When mining commenced in the seam a geotechnical program for design confirmation was implemented. The objectives were to gather geotechnical information which was not collected during the exploration program.

As the underground measurement and additional borehole geotechnical results became available the model was validated and used to assess various options for pillar widths, wide heading drivage and roof support. The initial results have been used for risk analysis and preparation for submissions to the mines department.

In parallel with the geotechnical program the mine implemented a training program on the basics of roof bolting and strata control for the entire workforce encompassing a review of the local mine geology and roof support in the context of coal mining in the Bowen and Sydney basins.

Strata management and mine mapping programs were initiated which recorded the main geological structures and roadway conditions and set trigger levels and accompanying action plans.

The ongoing integration of results from the various phases of the program has resulted in the mine plan and safe successful development and extraction phases to the present. More details of the various phases are presented below with an outline of future directions.

**Exploration Phase – Geology**

A total of 328 boreholes were drilled in the exploration program which was completed in 1992. All boreholes were logged by a site geologist, then geophysically logged using the coal combination tool (gamma, density and caliper). The majority of holes were also sonically logged. Continuous cores were taken from three locations across the lease for geomechanical testing.

The Tertiary sequence comprises basalt up to 20 metres thick overlying a clay unit (up to 12 metres thick) which in turn overlies a basal sand unit (0-8 metres thick). The Permian sequence is predominantly interlaminated sandstone and claystone, with five coal seams less than one metre thick (Pleiades, Aquila, Tier1, Tier2 and the Corvus seam), and the Lilyvale Seam which is mined at Crinum (3.5-4.5 metres).

Continuous cores were taken from three locations across the lease for geomechanical testing. The results from this testing gave UCS values of 10 to 45 MPa for the roof and floor. However, further testing was carried out on samples retaining in-situ moisture. For these samples the UCS were generally lower (5 to 30 MPa). The difference in strength was attributed to the moisture retention.

A sedimentological model was compiled by Falkner (1991) using downhole geophysical logs combined with roof and floor information from three fully cored boreholes. The Permian sequence was analysed for sandstone channel deposits and other sedimentological features.
Fig. 1 - Roof zone map derived from exploration geophysics.
A roof zone map (Figure 1) was compiled for development purposes by interpretation of downhole geophysical logs (McManus, 1995). Four zones were defined according to the proportion and position of claystone units within the immediate 2 metres of roof (Zone 1 the strongest and Zone 4 the weakest).

A correlation was developed between UCS and Sonic Transit Time ($\Delta t$) for converting sonic logs to synthetic UCS logs.

$$\text{UCS} = 2550 \times 0.95^{\Delta t}$$

These UCS logs were averaged over 1, 2, 3 and 5 metres of roof and contoured over the initial mine plan. Figure 2 is the contour plan of the first metre.

**Exploration Phase - Modelling**

The Initial modelling study was an appraisal of recommended roadway geometry and suitability of bolting patterns placeable with a Joy 12CM30 continuous miner. The strata section compiled for the initial modelling (Figure 3) was based on rock testing data (exploration holes) and geophysical strength estimates according to McNally’s formula ($\text{UCS} = 1458e^{0.0366t}$ where $t$ is the sonic transit time).

The testing indicated two major strength categories defined from triaxial strength properties of the rocks and in particular the residual strength properties. Category 1 materials are low strength and do not gain significant strength under increasing confining pressure. This category is noted in Figure 4 as the lower curve. Strata of this type reduces pillar strength characteristics.

Category 2 materials are low to moderate strength and appear to have post failure strength characteristics more typical of other localised strata. Strength properties of the samples were sensitive to moisture content, whereby if the samples dried out their strength increased markedly. This effect influenced prior testing of the strata in the area and the initial correlations with sonic velocity. In this paper rock properties have been based on “in-situ” moisture content test results.

Bedding plane properties had not been tested for the initial modelling. The triaxial properties of Category 1 samples indicate that bedding plane properties of the mudstone/clay-rich strata would have low cohesive strength and friction angles in the range of 8-10 degrees under the moderate confining pressures anticipated during mining. Friction angles of the roof laminates containing higher quartz content of the fine material were anticipated in the region of 25-30 degrees.

The exact nature of the stress field was not known before the initial modelling. The regional direction of the maximum horizontal stress within the strata is typically N-NE although local structures such as faults and folds can vary the direction and magnitude. The magnitude of maximum horizontal stress was assumed to be 1.5 to 2 times the vertical stress. In order to assess the effect of possible stress geometry’s and magnitudes associated with tectonic deformation of the strata a range of stress conditions were modelled and the effects noted. Vertical stressess were determined on the basis of overburden weight as approximately 2.5 MPa per 100m of depth. In the pit bottom area where depth of cover is approximately 100m expected vertical and maximum horizontal stresses were 2.5 MPa and 3.7 to 5.0 MPa respectively.
Fig. 2 – Plot of average synthetic UCS over immediate 1m roof derived from exploration geophysics and results from borehole strength tests. Stress measurement location and orientation also depicted.
Fig. 3 – Rock strength properties model
Fig. 4 – Rock strength characteristics
Boreholes 5391, 5392, 5393, 5394, 5439, 5454.
Initial modelling results indicated rig positions on the mincr were sufficient to provide adequate bolting geometry should rock failure occur. The rigs were able to place a 4,6 or 8 bolt pattern of roof bolts of suitable geometry (Figure 5). The modelling also indicated rock failure at the shallow areas would be unlikely during development under a range of horizontal stresses. In deeper areas (150m depth) the model showed rock failure was initiated during development driveage at the upper end of the expected stress range. The model results indicated a 6 or 8 bolt pattern where rock failure was initiated and a 4 bolt pattern in areas where no rock failure was anticipated.

![Diagram of bolt patterns](image)

**Fig. 5 – Roadway 4.8m wide x 3.5m high, bolt patterns.**

As more rock test data became available, modelling was extended to encompass the lox line area where rock strengths were less and depth of cover was approximately 100m. Roof behaviour was examined under a range of stresses and although the rock was weak, the model showed no major ground failure during development conditions. The effect of leaving coal tops was beneficial. Minimum roadway dimensions (4.8m wide) were recommended in the weak clay rich environment to minimise roof spans.

The behavior of the “normal” (Figure 3) and lox line roof during development at 100m depth was typified by a lack of failure. At 150m depth the “normal” roof areas were typified by modest levels of deformation (up to 25mm) depending on the degree of lamination in the roof and load transfer characteristics of the roof bolts.

The effect of stress changes during longwalling was also examined and it was anticipated a 6 bolt pattern would be adequate for more massive roof types under 100m depth. In deeper areas “normal” roof types showed no additional deformation under longwall stress changes. The more laminated weaker roof types were expected to show increased bedding plane failure and deformation requiring additional support if failure occurred during development or at stress concentrations during longwall retreat.
Initial modelling of face installation roadways having “normal” roof at 150m depth indicated that widening caused substantial roof deformation at all but the lowest stress levels.

It was recommended that a review of the design study results and the updated geotechnical information be undertaken once the nature of the stress field, pillar strength characteristics and geological environment were better defined.

In summary, a range of mining scenarios were examined based on assumptions of stress conditions and initial borehole test results. The bolt placement by a Joy 12CM30 miner was acceptable. Development roadway conditions were expected to be good for both weak and stronger roof types in the shallower areas. In deeper areas some roof deformation was expected particularly in the weaker roof types and structured areas. The effect of longwall abutments on gateroads was minimal in the shallower areas for all strata types but at depths greater than 150m the weaker types were expected to show increased bedding plane failure and deformation. Longwall installation roads were expected to be difficult to maintain without stress relief methods or cut and install procedures.

It was anticipated 4 bolt support patterns would be adequate where no roof failure occurred and 6 bolt patterns would be required for weaker areas at depth and longwall gateroads during retreat. Secondary support would be required in areas with weakest roof, near structures and where stress concentrations occurred during longwall retreat.

Underground Phase – Geotechnical confirmation and modelling

When coal mining commenced the recommended geotechnical program for design confirmation was implemented. The stress field was measured, roadway behaviour characterised and rock bedding properties determined for the roof and floor. Roof bolt pullout tests were also performed to assess anchorage characteristics in the various roof types.

Two in-situ stress measurements were undertaken in the vicinity of pit bottom (Figure 2) using the overcoring technique and ANZI 3-dimensional stress cells. The measurements were taken 5m above the seam in sandstone. Both tests were of good quality, measuring approximately the same stress field. The results indicated the major principal stress direction is slightly east of north. The constant depth of cover and absence of major changes in geology at pit bottom suggests the magnitude and direction of the maximum lateral stress may represent a regional stress. The measurements confirmed the ratio of horizontal stresses was approximately 2:1 and the maximum lateral stress was approximately 1.7 times the vertical stress in this area.

Samples of roof and floor rock were recovered from inclined core holes during the stress measurement. Multistage triaxial strength tests were performed on 10 samples to obtain bedding plane properties for modelling. The results indicate friction angles of about 25 degrees for higher friction planes and less than 10 degrees for weaker planes. These values were consistent with those used for the initial modelling.
Roof and rib displacements were measured at two mid-pillar sites, one in a heading and one in a cut-through. Roof displacement was also measured in a 4-way intersection. This roof was classified as zone 1, which was composed entirely of sandstone in the first two metres. 7.5m sonic extensometers were installed at the working faces and monitored during subsequent mining. Results indicate roof and rib displacements within expected limits, or less than 5mm movement for the roof and depths of yield being less than 0.5m for both roof and rib.

Short encapsulation pullout tests were carried out on 20 bolts in the main headings in zone 1 roof. Roof bolts of different lengths were installed with short anchors and pulled to test 4 horizons within the first 2.1 metres of the roof. Bolt displacement and pullout force were recorded and used to calculate shear stress, system stiffness and average pullout force per 300mm of encapsulation. Bolt system stiffness characteristics were sufficient for good performance, at greater than 6 tonnes per mm of displacement. Pullout forces ranged from 11 to 22 tonnes per 300mm encapsulation. The average forces range from approximately 15 tonnes in the lower 1.5m of roof to 12 tonnes in the upper 1.5 to 2.1m of the roof. That is, between 4 and 7 MPa shear stress on the bolt surface. A value of 15 tonnes was used for modelling of good load transfer conditions.

In more clayey strata at other sites such as the Longwall 2 installation road, pullout values fell to approximately 8 tonnes per 300mm of encapsulation. This was regarded as a poor load transfer characteristic. Again this value was consistent with the initial modelling value for poor load transfer cases.

A study of roadway behaviour expected under the action of a longwall side abutment stress distribution was conducted using the updated models.

The side abutment stresses were expected to be a combination of vertical stress increase and horizontal stress decrease. A series of potential stress states were progressively applied to a development roadway at 150m depth at a modest tectonic stress level.

The model results indicated vertical abutments had a marked effect on rib deformation and floor heave due to the weak floor material for stress increases of 3 MPa or greater. They also indicated roof conditions were not significantly affected. However, bolt loads increased up to yield for vertical stress increases above about 4 MPa.

In general, the results indicated total vertical stresses about the long-term roadways should be limited to approximately 5.0 MPa - 5.5 MPa. If the floor was stronger than anticipated, this stress level may be increased.

To achieve limited stress increase from the longwall panels on long-term roadways, it was recommended roadways must be distanced from the goaf such that the abutment stresses were reduced sufficiently. At 150m depth, the distance envisaged was 60m, such that the vertical stress increases are less than 1.5 MPa, hence 60m pillars to keep the tailgate access open during life of mine.
Chain pillar sizes were recommended at 30m rib to rib based on an expected vertical stress increase of approximately 3 MPa from the longwall one goaf and an additional 2MPa adjacent to the faceline in the tailgate of longwall two. The exact side abutment distribution was difficult to determine due to expected variable behaviour of the weak floor.

An increase in vertical stress of 2 MPa - 3 MPa was expected to initiate rib spall and floor heave. Roof integrity was expected to be maintained by the bolting pattern. This magnitude was not expected to be a major problem about the maingate end but could influence the travelling road (tailgate of Longwall 2) as the side abutment builds up during extraction of Longwall 1.

The option of a larger pillar for example from 30m coal to 35m coal is unlikely to significantly increase the chain pillar capacity or limit the tailgate stresses during Longwall 2 such that additional deformation does not occur.

On balance it was recommended to develop a 30m (coal) chain pillar and monitor its performance, the potential moisture effects in the weak strata and roadway behaviour during extraction of Longwall 1. Chain pillar sizes were thus based on roadway stability considerations. Traditional pillar design approaches yield pillar strength of approximately 22MPa. At 130m depth nominal safety factor for a chain pillar in the goaf between longwalls ignoring the effects of weak roof and floor is 1.6.

The updated models were used to examine further the effects of poor bolt load transfer and various options for installation road widening.

In summary, the initial assumptions used for the modelling had been confirmed and the model validated by underground measurements. Bolt pullout tests had confirmed the poor load transfer characteristics of the clay rich strata and rock strength data from additional exploration holes had confirmed the wide distribution of weaker rock types. Further modelling was undertaken to provide estimates of barrier and chain pillar widths and to review installation road options. Chain pillars in the tailgate and barriers behind the longwall installation roads were set at 60m wide to prevent long term deformation of the pump access roadway. Normal chain pillars were set at 30m initially with a recommendation to monitor performance and roadway behaviour during extraction of longwall 1.

Modelling of installation road widening options indicated that stress relief roads would be relatively ineffective and that cut and install methods were very effective in limiting strata deformation. The application of megabolts after the first pass was modelled. The results indicated that they were unable to significantly modify roof failure modes.
Underground Phase – Training and Development of the Strata Management Plan

In parallel with the geotechnical program the mine implemented a training program on the basics of roof bolting and strata control for the entire workforce. This involved tailoring the statutory induction training on roof support specifically to Crinum conditions and a review of the local mine geology and roof support in the context of coal mining in the Bowen and Sydney basins. This provided a unifying theme to encompass the diverse backgrounds of the new workforce. Training in the installation and recording procedures for roof monitoring “Tell-Tales” was also provided to relevant personnel in readiness for implementation of the Strata Management Plan.

Risk reviews were coordinated resulting in a series of management plans of which the Strata Control Management Plan (Jackson, 1997) was one. This management plan outlined the various roof conditions characterised by the roof zone map, strength testing, pull tests, occasional roof cores and overcoring. Explanations for the managers support rules, expected geological hazards, procedures for installation and data recording of roof monitoring equipment were given. Telltales were to be installed at least every intersection along the gateroads, throughout trial areas, along faceroads and through faulted ground. Most importantly, trigger levels and accompanying action plans were established for these instruments. The success of this plan is evident in that Crinum is yet to experience a roof fall. This management plan is presently undergoing review as are Crinum’s support rules in an attempt to refine and improve the efficiency of our support practices.

Ongoing Continuous Improvement - Support trials and hazard map

- Crinum has undertaken various trials in an attempt to support the roof using minimum hardware as is safely possible. Most of the following trials were accompanied with roof instrumentation and pull tests.
  - Flexibolts
  - Flexibolts-pretensioned
  - Cablebolts (trussed)
  - 4 x 2.1 CX bolts/m, fully encapsulated
  - 4 x 2.1 HPC bolts/m
  - 4 x 1.5 CX bolts/m, pretensioned
  - “The Can”
  - Megabolts-pretensioned
  - 100 mm washers (not 150mm)
  - High torque motors

With the volumes of quality data accumulated over the last 8-10 years at Crinum, the goal is to produce a series of Hazard plans and cross sections. This will ensure safer working conditions and a Strata Control Management Plan tailored to the changing geological conditions. Development rates will be tuned accordingly and longwall extraction optimised. A schematic showing evolution of this hazard map is shown on Figure 6.
Conclusions

Strata management at Crinum commenced during the exploration phase and developed over a period of years. The results of the initial data gathering and modelling exercises have been incorporated into the mine plan and stand testament to themselves. The mine is laid out favourably with respect to the stress field, the roadways have been stable and the barrier and chain pillars are behaving well. No roof falls have occurred.

The ongoing monitoring is providing a solid data base for assessment of new approaches and for refinement and optimisation of pillars and support. Integration of the geological and geotechnical data bases with validated models provides valuable predictive tools for new panels. The hazard map concept is an example of this type of integration.

A variety of secondary support has been trialled and the “Cans”, in the longwall tailgates have performed particularly well. Optimisation of primary support is also in progress for selected areas.

The near future will see greater pressure to reduce costs, improve productivity and improve safety standards. This integrated approach to strata control will assist this process.
Acknowledgments

The authors would like to thank BHPC Crinum Mine for permission to publish this paper. K. Rixon wishes to acknowledge contributions of the various SCT personnel upon whose work he has drawn heavily. These are Dr. W.J. Gale, Mr. S.M. Matthews and Mr. J.A. Nemcik.

References


Overview of Strata Management at Crinum Mine

L.K. Rixon\textsuperscript{1} and J.R. Armstrong\textsuperscript{2}

\textsuperscript{1}Strata Control Technology  
P.O. Box 1676, Emerald, QLD 4720, Australia  
\textsuperscript{2}BHPC Crinum Mine  
P.O. Box 1526, Emerald, QLD 4720, Australia

Abstract

Strata management at Crinum commenced during the exploration phase and developed over a period of years as the mine progressed. An integrated approach evolved which linked geological and geotechnical data with computational modelling of roadway stability. Initial results were used for mine layout, roadway dimensions, assessment of bolting patterns, equipment selection and support type and density.

As mining commenced information was gathered on stress field, roadway behaviour, bolt performance and strata properties and used to validate and refine the models which were then used to reassess roadway performance under a variety of conditions. Barrier and chain pillar widths were recommended and installation roadway options examined. Performance monitoring of longwall chain pillars and adjacent roads is continuing.

Parallel programs of workforce training in strata control along with the implementation of a strata management plan maintained workforce awareness and ongoing monitoring of underground strata conditions.

Ongoing work is aimed at reducing costs and improving productivity via use of hazard maps and refinement of support techniques.

\textit{Key Words:} Crinum Mine, strata management, modelling, hazard map, mine design

Introduction

This paper outlines the progressive understanding of strata management throughout the design and early operating phases of BHPC Crinum mine. Some of the major geotechnical issues are highlighted and some of the geotechnical findings and mining outcomes summarised.

The exploration program was completed in 1992. A sedimentological model was compiled (Fallner 1991) and a roof zone map was also compiled for development purposes by interpretation of downhole geophysical logs (McManus, 1995).

Roadway design studies were initiated during the exploration phase. They concentrated on initial mining areas about proposed longwalls one and two and the methodology was to develop a computational model of the strata about the Lilyvale seam under a variety of stress conditions.