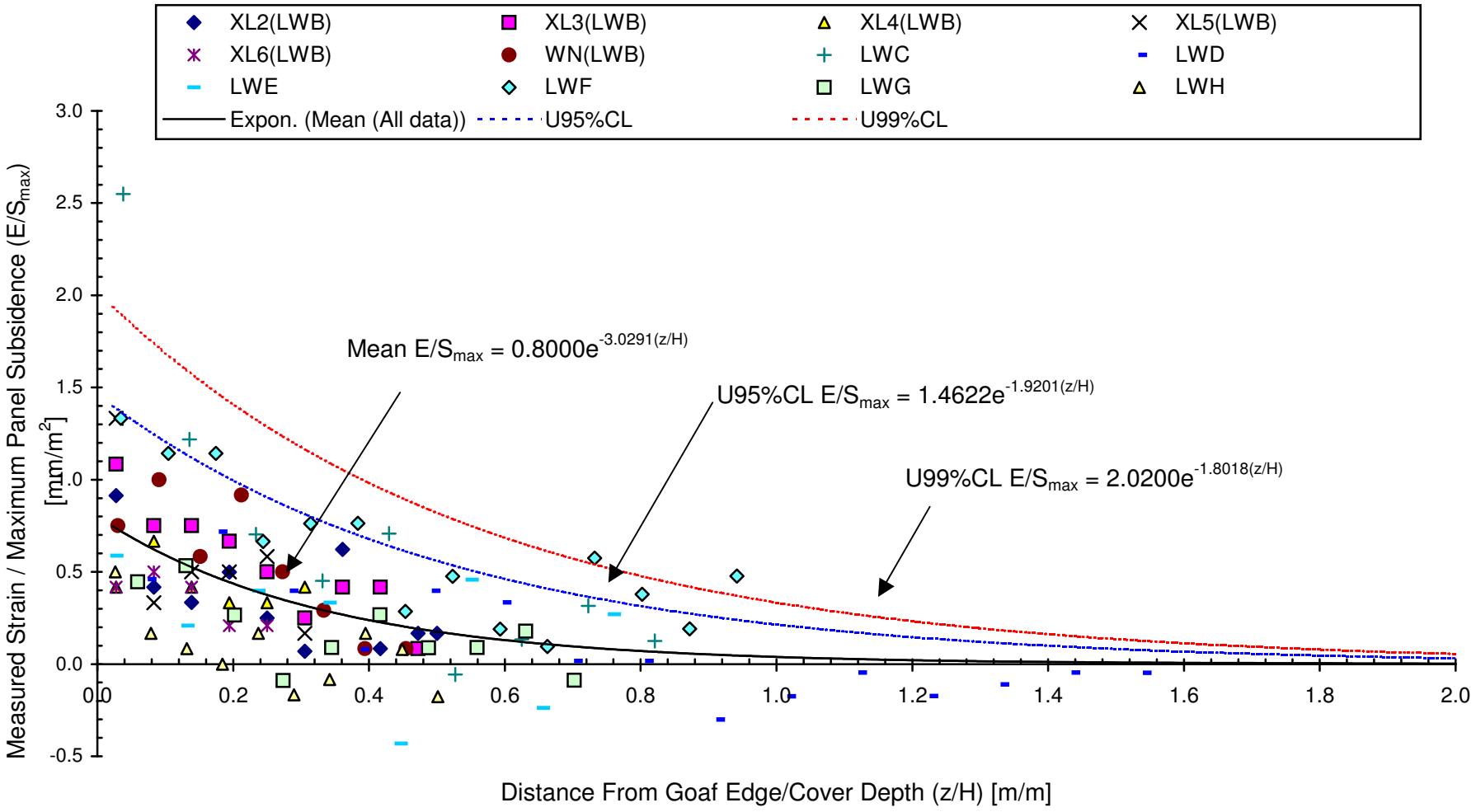
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	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Empirical far-field displacement prediction model using cummulative steel tape measurements from longwall sides and normalised to maximum panel subsidence	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A47



DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Combined empirical far-field displacement prediction models for longwall panel sides, ends and corners.	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A48



DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Example of Map-3D Elastic Boundary Element Model Far-Field Displacement Contours Around a Complex Pillar Extraction Mining Layout	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A49



DgS	Engineer:	S.Ditton	Client:	DgS, 2007	
	Drawn:	S.Ditton			
	Date:	22.05.07	Title:	Empirical far-field strain prediction model using cummulative steel tape measurements from longwall sides and normalised to maximum panel subsidence	
	Ditton Geotechnical Services Pty Ltd		Scale:	NTS	Figure No: A50

S D P S

Surface Deformation Prediction System
for Windows
version 5.2

Quick Reference Guide and Working Examples

by

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This software package is the property of the Department of Mining and Minerals Engineering, VPI & SU. It has been licensed and may be distributed only to O.S.M.R.E. and State Regulatory Agencies. The SDPS software can be purchased by individuals and/or companies through Carlson Software.

February 2002

List of Symbols

w	the panel width; the minimum dimension of a panel
h	panel depth; the vertical distance between the mining horizon and the surface; also known as the overburden thickness
m	the seam thickness; the extraction thickness (note that the extraction thickness may be different than the seam thickness)
R	the extraction ratio
R*	the adjusted extraction ratio
d	the distance of the inflection point from the rib (a positive value indicates that the position of the inflectionpoint is inby); also referred to as the “edge effect”
β	the influence angle
r	the influence radius
Smax	the maximum subsidence
a	the maximum subsidence factor
Bs	the strain coefficient
%HR	the percent hardrock in the overburden
Wp	the pillar width
Hp	the pillar height
Wo	the opening width

1.7 Overview of Subsidence Parameters

Maximum Subsidence Factor
The values of maximum subsidence factor, as function of the width-to-depth ratio and the percent hardrock in the overburden, are shown in the supercritical subsidence factor tables for longwall panels and for room-and-pillar panels respectively. When using the profile function method, the subsidence factor is calculated for the actual width-to-depth ratio of the panel. For example, for a panel with W/h = 0.8 (subcritical) and %HR = 50% the subsidence factor is equal to 0.38.

When using the influence function method, the technique requires knowledge of the supercritical subsidence factor, which will subsequently be adjusted through the superposition concept by the program itself. For example, for a panel with W/h = 0.8 (subcritical) and %HR = 50% the subsidence factor is found for W/h = 1.5 (supercritical) and equal to 0.40.

Notes:
A panel is considered supercritical for W/h greater than 1.2. Due to numerical approximations there may be slight variations to the supercritical subsidence factors presented in the supercritical subsidence factor tables.

Inflection Point
The location of the inflection point from the rib, with respect to overburden depth (d/h), can be estimated based on two empirical curves (see the Inflection Point Diagram). Both curves were statistically generated from the available field data. The first is an average curve based on a least squares estimator, while the second is considered an envelope or conservative curve in the sense that it tends to overpredict the surface impact of a given excavation area. In essence, this means that for average data the predicted subsidence profile could be either inside or outside of the measured subsidence line, whereas for conservative (envelope) data, an attempt is made to keep the prediction lines outside the measured ones, i.e. overestimate the influence of the mined area to the surface.

From experience and constant validation of the programs, the authors recommend that, for Appalachian predictions, improved accuracy is obtained by using the following rule:
determine the d/h ratio using the conservative curve for subcritical panels (W/h < 1.2)
determine the d/h ratio using the average curve for supercritical panels (W/h >= 1.2).

Notes:
Always use the actual width-to-depth ratio.

Angle of Influence
The angle of principal influence (β, beta) is one of the basic parameters used in the influence function method since it has a major impact on the distribution of the deformations on the surface. It is measured in degrees from the horizontal and the

average value determined for the Appalachian coalfields is beta=67 deg. The parameter required for these calculations is the tangent of this angle (i.e. tanβ = 2.31). The angle of influence is related to the radius of influence as shown in the equation:

$$\tan\beta = \frac{h}{r}$$

where
h = the overburden depth
r = the radius of influence

This value should be determined for each site by fitting a calculated subsidence profile to a measured subsidence profile. If this is not possible, the influence angle can be approximately set as the complementary angle to the angle of draw.

Supercritical Subsidence Factor Tables
The supercritical subsidence factors used in the calculations are presented in Tables 1.7.1 and 1.7.2.

Table 1.7.1: Calculation of maximum subsidence factors (Smax/m) for longwall panels

	Percent Hardrock in the Overburden							
W/h	10%	20%	30%	40%	50%	60%	70%	80%
0.6	0.64	0.59	0.51	0.42	0.34	0.26	0.21	0.16
0.7	0.69	0.63	0.55	0.46	0.36	0.28	0.22	0.18
0.8	0.71	0.65	0.57	0.47	0.38	0.29	0.23	0.18
0.9	0.72	0.66	0.58	0.48	0.38	0.30	0.23	0.19
1.0	0.73	0.67	0.58	0.49	0.39	0.30	0.24	0.19
1.1	0.74	0.68	0.59	0.49	0.39	0.31	0.24	0.19
1.2	0.74	0.68	0.59	0.49	0.39	0.31	0.24	0.19
1.3	0.74	0.68	0.60	0.49	0.40	0.31	0.24	0.19
1.4	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.5	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.6	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.7	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.8	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.9	0.76	0.69	0.60	0.50	0.40	0.31	0.24	0.19
2.0	0.76	0.69	0.60	0.50	0.40	0.31	0.24	0.19

Table 1.7.2: Calculation of maximum subsidence factors (Smax/(m R*)) for high extraction room-and-pillar panels

	Percent Hardrock in the Overburden							
W/h	10%	20%	30%	40%	50%	60%	70%	80%
0.6	0.52	0.48	0.42	0.35	0.28	0.22	0.17	0.13
0.7	0.57	0.53	0.46	0.38	0.30	0.24	0.19	0.15
0.8	0.60	0.55	0.48	0.40	0.32	0.25	0.19	0.15
0.9	0.61	0.56	0.49	0.41	0.32	0.25	0.20	0.16
1.0	0.62	0.57	0.49	0.41	0.33	0.26	0.20	0.16
1.1	0.62	0.57	0.50	0.41	0.33	0.26	0.20	0.16
1.2	0.63	0.58	0.50	0.42	0.33	0.26	0.20	0.16
1.3	0.63	0.58	0.51	0.42	0.34	0.26	0.20	0.16
1.4	0.64	0.58	0.51	0.42	0.34	0.26	0.21	0.16
1.5	0.64	0.59	0.51	0.42	0.34	0.26	0.21	0.16
1.6	0.64	0.59	0.51	0.42	0.34	0.26	0.21	0.16
1.7	0.64	0.59	0.51	0.43	0.34	0.27	0.21	0.16
1.8	0.64	0.59	0.51	0.43	0.34	0.27	0.21	0.17
1.9	0.64	0.59	0.51	0.43	0.34	0.27	0.21	0.17
2.0	0.64	0.59	0.52	0.43	0.34	0.27	0.21	0.17

Horizontal Strain Factor

The value of this factor is directly related to the magnitude of the calculated strains and curvatures over an undermined area. It can be empirically estimated by the average ratio of measured strain and curvature over a set of surface points.

The average value determined for the Appalachian coalfields is:

$$Bs = (0.35 \pm 0.05)\ \frac{h}{\tan\beta}$$

where h is the excavation depth and tanβ is the influence angle. The horizontal strain factor is expressed in units of length. The horizontal strain coefficient is unitless and its default value is 0.35.

Note: The higher the value for this coefficient, the larger the predicted strains and displacements.

Chapter 3: The Influence Function Method

3.1 Overview of the Influence Function Method

Influence function methods for subsidence prediction have the ability to consider any mining geometry, to negotiate superposition of the influence from a number of excavated areas having different mining characteristics and, also, to calculate horizontal strains as well as other related deformation indices. The function utilized in SDPS is the bell-shaped Gaussian function. This method assumes that the influence function for the two-dimensional case is given by:

$$g(x,s) = \frac{S_o(x)}{r}\exp\left[-\pi\frac{(x-s)^2}{r^2}\right]$$

where:

r	=	the radius of principal influence = h / tan(beta);
h	=	the overburden depth;
beta	=	the angle of principal influence;
s	=	coordinate of the point P, where subsidence is considered;
x	=	coordinate of the infinitesimal excavated element; and
So(x)	=	convergence of the roof of the infinitesimal excavated element.

Subsidence at any point P(s), therefore, can be expressed by the following equation:

$$S(x,s) = \frac{1}{r}\int_{-\infty}^{+\infty} s_o(x)\exp\left[-\pi\frac{(x-r)^2}{r^2}\right]$$

where:

So(x)	=	m(x) a(x);
m(s)	=	extraction thickness; and
a(x)	=	roof convergence (subsidence) factor.

The influence function formulation can thus be applied to calculate surface deformations (subsidence, strain, slope, curvature, displacements) above longwall and room-and-pillar panels, given the geometry of the excavation, information on the overburden geology, as well as the location of the prediction points on the surface. More specifically, the required data include:

- the geometry of the mine plan and the associated properties (extraction thickness, subsidence factor for supercritical conditions)

- the location (coordinates) of the points on the surface for which prediction of the deformation indices (subsidence, strain, slope, curvature, horizontal displacement) is to be performed
- the empirical parameters that numerically represent the behavior of the overburden

The typical steps required to calculate surface deformations using the influence function method, are shown below. The corresponding flowchart is also shown in Figure 3.1.1. Figure 3.1.2 presents a schematic diagram for creating the input data. Figure 3.1.3 presents typical distributions for the deformation indices that can be calculated by the influence function method. Table 3.1.1 shows all the indices that can be calculated by the influence function method.

✓ Load the Influence Function Program
✓ Input Data
✓ Mine Plan Data
  - Prediction Point Data
  - Empirical Parameters
✓ Select calculation options
  - Subsidence
  - Horizontal Strain
  - Horizontal Displacement
  - Slope
  - Curvature
✓ Save Project File
✓ Calculate Surface Deformations
✓ Load Graphing Program
✓ View Calculated Deformations

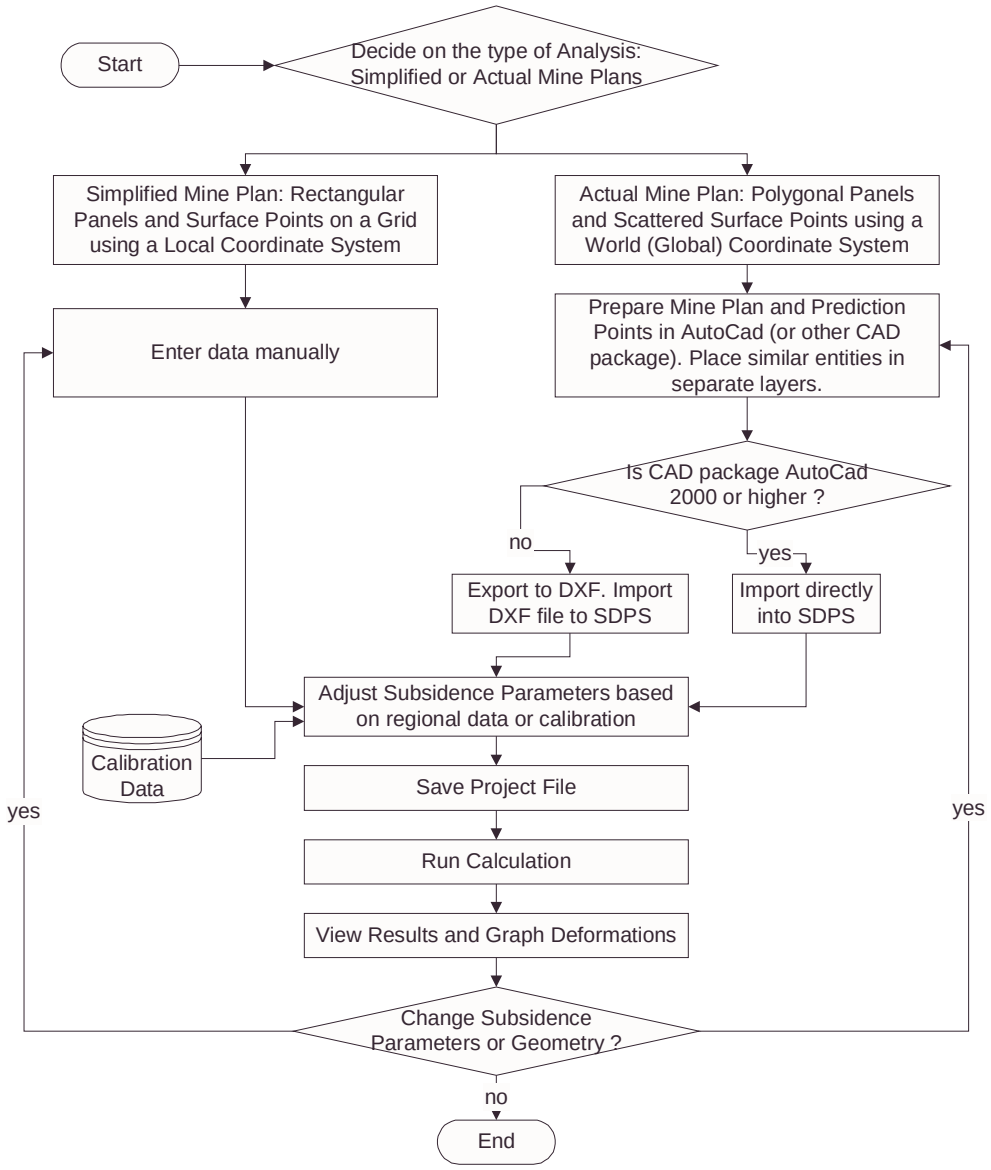
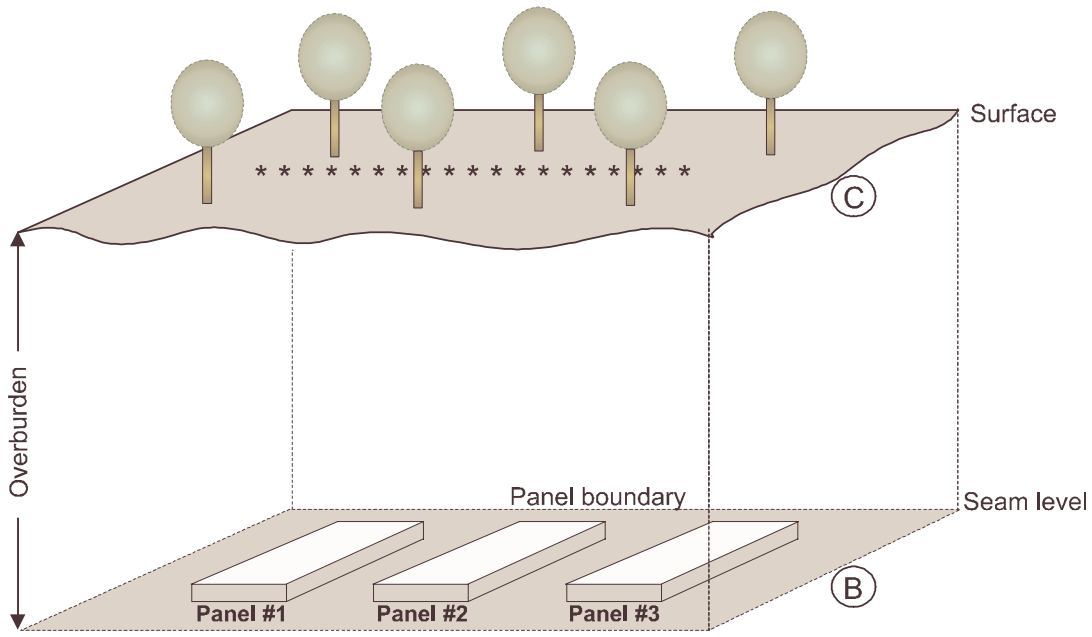


Figure 3.1.1: Flowchart diagram for using the influence function module



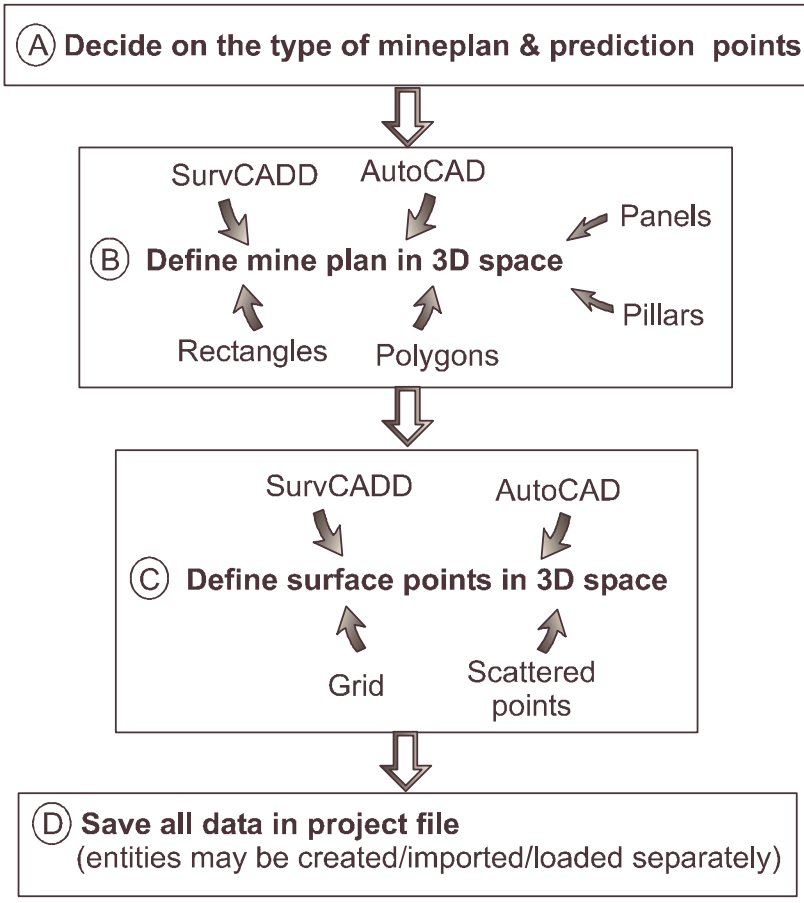
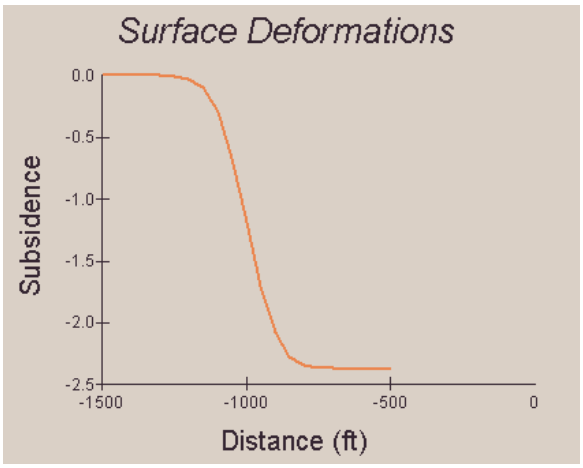
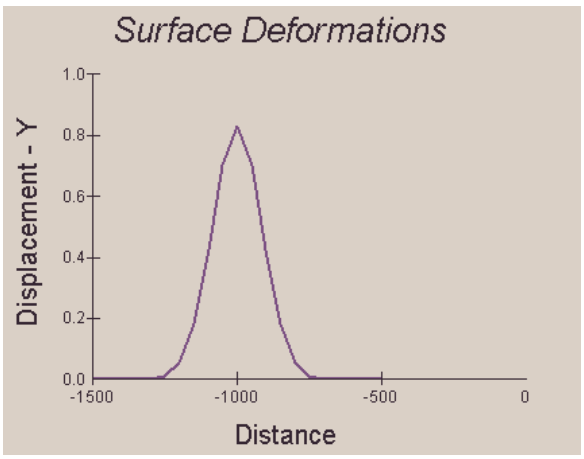
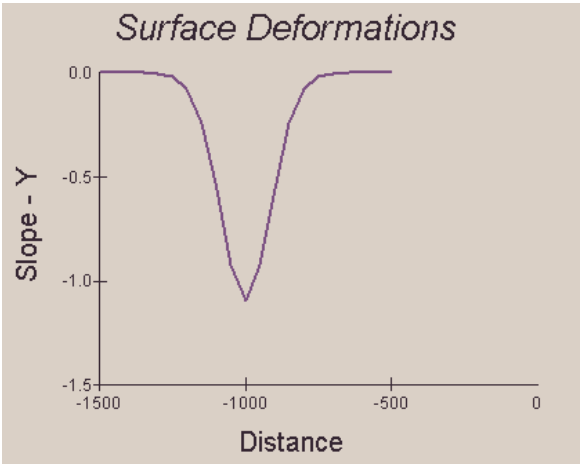


Figure 3.1.2: Steps in defining a project file







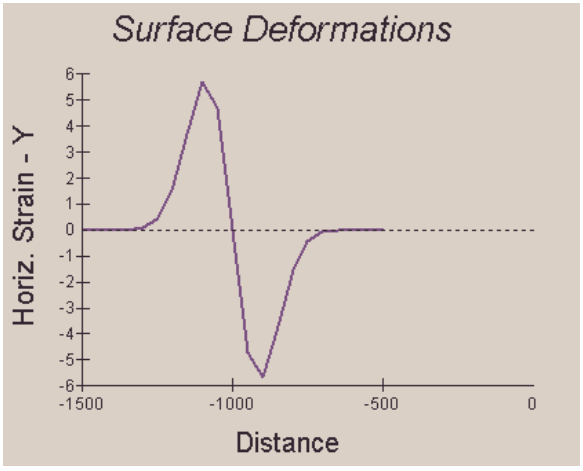


Figure 3.1.3: Typical deformation distributions

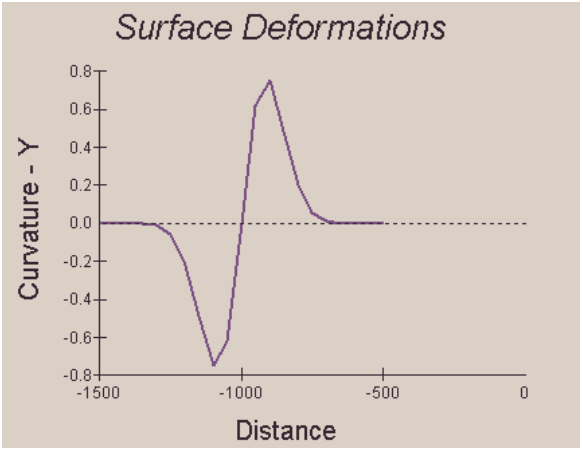


Table 3.1.1: Identification codes for deformation indices

Number	Deformation Index Name	Code	Units
1	Subsidence	SU	ft or m
2	Slope in the X-direction	TX	%
3	Slope in the Y-direction	TY	%
4	Directional Slope	TA	%
5	Maximum (Total) Slope	TM	%
6	Angle[1] of Maximum Slope	TE	deg
7	Horizontal Displacement in the X-direction	VX	ft or m
8	Horizontal Displacement in the Y-direction	VY	ft or m
9	Directional Horizontal Displacement	VA	ft or m
10	Maximum (Total) Horizontal Displacement	VM	ft or m
11	Angle[1] of Maximum Horizontal Displacement	VE	deg
12	Curvature in the X-direction	KX	1/ft or 1/m [2]
13	Curvature in the Y-direction	KY	1/ft or 1/m [2]
14	Directional Curvature	KA	1/ft or 1/m [2]
15	Maximum Principal Curvature	K1	1/ft or 1/m [2]
16	Minimum Principal Curvature	K2	1/ft or 1/m [2]
17	Maximum Curvature	KM	1/ft or 1/m [2]
18	Angle[1] of Maximum Principal Curvature	KE	deg
19	Horizontal Strain in the X-direction	EX	- [3]
20	Horizontal Strain in the Y-direction	EY	- [3]
21	Directional Horizontal Strain	EA	- [3]
22	Maximum Strain	EM	- [3]
23	Maximum Principal Strain	E1	- [3]
24	Minimum Principal Strain	E2	- [3]
25	Angle[1] of Maximum Principal Strain	EE	deg

[1] This angle is calculated in degrees from the positive x-axis in a counter-clockwise direction. It gives the direction of the maximum value of the corresponding index on the x-y plane.

[2] expressed in tenths of ppm (divide by 10.000 to obtain result)

[3] expressed in millistrains (divide by 1000 to obtain result)

3.2 Definition of the Mine Plan in the Influence Function Program

Mine plan data describe the extraction area under consideration using various conventions. An extraction area is always defined in three-dimensional space by specifying the X,Y,Z coordinates of the points defining that area. Mine panels and pillars are referred to as excavation parcels. A parcel can be either active or not active. A parcel, which is not active, is not deleted from the file, but it does not participate in the calculations.

Geometry and Boundary Adjustment:

The geometry of a mine plan is determined by the geometry of the excavation panels adjusted by the edge effect. This parameter represents the distance between the actual rib of the excavation and the position of the inflection point, as determined by panel geometry and site characteristics. The location of the inflection point, which defines the transition between horizontal tensile and compressive strain zones, is very important for the application of the influence function method. The distance of the inflection point from the rib using either an average and a conservative estimate as a function of the width-to-depth ratio of a panel can be estimated using this graph.

Thus, the magnitude of the edge effect can be determined as follows:

- ✓ from the graph estimating the location of the inflection point for the conservative or average estimate (Figure 3.1.1),
- ✓ by clicking on the *Subs.Parm* button in the rectangular mine plan form of the influence function program,
- ✓ by analyzing subsidence curves measured at a specific site or region.

Panel Representation:

- ✓ Simple mine layouts can usually be approximated using sets of rectangular extraction areas. In this case, the input required for every parcel includes the parcel number; the coordinates of the west, east, south, and north borders; the seam elevation; the extraction thickness (mining height); and the average supercritical subsidence factor (in percent) associated with it. These coordinates can be specified in a local or a global coordinate system with axes parallel to the parcel sides. In the Influence function module, this option is implemented as **Rectangular Mine Plans.**

- ✓ Complex mine layouts can usually be approximated by a closed polygon (i.e. a piece-wise linear shape). In this case, the input required for every point within a parcel includes the point reference number; the northing (Y), easting (X), and elevation (Z); the extraction thickness (mining height); and the supercritical subsidence factor (in percent) associated with it. The mine plan editor can

provide access to all points in a parcel, add new points, and add new parcels provided that the current parcel is defined by three or more points. The points should be entered in a counter-clockwise fashion. The location of each point should be adjusted to reflect the edge effect, or the relative position of the inflection point. The maximum number of parcels and points per parcel can be adjusted within the limits of the available memory. In the Influence function module, this option is implemented as Polygonal Mine Plans.

Warning:

Pillars can not exist outside extracted areas. If a pillar is defined outside an extracted area the results are unpredictable. Currently, the parcel definition module of the program can not check for such inconsistencies. Examples of erroneous panel definitions are given in Appendix 3.

Notes:

- ✓ If no adjustments are made to the geometry of the mine plan, the program assumes that the inflection point is over the rib of the excavation.
- ✓ The user must specify whether each parcel represents an extracted panel or a pillar within an extracted panel. A pillar is mathematically represented as a parcel with a negative subsidence factor. Setting the pillar option on a parcel will reset the subsidence factor associated with this parcel. In that sense, an extraction area can be either positive (i.e. longwall panel) or negative (i.e. pillar in the middle of a panel). Thus, a mine plan that consists only of pillars (without an extraction boundary) will produce a mathematically positive! subsidence.
- ✓ It should be emphasized that the subsidence factor used here is the subsidence factor for supercritical conditions.
- ✓ The reason for supporting more than one format for input data is for the user's convenience. For example, certain panels or pillars can be easily represented as rectangles and can be entered as single entities, compared to four or more entries required if these panels are digitized point by point. Additionally, calculations for rectangular parcels are much faster compared to calculations for parcels defined by individual points.

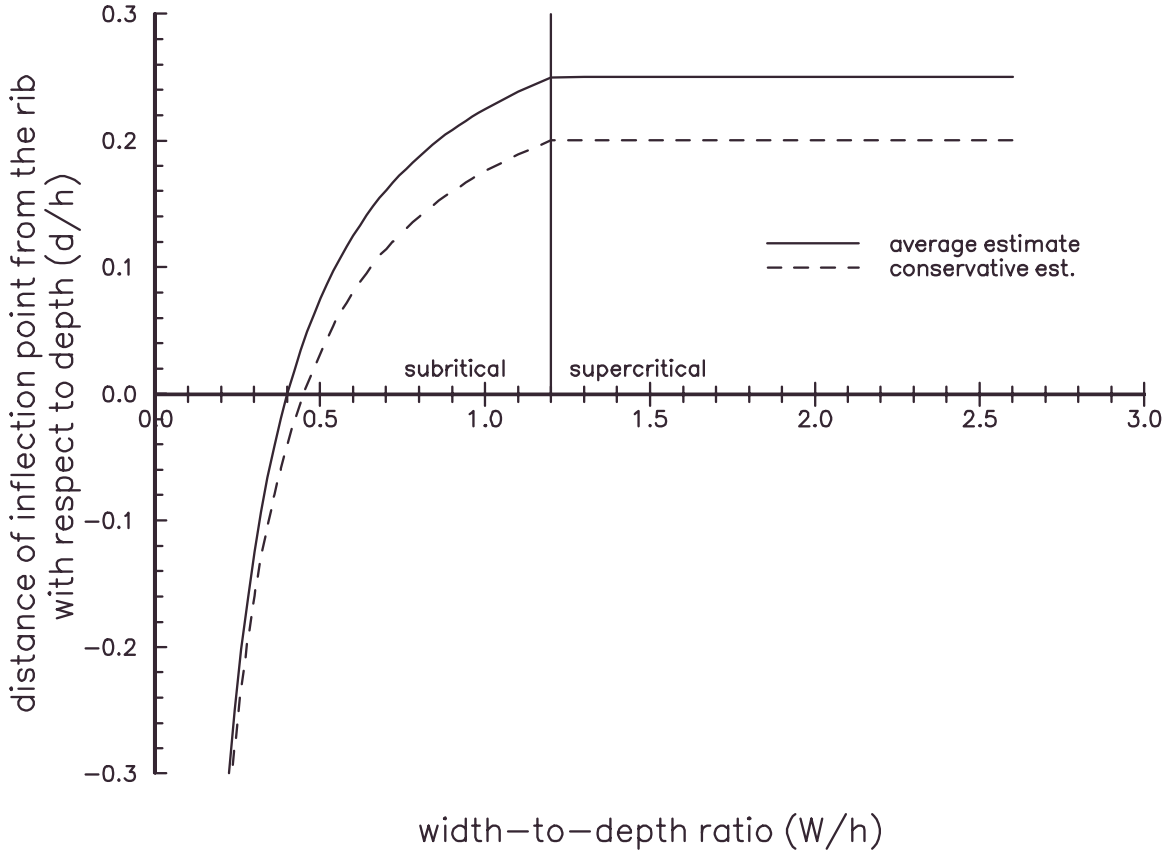


Figure 3.2.1: Determination of the offset of the inflection point.

3.3 Definition of the Prediction Points in the Influence Function Program

Prediction point data describe the surface points where the deformation indices will be calculated. Prediction points are always defined in three-dimensional space, by specifying the X,Y,Z coordinates of these points. A point can be either active or not active. A point which is not active is not deleted from the file but will not be included in the calculations.

Scattered Points

A scattered point set may consist of any number of points that are randomly located on the surface. If such points can be specified as part of a grid, then the Grid Points option should be used. Required parameters for each point include:

- ✓ the point reference code which can be any alphanumeric string,
- ✓ the easting, northing and elevation of each point,
- ✓ the point status, i.e. active or not active (an inactive point will not be displayed in the View option and will not participate in any of the calculations)

Grid Points

A grid point set may consist of any number of points in a window. This window is defined by minima and maxima in the X- and Y- directions as well as the cell size in each direction.

The grid can only be oriented parallel to the current coordinate system. If the grid needs to be oriented at an angle to the current coordinate system, the grid points should be generated by a different tool and imported as scattered points into the Influence Function module.

The user has two options regarding grid elevations.

- ✓ to consider a flat surface and specify a uniform elevation for all points, and
- ✓ to consider each point on an individual basis and specify individual point elevations.

Surface Deformation Characteristics Above Undermined Areas: Experiences from the Eastern United States Coalfields

M. KARMIS, A. JAROSZ, P. SCHILIZZI & Z. AGIOUTANTIS*

SUMMARY Damage resulting from surface movements due to underground mining may range from simple land settlement to severe structural damage. Since subsidence prevention is not feasible, it is important that accurate ground movement prediction techniques are developed, so that damage due to underground mining as well as the amount of coal lost due to the protection of surface structures can be minimized.

To facilitate the mitigation of the deleterious effects of subsidence in the Eastern U.S. region, empirical subsidence prediction techniques for longwall mining were developed from 45 case studies collected within the coalfield. From these subsidence prediction techniques a strain prediction model was also formulated. These subsidence and strain prediction methods can be used to predict ground movements as part of the mining plan and to evaluate the impacts of underground mining on the surface.

1 INTRODUCTION

Surface subsidence is rapidly gaining emphasis as an important environmental consequence of underground coal mining in the United States. Its impact has been witnessed in both rural and urban areas, and can be associated with active as well as abandoned mining operations. The damage associated with this phenomenon may include land settlement and fracturing, structural damage to surface buildings or facilities and disruption or contamination of ground water supplies.

As the need for energy increases, coal production will undoubtedly be accelerated, and since over 99 percent of all subsidence recorded in the United States arises from underground mining, it is evident that the incidence of subsidence will increase. With this increase in production and as underground mining moves into more populous areas, the prediction of surface subsidence, horizontal displacements, strains, and associated damages will surely become a requisite.

To exemplify the significance of this problem, a recent U.S. Bureau of Mines report indicated that over 32,000 km^2 have been undermined in the United States in extracting coal, metals and nonmetallic ores. Over one-fourth of this area, or approximately 8100 km^2, has been disturbed by subsidence, with underground mining of bituminous coal accounting for 7700 km^2 and metal and nonmetallic ores accounting for 68 km^2 of disturbed land. Thus, over 99 percent of all subsidence incidents are attributed to underground coal mining. Moreover, the Bureau of Mines estimates that an additional 10,000 km^2 will be undermined in the United States by the year 2000 (Chen et al., 1982), thus increasing considerably the number of areas in the country affected by subsidence.

Even though, under present technological and economic conditions, subsidence prevention is not feasible, it has been demonstrated in many coalfields that surface subsidence can be predicted and controlled, thus minimizing the deleterious effects of ground movement. Therefore, it is imperative that reliable methods of surface movement prediction and control be established for the United States. With such techniques available, ground movements can be predicted as part of the mining plan, and if environmentally, economically or legally unacceptable situations are foreseen, remedial measures can be implemented.

2 TYPES OF MINING SUBSIDENCE EXPERIENCED IN THE UNITED STATES

Underground excavations disturb the natural equilibrium of the rock mass, causing redistribution of loads in the medium and thus producing horizontal and vertical displacements. Subsidence occurs when these displacements propagate from the mine opening, through the overlying strata, to the surface and can manifest two principle modes of ground settlement: sinkhole and trough subsidence (Figure 1).

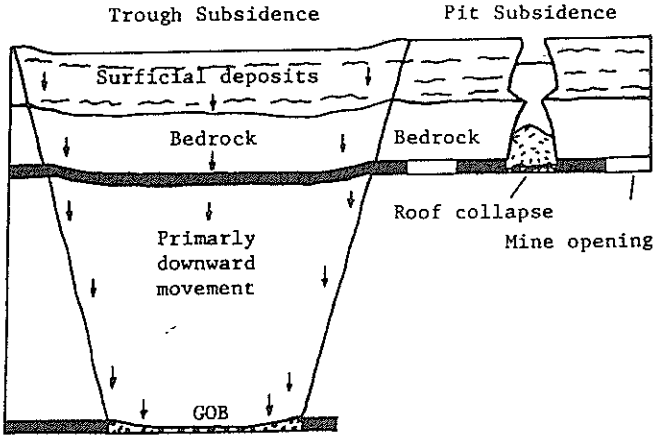


Figure 1 Trough and pit subsidence (after Wildanger et al., 1980).

2.1 Sinkholes, or Pit Subsidence

Sinkholes, or pit subsidence, are characterized by a sudden and sometimes violent collapse of the surface and usually occur above shallow, abandoned room and pillar mines with incompetent overburden; in rare instances, however, this type of subsidence

can also occur over active mines, given the proper mining and geological conditions. Pit subsidence is expressed by an abrupt drop in the surface and has vertical to bell-shaped walls. The washing of bedrock and surficial deposits into the mine void may cause the depth of sinkhole to exceed the mining height.

Obviously, the effects of pit subsidence can be serious. The damage caused is the result of a loss of support over all or part of the structure. Also, due to the uncertainty of mine and geologic parameters, the time, location and extend of such a subsidence event is very difficult to predict. Since the goal of subsidence and strain prediction is to minimize the cost of extracting coal in active mines that are below structures, the characteristics of trough subsidence have been studied more extensively than those of sinkholes.

2.2 Trough Subsidence

Trough subsidence is expressed by a gradual and general movement over an observed area with a subsidence basin being formed. Trough theory considers the phenomenon of subsidence to be represented by a complicated combination of material movement and interaction, as depicted in Figure 2. Caving occurs above the mine opening (zone a). The strata above the caving zone moves toward the excavation, experiencing fracturing (zone b) and beam bending phenomena (zone c). This representation of ground movement around a mining excavation is considerably complex to analyze and model; therefore, this concept is simplified by treating only the effects of underground excavation on the surface, or other strata levels within the bending zone.

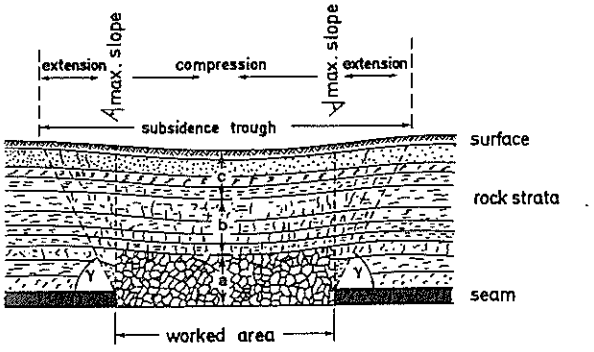


Figure 2 Strata movements above an extracted area (after Kratzsch, 1983)

Trough theory considers a zone of influence in which movement occurs and which spreads from the excavation to the surface, forming a subsidence trough. When an excavation is made at depth, the movement of the strata extends to the surface and manifests itself as vertical displacement (subsidence) and horizontal displacement within a zone of influence. The zone of influence is bounded by a plane that extends from the edge of extraction to the line on the surface where movement ceases. A vertical cross-section of the subsidence trough along with its associated parameters is shown in Figure 3. The angle defined by the vertical from the rib and the line of influence is the angle of draw (or limit angle).

3 DEVELOPMENT OF SUBSIDENCE PREDICTION METHODS

A number of different methods have been proposed for or applied to prediction of surface ground movements due to underground mining. These

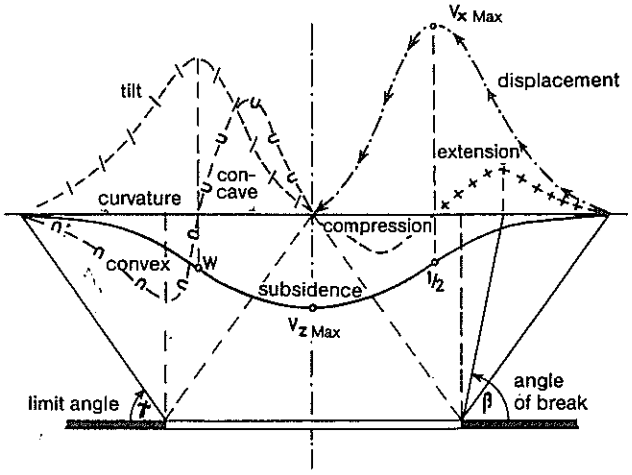


Figure 3 Components of ground movement (after Kratzsch, 1983)

approaches can be broadly divided into three groups. The first two are:

- Theoretical models based on the elastic, plastic, viscoelastic or other phenomenological models which are widely used in other engineering fields (Voight and Pariseau, 1970).

- Numerical methods, mostly used as solutions to complex situations involving the phenomenological methods.

Both these approaches assume that the strata in the overburden behaves in a specific and predictable manner. In using these models, considerable information describing the behavior of the overburden is required, which has often limited the applicability of these methods. Furthermore, in order to adapt their results to field data, a large number of adjusting coefficients may have to be determined.

The third approach can be defined as:

- Empirical or semi-empirical methods such as profile functions, influence functions, the zone area method (Brauner, 1973; Karmis et al., 1981b and 1983).

In this research, the latter approach was pursued since empirical methods are realistic, flexible, and easy to use. Their application, however, requires that a significant number of field measurements be made in order to determine the essential input parameters of the equations.

3.1 Data Collection and Analysis

During the initial stages of this research effort, a large number of subsidence case studies were collected from literature, the coal industry and government agencies. In total, data from 45 longwall panels and 70 room and pillar panels were collected. The limitations of the collected case studies data, i.e. accuracy of surveys, frequency of monitoring, lack of horizontal movement measurements, etc, led Virginia Polytechnic Institute and State University to the initiation of a detailed subsidence and strain monitoring program

above a number of active mines, located in three major coal producing counties of Virginia. The aim of this program was to enhance the data base with accurate and complete measurements of surface movements and to subsequently allow the refinement of the prediction techniques.

In this major monitoring effort, a total of sixteen room and pillar sections and seven longwall panels, in nine mines, were instrumented. Above each panel or section a number monument lines were installed. The lines were extended on either side of the panel well beyond the maximum expected area of influence. The final effort included approximately 1,200 stations over 35,000 feet of monitoring lines (Schilizzi et al., 1986).

This data bank was used to determine some basic ground movement relationships between the basic mining and subsidence parameters, in order to allow the evaluation of the various prediction methods for the Appalachian coal region.

Analysis of the subsidence information has revealed some interesting subsidence characteristics for Appalachian longwall panels. The observed angles of draw varied considerably; however, the angle of draw appears to approach a constant value of approximately 30 degrees at width-to-depth (W/h) ratios in excess of 1.2 (Figure 4). The range of maximum subsidence factors for the collected case studies is shown in Figure 5. It shows two lines constructed from the data. Line (1) represents the average values S_{max}/m, whereas line (2) is an envelope line, covering all data points. The figure also shows that this parameter asymptotes to a constant value at a width-to-depth ratios greater than 1.2. These results suggest that critical conditions are reached for W/h ratios of about 1.2,

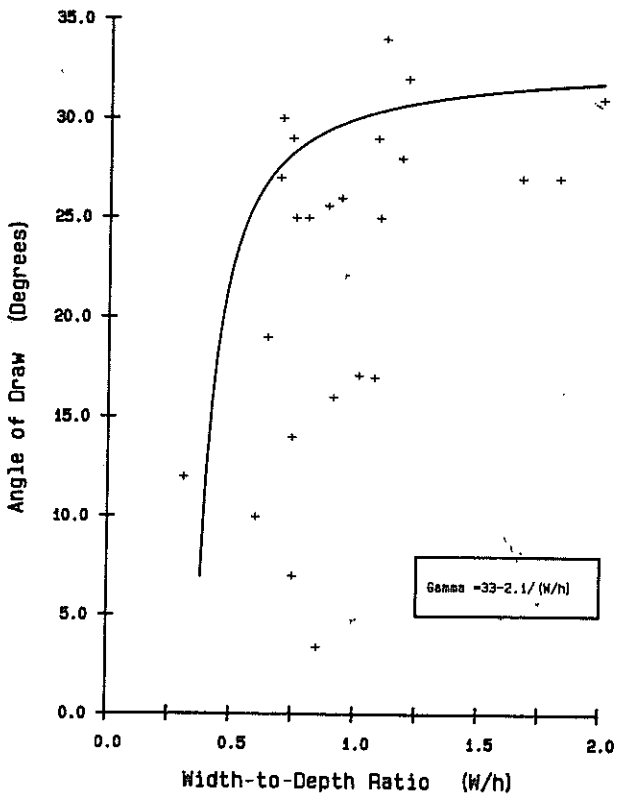


Figure 4 Observed angles of draw for various case studies

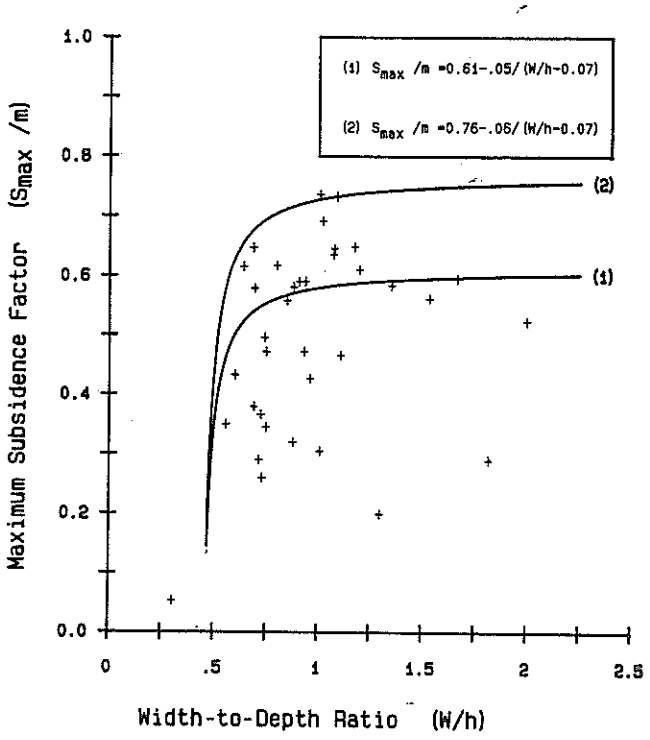


Figure 5 Influence of W/h ratio on maximum subsidence factor

as confirmed by the relationship between the position of the inflection point and the width-to-depth ratio of the panel shown on Figure 6.

According to the collected data and their dispersion, it was hypothesized that two factors influenced the subsidence: geology of the overburden and geometry of the panel. In order to establish the relationship between geology (lithology) and subsidence, the subsidence factor was plotted against the percent of hardrock (percent of limestone and sandstone) in the overburden for critical and supercritical panels only (Figure 7). Since the effect of panel geometry was thus eliminated, a relationship between subsidence and geological conditions was established. Once this correlation was possible, a complete relationship between subsidence and panel geometry was developed for varying lithologies (Figure 8).

To determine characteristic subsidence profiles, different empirical or semi-empirical methods were tested and adopted. Data collected during the monitoring program were primarily used, because of their completeness and accuracy.

3.2 Profile Function Methods

A profile function method defines the distribution of subsidence or strain values on the surface along a profile, orthogonal to the boundary of (theoretically) an infinitely long underground excavation. In general, a function which is tangent or asymptotic to two horizontal lines is required. The parameters to be used for this equation must be determined from field data.

The advantage of such a method is that it can be implemented easily through the use of a computer, or of pre-calculated tables. The main disadvantage is that it cannot negotiate excavations of complex shape or significant variations in mining

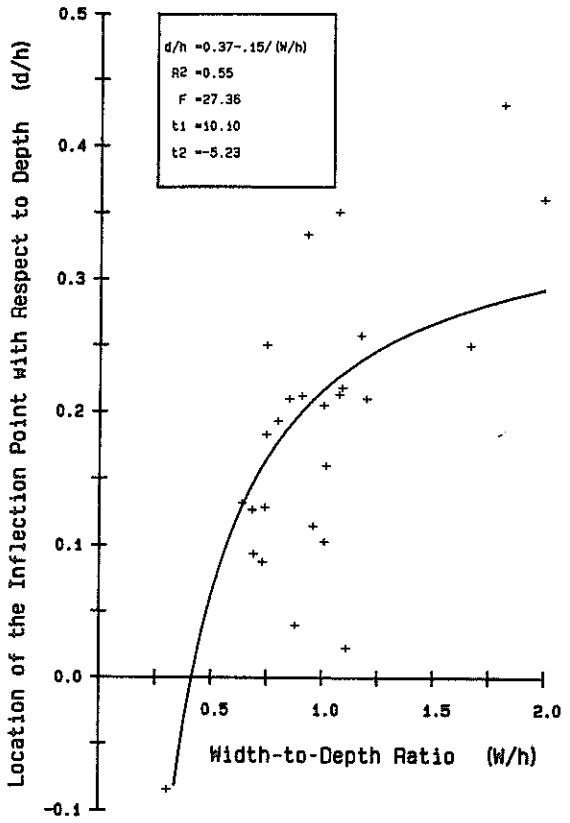


Figure 6 Effect of W/h ratio on inflection point location

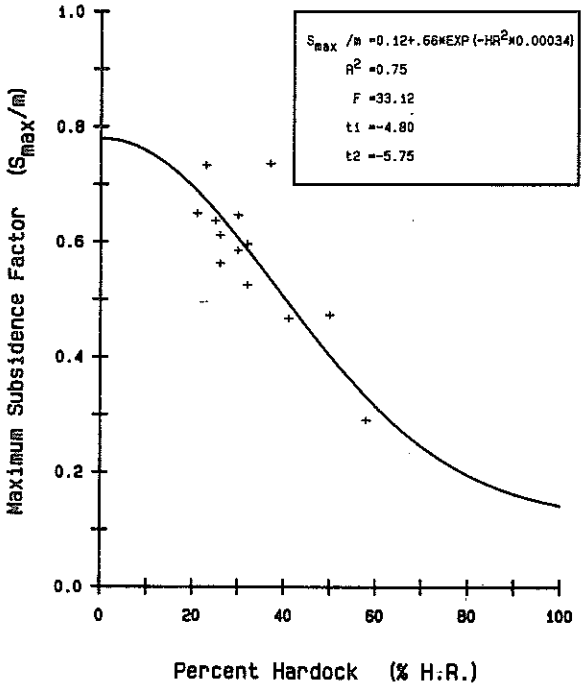


Figure 7 Effect of lithology on maximum subsidence factor

Parameters such as mining height, percent of extraction, and depth of the excavation (Brauner, 1973; Karmis et al., 1981a).

In this approach, a number of accepted profile functions were fitted to the subsidence profiles

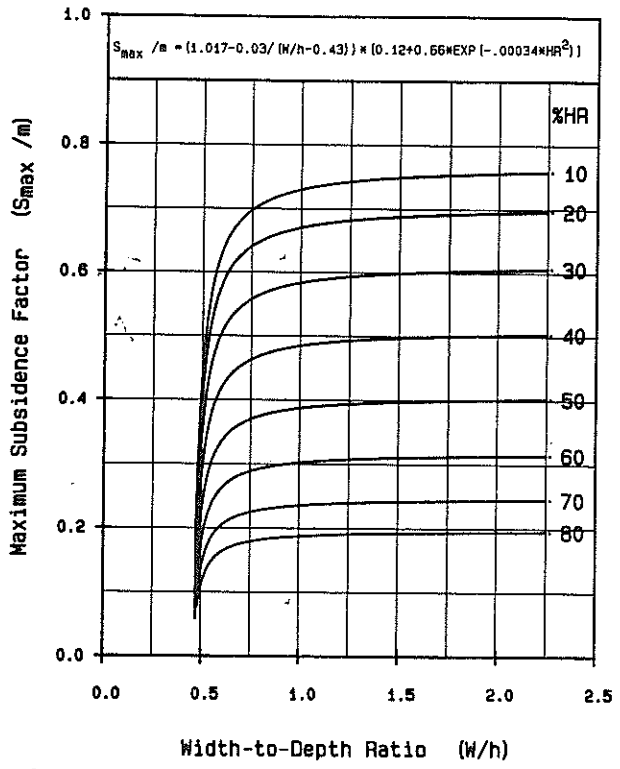


Figure 8 Nomograms for maximum subsidence prediction

developed from collected case studies. This analysis demonstrated that the hyperbolic tangent function given by the following equation, provided the best fit curve (Karmis et al., 1981b and 1984):

$$S(x) = 0.5\ S_{max}[1-\tanh(cx)/B] \qquad (1)$$

where,

S(x) = subsidence at a given point on the surface;
S_{max} = maximum subsidence (obtained from a table [Table 1] or nomogram [Figure 8]);
c = constant, calculated as 1.8 for critical or supercritical panels and 1.4 for subcritical panels;
x = distance from the inflection point to the point in question; and,
B = distance from the inflection point to S_{max} (which can be assessed from tables or nomograms [Figure 6] as a function of panel geometry and width-to-depth ratio).

The latter equation can be used in conjunction with predictions of S_{max} (Figure 8) and position of the inflection point (Figure 6) to allow for complete subsidence pre-calculation.

3.3 Influence Function Methods

This approach to subsidence prediction was initially developed by Dutch and German engineers (Bals, 1932) and has been extensively used in the Central and Eastern European coalfields. An influence function describes the distribution of vertical ground movement, i.e. subsidence, on the surface or other levels of the overburden, caused by an infinitesimal underground excavation. Considering the two dimensional situation:

$$dS(x_1,z) = f(x_1-x_2,z)dV \qquad (2)$$

where,

$dS(x_1,z)$ = subsidence at point $P(x_1,z)$;
dV = infinitesimal underground excavation (void);
$f(x_1-x_2,z)$ = influence function;
x_1 = coordinate of surface point;
x_2 = coordinate of infinitesimal excavation; and,
z = vertical distance from excavation to prediction point $P(x_1,z)$.

The Budryk-Knothe influence function method (Knothe, 1957), developed in Poland, was selected for this research as the most appropriate function for use in the Eastern U.S. coalfields. Initially, a two-dimensional situation was considered for the analysis of data obtained from panels of an almost orthogonal shape and with uniform mining conditions i.e. mining height, percent extraction, depth. The equation used is as follows:

$$f(x,z) = -\frac{1}{r}\exp(-\pi\frac{x^2}{r^2}) \qquad (3)$$

where,

r = the radius of influence (r=z/tan(b));
b = angle of influence; and,
x,z = coordinates of surface point on a system where the origin is located at the infinitesimal excavation.

For the three-dimensional approach:

$$f(x,y,z) = \frac{1}{r^2}\exp[-\pi\frac{(x^2+y^2)}{r^2}] \qquad (4)$$

where,

r = the radius of influence; and,
x,y,z = coordinates of a surface point on a system where the origin is located at the infinitesimal excavation.

Subsidence at any point will be:

$$S(x,y,z) = \frac{S_{max}}{r^2}\iint_A \exp[-\frac{\pi}{r^2}(x^2+y^2)]dxdy \qquad (5)$$

where,

$S(x,y,z)$ = subsidence at a point having coordinates x,y,z;
S_{max} = maximum subsidence for supercritical excavation;
r = the radius of influence; and,
A = the area of excavation.

The above integral was transformed and solved in polar coordinates, for polygonal excavations.

For this method, as with most mathematical models, the inflection point of the subsidence profile is located above the rib of the excavation. In practice, however, the inflection point is displaced at a distance, d, from the rib. In order to accommodate this, the outer boundaries of the excavation have been adjusted accordingly.

3.4 Zone Area Method

This method was initially developed in Britain for irregular longwall or room and pillar panels (Marr, 1975). It assumes that movement at a specific point on the surface is affected by the excavation of a circular underground area which is further sub-divided into a series of angular rings. To determine the amount of movement caused by each ring, the extracted area of the ring is calculated and multiplied by the zone factor of the respective ring. Appropriate zone factors for Appalachia have been calculated from the field data (Goodman, 1980; Karmis et al., 1981b and 1984). The same procedure is followed for all rings, and the superimposed results will yield total movement.

4 DEVELOPMENT OF STRAIN PREDICTION METHODS

One of the most damaging manifestations of surface subsidence is the development of horizontal strains. As noted previously, subsidence measured in Appalachia is smaller than that found in certain other coalfields, such as the U.K. However, the strains experienced in the U.S. often appear to be greater than those predicted for British conditions. Thus, an effort was directed toward the identification of the cause of these higher strains and toward the subsequent formulation of an acceptable strain prediction model for Appalachia.

As a first step, the relationship between strain and curvature had to be determined. Factor B was used to calculate horizontal strain as a function of curvature, i.e.:

$$\text{Horizontal Strain} = -B * \text{Curvature} \qquad (6)$$

In the original stages of this research a direct relationship between strain and curvature was sought which could describe B independent of any other mining parameters (Karmis et al., 1983). As more case studies were made available through this project, it became apparent that such a relationship will be difficult to establish (Figure 9). As a result, a different approach was adopted, based on the work of Awershin (1947), Budryk (1953) and Akimov and Zemicev (1970), which suggested that the magnitude of the horizontal strain factor (B) is a function of the excavation depth or the radius of principal influence (r).

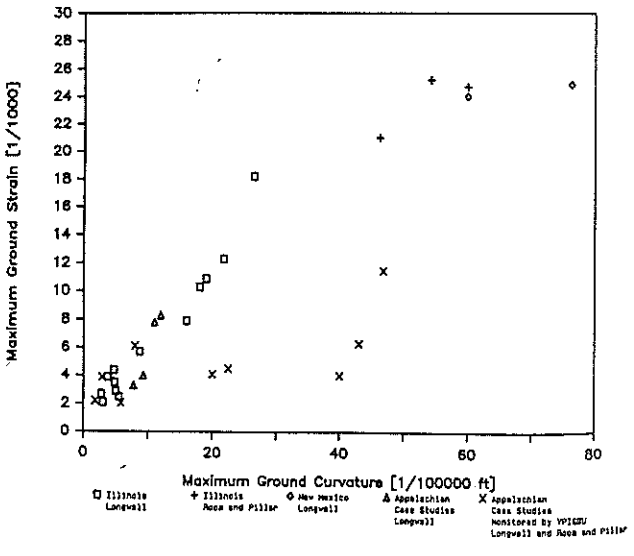


Figure 9 Maximum ground strain and curvature data

For each of the collected case studies, factor B was determined by comparing the measured strains and the fitted curvature profiles.

Using the established values of parameter B and the corresponding values of excavation depth (h), radius of influence (r), and angle of principal influence (b), a statistical relationship was found (Figure 10) as expressed by the equation:

$$B = (0.35 \pm 0.05)\ r \qquad (7)$$

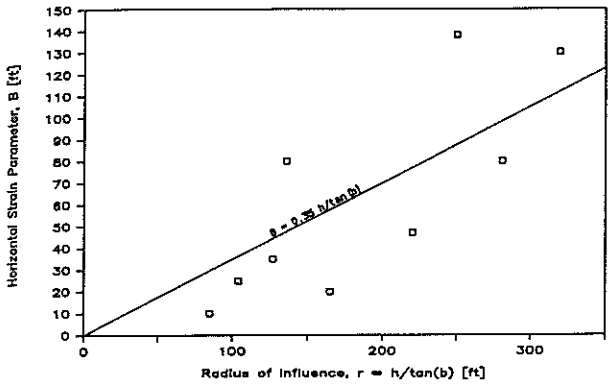


Figure 10 Effect of radius of influence on the horizontal strain parameter

or

$$B = (0.35 \pm 0.05)\ h/\tan(b) \qquad (8)$$

where,

r = radius of the principal influence;
h = depth of the excavation; and,
b = angle of the principal influence.

5 DEVELOPMENT OF COMPUTER SOFTWARE

The development of a comprehensive software package was necessary in order to facilitate the analysis of the field measurements. All field data were stored in an 880-line memory incorporated in the surveying instrument, and then transferred to magnetic diskettes for further processing on an HP micro-computer system. Stored field data included coordinates, sometimes on a localized system, elevations and the values of subsidence and strain for individual stations on the monitoring lines for each date.

Computer software for the application of the prediction methods under consideration was developed for two widely used personal computer systems.

For the profile function, the program is rather simple and involves the calculation of subsidence values along a line orthogonal to the rib of the excavation. The parameters used for this calculation depend on the given geologic conditions, width-to-depth ratio and mining height, and must be obtained from tables or nomograms and entered manually. The origin of the coordinates can be adjusted manually if necessary.

For the application of the influence function method, a number of programs were developed, each of them for specific conditions. For general cases involving complex mining conditions, where the mining section under consideration must be divided into polygons of uniform conditions, the influence function equation was converted to polar coordinates and was used in the program in this form. The computer program calculates subsidence at any point along a polygonal line or on a grid. For mine sections of irregular shape or where areas of different mining height, extraction ratio or seam elevation exist, the section is separated into homogeneous polygonal sub-sections. Subsidence and other related indices of deformation, in any given direction, caused by each of these sub-sections is calculated and their total value is determined by superposition. This procedure, however, requires considerable computational time for each point.

For simple conditions, however, where areas of different mining height, extraction ratio or seam elevation can be described by rectangular homogeneous sub-sections, different programs have been written for considerably faster execution on a microcomputer, yielding comparable results. Furthermore, a program using the two dimensional approach has been written for single panels of uniform overall parameters.

The program for the zone area method was initially developed for mainframe computers (Karmis et al., 1982); however, it is currently being adapted for use with personal computers.

It should be noted that these programs also produce data compatible with commercially available plotting and contouring software packages. Mine plan coordinates and the corresponding parameters can be entered manually or by a digitizer or by a plotter with digitizing capabilities.

6 APPLICATION OF PREDICTION METHODS

In this paper, data obtained from three case studies are presented to demonstrate and compare the prediction methods. The first two are from room and pillar mining operations, whereas the last one is from a longwall case study.

In the first example, the two dimensional approach was used. Predicted and fitted subsidence curves, using the profile and influence function methods, are presented in Figure 11.

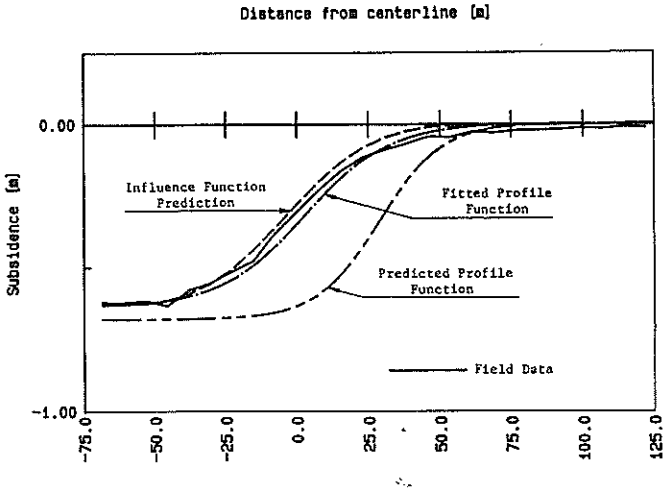


Figure 11 Example #1: Field data and prediction curves

In the second example (Figure 12), a three dimensional influence function approach was used to take into account a number of pillars left in place for roof control purposes. This case demonstrates the accuracy which can be obtained through adjustment of the influence function parameters, especially for subsidence predictions.

In the last example (Figure 13), a three dimensional influence function method was used for a longwall operation with considerable variation in overburden depth. Subsidence and horizontal strain values, calculated using this technique, show excellent correlation with the corresponding measured values.

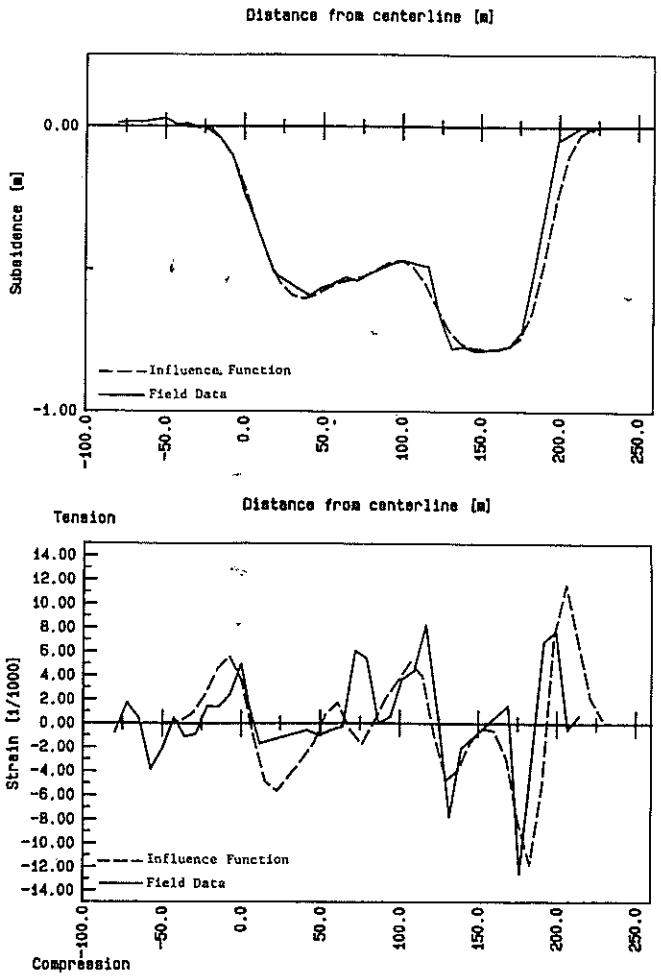


Figure 12 Example #2: Field data and prediction curves for subsidence and horizontal strain

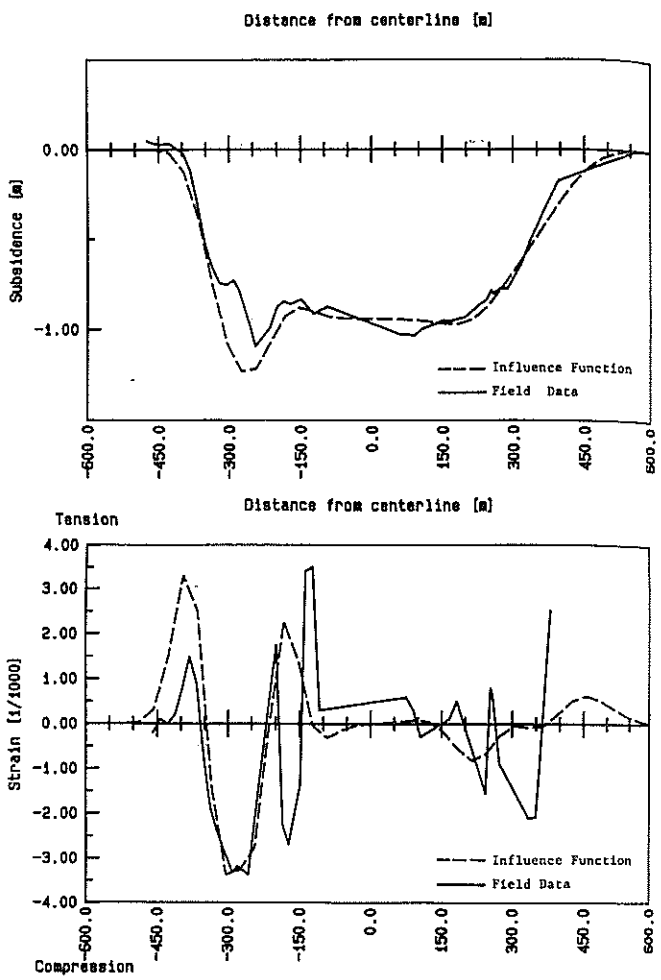


Figure 13 Example #3: Field data and prediction curves for subsidence and horizontal strain

7 CONCLUSIONS

The expansion of underground mining into more populous areas, and the resultant increase in the potential for surface and structural damage, have rendered the formulation of accurate surface deformation models an important requisite. To meet this demand, accurate subsidence and strain prediction techniques have been formulated for the Eastern U.S. coalfield. The semi-empirical subsidence prediction techniques discussed in this paper were developed from a substantial number of case studies collected within the Appalachian coalfield. Using the subsidence model as a base, the strain model was formulated using empirically and mathematically derived relationships. These models can greatly facilitate mine planning and allow the amount of coal lost due to the protection of surface structures to be minimized.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

1. Akimov, A. and B. Zemicev, 1970, Subsidence of the Rock Strata Caused by the Underground Excavation of Coal and Lead Ores, Nedra Publishing, Moscow, (in Russian).

2. Awershin, S. G., 1947, Subsidence of the Rock Strata Caused by Underground Excavation, Ugletekhizdat Press, Moscow, (in Russian), 245 p.

3. Bals, R., 1932, "A Contribution to the Problem of Precalculating Mining Subsidence," Milteilungen aus dem Markscheidewesen, Vol. 42/43, pp. 98-111 (in German).

4. Brauner, G., 1973, "Subsidence Due to Underground Mining (in two parts)," U.S.B.M. Info. Circ. 8571, 8572.

5. Budryk, W., 1953, "Determination of the Magnitude of Horizontal Strains," Archives of Mining and Metallurgy, Vol. I, Part 1, (in Polish).

6. Chen, C. Y., D. E. Jones and D. K. Hunt, 1982, "Government Regulation of Surface Subsidence due to Underground Mining," Proceedings, International Symposium on the State of the Art of Ground Control in Longwall Mining and Mining Subsidence, Honolulu, Hawaii, pp. 245-252.

7. Goodman, G., 1980, "Computer Modeling of Mining Subsidence Using the Zone Area Method," M.S. Thesis, VPI&SU.

8. Karmis, M., C. Haycocks, I. Eitani and B. Webb, 1981a, "A Study of Longwall Subsidence in the Appalachian Coal Region Using Field Measurements and Computer Modeling Techniques," Proceedings, 1st Conference for Ground Control in Mining, West Virginia University, July 27-29, pp. 220-229.

9. Karmis, M., C. Haycocks, B. Webb and T. Triplett, 1981b, "The Potential of the Zone Area Method for Mining Subsidence Prediction in the Appalachian Coalfield," Proceedings, Workshop on Surface Subsidence Due to Underground Mining, Morgantown, West Virginia, November 30-December 2, pp. 48-62.

10. Karmis, M., G. Goodman, C. Haycocks and T. Triplett, 1982, "The Development and Testing of a Regional Subsidence Prediction Model," Proceedings, 17th Inter. Symposium on Computer Applications to the Mineral Industry, APCOM, Denver, Colorado, pp. 240-252.

11. Karmis, M., T. Triplett, C. Haycocks and G. Goodman, 1983, "Mining Subsidence and Its Prediction in the Appalachian Coalfield," Proceedings, 24th U.S. Symp. on Rock Mech., College Station, Texas, June, pp. 665-675.

12. Karmis, M., G. Goodman and G. Hasenfus, 1984, "Subsidence Prediction Techniques for Longwall and Room and Pillar Panels in Appalachia," Proceedings, Second International Conference on Stability in Underground Mining, Lexington, Kentucky, August 6-8, pp. 541-553.

13. Knothe, S., 1957, "Observations of Surface Movements Under Influence of Mining and the Theoretical Interpretation," Proceedings, European Congress on Ground Movement, The University of Leeds, April 9-12.

14. Kratzsch, H., 1983, "Mining Subsidence Engineering," Springer-Verlag, Berlin, Heidelberg, New York.

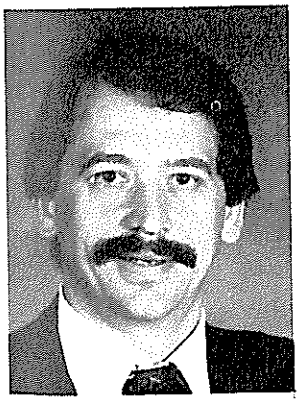
15. Marr, J. E., 1975, "The Application of the Zone Area System to the Prediction of Mining Subsidence," Min. Eng., Vol. 135, No. 176, pp. 53-62.

16. Schilizzi, P., M. Karmis and A. Jarosz, 1986, "Development of Subsidence Prediction Technology from an Extensive Monitoring Program," Proceedings, 2nd Workshop on Surface Subsidence Due to Underground Mining, Morgantown, West Virginia, June 9-11, in press.

17. Voight, B. and W. Pariseau, 1970, "State of Predictive Art in Subsidence Engineering," Journal of the Soil Mechanics and Foundations Div., Proc., ASCE, Vol. 96, No. SM2.

18. Wildanger, E. G., J. Mahar and A. Nieto, 1980, "Sinkhole-type Subsidence Over Abandoned Coal Mines in St. David, Illinois," Illinois Abandoned Mined Lands Reclamation Council, 88 p.

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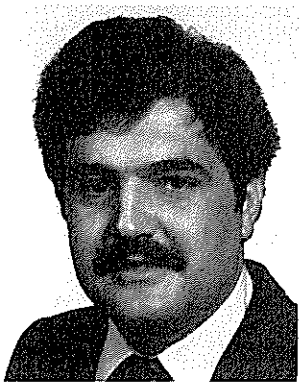


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Dr Jarosz's research interest is in the areas of subsidence monitoring and prediction as well as the practical applications of ground control principles in mining. He has authored or co-authored many technical papers on this subject.



P P G SCHILIZZI

Paul P G Schilizzi received his education at the National Technical University, Athens, Greece, and graduated in July, 1980, with a Diploma in Mining and Metallurgical Engineering. Mr Schilizzi attended graduate school in the Department of Mining and Minerals Engineering, Virginia Polytechnic Institute and State University, where he completed his M.S. degree in July, 1982. He received an assistantship to continue his education leading to a Ph.D. degree in the same department and completed his work for this degree in January, 1987.



Z AGIOUTANTIS

Zacharias Agioutantis graduated from the National Technical University, Athens, Greece, in November, 1982, with a Diploma in Mining and Metallurgical Engineering. He was then admitted to the graduate program at Virginia Polytechnic Institute and State University, Blacksburg, Virginia, under an assistantship, and received his M.S. degree in Mining Engineering. Since September, 1984, he has been pursuing a Ph.D. degree at the same school while working on different research projects. His research work is reflected in several publications in the fields of Rock Mechanics and Ventilation.

APPENDIX 4

Community Newsletter

Westside Mine Closure Update

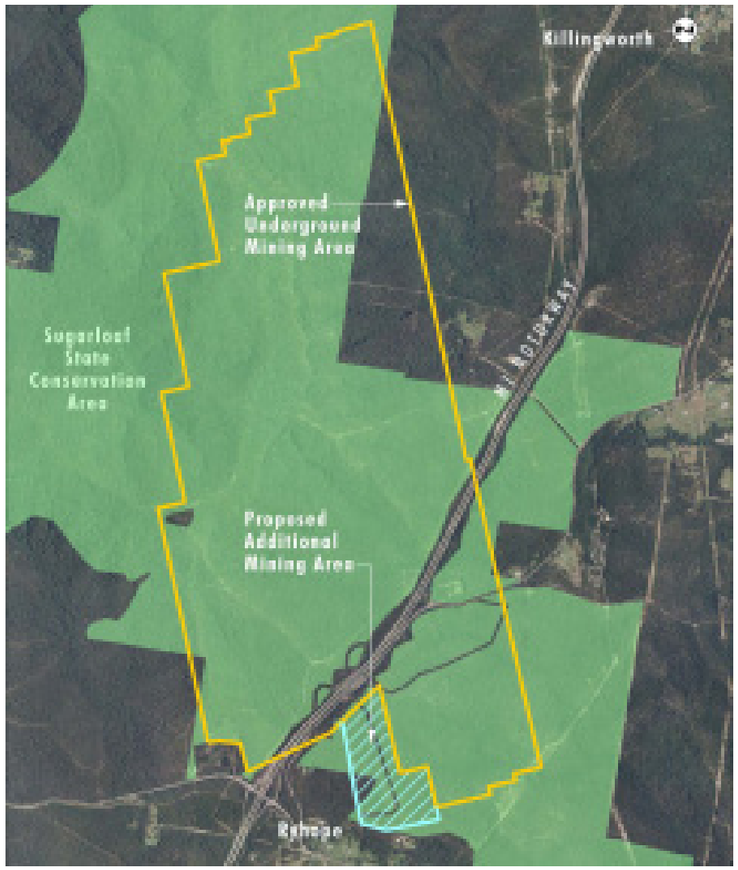
Rehabilitation

Westside Mine ceased coal mining activities in early 2012 after 30 years of mining. Rehabilitation works are progressing on schedule behind the active mining area to revegetate the remaining sections of the mining area. Over 30 hectares were successfully revegetated last year following the completion of mining. In addition to the rehabilitation efforts, all of the coal mining machinery (trucks, dozers etc.) has been removed from the site along with some key infrastructure no longer needed to support future activities (e.g. coal crusher). Monitoring and maintenance works of the rehabilitated areas will continue in the coming years to ensure that Westside Mine is returned to a sustainable post-mining landform.

In addition, Westside Mine recently received the Xstrata Coal Chief Executive's Environment and Community Excellence Award for the quality of rehabilitation achieved at Westside Mine since it commenced operations in 1992. Westside Mine was awarded $10,000 which was donated to the Hunter Breast Cancer Foundation and the Hunter Prostate Cancer Alliance in consultation with the mine's Community Consultative Committee.



Established Westside Mine Rehabilitation in the Southern mining area.



LW51 & 52

At the time the WWC Project Approval was granted in 2012, part of WWC's Mining Lease was subleased to an adjacent mining operation. This area is predominantly below the Sugarloaf State Conservation Area to the south east of the M1 Motorway and north of Ryhope. The sublease has now been transferred back to WWC, and WWC is proposing to alter the current mine plan to include mining of part of this area. Environmental studies and mine planning work is currently underway to confirm the approach to mining in this area.

WWC plan to make an application to modify the Project Approval in consultation with the community and relevant government departments and other stakeholders. The mine layout is being developed in consultation with stakeholders to protect Aboriginal cultural heritage sites and minimise environmental impacts. It is planned that the application will be submitted to the Department of Planning and Infrastructure in December 2013.

CONTACT US

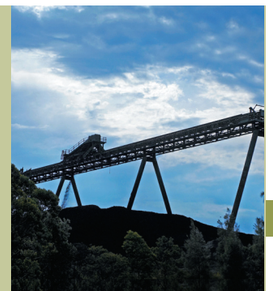
For more information about the Project contact:

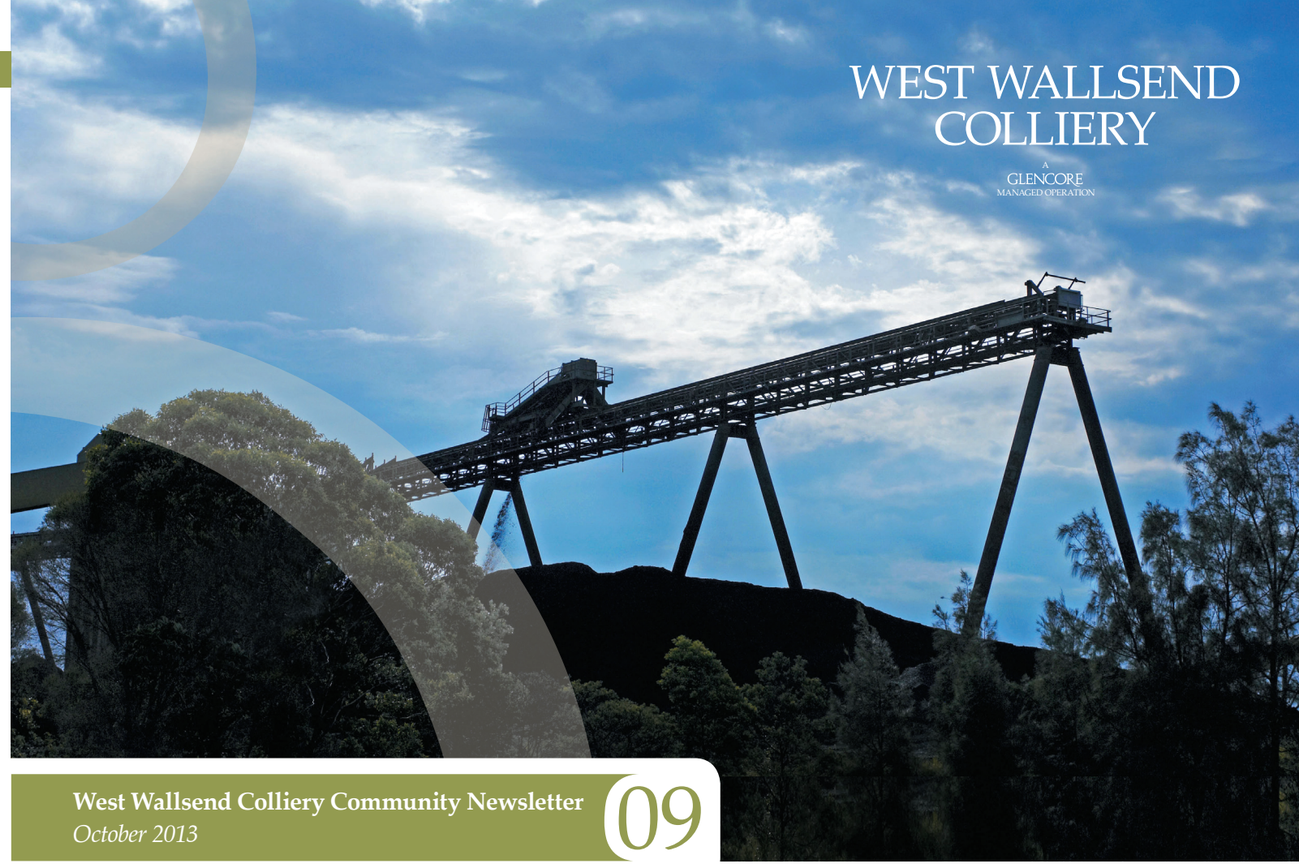
Wade Covey - Environment and Community Manager, Oceanic Coal Australia
T (02) 4941 2163 E Wade.Covey@Glencore.com.au

Community complaints and enquiries hotline:
West Wallsend Colliery - T (02) 4941 2100
Westside Mine - T (02) 4955 1144

GlencoreXstrata commitment to sustainable development

We are committed to the goal of sustainable development. We balance social, environmental and economic considerations in how we manage our business. We believe that operating to leading standards of health, safety and environmental management, contributing to the development of sustainable communities, and engaging with our stakeholders in two-way, open dialogue, regardless of our location, enhances our corporate reputation and is a source of competitive advantage. This enables us to gain access to new resources, maintain a licence to operate, attract and retain the best people, access diverse and low-cost sources of capital, identify and act upon business opportunities, and optimise our management of risks.





West Wallsend Colliery Community Newsletter 09
October 2013

Recent events in the Sugarloaf State Conservation Area (SSCA) have drawn commentary from detractors as well as supporters of the coal mining industry, and brought operations at West Wallsend Colliery under intense scrutiny.

The effects of underground mining on both the underground and surface environments attract regulatory attention, as they should.

And at West Wallsend, we accept these conditions and operate at all times in accordance with robust approvals that cover our activities, especially mining beneath the SSCA.

As the Operations Manager of West Wallsend, I lead a team which includes a highly dedicated group of environmental professionals.

We are not a workforce who reside great distances from our mine.

We live in Newcastle, are responsible neighbours and are active members of our local communities.

We understand that what we do will impact on the environment, but we consult widely as part of the planning process and we only mine an area when given approval to do so.

We monitor our environmental performance and understand that we will be held accountable for meeting our conditions of approval.

However, we are a legitimate business and as such have the right to operate provided we do so within our well-governed boundaries.

We produce an export product but also sell to domestic customers so that our community's electricity needs can be met.

I speak for the West Wallsend team when I say we are deeply disappointed by the unexpected exceedance of our predicted surface impacts and the grouting incidents.

But we ask that we be judged with a balanced mind.

The recent events are completely at odds with our strong record of responsibility and consideration when it comes to our community and our environment.

This is especially so in the SSCA, where many of our people are horse riders, bush walkers, mountain bikers and drivers who spend time with families enjoying this area.

Removal of the grouting material commenced in October following the approval of the Grout Remediation Plan from relevant agencies.

Remediation of the area affected by greater than predicted subsidence is taking more time. First, there are no "text book" solutions in an area of such challenging, steep terrain. Second, remediation cannot commence until specialists engaged to provide expert advice have confirmed the area is stable. Third, the remediation plan is to be reviewed by relevant specialists, then finally by relevant government authorities prior to the commencement of any work.

Rest assured, however, that we are steadfastly committed to working with all parties to return these areas to public use, and to ensure these events remain an exception in a proud record of responsible mining at West Wallsend that extends more than 40 years.

Charlie Allan – Operations Manager, West Wallsend Colliery

Frequently Asked Questions

Who is West Wallsend Colliery and what approval do they have to mine in the State Conservation Area?

West Wallsend Colliery (WWC) is an underground coal mining operation that is managed by Glencore. WWC mines the West Borehole coal seam using longwall mining techniques and operates 24 hours per day, seven days per week. The majority of the coal from WWC is washed, loaded onto trains and transported to Newcastle Port for export.

WWC undertakes its mining operations in accordance with a Project Approval (PA09_0203) issued by the Minister for Planning and Infrastructure as well as it's approved Extraction / Subsidence Management Plans developed and approved by the Department of Industry and Investment and the Department of Planning and Infrastructure.

Mining activities are permitted within State Conservation Areas which are managed by the National Parks and Wildlife Service.

What caused the "greater than predicted" subsidence impacts in the Sugarloaf State Conservation Area (SSCA) that the Media reported on?

The impacts that were reported by the Media were generally confined to an isolated, remote area of the SSCA. Geotechnical investigations of the affected area at the time of the incident confirmed the presence of a highly fractured zone of jointing and faulting in the immediate area that was present prior to mining occurring. It is believed that as subsidence impacts (cracking) began to impact on the area it weakened the pre-existing intersecting jointing in the hillside which resulted in a series of downward wedges developing as the hillside moved in toward the subsided area.

When did the incident occur?

The Incident was identified on the 2nd October 2012 during a weekly geotechnical inspection of the surface affected subsidence zones associated with Longwall 41.

Who was it reported to?

The incident was reported the following agencies:

- NSW Department of Planning and Infrastructure
- NSW Department of Infrastructure and Investment
- NSW Office of Water
- Office of Environment and Heritage
- Mine Subsidence Board

What actions were taken by West Wallsend Colliery at the time of the incident?

The affected area was demarcated with safety mesh and barrier tape in accordance with the sites Public Safety Management Plan. A monitoring program was also initiated to monitor the affected area over time for any changes. A geotechnical investigation into the subsidence impacts was commenced in consultation with the relevant agencies.

Shouldn't these impacts have been predicted?

WWC has developed a detailed subsidence model in consultation with experienced subsidence specialists which is based on industry knowledge and has been built around extensive subsidence monitoring results obtained from previous underground mining at West Wallsend Colliery.

Based on the outcomes of the subsidence model WWC was expecting that surface cracking would develop in the affected area (which it did) as a result of subsidence however it was not known that the area was highly affected by jointing/ fracturing at the surface. Jointing and fracturing is a common geological process that is encountered from time to time in underground mining. It is extremely difficult to predict how ground will react to subsidence through these areas even when they are readily identified

How will the impacted area be remediated?

WWC is still investigating potential remediation options for the site in consultation with the relevant stakeholders and remediation specialists. Due to the remote nature of the site, difficult terrain, and a lack of formed access tracks in the area, the use of earthwork machinery is extremely difficult and potentially unsafe. WWC is also investigating less intrusive remediation methods such grouting techniques which have successfully been used in the SSCA to remediate surface cracking.

Is there currently a risk to public safety in the SSCA?

The surface affected subsidence zones associated with Longwall 41 are clearly demarcated and signposted warning the public of the hazards associated with underground mining in the area. Security is also posted on access points into the affected area to warn the public of the hazards in the area and to stay away. As long as the public remain outside of these demarcated areas there is no risk to public safety associated with the subsidence impacts.

Will the whole area ever be safe to the public?

Given the nature of the topography associated with the SSCA there has always been a level of risk to the public prior to mining. The SSCA is characterised by steeply sloping terrain, clifflines and terraces which have been formed from geological processes that created the Sugarloaf Range.

The main impacts that result from by mining within the SSCA involve surface cracking, occasional rock falls and tree falls. WWC has management plans in place to manage these impacts as they occur within the SSCA. WWC has an extensive subsidence remediation process in place to remediate impacts as mining progresses. WWC is committed to remediating subsidence impacts to ensure that sustainable long term environmental outcomes are achieved and that risk to the public associated with mining, is minimised.

Did you continue mining Longwall 41 after the issue was discovered?

Yes. Mining was continued in Longwall 41 after the incident was identified. Additional monitoring was undertaken for the remainder of the longwall block to monitor subsidence impacts and outside of the above described areas subsidence impacts were generally minimal.

Have there been any further incidents in the SSCA since this time?

There have been no other subsidence impacts of similar nature to the impacts reported by the media on Longwall 41. WWC did however, report two remediation incidents relating to subsidence on the 4th June 2013 and 20th September 2013 to the relevant authorities. Both incidents involved a spillage of the site's approved grouting product from surface crack remediation sites within the SSCA.

WWC, in consultation with the Office of Environment and Heritage, has prepared a Grout Remediation Plan for both of the affected areas. The Grout Remediation Plan has been approved and remediation will commence in October. The Grout Remediation Plan is available on the West Wallsend Colliery Website.

How much longer will you be mining in the area?

In accordance with the site's Project Approval, WWC has approval to continue underground mining in the area till 2021.

What assurances can you give about predicted subsidence impacts in the SSCA and the successful management of these impacts as mining continues?

A full review of the sites subsidence model has been undertaken by the sites subsidence consultant following the outcomes from the incident and the monitoring results obtained from Longwall 41. Based on this review WWC has significantly modified the mine plan to reduce impacts on steep slopes and cliff lines within the SSCA as a result of subsidence.

Based on this review and the associated modifications to the mine plan, WWC is not expecting to see impacts of a similar extent to the impacts that were experienced adjacent to longwall 41.

Why is grout being used to repair surface cracking?

Remediation of surface cracking on gently sloping terrain with vehicular and equipment access is generally undertaken using small earthworks machinery. In areas where access is limited or in steeper terrain WWC has utilised a specialist contractor to assist with filling surface cracking using grouting techniques. The grouting process has proven to be a less intrusive method of remediation that requires limited disturbance to fill surface cracking to prevent surface water ingress and minimise public safety risk associated with the exposed cracks.

Community Support Program

West Wallsend Colliery has been involved in a variety of community support initiatives since the last newsletter, contributing over $100,000 to the local community. Oceanic Coal takes great pride in its ability to support these worthy community initiatives and has a strong history of community support and involvement through its well established Social Involvement Plan. Some of the Community Support initiatives undertaken since the last newsletter include:

- Speers Point Public School – Funding of a school trip to Dubbo Zoo for disabled children
- Woodrising OOSH – Donation to assist with the purchase of new air conditioners for the building
- Lake Macquarie Research Grants Sponsorship
- Salvation Army Tinned Food Appeal
- West Wallsend Primary School – Donation of Computers
- Sugar Valley Neighbourhood Centre – establishment of a Breakfast Club for local school children
- Barnsley School ClimateCam project
- Community BBQ Trailer partnership with the Lions Club
- Killingworth Rural Fire Brigade – Purchase of working at heights equipment to assist in emergency response situations
- Lake Macquarie State Emergency Service - Purchase of an industrial floodlight to assist night time emergency operations in the local area
- Newcastle Wildlife Rescue Service – Care for injured native wildlife
- Alzheimers Australia Partnership
- Teralba Public School – iPad donations















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