Monitoring of Ground Movements at Sandy Creek Waterfall and Implications for Understanding the Mechanics of Valley Closure Movements

RV Walsh, BHP Billiton-Illawarra Coal
KW Mills, Strata Control Technology
MA Nicholson, Michael Nicholson Consulting previously BHP Billiton-Illawarra Coal
J Barbato, Mine Subsidence Engineering Consultants
BK Hebblewhite, University of NSW
G Li, Department of Trade & Investment, Regional Infrastructure & Services
PJ Brannon, BHP Biliton-Illawarra Coal, Dendrobium Mine

Summary

BHP Billiton-Illawarra Coal operates Dendrobium Mine in an area 10-20km west-northwest of Wollongong in New South Wales, Australia. The mine recently completed mining the Wongawilli Seam in Area 3A adjacent to a natural rock overhang known as Sandy Creek Waterfall. Illawarra Coal undertook to protect the waterfall and the section of Sandy Creek immediately upstream of the waterfall from the effects of adjacent longwall mining using an innovative management process and an array of very high resolution monitoring systems. This paper describes the results of the high resolution monitoring systems and the implications of these results for general understanding of natural and mining induced ground movements around valleys.

The program of monitoring conducted at Sandy Creek Waterfall measured closure, stress changes, microseismic activity and shear movements adjacent to the waterfall during mining of Longwalls 6, 7 and 8. These measurements provided insights into the mechanics of both mining induced valley closure and natural erosion processes. At the completion of Longwall 8, the monitoring strategy and the management decisions based on this monitoring have been effective in protecting the overhanging sandstone rock structure that forms Sandy Creek Waterfall and the upstream section of Sandy Creek, as required by the NSW Department of Planning and Infrastructure.

The measurements and observations made at Sandy Creek Waterfall and the interpretation placed on these results are considered to provide a coherent understanding of the relatively complex deformation mechanics at this site. These mechanics are consistent with measurements and observations made at other sites.

1. Introduction

Sandy Creek Waterfall is located at the head of deeply incised valley located in the upper reaches of Cordeaux Reservoir. The rock structure that forms the waterfall feature is approximately 20m high, 70m wide, and overhangs up to 21m in the centre. Figure 1 shows a photograph of the waterfall and the surrounding area. The impressive nature of this natural rock structure is due largely to its location within the bottom 6m of the Hawkesbury Sandstone formation and immediately above the more readily erodible Bald Hill Claystone. Erosion of the Bald Hill Claystone has undercut the sandstone ledge to form a sandstone plate that is 6m thick at its root and tapers to less than 1m thick at the lip of the waterfall. This cantilever is too large to be self-supporting on its own, but additional support is provided by the concave shape of the structure in plan.

The arcuate shape of the rock allows an arching action in the third dimension across the valley that supports the weight of overhanging rock.

Figure 1 **Aerial photograph of Sandy Creek Waterfall**

The effectiveness of this arching action and the stability of the waterfall are likely to be sensitive to any changes in the horizontal compression across the valley. Mining-induced valley closure effects therefore present a threat to the stability of the waterfall.

BHP Billiton-Illawarra Coal (Illawarra Coal) mines the Wongawilli Seam at Dendrobium Mine using the longwall mining method at a depth below surface in the vicinity of Sandy Creek Waterfall of between 240m and 260m. A development consent condition for mining in close proximity to Sandy Creek Waterfall was that Sandy Creek waterfall and the creek bed immediately upstream of the waterfall should not be adversely impacted.

A number of management options were considered and are discussed in more detail in Walsh et al (2014(a)). The preferred approach, and the approach ultimately adopted, was to closely monitor ground movements and stress changes in the rock structure in the vicinity of the waterfall to determine when adjacent longwall mining was beginning to have a perceptible effect at the waterfall, and to then to cease mining as soon as practical by taking the longwall face off at the next available opportunity i.e. the next cut-through.

The monitoring program started in 2009 during mining of Longwall 5 to the east of the site, was ramped up during mining of Longwalls 6, 7, and 8, immediately to the west of Sandy Creek, and will continue until the end of winter 2014 to confirm that the natural cycle of seasonal variations has been re-established without impacting on Sandy Creek Waterfall over the almost two years since mining was completed.

2. Site investigation and monitoring program

An integrated program of drilling, core testing, laser scanning, in situ stress measurements, stress change monitoring, conventional and far-field subsidence monitoring, high resolution point-to-point surveying, micro-seismic monitoring, groundwater monitoring, ground temperature monitoring, and inclinometer shear monitoring was undertaken immediately adjacent to Sandy Creek Waterfall, in the general vicinity of the adjacent longwall panels, and at control sites remote from mining.

Figure 2 shows a plan of the site and the location of various measurement and monitoring systems that were installed in the vicinity of Sandy Creek Waterfall. In general, drill sites were located on existing roads and access tracks, but some additional tracks were required for instruments located immediately adjacent to the waterfall.

In 2009, a program of site investigation drilling was undertaken to determine the stratigraphy, rock properties, and in situ stresses across the site. Overcore stress measurements and an initial batch of stress change monitoring ANZI strain cells (Mills 1997) were also installed during this drilling program. Conventional survey lines were installed to measure subsidence movements above the longwall panels and at several locations across Sandy Creek. Strain gauges were installed across a number of prominent cracks on the waterfall overhang. The temperature was also monitored at the strain gauge locations to try to compensate for surface thermal variations that were found to range from 0°C to 50°C.

In 2010, a second batch of stress change monitoring instruments was installed at two sites closer to the waterfall, named Sites G and H. Vibrating wire stress change monitoring instruments were included as an independent measurement to correlate with stress changes interpreted from the ANZI strain cells and provide temperature monitoring below the ground. Two additional sites, remote from the waterfall location, were also established during this campaign to act as independent controls for the instrumentation systems.

The results from one of these remote sites, Site I, located over the longwall panels some 970m from the waterfall are presented in this paper. Overcoring stress measurements were made at several sites in the general vicinity of the waterfall to measure the in situ stresses in the Hawkesbury Sandstone.

Eight high resolution, one dimensional survey lines were installed across the waterfall to measure valley closure with a nominal resolution of ±1mm, but in practice the results indicated a resolution that was somewhat better, at about ±0.4mm over base lengths from 50m to 153m. These high resolution lines replaced the conventional cross lines previously installed across Sandy Creek.

A micro-seismic monitoring array was set up in the area between the end of the longwall panels and Sandy Creek to measure mining-induced micro-seismicity as mining approached.

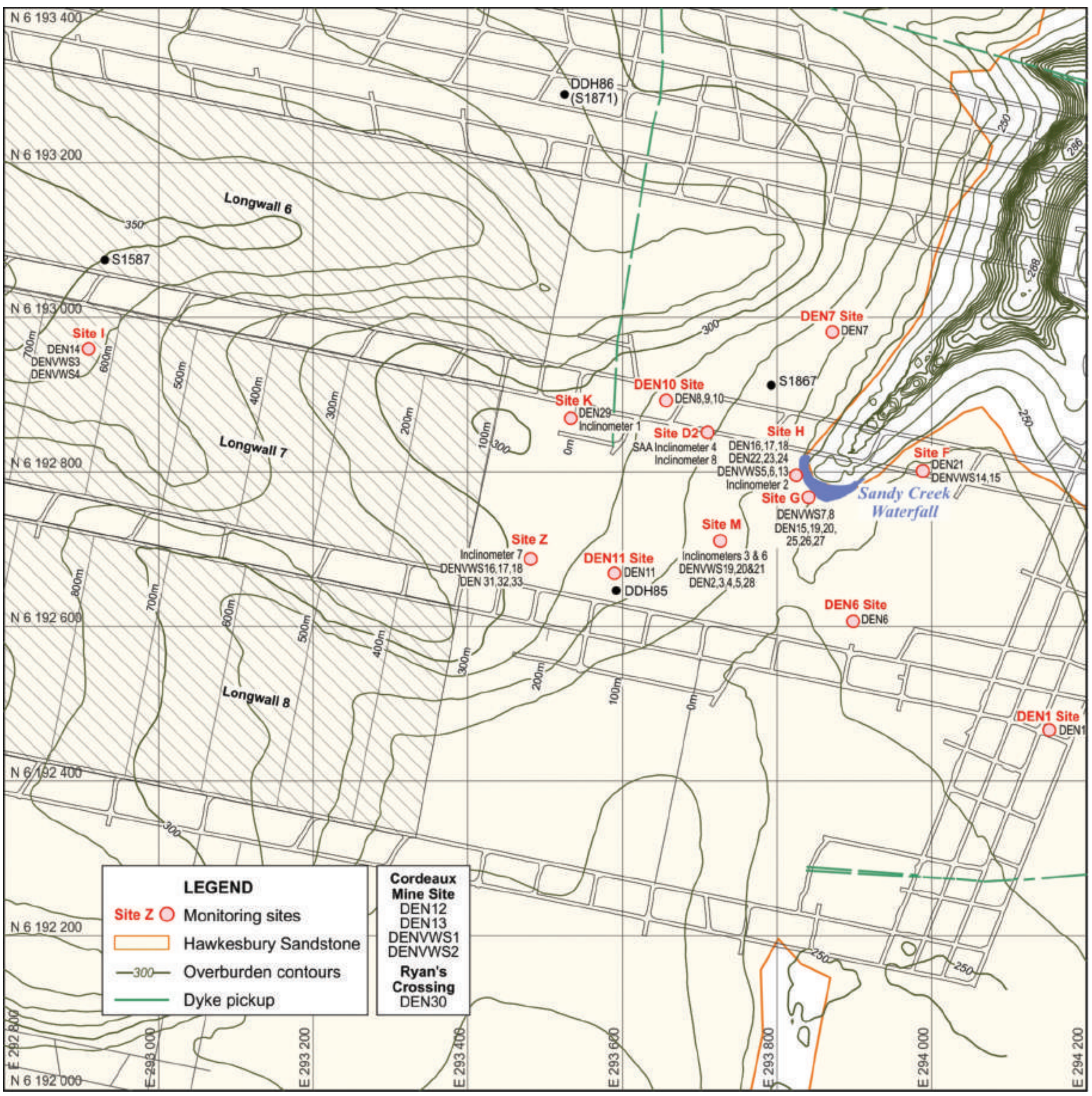

Figure 2: **Site plan showing the location of measurement and monitoring sites relative to longwall panels and Sandy Creek Waterfall**

Following the completion of Longwall 6, the monitoring was further upgraded with additional stress change monitoring instruments, a repeat set of overcore stress measurements at Sites G and H, and the installation of several borehole inclinometers, including a Shaped Accelerometer Array (SAA) at Site K that was able to record movements at 0.5m intervals over a 50m vertical section every minute. This instrument also provided a measure of the thermal gradient over the measuring section.

An additional control site, Site N, was established near Ryan's Crossing downstream of Cordeaux Dam to see if there was any evidence of natural changes remote from mining. This site included high resolution survey monitoring, an inclinometer, and a stress change monitoring instrument.

In 2012 at the completion of Longwall 7, additional instrumentation was installed, including several more manual inclinometers, additional stress change monitoring, and an overcore stress measurement. The SAA inclinometer was moved to Site D2 and installed to measure two shear horizons that had been identified from earlier shear monitoring.

Pore pressures in the Hawkesbury Sandstone were monitored in two exploration boreholes drilled prior to any mining in the area using an array of vibrating wire piezometers. Rainfall was initially measured at several locations several kilometres from the waterfall, but an upgrade in early 2012 provided rainfall data at Sandy Creek.

3. Monitoring results

3.1 Site investigation drilling

The site investigation drilling showed that locally the strata dips very slightly to the west at about 1 in 200. The Hawkesbury Sandstone is approximately 6m thick at the waterfall and thins to the south becoming completely eroded away some 600m upstream of the waterfall. The Hawkesbury Sandstone is also completely eroded away downstream of the waterfall.

3.2 Core testing

Figure 3 shows a summary of the material properties measured from core recovered from the site. Both vertical and angled core drilling showed that contacts at the base of the Hawkesbury Sandstone and at the base of the Bald Hill Claystone were strong and showed no signs of being low strength shear horizons.

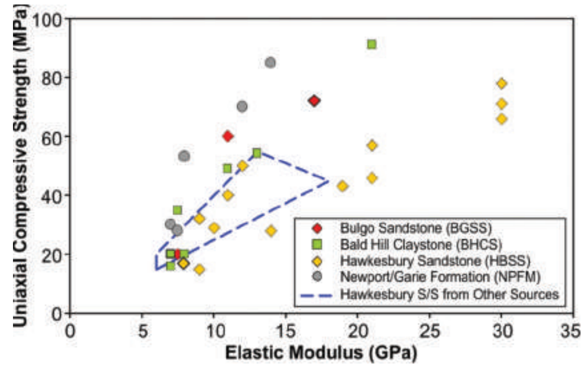

Figure 3 Material properties for rock strata in the vicinity of Sandy Creek Waterfall

The Hawkesbury Sandstone properties were somewhat variable but indicated an average elastic modulus on laboratory-sized specimens ranging from 8-30GPa and unconfined compressive strengths ranging from 15-80MPa. There did not appear to be any strong variation with distance above the base of the Hawkesbury Sandstone.

Other rock units had a relatively lower elastic modulus ranging 8-20GPa, but generally about 10GPa, with a similar range of unconfined compression strengths.

3.3 In situ stress measurements

Figure 4 summarises the in situ stresses measured in the vicinity of Sandy Creek Waterfall and more regionally in the inset. Borehole breakout observed during exploration drilling for Dendrobium Mine indicates the in situ stress directions are oriented northeast-southwest. Overcore stress measurements conducted in vertical boreholes using ANZI strain cells indicated in situ horizontal stresses were somewhat variable, consistent with the uneven topography and valley erosion mechanisms.

The in situ stress magnitudes were within the range of other measurements at similar depth reported in Hawkesbury Sandstone more generally in the Sydney Basin (McQueen 2004). The measured stresses were however much lower than was expected from numerical modelling given the potential for horizontal stress concentrations at the waterfall due to the shape of the valley and much less than the rock strength.

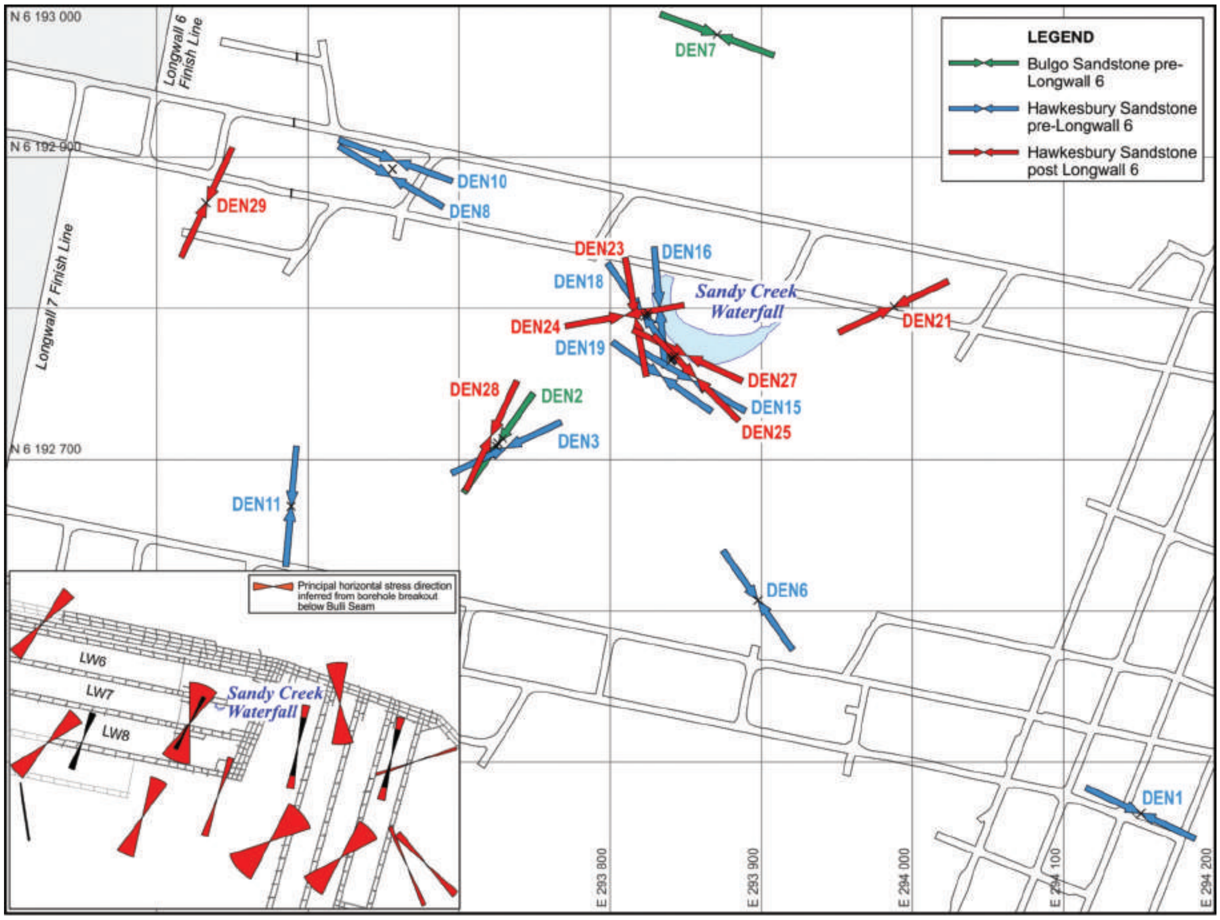

Figure 4 **In situ stress directions indicated in the vicinity of Sandy Creek Waterfall from overcore measurements, pressure tests, and borehole breakout (inset)**

The horizontal stresses measured at Sites G and H in the rock strata immediately behind the waterfall – it was not considered safe to drill on the overhanging shelf of the waterfall – indicated horizontal stresses aligned with the edge of the waterfall with a magnitude of approximately 1.5MPa.

The alignment of the horizontal stresses was also able to be measured from pressure tests conducted on the ANZI monitoring cells.

The maximum horizontal stress parallel to the back of the waterfall is much lower than the in situ strength of the rock strata and implies that either the rock strata that forms the overhang is relatively lightly loaded or the rock strata that forms the overhang, or is immediately adjacent to the overhang, has already failed in some way so that the horizontal stresses are limited by the residual post failure state of whatever has failed.

Repeat measurements were conducted at Site G after the completion of Longwall 6 to confirm the magnitude of the stress changes that were observed during the approach of Longwall 6. These repeat measurements showed essentially the same magnitude stresses as the first set of overcore measurements despite the stress monitoring indicating a relatively significant horizontal stress relief as Longwall 6 approached. The first set of overcore measurements indicated the major horizontal stress was in the range 1.4-1.6MPa. The second set of overcore measurements indicated major horizontal stresses of 1.1MPa and 1.8MPa in two independent tests.

The change in horizontal stress observed in the stress change monitoring as Longwall 6 approached the site indicated about 2.5MPa of stress relief in the major horizontal stress direction. The reasons for this difference are unclear but may be related to local variations in stress in the rock strata in which the individual measurements were made but also by the assumption in the calculation of stresses from measured strains that the rock strata can be represented as a linear, elastic, isotropic, homogeneous material. For instance, an observed sensitivity of the elastic modulus of the sandstone to confining pressure may have contributed to overestimation of the horizontal stress relief when Longwalls 7 and 8 were mined.

Overcore stress measurements conducted in the finish line area of Longwall 7 prior to Longwall 8 indicated low levels of near-surface in situ horizontal stress consistent with previous stress measurements in the general vicinity of Sandy Creek Waterfall. This observation suggests that the generally low level in situ stresses observed across the site prior to mining may be controlled by some process of limiting equilibrium whereby movement occurs without any increase in stress above residual. A process involving horizontal shear on bedding planes where only a given amount of shear capacity can be mobilised before sliding occurs is considered a mechanism that would be consistent with this type of behaviour.

3.4 Stress change monitoring

Three stress change monitoring ANZI stresscells, DEN14 at Site I, DEN15 at Site G, and DEN18 at Site H, provided the bulk of the high confidence stress change monitoring data for the site. Other instruments were installed as backups to these instruments, or were installed to confirm low levels of change in areas where no significant change was expected.

ANZI stresscells used for overcoring and stress change monitoring measure the strain changes on 18 5mm long electrical resistance strain gauges pressure-bonded directly onto the rock on the borehole wall. The stress changes are calculated from multiple linear regression analysis of these strains and the properties of the rock strata measured during an in situ pressure test and subsequent laboratory testing of core specimens recovered from the hole at the location where the instrument is installed. Only six independent strain measurements are required from the eighteen strain measurements recorded, so there is a high degree of redundancy available to determine the level of confidence that can be placed in the measurements as point measurements of the stress.

3.4.1 DEN14 result

DEN14 was installed at Site I above Longwall 7 approximately 530m from the end of the panel, 970m from Sandy Creek Waterfall, and 97m from the northern goaf edge of Longwall 7. The instrument was installed in Hawkesbury Sandstone at a depth of 15m below surface and height above the mining horizon of approximately 325m. This instrument successfully monitored the stress changes as three longwall panels were mined nearby. It provided confidence in the monitoring system and an indication of the levels of stress change that could be expected directly above a longwall panel.

Figure 5 shows a summary of the horizontal stress changes observed at Site I during the passage of each of the three adjacent longwall panels. The horizontal stresses presented have been scaled to the stresses that would be expected in rock with an elastic modulus of 10GPa based on the in situ elastic modulus measured during the pressure test. This scaling or normalisation allows direct comparison between the stress changes in rock of different elastic modulus.

Longwall 6 did not pass directly under the instrument but the stress changes associated with its passage are nevertheless clearly apparent. Horizontal stresses initially increased in magnitude in a northeast direction consistent with the stress concentrations that would be expected around the corner of a retreating longwall panel reaching a maximum stress of approximately 0.9MPa. As the longwall passed, the horizontal stresses increased in magnitude and rotated in a direction aligned with the ridgeline downhill of the site.

When Longwall 7 passed under the site, the horizontal stresses initially continued to increase along the ridge line peaking at 3MPa in compression when the longwall was about 100m past before reducing in magnitude and going into a reduced state of stress (i.e. stretched relative to the initial stress state) when the longwall was about 230m (0.7 times overburden depth) past the site with the stretching continuing until the end of the panel with a stress reduction of about 1.5MPa. Tension cracks that developed in the vicinity of the site suggest that the residual stresses were close to zero at this time and by implication the original in situ horizontal stress was approximately 1.5MPa.

Longwall 8 also caused a slight increase in horizontal stress at Site I as it passed, but the changes were small and the final stress state indicated suggests that the residual horizontal stresses at the site are low.

3.4.2 DEN15 result

DEN15 was installed at Site G, in the creek channel 9.5m upstream of the back of the Sandy Creek Waterfall overhang. The instrument was installed at a depth below surface of 3.6m so as to be approximately in the middle of the 6m thick layer of Hawkesbury Sandstone that forms the overhang. This instrument monitored the stress changes as Longwalls 6, 7 and 8 approached the site.

Figure 6 shows a summary of the horizontal stress changes observed at Site G during the approach of each of the three adjacent longwall panels. The horizontal stresses presented have been scaled to the stresses that would be expected in rock with an elastic modulus of 10GPa, based on the in situ elastic modulus measured during the pressure test.

The stress changes are characterised by horizontal compression in a north-northeast direction directly towards the free surface of the waterfall overhang and by stretching in the orthogonal direction. Both horizontal stress components increased during the approach of Longwall 6. From the end of Longwall 6, the horizontal stresses have shown a seasonal variation, decreasing in the cooler months and increasing again during the summer months when, coincidentally,

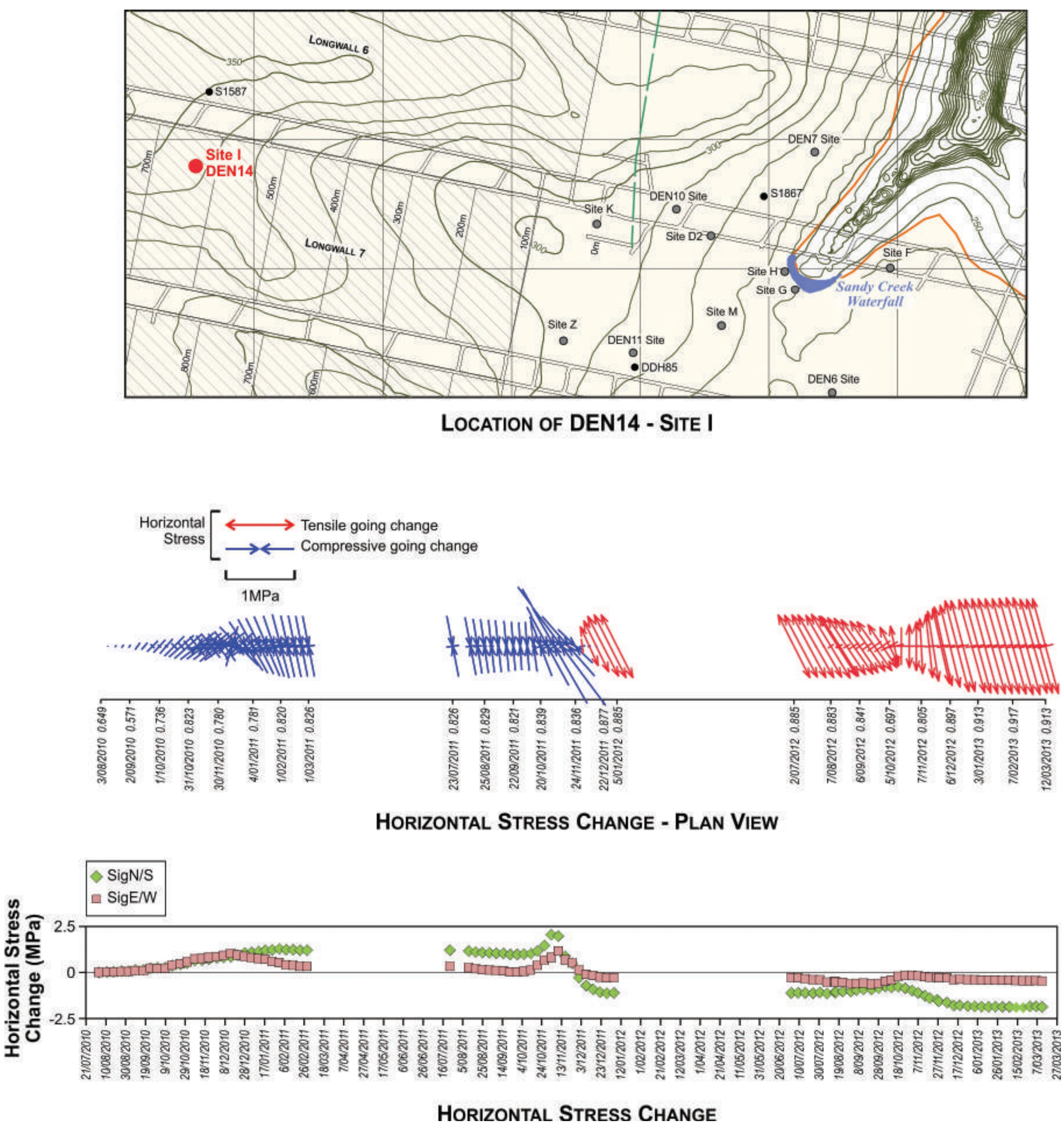

Figure 5 **Summary of stress changes observed at Site I**

Longwalls 7 and 8 approached the site, but there has been no further overall increase in the compressive stress component.

The stretching component of horizontal stress has continued to increase from soon after installation of the instrument. This component is thought likely to be associated with upsidence style movements caused by horizontal compression in the strata below the Hawkesbury Sandstone. This component appears more sensitive to the approach of the longwall panels and the various stoppages, albeit with some delay. The magnitude of this stretching component is much higher than the original in situ stresses measured at the site. The measured strains are likely to be much higher because of a reduction in in the elastic modulus of the rock observed at low confining pressures. This effect cannot be accommodated in the analysis of stresses and gives an exaggerated value of the tensile going stress.

3.4.3 DEN18 result

DEN18 was installed at Site H on the western side of Sandy Creek Waterfall at a depth of 12m, approximately 3m above the base of the Hawkesbury Sandstone and a horizontal distance of 5.5m from the back of the overhang. This instrument monitored the stress changes as Longwalls 6, 7 and 8 approached the site.

Figure 7 shows a summary of the horizontal stress changes observed at Site H during the approach of each of the three adjacent longwall panels. The horizontal stresses presented have been scaled to the stresses that would be expected in rock with an elastic modulus of 10GPa, based on the in situ elastic modulus measured during the pressure test.

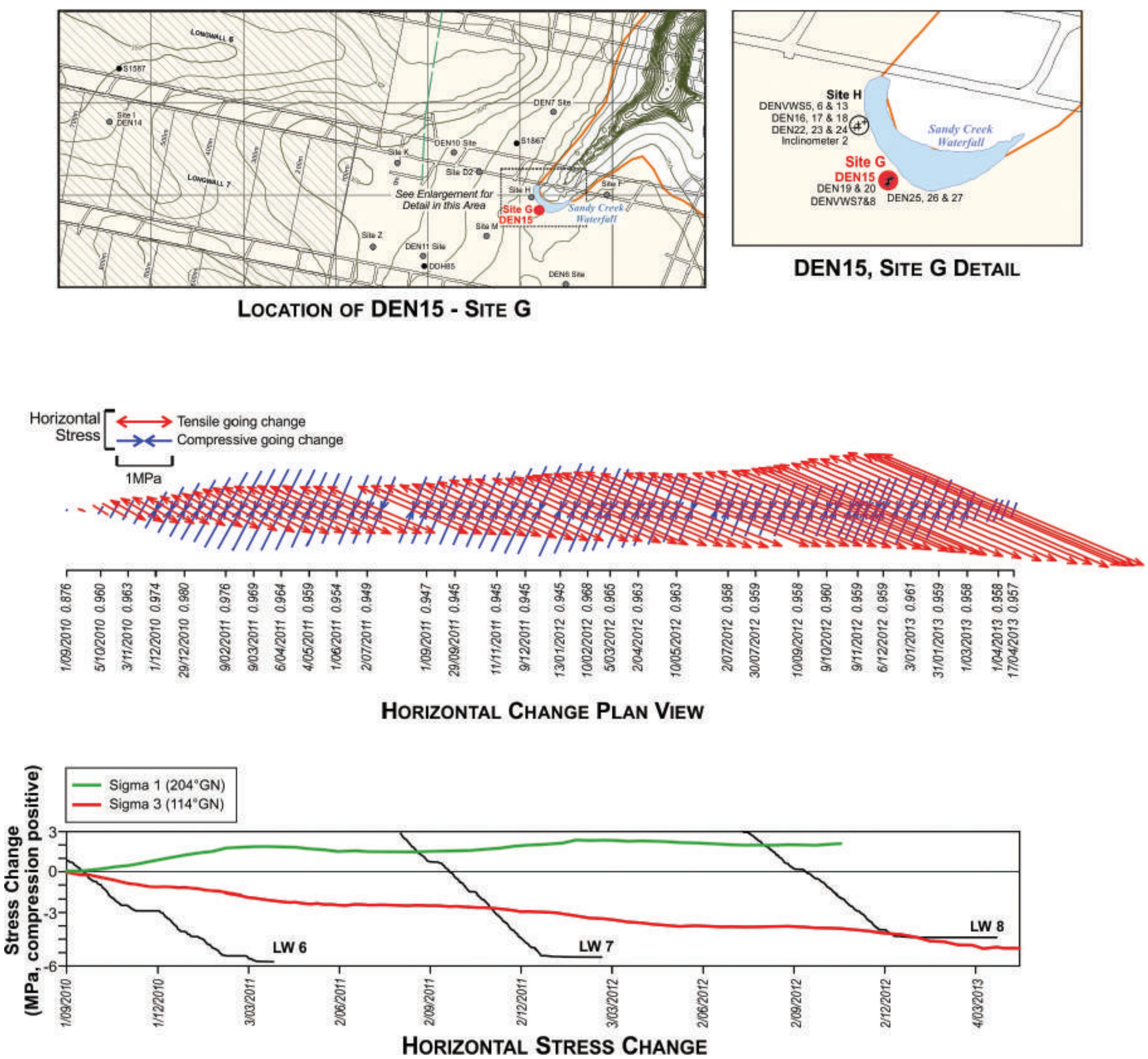

Figure 6 Summary of stress changes observed at Site G

The stress changes are characterised by horizontal compression of approximately equal magnitude parallel and perpendicular to the free face of the waterfall. Most of the stress increase occurred during the approach of Longwall 6, when the indicated increase in stress of 1.5MPa is approximately equal to the magnitude of the original in situ stress. Since then the stress changes have been less than about 0.5MPa and appear to have a component of seasonal variation consistent with thermal changes. The repeat overcore measurements at this site at the end of Longwall 6 were unsuccessful due to a drilling issue, so these changes have not been directly confirmed.

3.4.4 Site N – control site

A control site remote from mining was established in a smaller valley at Ryan's Crossing, near Cordeaux Dam. DEN30 was installed at a depth below surface of 9.5m. Strain changes were observed at this site over a period of 18 months and showed a hint of seasonal variation in the strains but horizontal stress changes were less than 0.1MPa and 0.2MPa for the two components.

3.5 Vibrating wire stress change monitoring

During the precautionary stoppages of Longwall 6, a number of vibrating wire stress change monitoring instruments were installed at Sites G and H at the same depths as the ANZI cells as independent confirmation of the ANZI stress change monitoring. These instruments comprise a steel tube that is wedged in the hole across one diameter of the borehole. The tension on a wire stretched across the internal diameter of the tube

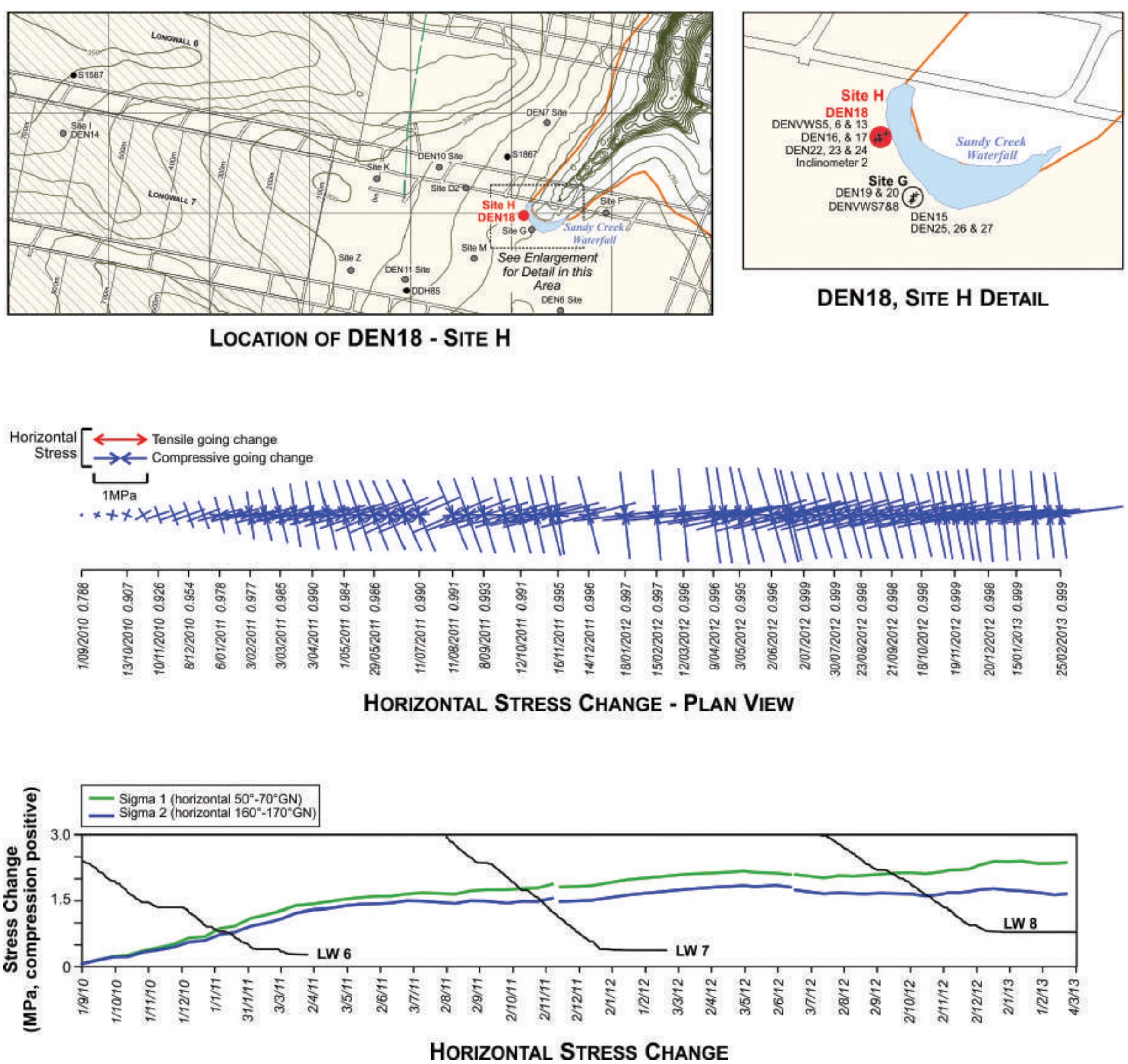

Figure 7 **Summary of stress changes observed at Site H**

changes as the tube is compressed by stress changes in the rock in the direction the instrument is aligned. The tension in the wire is measured by the frequency it resonates at when plucked. These instruments also measure the rock temperature.

It was found to be difficult to develop a convincing theoretical calibration of stress magnitude in low modulus Hawkesbury Sandstone rock material with uncertain elastic modulus. The magnitude was determined by correlation with the ANZI measurements nearby. Figure 8 shows the stress changes indicated by the vibrating wire instruments. There is clearly a significant component of thermal variation associated with seasonal change that is expected in the rock strata at these shallow depths.

3.6 High resolution closure movements

During the lead up to the first precautionary stoppages in Longwall 6, it became clear that the conventional three dimensional survey lines previously installed and surveyed at the site were not going to be sensitive enough to detect the very low level deformations that the stress cells were indicating. In response to this realisation, a network of eight high resolution one dimensional survey monitoring points was established across Sandy Creek Waterfall and the incised valley immediately downstream. Figure 9 shows the location of these lines and the movements that have been observed.

The stated precision of the new high resolution closure lines was ±1.0mm at two standard deviations (95% confidence interval). In practice the observed survey data proved to be substantially more precise, with results indicating long term precisions in the order of ±0.4mm at two standard deviations. These survey precisions were achieved by reverting to one dimensional closure lines and only measuring distance. The new survey network was established using Leica's TDA5005 industrial measurement total station, set up so that it was collinear with the measurement points being observed. This approach essentially eliminated angular inaccuracy as an error source.

Figure 9 shows that there was a gradual change evident during the approach of Longwall 6, especially on H Line, the longest of these lines. The change is less than the nominal resolution of the surveying, and was therefore not considered grounds to cease mining, but it is nevertheless consistent with the stress increases measured by DEN15 and DEN18.

A significant increase in closure began on 25 January 2011 when Longwall 6 was at CH215m, some 550m from Sandy Creek Waterfall. Similar

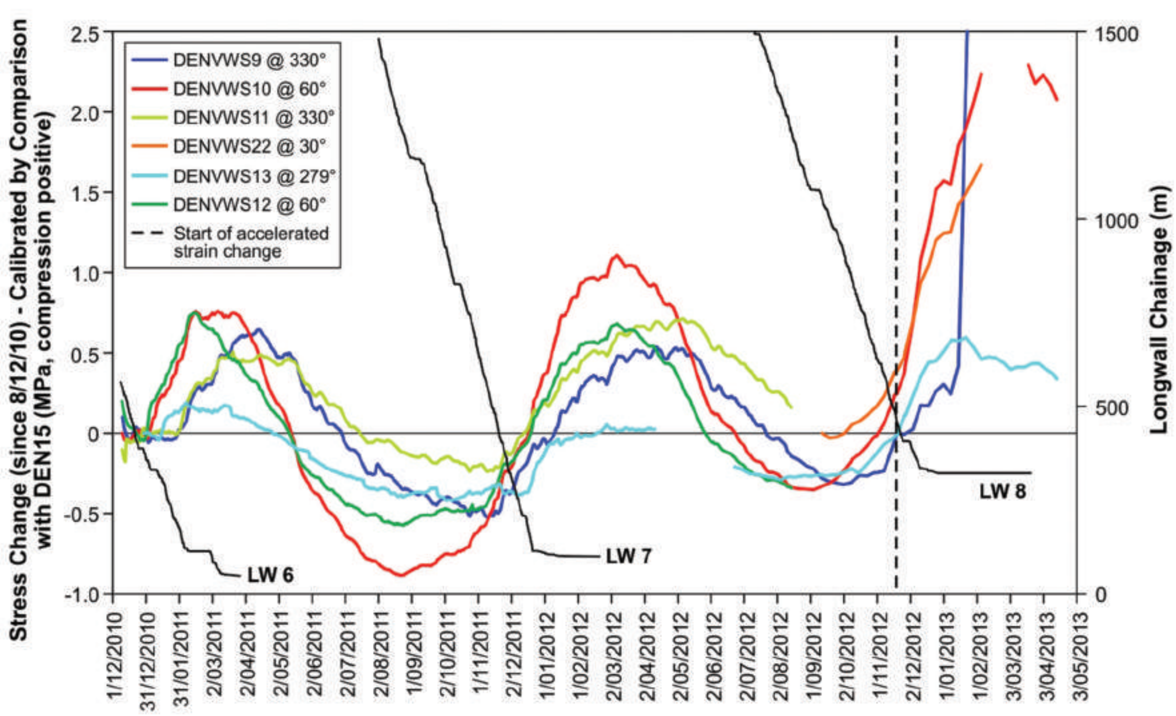

Figure 8 Summary of stress changes observed on vibrating wire stresscells

increases in closure were observed for Longwall increases in closure were observed for Longwall 7 on 12 December 2011 at CH220m and for Longwall 8 on 16 November 2012 at CH507m (equivalent to CH280m on the previous panels). In each case, these increased closures led to a decision to being preparations to finish the longwall panels at the first available opportunity.

Some seasonal variation is evident in the high resolution surveying results, particularly during the finishing stages of Longwall 8. Practical issues relating to vegetation regrowth interfering with the line of sight and weather conditions appear to have influenced the accuracy of the measurements from time to time, but it is more difficult to explain the gradual increase in length of about 2mm on H Line over a period of eight months. A period of rainfall deficit occurred during this period. The observed opening of the valley may be related to this rainfall deficit either on a broad scale or at some local scale that affected the survey points.

The high resolution surveying provided the primary basis for decision making because it clearly showed the onset of accelerated closure of the valley when the longwall face was approximately 560m away from the waterfall for Longwalls 6 and 7 and 660m away for Longwall 8.

3.7 Shear monitoring results

Inclinometers were installed at several locations adjacent to Sandy Creek Waterfall and provided the basis for a significant step forward in understanding the mechanics of mining-induced valley closure processes as well, as the natural erosion processes that form valleys in Hawkesbury Sandstone.

After the completion of Longwall 6, conventional inclinometers were installed at three sites (H, K, and M), extending approximately 20m into the Bulgo Sandstone. These instruments were read weekly. A 50m long shaped accelerometer array (SAA) inclinometer was also installed at Site K and recorded shear movements at one minute intervals.

At the completion of Longwall 7, three more conventional inclinometers were installed, one as a replacement, a second that did not work, and the SAA inclinometer was moved to Site D2 closer to the waterfall. Figure 10 shows an example of an inclinometer measurement from Site M that shows the development of two shear planes at horizons just below the floor of Sandy Creek above and below the waterfall.

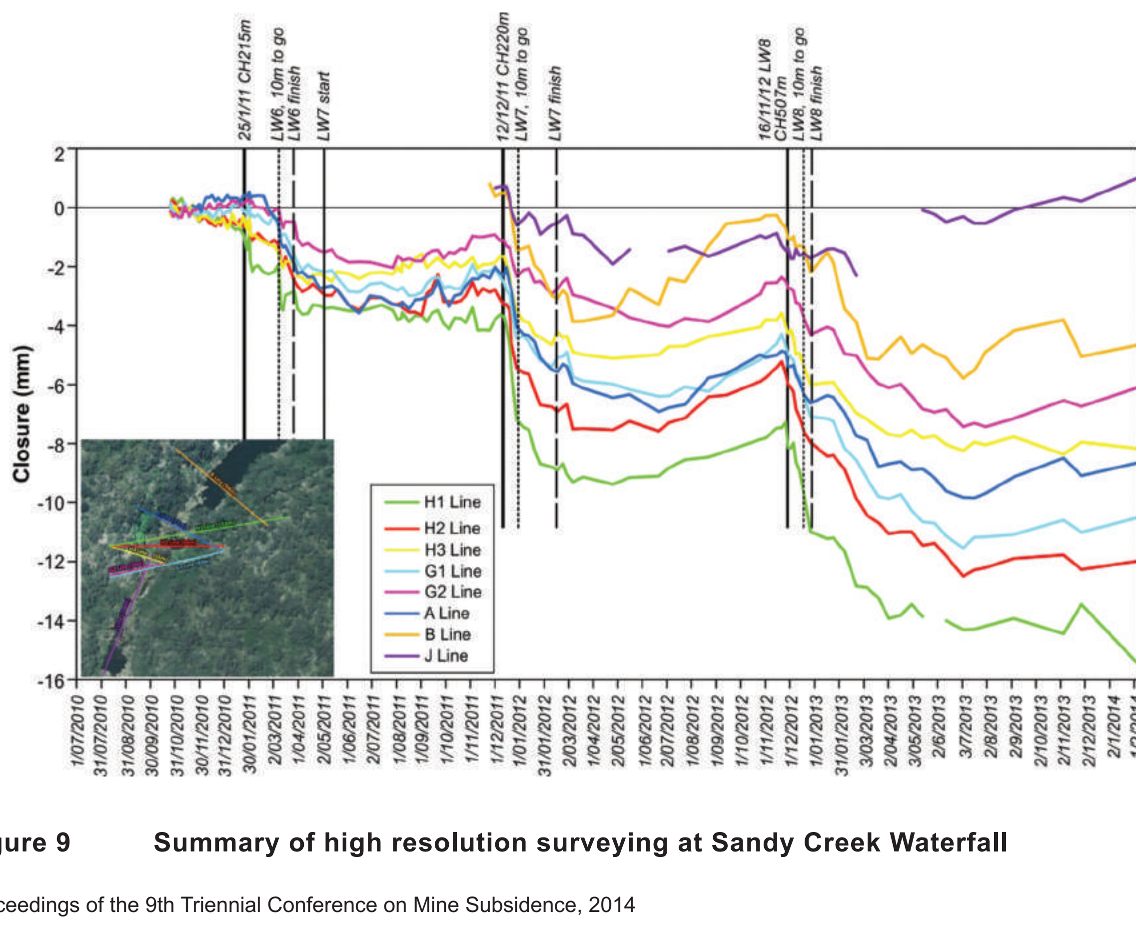

Figure 9 Summary of high resolution surveying at Sandy Creek Waterfall

Figure 11 shows two cross-sections through the site and the location of the shear horizons that were observed. Two major shear horizons were detected. The first was located at an elevation ranging from RL311m at Site Z through to RL317m at Site K. This horizon correlates approximately with the elevation of the Newport/Garie formation at the base of the Hawkesbury Sandstone, approximately 6m below Sandy Creek upstream of the waterfall. The second is located some 20-30m deeper at an elevation between RL280m and RL290m in the upper part of the Bulgo Sandstone and seems to be split into two horizons at some of the inclinometer sites. This horizon correlates with a horizon estimated to be about 5-10m below the base of Sandy Creek downstream of the waterfall. The exact depth of the base of Sandy Creek downstream of the waterfall is difficult to determine precisely because of the boulder debris present in this area.

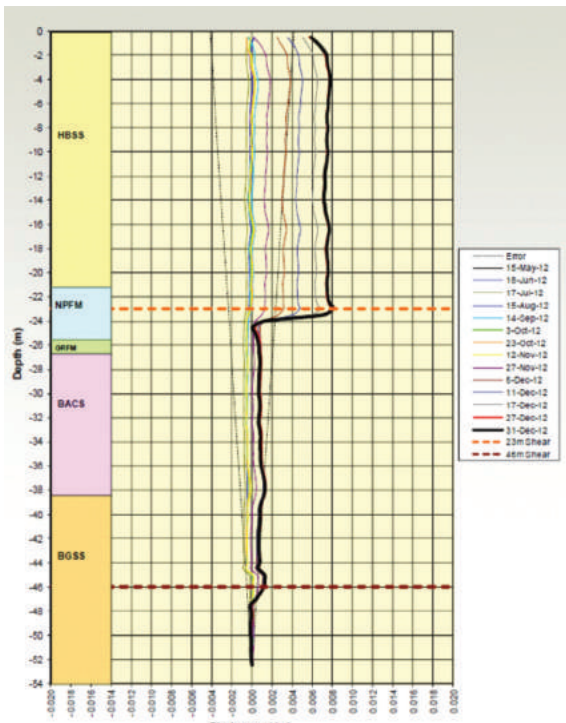

Figure 10 **Example of inclinometer monitoring showing the development of two distinct shear planes**

The two major shear horizons that have moved as a result of mining correspond to an elevation just below the floor of the adjacent valley. The direction of movement on all the inclinometers is in a downslope direction toward the valley.

The approximately 30m high step in topography at Sandy Creek Waterfall, allowing for the downstream boulder infill, correlates with the vertical separation between these two major shear horizons. This correlation is considered very significant in the context of the mechanics of the processes that cause valley closure movements, especially when the nature of the shear movements is also taken into account.

Figure 12 shows the SAA monitoring results at Site D2 during the approach of Longwall 8. The onset of shear movements and the gradual increase over time are apparent.

The SAA shear monitoring provides insight into the nature of the initial shear movements because

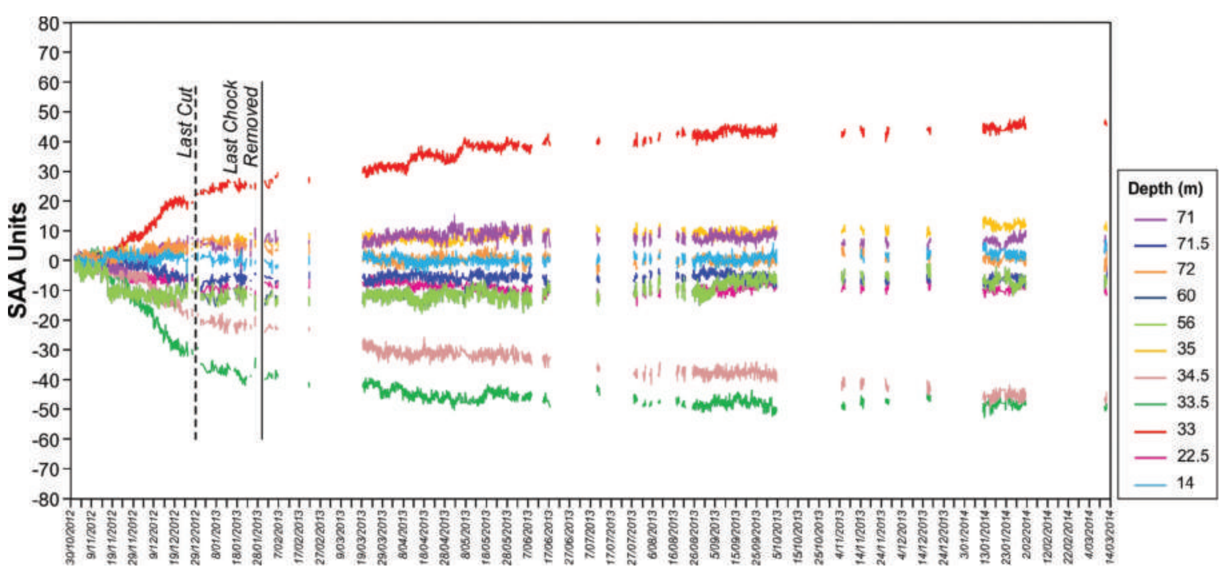

Figure 12: SAA results for Site D2 during the approach of Longwall 8

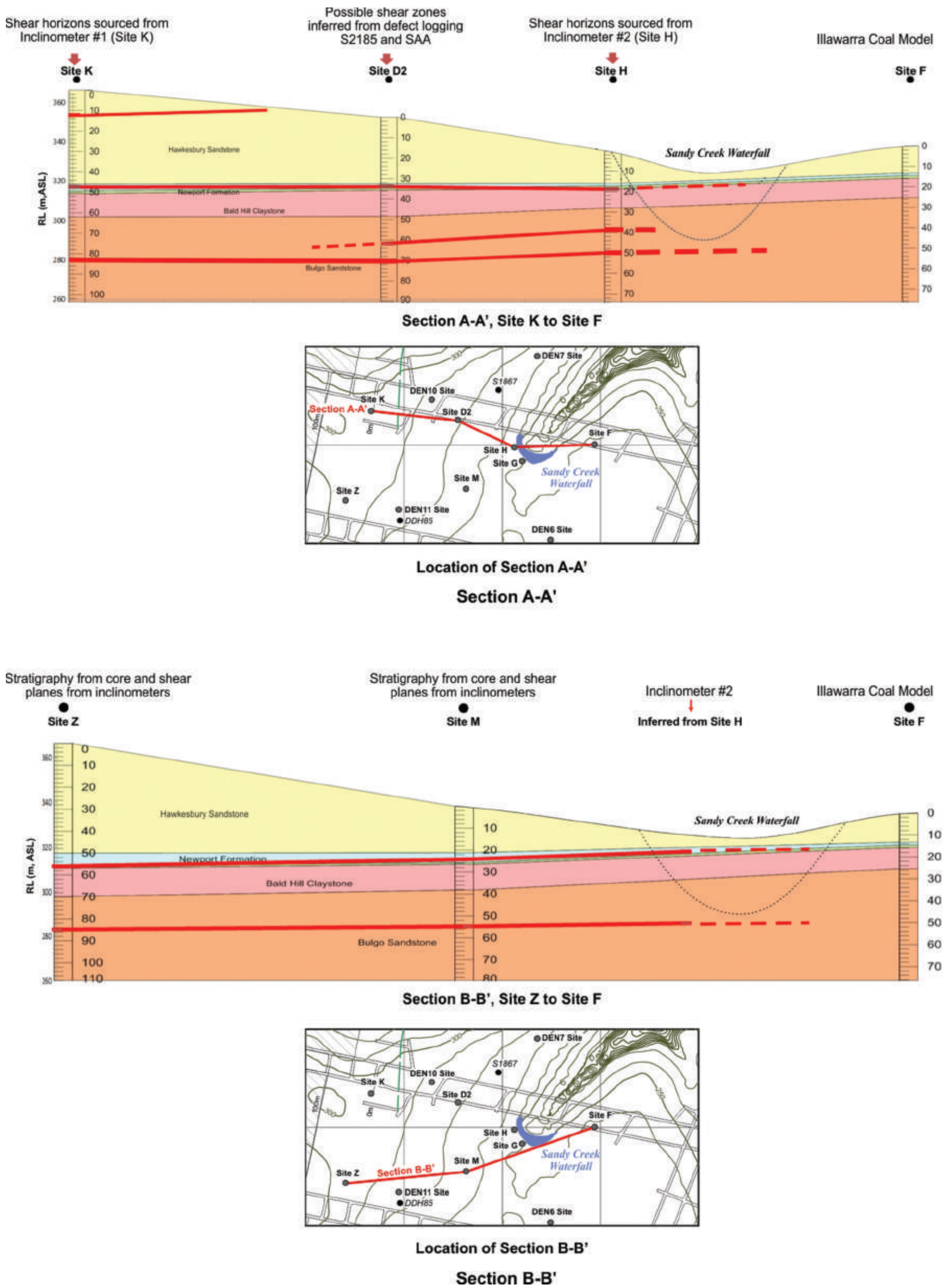

Figure 11 Cross-sections showing the development of two basal shear planes corresponding to the base of Sandy Creek upstream and downstream of the waterfall

of the one minute frequency of monitoring. Figure 13 shows the changes that were observed at Site K during the approach of Longwall 7 and at Site D2 during the approach of Longwall 8. Unfortunately the exact moment of initial movement was not captured at Site K due to a power outage at the critical moment, but it is clear from the data that there was no change at any horizon prior to 2 December 2011; however by 8 December 2011 there was a gradual change occurring at both the main shear horizons.

During the approach of Longwall 8, the exact moment of recommencement of shear was detected at Site D2 on both main shear horizons and a third horizon at 9:56pm on 16 November 2012 as a small step jump when Longwall 8 was 670m from Sandy Creek Waterfall. From then until about 3 December 2012, when Longwall 8 was 580m from Sandy Creek Waterfall, there was slight gradual increase apparent but thereafter the rate of change increased with additional mining until the last longwall cut was made on 29 December 2012. The rate of shear then continued at a significantly reduced rate, which has reduced further with time but shows occasional step jumps after periods of heavy rain.

The small step to start, the distinct shear horizons, and the gradual increase in shear movements with mining are all characteristics of a system that is in a state of limiting equilibrium (just on the edge of moving but not quite) and able to yield without significant release of energy as it moves. These characteristics are not consistent with failure of intact rock and the accompanying sudden releases of energy that occur during earthquakes, for instance.

Further evidence of this limiting equilibrium is that the micro-seismic monitoring, which is not discussed in detail here, did not detect any significant shallow micro-seismic energy releases during the approach of Longwalls 7 or 8.

3.8 Thermal profile

The thermal profile with depths was measured at Sandy Creek Waterfall across the site and the results are helpful in the context of understanding the thermal changes in the rock strata that occur naturally on a seasonal and diurnal basis.

Figure 14 shows the range of temperatures observed on the various instruments as a function of depth. The surface temperatures on the rock surface of the waterfall range seasonally from 0°C through to about 50°C and daily over a 30°C range. This range diminishes with depth below the surface, so that at 3m below the surface, the temperature ranges seasonally from 11°C in August/September through to 19°C in February/March: diurnal variations are not apparent. At 10m below surface, the seasonal variations are less than 1°C and lag about three months behind the seasonal variations at 3m below surface. Below about 15m, the seasonal temperature variation disappears and the temperatures settles back to a geothermal gradient that increases at a rate of about 25°C/km depth.

The coefficient of thermal expansion is of the order of 11x10-6m/m/K (Engineering Toolbox 2014) for Hawkesbury Sandstone, so the stress changes caused by thermal expansion in rock with an elastic modulus of 10GPa are of the order of 0.1MPa/°C. At the surface, where the annual thermal variation is 50°C, the thermal stresses generated naturally are of the order of 5MPa; at 3m these stresses are of the order of 0.8MPa; and by 10m below surface they become insignificant.

3.9 Rainfall and pore pressure monitoring

Rainfall monitoring indicates approximately average rainfall from July 2009 through to July 2012 followed by a period of rainfall deficit through to two intense rainfall events in February/March 2013.

Piezometer monitoring in the Hawkesbury Sandstone in borehole DDH85 indicates that a dry period throughout 2012 reduced the groundwater level in the general area of Sandy Creek Waterfall by about 4m up to the end of January 2013. Sandy Creek was observed to cease flowing from November 2012 for the first time during the monitoring of Sandy Creek Waterfall. The creek has continued to flow since the February/March 2013 rainfall events.

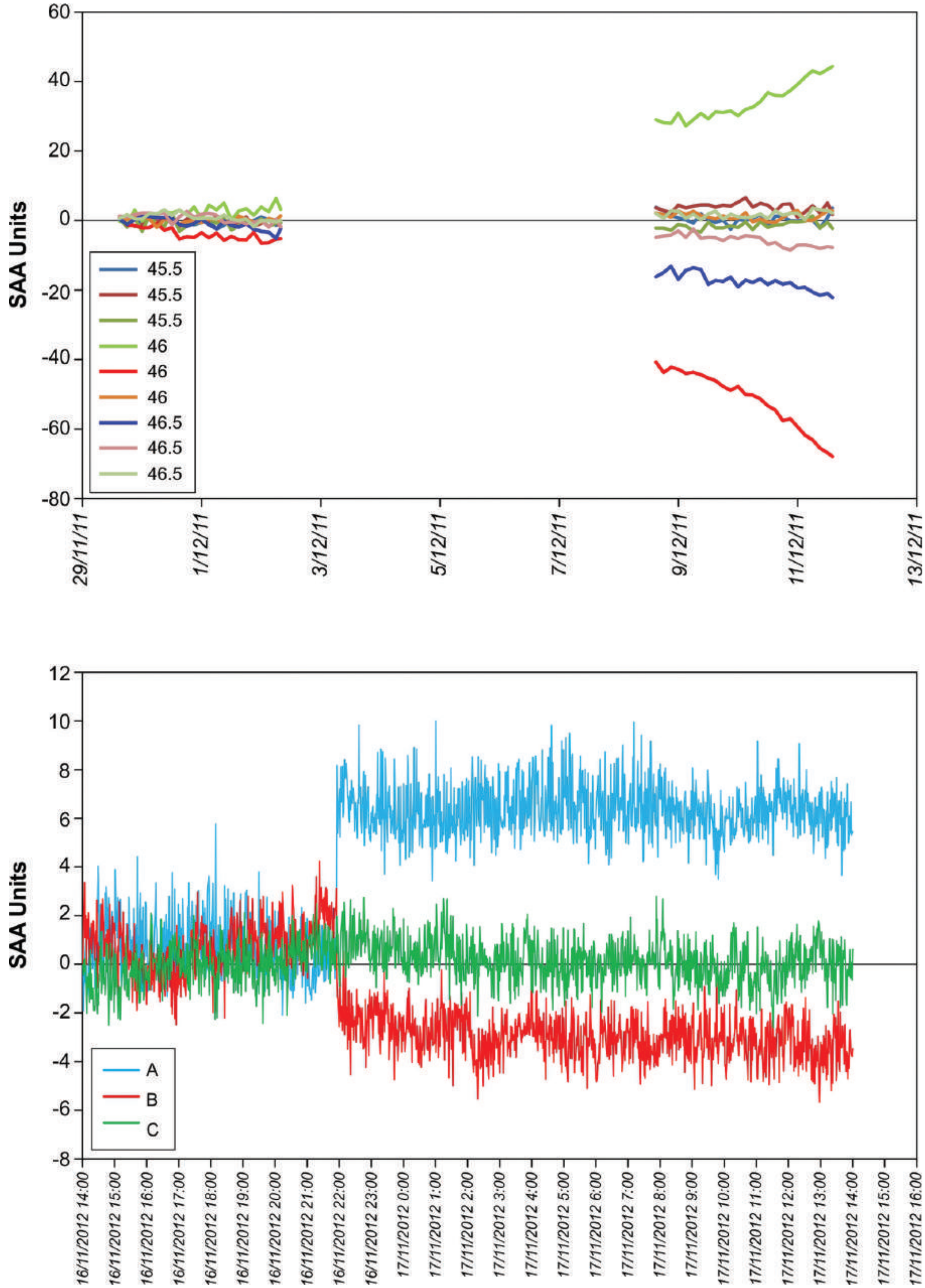

Figure 13 **SAA results showing the onset of mining induced shear movements during mining of Longwalls 7 and 8**

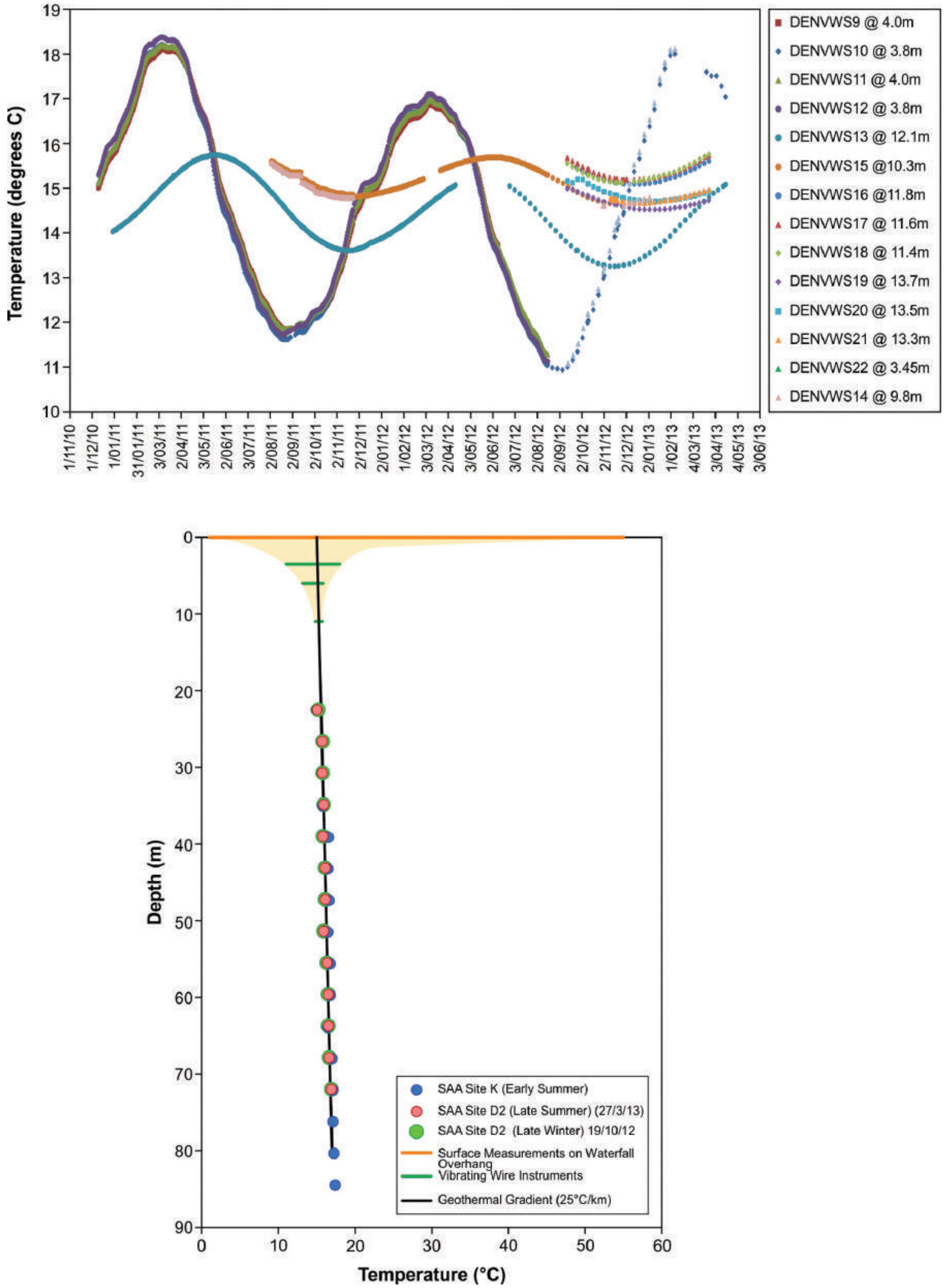

Figure 14 **Temperatures observed at Sandy Creek Waterfall over time and as a function of depth below surface.**

4. Interpretation of results and conclusions

The measurements indicate that at the Sandy Creek Waterfall site the strata that form the valley sides are naturally in a state of limiting equilibrium on near horizontal shear horizons that extend laterally below the adjacent slopes at an elevation 5-10m below the valley floor and are substantially independent of stratigraphy.

In situ stresses in the base of the valley are of low magnitude compared to the intact rock strength of the Hawkesbury Sandstone and, apart from a small increase prior to initial movement during the approach of Longwall 6, the stresses do not change significantly with further closure, indicating a condition of limiting equilibrium (yield) within the rock mass at the base of the valley.

Mining subsidence below the slopes leading down to a valley generates a horizontal force/displacement in a downslope direction, which disturbs the natural limiting equilibrium and causes lateral movement toward the valley. The forces that generate this horizontal displacement are clearly displacement-driven rather than stress-driven, as evidenced by their gradual increase with mining once movement has commenced. These forces are considered to be a result of dilation within the subsiding strata, as described in Mills (2001) and Mills (2007).

Monitoring of the horizontal closure and lateral shear indicates that high intensity rainfall events and associated elevations in pore pressure generate sufficient force to allow incremental movement on basal shear planes unrelated to mining. The equilibrium that exists between the forces pushing the western side slope of Sandy Creek toward the valley and the balancing forces pushing back is, by implication, finely balanced.

Destabilising forces include mining and natural processes, such as rainfall. Stabilising forces include resistance to shear along the basal shear plane, the residual strength of rock strata in the base of Sandy Creek, and thermal forces which come and go with the seasons. It is clear from the observations at Sandy Creek that these movements occur naturally and the state of limiting equilibrium observed at Sandy Creek Waterfall is, therefore, also part of the natural erosion processes that create valleys. The horizontal shear planes evident in the rock tiers common on valley sides in Hawkesbury Sandstone terrain are considered likely to be remnant of the processes of valley down-cutting through this mechanism.

The potential for perceptible impacts at the waterfall continues to hinge on whether the ongoing movements remain low enough to be accommodated by the rock structure of the waterfall. Elevated pore pressures are likely to change the equilibrium between shear resistance along basal shear planes and load on the rock structure of the waterfall. Thermal stresses are expected to provide low level cycling of the load across the rock structure of the waterfall. High intensity rainfall events may also cause further closure movements. Eventually, these effects will cause perceptible impacts at the waterfall in the way that has been occurring naturally over geological time.

The key to managing the mining-induced impacts on Sandy Creek Waterfall has been keeping the mining-induced movements at a level that is barely perceptible above the background of natural processes.

High resolution surveying, inclinometer monitoring, and stress measurements have provided insight into the mechanics of the processes that have caused natural and mining-induced valley closure. These observations provide strong evidence that basal shear horizons on which valley closure movements occur are controlled by the elevation of the valley floor. The mechanics of ground movement considered to be operating at Sandy Creek involve lateral dilation of subsiding strata above the longwall panels, causing mobilisation on naturally developed horizontal shear planes. These shear planes allow mass movement toward the valley floor primarily on bedding planes that exist 5-10m below the base of the valley. At Sandy Creek there are two main shear horizons that have been mobilised, consistent with the 20-30m step change in elevation of the creek channel upstream and downstream of the waterfall.

Seasonal variations in temperature have been observed at the surface and below the ground surface, decreasing in magnitude with depth to be effectively stable at a depth below the surface of 10-15m.

The mechanics of the processes that are causing overall closure at Sandy Creek are being driven by movements on shear planes that are 10-70m below the surface, where there is very little variation in temperature. However, the signature of seasonal thermal variation is evident in the stress change monitoring and the high resolution surveying at magnitudes consistent with thermal expansion and contraction of exposed sandstone strata in the floor of the valley. The thermal variations are therefore considered to be separate to the processes causing overall valley closure, but nevertheless capable of providing a seasonal loading onto the waterfall rock structure.

5. References

Engineering Toolbox 2014 http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html

Mills KW 1997 'In situ stress measurements using the ANZI stress cell in Proceedings of the International Symposium on Rock Stress Sugawara K and Obara Y (eds), Kumamoto, Japan 7-10 October 1997, pp149-154

Mills KW 2001 'Observations of horizontal subsidence movement at Baal Bone Colliery' in Proceedings of 5th Triennial Conference of the Mine Subsidence Technological Society, 26-28 August 2001, Maitland, pp 99-111

Mills KW 2007 'Subsidence Impacts on River Channels and Opportunities for Control' in Proceedings of the 7th Triennial Conference of the Mine Subsidence Technological Society, 26-27 November 2007, University of Wollongong, pp 207-217

Walsh RV, Hebblewhite BK, Li G, Mills KW, Nicholson MA, Barbato J and Brannon PJ 2014 'Successful Management Strategy for Mining Adjacent to a Sensitive Natural Feature' in Proceedings of the 9th Triennial Conference of the Mine Subsidence Technological Society, 11-13 May 2014, Pokolbin, pp43-50