

# FURTHER INSIGHTS INTO THE MECHANICS OF MULTI-SEAM SUBSIDENCE FROM ASHTON UNDERGROUND MINE

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**ABSTRACT:** Ashton Underground Mine (Ashton) is an underground longwall mine located northwest of Singleton in the Hunter Valley of NSW. The mine has so far extracted longwall panels in three seams with mining in a fourth seam planned and each seam progressively deeper than the last. The mining geometry in each of the seams is regular, parallel and either offset or stacked relative to the panels in the seams above. A subsidence line crossing all panels in each seam has been regularly surveyed in three dimensions since the commencement of mining. The high quality data set available from this line provides insight into the mechanics of ground behaviour in a multi-seam environment. This paper presents an update of the observations and interpretation presented in Mills and Wilson (2017) for mining in two seams with the inclusion of results from mining in a third seam.

Observations of the characteristics of multi-seam subsidence continue to indicate that although subsidence movements above multi-seam mining are more complex than single seam mining, these movements are nevertheless regular and predictable. In an offset geometry, remote from pillar and goaf edges, tilt and strain levels are similar or lower than single seam levels, despite the greater vertical subsidence, due to the general softening or reduction in shear stiffness of the overburden with each episode of subsidence. At stacked and undercut goaf edges, transient tilts and strains are significantly elevated.

Cumulative vertical subsidence after longwall mining in three seams has now reached 5.8m with incremental vertical subsidence increasing as a percentage of incremental mining height with each episode of subsidence. Latent subsidence from near stacked goaf edges is recovered when mining in the seam below. A site-specific methodology developed to forecast subsidence behaviour is allowing measured subsidence effects to be estimated reliably.

## INTRODUCTION

Since the multi-seam subsidence monitoring data and interpretation from Ashton Underground Mine (Ashton) was last prepared in late 2016 and early 2017 (Mills and Wilson 2017), two additional longwall panels in the second seam of mining have been completed and three longwalls have been mined in the third seam. Observations from the monitoring of these extra panels have enhanced the previous dataset for Ashton and confirmed the contemporary understanding of multi-seam subsidence behaviour at this site.

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The mining at Ashton provides a unique opportunity to study the mechanics and interactions of multi-seam mining to improve understanding for the preparation of future mining applications. The characteristics that make this site unique include:

- Longwall mining occurs in a regular, parallel layout with substantial chain pillars remaining.
- Modern, reliable mine plan records are available in all three seams mined.
- There are no areas of irregular bord and pillar mining or pillar extraction.
- There is no potential for small pillars (or 'stooks') to fail and contribute to risk of pillar run or pillar creep.
- Gradually increasing overburden thickness towards the west provides data for a range of panel width to depth ratios.
- Longwall panels with different starting and finishing positions and goaf edge geometries enable a range of mining scenarios to be studied.

A methodology for estimating multi-seam subsidence effects at Ashton was developed based on site specific data and observations after the first two longwalls in the second seam. For vertical subsidence, this method involves the forecast of an incremental subsidence profile for a seam or seams. The forecast profile(s) is then added to the actual measurements along the subsidence profile of the overlying seam or seams to forecast the cumulative vertical subsidence. The forecasting of incremental and cumulative values of tilt and strain is based on the Holla (1991) guidelines for the Western Coalfield using K values for the constant of proportionality derived from site-specific measurements for general background, stacked goaf edges and undercut goaf edge areas.

## **BACKGROUND AND SITE DESCRIPTION**

Ashton Coal Operations Pty Ltd (ACOL), owned by Yancoal Australia Ltd, operates the Ashton Underground Mine near Camberwell in the Hunter Valley of New South Wales. The mine operates via modified development consent for the Ashton Coal Project (ACP). The mining approval includes underground longwall mining in four seams. In descending order these seams are the Pikes Gully (PG), Upper Liddell (ULD), Upper Lower Liddell (ULLD) and Lower Barrett (LB).

The first longwall in the uppermost PG Seam commenced extraction in 2007. A series of eight longwall panels have been mined in the PG Seam. The longwalls in the second seam (ULD Seam) started secondary extraction in 2012 and six longwalls were completed to mid-2017. Longwalls in the third seam (ULLD Seam) started in mid-2017 and three longwall panels were completed by mid-2020.

Figure 1 is a site plan showing the outline of the longwall voids for the PG, ULD Seams and the three longwalls mined to date in the ULLD Seam superimposed onto a topographic map of the surface area. The positions of subsidence monitoring lines are also shown.

The longwalls in the ULLD Seam are substantially within the footprint of the overlying PG and ULD Seam longwalls, so that the majority of ULLD Seam longwall mining represents three seam extraction with smaller areas of two seam extraction.



The panels in each of the four seams were originally approved to be arranged in a regular, parallel, stacked (superimposed) geometry. However, the layout design has been altered to an offset (staggered) geometry to reduce the subsidence profile and surface impacts and to take advantage of the potential for reduced stress conditions during roadway development. In this offset geometry, longwall panels in the first (PG) and third (ULLD) seams are superimposed. Longwall panels in the second (ULD) and fourth (LB) seams are also superimposed. The ULD and future LB longwall panels are offset 60m to the west relative to the PG and ULLD seam longwall panels.

In the regular geometry, all longwall panels form a void that is nominally 216m wide and all inter-panel chain pillars are 24m wide (coal rib to rib). The panels are aligned in an approximately north-south direction with the longwall face retreating from south to north. The panel mining sequence is from east to west. The naming convention for longwall panels in each seam starts with Longwall 1 in the PG Seam, Longwall 101 in the ULD Seam and Longwall 201 in the ULLD Seam.

The mining height for each seam is approximately 2.5m  $\pm$  0.3m. Mining heights are limited by the seam thickness and the practical operating range of the mining equipment.

The overburden strata and seams dip moderately to steeply to the west at approximately 1 in 10. The gradient of the strata is typically greater than the gradient of the surface topography. The overburden depth to the PG Seam increases from 40m in the northeast corner of Longwall 1 to 180m in the southwest corner of Longwall 7. The interburden thicknesses are typically 35-40m for the PG to ULD seams, 20-25m for the ULD to ULLD seams and 35-45m for the ULLD to LB seams.

The surface topography above the mining area is dominated by a steeply rising ridge line adjacent to Glennies Creek in the east from which the ground slopes west toward Bowmans Creek and the Hunter River to the south.

The longwall mining area is bounded by consideration of the subsidence impacts and consequences to both the natural and built surface and sub-surface features. The main features include the New England Highway and infrastructure in the north, Glennies Creek to the east, the Hunter River to the south and to the west, a combination of Bowmans Creek, Bowmans Creek diversion channels and adjacent mining operations.

### **Subsidence Monitoring**

A comprehensive subsidence monitoring program involving high confidence three-dimensional (3D) survey measurements on conventional monitoring lines has been in place since the start of longwall mining at the Ashton site. Aerial imagery and LIDAR surveys are also regularly captured at Ashton.

For the PG Seam longwalls, some 35 monitoring lines were installed and surveyed regularly. These subsidence monitoring lines are aligned both along the panels (longitudinal) and across the panels (transverse). The main cross panel line (XL5) extends over all the southern longwalls. Sections of this line are surveyed for each individual panel as it is mined. The full length of this line was resurveyed at the completion of the PG Seam longwalls and again after completion of mining in the ULD Seam. Sections of XL5 have been surveyed regularly during the mining of the first three longwalls in the ULLD Seam.

A series of 12 additional longitudinal lines were established for the offset geometry in the ULD Seam. These lines are adjacent to the PG Seam lines at both the southern and northern ends of each panel. Additional 3D monitoring is conducted at other surface features or infrastructure

including the poles on the 132kV powerline that traverses the surface above the southern longwall panels.

## **SUBSIDENCE BEHAVIOUR FOR TWO SEAMS OF MINING**

Contemporary understanding of the mechanics of multi-seam subsidence at Ashton is presented in Mills and Wilson (2017) based on two seams of mining at Ashton. Observations from the monitoring of the two additional longwalls in the ULD Seam have enhanced the existing dataset for Ashton and confirmed the understanding previously presented for multi-seam mining in two seams. The key findings are summarised in this section.

The results of the ULD Seam monitoring show that subsidence behaviour falls into two categories depending on the relative geometries of the mining in the two seams. Subsidence behaviour can be categorised as general background subsidence behaviour for areas remote for pillar edges with tilts and strains of similar magnitude to those observed for single seam mining and behaviour near goaf edges where temporary or permanent stacked goaf edges are formed.

The monitoring dataset also provides significant insight into the mechanics that drive the magnitude and the distribution of subsidence movements in the multi-seam environment at the site including:

- the difference in behaviour between strata that is undisturbed by previous mining and strata that has already been subsided (disturbed or modified)
- increased incremental vertical subsidence as a percentage of the second seam mining height
- the concentrating effect of mining under overlying goaf edges on tilts and strains
- effect of mining direction on subsidence behaviour above solid goaf edges
- recovery of latent subsidence from the overlying seam.

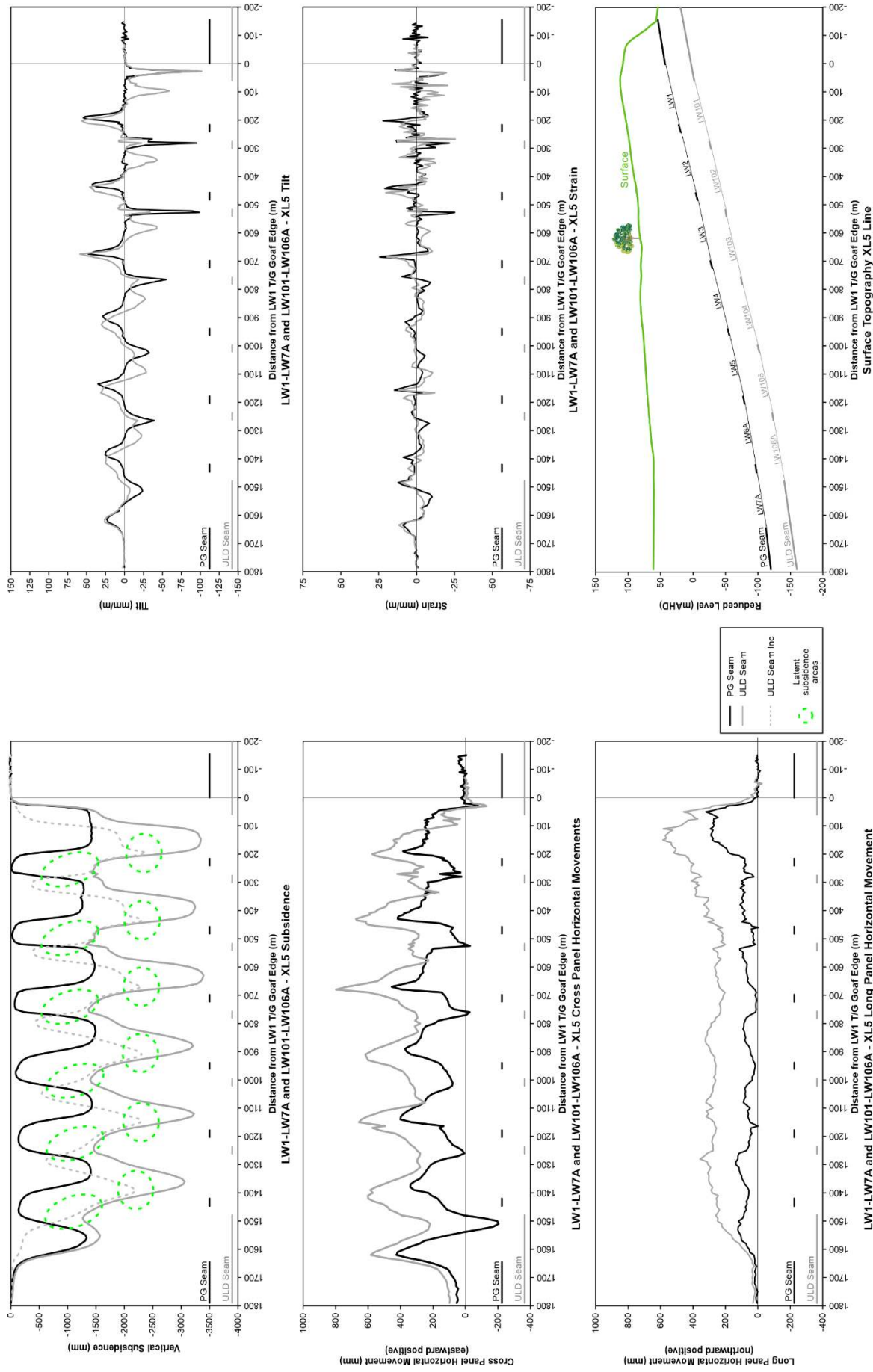
Latent subsidence is a term referring to subsidence which did not occur during mining of the first seam owing to the support provided by nearby pillar or abutment edges.

When the second seam mines under the chain pillars and other abutment edges, the strata above the first seam chain pillar and abutment edges is disturbed and the supporting effect around the edges is lost with additional subsidence occurring at these edges. The latent subsidence increment has both vertical and horizontal components. These components affect tilt and strain levels measured at the surface.

### **General Subsidence Behaviour**

Figure 2 shows a summary of subsidence monitoring results from XL5 Line, the main cross-panel subsidence line over all the southern panels at the completion of mining the sixth longwall (Longwall 106A) in the ULD Seam.

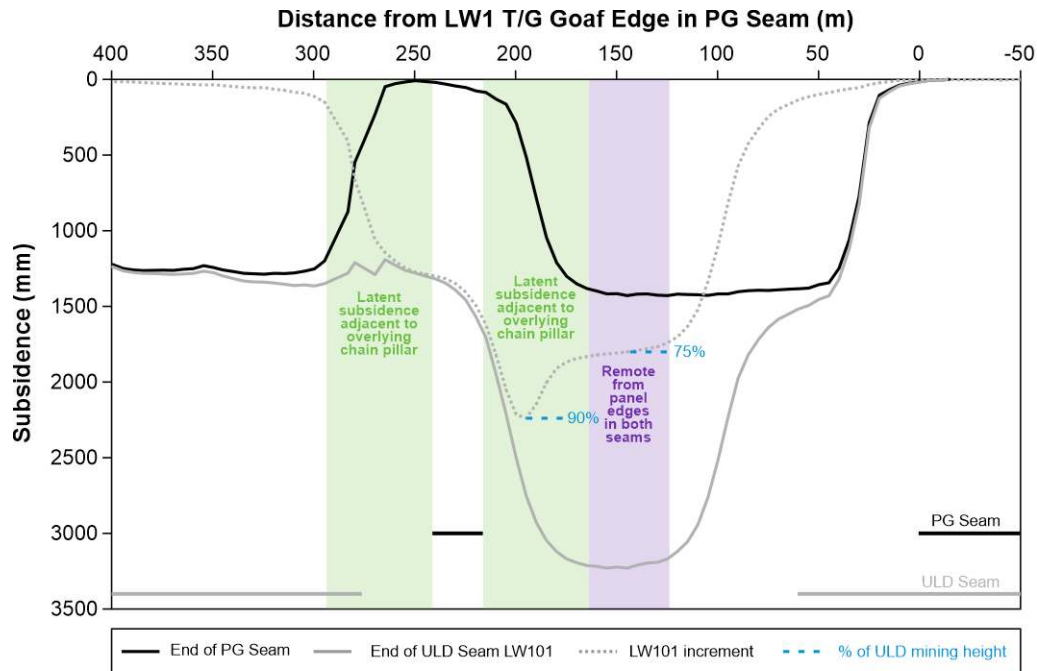
The vertical profiles show the effects of increasing overburden depth and a change from supercritical width caving behaviour to more critical width behaviour with a smoothing of the profile shape and reduction in the magnitude of total subsidence. The areas of latent subsidence are highlighted in the incremental profile shown in Figure 2.





### Multi-Seam Subsidence Zones Across the Panel Width

Figure 3 shows the vertical subsidence profiles over the first longwalls in the PG and ULD seams to highlight the main zones of ground behaviour. Average or more typical magnitudes of incremental subsidence expressed as a percentage of ULD Seam mining height are also shown.



**Figure 3: Individual components of incremental subsidence profile.**

Where panels in two seams overlap in the offset geometry, mining a second seam below disturbed ground causes maximum incremental subsidence in the order of 70-83% of the second seam mining height remote from the pillar edges.

Near goaf edges in the overlying seam, maximum incremental subsidence is observed to increase as latent subsidence is recovered. Vertical subsidence as high as 92% of the second seam mining height is apparent when latent subsidence occurs, but the magnitude of this additional subsidence is not a function of the seam mining height in the lower seam, but rather a function of recovering subsidence that did not occur when the first seam was mined due to the presence of the chain pillars. Latent subsidence of approximately 300-400mm from the PG Seam edges was observed during the mining of the ULD Seam.

In general background areas, remote from pillar and goaf edges, the maximum values of tilt and strains are typically of a similar or lower magnitude to the tilt and strains measured for the first seam mined despite the greater total of vertical subsidence. This behaviour is thought to be due to a general softening or reduction in 'shear stiffness' of the overburden due to the multi-seam mining resulting in a difference in behaviour between strata that is undisturbed by previous mining and strata that has already been subsided (disturbed or modified).

### **Strata Compression Above Chain Pillars**

Incremental vertical subsidence above the ULD Seam chain pillars is much greater than the elastic strata compression observed above PG Seam chain pillars when mining in the PG Seam. This is the result of compression of the disturbed ground above the lower seam chain pillar and the reduced stiffness of this ground from the previous episode of subsidence.

### **Behaviour at Stacked Goaf Edges**

The ULD Seam longwalls formed stacked or almost stacked edges at several locations. Consistent with previous experience, the measured tilt and strain near the stacked goaf edges are significantly elevated compared to tilt and strain observed in areas remote from goaf edges, particularly when the deeper seam undercuts the upper seam.

The direction of mining in the second seam under an existing goaf edge has a significant influence on the surface effects that develop. Mining from a goaf under solid leads to a stacked goaf edge that produces very high tilts and strains and much higher than the general background values. Mining from solid to under a goaf produces en-masse subsidence with tilts and strains that are comparable to general background levels.

### **Mining from Under Goaf to Under Solid**

At a stacked goaf edge where the lower seam is mined into solid from below an existing goaf in the upper seam, maximum tilts are observed to be approximately double the maximum tilts observed elsewhere. Horizontal strains are observed to peak at about four times the background levels measured more generally along the panel. These maxima are observed when the goaf edge in the upper seam is undercut to a distance where the caving of the goaf in the lower seam intersects the goaf edge in the upper seam.

The presence of the pre-existing fractures in the overburden from the upper seam mining acts as a preferred separation point to localise deformations from the lower seam mining. Deformations become concentrated on pre-existing fractures with the result that tilt and strain magnitudes are significantly elevated.

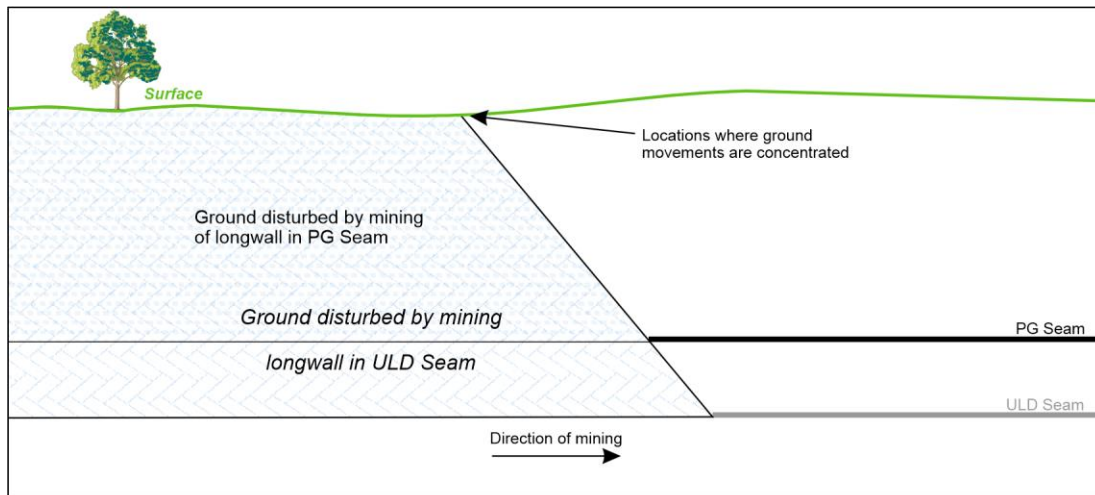
Figure 4 illustrates the retreat of the ULD Seam longwalls under the PG Seam goaf edge/solid coal and how the subsiding strata interacts with the overlying goaf edge as the panel retreats.

### **Mining from Under Solid to Under Goaf**

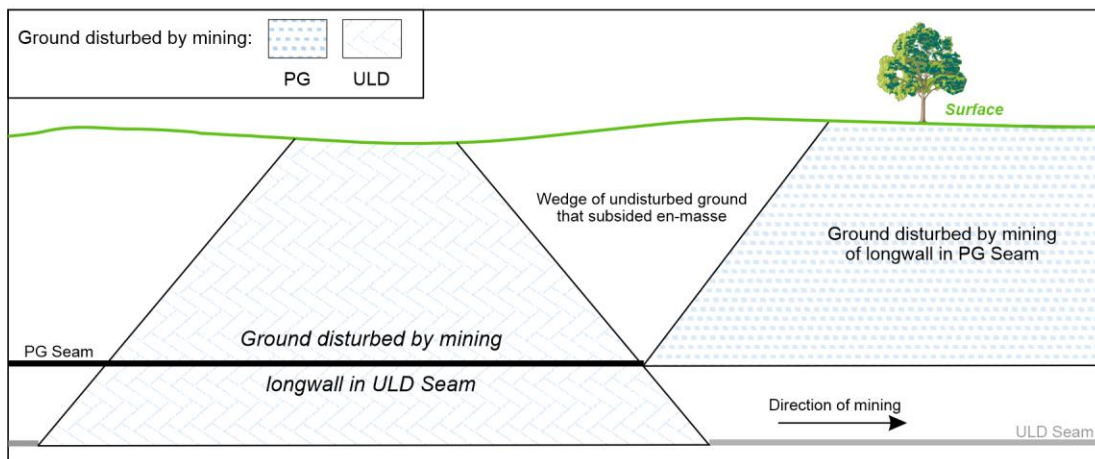
Where the lower seam is mined initially as a single seam and proceeds to mine under an overlying goaf, a different subsidence behaviour is observed. A wedge of undisturbed strata is observed to subside en-masse. Tilt and strain magnitudes are of similar magnitude to single seam mining.

Figure 5 illustrates the geometries involved and shows how the disturbance caused to the ground by mining longwall panels in the two seams leaves a triangular wedge of largely undisturbed ground above the start of the PG Seam longwall. This triangle of rock subsided gradually en-masse as mining in the underlying ULD Seam progresses.





**Figure 4: Sketch illustrating the mechanism that concentrates the strata movements during mining in the ULD Seam at the same location as they were concentrated during mining in the PG Seam.**



**Figure 5: Sketch illustrating the mechanism by which a wedge of undisturbed strata subsides as the ULD Seam longwalls mine under the start of the PG Seam longwalls.**

### Horizontal Movements

The magnitude, direction, and form of horizontal movements observed during mining the ULD Seam are consistent with the horizontal movement observed during mining of the PG Seam. Total horizontal movements measured for mining in the ULD Seam are typically in the range of 20-30% of the vertical subsidence.

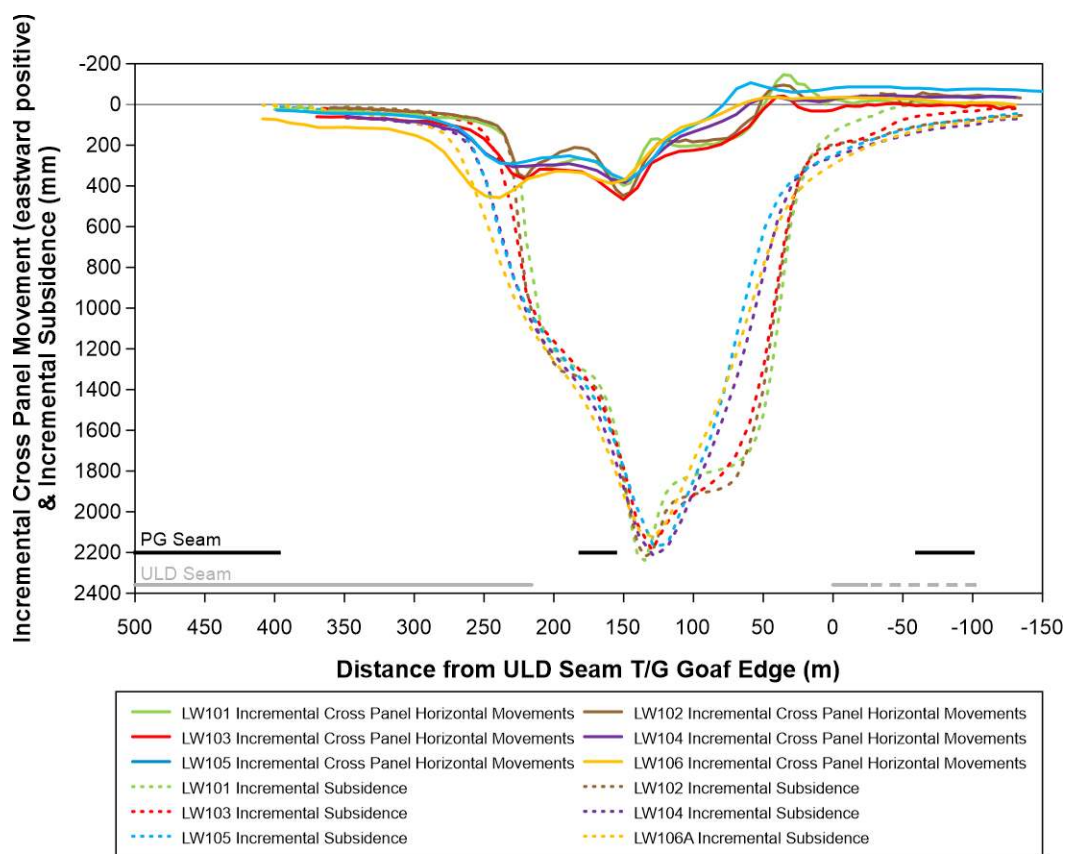
There is a strong similarity in the characteristics and distribution of cross-panel horizontal subsidence movements associated with each longwall panel indicating a consistent mechanism driving horizontal movements. The influences of the offset geometry and latent subsidence recovered from the PG Seam are seen as a regular pattern of incremental horizontal movements associated with mining in the ULD Seam. There is also a strong influence of strata dilation in the

development of horizontal movements. This strata dilation causes a general shift in an uphill direction.

The incremental long-panel horizontal movements are characterised by movement toward the approaching longwall face, followed by movement in the reverse direction after the longwall face has passed. This behaviour is observed in single seam mining as well.

### Incremental Subsidence Movements

Figure 6 shows the incremental vertical subsidence and incremental cross-panel horizontal movements and measured above Longwalls 101 to 106A at the time of mining in each panel. The horizontal distance is plotted relative to the tailgate or eastern ULD Seam goaf edge.



**Figure 6: Incremental Cross Panel Horizontal Movements and Vertical Subsidence for LW101 - LW106A.**

Figure 6 shows:

- the vertical subsidence profile has a regular, repeatable form, with a general smoothing and reduction in peak values with increasing overburden depth
- the maximum vertical and horizontal movements occur substantially within the footprint of the active panel

- the influence of the recovered latent subsidence from the PG Seam extends over the disturbed ground of the next panel
- movements over previous panels are generally small and insignificant for practical purposes.

### **SUBSIDENCE MOVEMENTS FOR THREE SEAMS OF MINING**

Monitoring data from XL5 Line and the longitudinal lines at the start of Longwalls 201 and 202 provide insights into, and understanding of, the mechanics of multi-seam mining in three seams. Figure 7 shows the subsidence effects along XL5 Line after the mining of Longwalls 201-203. The incremental vertical subsidence profile, with prominent latent subsidence areas adjacent to the overlying chain pillars, is the mirror image of the incremental profile for the ULD Seam. This is due to the panel offset being in the opposite direction, relative to the panel geometry in the overlying seam.

Remote from chain pillars and goaf edges in overlying seams, incremental subsidence ranges 82-88% of ULLD Seam mining height. Maximum values of tilt and strain are similar or of a lower magnitude than those measured for the PG and ULD Seams despite the increased vertical subsidence.

Close to chain pillars and goaf edges in overlying seams, incremental subsidence ranges 96-105% of the height of the seam being mined with the inclusion of latent subsidence from the overlying seam. The areas of latent subsidence adjacent to pillar edges are similar in extent and magnitude to those observed from the ULD Seam mining. The additional vertical displacement from latent subsidence is estimated at 300-500mm. Maximum tilt and strain are higher than over the centre of the panel.

After three seams of mining at Ashton, maximum cumulative subsidence has reached 5.8m. Cumulative subsidence ranges 72-77% of the combined mining heights in all three seams. Maximum incremental subsidence from the ULLD Seam mining is 2.7m representing approximately 105% of the ULLD Seam mining height with the inclusion of latent subsidence from the ULD Seam.

### **Behaviour at Stacked Goaf Edges**

Stacked goaf edges associated with mining from goaf to solid were avoided in Longwalls 201-203 to improve longwall conditions during start-up and take-off. However, Longwalls 201 and 202 created a variation of mining direction effects at stacked goaf edges not previously observed when they mined from below a single seam goaf to under goaf in two seams. Mining in the third seam progressed from solid to under a goaf edge for a second time. During the first episode of mining, a wedge-shaped block of overburden subsided en-masse as illustrated in Figure 5. This block remained relatively undisturbed by incremental subsidence effects. A second episode of mining in the third seam led to additional subsidence when incremental mining caused dilation and fracturing of the previously undisturbed strata. Figure 8 shows the mining geometry and the observed subsidence profile.

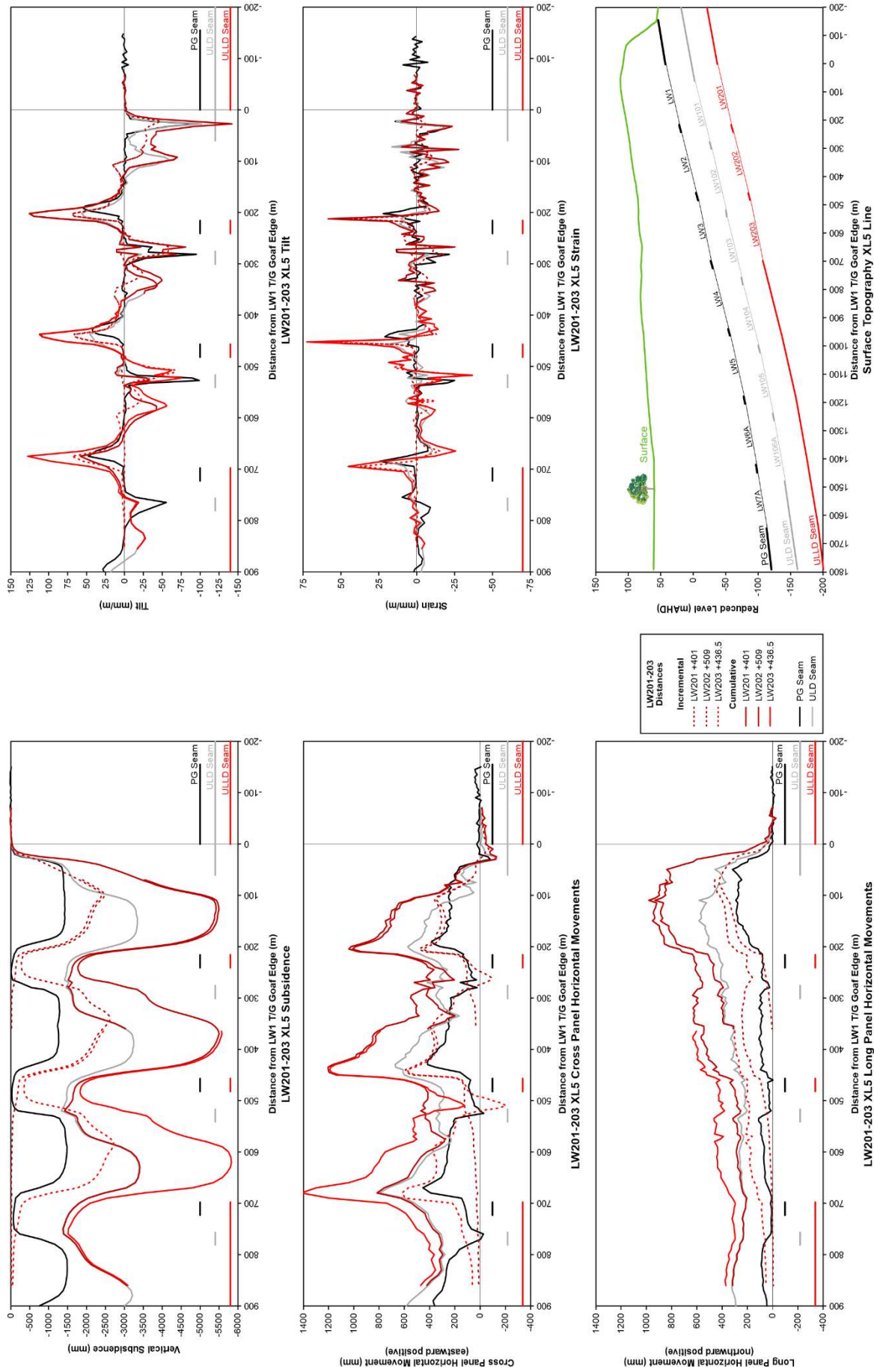
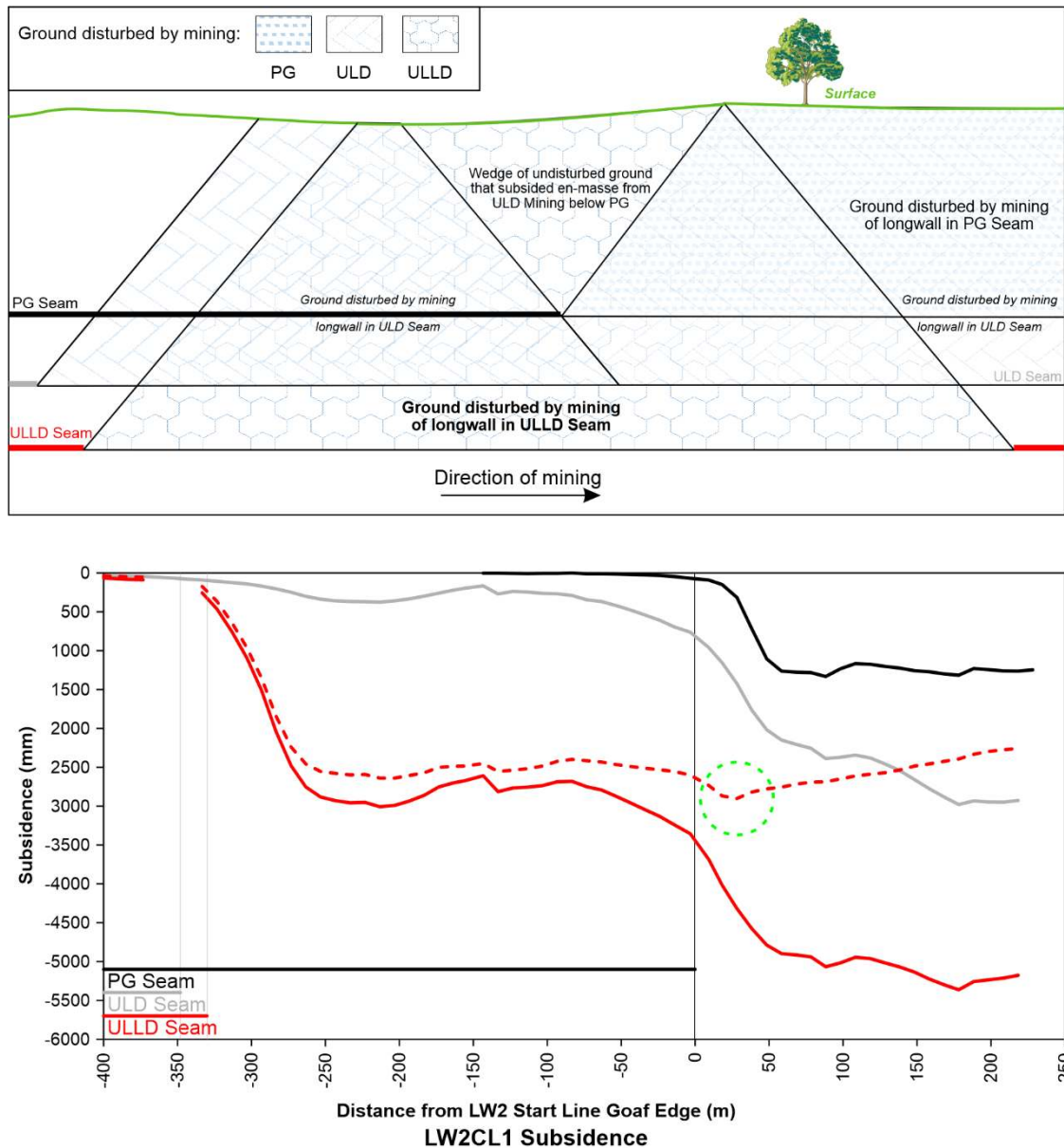


Figure 7: Summary of the subsidence movements measured on XL5 Line to the end of LW203.



**Figure 8: Sketch illustrating the geometry and the mechanisms driven by mining direction at start of panel and vertical subsidence profile.**

The mining layout in the ULLD Seam is directly below the PG Seam goaf leading to stacked edges along both sides of the panel. The PG Seam panel edges had previously been remediated. They were then mined under by a ULD Seam longwall which is offset 60m to the west before being mined under again by the ULLD Seam longwall. Tilt and strain measured on XL5 Line at the panel edges of the PG Seam approach the levels observed at stacked goaf edge levels at other locations where only two seams are mined. Even though the panel edge had subsequently been mined under by a ULD Seam longwall without forming a stacked edge, movements continue to be focussed on the pre-existing fractures in the overburden when a stacked edge is subsequently formed by mining in a third seam. Fracturing in the overburden from the first seam of mining is reactivated and further

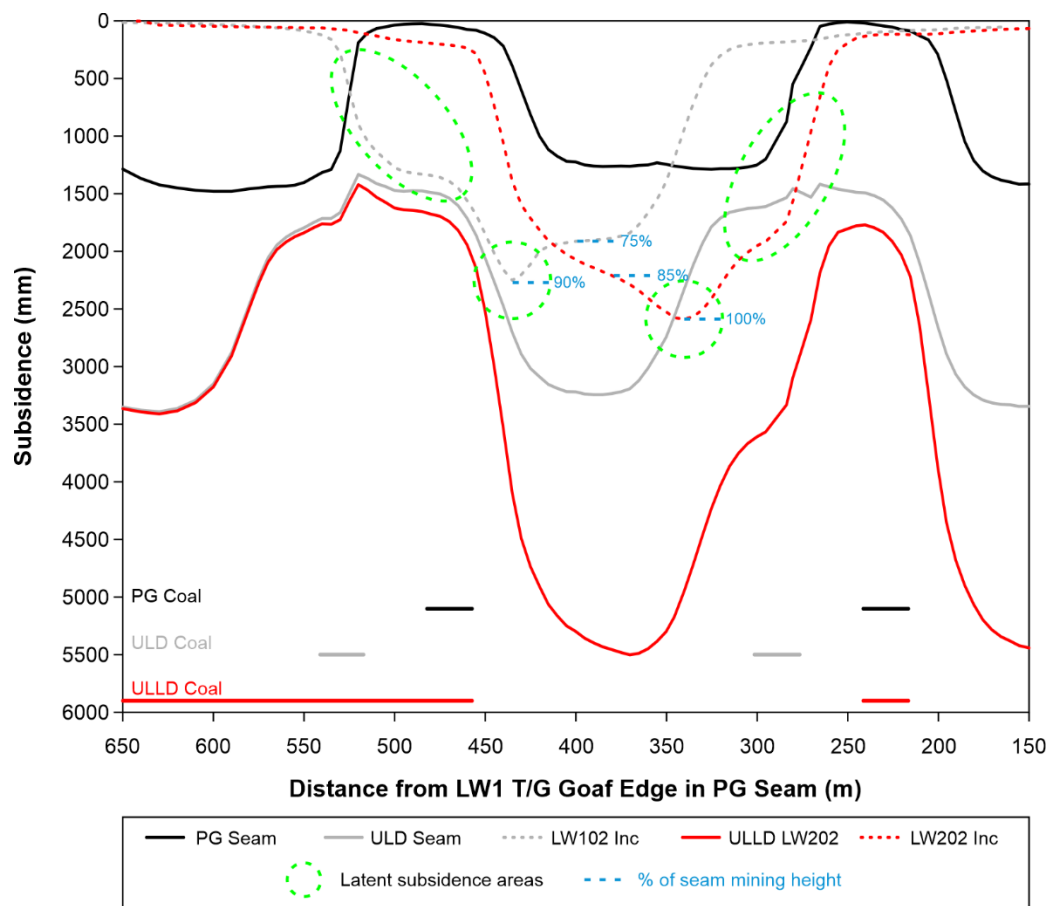


movements are concentrated or localised at the original fractures. Surface cracks along the PG Seam panel sides opened again during mining of the ULLD Seam longwalls.

### Multi-Seam Subsidence Zones across the Panel Width

As a proportion of mining height, the values for incremental subsidence in the centre of the panel, maximum incremental subsidence with latent subsidence effects and cumulative subsidence from the third seam of mining are all generally 5-10% greater than after two seams of mining in the same location.

Figure 9 shows a comparison of the increment profiles against the cumulative profiles for the ULD and ULLD Seams with the magnitudes of incremental subsidence as a percentage of the mining height within the main zones of ground behaviour highlighted in Figure 3.



**Figure 9: XL5 Subsidence - LW102 and LW202 with second and third seam increments.**

### Angle of Draw

The conventional concept of an angle of draw varies depending on the relationship of the extracted panels. The angle of draw outside of the outermost goaf edge is the same as in single seam mining.



The angle of draw for the seam being mined extends much further when the overlying strata has been disturbed or modified by previous mining.

The angle of draw from the outer edge of multi-seam panels based on the depth to the seam of the outer panel edge is similar to single seam mining. Where panels start or finish within the boundary of overlying panels changes to the angle of draw for the upper seam(s) are imperceptible for all practical purposes. No significant change in angle of draw has been observed where multiple panels are aligned at a stacked goaf edge and additional goaf edge subsidence is measured.

Where panels start well below an established goaf, the subsidence and angle of draw at the start line is greater, consistent with a general softening of the overburden strata from the previous episode of subsidence.

Subsidence across panels is observed to extend over overlying goaf areas to the next load bearing pillar or solid coal. These low magnitude movements are a secondary subsidence effect from low-level subsidence or compression of the previously disturbed ground. While this low-level subsidence is generally insignificant, consideration of this interaction is helpful in determining assessment areas for impact and environmental consequence assessments as required by the mining approval process.

### **Multi-Seam Incremental Subsidence Observations**

Figure 10 shows the incremental vertical subsidence profiles for the Longwalls 201-203. A regular pattern of behaviour is observed similar to the pattern shown in Figure 6 for the ULD Seam panels.

When compared to two seams of mining, the cross-panel incremental profiles indicate a further 'softening' of the overburden from the third episode of mining. This softening results in a slightly wider, steeper subsidence trough and greater subsidence as a proportion of mining height in the third seam.

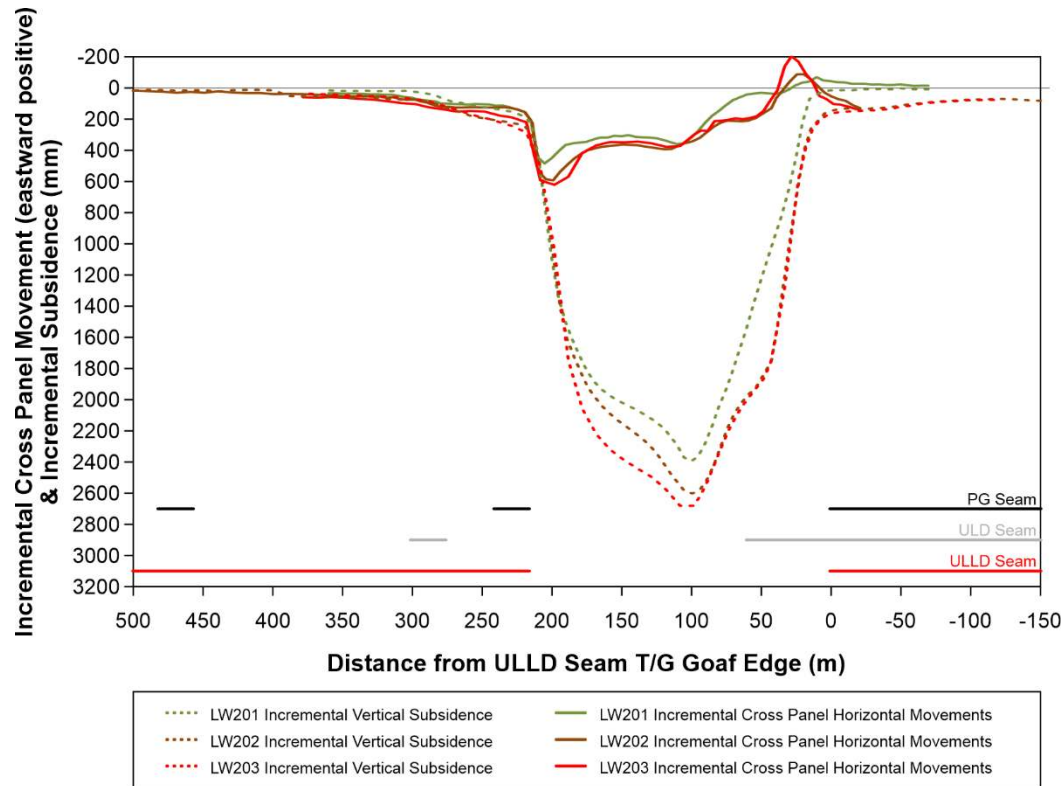
### **Horizontal Movements**

Figure 10 also shows the incremental cross-panel horizontal movements associated with mining Longwalls 201-203. The magnitude, direction and form of horizontal movements observed are consistent with the horizontal movements observed during mining of the PG and ULD Seam longwalls. The influences of the offset geometry and latent subsidence areas are seen in the profile as a regular pattern of incremental horizontal movements. The characteristics and distribution of horizontal subsidence movements indicates a consistent mechanism driving the horizontal movements.

Total horizontal subsidence movements are now 1.4m, representing 20-30% of the cumulative vertical subsidence consistent with the experience of the previous mining in the upper seams. Most of the horizontal movement occurs in an up-dip, easterly direction toward the free surface associated with the slope leading down to Glennies Creek.

### **Comparison of Predicted and Observed Subsidence**

Monitoring data indicates the methodology used to forecast the subsidence behaviour for the third seam of mining is providing a reasonable estimation of the measured subsidence effects for impact assessment purposes.



**Figure 10: Incremental vertical subsidence and cross panel horizontal movements for LW201-LW203.**

The maximum incremental and cumulative vertical subsidence measured on XL5 Line to date is consistent with forecast (within 1%). The results are well within the 15% allowance for natural variation expected in single seam mining and significantly less than the 20% recommended as performance indicators to set Trigger Action Response Plan (TARP) levels for compliance reporting in accordance with mining approval conditions. Observed tilt and strains, both incremental and cumulative, are all less than the maxima forecast using the Holla approach and the K values derived for general background, stacked goaf edges and undercut goaf edge areas (Mills and Wilson 2017). The main variation from predictions is that areas of maximum latent subsidence are located slightly further to the west than forecast in the moderately to steeply dipping strata.

Estimates of incremental subsidence effects for the ULLD Seam mining are derived from the differences in subsidence movements between the ULD and ULLD Seam mining. However, it is recognised the maximum latent subsidence movements, adjacent to overlying panel or pillar edges, are not necessarily captured on the longitudinal lines at the panel ends and that the calculation of incremental subsidence movements is subjective. With the offset geometry, there is scope for longitudinal lines which are not necessarily at locations of maximum subsidence to provide misleading indications of incremental subsidence as performance indicators. Performances indicators should be based on measured cumulative subsidence movements and not calculated incremental subsidence to overcome this issue.

## **CONCLUSIONS**

The monitoring dataset from Ashton provides significant insight into the mechanics of ground behaviour that drive the magnitude and the distribution of subsidence movements in the multi-seam environment at the site.

Subsidence behaviour from the third seam of mining is consistent and predictable once the various geometry effects are recognised and considered. The patterns of incremental subsidence movements are regular and repeatable.

Ongoing softening of the overburden with each episode of subsidence and recovery of latent subsidence from previous episodes is evident as:

- incremental subsidence as a percentage of seam height is greater than for two seams of mining
- slightly wider, steeper subsidence troughs.

The methodology developed to forecast the subsidence behaviour for the later longwall panels in the second seam and for the first three longwalls in the third seam is providing a reasonable estimation of the measured subsidence effects for impact assessment purposes. The maximum incremental and cumulative vertical subsidence measured is consistent with forecast and the actual levels of incremental and cumulative tilt and strains are all less than the maxima forecast for compliance reporting.

Further refinement and adjustments to the adopted method of forecasting subsidence effects at the site is expected from ongoing monitoring to enable ACOL to continue to effectively manage the risks to health and safety from subsidence.

## **ACKNOWLEDGEMENTS**

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