# Cowal gold mine;
## Success in mining through saprolites - a case history

**by Ron Crouse and Shane Wright**

The Cowal gold mine is located in central New South Wales, approximately 38 km northeast of the town of West Wyalong, and 350 km west of Sydney. The mine is located on the western side of Lake Cowal, within the Bland Creek Valley, which is a region that supports mainly dry land agriculture with irrigation farming. Lake Cowal is an ephemeral lake fed by its major tributary (Bland Creek), and by large but infrequent floods from the Lachlan River.

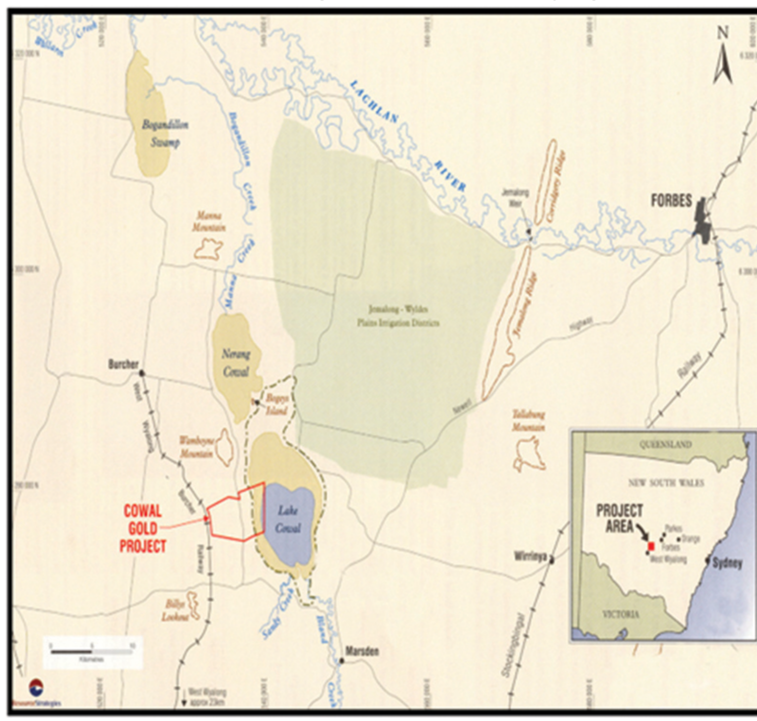
Rio Tinto Ltd. acquired the property in 2001, and subsequently sold it to Homestake Mining Co. the same year. Barrick acquired the project through its merger with Homestake in 2002. The mine produces approximately 7 Mt/a (7.7 million stpy) of ore. The processing plant and associated infrastructure has a gravity circuit plus a conventional carbon-in-leach and cyanide leaching circuit for oxide ore, as well as a grinding, flotation and cyanide leaching circuit for primary sulphide ore.

Mine production statistics are presented in Table 1.

The gold deposit is located within the 40-km long by 15-km wide Ordovician Lake Cowal Volcanic Complex, east of the Gilmore Fault Zone, within the eastern portion of the Lachlan Fold Belt. The orebody is hosted in a volcanic sequence informally referred to as the Lake Cowal Volcanic Complex, which includes andesite, lava, volcaniclastics and diorites. The intrusive formations are dissected by the Cowal Fault Zone, as well as several intersecting high-angle faults with varying offsets.

The orebody is a structurally hosted, epithermal-to-mesothermal gold deposit occurring within and marginal to a 230-m thick

### Figure 1
**Cowal Gold Project Location (from Resource Strategies).**




### Table 1
**Mill production statistics.**

| Year | Tonnes | Grade (g/t Au) | Ounces |
|---|---|---|---|
| 2006 | 4,055,000 | 1.21 | 122,000 |
| 2007 | 6,615,000 | 1.42 | 240,000 |
| 2008 | 7,246,000 | 1.06 | 192,000 |
| 2009 | 7,393,000 | 1.26 | 232,000 |
| 2010 | 7,211,000 | 1.57 | 299,000 |
| 2011 | 7,034,000 | 1.46 | 269,000 |
| 2012 | 7,289,000 | 1.39 | 267,000 |
| 2013 | 7,032,000 | 1.59 | 297,000 |
| Total | 53,874,000 | 1.38 | 1,918,000 |

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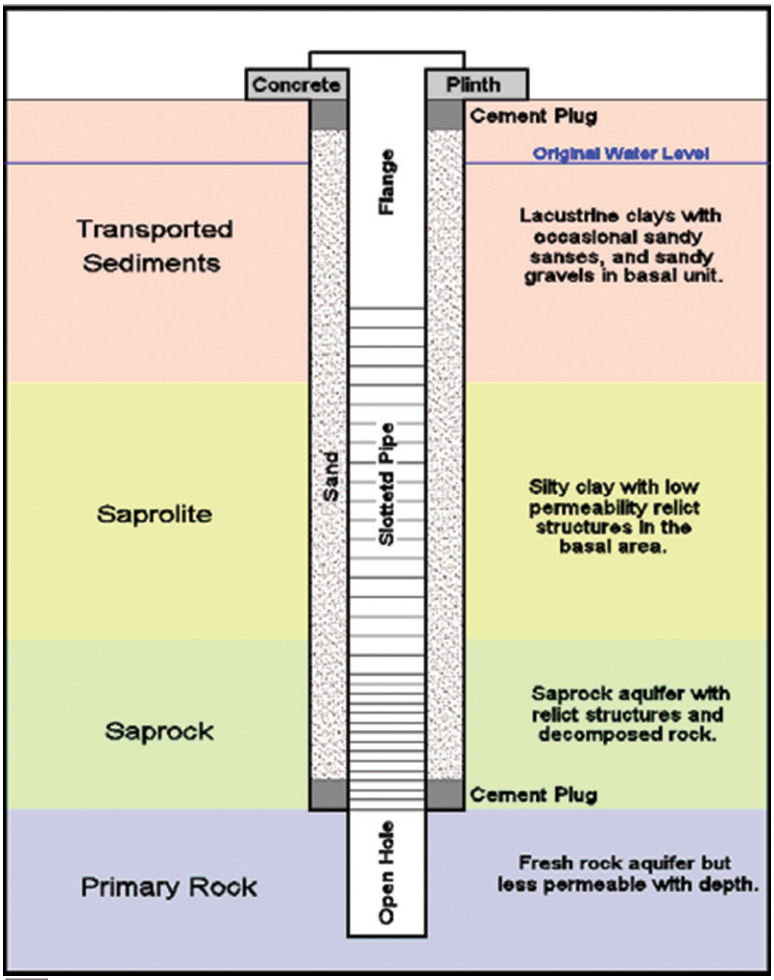
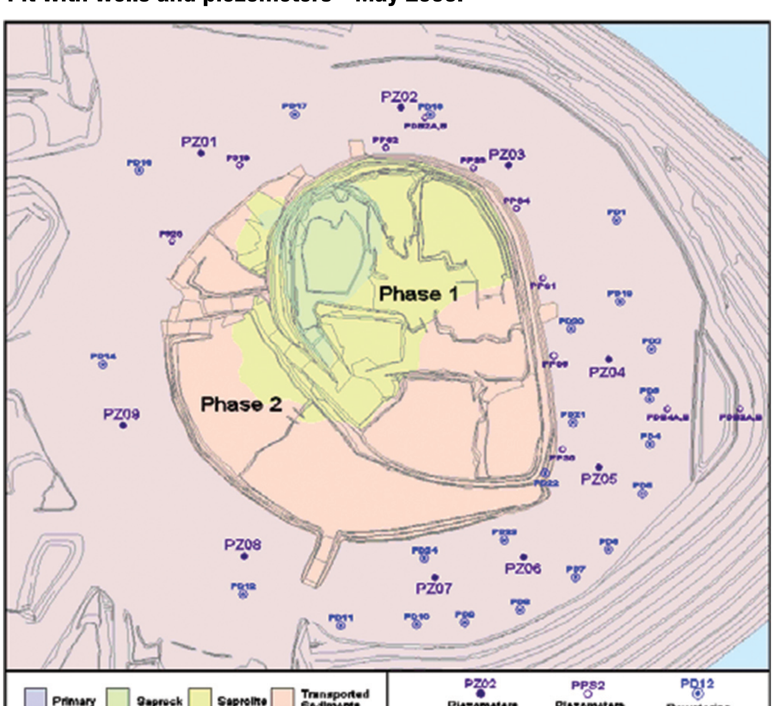
### Figure 2

**Typical well completion diagram.**




### Figure 3

**Pit with wells and piezometers - May 2006.**




dioritic to gabbroic sill intruding trachyandesitic volcaniclastic rocks and lavas. The majority of the gold mineralization occurs in quartz-carbonate-sulfide veins. Alteration is typically early chlorite-K-feldspar-hematite-calcite-pyrite, with a later sericite ± ankerite assemblage associated with a base-metal-gold event.

Weathering of primary rock has resulted in the development of a saprolite profile with a thickness of 20-m to 50-m. The basal 5 m to 10 m of this profile is comprised of saprock materials. Transported sediments, consisting of predominantly lacustrine clays deposited in the Lake Cowal basin, cover the saprolites. Some relic channel structures containing coarser-grained sediments have been intersected within the transported profile. The total thickness of these sediments varies across the site, ranging between 10 m and 50 m. The combined thickness of the transported sediments and the saprolites is as much as 100 m in some places.

The initial design interramp angles recommended for the transported sediments and saprolite was 27° for the east pit sector, and 25° in the southeast and south pit sectors. The one caveat made to the recommendation was that "effective depressurization" was assumed in the initial slope stability analyses. These design interramp angle recommendations were not followed, and effective depressurization was not achieved.

The sediments and saprolites were mined at an interramp angle of 30 ° on the north and east walls of the Phase 1 pit, creating an oversteepened wall. Due to the combination of mining at the steeper angle and high ground water pore pressures, two slope failures occurred through the saprolite and transported sediments during 2007. Back analysis of the failures reiterated the initial recommendation that depressurization of the transported sediments and saprolites had to be achieved before additional mining could take place.

Overall, the ground water management story was one of moving from a generic system that was managed by simple compliance, to a final system that was targeted with strong feedback and proactive management. This change eventually paid the dividend at the end of the excavation through the saprolites in 2013. After the 2007 failures, there was a geotechnical imperative to depressurise the surficial units, especially the saprolite, prior to mining the later pit phases. The purpose of this article is to show how this goal was achieved.

### 2005-2007 prestripping to east wall failures

Early interpretations of the mine-scale hydraulic system chose to focus on the definition of ‘aquifers’ within the mined profile, and the zones that would require active dewatering. While early work did acknowledge the limited effect that dewatering would likely have on the depressurisation of other ‘non-aquifer’ type materials, the treatment of ground water flow was one of a compartmentalized description using individual water tables and perched water tables for each ‘aquifer’ of interest. This ultimately fell short of adequately describing the dynamics of the local ground water system and providing the inputs for suitable drainage management strategies.

Ground water permeability and storage is variably developed within the mined profile at Cowal. However, some general descriptive statements can be made. Within the saprolite, permeability is observed to increase with depth into the saprock materials, after which permeability rapidly decreases with depth into the primary rock. Water storage is inferred to generally decrease with depth into the primary rock – transitioning from a high primary storage component within the transported sediments into a predominantly low secondary (structural) storage at depth in the primary rock.

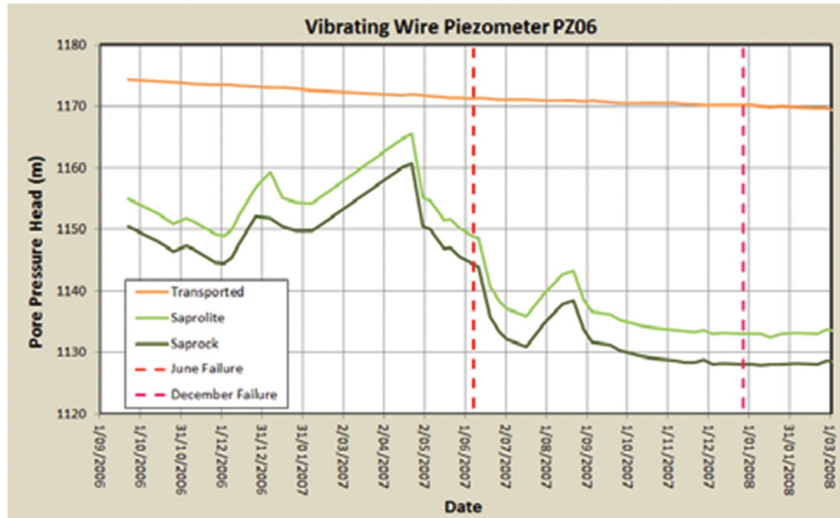
Despite the clayey makeup of the saprolite profile, observed drainage responses support a strong structural overprint. Relic structures, including the Cowal Fault Zone and associated features, provide for a vertical flow anisotropy that makes the saprolite materials amenable to underdrainage via the enhanced permeability that is observed in the lower saprock and upper primary rock profile. The transported materials respond poorly to underdrainage, or even pumping, from adjacent coarser textured channel structures.

The geological structure that allows for an enhanced underdrainage of the saprolite profile also connects the local Cowal ground water system with a regional source of recharge. Even though there is periodic flooding of Lake Cowal, this source of additional water is difficult to intercept inside the area of influence of the mine.

Early in the mine life, development of drainage measures generally preceded the construction of the associated ground water monitoring infrastructure that was necessary to track drainage performance. Dewatering bores targeting the saprock and upper primary profiles were the primary form of early water management. Open stand pipe monitoring bores were also installed during this period. However, they also targeted the saprock and

## Figure 4

**Piezometer PZ06 pore pressure head.**

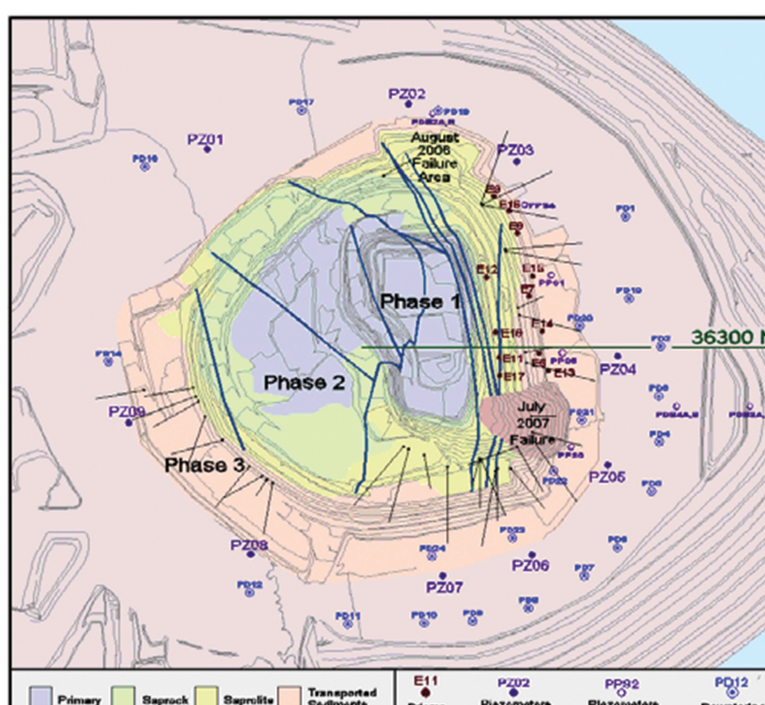



upper primary materials. The overlying saprolite and transported sediments remained largely un-monitored.

In early 2005, a series of dewatering bores was installed that targeted the permeability that had been initially identified in the saprock and upper primary rock. Water production for the wells, based on the testing done at the time of completion, was expected be on the order of 1-1.5 L/sec for the transported sediments, and

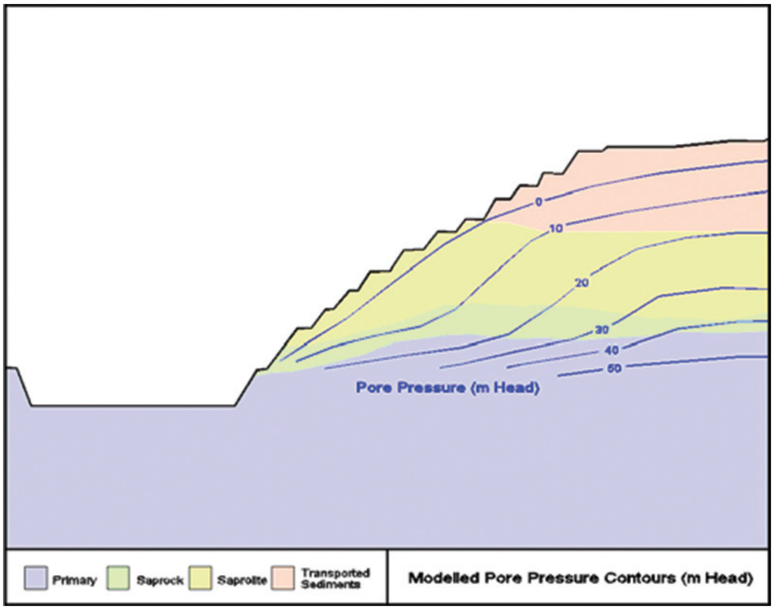
## Figure 5

**Pit prior to second east wall failure – mid December 2007.**



## Figure 6

**Cross section 36300N prior to second east wall failure.**




0.2-2 L/sec for the saprolites.

Site dewatering was heavily reliant upon the effectiveness of the dewatering bore well system. This system was designed and quite rigidly constructed around the initial yields that had been tested during the project feasibility stages.

In 2005, prestripping was begun. Pit dewatering became an issue immediately during the initial 20 m to 30 m of the pit development. In December 2005, a site visit was made by a consulting engineering geologist. At that time the pit excavation had not reached primary rock. One important observation he made was that only about 20 percent of the dewatering wells were operational at the time of his visit. The average flow from the bore field had been on the order of 6 L/sec over the past year. The ground water level was at the base of the pit, resulting in generally wet and boggy conditions.

The aggregate dewatering pumping rate peaked at 9 L/sec in January 2006. Mining through the lower transported sediments necessitated the excavation of drainage channels and the installation of pumping sumps. The in-pit sumps and drains produced another 4 to 10 L/sec. The feasibility study had predicted a combined flow rate in excess of 100 L/sec. from these wells. Clearly something was wrong.

Due to an awkward power reticulation system, the dewatering network proved to be quite inflexible for ongoing dewatering, as well as management of the inevitable declines in bore well yields. The system proved to be poorly scalable, meaning that the system had a lot of down time, which compromised the dewatering effort and also the depressurisation effort – a familiar problem for a lot of mine operators.

Until that time, the series of open stand pipe piezometers that targeted the permeable zones in the saprock and upper primary were the only mechanism for observing the performance of the dewatering system. Because these installations targeted a zone that had an enhanced natural drainage, the overall poor performance of the dewatering system was not initially apparent. Efforts were made to improve the ground water monitoring situation by installing nine vertical vibrating wire piezometers in April 2006. However, doubts remained as to the quality of those completions.

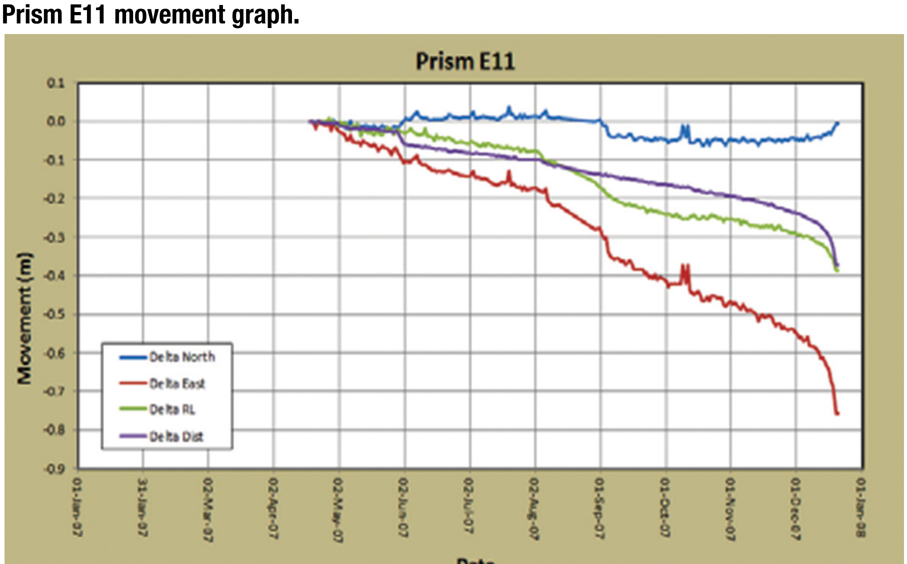
By mid-2006, primary rock had almost been reached in the north of the Phase 1 pit. However, most of the excavation was still in transported sediments. Nine prisms were installed on the east wall, all of which were manually surveyed. Unfortunately, no prisms were placed at the toe of the wall.

In August 2006, a multi-bench failure occurred on the north wall, beginning with a tension crack opening behind the pit crest. The failure occurred through the transported sediments and the upper saprolite. The area was stabilized by unloading the top of the failure and dozing it down.

In September 2006, a horizontal drain hole drill program was begun. Horizontal drain holes were drilled into the toe of the north wall failure

## Figure 7

**Prism E11 movement graph.**



in an attempt to depressurize the wall. These holes had high flow rates, and continued to produce significant water for approximately 2.5 years, when they were mined out. Many of the horizontal drain holes could not be cased to full depth. In addition, many holes could not be sited at their design locations, due to ground conditions that created difficulties with pad construction. Significantly, many of the planned drain holes could not be drilled in the eastern pit wall area.

In February 2007, a tension crack was noticed about 5 m back from the crest along the entire east pit wall. In April, two prisms were placed above the toe of the east wall. In June a failure occurred in the southern part of the east wall, in an area with essentially no prism coverage. The failure surface began at the saprolite/saprock boundary, and progressed upward through the transported sediments to the pit crest. Although the failure was large, it had little impact on the mining in Phase 1 due to the geometry of the mining area.

At first, the failure was thought to be structure-related. However, subsequent evaluation indicated that the failure was of circular nature, with structure playing only a minor role. Significant areas of saturated wall were also noted.

At the time of the failure, a solid understanding of the ground water pore pressure conditions in the surficial materials had not yet been attained. However, based on knowledge gained in the years after the failures, the horizontal drain hole program was deemed to lack sufficient intensity to adequately depressurise the saprolite. The transported sediments also remained a problem for depressurization.

There were several piezometers located around the pit crest, but most of them were open stand pipe type installations, which measured the combined water level in the transported sediments and saprolites. There were a few vibrating wire piezometers in place, but they were located further behind the pit crest.

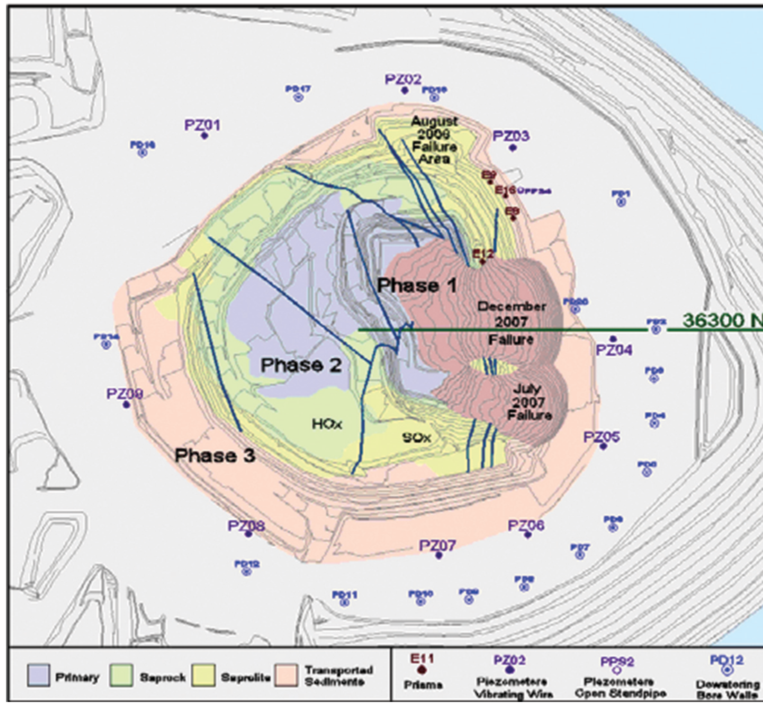
It was interesting to note that a number of the vibrating wire piezometers installed in 2006 began to exhibit a characteristic response throughout the fourth quarter of 2006 and the first quarter of 2007 within the saprolite and saprock horizons. Monitoring stations PZ05 and PZ06, located in the vicinity of the first failure zone, and offset some 100 m from the pit crest, exhibited a steady rise in pressure for this period, which was then followed by a rapid decline in pressure commencing late April 2007 – approximately seven weeks prior to the observed failure of June 2007.

Given the relatively short monitoring record available from the new vibrating wire piezometer network and the prevailing doubts over completion quality at other locations, these responses were not considered significant at the time.

A subsequent reconciliation of the

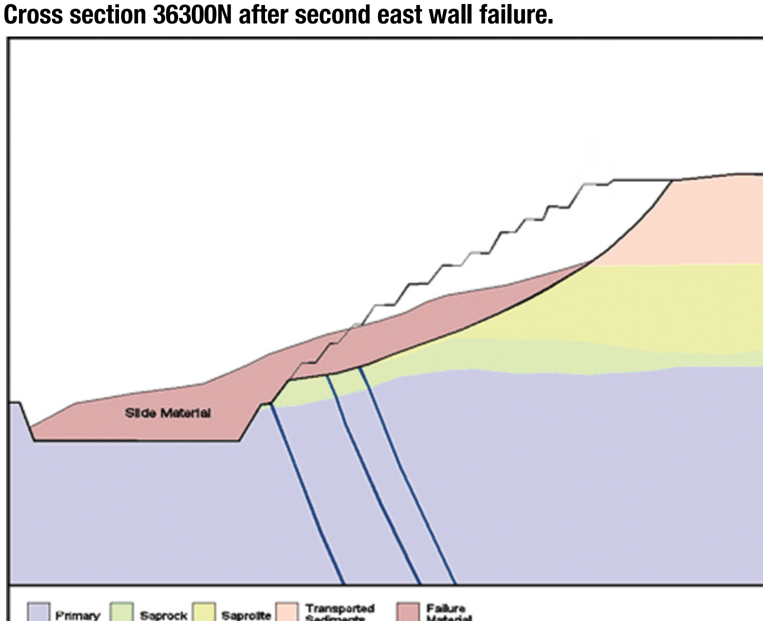
## Figure 8

**Pit prior to second east wall failure – mid December 2007.**




## Figure 9

**Cross section 36300N after second east wall failure.**



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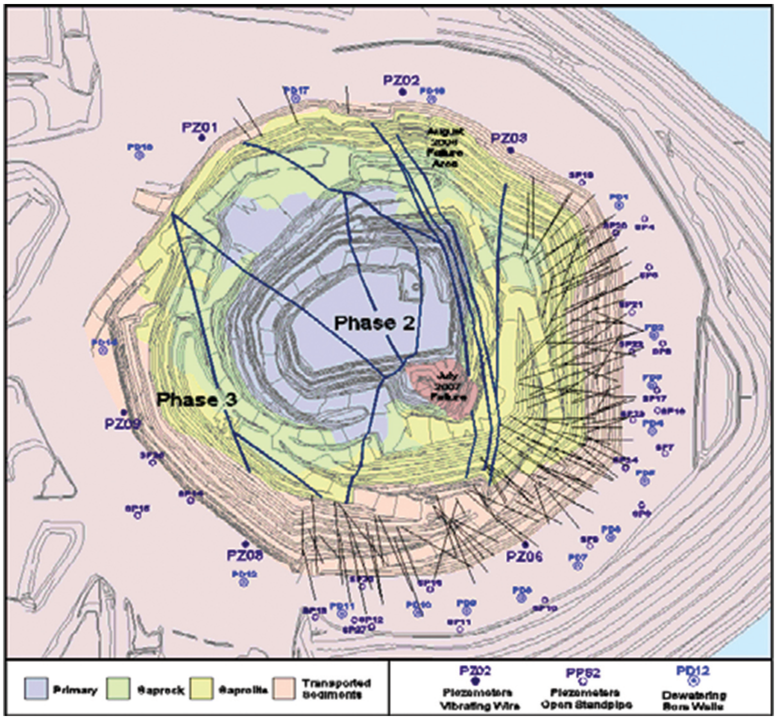
## Figure 10

**Pit map with wells and horizontal drains as of December 2008.**




mining and drainage activities that were being undertaken during this period failed to identify an obvious driver for the observed depressurization in the two piezometers. However, by a process of elimination, the initial pore pressure increase is now believed to have been the direct result of the poor performance of the depressurization/dewatering systems, followed by the onset of slope failure, a corresponding dilatation of the rock mass (primary and secondary), and a temporary enhancement to drainage - hence the apparent depressurization. There is a useful analogue within these responses – using ongoing pressure monitoring and trends to anticipate problems ahead of time, and allow corrective actions to be set in place.

In August 2007, seven additional prisms were installed on the east pit wall. However, the resulting prism coverage was still barely adequate to provide advance warning of the initial stages of further instabilities.

The entire pit monitoring system was playing catch up to the processes that had been occurring throughout 2007. The transported sediments and saprolite in the east wall of the Phase 1 pit had been mined at an inter-ramp angle of 30°, which was several degrees steeper than the recommended design inter-ramp angle. In addition, the saprolite in that portion of the deposit was deeper than the average saprolite depth over the rest of the deposit. The result was an over-steepened wall in highly weathered clays, with high ground water pore pressures.

Figure 6 exhibits an interpretation, based on the information available at the time, of the distribution of the pore pressure head within the east wall slope prior to the failure. A natural drainage of the saprock materials was captured with this interpretation but, overall, a high degree of ground water pressure was retained in the slope.

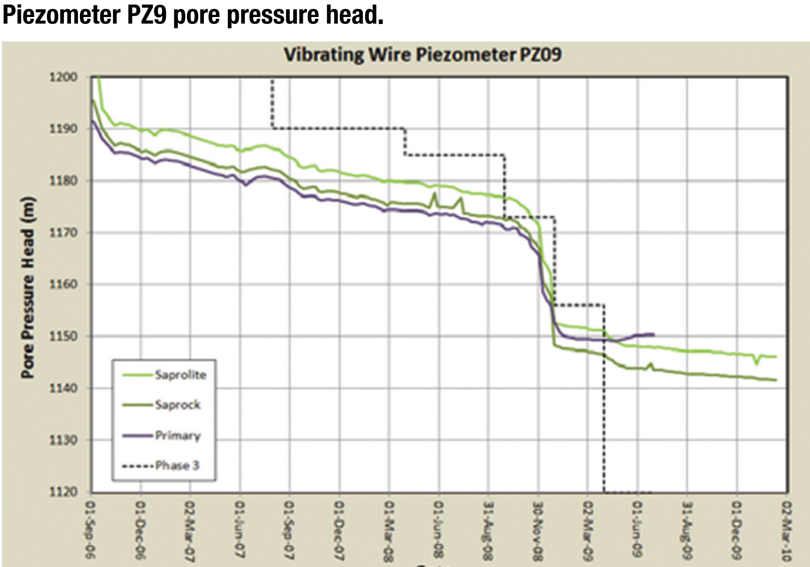
Despite the fact that there had already been a large failure in the southeast corner of the east wall, the observation of a tension crack behind the pit crest, and the fact that several prisms indicated real movement immediately after their installation, mining was continued at the bottom of the Phase 1 pit. Primary ore had only recently been exposed, and the desire was to provide material to feed the mill.

At the end of December 2007, the second east wall failure occurred. Pit crest cracking had been observed and monitored in the previous months. The failure started at the toe and unravelled upward toward the pit crest. The failed material appeared to flow, indicating presence of a lot of internal water, especially in the transported sediments, which were a dark red in the area of the failure.

At the time, prism monitoring and movement analysis procedures prior to the failure had not been well defined. The prism coverage was inadequate, so the initial wall movement in the area of the second failure was not recorded. The graph for prism E11, which was located in the saprolite above the toe of the second failure, is illustrated in Fig. 7. It is clear from the graphs that

## Figure 11

**Piezometer PZ9 pore pressure head.**



wall movement had already begun prior to installation of the prism.

The map in Fig. 8 shows the pit after the second failure. Note that almost the entire bottom of the Phase 1 pit had been filled with failure debris.

A photo taken two days after the failure confirmed that the failed mass contained a lot of internal water, as shown in Fig. 8.

The 2007 failures occurred in an area where the saprolites were very deep. The geometry of the failure surface followed the geometry of the base of the saprolite at the toe of the failure, which also happened to be at the location of the Cowal Fault Zone, represented by the three blue lines in Fig. 9.

Observations of the pit after the failure included bench degradation, seepage, and slope saturation of the south wall in the saprolite zone.

### 2008-2009 learning to get it right

In February 2008, the hydrologic model was updated, and further reviews were undertaken with regard to dewatering practices. Mining was started on the east wall to unload the failed material.

In March 2008, a back-analysis of the failures was completed. In the report, it was noted that the initial pit design had assumed dewatered slope conditions. Efforts to address dewatering and slope depressurization were also reviewed. Hydrogeological observations at the time inferred a relatively shallow phreatic surface in most areas of the mine, and only partial depressurization within, which was clearly at odds with the earlier design assumption of 'depressurized' slope conditions.

Going forward, a comprehensive drainage program targeting the transported sediments and saprolites was recommended to enhance depressurization and improve overall slope performance.

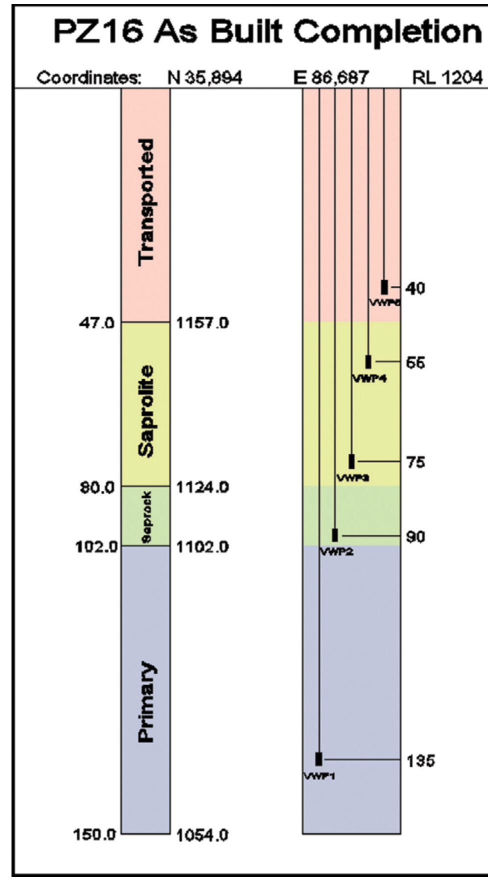
In April 2008, a second horizontal drain drilling program was started. Greater emphasis was made to target all saprolitic zones on the east and south pit walls. Initial flows of 0.5-1 L/sec, followed by a relatively rapid decline in flow rates, were not uncommon. Those drains orientated across the predominantly north-south structural fabric tended to yield greater flows than those drains orientated subparallel to the structural fabric.

Higher and longer sustained flows were also observed where the regional structures (e.g. Cowal fault zone) were intersected. This later observation highlighted the importance of the regional structures in the vicinity of the mine in maintaining a source of groundwater recharge into the pit slopes and the ongoing requirement to keep these structures actively discharging/draining.

Preceding the completion of updated structural and hydrological models, the slopes in the transported sediments and saprolites were designed with flatter interramp angles. The resulting pit design contained a 23° inter-ramp angle for these areas, except the northwest sector, which contained a 25° inter-ramp angle. A new pit phasing strategy was also implemented, with the new phases designated by letters instead of numbers, i.e., Stage D

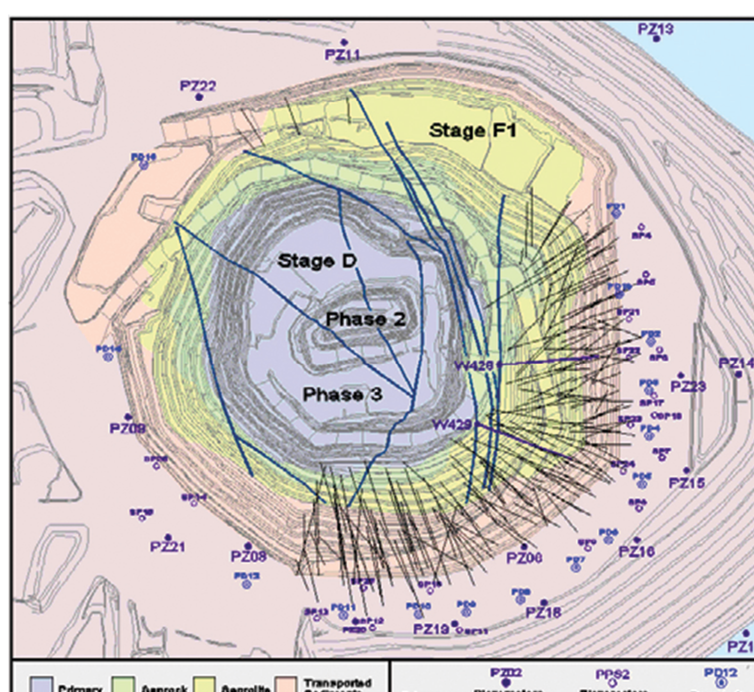
## Figure 12

**Typical VWP completion.**



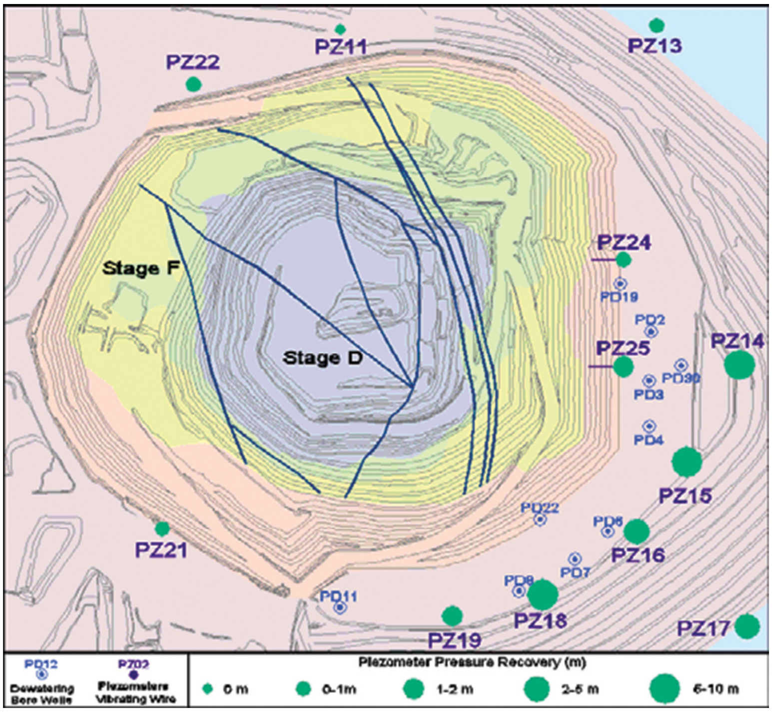

## Figure 13

**Pit with piezometers, wells and horizontal drains drilled - December 2009.**



## Figure 14

**Piezometer pressure rebound (June 2010) during recovery test.**




followed Phase 3.

In November 2008, a geotechnical assessment of the stability in the next stage of mining was completed. Revised design recommendations were made for mining at inter-ramp angles. The temporary inter-ramp angles of 23-35 ° were replaced by inter-ramp angles of 25-27° for the transported and saprolite materials. The revised values were similar to the initial project inter-ramp angle recommendations. Then main difference was that the design angles were implemented with a more proactive and targeted ground water drainage program.  It was noted and understood that a suitable monitoring program would be required to maintain adequate feedback loops of the performance of pit dewatering activities.

By December 2008, the revised inter-ramp design parameters had been implemented, and an ambitious horizontal drain drilling program was undertaken, resulting in stable walls in the transported sediments and saprolites in the east and south pit sectors. Pore pressures in piezometer PZ09, located on the west pit crest, clearly reflected the effectiveness of the horizontal drain program for depressurisation throughout the development of the Phase 3 pit.

In January 2009, an automated prism monitoring system was installed, using two Leica TPS1200 instruments controlled by GeoMoS software.  These installations made it possible to install hundreds of prisms, instead of the few dozen that could be installed when they had been surveyed manually.

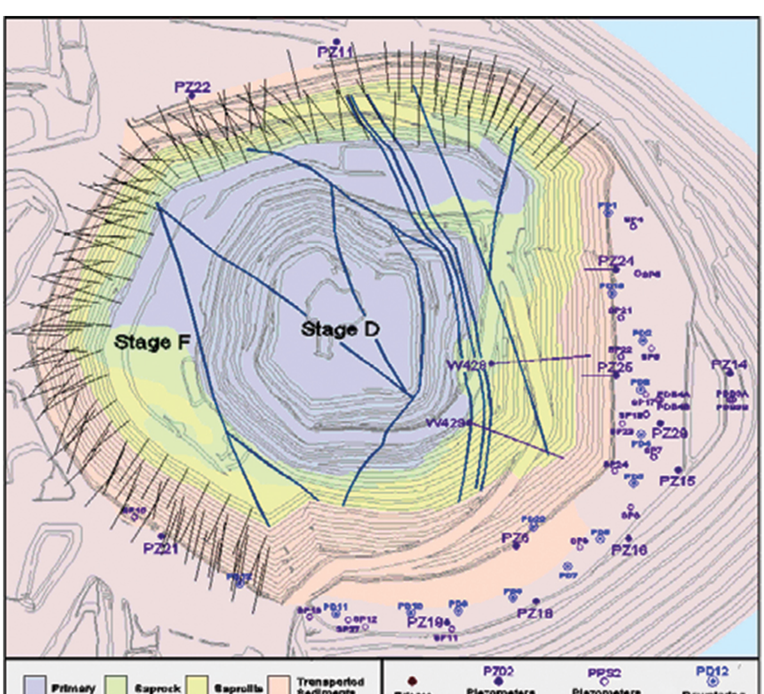
In mid-2009, the pore pressure monitoring network was expanded and developed to a higher standard. Multiple vibrating wire piezometers were installed in 11 vertical and sub-vertical pilot holes. In general, one gauge was placed in the upper primary rock below the saprock, one gauge was placed in the saprock, two gauges were placed in the saprolite, and one gauge was placed in the lower transported sediments. An example completion diagram is shown in Fig. 12.

Vibrating wire piezometers were also installed in two horizontal drain holes within the pit.  These installations contained two gauges each, specifically designed to measure pore pressures in the upper primary rock below the saprolites.

After the installation of the additional vibrating wire piezometers, stronger concepts of ground water movement within the saprolites were developed and tested.  The expanded monitoring system began to be used as a proactive management tool to better target the horizontal drain program, as well as better understand the late-stage dewatering and depressurization responses. The strength of this information ultimately allowed the decommissioning of the old dewatering network.

## Figure 15

**Pit with piezometers, wells and horizontal drains drilled - December 2010.**



As a result, the company successfully mined through the transported sediments and saprolites in Phase 3, as shown in the following photograph.

In September 2009, a preliminary stability analysis was completed for the final pit phase, Stage G. The report provided slope design recommendations for the transported sediments and saprolites based on current knowledge of the operating pit, the Stage D analyses completed to date, and cursory stability analyses of the Stage G slopes in the transported sediments and saprolites. An interramp angle of 25° was subsequently recommended for the east and south pit sectors in the transported sediments and saprolite.

Additional horizontal drains (almost 16,000 m installed) and dewatering bores (targeting the saprock and upper primary profiles) were completed during this period. While effecting clear depressurization gains in the saprolite profile, the program continued to be largely ineffective within the transported sediments. This response was not surprising, and was indeed predicted by the early geological and hydraulic investigations.

Further hydraulic testing of the transported sediments was undertaken to ascertain whether an enhanced drainage response could be achieved using closely spaced, low yielding, pumping bores targeting just the transported sediments. These installations failed to produce a practical and economic outcome for an up-scaled application. Subsequent slope designs for the transported sediments incorporated the inherent difficulty in draining these materials by implementing decreased slope angles in critical sections of the pit walls.

By the end of December 2009, the Phase 2 pit had been completed, Phase 3/Stage D was nearing completion, and Stage F1 was underway on the northeast pit wall.

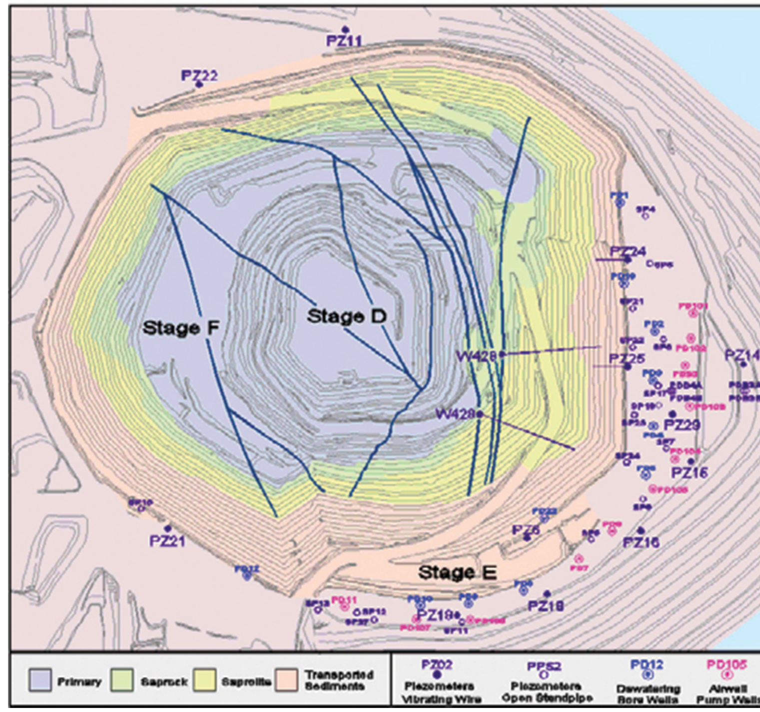
## 2010-2013 final cuts through the transported sediments and saprolite

The earlier hydraulic investigations focused on reconciling the available ground water data with the operation of the inpit horizontal drains and pit peripheral dewatering bores. That work inferred a strong contribution to depressurization from both systems. However, the contributions from each individual system were unable to be resolved with the data available. A partial insight into the performance of the dewatering bores was attained during temporary decommissioning of the main dewatering bore ring in December 2009. All pumping ceased for eight days, during which time nearby vibrating wire piezometers recorded a small magnitude of pore pressure recovery.

In order to further understand this response, as well as to ascertain the potential depressurization contribution provided by the dewatering bores, a dedicated recovery test

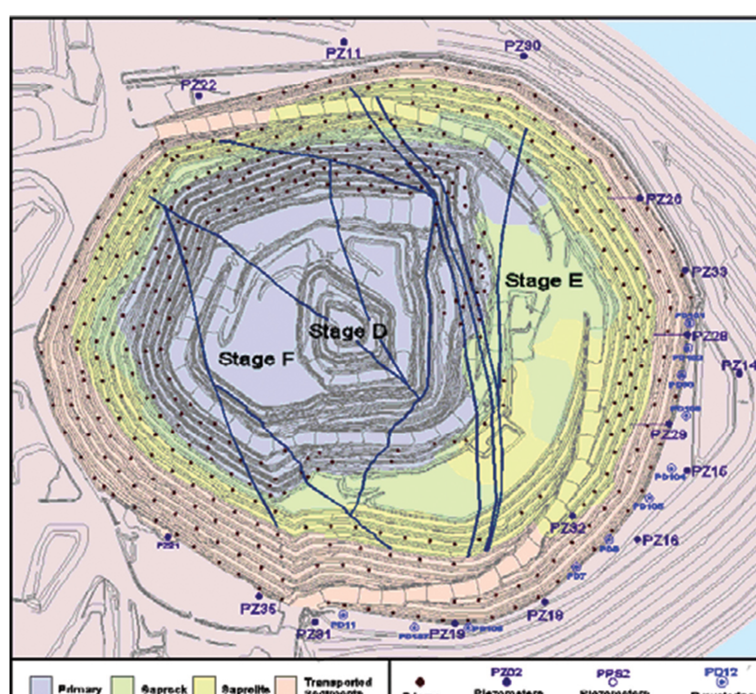
### Figure 16

**Pit with Piezometers and Wells - May 2011.**




### Figure 17

**Pit with piezometers, wells and prisms – November 2012.**



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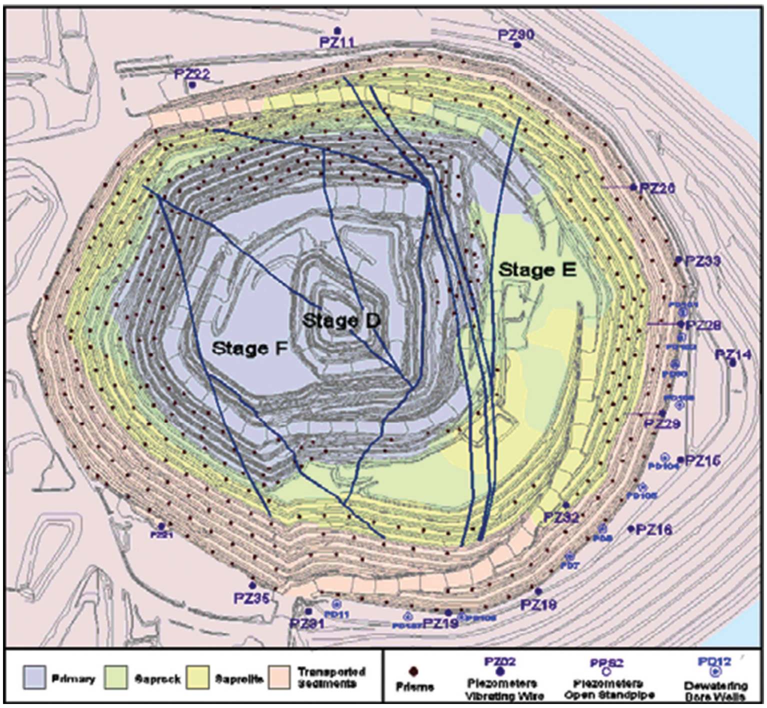
## Figure 18

**Pit with all existing horizontal drains - November 2012.**




was undertaken. The program was set up to reconcile a controlled hydraulic stress with the resultant pore pressure response in surrounding piezometers.

The program involved the (mostly) continuous operation of 10 dewatering bore wells through the first half of 2010, followed by a complete shut down on June 2, 2010. Aggregate pumping discharge prior to the shutdown was less than 300 m³/d. Bore wells PD7, PD19, and PD30 were restarted on 29 June, and the remainder of the wells were restarted on 6 July.

During the one month duration of the recovery test, a widespread response was registered in the vibrating wire piezometers around the pit perimeter. Maximum recoveries were on the order of 10 m (equivalent pressure head increase) and occurred within the saprock and upper primary rock materials, i.e., the main draw zone targeted by the dewatering bores. The distribution of the observed recoveries, in proportional symbol format, is presented in Fig. 14.

Overall, the recovery distribution showed an extensive response to the operation of the dewatering bore network. The majority of response maxima were observed within the deeper-set vibrating wire piezometer gauges, which were usually set in upper primary rock and saprock. These responses also propagated to shallower sections of the piezometer profile, into the saprolite. Responses within the transported sediments were more variable.

The recovery test indicated that the dewatering bore well network exerted a control on the depressurization of the upper primary rock and into the saprock, which assisted in development of an underdrain zone below the saprolite and transported sediments. The extent of these responses was most clearly developed within 200 m offset from the nearest pumping dewatering bore.

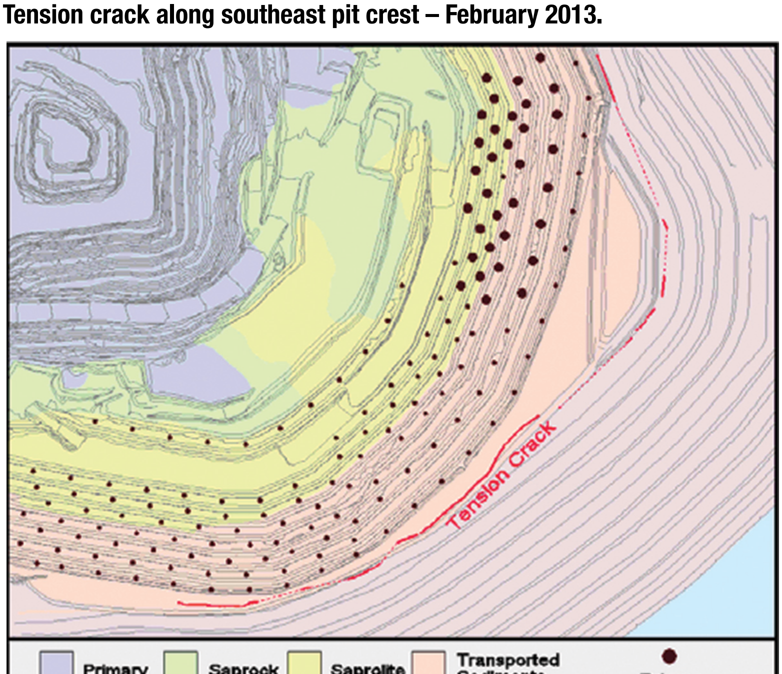
However, the installation and effective operation of dewatering bores had been historically difficult to achieve at the mine – using vertical dewatering bores to target subvertical structures had been met with limited success. As these bores would soon be condemned by the development of the east wall, a decision needed to be made to commit to further (difficult) dewatering bore completions, or to expand the horizontal drain drilling program, which had exhibited some success with pit slope depressurization.

An expanded horizontal drain installation program was considered to be the lowest risk measure to offset the pressure recovery that would result from decommissioning of the pit peripheral dewatering bore wells prior to beginning the Stage G cut. Opportunistic development of new, low yielding, dewatering bores were also included in the plan where observed subsurface conditions permitted these types of constructions.

During 2010, most of the mining effort was

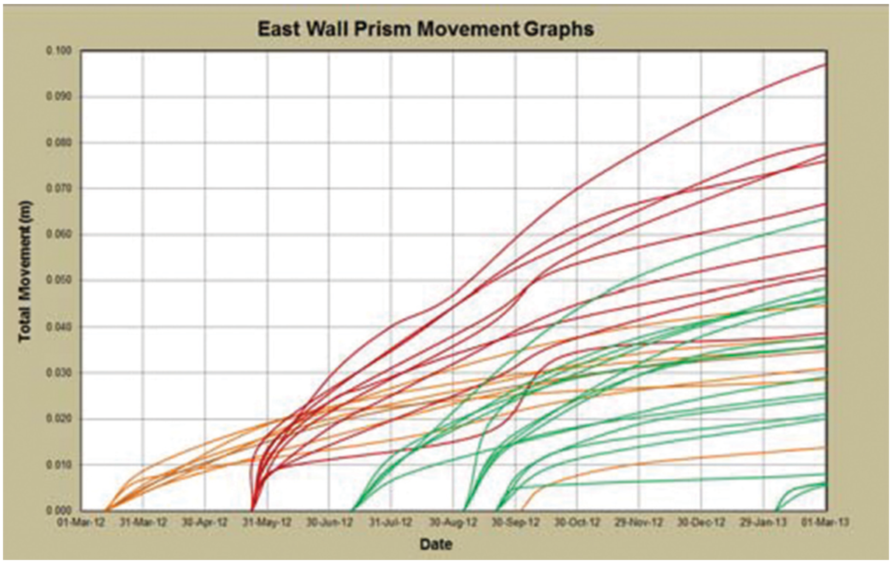
## Figure 19

**Tension crack along southeast pit crest – February 2013.**



## Figure 20

**Graph of east wall prism movement as of February 2013.**




concentrated in mining Stage F, which was on the north and west sides of the pit, where the saprolite was not as thick as it was on the south and east sides of the pit. However, more than 19,000 m of horizontal drain holes were still drilled that year. A few additional infill low-yielding dewatering bore wells were also developed, as an ongoing security measure.

In January 2011, seven new dewatering bore wells were drilled and cased along the south and east pit crest. These bores were designed to be fitted with Airwell displacement pumps, replacing existing dewatering bores that would be destroyed by the Stage G cut. Airwell displacement pumps were also placed in four existing PD bore holes that would not been mined out. The Airwell pumps, shown as magenta in Fig. 16, allowed the very low pumping yields in the surficial materials to be managed. It would soon be demonstrated, due to pump failures and other downtime events that were reconciled against the ongoing pressure monitoring, that these pumping bores could be decommissioned without adverse impact on the control of water within the pit slopes. (At this point in time, the horizontal drains were doing the lion share of the depressurization of the pit slopes.)

In May 2011, the Stage E cut was begun. With the exception of a south haul ramp, which would be mined out by Stage G, Stage E represented the final cut on the south and east pit slopes. As a precaution, despite the fact that the south haul ramp was only a temporary feature, it was decided to drill horizontal drains to a depth of 50 m in the transported sediments and saprolites below the haul ramp. More than 7,700 m of horizontal drain holes were drilled in 2011.

Excavation of Stage E through the transported sediments and saprolites continued without interruption through 2012. As predicted from past experience and other investigations, the transported sediments continued to sustain elevated pore pressure and a high degree of saturation, making it necessary to plate the haul roads as mining proceeded.

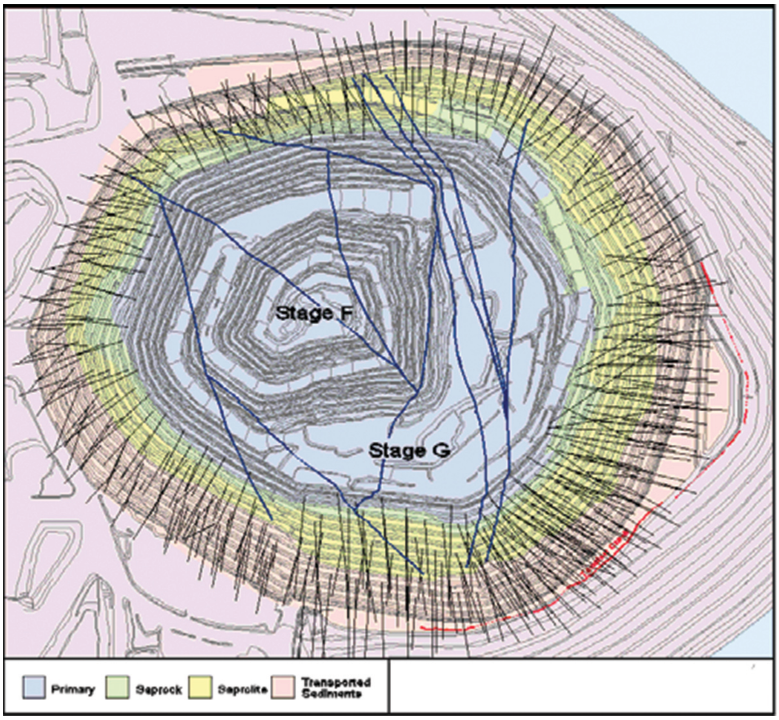
Eight additional vibrating wire piezometers were installed around the pit perimeter in late 2012, creating a semicircle of vibrating wire piezometers that extended around the majority of the pit crest. Each piezometer had multiple gauges, as was the case with the earlier installations. All of the piezometers were added to the data logger system via radio telemetry. The system made uploading data from the piezometers a quick and easy process.

By this time, the automated prism surveying system had been augmented to four survey stations. Prisms had been installed on an on-going basis, producing a tight network of prisms on all of the pit slopes.

By November 2012, the Stage E excavation through the transported sediments and saprolites

## Figure 21

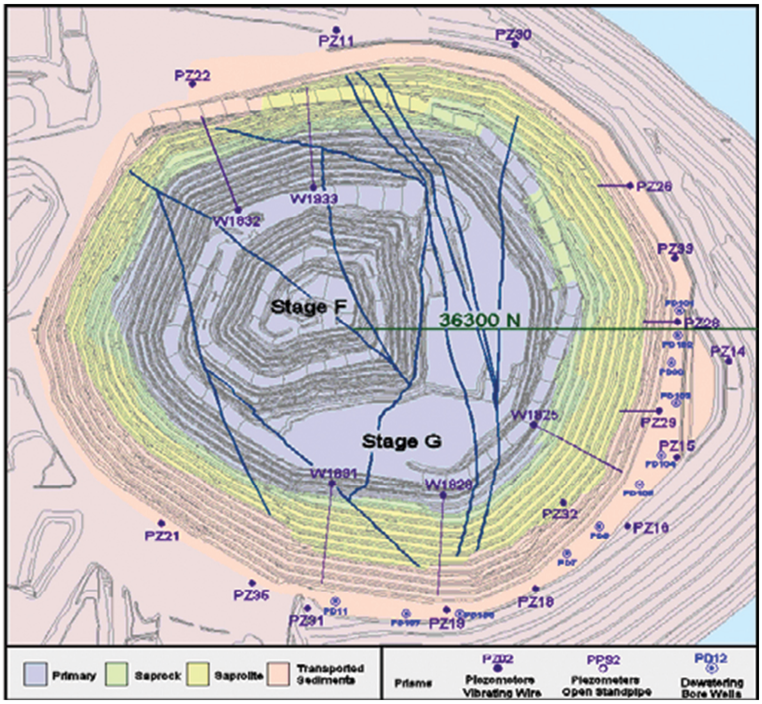
**Pit with all horizontal drains – December 2013.**



# Web Exclusive

## Figure 22

**Pit with piezometers and wells – February 2014.**




was almost complete. Almost 19,000 m of horizontal drain holes had been drilled in 2012.

The Stage G cut would be the first cut through the transported sediments and saprolites on the south and east pit slopes without a haul ramp, which meant the overall slope angle would be the steepest slope that had been mined in those units since 2007. The first bench of the south haul ramp was mined out in January 2013, after which mining of the haul ramp advanced relatively quickly.

In February 2013, a tension crack was observed that paralleled the southeast pit crest. The crack was 2 cm wide at its widest, but nothing more than a hair line in many areas. Twelve pin sets were placed across it, which were measured weekly to determine if the crack was active. The pin sets showed no signs of active movement afterward.

Movement graphs for prisms located in the transported sediments and saprolite in the southeast pit wall (identified as larger circles in Fig. 19) indicated pitward movement on the order of several centimetres, with movement of 7-10 cm for prisms located at the base of the transported sediments, as shown in Fig. 19. The orange lines indicate prisms located above the base of the transported sediments, the red lines indicate prisms located at the base of the transported sediments, and the green lines indicate prisms located in saprolite.

The prism graphs showed that the transported sediments above the basal layer were moving at about the same rate as the saprolites, and were showing a gradual slowing of movement rates. The benches at the base of the transported sediments were moving at about twice the rate as the areas immediately above and below them. Due to the fact that the prism graphs in the transported sediments above the basal sediments, as well as the prism graphs in the saprolites, showed gradual slowing through time, it was suspected that the prism movement was documenting elastic rebound, and not overall slope movement.

The Stage G horizontal drain program was modified based on the results of the previous Stage E drain drilling, with closer spacing and longer holes in areas that had produced the most water. As expected, large flows were observed in some drain holes in the base of the saprolite, as shown in Fig. 24.

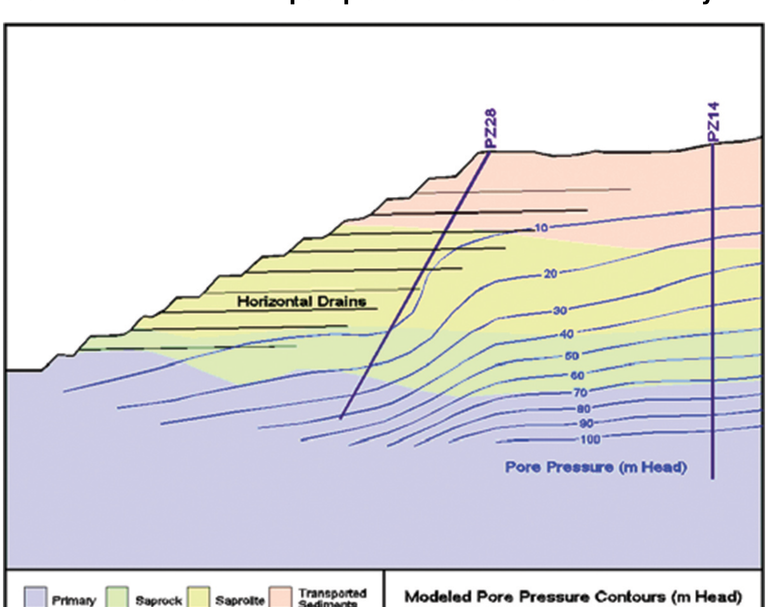
By September 2013, the Stage G excavation through the transported sediments and saprolites was complete, as shown in Fig. 25.

Despite continued creep, the southeast pit slope remained stable, except for several areas of multi-bench failures in the base of the transported sediments, which had retained high ground water pore pressures, and could not be effectively depressurized. Several of these failures are shown in Fig. 26.

The benches along the base of the transported sediments were wet, with small springs scattered along their length in the area with the failures. These failures, while ugly, were

## Figure 23

**Cross section 36300N with pore pressure head contours – February.**



nothing to be concerned about. The benches in the transported sediments above the failures remained intact.

Almost 21,000 m of horizontal drain holes were drilled in 2013. A map with all of the horizontal drains in the pit wall, regardless of the year they had been drilled, is presented in the Fig. 21. It is truly an impressive figure.

In February 2014, piezometers were installed in five horizontal drain holes located below the base of the saprock, as shown in Fig. 22. The purpose of the new piezometers was to allow better calibration of the ground water pore pressure model, which was to be used in a three-dimensional numerical slope stability model in mid-2014.

The updated piezometer information enabled further refinement in the details of the ground water pore pressure model in the transported sediments and saprolites. The modeled pore pressure distribution for cross section 36300N, the same cross section shown previously, is shown in Fig. 23

Pore pressure magnitudes (equivalent metres pressure head) are presented in Fig. 23 along with the horizontal drains that were active at the modelled time step. The available pressure control used to construct the model has delineated a continued response to the drain installations, along with a sustained depressurisation within the underdrained zone.

This ground water model was developed in 3D, after which the resultant grid of pressure heads was passed to the geotechnical team for analysis in their slope stability assessments The three-dimensional numerical slope stability model indicated a factor of safety (FOS) of 1.35-1.40 for the transported sediments and saprolites in the south and east pit slopes.

By February 2014, the pit monitoring system had grown to include hundreds of prisms, in addition to a complete network of vibrating wire piezometers. The prism locations are shown in Fig. 27.

Movement graphs for the same prisms as shown in Fig. 20 indicate an increase in pitward movement, i.e. defined as creep, in the year of time between the two graphs. The prisms indicated movement of 8-13 cm for prisms located at the base of the transported sediments, a maximum of 5 cm for prisms located above the base of the transported sediments, and 8 cm for the saprolites below.

The steady decrease in rate of movement, along with the lack of movement across the tension crack located in February 2013, convinced the authors that the movement was the result of elastic rebound, and was not

## Figure 24

**Horizontal drain flow near base of saprolite - April 2013.**

## Figure 25

**Stage G successful excavation throught saprolites - September 2013.**

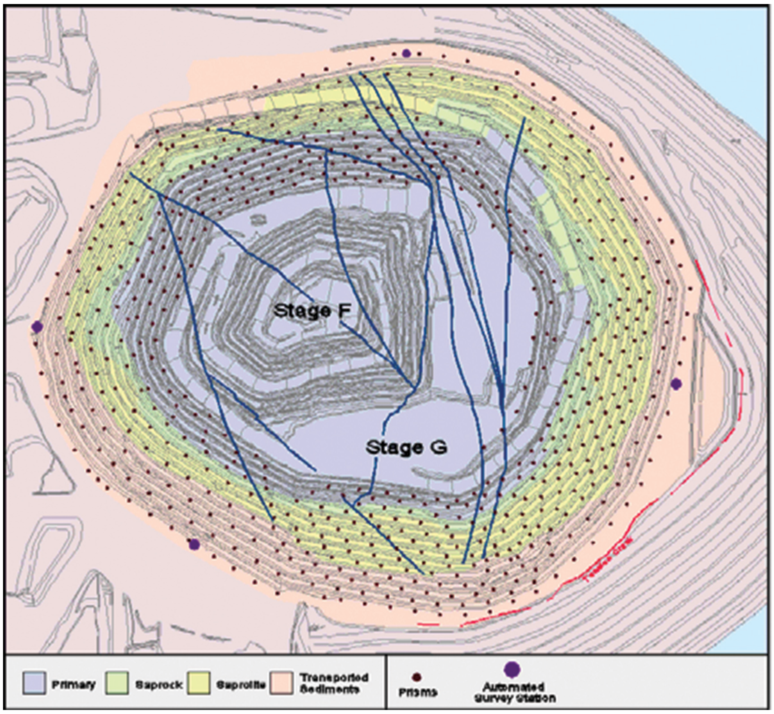
## Figure 26

**Multi-bench failures at the base of the transported sediments.**

# Web Exclusive

## Figure 27

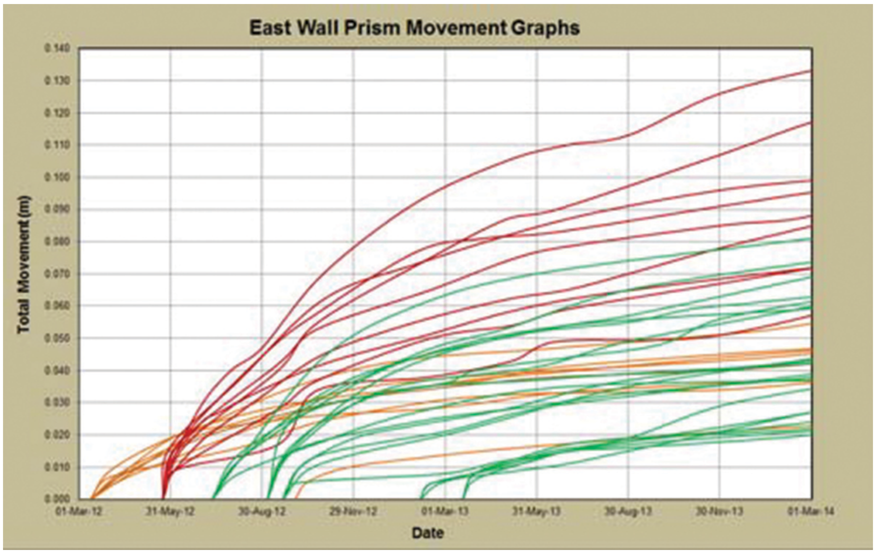
**Cross section 36300N with pore pressure head contours – February.**




indicative of eventual wall instability. Additional multi-bench failures are expected to form at the base of the transported sediments where prism movement of greater than 10 cm have been recorded.

## Figure 28

**Graph of east wall prism movement as of February 2014.**




### Conclusions

Successfully mining through clayey sediments and saprolites requires a good understanding of the distribution of ground water pore pressures and how they respond to employed drainage measures. This is generally the only aspect of slope stability control that can be engineered within an otherwise fixed environment of weak materials that are prone to failure.

An adequate investment in a suitable monitoring system in advance of mining is a prerequisite. Reliable pore pressure analogues or models are also required to assess the effect of various drainage measures on the mine-scale groundwater flow regime over time. Vibrating wire piezometers, strategically staged, are an important tool in the delineation and management of (excess) pore pressure that may exacerbate slope instability. Appropriate familiarisation with the relevance of the outputs from these systems is also required if the critical operating conditions are to be identified to then allow the correct management decisions to be implemented.

It is the opinion of the authors that the failures which occurred at Cowal in 2007 could have been avoided if such an investment had been made prior to mining in 2005. A reliance on the assumed effectiveness of the dewatering bore network early during the development of the mine ultimately distracted from the rollout of the horizontal drain program and the coordinated geotechnical design activities that delivered the final successful outcome of mining through the saprolites. This article documents that this was ultimately achieved.

In the year after the 2007 failures, renewed efforts were made to “get it right.” The results are self-evident.■