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THE USE OF SONIC VELOCITY LOGS TO DEFINE POTENTIAL GOAF DELAMINATION HORIZONS

Barry Ward[1]

INTRODUCTION

This paper presents the findings of part of ACARP Project C9003 (Green & Ward, 2002) which examined the possibility of deriving quantitative guidelines for the use of sonic velocity logs in the identification of potential goaf delamination planes, with a view to improving predictive capability for the delineation of heavy roof conditions.

The downhole sonic velocity log is widely used for the interpretation of overburden strata into geomechanical units and for identifying thick or strong sandstone layers in the main overburden. It can also depict discrete weaker horizons that can act as goaf delamination planes within such layers as high transit time (low velocity) spikes. However, delineation of these planes becomes subjective if the contrast between the peak velocity and the background velocity diminishes.

In terms of predicting goafing behaviour the question then arises as to whether the potential for bed separation can be predicted on the basis of the sonic velocity contrast alone. There were no quantitative guidelines for using the sonic velocity log for this purpose.

The research carried out under C9003 was thus directed at establishing the value of the sonic log for the delineation of potential goaf delamination planes. The proposal was to systematically test sonic log responses for potential separation planes against monitored goafing behaviour from a number of mine sites, with the objective of deriving quantitative guidelines for the identification of goaf delamination planes from the sonic velocity log.

BACKGROUND

It is believed that the first systematic use of the sonic velocity log for the prediction of delamination planes was in the late 1980's, for defining roof conditions in the 600's block at Southern Colliery. A typical Southern Colliery 600's log is shown in Figure 1. The immediate roof was an homogeneous fairly massive strong sandstone up to 9m thick, with an average strength of around 80 MPa. However the sandstone invariably contained one or two persistent thin siltstone partings that acted as separation planes. The term 'active sandstone' was coined to refer to the sandstone component directly overlying the seam (Paterspn and Ward, 1994). The active sandstone was subsequently defined as 'the thickness of sandstone up to the first potential delamination plane as indicated by the sonic velocity log' (Paterson and Ward, 1994).

Extraction in the 600's block suffered intense but short-lived periodic weighting at around 12m frequency. Observation and monitoring during longwall extraction (Frith and Stuart, 1991; Everett, 1992) indicated that the severity and spacing of the periodic weighting was directly related to the thickness of the active sandstone.

The occurrence of the weak siltstone partings was not necessarily continuous or consistent, and the sonic response varied accordingly. Experience on site led to a minimum peak value of 85 µsec/ft being adopted as the cut-off value for delamination to occur. This is equivalent to a sonic velocity contrast of approximately 10 to 15 µsec/ft against the background level.

The validity of using the sonic velocity log systematically on a quantitative basis for predicting delamination planes was thus established at Southern Colliery with respect to strata forming the immediate roof to a height of some 10m to 12m above the seam.

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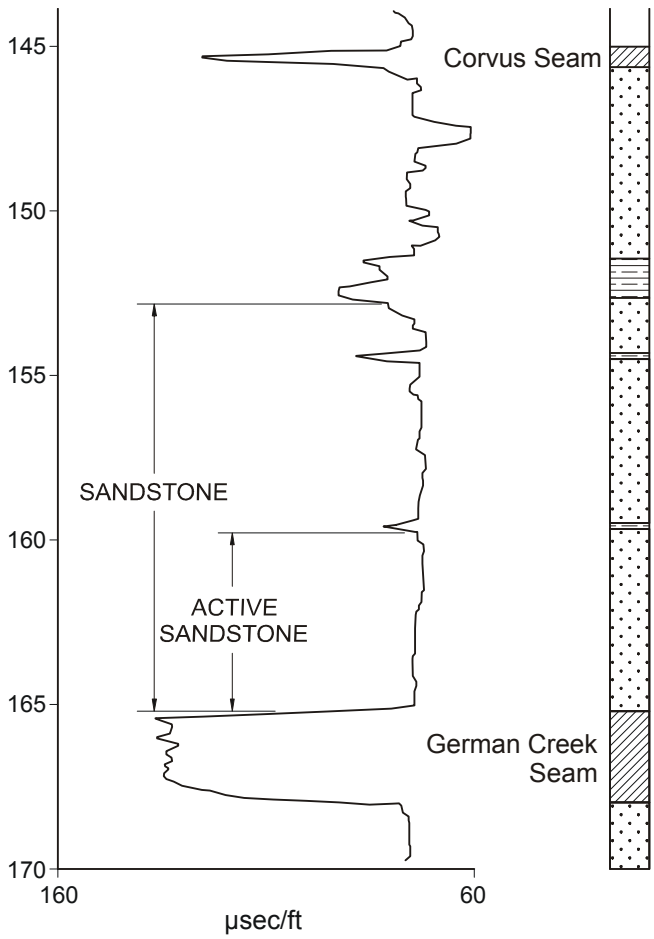

FIG. 1 - Southern Colliery Active Sandstone

Since then attention has been focussed on massive thick sandstone bodies in the upper overburden, triggered by weighting events at a number of mines, including Southern Colliery (700's), South Bulga and Crinum, and by the widespread identification of sandstone bodies in the Bowen Basin (Esterle et al., 2001).

The Corvus sandstone at Crinum is a massive sandstone up to 25m thick with an average strength of 35 MPa. It occurs as a channel facies within weaker laminated strata within the Corvus - Tieri seam interval at a height of 25m or more above the mining horizon, and was a focus of attention for a time as a major contributor to roof weighting.

Examination of the sonic velocity logs indicated that the Corvus sandstone invariably contained a number of weaker horizons, which could act as separation planes. The question then was whether the total sandstone thickness or an active sandstone component was applicable in defining areas of potential weighting, and if so, what value of velocity contrast could be used to define the potential goaf parting.

A more significant case for definition was the Aquila seam conditions at the Grasstree Project (Ward, 1998). This is illustrated in Figure 2. The overburden comprises 2.5m to 4.5m of relatively weak, thinly laminated siltstone and mudstone, overlain by approximately 20m of strong massive 80 MPa sandstone. The sandstone contains a weak carbonaceous siltstone or mudstone parting in the middle, which shows up as a weaker horizon on the sonic velocity log. The strength of this parting material appears to vary from 20 to 50 MPa across the minesite but in some places the parting grades into the surrounding rock and is no longer discernible.

There is no doubt that a 30 µsec/ft contrast will act as a delamination plane. In terms of predicting goaf behaviour however, the question is at what point (i.e. what velocity contrast) can the parting be discounted as a potential goaf delamination horizon. This could be somewhat significant in that where the parting is ineffective as a delamination plane, the solid 20m thickness of 80 MPa sandstone could render conventional longwall mining unmanageable.

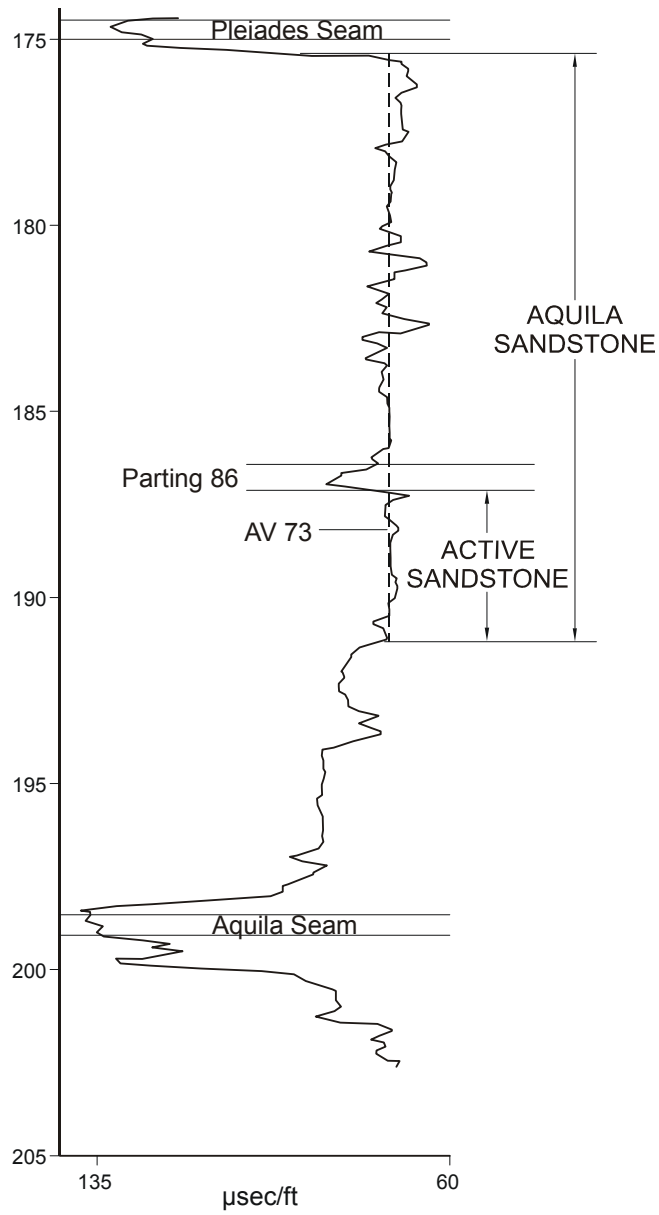

FIG. 2 - Grasstree Project Aquila Sandstone

RESEARCH PROJECT

The objective of the research project was to see if potential goaf delamination planes could be identified from sonic velocity logs according to the differential magnitude of the transit time. The proposal was to compare sonic velocity logs to actual goafing behaviour as monitored from surface extensometer installations and see if any relationship could be established.

Boreholes with both sonic velocity logs and surface extensometer installations were selected from a number of longwall mines for this purpose. It was intended to utilise only historical data in order to undertake an initial assessment of the proposition at minimum cost, rather than attempt a more rigorous and expensive field programme specifically for this purpose. It was recognised that this was less than optimum insomuch that the extensometer anchor locations would not necessarily be positioned at the most appropriate horizons to test the behaviour of specific sonic partings. However it was considered that sufficient information would be forthcoming to permit a judgement to be made on the validity of the proposition if the objectives were not met.

When the project was first proposed only 5 surface extensometer sites were known but since then more sites became available, giving a total of 12 installations from 5 different minesites, as listed in Table 1. South Bulga was on the original list but unfortunately sonic velocity logs were not run in the surface extensometer boreholes.

TABLE 1 List Of Test Sites

Site	Borehole	Panel	Depth to Roof	Mining Height	Comments
Southern Colliery	DD403	703	139.15	3.0	
	DD411	703	185.76	2.9	installation aborted
	DD412	703	190.73	2.9	installation vandalised
	DD413	704	121.90	3.0	
	RD3381	704	125.38	3.1	
	DD432	704	176.88	3.1	no suitable sonic log
	DD433	704	181.92	2.9	no suitable sonic log
	DD416	705	131.72	2.8	
Central Colliery	DD427	308	326.32	2.6	
Crinum Mine	5592	LW5	188.52	3.6	
	5593	LW5	159.92	3.6	
Moranbah North	RD255	101	146.80	4.5	
	RD256	101	119.40	4.5	
	DD92	102	147.35	4.5	
	DD93	102	162.02	4.5	
Dartbrook Mine	DD149	LW1	217.00	4.0	sonic extrapolated
	RD468	LW4	286.80	4.0	installation failure

PROPOSITION

As described above, it has been established at Southern Colliery that small transit time differentials of 10 to 15 µsec/ft were indicative of separation planes with respect to the immediate roof. This applied to the particular condition of first layer goafing, that is, where the lowest roof layer can become detached and cave into the mined void.

It is highly unlikely that a constant small differential would apply throughout the overburden, as the relative amount of strata separation and subsidence decreases with increasing height above the mined horizon. The expectation was that the further away from the source (height above mining horizon), the greater would be the response required to initiate the same effect. In other words, whereas a 10 µsec/ft contrast could generate strata separation at a height of, say, 10m, it would require a contrast of, say 15 µsec/ft to cause the same effect at a height of 20m.

The proposition was thus made that there would be a quantitative relationship between the magnitude of the transit time contrast required to initiate separation, and the height above the mined horizon. It was proposed to test this proposition by comparing transit time differentials against actual caving examples as monitored by surface extensometers.

If the proposition was correct the results should plot as two populations, with a grouping of separation and non separation values, from which a bounding curve could be defined. This would allow the propensity for strata separation at any given height to be defined by a single variable, namely the transit time contrast.

ANALYSIS OF DATA

Transit Time Contrast

Figure 3 shows an example of a sonic velocity log with extensometer anchor locations marked at the appropriate depths. For each log the sonic response over each anchor interval was examined and potential partings identified. A single parting where appropriate was selected for each interval under the following categories:

1. low strength parting or contrast
2. high strength parting or contrast
3. no partings present

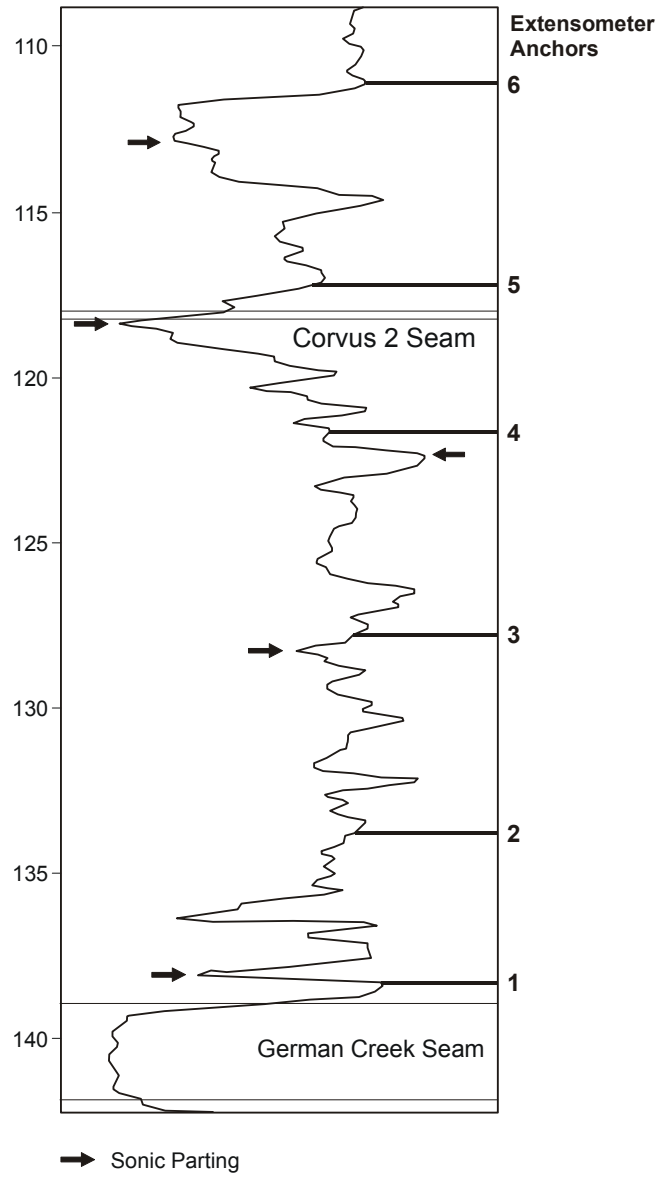

FIG. 3 - Sonic Velocity Log Example

Where several potential partings occurred within the interval, the parting with the largest contrast was selected. This was a simplification in that delamination could occur over several partings within the interval, however it was considered that the largest contrast would see the first reaction to any movement.

The velocity contrast and height above the mining horizon was noted for each selected parting. Low strength (high transit time) partings were the obvious choice but high strength contrasts were also noted since, theoretically at least, they could also act as separation planes under bending stresses.

The magnitude of the differential transit times identified ranged from 7 to 66 µsec/ft for the low strength partings, and from 15 to 28 µsec/ft for the high strength partings. Most of the high strength partings were probably due to sideritic bands; where these were selected a check was made against adjacent borehole logs to ensure they represented persistent layers and not individual lenses.

Extensometer Response

Having identified a transit time contrast for each anchor interval, the extensometer response was examined to ascertain if any delamination had taken place over the corresponding interval. Figure 4 shows an example of an extensometer record.

The extensometer records were complex and contained a lot of information, not all of which was real. It was not possible within the scope or budget to analyse the records in detail, hence a simple systematic geophysical first break approach was adopted. Because settlement invariably occurred in several stages with varying amounts of differential movement, the analysis was restricted to picking the first break, that is, the first measurable instance of differential movement between anchors.

Examples of first break picks indicating the onset of movement are shown in Figure 4. In this instance anchors 1 and 2 subsided sequentially with differential movement, whereas anchors 3 and 4 moved simultaneously with zero immediate differential movement. First break picks were categorised as either differential movement or no differential, and matched to the selected transit time response between the same anchors.

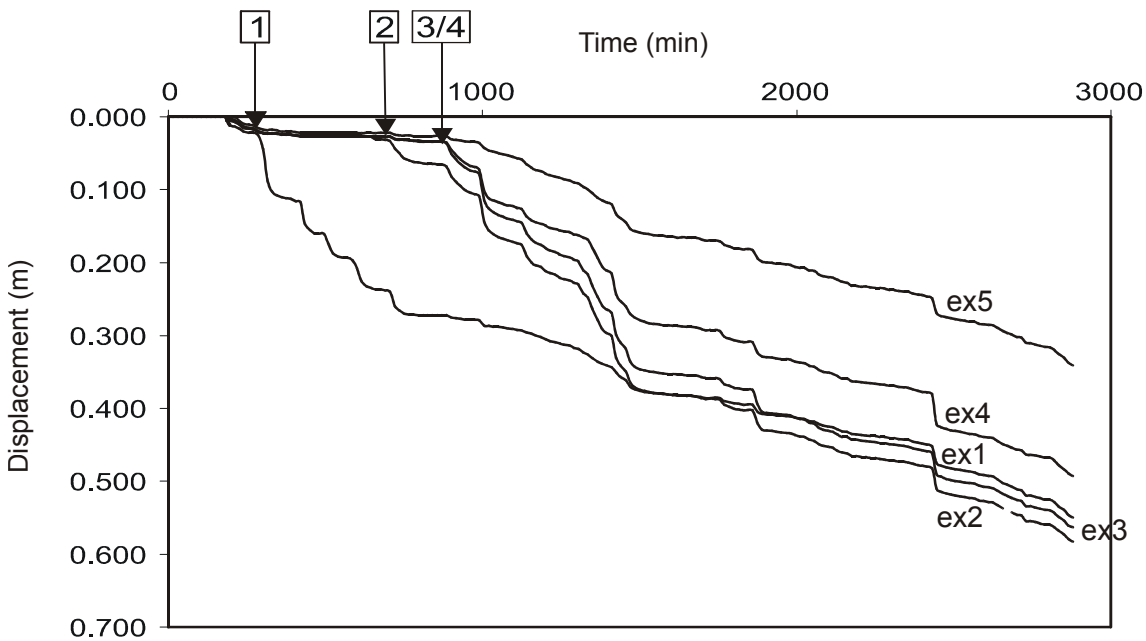

FIG. 4 - Surface Extensometer Example

Results

The matched data points for horizons to a height of 100m above the seam are plotted on Figure 5. The data is presented as weak and strong partings that correspond to differential movement (strata separation) and weak partings that showed no differential movement (no separation). Strong partings with no differential movement are not shown.

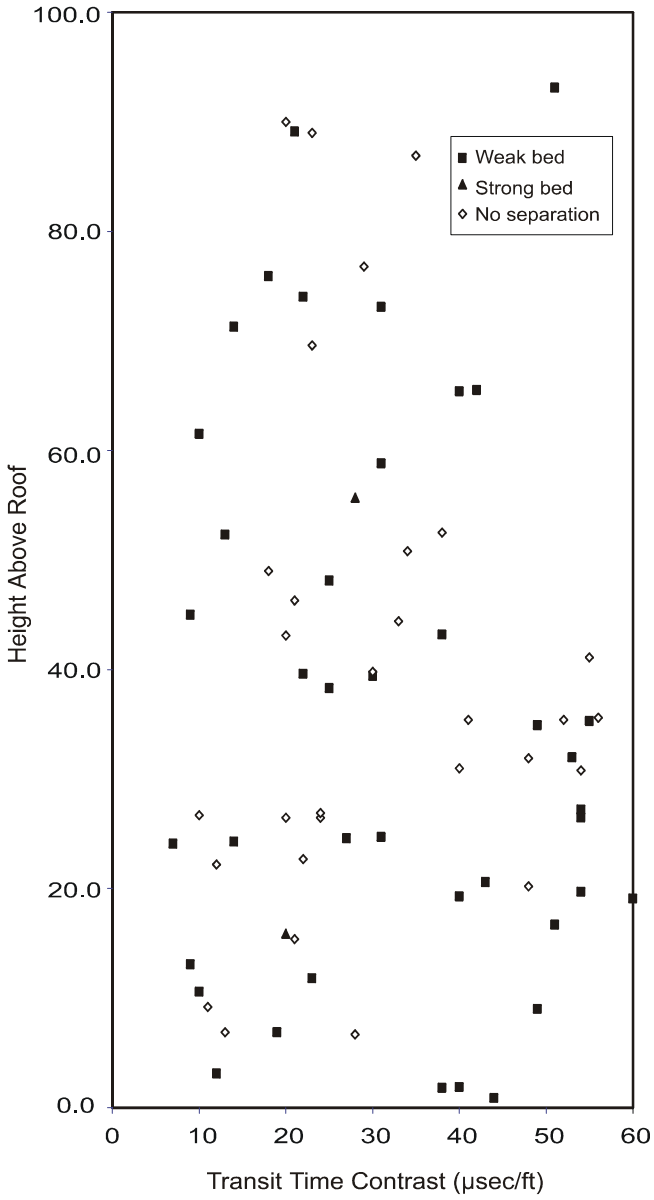

FIG. 5 - Results of Analysis

It is clear from the distribution of data points that there is no discernible differentiation into two populations of strata separation and no separation, the results for both types being scattered throughout. It is also clear that there is no discernible relationship between transit time contrast, height above mining, and propensity for strata separation. The conceptual picture of two separate populations has not been generated, and the results thus refute the proposition. This means that the sonic velocity alone is not a reliable indicator of goaf delamination planes within the general overburden sequence.

This conclusion is of course based on the data set used in the analysis. Of the 12 sites analysed 5 were start-up installations designed to monitor the first goafing event rather than normal periodic caving (4 at Southern Colliery, 1 at Moranbah North). First goafing covers the transitional caving stage from initial spanning to full caving and is generally different to normal caving where fracturing and subsidence occurs in a cyclic pattern (Gale, 2001). However, exclusion of first goafing data does not improve the validity of interpretation.

One of the main sources of potential error is that the extensometers cannot differentiate lateral movement of strata, as all movement is recorded as vertical displacement, which in the extreme case can lead to some kinematically strange results. The bottom two anchors at Southern Colliery 703 panel, for example, show total displacements greater than the height of mining, and also show intermediate periods of no movement that clearly cannot reflect the fall of strata into the goaf.

Although such idiosyncracies can significantly complicate a full quantitative analysis of strata movement, their potential impact in this study was mitigated by using the first break only as an indicator of movement and ignoring all subsequent variation. Nevertheless there was no way of knowing if some of the small differential anchor movements in the data set could be due to shearing rather than separation. However, the data set had only five separations where the differential movement was less than 25mm, and the exclusion of these made no difference to the distribution of data points.

DISCUSSION OF RESULTS

The results clearly indicate that goafing behaviour in general is governed by other factors than the presence of weak horizons, bedding planes or modulus contrast between layers. It is suspected that a combination of factors is involved, including bed thickness, strength homogeneity, and the juxtaposition of beds of contrasting character. In other words, more than one variable needs to be considered in the prediction of goafing behaviour.

This does not mean that the sonic velocity log cannot be used to identify potential separation planes, but that it cannot be used to predict which potential separation planes will influence goafing, at least away from the immediate roof.

Subsidence of strata over a longwall panel has traditionally been grouped into three zones. The zone immediately overlying the seam collapses as broken rock into the mining void and eventually fills up the free space through bulking. The height of this initial caving zone is generally taken as 9 times the mined thickness but can be less in stronger strata. In the middle zone the strata are not broken up but tend to incur physical dislocation with induced fractures or bed separation. The height of this intermediate zone is usually taken as 30 times the mined height as a general approximation. In the upper zone above this the strata tend to subside as an intact block without damage.

The goafing behaviour is obviously different in each of these zones and hence it is not unreasonable to expect that different predictive parameters would apply in each case.

In the intermediate zone, from say 20m to 100m above the seam, the presence of thin sonic partings or bedding planes within a rock layer of constant strength does not appear to influence goafing and the propensity to hang up or span is more likely to be governed by the thickness and tensile strength of specific beds. In respect of the Corvus sandstone example at Crinum Mine it would appear that a sandstone body 25m or more above the mining horizon cannot be reliably sub-divided into an active sandstone component on the basis of weaker partings identified from the sonic velocity log.

Only caving within the immediate roof layer would appear to present any opportunity for analysis within the context of this study; the application of the sonic velocity log for delineating the active sandstone component in the immediate roof zone having been established previously at Southern Colliery by observation and monitoring.

Accordingly, the values in the data set pertaining to the immediate roof zone only were plotted. The result is shown in Figure 6, which displays values for picked horizons to a maximum height of 23m. Although there is still some scatter, there is now a discernible separation of the two populations as per the original concept, and a line can be drawn between the two populations, albeit tentatively, from 5 µsec/ft at zero height to 40 µsec/ft at 20m. Interestingly, this line passes through a value of 15 µsec/ft at a height of 6m, which matches the value derived from operational experience at Southern Colliery.

The cut-off height of 23m marks the position where the data show a significant scatter. This height could be taken as representing the average height of the initial caving zone for the data set used, which would be equivalent to 7 times the average mining height of 3.3m.

It is proposed that the line shown on Figure 6 could be used as an interpretation guide for estimating active sandstone, at least for a first approximation. The equation of this line is approximately:

$$\text{critical transit time contrast } (\mu\text{sec/ft}) = 1.75 \times (\text{height above roof} + 2.85)$$

The critical transit time contrast represents the minimum value for a weak parting on the sonic log, relative to the background strength of the stratum containing the parting, for which strata separation could be expected. The relationship is only valid for the immediate roof zone to a height of about 20m. Obviously experience and

intuition must be exercised in the interpretation of roof behaviour, as local geological and geotechnical conditions could cause variations in ground reaction.

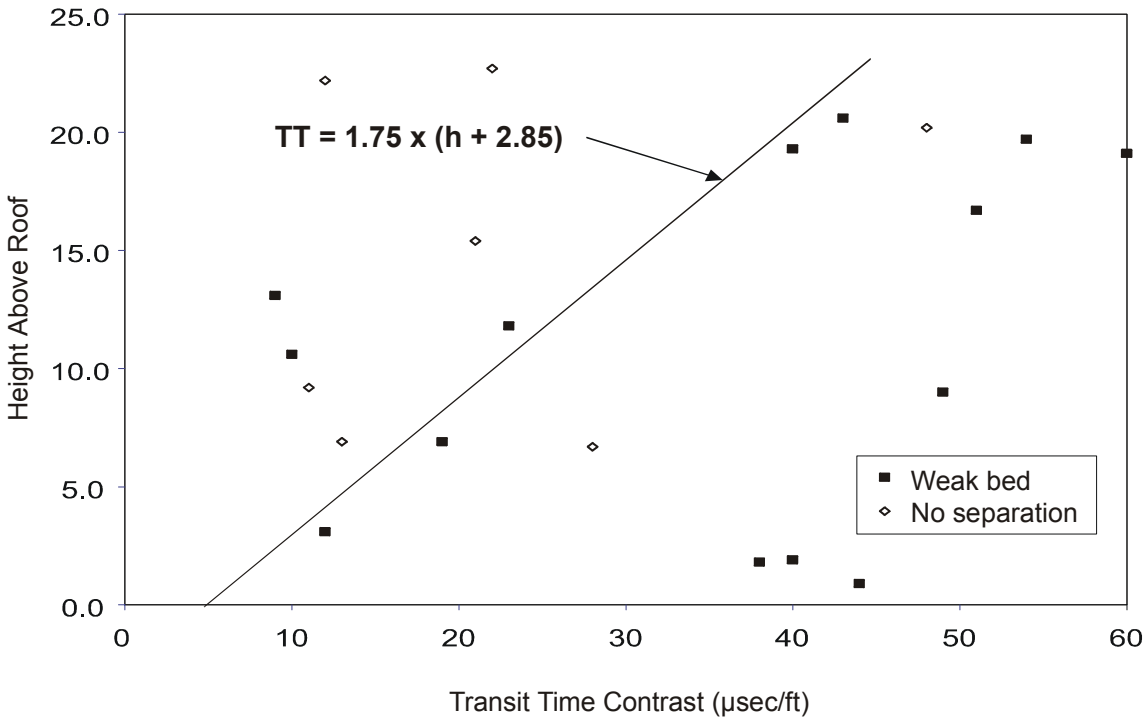

FIG. 6 - Immediate Roof Zone

Application of this relationship to the Grasstree Project example shown in Figure 2 would suggest a minimum contrast of 25 µsec/ft would be needed to cause the lower portion of the Aquila sandstone to become detached and goaf separately from the remainder. As the contrast in the example is only 13 µsec/ft, detachment would not be predicted and the Aquila sandstone would be expected to act monolithically. The active sandstone component would thus be equal to the full sandstone thickness of approximately 16m.

CONCLUSIONS

The conclusions reached in this study, based on the dataset established from the 12 sites examined, were as follows:

- The sonic velocity log can be used to predict bed separation in the immediate caving zone to a maximum height of 23m above the mined horizon.
- The relationship between the transit time contrast and the height above mining within the critical immediate caving zone can be tentatively expressed by the equation: transit time contrast (µsec/ft) = 1.75 x (height above roof + 2.85)
- This relationship can be used to help interpret the active sandstone component where thick sandstone bodies occur within the immediate caving zone above the mined horizon.
- There is no discernible relationship between transit time contrast and height above mining, with respect to propensity for bed separation in the intermediate and upper caving zones at levels higher than 23m above the mined horizon.
- The transit time contrast alone cannot be used to predict goafing behaviour in the intermediate and upper caving zones.

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