



APPENDIX A

Strata Engineering's Empirical Geological Subsidence Prediction Model Summary - GEOSUB



A1 INTRODUCTION

Strata Engineering has developed an empirical subsidence prediction model for the Newcastle Coalfield. The model enables the influence of massive strata units such as conglomerate and sandstone channels to be included in the prediction of subsidence over single and multiple longwall panels. It has been recognised for some time that the presence of massive strata units above longwall panels has resulted in reduced subsidence compared to that measured over longwall panels with similar geometry and thinner strata units.

A database of maximum single and multi longwall panel subsidence and associated massive strata units has been 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 70m and 351m) as shown in **Figure A1**.

The project database has included single seam mining data from eleven collieries in the Lake Macquarie area of the Newcastle Coalfield as presented in **Table A1**.

Table A1 - Empirical Database Sources

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

The wide range of W/H in the database for single extraction panels is unique compared to the other Australian coalfields and has therefore been the focus of the study. Pillar extraction or multiple panel data has not been used for producing the subsidence prediction curves, as it invariably makes the assessment of geological influences difficult, if not impossible.

Apart from the above stated issues, current empirical design curves are also now out of date and unable to adequately predict subsidence for cover depths > 250 m in the Newcastle Coalfield. It has also been realised that it is necessary to divide the database into various cover depth categories before the influence of geology can be reliably assessed as shown in **Figure A1** and **A2**. The main reason for this approach is that the minimum thickness of the strata units required to span or bridge across an extracted longwall panel is a function of the cover depth (i.e. the load acting on the beam) and the width of the panel (the span of the beam).

Details of the database and prediction methodology are presented in the following sections.



A2 MODEL DEVELOPMENT

The first stage of the development of the subsidence prediction model addressed the influence of significant overburden lithology over single longwall/miniwall panels only. **Figure A3** illustrates a physical model showing the subsidence reducing effects of a massive strata unit. The subsidence prediction model has been developed with the goal of providing the industry with a robust and reliable technique to utilise the vast amount of geological and testing information already gathered by mining companies. It was considered that once the prediction of S_{max} could be made with a confidence level of 90 to 95%, other parameters such as tilt, curvature, horizontal strain and the angle of draw could then be derived from the S_{max} and associated key geometrical parameters with improved, if not similar, confidence levels. The impact of multi-panel subsidence effects and the role of the chain pillars on final subsidence have also been subsequently addressed.

The development of the new empirical prediction methodology has used borehole data to derive the thickness and location of massive strata units that have been 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).

It has been found that the subsidence above a panel of a given cover depth (H) and a panel width (W) decreases significantly when a massive strata unit is thicker than a certain threshold value. The threshold thickness is also reduced when the unit is located closer to the surface. In this case, the strata unit is considered to have a 'high' subsidence reduction potential (SRP) as shown in **Figure A4**.

Obviously, for a thin strata unit located relatively close to a panel, the subsidence reduction potential will be 'low'. However, there also appears to be an intermediate zone where a single strata unit (or several thinner units) below the 'high' subsidence reduction threshold thickness can result in a 'moderate' reduction in subsidence. A second threshold line can therefore be drawn which represents the threshold between 'moderate' and 'low' subsidence reduction potential as shown in **Figure A4**. Similar threshold lines have been determined for strata units located at various heights (y) above the workings as shown in **Figure A4**.

Based on the above analysis, the subsidence reduction potential for a strata unit can now be defined as being 'high', 'moderate' or 'low'.

Overall, the massive unit thickness, panel width, depth of cover and height of unit above the workings are considered to be key parameters for assessing the overburden stiffness and spanning capability over a given panel width which control surface subsidence. A concept model for overburden behaviour is illustrated in **Figure A5**.



A3 MODEL OUTCOMES

The major finding of the project is that the historically used relationship between subsidence and panel width to cover depth ratio (W/H) is not a constant for the range of cover depths (H) involved. Surface subsidence increases with increasing cover depth (H) for the same W/H ratio, and is primarily a function of the increasing panel width (W). For constant single panel width (W), subsidence will decrease with increasing cover depth (H).

Therefore it has been necessary to separate the data into various depth ranges. Three depth categories of $H = 100, 200$ and 300 m have been identified which divide the database up into $H = 70\text{m to }150\text{m}$, $151\text{m to }250\text{m}$ and $251\text{m to }351\text{m}$.

The influence of overburden lithology was found to be readily apparent once the database was filtered using the above cover depth ranges.

Other outcomes of this new methodology are the introduction of several new parameters to improve the definition of various types of overburden behaviour and the associated mechanics.

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.

Variation in subsidence along the length of a panel may be due, partial, to the SRP variation of geological units within the overburden.

The database for the Newcastle Coalfield 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 A6**. This behaviour occurs when panel width to cover height ratio (W/H) is in the range from 0.6 to 0.8. This phenomenon can be simply explained as a point of significant shift in structural behaviour of the overburden.

This model allows the user to determine a range of subsidence magnitudes that may be expected and the location of geology related SRP and/or 'geometrical transition zones' along a panel. The identification of the transition zones is an important factor when assessing potential damage risks of differential subsidence to important infrastructure, buildings and natural surface features such as rivers, lakes and cliff lines etc.

For W/H ratios <0.7 , the overburden appears to behave as a 'deep' beam or linear arch whereby the mechanics of load transfer to the abutments is predominantly by axial compression along an approximately parabolic shaped line of thrust. This is depicted by the load vectors as shown in **Figure A7(a)**.

For W/H ratios >0.7 the geometry of the overburden will no longer allow axially compressive structural behaviour to dominate, as the natural line of thrust now lies outside of the overburden and bending action due to subsequent block rotation occurs as depicted in **Figure A7(b)**.

Provided that the abutments are able to resist this rotation, flatter lines of thrust will still develop within the overburden units, but the structural action is now dominated by bending action. This type of overburden behaviour has been defined as 'shallow' beam



behaviour in the context of this project. ‘Shallow’ beam behaviour in structural terms is fundamentally less stiff than ‘deep’ beam behaviour, resulting in a significant increase in subsidence or sag across an extracted longwall panel (all other factors being equal) as shown **Figure A7(b)**.

“Voussoir beam” or “fractured linear arch” theory can be used to explain both types of overburden behaviour, as deep seated and flatter arches develop in the strata in an attempt to balance the disturbing forces in a jointed sedimentary rock mass with essentially zero-tensile strength.

The ‘strata unit location factor’ (y/H) has been developed to assess 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 horizontal stress 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 horizontal 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. material 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 for the same SRP above a given panel width as shown in **Figure A8**.

Subsequent stages of the project expanded the single panel model to predict:

- panel goaf edge or rib subsidence
- angle of draw
- maximum final subsidence after multi-panel effects, which includes subsidence over chain pillars
- maximum transverse and longitudinal tilt, curvature 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.

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}).



After the completion of the project the majority of the above project outcomes have been successfully incorporated into a spreadsheet-based subsidence analysis tool.

The conceptual models of overburden behaviour have been developed and tested such that it is now possible to address subsidence behaviour in other coalfields including the prediction of multiple seam mining effects by pseudo-superposition techniques as shown in **Figures A9 to A11**.

To date, the model has been used to make successful subsidence profile predictions for Mandalong, Newstan and West Wallsend collieries, an example is provided in **Figure A12**. The model has also made credible 'blind' predictions of subsidence for Springvale Colliery in the Western Coalfield based on the geometry and geology information provided by the mine.

The key input parameters required to make subsidence predictions using the model include the following:

- Panel Width (W)
- Cover Depth (H)
- Seam Working Height (T)
- Overburden lithology, specifically the thickness and location of massive strata units (t, y)
- Chain Pillar Width (w_{cp})
- Number of panels extracted

The statistical inferences and estimates of the model uncertainty of the prediction methodology are presented in **Sections A4 to A6** with examples of the prediction method presented in **Section A7**.

A4 Subsidence Impact Parameter Predictions above Longwall Panels

The database 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.

Predicted 'smooth' subsidence profiles have been determined based on cubic spline curve interpolation through a number of key points along the subsidence trough (i.e. maximum in-panel subsidence, inflexion point, goaf edge or rib-side subsidence, subsidence over chain pillars and 20 mm subsidence or angle of draw limit) that have been empirically derived from regression relationships between the variables and the geometry of the panels. Both transverse and longitudinal profiles have been derived in this manner.

The first and second derivatives of the fitted spline curves provide the '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 (and



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 the predictions of subsidence at surface features that are located over the goaf or extracted area.

Subsidence contours have been created based on the empirically derived subsidence profiles along cross lines, centre lines and corner lines around the ends of the longwall panels. The contours were derived using geostatistical kriging techniques and the data processing software Surfer 8[®]. Vertical 'slices' were then taken through the contours where required to (i) determine the final CWC subsidence profiles, and (ii) assess the likely impacts on the relevant surface features.

A5 Prediction of Subsidence Impact Parameters Using Regression Analysis Techniques

The prediction of key impact parameters inside or outside the limits of extraction have been estimated using normalised longwall subsidence data from the Newcastle Coalfield. This approach allows a reasonable assessment of the uncertainty of the predictions to be considered using statistical regression techniques. A linear or non-linear regression line has been fitted to the database for each impact parameter, which has been normalised to easily measured parameters such as maximum subsidence, panel width and cover depth. The quality or significance of the regression line is significantly 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 have been reviewed carefully because they 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 strongly biased by the database and may not reflect the true 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. SEA has developed the regression techniques presented in the **ACARP, 2003** report 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, and were removed only when a reasonable explanation could be given for each anomaly (i.e. multiple seam subsidence, geological faults and surface cracking effects).

The regression equations developed by SEA in the **ACARP, 2003** study have R^2 (i.e. Coefficients of Determination) values that are mostly greater than 50%; which indicates that the relationships between the variables are significant.



A6 Prediction Model Uncertainty

Provided there are (i) more than 10 data points in the data sets which cover 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 the data set.

On-going review of each of the regression equations used in this report over the past three years have not required significant adjustment of the equations in order to include new measured data points.

A7 WORKED EXAMPLE OF MAXIMUM SUBSIDENCE FOR A SINGLE PANEL

An example is presented below to demonstrate how to use of the model to predict the maximum subsidence for a single longwall panel. The overburden is first characterised by contouring the key input parameters over the proposed mining area and selecting the average values for a given panel.

Input Parameters:

The average mining geometry for this case is assumed to be:

Panel Width, $W = 200$ m,

Cover Depth, $H = 200$ m,

Working Height, $T = 4$ m,

Surface ground slopes $< 20^\circ$.

Geology:

A review of several borehole logs above the panel from the surface to below the seam floor indicates that a massive sandstone channel ranging in thickness between 30 and 35 m exists over half of the area of the panel. The base of the unit is situated at about 160 m depth. The remaining strata in the overburden generally consists of a typical inter-bedded coal measures sequence of shale, sandstone, siltstone and coal with strata unit thicknesses ranging between 0.1 and 5 m.

A7.1 Analysis of Subsidence Reduction Potential

The first step of the analysis is to assess the geometry of the panel and select the appropriate cover depth range.

For a cover depth of 200 m, the appropriate subsidence prediction and SRP curves for cover depths between 150 and 250 m are presented in **Figures A13** and **A14**.

Based on these two figures, the Subsidence Reduction Potential (SRP) of the overburden lithology above the panel may be considered for two areas as follows:

**Area 1 – Affected by Massive Strata:**

Maximum Unit Thickness, $t = 30$ m,

Height above Workings, $y = 40$ m,

Panel Width, $W = 200$ m,

Cover Depth, $H = 200$ m,

Massive Unit Location Factor, $y/H = 40/200 = 0.2$.

As shown in **Figure A13**, for a unit location factor of 0.2, the massive unit has a 'Moderate' to 'High' SRP.

*Note : The SRP lines are used to determine the range of subsidence reduction that has been observed over longwall panels. It is therefore possible that a particular unit impact will range between moderate to high or moderate to low. For cases that plot between the High and Moderate SRP threshold limits, the closest SRP line will be selected by the model to infer the most likely SRP range. For cases which plot above the High SRP line, the SRP range is assumed to be High only, but a range of S_{max} will still be defined by the subsidence prediction boundary limit lines shown in **Figure A14**.*

Area 2 – Not Affected by Massive Strata:

Maximum Unit Thickness, $t = 5$ m

Height above Workings, $y = 200$ m

Note: it is considered that where there is no obvious massive strata unit with a thickness greater than say 5m, it is appropriate to adopt a value of $y = H$ or $y/H = 1$ for the SRP analysis.

Panel Width, $W = 200$ m

Cover Depth, $H = 200$ m

Massive Unit Location Factor, $y/H = 200/200 = 1$

*Note: in the case where a specific y/H line is not shown on the SRP charts it is intended that the next lowest y/H line be adopted when assessing the SRP of a geological unit (i.e. for a y/H of 1.0, the $y/H = 0.5$ line should be used on **Figure A13**).*

Several massive units that exist in the overburden may also be assessed using the same methodology.

In this case, the strata unit plots below the 'Moderate' SRP line on **Figure A13** and is assessed to have a Low to Moderate SRP.



A7.2 Analysis of Maximum Subsidence for a Single Panel

The maximum subsidence range above the Area 1 and Area 2 may now be assessed as follows:

Area 1 – Affected by Massive Unit:

By reference to the 'Moderate' to 'High' SRP subsidence prediction curves shown in **Figure A14**, for a $W/H = 1$ and an extraction height $T = 4$ m:

High SRP Limit $S_{\max}/T = 0.342$ so that $S_{\max} = 0.342 \times 4.0 = \underline{1.37 \text{ m}}$, and

Moderate SRP Limit $S_{\max}/T = 0.425$ so that $S_{\max} = 0.425 \times 4.0 = \underline{1.70 \text{ m}}$.

Therefore, the predicted single panel $S_{\max} = 1.37$ to 1.70 m, or in average terms

Area 1 $S_{\max} = 1.54 \text{ m} \pm 0.17 \text{ m}$ (the mean value with 95% Confidence Limits).

Area 2 – Not affected by Massive Unit:

By reference to the 'Low' to 'Moderate' SRP subsidence prediction curves shown on **Figure A14**, for a $W/H = 1$ and an extraction height $H = 4$ m:

Low SRP Limit $S_{\max}/T = 0.545$ so that $S_{\max} = 0.545 \times 4.0 = \underline{2.18 \text{ m}}$, and

Moderate SRP Limit $S_{\max}/T = 0.425$ so that $S_{\max} = 0.425 \times 4.0 = \underline{1.70 \text{ m}}$.

Therefore, the predicted single panel $S_{\max} = 1.70$ to 2.18 m, or in average terms.

Area 2 $S_{\max} = 1.94 \text{ m} \pm 0.24 \text{ m}$ (the mean value with 95% Confidence Limits).



A8 MULTI-PANEL SUBSIDENCE PREDICTION MODEL

The effect of extracting several longwall panels adjacent to one another is dependent on the stiffness of the overburden and the chain pillar(s) left between the panels. Invariably, 'extra' subsidence above a previously extracted panel, and is considered to be caused primarily by the compression of the chain pillars left between the extracted panels.

A chain pillar will undergo the majority of its life cycle compression after it has been 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 effect up to three or four gate road chain pillars that have been formed between previously extracted panels. The stiffness of the overburden and chain pillar system will determine the extent of load transfer to the preceding chain pillars.

Multiple-panel effects have therefore been included in the subsidence prediction 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, has been based on the regression equation presented in **Figure A15**. The model compares the ratio of chain pillar subsidence (S_p) over the extraction height (T), to the width of the chain pillar divided by the cover depth multiplied by the total extracted width ($1000w_{cp}/W'H$).

A regression analysis on the data indicates a strong exponential relationship for $1000w_{cp}/W'H$ values up to 0.543. For values > 0.543 , the relationship becomes constant.

$$S_p/T = 7.4044e^{-10.329F} \quad (R^2 = 0.92) \text{ for } F < 0.543, \text{ and}$$

$$S_p/T = 0.023 \text{ for } F > 0.543$$

where

$$F = 1000w_{cp}/W'H$$

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. $W' = W_i + w_{cp(i)} + W_{i+1}$). Note that this approach does not include a caving angle.

A reasonable, but generally conservative estimate of the final subsidence for a panel with several subsequent extracted panels of similar geometry, can then be determined by adding 50% of the predicted chain pillar subsidence (S_p) to the single panel S_{max} estimate.

However, the above chain pillar model has now been superseded as more data from other coalfields has shown that subsidence above chain pillars is strongly influenced by the Factor of Safety (FoS) of the pillars and the caving angle of the overburden above them. The maximum subsidence generally occurs when the pillars are subject to double abutment loading conditions (i.e. goaf on both sides).

In the new approach, the measured subsidence above chain pillars is considered to be strongly influenced by the following key parameters:



- The volume of the rock prism (i.e. the load) acting on the pillar and immediate roof and floor strata ($W'D$). *Note: this has been conservatively estimated for an assumed caving angle of 21 degrees.*
- The longwall face extraction height (T).
- The pillar width and development height (w and h).

The coal pillar and column of rock above and below the seam will behave either elastically or plastically (depending on their strength and stiffness properties) under double abutment loads.

The subsidence above the pillars is a function of the following combination of these key parameters:

$$S_p = f(T, W'H/w_{cp}, h/w_{cp}) \text{ or}$$

$$S_p/T = f(W'Hh/w_{cp}^2) = \text{the "Chain Pillar Subsidence Index" (CPSI)}$$

where:

T = the extraction height (or sometimes the seam height) is applied instead of the pillar development height as this approximates to the column of coal that is subject to maximum pillar stresses.

$W'H/w_{cp}$ = a pillar stress index

w_{cp}/h = a pillar strength index.

Prediction curves for the mean and U95%CL subsidence magnitudes above the chain pillars have been included in the updated model as shown in **Figure A16**.

Multiple panel subsidence predictions can then be made using the models presented to predict first and final subsidence above a given longwall panel.

The definition of first and final S_{max} is as follows:

First S_{max} = the total 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 total subsidence over an extracted longwall panel after at least three more production panels have been extracted, or when mining is completed.

The prediction of the 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 and is further explained below.



A8.1 Methodology for Calculating First and Final Subsidence for Multiple Longwall Panels

For $i = 1$ to n longwalls with known panel width (W), cover depth (H), extraction height (T), massive unit thickness (t), massive unit height above extraction (y) and pillar width (w_{cp}), the mean first and final S_{max} and S_p values are determined as follows:

Step 1 - Calculation of pillar subsidence (First S_p), and final pillar subsidence (Final S_p), for the chain pillar under double abutment loading conditions for a given chain pillar FoS:

For the subject panel under consideration, first pillar subsidence S_p refers to the first subsidence which develops over a chain pillar when subject to double abutment loading conditions and may be estimated as follows:

$$\text{Final } S_{p(i)} = \text{First } S_{p(i)} + b S_{p(i+1)} + c S_{p(i+2)}$$

$$\text{U95\% Final } S_{p(i)} = S_{p(i)} + \text{U95\% } S_p \text{ error,}$$

where:

Single $S_{p(i)}$ - is the pillar subsidence under double abutment load and can be derived from **Figure A16**; “ i ” denotes the subject panel and the pillar under consideration; $S_{p(i+1)}$ and $S_{p(i+2)}$ are the pillars subsidence for the subsequent pillars after the second and third panels are extracted.

Note : If the panels and pillars have the same geometry, then $S_{p(i)} = S_{p(i+1)} = S_{p(i+2)}$.

c and b - multiple longwall panel effects constants presented in **Table A2**,

It is assumed that after three more longwall panels are extracted subsequently, any panel extracted afterwards will have negligible impact on pillar subsidence for the pillar under consideration.

Table A2 – Coefficient Constants b and c for Various w_{cp}/H

w_{cp}/H	b^*	c^*
< 0.15	0.2	0.035
> 0.15 and <0.3	0.15	0
> 0.3	0.005	0

Note:

* - The overburden load coefficients coefficients b and c are used to calculate the increase in chain pillar compression or subsidence due the extraction of subsequent longwalls; b represents the relative increase in pillar compression from the next extracted panel and c indicates the influence of subsequent longwalls to that. Their magnitude has been linked to the relative stiffness index or the pillar width to cover depth ratio (w_{cp}/H) as shown in **Table A3**.



Table A3 - Proportional Coefficients for Adjacent Panel Chain Pillar Subsidence Effects on the Subject Chain Pillar

Coefficient Name	Value for $w_{cp}/H < 0.15$	Value for $0.15 < w_{cp}/H < 0.3$	Value for $w_{cp}/H > 0.31$
a	0.07	0.035	0.0
b	0.20	0.15	0.005
c	0.035	0.0	0.0

Step 2 - Calculation of single mid-panel subsidence (Single S_{max}), first subsidence (First S_{max}), and final subsidence (Final S_{max}) for the subject panel:

Single S_{max} can be derived using either of **Figures A17 to A23**, depending on the cover depth.

First S_{max} is calculated by adding 50% of the predicted pillar subsidence of the chain pillar positioned between the previous and current panel, $S_{p(i-1)}$, less the goaf edge subsidence, S_{ge} , to the single subsidence, S_{max} . Where S_{ge} is the goaf edge subsidence of the subject panel respecting to Single S_{max} and can be derived using **Figure A24**.

Final S_{max} is calculated by adding 100% of the predicted Final $S_{p(i)}$ less the goaf edge subsidence due to first S_{ge} , where first S_{ge} is the goaf edge subsidence due to first S_{max} and can also be derived using **Figure A24**.

In summary, the mean values of the First S_{max} and Final S_{max} are calculated as:

$$\text{First } S_{max} = \text{Single } S_{max} + 0.5 (S_{p(i-1)} - S_{ge}),$$

$$\text{Final } S_{max} = \text{First } S_{max} + (\text{Final } S_{p(i)} - \text{First } S_{ge}).$$

The U95% Confidence Limits or Credible Worst Case Values are then,

$$\text{U95\% First } S_{max} = \text{mean First } S_{max} + 1.64 (\text{U95\% } S_{max} \text{ error} + \text{U95\% } S_p \text{ error})^{1/2},$$

$$\text{U95\% Final } S_{max} = \text{mean Final } S_{max} + 1.64 (\text{U95\% } S_{max} \text{ error} + \text{U95\% } S_p \text{ error})^{1/2},$$

A8.2 Example of Predicting Subsidence above a Panel Due to Multiple Longwalls

Input parameters:

Panel width, $W = 150$ m,

Pillar height, $h = 2.4$ m,

Pillar FoS = 3.46,

Pillar width, $w_{cp} = 25$ m, and

Cover depth, $H = 145$ m.

It is assumed that all the panels and pillars have the same geometry.

**Step 1 - Calculation of chain pillar subsidence:**

According to **Figure A16**, the first and final subsidence above the chain pillars (S_p) between two extracted areas are determined as follows:

$$S_p/h = 0.2934 (\text{FoS})^{-0.14901} \quad \text{when FoS} < 2;$$

$$S_p/h = 0.0465 (\text{FoS})^{-0.3314} \quad \text{when FoS} > 2.$$

For $\text{FoS} = 3.46 > 2$,

$$\begin{aligned} S_{p(i)}/h &= 0.0465 (\text{FoS})^{-0.3314} \\ &= 0.0465 (3.46)^{-0.3314} \\ &= 0.0308, \text{ and} \end{aligned}$$

$$\underline{S_{p(i)} = 0.074 \text{ m (the mean value).}}$$

$$\begin{aligned} \text{U95\% } S_p \text{ error} &= 0.07 h \quad \text{when FoS} < 2; \\ &= 0.03 h \quad \text{when FoS} > 2; \end{aligned}$$

For $\text{FoS} = 3.46$, $S_p \text{ error} = 0.03 h$ and

$$\begin{aligned} \text{U95\% } S_{p(i)} &= S_{p(i)} + S_p \text{ error}, \\ &= 0.074 + 0.03 \times h, \\ &= 0.074 + 0.03 \times 2.4 \\ &= \underline{0.146 \text{ m (the credible worst case value).}} \end{aligned}$$

According to **Table A2** and **A3**, for $w_{cp}/H = 25/145 = 0.172$, then $b = 0.15$ and $c = 0$.

$$\begin{aligned} \text{Final } S_{p(i)} &= \text{First } S_{p(i)} + b S_{p(i)} + c S_{p(i)}, \\ &= (1 + b + c) S_{p(i)}, \\ &= (1 + 0.15) \times 0.074, \\ &= \underline{0.085 \text{ m (the mean value)..}} \end{aligned}$$

$$\begin{aligned} \text{Final U95\% } S_{p(i)} &= \text{Final } S_{p(i)} + S_p \text{ error} \\ &= 0.085 + 0.072 \\ &= \underline{0.157 \text{ m (the credible worst case value).}} \end{aligned}$$

**Step 2 - Calculation of maximum mid-panel subsidence:**

According to **Figures A17 to A24**, the maximum mid-panel subsidence (S_{\max}) and goaf edge subsidence (S_{ge}) may be estimated as follows:

$$\text{Single } S_{\max} = 0.818 \text{ m, U95\% error} = 0.12 \text{ m and } S_{ge} = 0.054 \text{ m,}$$

hence,

$$\begin{aligned} \text{First } S_{\max} &= \text{Single } S_{\max} + 0.5 (S_{p(i-1)} - S_{ge}), \\ &= 0.818 + 0.5 (0.078 - 0.054), \\ &= \underline{0.83 \text{ m (the mean value)}}. \end{aligned}$$

It follows then that,

$$\text{First } S_{ge} = 0.055 \text{ m, and}$$

$$\text{U95\% } S_{\max} \text{ error} = 0.12 \text{ m.}$$

$$\begin{aligned} \text{U95\% First } S_{\max} &= \text{First } S_{\max(i)} + \text{U95\% } S_{\max} \text{ error} \\ &= 0.83 + 0.12 \\ &= \underline{0.95 \text{ m (the credible worst case value)}} \end{aligned}$$

The final mid-panel subsidence may then be calculated as follows:

$$\begin{aligned} \text{Final } S_{\max} &= \text{First } S_{\max} + (\text{Final } S_{p(i)} - \text{First } S_{ge}), \\ &= 0.83 + (0.085 - 0.055) \\ &= \underline{0.86 \text{ m (the mean value)}}. \end{aligned}$$

$$\begin{aligned} \text{U95\% Final } S_{\max} &= \text{Final } S_{\max} + \text{U95\% } S_{\max} \text{ error} \\ &= 0.86 + 0.12 \\ &= \underline{0.98 \text{ m (the credible worst case value)}}. \end{aligned}$$



A9 SUBSIDENCE AND ASSOCIATED PARAMETER PROFILE PREDICTION

Regression analysis techniques have been used to develop subsidence and associated parameter profiles based on correlation with the measured key parameters.

Regression equations with Coefficients of Determination (R^2) ranging from 50% to 93% have been developed for each of the parameters listed in the tables below. In some cases, regressions were analysed for several parameters and the regression with the maximum R^2 value was adopted. The derived regression lines are presented in **Tables A4 to A7**.

Table A4 - Key Subsidence Profile Parameter Predictions for Panel Crosslines

Parameter	Regression Equation (and +/- 95% Confidence Limits)	Coefficient of Determination (R^2)	Figure No.
Mean Chain Pillar Subsidence, S_p (m)	$S_p/h = 0.2934(FoS)^{-1.4901}$ +/- 0.07 for $FoS < 2.0$ $S_p/h = 0.0465(FoS)^{-0.3314}$ +/- 0.02 for $FoS > 2.0$	0.77	A16
TG & MG Rib Subsidence, S_{side} (m)	Mean $S_{side}/S_{max} = 0.0722(W/H)^{-2.557}$ U95%CL $S_{side}/S_{max} = 0.0719(W/H)^{-1.9465}$	0.82	A24
Angle of Draw, AoD (20mm limit) ($^\circ$)	$AoD = 7.646LN(S_{rib}) + 32.259$ +/- 8.7	0.56	A17
Distance to T_{max} from panel rib-side, d (m)	$d/W = -0.0739(W/H) + 0.3638$ +/- 0.1	0.19	ACARP, 2003
Subsidence at T_{max} , S_{Tmax} (m)	$S_{Tmax}/S_{max} = 0.6$ +/- 0.24	<0.1	ACARP, 2003
Distance to S_{max} from panel centreline, x (m)	$x/W = 0.0$ +/- 0.18	<0.1	ACARP, 2003

Table A5 - Key Subsidence Profile Parameter Predictions for Panel Centrelines

Parameter	Regression Equation (and +/- 95% Confidence Limits)	Coefficient of Determination (R^2)	Figure No.
Panel End Subsidence, S_{end} (m)	Mean $S_{end}/S_{max} = 0.0213(W/H)^{-3.2872}$ for $W/H < 0.9$ and $S_{end}/S_{max} = 0.03$ for $W/H > 0.9$ U95%CL $S_{end}/S_{max} = 0.0213(W/H)^{-3.2872}$ 0.063	0.98	A25
Angle of Draw, AoD (20mm limit) ($^\circ$)	$AoD = 7.646LN(S_{end}) + 32.259$ +/- 8.7	0.56	A17
Distance to T_{max} from panel end, d (m)	$d/W = 0.5569e^{-0.413(W/H)}$ and $d/W > 0.18$ +/- 0.2	0.24	ACARP, 2003
Subsidence at T_{max} (m)	$S_{Tmax}/S_{max} = 0.6$ +/- 0.27	N/A	ACARP, 2003
Distance to S_{max} from panel end, a (m)	$a/W = 1.3571e^{-0.6571(W/H)}$ and $a/W > 0.3$ +/- 0.36	0.43	ACARP, 2003



Table A6 - Maximum Subsidence Parameter Predictions Along Panel Crosslines (i.e. Tilts, Curvatures and Strain)

Parameter	Regression Equation (and +/- 95% Confidence Limit)	Coefficient of Determination (R ²)	Figure No.
Maximum Tilt, T _{max} (mm/m)	T _{max} = 0.9651(S _{max} /W) ^{1.5054} +/- 0.4T _{max} and W _{max} < 1.4 - 2H	0.93	ACARP, 2003
Maximum Convex Curvature, +C _{max} (km ⁻¹) {Uniform}	+C _{max} = 15.83(S _{max} /W ²) +/- 0.42 and W _{max} < 1.4 - 2H	0.74	ACARP, 2003
Maximum Concave Curvature, -C _{max} (km ⁻¹) {Uniform}	-C _{max} = 19.79(S _{max} /W ²) +/- 0.37 and W _{max} < 1.4 - 2H	0.79	ACARP, 2003
Maximum Tensile Strain, +E _{max} (mm/m) {Uniform}	+E _{max} = 5.2 - 10* (+C _{max}) +/- 2.4mm	0.72	ACARP, 2003
Maximum Compressive Strain, -E _{max} (mm/m) {Uniform}	-E _{max} = 5.2 - 10* (-C _{max}) +/- 2.4mm	0.72	ACARP, 2003
Maximum Horizontal Displacement (mm) (Tension)	+HD _{max} = 32.308Ln(+C _{max}) + 93.659 +/- (+HD _{max})	0.28	ACARP, 2003
Maximum Horizontal Displacement (mm) (Compression)	+HD _{max} = 54.306Ln(-C _{max}) + 110.94 +/- (+HD _{max})	0.50	ACARP, 2003
Maximum Concentrated Strain (Surface Cracks)	Mean = HD _{max} /Bay-length U95%CL = 2HD _{max} /Bay-length	0.3	ACARP, 2003

Table A7 - Maximum Subsidence Parameter Predictions Along Panel Centrelines

Parameter	Regression Equation (and +/- 95% Confidence Limit)	Coefficient of Determination (R ²)	Figure No.
Maximum Tilt, T _{max} (mm/m)	T _{max} = 0.7479(S _{max} /W) ^{1.5883} +/- 0.5T _{max} and W _{max} < 1.4-2H	0.87	ACARP, 2003
Maximum Convex Curvature, +C _{max} (km ⁻¹)	+C _{max} = 1081(S _{max} /W ²) ^{2.5039} +/- (+0.5C _{max}) and W _{max} < 1.4 - 2H	0.74	ACARP, 2003
Maximum Concave Curvature, -C _{max} (km ⁻¹)	-C _{max} = 479(S _{max} /W ²) ^{2.1646} +/- 0.5(-C _{max}) and W _{max} < 1.4 - 2H	0.74	ACARP, 2003
Maximum Tensile Strain, +E _{max} (mm/m) {Uniform}	+E _{max} = 5.2 - 10* (+C _{max}) +/- 2.4mm	0.70	ACARP, 2003
Maximum Compressive Strain, -E _{max} (mm/m) (Uniform)	-E _{max} = 5.2 - 10* (-C _{max}) +/- 0.5E _{max}	0.70	ACARP, 2003
Maximum Horizontal Displacement (mm) (Tension)	+HD _{max} = 40.193Ln(+C _{max}) + 119.7 +/- (+HD _{max})	0.29	ACARP, 2003
Maximum Horizontal Displacement (mm) (Compression)	+HD _{max} = 49.7Ln(-C _{max}) + 109.2 +/- (+HD _{max})	0.39	ACARP, 2003
Maximum Concentrated Strain (Surface Cracks)	Mean = HD _{max} /Bay-length U95%CL = 2HD _{max} /Bay-length	0.3	ACARP, 2003

Notes:

- S_{max}/W and S_{max}/W² have the same units as the dependent variables (i.e. T_{max} and C_{max}).
- For cases where C_{max} or C_{min} are > 1km⁻¹, the measured strains may be 2 to 4 times the predicted values due to strain concentration effects (i.e. joints or near surface rock mass failure or cracking). * - a value of 10 m has been assessed for Ulan and Moolarben lithology.
- Maximum strains due to strain concentration effects from surface cracking may be predicted by dividing HD_{max} by the bay-length.



A10 Estimation of Surface Strain Concentrations, Crack Widths and Crack Depths

Strain and curvature concentrations can increase 'smooth' profile strains by 2 to 3 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, 2003a**.

The measured strain at a particular section of the subsidence trough will in fact be independent of the bay-length on a 'smooth' profile that is not affected by strain concentrations. However, where strain concentrations do occur, the measured strains will be highly dependent on the bay-length.

Where relatively stiff rock exposures with widely spaced or adversely orientated jointing exist, much larger crack widths (than for the deep soil profile case) can occur. The reason for this phenomenon is that once cracking occurs, the sudden reduction of stiffness results in the majority of the movement then concentrate at the point of failure.

For example, for a measured strain of 3 to 5 mm/m along a recently observed cross line above a longwall panel in the Newcastle area, several cracks developed in the soil surface, which ranged in width between 10 and 30 mm, whilst within 10 m of the area, a single 100 mm wide crack developed in a sandstone rock exposure of medium strength and with widely spaced jointing, see photograph below.



Measured crack width = 100 mm.

Measured crack depth >5 m

Location = 27 m from solid rib.

- $S_{\max} = 1.4 \text{ m}$.
- Cover depth, $D = 180 \text{ m}$.
- LW panel width, $W = 175 \text{ m}$.
($W/D = 0.97$)
- Measured curvature,
 $C = 1.15 \text{ km}^{-1}$
(radius of 867 m)
- Measured strain over 10 m,
 $E = 5.8 \text{ mm/m}^*$

Concentrated strain = crack width/bay-length = $100/10 = 10 \text{ mm/m}$.

Therefore, concentrated strain = $10/5.8 = 1.7 \times$ uniform strain

*- peak strains measured 10 m to south of crack at same distance from rib.



In the context of subsidence surveys, the definition of strain is the change in length (extension or compression) of a bay-length divided by the original value of the bay-length.

It is also apparent that, based on study of the strain and curvature data collected for the project, the majority of horizontal strain is caused by the ground curvature - which occurs within a subsidence trough. The tensile and compressive strain peaks also generally coincide with the convex and concave curvature peaks respectively. Diversions from this behaviour are common in undulating terrain when down slope movements can cause strain concentrations outside zones of bending.

The development of the strain prediction model has initially been based on strain due to bending deformation only. For cases where the toe of a slope is to be undermined, the location of the peak strain may be shifted outside the mining limits to the associated ridgeline. The database in the model already includes undulating terrain data (i.e. ground slopes up to 20 degrees) so the magnitude of the predicted concentrated strain is assumed to include the topographic effect.

In the context of an elastic, homogenous, bending beam, the change in length of the surface of the beam can be determined by the curvature of the beam and the depth or distance to the neutral axis of the beam (i.e. the point or axis of rotation).

Based on reference to standard structural beam theory presented in **Hall, 1986**, it can be shown that the surface strain due to bending is a linear function of the curvature:

$$E = C \times d_n$$

where E = tensile or compressive strain on surface of beam
 C = convex or compressive curvature of bending beam
 d_n = distance to the neutral axis or "zero" strain

The implication here is that the measured strain will be a function of both the panel geometry and the surface geology – including both lithology and structural defects.

The parameter d_n also indicates that the depth to the neutral axis of the bending beam is (i) the likely depth of cracking from the surface that is subject to convex curvature or tensile strains, and (ii) it represents approximately half of the total near surface beam thickness that is assumed to be bending.

For the case of a near surface rock mass, the value of d_n is likely to vary significantly over a longwall panel and could explain why strains and curvature measurements are usually quite erratic where soil cover depths are shallow and surface failure or cracking results in strain concentration effects. For the database, the mean d_n was found to equal 5.2 m with a median value of 7.3 m for the "smooth" profile or non-failed cases.

Failure of the near-surface rock mass is also apparent when curvatures exceed a certain threshold limit; as a result, large localised increases in both curvature and strain can occur with strain relief occurring in adjacent bays.



A11 SUB-SURFACE FRACTURING MODEL DEVELOPMENT OUTCOMES

A11.1 Whittaker and Reddish Physical Model

The most significant published work ever undertaken in the area of sub-surface fracturing over longwall panels, which gives specific guidelines (over and above such work as the Wardell Guidelines for the prevention of inundation of mine workings beneath surface and sub-surface water bodies) is that of **Whittaker and Reddish (1989)**.

The model in question 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 that was 77 m above the seam.

The model identifies the existence of two distinct zones of fracturing above super-critical width extractions (continuous and discontinuous fracturing) and relates the height of each to “predicted maximum tensile strain at the surface”. As such, its use is also based upon being able to make credible subsidence predictions. The basis of the model is summarised in **Figure A26**.

A review of the methodology that was undertaken to develop the model and its key features have been summarised below:

The model was based on laboratory controlled measurements of longwall extraction physical models.

The physical model was constructed from multiple layers of coloured sand and plaster mixtures with sawdust bond breakers placed between each successive layer.

The scale and mechanical properties of the model and prototype satisfied dimensional analysis and similtude laws.

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’ was measured and plotted with the associated peak tensile strain predictions at the surface. *Notes:- It is not clear from the text as to how the tensile strains were predicted; it would seem likely that the SEH(1975) was used based on the comparisons that were made with the SEH subsidence predictions during the modelling work.* The fracturing path progressed up at an angle from the solid rib-side and inwardly towards the centre of the panel – see **Figures A26** and **A3**.

The definition of the extent of ‘continuous’ fracturing refers to the height at which a direct connection of the fractures occurs within the overburden and the workings; it represents a ‘direct’ hydraulic connection for groundwater inflows.

The definition of the extent of ‘discontinuous’ fracturing refers to the height at which the horizontal permeability increases as a result of strata de-lamination and fracturing.



However, a direct connection of the fractures within the overburden and the workings does not occur.

The fracturing in question occurred close to the rib-side only as the fracturing in the overburden above the middle portion of the panel tended to 'close' and did not appear to represent an area in which groundwater inflows into the workings would be generated.

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

The maximum depth of vertical downward fracturing from the surface was 7.5 m.

Overall, the results of the model cannot be directly applied to Australian conditions as the total lift thickness and predicted strains for the W/H ratios modelled appear to be incompatible with Australian mining conditions. It was therefore considered necessary to calibrate the model based on actual drilling data before it could be applied with confidence.

A case study at Oaky Creek Colliery in the Bowen Basin was presented in **Colwell (1993)** that attempted to calibrate the Whittaker and Reddish model with actual drilling and strain measurement data. Three fully cored boreholes were drilled over already extracted longwall panels with a W/H ratio of 2.11 and strain measurement data was obtained from a nearby operating LW panel with a W/H of 1.37. The results of the study are highly encouraging and have been subsequently collated with further case histories in **Section A10.2**.

A11.2 Preliminary Sub-Surface Fracturing Prediction Model For Australian Coalfields

The database of drilling data obtained from previously published documents has been summarised below in **Table A8**.

Table A8 – Predicted Tensile Strains and Sub-Surface Fracturing Data

Mine No. (refer to Appendix D for Mine details)	W (m)	H (m)	T (m)	S _{max} (m)	Predicted Smooth Profile Strain, E _{max} (mm/m)	a* (m)	b* (m)	A (a/H) (m)	B (b/H) (m)	a/T	S _{max} /W ² **
1-NSW	170	185	2.0	0.9	2.7	63	163	0.34	0.88	31.5	0.034
2-NSW	250	210	3.1	1.8	2.2	40	170	0.20	0.85	12.5	0.030
3-NSW	105	75	2.8	1.27	9.9	58	64	0.77	0.85	20.7	0.115
4- QLD	205	132	2.4	1.28	2.4	21	117	0.16	0.89	8.9	0.038
5- QLD	200	142	2.8	1.40	2.7	18	127	0.13	0.89	6.4	0.035
6- QLD	205	95	3.2	1.75	4.2	55	85	0.58	0.89	17.2	0.044
7-NSW	150	350	2.7	0.64	0.8	n/m	150	n/m	0.43	n/m	0.018

Note : * - a = Distance to total drilling fluid loss above workings.
 * - b = Distance to partial drilling fluid loss above workings.
 ** - S_{max}/W² = a new robust term (i.e. Overburden Curvature Index) to plot A and B against instead of tensile strain (see below for further explanation).
 n/m – not measured as drilling terminated before depth was reached.



The Australian data was initially plotted with the UK Model results as shown in **Figure A27**. It was then decided that a regression analysis would probably be useful in defining a relationship between the parameters and assess whether other parameters of significance could be identified.

The results of a regression analysis on the Australian database and UK model is presented in **Figure A28** and summarised below:

$$\{\text{A-Line}\} \quad A = a/H = 0.2077 \ln(+E_{\max}) + 0.150, R^2 = 0.44 \text{ and S.E.} = 0.164;$$

$$\{\text{B-Line}\} \quad B = b/H = 0.1582 \ln(+E_{\max}) + 0.651, R^2 = 0.46 \text{ and S.E.} = 0.106;$$

where

a, b = height above workings to A and B Horizons,

H = cover depth,

$+E_{\max}$ = the maximum predicted tensile strain for a 'smooth' profile,

S.E. = Standard Error for the regression equation.

The Australian database appears to be similar to the Whittaker and Reddish model, however the predicted surface strains are much lower for a given height of 'continuous' and 'discontinuous' fracturing above the workings. It is also apparent that the model relies on the measured surface strain data which has been noted previously for its high variability.

To overcome this issue it was decided to re-plot the database using the previously derived S_{\max}/W^2 term to provide a readily measurable field parameter that would not be compromised by surface strain concentration effects. The revised regression results are shown in **Figure A29** and summarised below:

$$\{\text{A-Line}\} \quad A = a/H = 0.2295 \ln(S_{\max}/W^2) + 1.132, R^2 = 0.44 \text{ and S.E.} = 0.11;$$

$$\{\text{B-Line}\} \quad B = b/H = 0.1694 \ln(S_{\max}/W^2) + 1.381, R^2 = 0.46 \text{ and S.E.} = 0.16;$$

where a, b = height above workings to A and B Horizons,

H = cover depth (m).

S_{\max}/W^2 = Overburden Curvature Index,

S.E. = Standard Error for the regression equation.

The same apparent difference still remains between the Australian and UK databases, however it is of interest to note that the UK physical models B horizon coincides with the Australian field data derived A horizon.

The apparent discrepancies between the model indicate that the difference in the method of assessment for the various fracture heights may also be the reason for the differences



between the models (i.e. the physical models A and B horizons were based on visual mapping of cracks, whereas the water loss data during the drilling programs was used to derive the Australian model).

The A and B horizons in the sub-surface fracturing model presented also appear to be the same as the heights to the top of the 'Fractured Zone' and 'Constrained Zone' (above an extracted longwall panel) defined in **Forster (1993)**. There is also a departure in this model from assessing heights of fracturing based on the extraction height only, although the predicted tensile strain or S_{max} is directly related to the extraction height. It is considered that sub-surface fracture heights are a function of overburden bending deformation and is therefore primarily a function of the significant geometrical parameters S_{max} , W , H and T . The influence of massive lithology is included in the S_{max} prediction.

Overall, the sub-surface fracturing model presented in this report is considered to be preliminary at this stage: more drilling data would increase our understanding and confidence in its use. The heights of fracturing derived from it however do appear to be conservative based on reference to several NSW and Queensland case studies.

It is recommended that future calibration work on the model presented herein consider both the tensile strain and S_{max}/W^2 parameters based on the results to date.

A11.3 Influence of Geology on Sub-Surface Fracture Heights

For the purposes of study completeness, an assessment was made on whether the geology effected the height of fracturing above a longwall panel.

Reference to the database presented in **Section A10.2**, indicates that two of the 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 massive strata unit affected data, however do not appear to plot at lower than predicted levels than those predicted for the low SRP cases, although this observation is based on a small sample of data. At this stage, the potential for a spanning strata unit to mitigate the height of continuous fracturing above the workings cannot be ignored.



A12 REFERENCES

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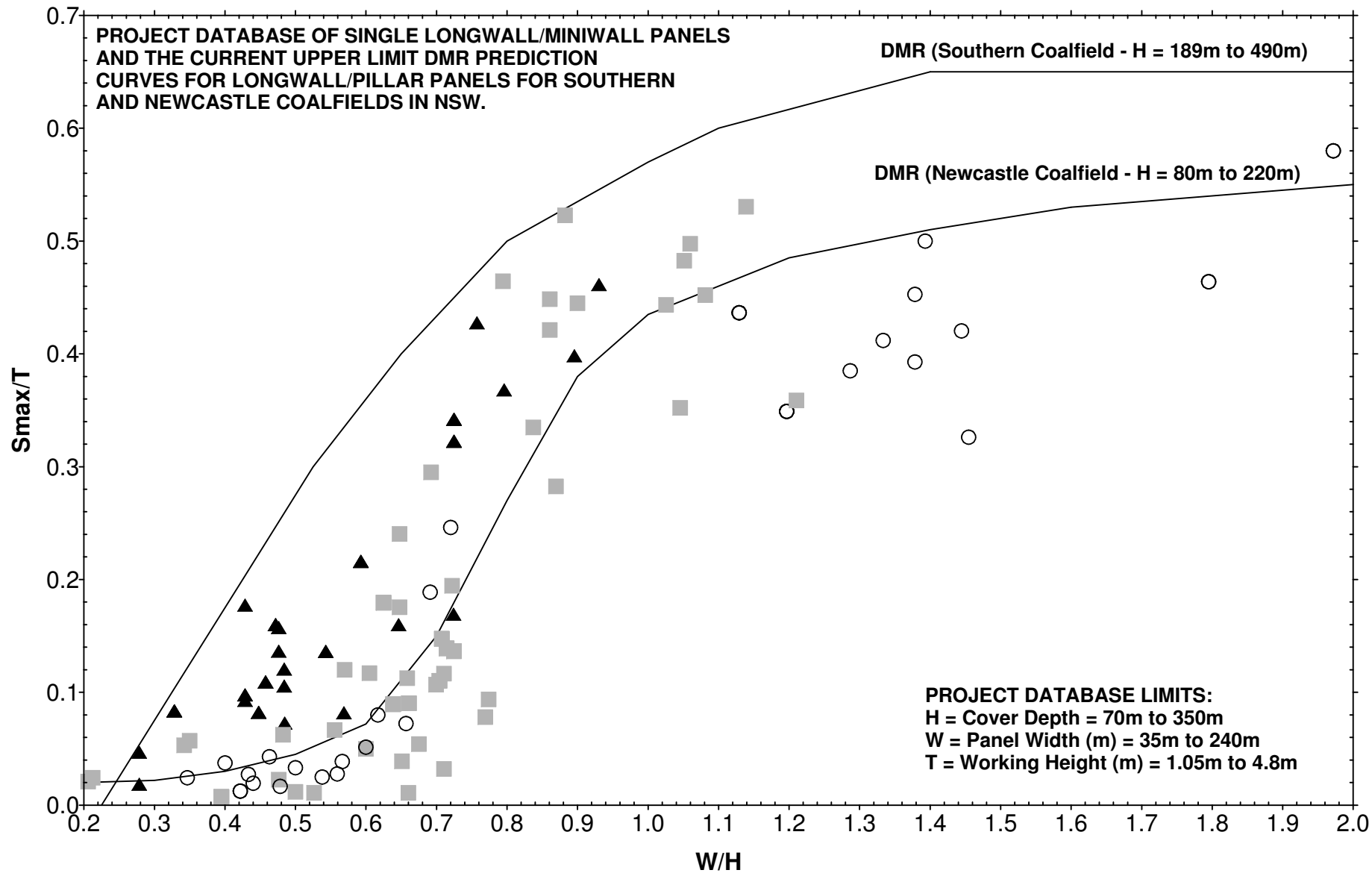
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PROJECT DATABASE OF SINGLE LONGWALL/MINIWALL PANELS AND THE CURRENT UPPER LIMIT DMR PREDICTION CURVES FOR LONGWALL/PILLAR PANELS FOR SOUTHERN AND NEWCASTLE COALFIELDS IN NSW.

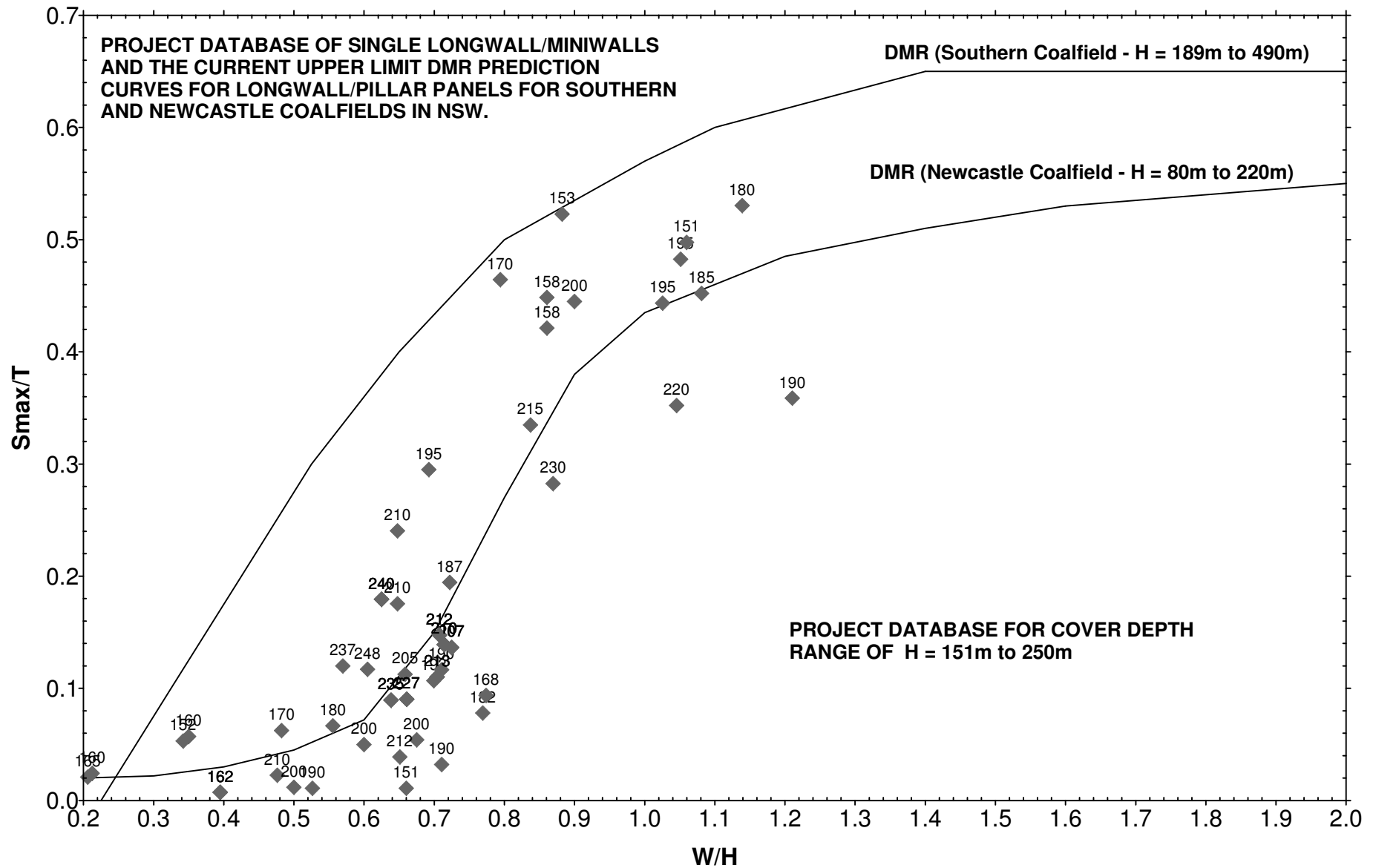
DMR (Southern Coalfield - H = 189m to 490m)

DMR (Newcastle Coalfield - H = 80m to 220m)

PROJECT DATABASE LIMITS:
 H = Cover Depth = 70m to 350m
 W = Panel Width (m) = 35m to 240m
 T = Working Height (m) = 1.05m to 4.8m

LEGEND	
Cover Depth, H (m)	
○	H = 70m to H = 151m
■	H = 151m to H = 251m
▲	H = 251m to H = 350m

Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023 00-181-ACR/1	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton			
Date:	05/03/06	TITLE:	Project Database and DMR Subsidence Prediction Curves	FIGURE A1
Scale:	NTS			



Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023 00-181-ACR/1	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton			
Date:	05/03/06	TITLE:	Project Database showing Cover Depth for Each Data Point	FIGURE A2
Scale:	NTS			

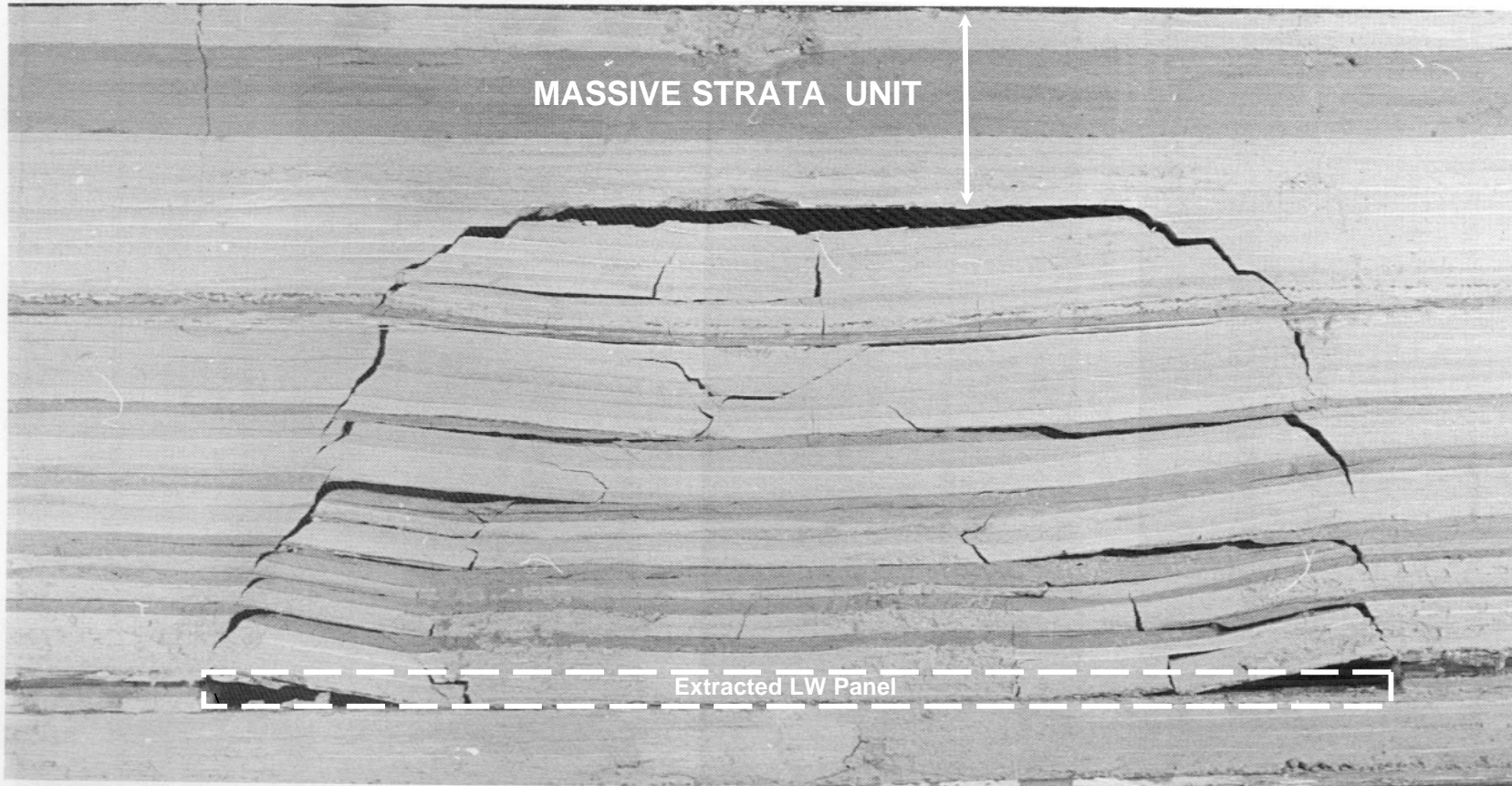
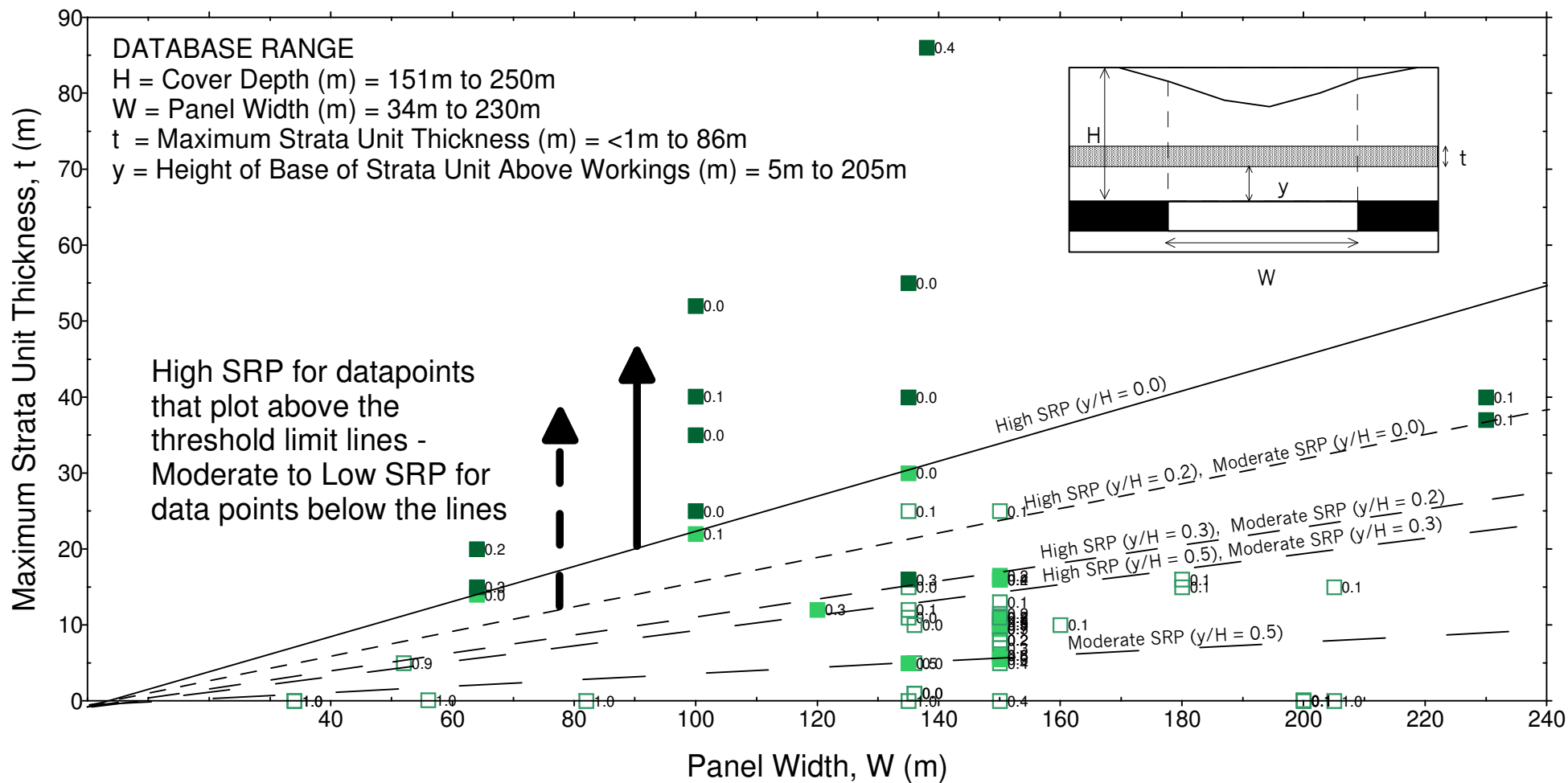


Figure 237 Physical model of caved strata above longwall extraction with strong overburden. Mining data: $h = 84\text{m}$; $w = 118\text{m}$; $M = 4\text{m}$.

Note :
Reference : Whittaker & Reddish (1989)

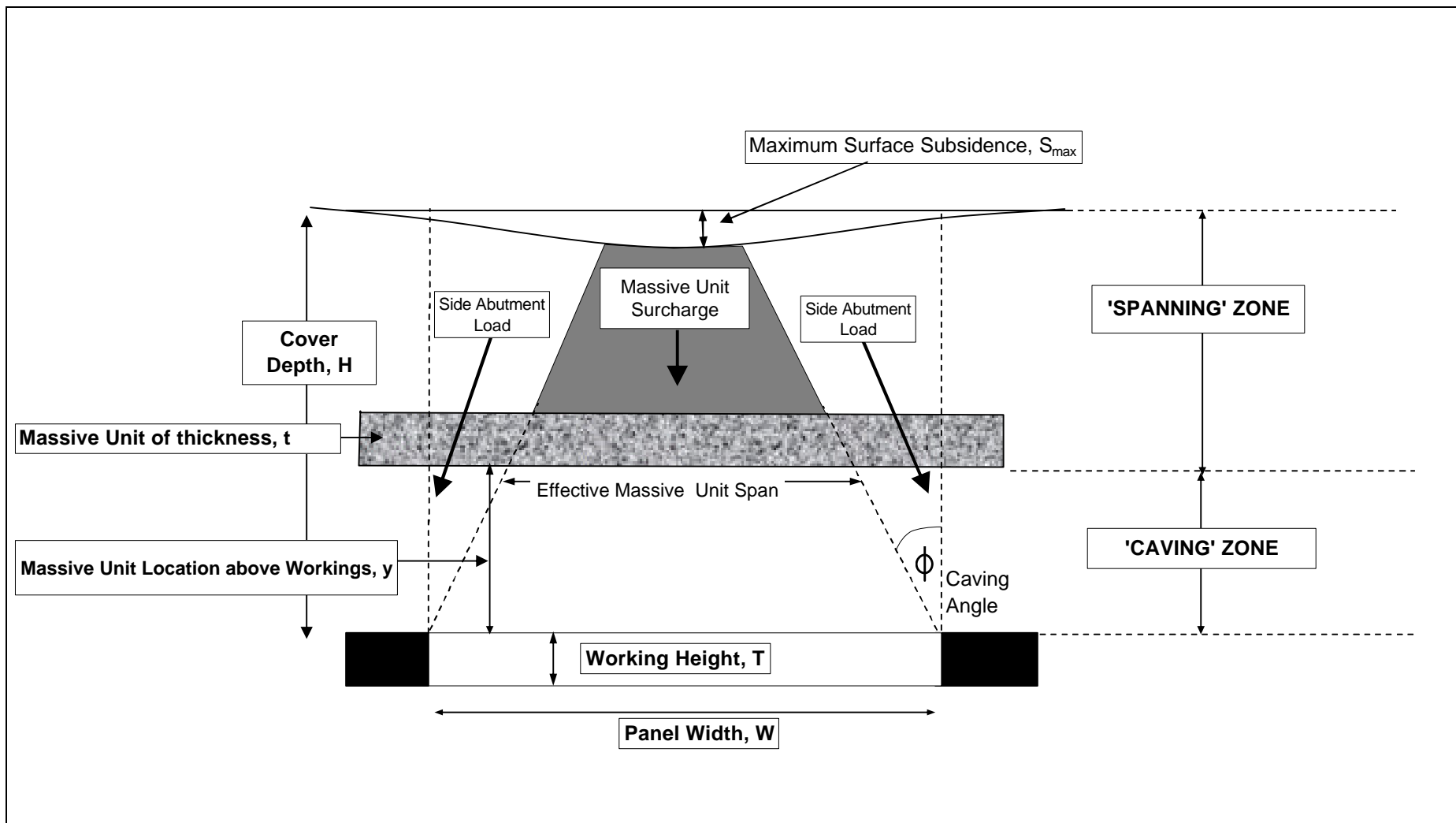
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	22/11/2002	TITLE:	Physical Model Showing the Subsidence Reducing Effect of a Massive Strata Unit	FIGURE:
SCALE:	NTS			A3



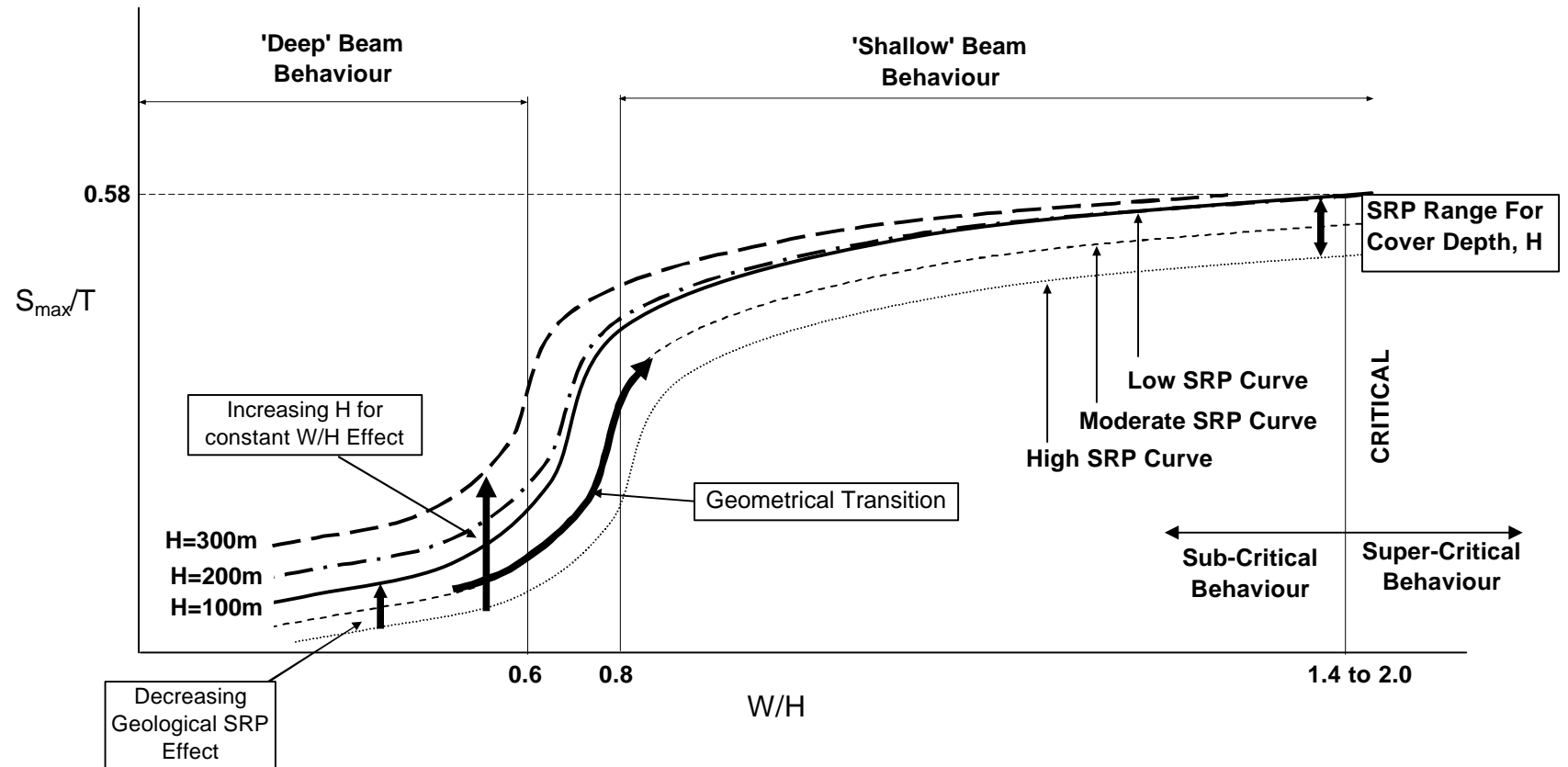
LEGEND
 Label = Strata Unit Location Factor, y/H
 Subsidence Reduction Potential (SRP)

□	Low
■	Moderate
■	High

Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton		00-181-ACR/1	
Date:	05/03/06	TITLE:	Project Database of Maximum Strata Unit Thickness and SRP Threshold Limit Lines for H = 151 to 250 m	
Scale:	NTS			FIGURE A4



ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	1/08/2002	TITLE:	Overburden Behaviour Concept Model for the	FIGURE:
SCALE:	NTS		Newcastle Coalfield - Definitions	A5

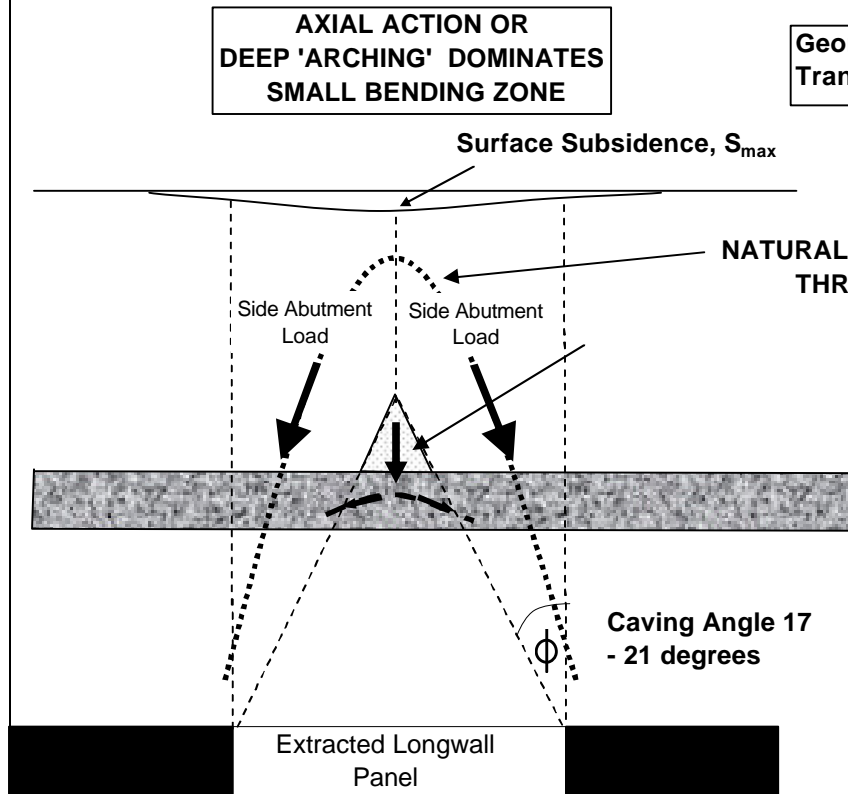


LEGEND

SRP = Subsidence Reduction Potential
 W/H = Panel Width / Cover Depth Ratio
 S_{max}/T = Max. Subsidence / Working Height Ratio
 (For Single Longwall Panels Only)

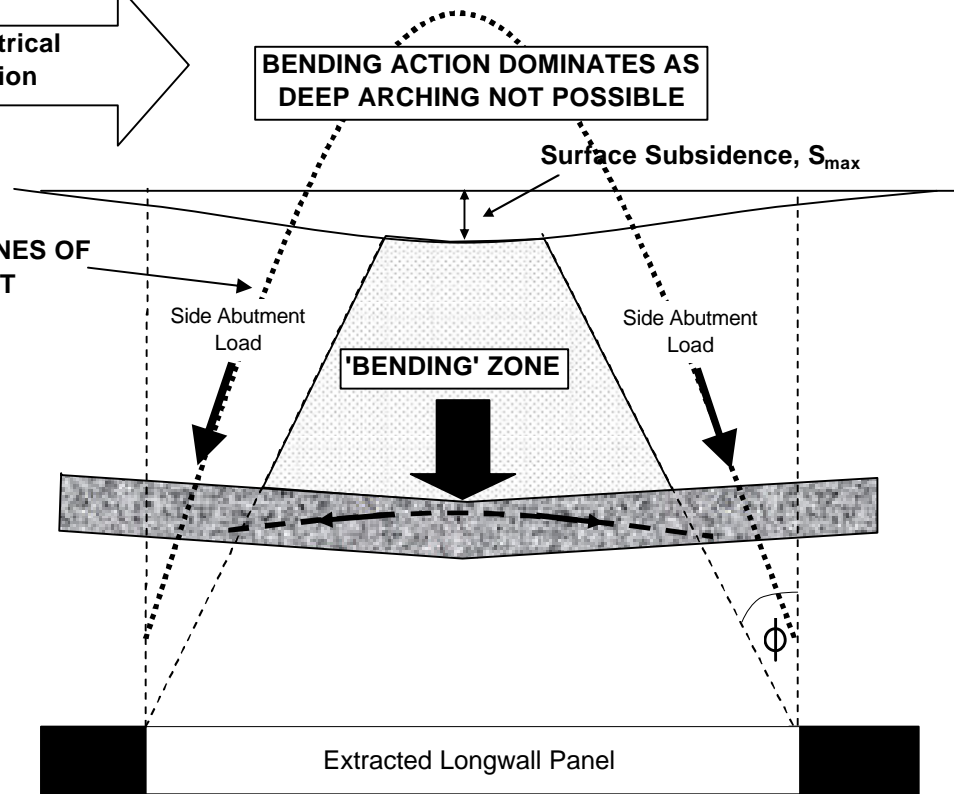
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	17/08/2002	TITLE:	Geometrical and Geological Effects of Overburden	FIGURE:
SCALE:	NTS		Behaviour on Maximum Subsidence for Single Panels	A6

**FIGURE A7(a) : DEEP 'BEAM' BEHAVIOUR
(W/H < 0.7)**

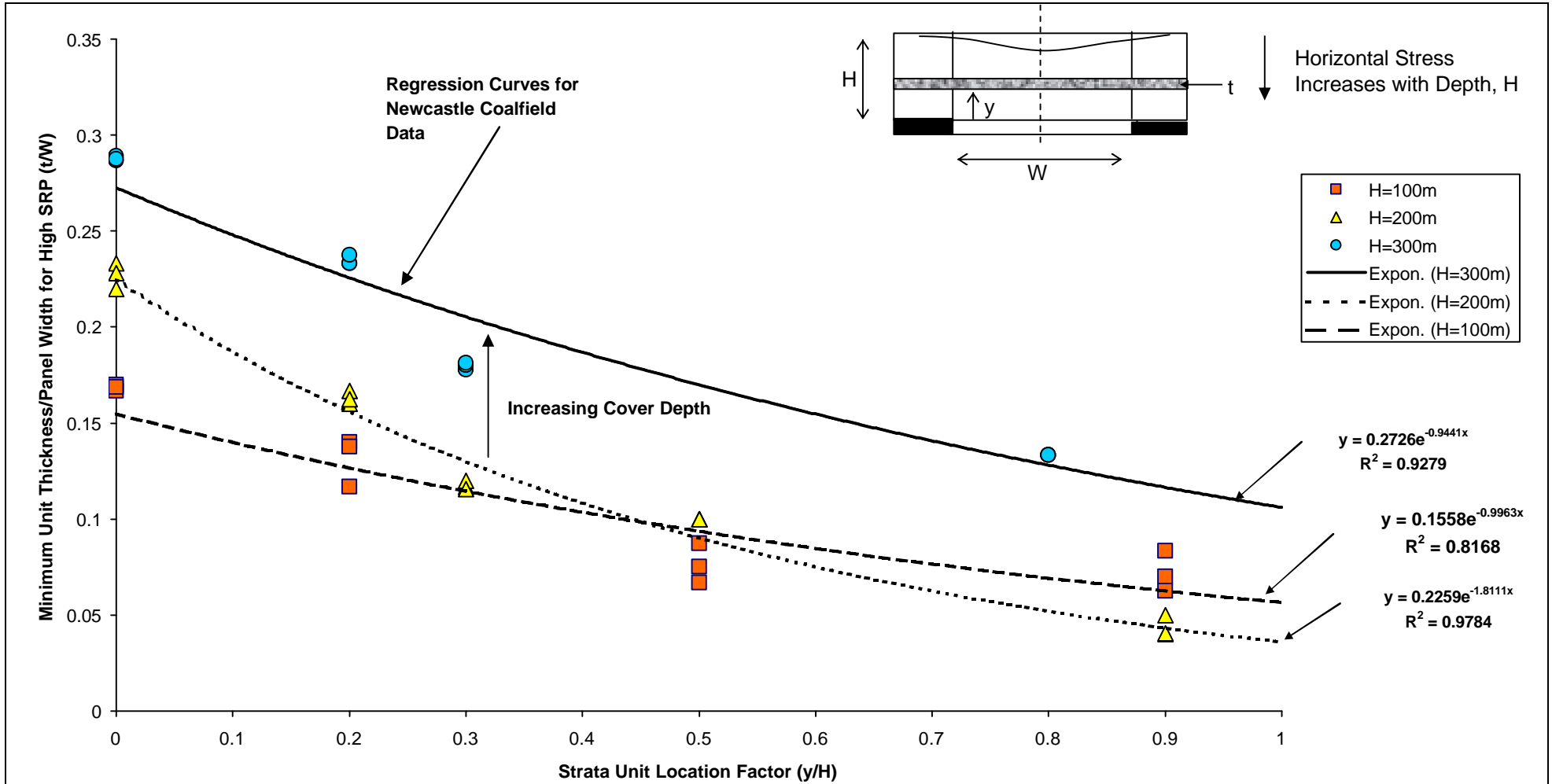


Geometrical Transition

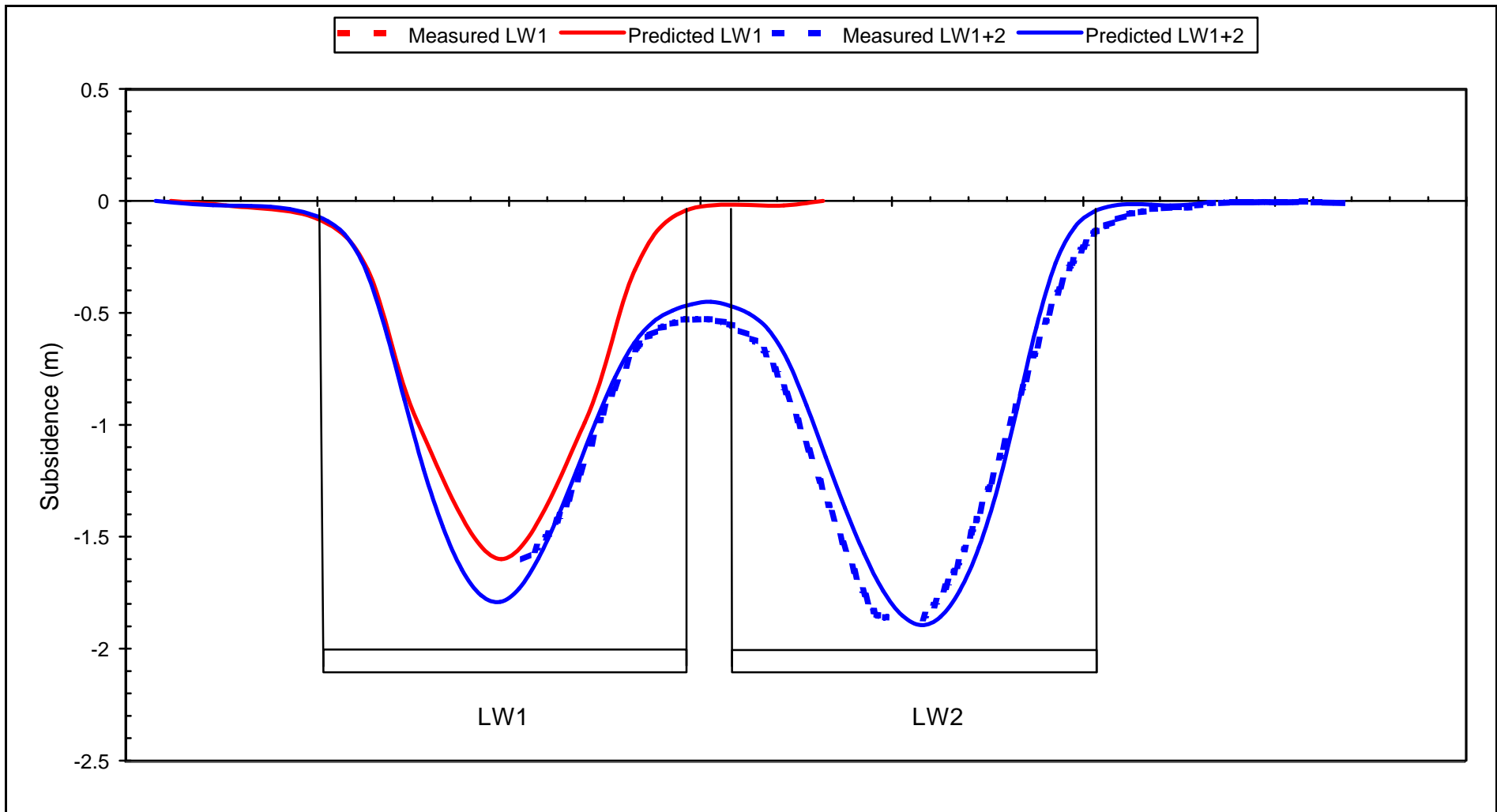
**FIGURE A7(b) : SHALLOW 'BEAM' BEHAVIOUR
(W/H > 0.7)**



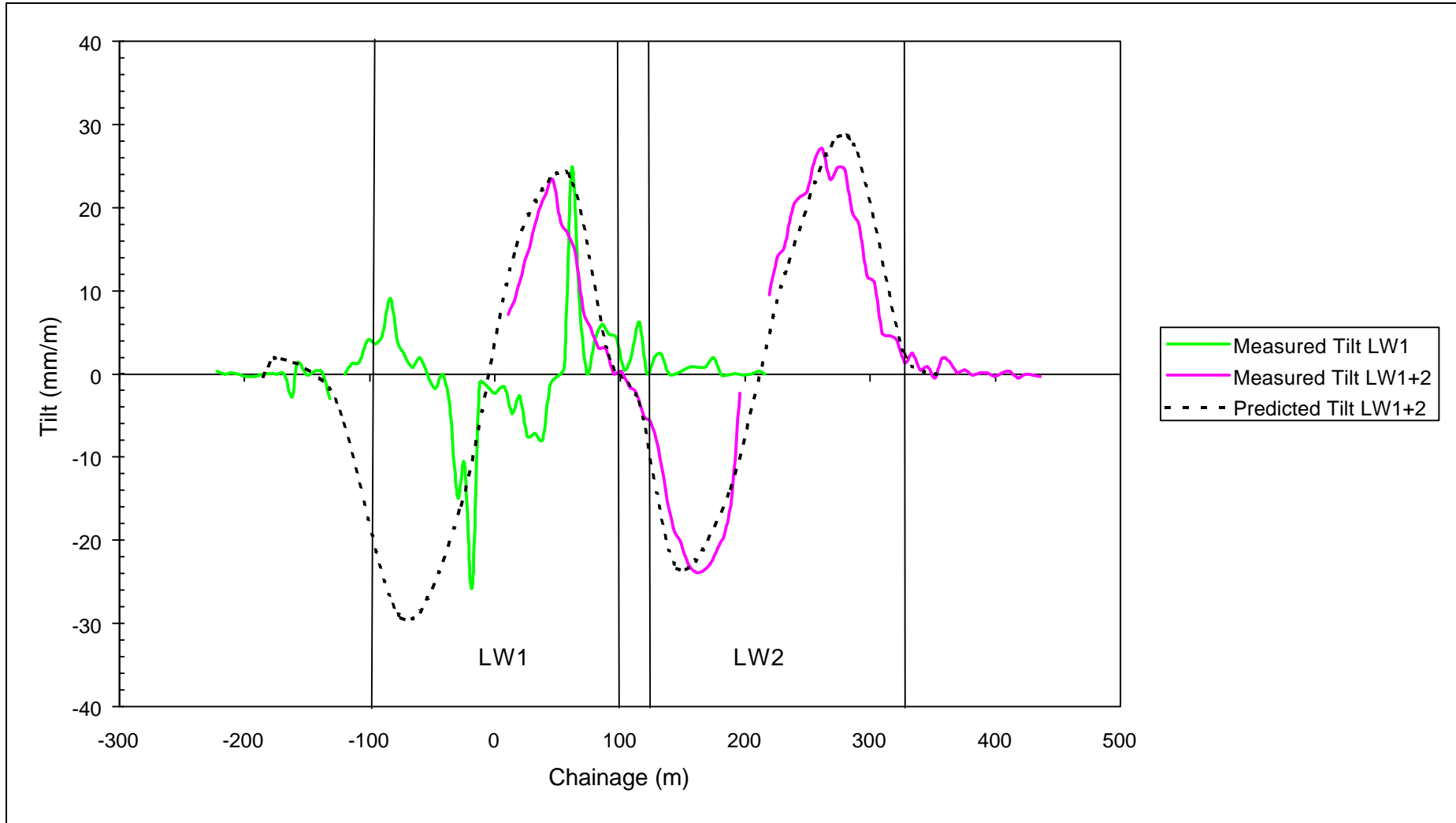
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	1/08/2002	TITLE:	Overburden Behaviour Conceptual Models	FIGURE: A7
SCALE:	NTS		- Beam Action Types	



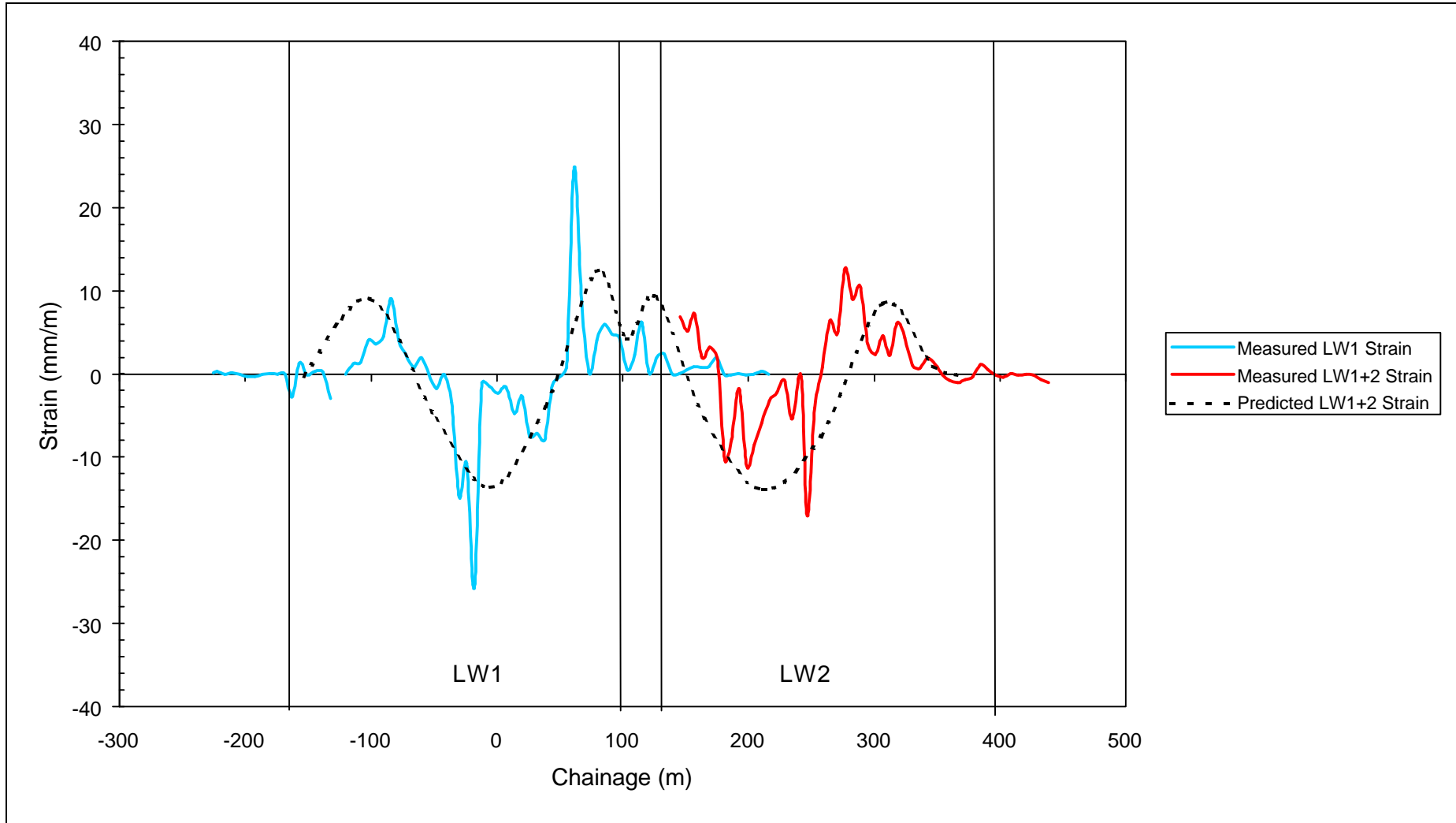
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	22/11/2002	TITLE:	Empirical Relationship Linking Minimum Massive Strata Unit Thickness Required for High SRP with Panel Width and y/H	FIGURE
SCALE:	NTS			A8



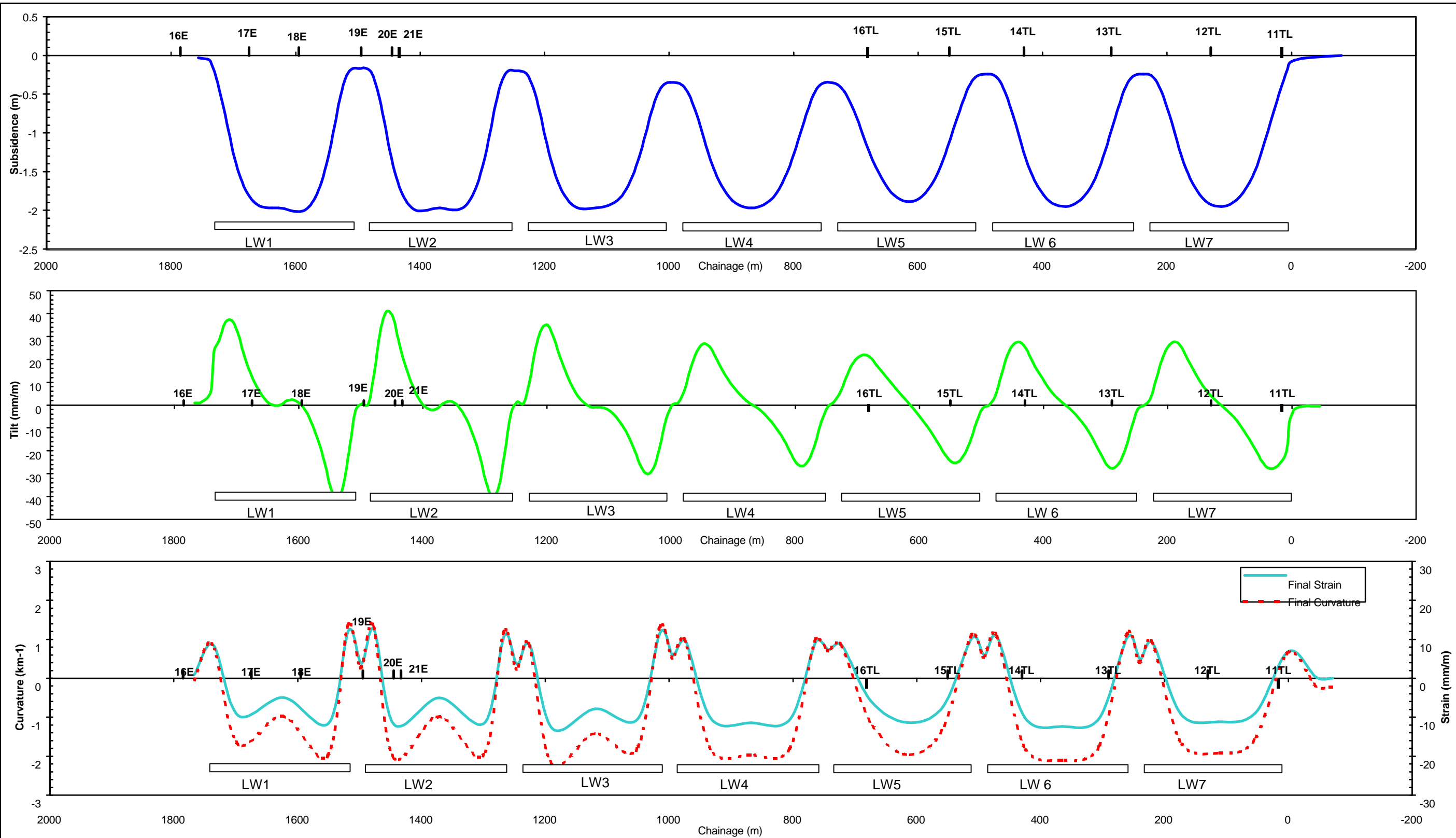
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	5/12/2002	TITLE:	Predicted v. Measured Crossline Subsidence Profiles	FIGURE A9
SCALE:	NTS		for Mine B, LWs 15 -16	



ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	5/12/2002	TITLE:	Predicted v. Measured Crossline Tilt Profiles	FIGURE:
SCALE:	NTS		for Mine B, LWs 1 - 2	A10



ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	5/12/2002	TITLE:	Predicted v. Measured Crossline Strain Profiles	FIGURE:
SCALE:	NTS		for MIne B, LWs 1 - 2	A11

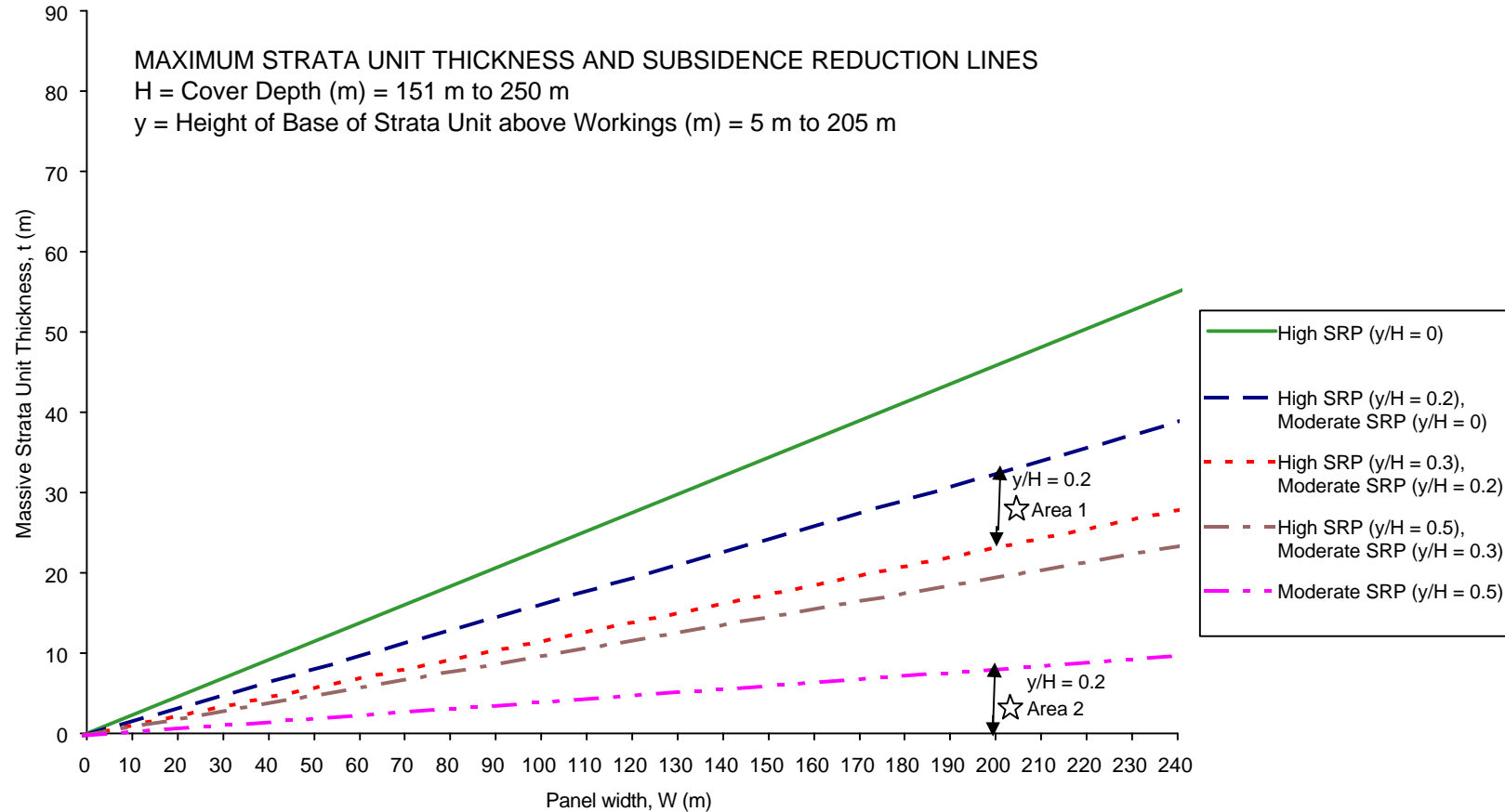


Legend

18E Transmission tower location
|

Note : Predictions based on a 10m baylength.

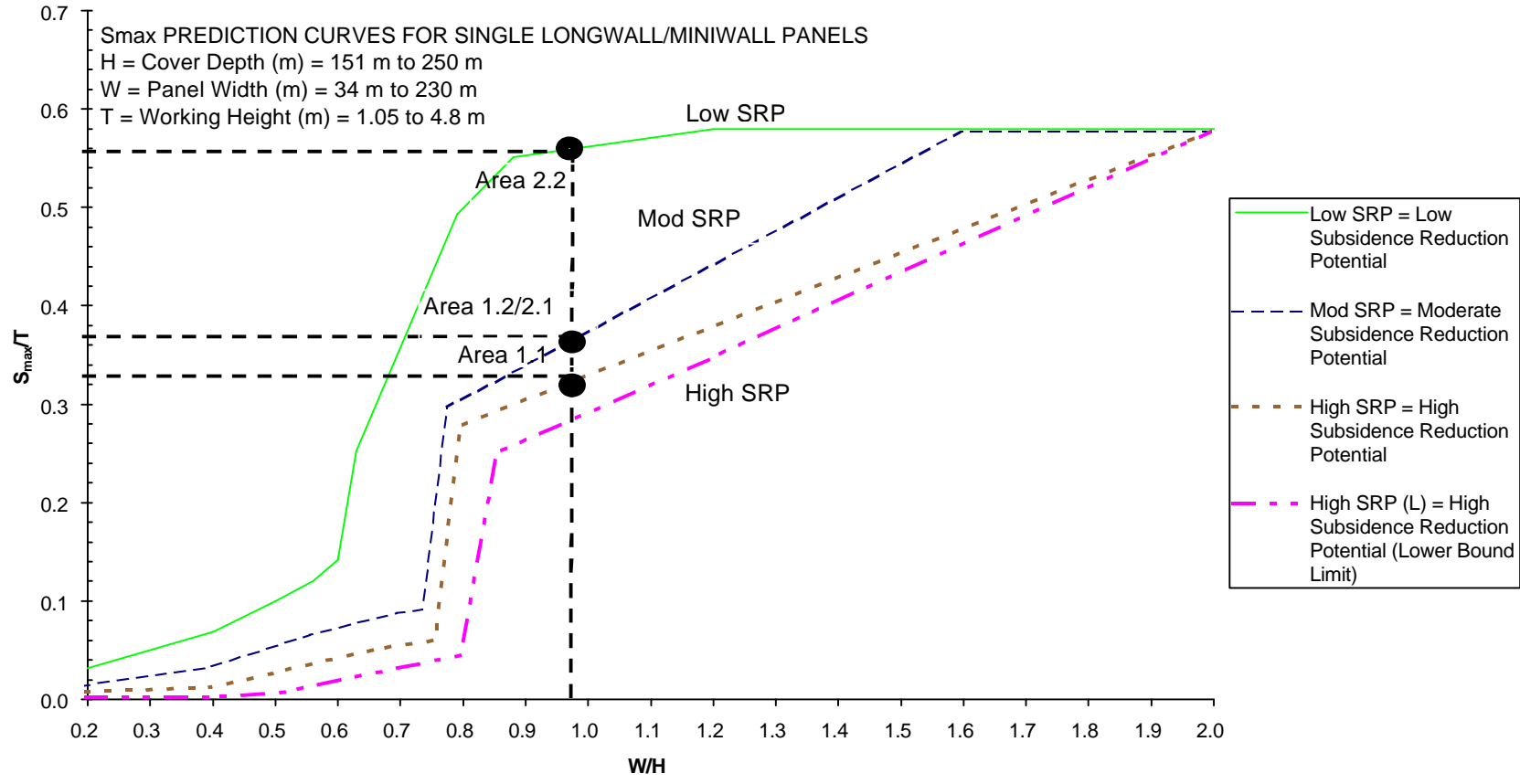
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	1/12/2002	TITLE:	Predicted Subsidence, Tilt & Strain Crossline Profiles	FIGURE: A12
SCALE:	NTS		for Multiple Longwall Panels	



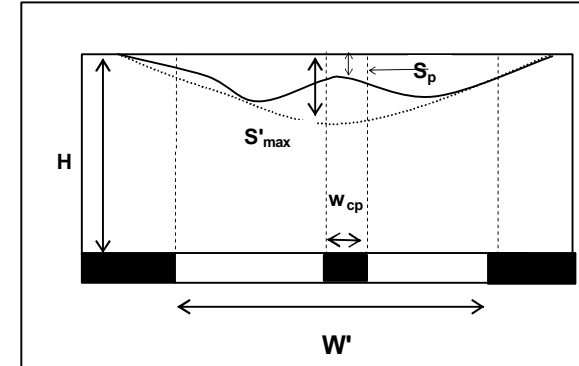
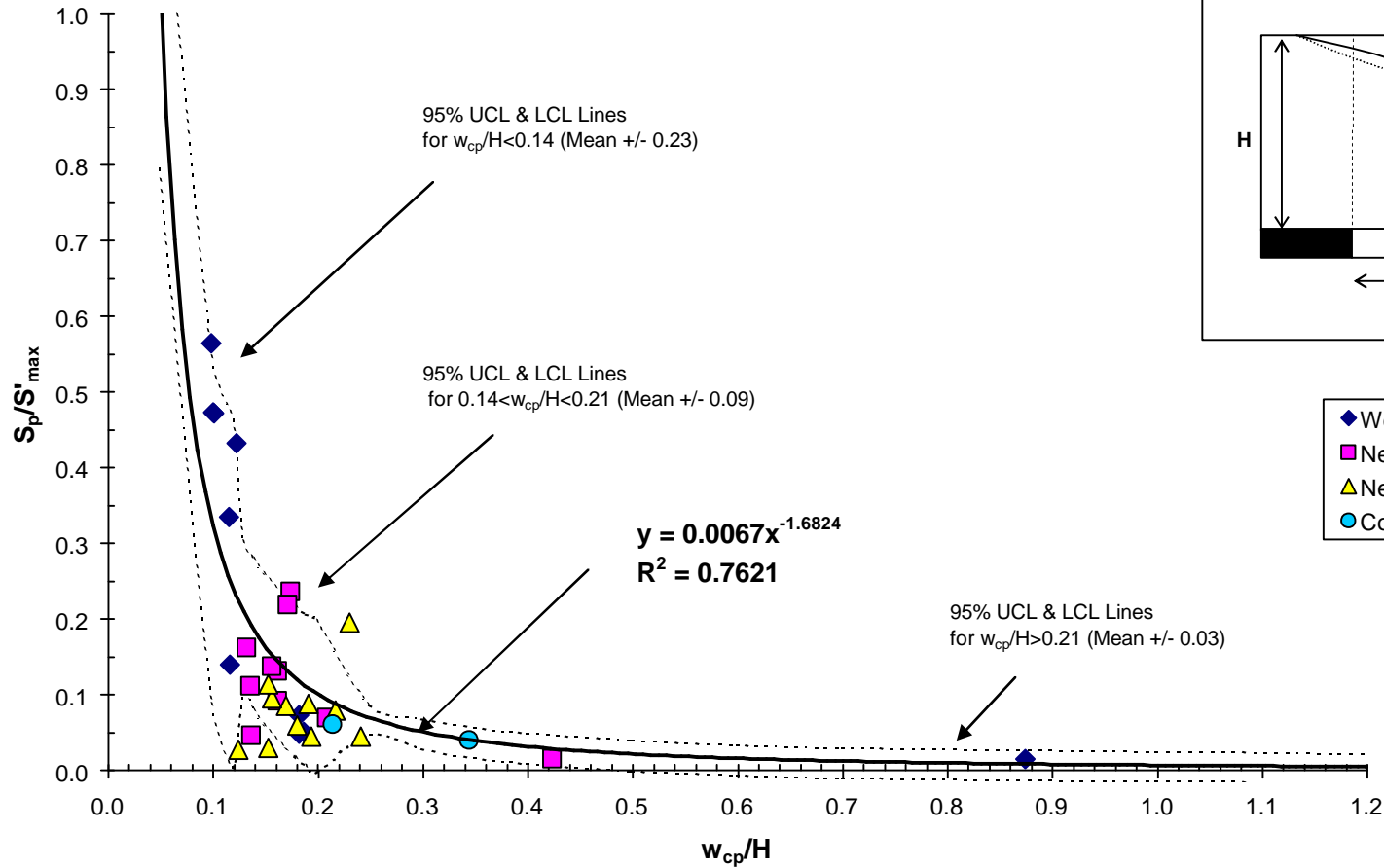
LEGEND

☆^{0.2} y/H
↕ SRP Limited for y/H

ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	5/12/2002	TITLE:	Strata Unit Thickness and SRP vs. Panel Width for a Depth	FIGURE:
SCALE:	NTS		Range of 151 to 250 m - Worked Example	A13



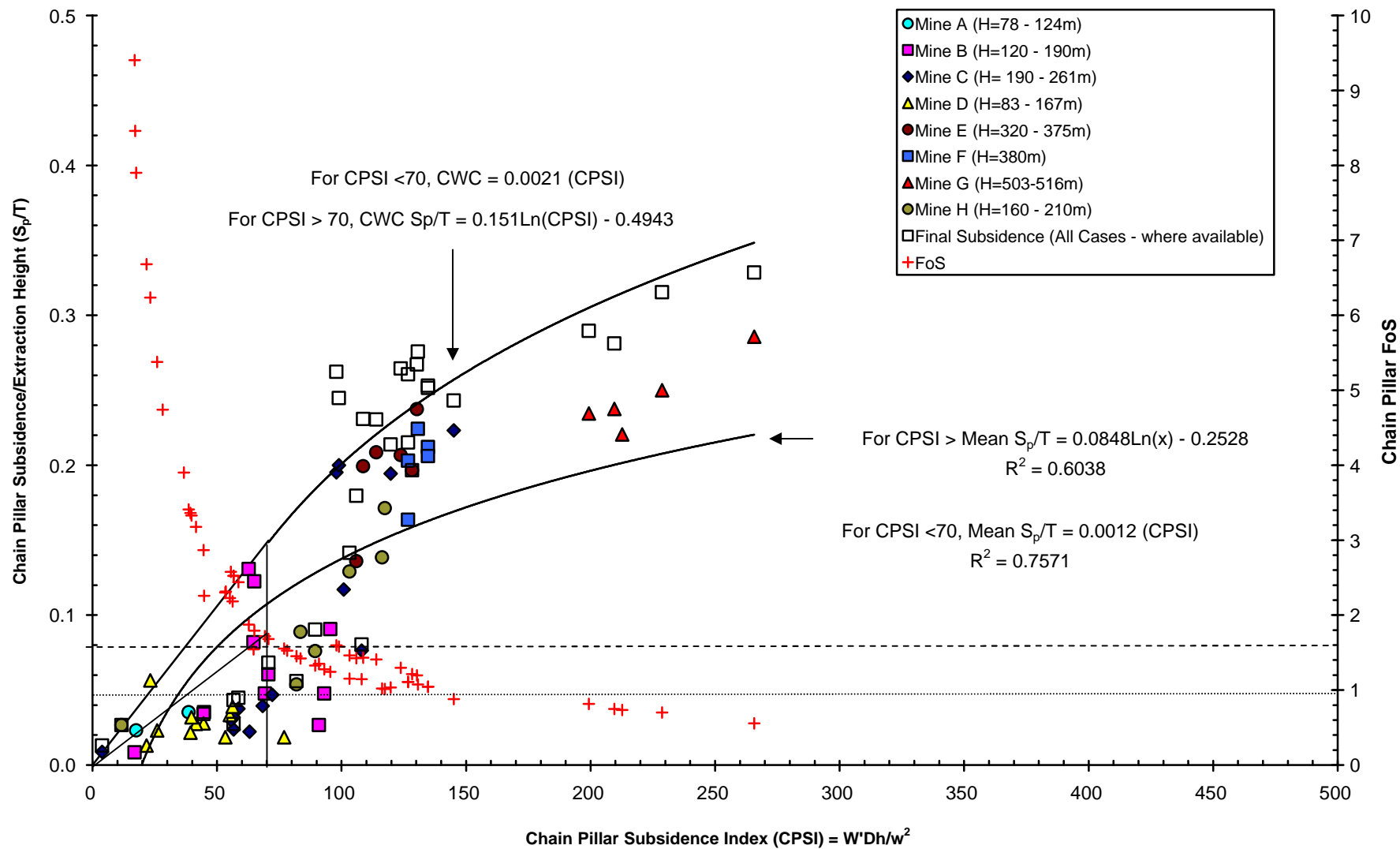
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	5/12/2002	TITLE:	S _{max} /T vs. W/H for a Depth Range of 151 to 250 m	FIGURE:
SCALE:	NTS		(Newcastle Coalfield) - Worked Example	A14



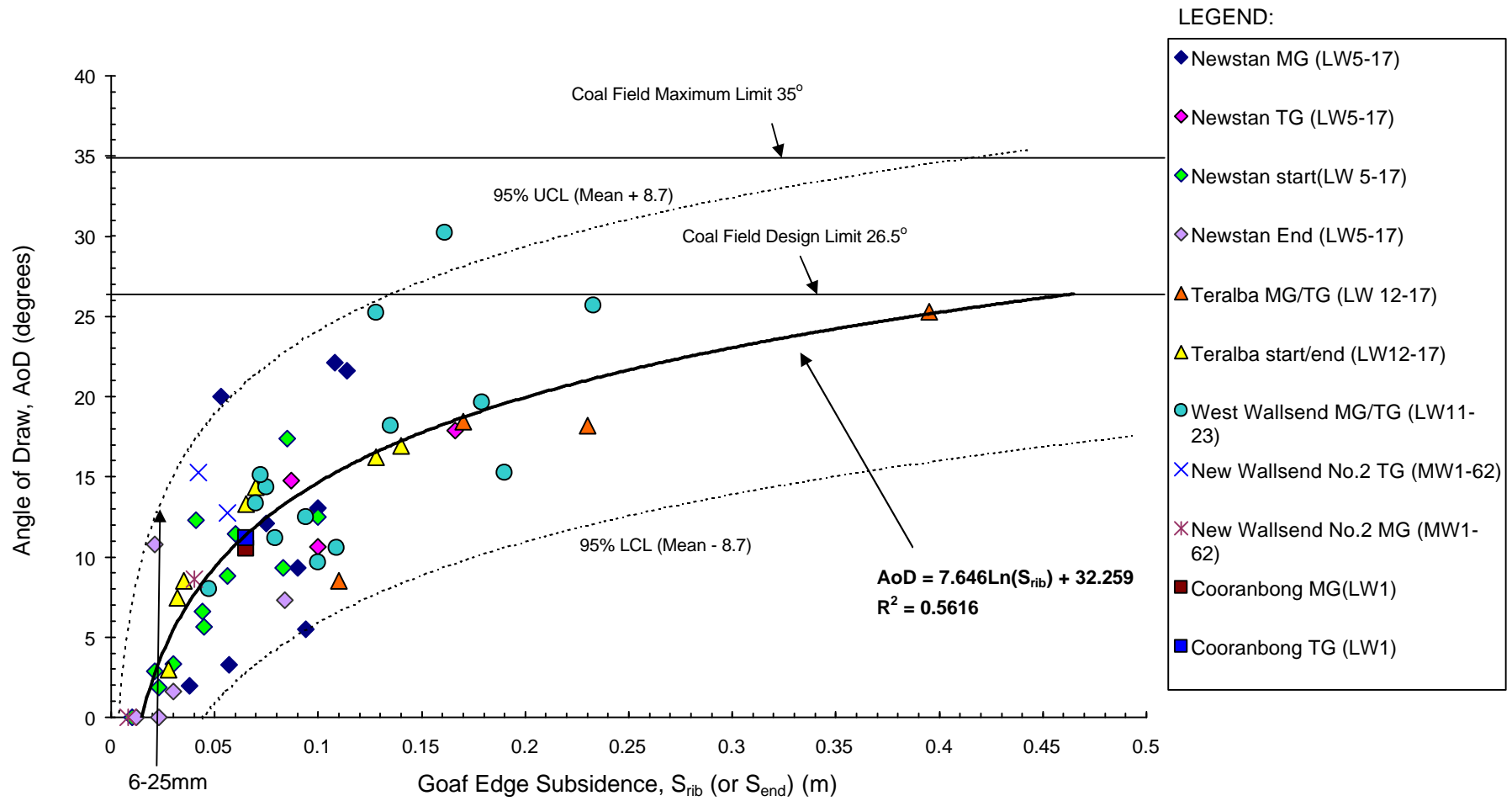
- ◆ West Wallsend
- Newstan
- ▲ New Wallsend No.2 (MW 1-62)
- Cooranbong (LW1-6)

Note :
 1. S'_{max} determined from Single Panel S_{max}/T using W'/H ratio for two adjacent panels.
 2. UCL & LCL are upper and lower confidence limits

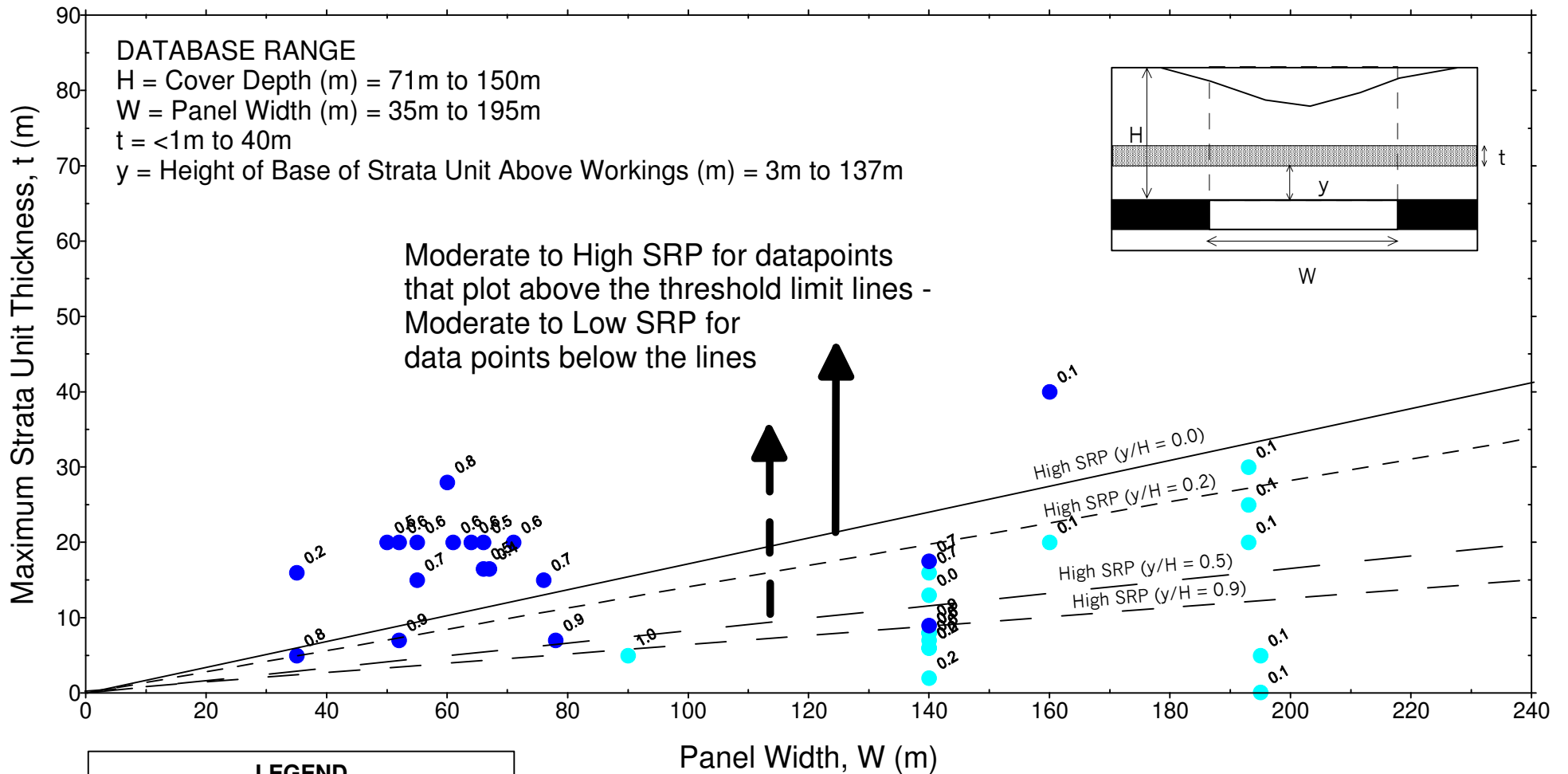
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	30/04/03	TITLE:	2003 Empirical Model for Predicting Subsidence Above	FIGURE: A15
SCALE:	NTS		Chain Pillars Subject to Double Abutment Loading	



ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	7/09/2006	TITLE:	2006 Empirical Model for Predicting Subsidence Above	FIGURE A16
SCALE:	NTS		Chain Pillars Subject to Double Abutment Loading	



ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	22/11/2002	TITLE:	Empirical Prediction Model for	FIGURE: A17
SCALE:	NTS		LW Panel Angle of Draw for Newcastle Coalfield	

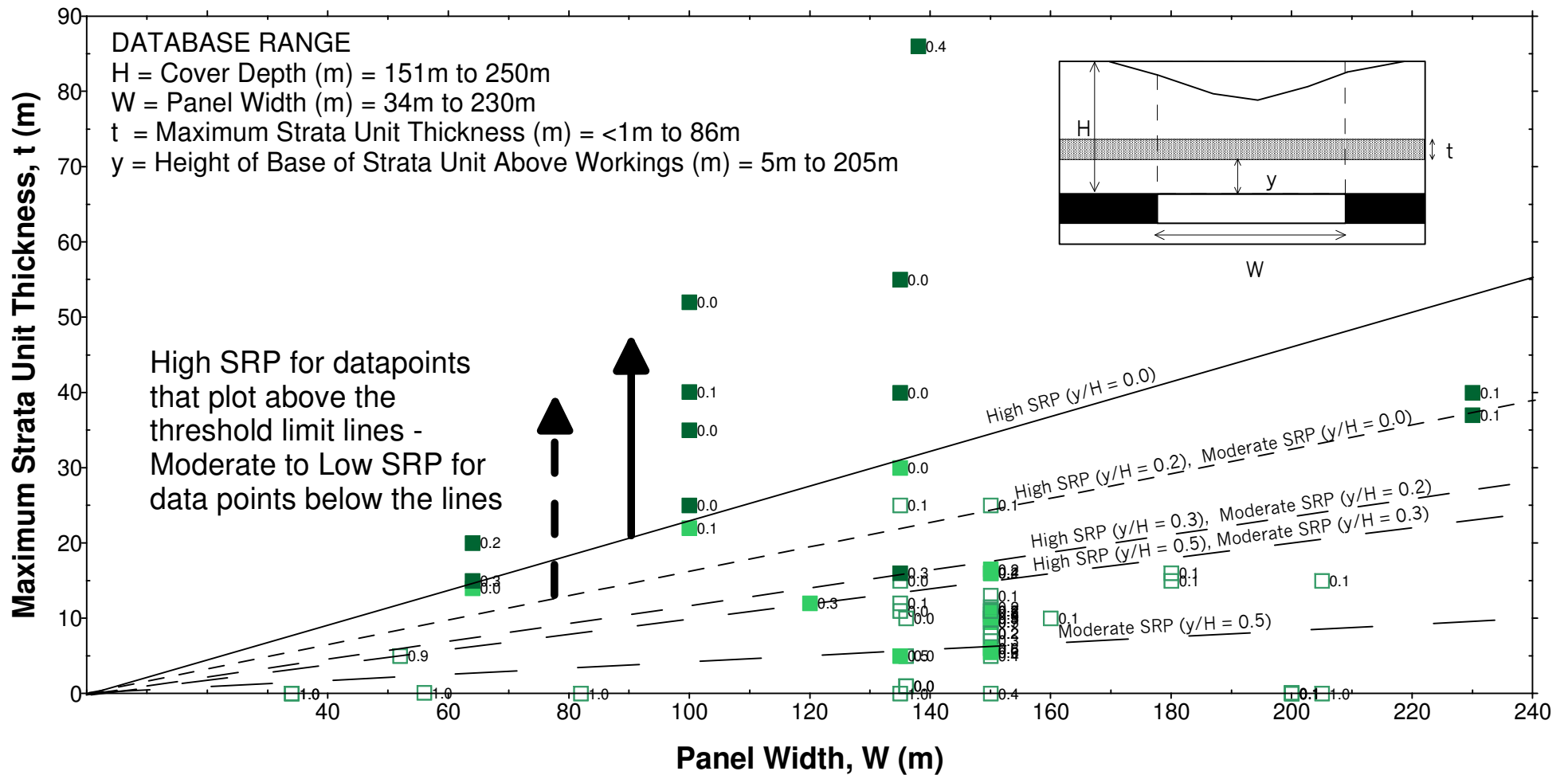


LEGEND
 Label = Strata Unit location Factor, y/H

Subsidence Reduction Potential (SRP)

● Low to Moderate
 ● Moderate to High

Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton		00-181-ACR/1	
Date:	05/03/06	TITLE:	Project Database of Maximum Strata Unit Thickness and SRP Threshold Limit Lines for H = 70 to 150 m	
Scale:	NTS			FIGURE A18



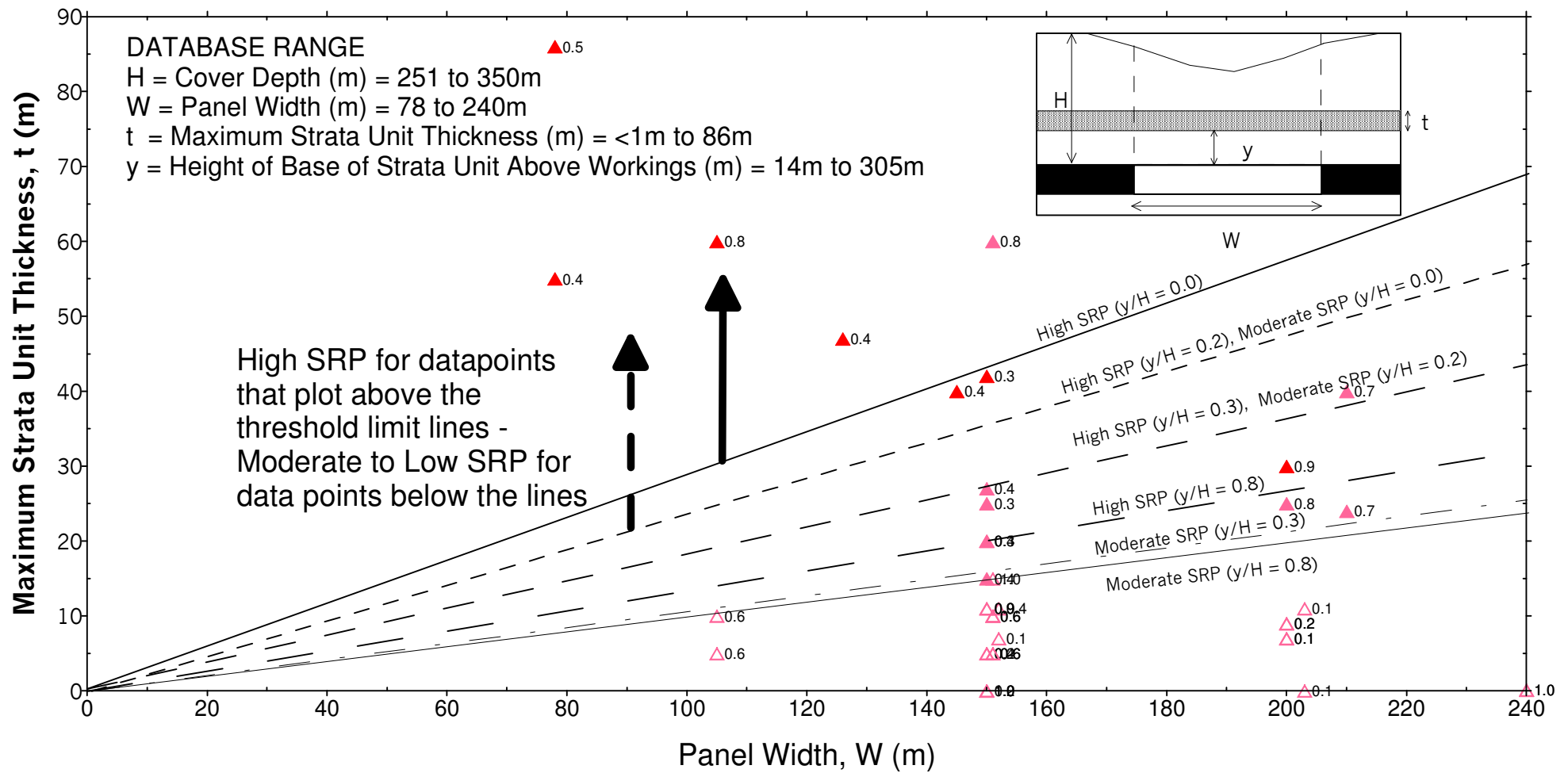
LEGEND

Label = Strata Unit Location Factor, y/H

Subsidence Reduction Potential (SRP)

Low
 Moderate
 High

Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton		00-181-ACR/1	
Date:	05/03/06	TITLE:	Project Database of Maximum Strata Unit Thickness and SRP Threshold Limit Lines for H = 151 to 250 m	
Scale:	NTS			FIGURE A19



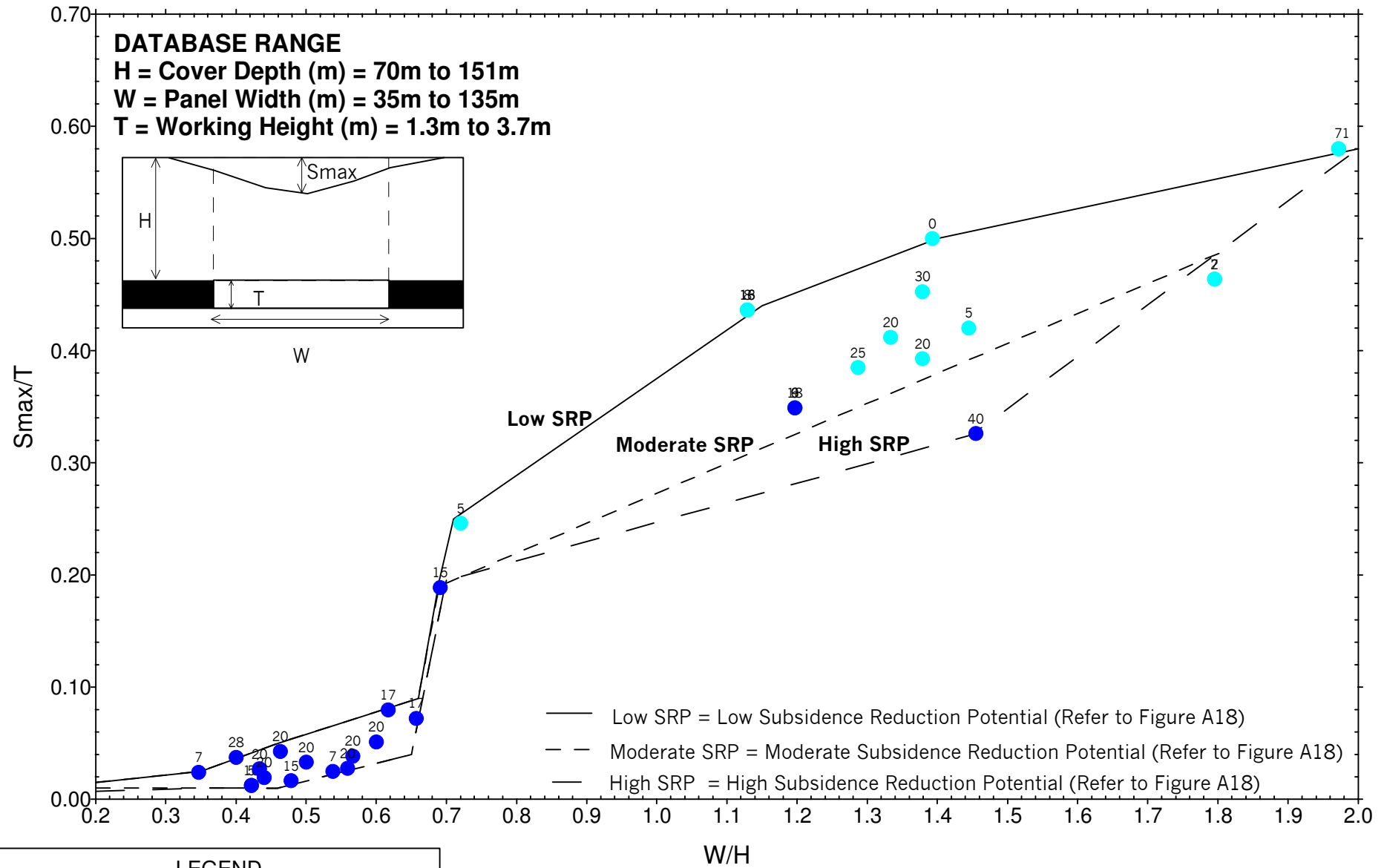
LEGEND

Label = Strata Unit Location Factor, y/H

Subsidence Reduction Potential (SRP)

	Low
	Moderate
	High

Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton		00-181-ACR/1	
Date:	05/03/06	TITLE:	Project Database of Maximum Strata Unit Thickness and SRP Threshold Limit Lines for H = 251 to 350 m	FIGURE A20
Scale:	NTS			

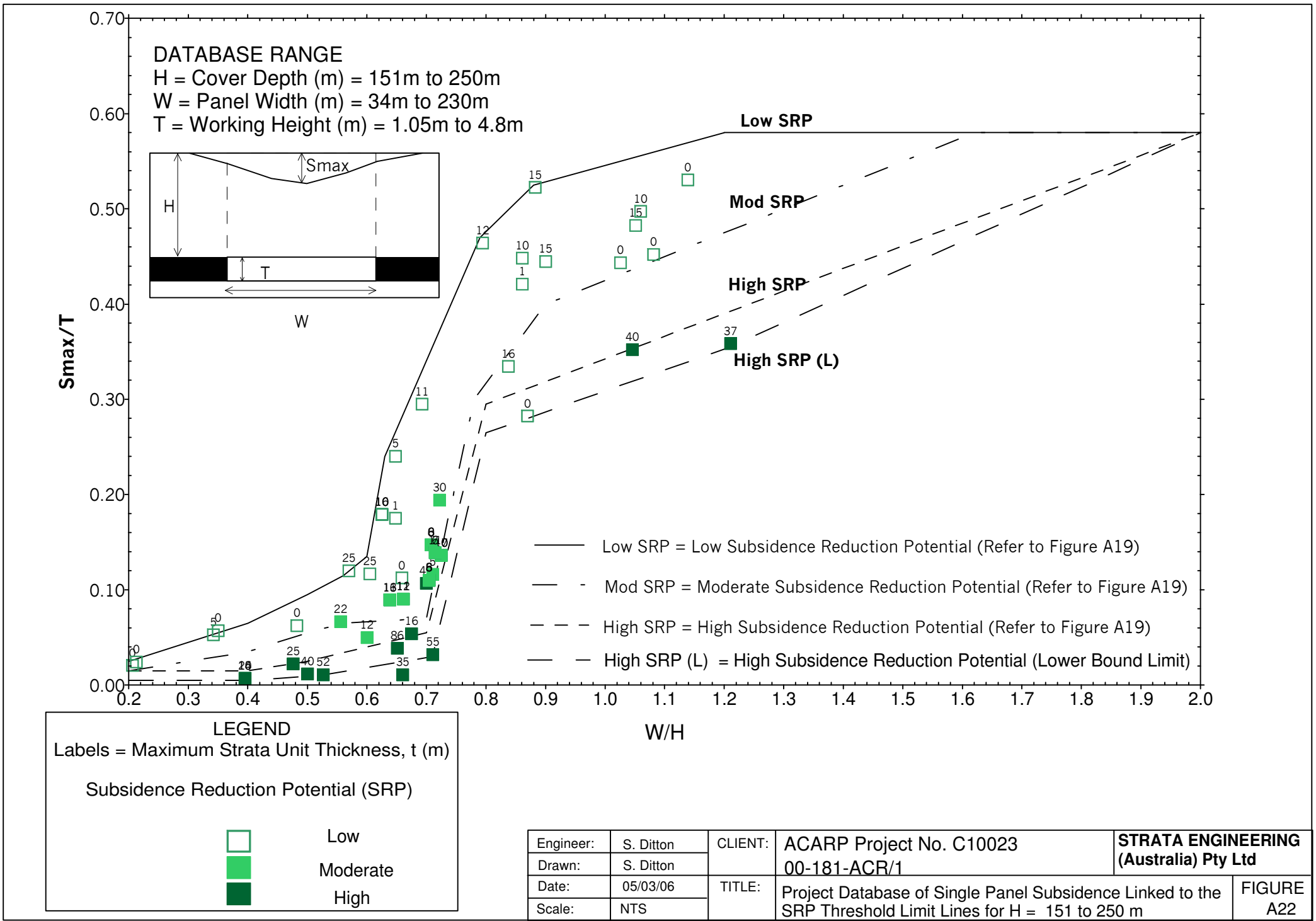


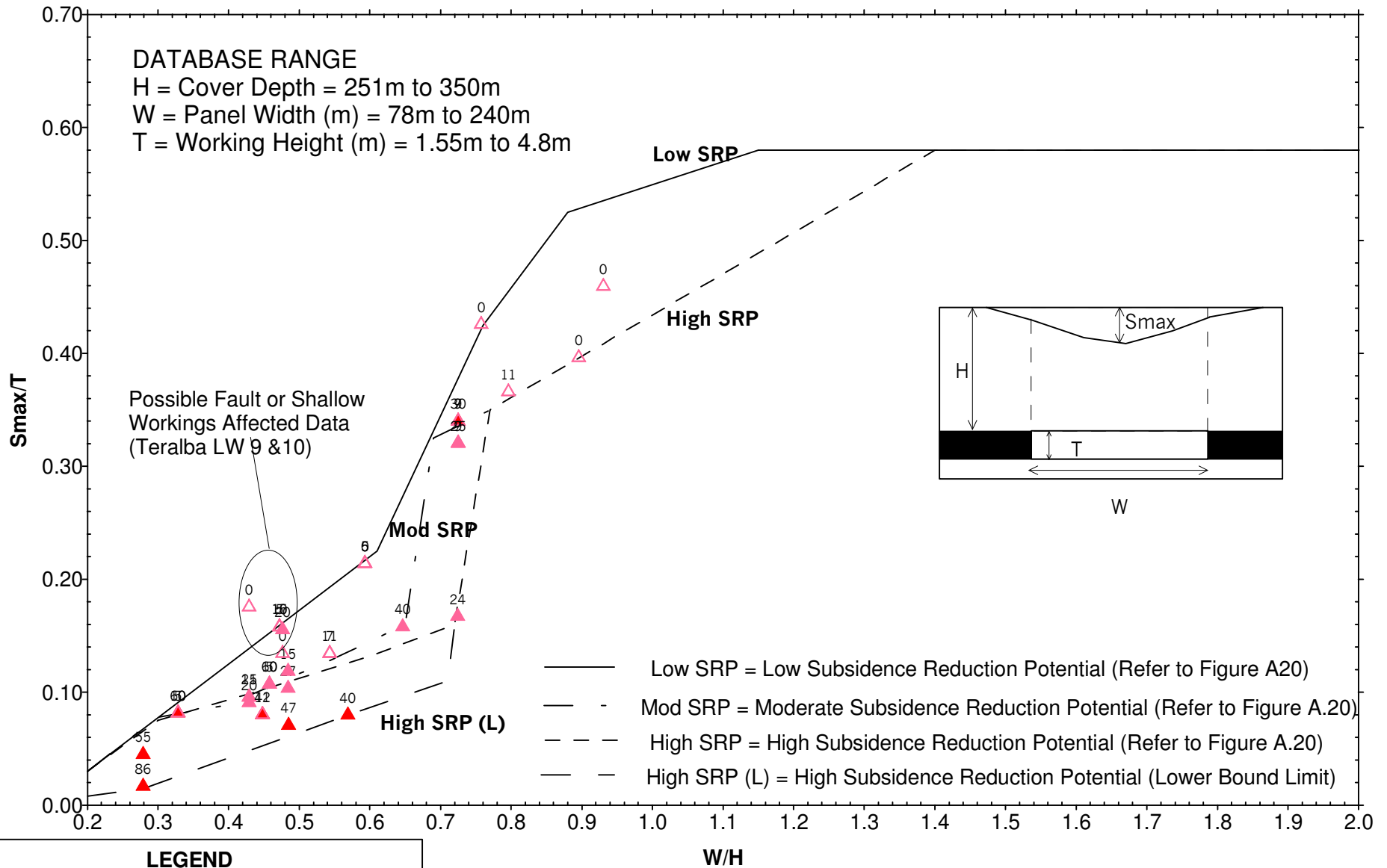
LEGEND
 Label = Maximum Strata Unit Thickness, t (m)

Subsidence Reduction Potential (SRP)

- Low to Moderate
- Moderate to High

Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton		00-181-ACR/1	
Date:	05/03/06	TITLE:	Project Database of Single Panel Subsidence Linked to the SRP Threshold Limit Lines for H = 70 to 150 m	FIGURE A21
Scale:	NTS			



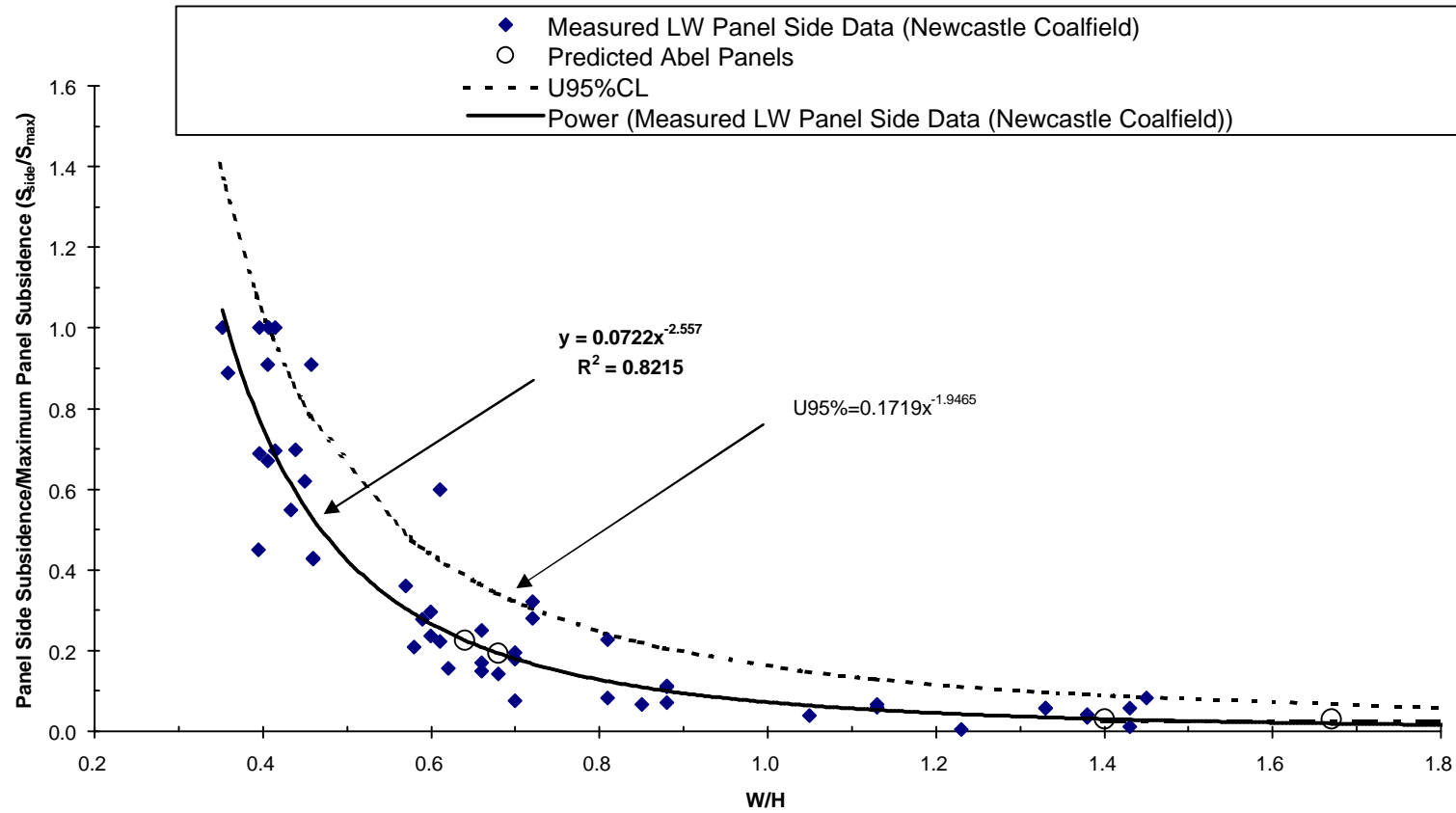


LEGEND
Label = Maximum Strata Unit Thickness, t (m)

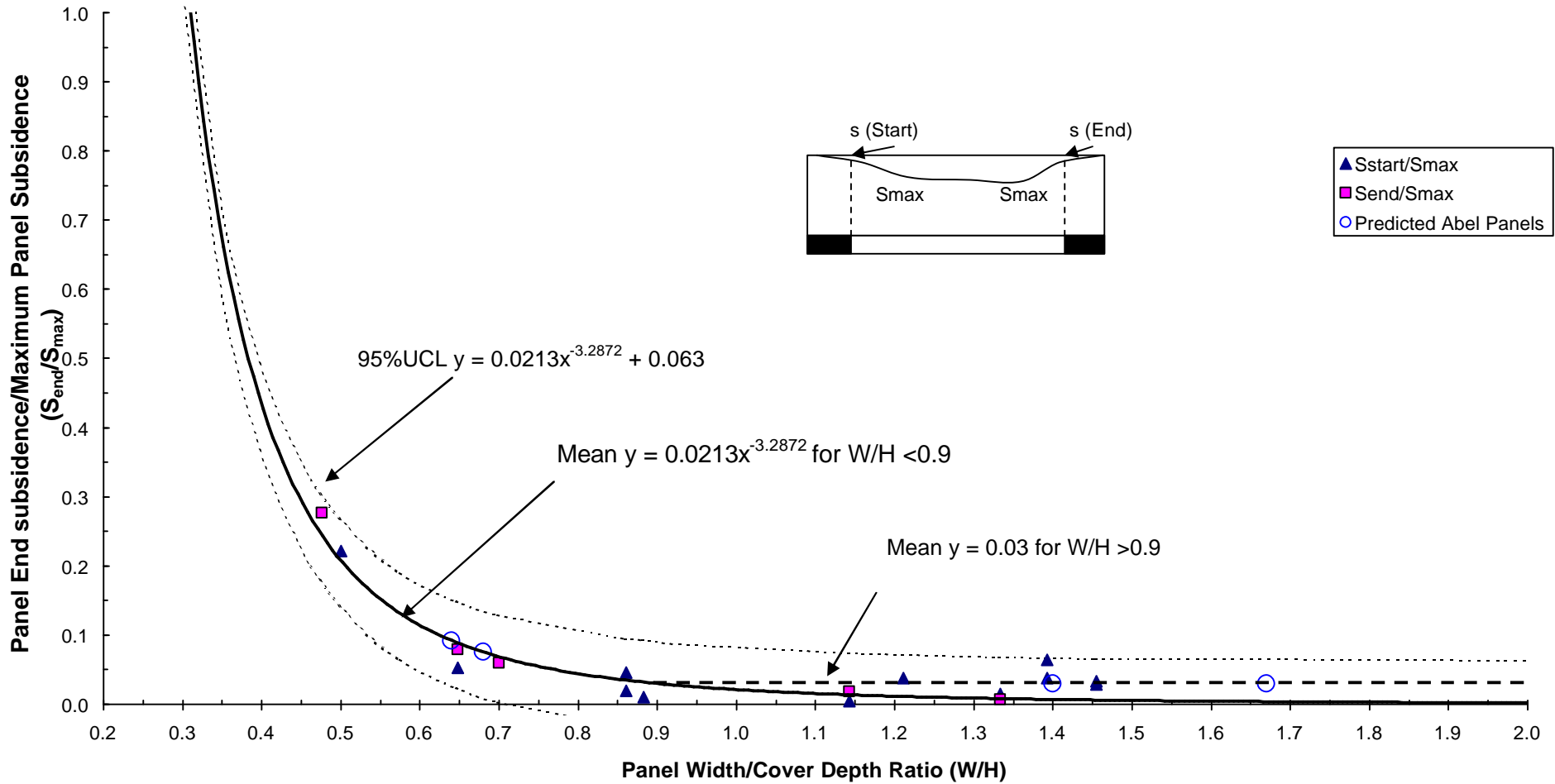
Subsidence Reduction Potential (SRP)

△ Low
▲ Moderate
▲ High

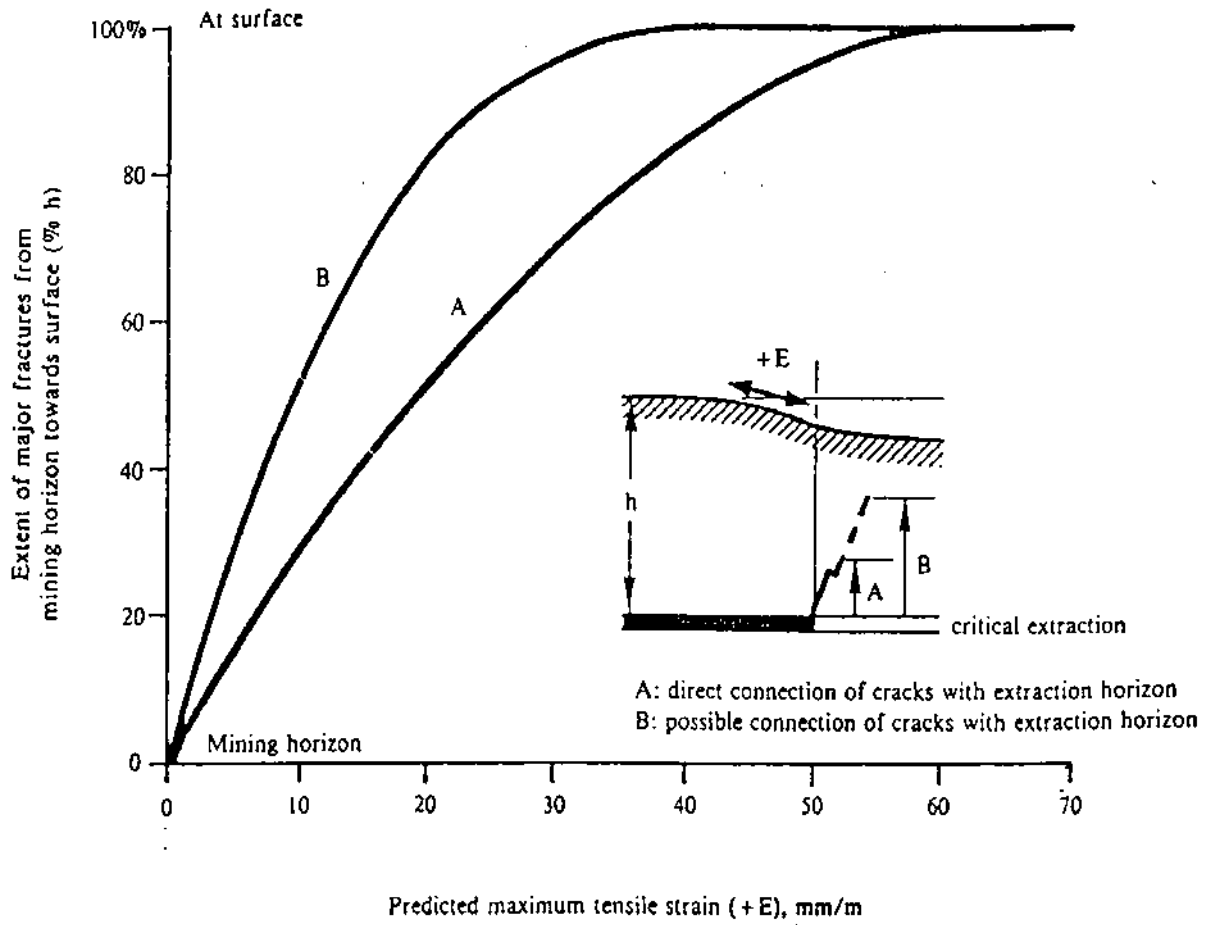
Engineer:	S. Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
Drawn:	S. Ditton		00-181-ACR/1	
Date:	05/03/06	TITLE:	Project Database of Single Panel Subsidence Linked to the SRP Threshold Limit Lines for H = 251 to 350 m	
Scale:	NTS			FIGURE A23



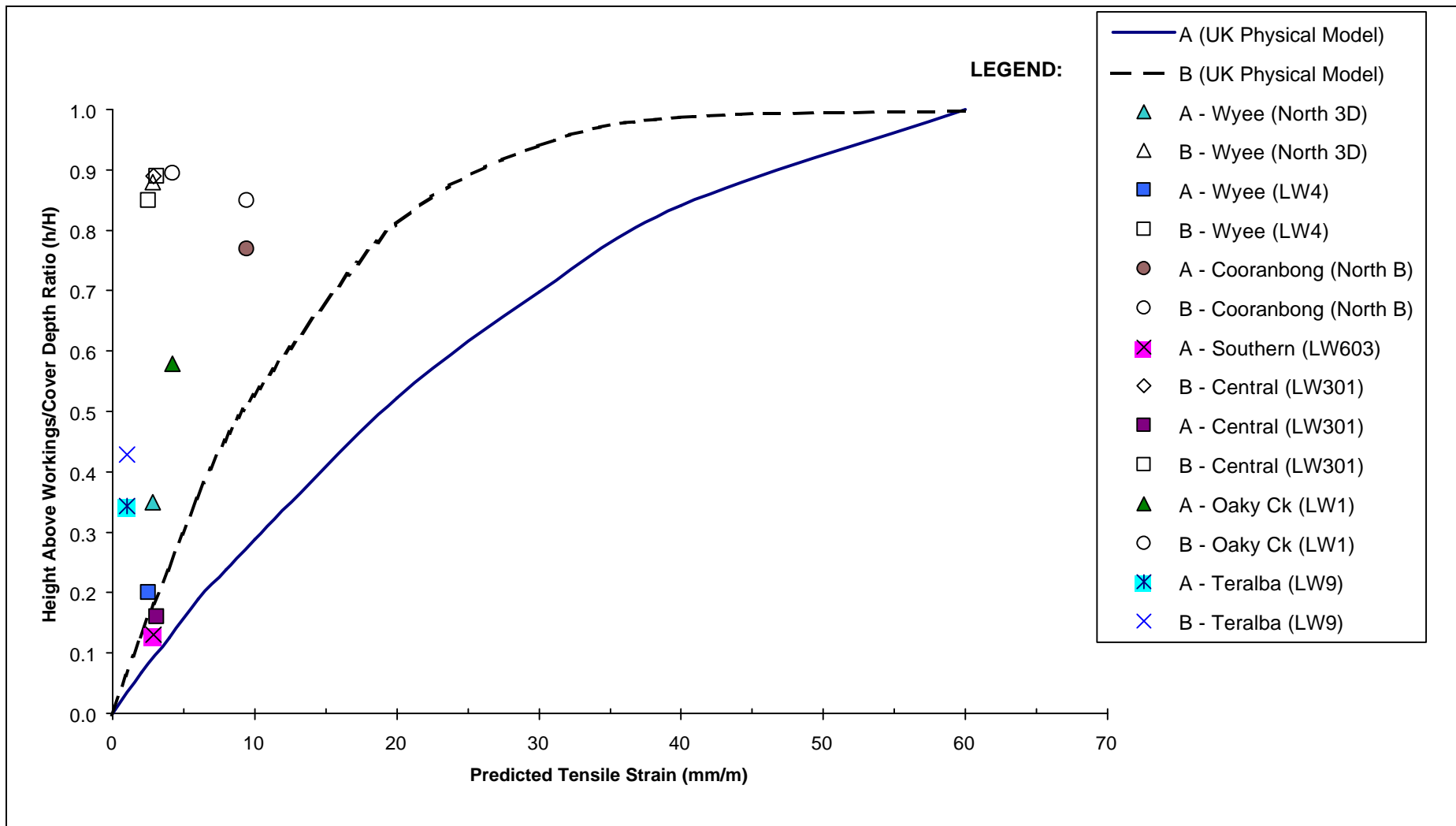
ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	7/02/2006	TITLE:	Empirical Prediction Model for Goaf Edge Subsidence	FIGURE:
SCALE:	NTS		Prediction Above Panel Crossline	A24



ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		00-181-ACR/1	
DATE:	7/02/2006	TITLE:	Empirical Prediction Model for Goaf Edge Subsidence	FIGURE: A25
SCALE:	NTS		Prediction Above End of Panel Centreline	



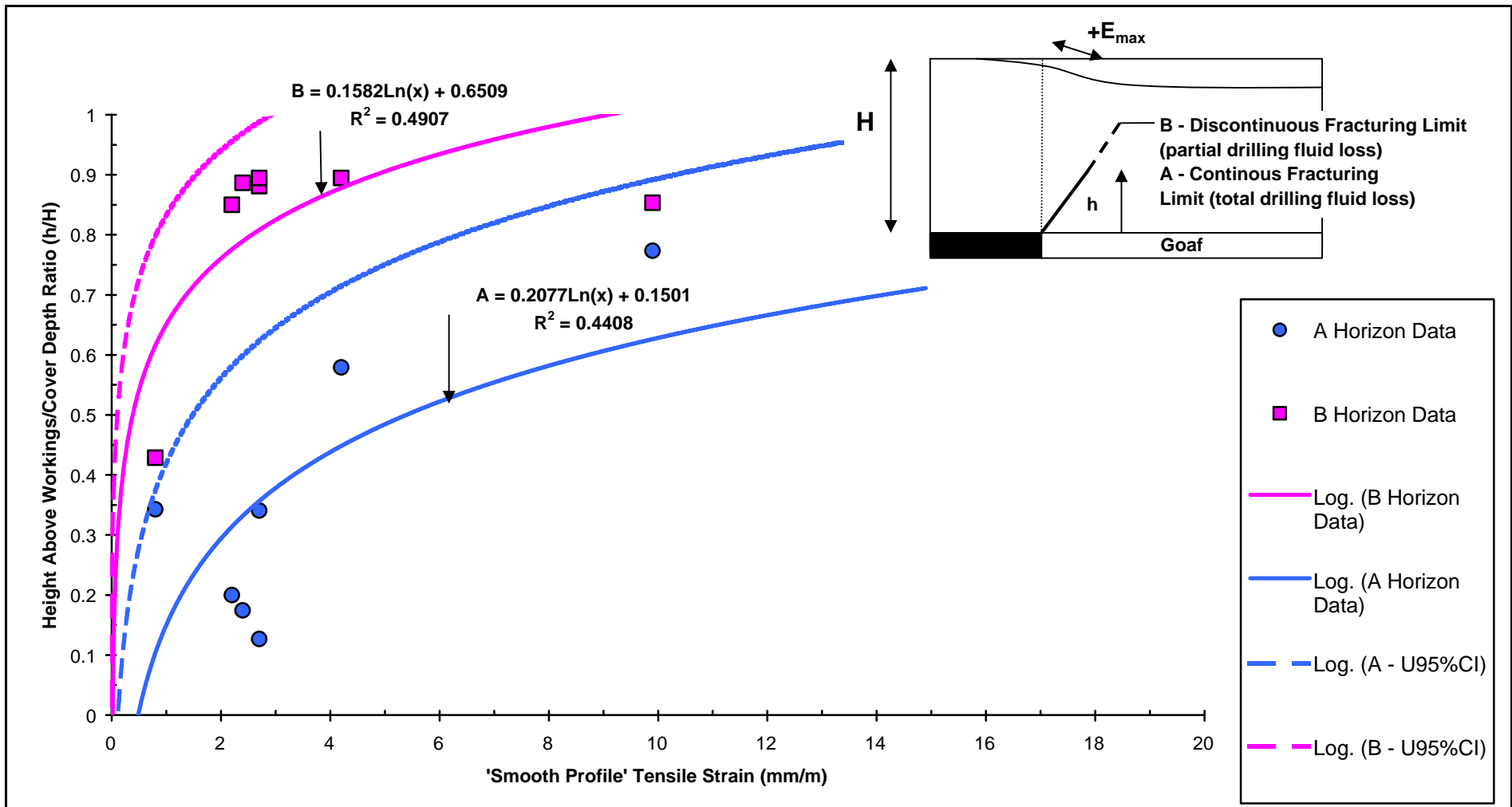
ENGINEER:	S. Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S. Ditton		Subsidence Prediction Review	
DATE:	23/09/2002	TITLE:	Empirically Based Sub-Surface Fracturing Model	FIGURE:
SCALE:	NTS		Presented in Whittaker & Reddish (1989)	A26



Legend Key

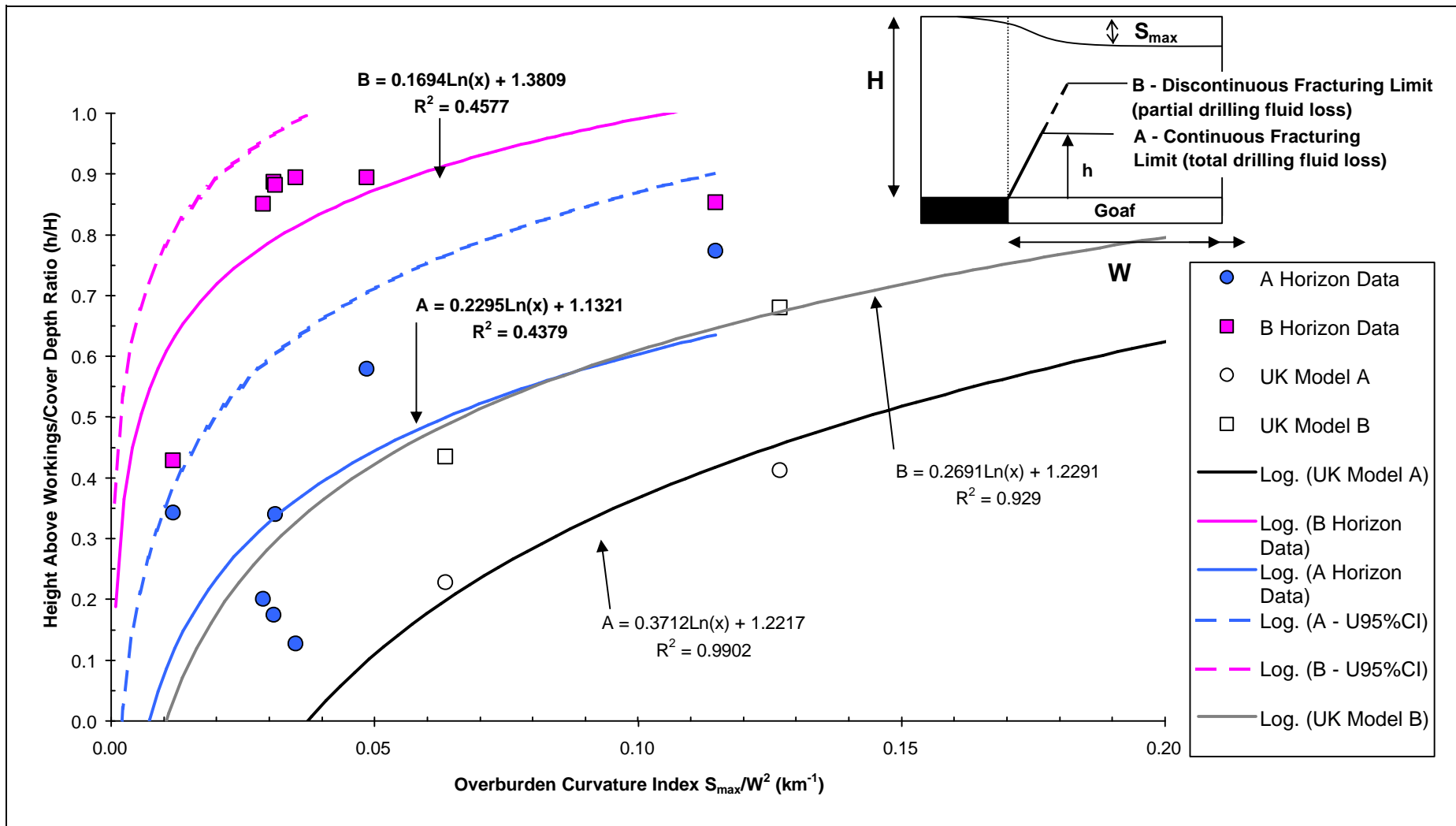
A - Maximum Continuous Fracturing Height
 B - Maximum Discontinuous Fracturing Height

ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		Subsidence Prediction Review	
DATE:	4/02/2003	TITLE:	Whittaker and Reddish Physical Sub-Surface Fracture	FIGURE:
SCALE:			Model and Australian Drilling Data Above Extracted LWs	A27



NOTE : Based on drilling fluid losses over goafed areas

ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		Subsidence Prediction Review	
DATE:	4/02/2003	TITLE:	Empirical Sub-Surface Fracture Height Above a Longwall	FIGURE:
SCALE:			Panel Based on Maximum Tensile Strain (Smooth Profiles)	A28



ENGINEER:	S.Ditton	CLIENT:	ACARP Project No. C10023	STRATA ENGINEERING (Australia) Pty Ltd
DRAWN:	S.Ditton		Subsidence Prediction Review	
DATE:	4/02/2003	TITLE:	Empirical Prediction Model for Sub-Surface Fracture Height	FIGURE:
SCALE:			Above a LW Panel Based on S_{max}/W^2 (Curvature Index)	A29