Ramp Failure – A Case Study of Monitoring and Management for Controlled Instability

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Abstract

A single haulage ramp and steepened pit slopes are two common design strategies used in open pits operations that aim to balance economics, safety and regulatory requirements in favour of financial returns. With the steepening of pit slopes, instability at one of the various scales of slope configuration will become inevitable. While small scale instability or failures, such as falling scat, crest and berm loss and/or batter failure are manageable, it is the large scale slope instability that is an issue, especially where critical infrastructure such as the haulage ramp is threatened. This paper focuses on the failure of the single ramp access at OZ Minerals Prominent Hill Open Pit Operation, where a multi-batter combination wedge planar-slide style collapse occurred in the slope beneath the ramp. The ramp running surface was reduced from 25m to 4m, resulting in the loss of access to the orebody production levels. The paper considers the precursor instability events leading up to the failure, the monitoring data and the geotechnical factors that contributed. Furthermore, the timeline, management and alternatives for remediation are discussed. This is a study of a failure event, its composition and its implications. It is an example that shows with monitoring and pro-active management the impacts from failure can be mitigated, risks to employees and equipment can be reduced and disruptions to the mine production can be minimised, ultimately providing control over the instability.

1 Introduction

1.1 The area of study

The Prominent Hill deposit is located in the northwest pastoral district of South Australia, approximately 650km north-northwest of the South Australian capital city, Adelaide (Fig. 1). It is an iron-oxide copper gold (IOCG) deposit that lies on the southern margin of the Mount Woods Inlier, of the Gawler Craton.

![Locality map and 2010 aerial photograph of the Prominent Hill open pit.](image-url)
1.2 The mining operation

In October 2006 OZ Minerals Limited commenced the development of an open pit mine to extract copper and gold from the Prominent Hill deposit. In February 2009 the first copper concentrate was produced from the mill and at the time of this publication approximately 372 Mt of material, containing 16.2 Mt of copper ore and 7.6 Mt of gold ore, had been excavated from the pit.

The open pit has four stages scheduled in the life of mine (LOM) plan. Stage 1 is complete, Stages 2 and 3 are underway and development of Stage 4 initiated in early 2011. With each successive cutback the pit will become deeper and the overall slope angle will steepen, until it reaches the economic pit limit at a depth of 470m with inter-ramp angles of 35º - 37º in the north and 47º in the south, for the basement rocks.

To service the concentration requirements of smelter customers in Asia, India and Europe the mill requires 27,500 tonnes of feed a day. In order to meet this obligation, a fleet of four Leibherr 996 hydraulic excavators and thirty-one CAT-793 dump trucks, with payloads of 60 tonnes and 240 tonnes respectively, operate to move a high daily target of 260,000 tonnes of material from the open pit. Of this total, 32,000 tonnes is sent to the run of mine (ROM) stockpiles whilst the remainder is dispatched to waste dumps.

In addition to delivering enough ore to feed the mill, the open pit must deliver a surplus of ore to build stockpiles used in the mill-blend to modify metal recoveries and as a buffer against unforeseen delays in pit production. At Prominent Hill there is an extra pressure to stockpile due to a tight schedule of ore availability in 2012/2013, when a short supply of copper tonnes is realised as the Stage 3 and Stage 4 cutbacks reach a strip ratio capable of ‘filling’ the mill.

1.3 The geology and geotechnical engineering characteristics

Belperio et al. (2007) and Freeman & Tomkinson (2010) describe the tectonic setting and geology of the Prominent Hill IOCG deposit in detail. A brief summary of the local in-pit geology from their work follows, as well as a schematic cross section through the deposit, showing the pit outline at the time of the ramp failure and the final pit outline.

The copper-gold mineralisation at Prominent Hill forms part of a large regional alteration system, related in genesis to the Gawler Range Volcanic / Hiltaba volcano-plutonic event (~1590 Ma – 1585 Ma). The orebody at Prominent Hill strikes east-west and dips sub-vertically to the north, at ~80 degrees (Fig. 2). Mineralisation is hosted by several hematite-rich breccias within a volcano-sedimentary package, of mafic to intermediate volcanics, greywacke, sandstone, shale, limestone and dolomite. The breccias were emplaced within zones of maximum dilation as part of a localised north-dipping reverse fault system. In addition to the significant hematite alteration the breccias have undergone extensive sericite and silica alteration.

The footwall lithologies comprise mafic to intermediate volcanics of the Lower Gawler Range Volcanics. Abutting the orebody to the north is the Hanging-wall Fault Zone, which contains a chloritic fault breccia, graphitic shear zones and a thin package of skarn, granitoid and dolomite in a zone 10m to 20m in true thickness. This fault zone is the northern limit of the orebody, it hosts low grade mineralisation and occurs in a similar orientation to the main orebody. To the north, a skarn-granitoid package and a deformed meta-sediment unit form the hanging wall lithologies.

Unconformably overlying the basement is a cover sequence of sub-horizontal glacial and marine sediments approximately 100m thick. In the north of the pit, a variable unit of Permian mudstone and diamictite lies above the basement rocks, pinching out over areas of harder basement, generally associated with the hematite breccias. Overlying the Permian sediments are the Cadna-Owie Sandstone and Bulldog Shale units, respectively. Significant weathering has led to oxidation of the top 20m – 30m of the Bulldog Shale unit and a 10m thick silcrete layer that often occurs as a surficial cap.

Of the various rock types mined at Prominent Hill, each has contrasting physical and in-situ properties. Each must be handled uniquely and the pit design must accommodate these differences in order to mine the deposit.
optimally. In the basement rock, the greatest geotechnical challenge to mining safely and economically is posed by the skarn domain in the hanging wall.

The skarn is a weaker rockmass containing zones of pervasive chlorite alteration and brecciation. It is highly faulted, with a significant set of structures that trend east-west and dip between 45° and 75° to the south and south-east. At this orientation, the structures daylight into the pit unfavourably along much of the length of the north wall. They form wedges and planes of low shear strength that slide easily and have a typical planar-undulating profile with a persistence that is greater than the batter height (24m).

To protect the integrity of the pit walls in this skarn domain, all interim and final wall shots are pre-split over the 24m double-bench profile. Thereafter, the shots are “free faced trim blasted”, initiating from east to west in order to decrease blast energy moving up into the structures and to minimise damage to the slope. Despite the allowances for the poor rockmass quality in the skarn several instability events have occurred in the domain, the largest of which – the NO3 Ramp failure – forms the subject of this paper.

![Schematic north-south section of the geology in the Prominent Hill open pit.](image)

**Figure 2.** Schematic north-south section of the geology in the Prominent Hill open pit.

## 2 Pre-cursor instability events

### 2.1 Historical rockmass response to mining in the skarn domain

Early indications that the skarn would become a challenge appeared with the first significant exposure of the rock type in the Stage 1 pit. In October 2007 a large dilation zone developed on the northeast wall in the skarn domain. The dilation did not progress into a failure and it was surmised that the tight radius of the pit had provided confinement, while the location of the Stage 1 Ramp in the wall had moderated the overall slope angle, both of which contributing to the apparent stability.

The next indication of the skarns poor rockmass response to mining occurred as the Stage 2 cutback mined through the domain. In March 2010 a single batter failure occurred between the 10100RL and 10088RL berms (Fig. 3a). The instability developed over a period of eight days. Its progression was monitored first by routine
berm inspections and observations of tension cracking and then by increasing prism velocities, as picked up by the automated theodolite prism monitoring system.

Figure 3a. Photograph of the single batter failure beneath the NO3 Ramp, note: blue shading indicates blasted material of the trim shot, 3b - Prism plot showing the failure of the batter.

Failure occurred during the firing of a trim blast directly beneath the zone of tension cracking, with prism movement plots showing a jump of 400mm (Fig. 3b). The failure mechanism was planar-sliding in a batter face with a dip and dip direction of ~65°/176°. A smooth chlorite infilled structure oriented at ~46°/181° was interpreted as the main planar slide structure. The release structure, in the west, was interpreted as a shear zone of crushed and brecciated rock, oriented at ~29°/119°. At the time of failure, tension cracks extended into the NO3 Ramp windrow and onto the running surface. Water was observed seeping from the batter, which would have exacerbated the poor rockmass conditions.

While the stability of the slope and potentially the ramp were compromised, and while their integrity was under investigation the NO3 Ramp was reduced to a single lane across the length where the failure had occurred. A review of the blast design revealed that the location of the blast initiation point had resulted in the bulk of the blast energy being pushed up along the planar structure. This had caused an instantaneous failure with firing of the trim blast.

Several remediation options were available for the failure. The batter could be buttressed, the pit design stepped-out, artificial support could be installed or the failed material could be excavated and the area backfilled. Because of the relatively small size of the failure the former two remedial actions were considered inappropriate. There were concerns regarding the effectiveness of artificial support, by way of cable bolting, due to the dilated and low strength nature of the failed skarn. Therefore, the preferred option was to remove the failed material and backfill. It was also recognised that the south dipping structure would continue with depth at an acute angle into the slope below. By removing the failed material and the next crest at the 10076RL berm the risk of a larger failure developing would be mitigated.

The batter failure was remediated by excavating the failed material to the uncompromised surface and backfilling the slope. The NO3 Ramp was restored back to duel lane by blasting and removing a portion of the batter behind the ramp where the failure had occurred, therefore widening the ramp. Although relatively small in extent, this failure provided plausible evidence to predict future behaviour of the skarn. It was also a valuable lesson in the sensitivity of skarn structures to blast energies.

2.2 Events leading up to the NO3 Ramp failure

In the days leading up to failure there were several signs to indicate the slope beneath the NO3 Ramp was unstable. Figure 4 summarises the details and dates of these events.
The first alert to the developing instability came from the prism monitoring system. In the basement rocks, a threshold of 0.5mm/24hrs is used as a rule-of-thumb to define potential instability. During November the velocities had been gradually increasing for the prisms on the windrow of the NO3 Ramp and the berms below. Prompted by the unusual movement an inspection by the geotechnical department identified the first tension cracks in the ramp windrow and slumping of material in the area. By the 1 December prism velocities on the windrow were varying between 1 – 4mm/24hrs and those on the 10076RL berm between 0 – 5mm/24hrs.

While monitoring this area for signs of collapse the production in the pit had to be maintained. A trim shot at the toe of the area of concern had been blasted and was being loaded. During loading, equipment operators had reported clouds of dust and frequent falling of scat from the 10052RL - 10028RL batter, in particular material was falling from a large south dipping structure, dipping at ~45º. For loading to continue safely three constraints were placed on the work at the toe of the slope. First, all loading was to be done during daylight hours, second a spotter had to be used and third the material had to be excavated such that the excavator was always set back from the batter with a portion of blasted material between it and the face. Under these conditions production could continue.

On the 3 December an 800 tonne wedge of skarn material failed from the 10052RL crest, while the excavator was loading from the area (Fig. 5a). The wedge left behind a large undercut block of material, sitting on the south dipping structure. Prism velocities on the ramp windrow and the 10076RL berm were varying between 1 – 2mm/24hr and 1 – 4mm/24hr, respectively. Although the excavator had been more than 50m away from the wedge at the time of failure, at this stage the risks were considered too high and the unknowns about the developing instability too many. The excavator was pulled from the area, leaving behind a significant portion of minable material at the toe of the batter.

Figure 4. Timeline of the events leading up to the NO3 Ramp failure.

Figure 5. Partial batter failure on the 10052RL - 10028RL batter, north wall skarn, 5a - Proximity of failure to excavator, 5b - South dipping structure, showing water seepage and lipping.
The following day during an inspection of the failed area it was noted that the block of material left behind on the structure was lipping – sliding down and off the block below. There was also water seeping along the length of the structure and out of the wall (Fig. 5b). Prism velocities on the ramp windrow had increased to ~10mm/24hr and those on the 10076RL berm were varying between 5 – 15mm/24hr. The expression of this movement was observed during the inspection of the ramp windrow, which revealed the previously identified tension cracks were increasing in length and dilating. In addition, hairline tension cracks were observed on the running surface of the NO3 Ramp. These tension cracks were the first indication that the instability would extend up into the ramp.

Although the tension cracks confirmed the instability would affect the ramp the extent was still unknown. It was considered unsafe to drive haul trucks and other heavy vehicles over the areas indicated as unstable. Therefore, a bund was constructed over the tension cracks directing traffic away from these areas and reducing the NO3 Ramp to a single lane.

Between the 5 December and the 9 December prism monitoring and visual inspections of the NO3 Ramp and the slope below continued. The prism movement remained constant and no further visual expressions of the instability appeared. On the 10 December the prism movement on the 10076RL berm suddenly began to trend with an accelerating velocity.

3 Ramp failure – December 2010

On the 11 December 2010 a multi-batter wedge planar-sliding failure initiated in the slope beneath the NO3 Ramp. The failure started on the running surface of the NO3 haulage ramp and terminated at the pit floor, ~60m below the ramp crest. The events of the failure, as they unfolded are presented in Figure 6 and described below.

![Timeline of the instability events on the 11 December 2010.](image)

There was a lag of several hours between the initial acceleration of prism velocities and the physical appearance of the developing instability. The first expression of the movement was a batter failure that occurred at 05:00am between the 10052RL berm and the 10028RL berm. Operation personnel working in the pit witnessed the single batter failure in the skarn (Fig. 7a). Within the hour, a visual inspection revealed the tension cracks previously identified along the NO3 Ramp windrow had dilated significantly and multiple new fine tension cracks had developed on the running surface of the ramp. Prism monitoring of the NO3 Ramp crest began to show an acceleration of movement trends and prisms on the 10076RL berm below began to show an exponential acceleration trend (Fig. 7b).
By 09:30am the decision was taken close the ramp to heavy vehicle traffic while more data was collected. Over the next three hours regular geotechnical inspections and focused monitoring of the prisms was undertaken. At each inspection new tension cracks were developing on the ramp running surface and in the windrows. These were marked up in different coloured spray paint and their locations surveyed (Figs. 8a – 8b). By 12:30pm prism velocities were approaching 43mm/24hr on the ramp crest and 94mm/24hr on the 10076RL berm, directly above the area where the single batter failure had occurred that morning.

Although no large fall of ground had thus far occurred a pro-active decision was taken to cease mining activities in Stage 2, until the extent of the instability became evident. At 13:00pm Stage 2 was closed and a windrow placed across the lower NO3 Ramp to prevent access. All personnel left the pit safely and small equipment and vehicles that were able to pass the section of ramp behind the areas where the tension cracks indicated instability, were allowed to tram out of Stage 2. Large equipment that could not pass the area safely, such as the Leibherr 996 excavator which weighed 700 tonnes and had a width of 6m, was left at the bottom of the pit. Monitoring and geotechnical inspections were undertaken throughout the day, crack monitors and extra prisms were installed on the running surface of the ramp and at the night-shift change over the pit remained closed.

The acute phase of the failure and fall of ground occurred in the early hours of the 12 December 2010 (Fig. 7b). Overnight prism velocities accelerated to between 1000mm/24hr and 4000mm/24hr, with deformation magnitudes of 1m – 3m recorded. Failure occurred along two dominant structures, oriented at ~42º/182º (Structure 1) and ~75º/114º (Structure 2) (Figs. 9a – 9d). A thick gouge of puggy infill was present on Structure 1, slickenlines and later desiccation cracks were observed on the surface, the latter indicating the structure had been moist at the time of failure.
The expression of the instability on the surface of the ramp came in the form two large slumps that extended ~18m back from the ramp crest, with a combined lateral extent of 40m (Figs. 10a – 10c). The tension cracks along the ramp extended back 27m from the crest and had a lateral extent of 138m along the length of the NO3 Ramp. The stable running surface of the ramp was reduced from 25m down to 4m. Expressions of instability in the pit slope below showed in the form of multiple batter sized wedge failures, on structures similar in orientation to Structure 2 (Fig. 9b).

Figure 9a. Photograph of the NO3 Ramp failure, 9b - Photograph with structures annotated, 9c - Photograph of the failure from the pit floor, 9d - N-S schematic of the S1 structure behind the pit slope.

Figure 10a. Eastern slump, 10b - Western slump, 10c - Western slump scarp two days after the failure.
4 Remediation

At the time of the ramp failure OZ Minerals Limited was at a unique stage of company growth. The business was worth approximately five billion dollars (AU) and was listed as one of the top 10 companies on the Australian Stock Exchange. What was unusual was that OZ Minerals Limited only owned one operation, Prominent Hill. Unlike other mining companies of equivalent standing this circumstance made its share price comparatively sensitive. With the failure of the ramp blocking access to the only supply of ore the ROM stockpile began to reduce. It was crucial that the remediation – if possible – be managed well and undertaken swiftly. If the work was delayed or took too long, the stockpiles would deplete, the plant would have to shut, and the company would no longer be producing a concentrate. There was a keen awareness that this could have impacts on job security and business sustainability.

4.1 The alternatives

Unlike the March 2010 instability the options for remediation were limited because of the size and depth of the failure and the urgency to access the ore production levels. Two viable options were identified, of which one was to push-back the NO3 Ramp into the wall behind the failure, thus moving the ramp into stable ground and increasing the width to a double running-lane again. Alternatively, the failure could be buttressed with waste rock, supporting the structures that had failed and stabilising the slope.

In order to move the ramp back, the pit walls and ramp sections above the failed portion would have to be reconfigured and pushed north approximately 30m. The plan would see 696,000m$^3$ of material drilled, blasted and hauled, all from within a narrow mining width. In terms of time, it was estimated the work would take seven weeks to complete.

To build a buttress of sufficient support capacity an estimated 52,000m$^3$ of suitable quality waste material would be required. Since the unaffected running surface width of the ramp was 4m and the slope below would not yet be stabilised, the material would have to be sourced from the pit floor below the failure. The buttress design would step-out from the original pit slope design, resulting in a modified Stage 2 pit cutback design. With each advancing mining bench, the step-out would increase in width and any ore beneath would become inaccessible. The time to completion and therefore access to the ore would be two weeks from the start of construction.

Critical factors taken into consideration were safety of personnel during and after the remediation, the volume of ore stockpiled and the targets for copper metal production in 2011 and the LOM schedule. Pushing the ramp back created narrow mining complications and delayed entry into Stage 2 by an extra five weeks. By building the buttress, the modified Stage 2 pit design would be short an estimated 900,000t of copper ore at 1.39% grade and 160,000t of gold ore at 0.88% grade. The ore would not be sterilised but rather it would be deferred from the Stage 2 cutback and to the Stage 4 cutback and picked up in 2015. However, the immediate loss of ore would contribute immense pressure to meeting the mining and milling schedule and OZ Minerals business plan.

With sufficient stock of ore on the ROM, it was decided to take the safer, quicker remediation option and build the buttress. In addition, the pit slope beneath the failure would be in the dolomite and shale domains, adjacent to the skarn. Therefore there would be no further risk of failure from the same structures in the slope below, as there had been in the March 2010 instability.

4.2 The plan and the action

The plan was to re-enter Stage 2 and construct the buttress using an excavator, three haul trucks and track dozer and sourcing waste material by “rat-hole” mining the pit floor. The buttress would be built in two parts, first a lower buttress would be built across the toe of the unstable slope, from the pit floor up. Thereafter, an upper buttress would be built by tipping material from the NO3 Ramp edge above. The duel buttress construction was designed to stabilise the toe of the failure before inducing an increase in driving forces on the failed berms by loading them with tipped material. Tipping for the upper buttress would commence on the ramp from the west, and would move east. This ensured personnel and equipment were not working on unstable, unsupported ground.
The lower buttress was designed to a width of 30m and a height of ~10m. The completed buttress was designed to a height of 60m and an angle of 37°. The berm width adjacent to the buttress was 15m, while the berm/batter configuration in the slope below the buttress was the same as the original slope design (Fig. 11).

Remedial action could not be taken until sufficient data was collected to gauge the extent of the instability and confidently determine that slope was no longer failing. Once movement trends for prism velocities showed decelerating trends the remediation plan was developed and implemented. Figure 12 denotes the sequence of events and timeframes for the remediation, from the date of ramp failure to completion of the buttress construction and access to the ore supply.

![Figure 11. Modified Stage 2 cutback design, with buttress and resulting “step-out” in pit design.](image)

![Figure 12. Timeline and sequence of events during ramp remediation.](image)

In preparation for the remedial work two safety tools were used to detail the steps required and ensure all new and irregular activities were carefully planned. The first was an assessment of the risks involved in the remediation. The risk assessment referenced material from the South Australian Occupational, Health, Safety and Welfare Acts and Regulations, as well as the Australian and New Zealand ISO 31000 standard. Furthermore, it included the input from a cross-section of personnel with varied backgrounds and work roles in the open pit operation. The hazards, consequences, controls and constraints identified in the risk assessment are summarised in Table 1. Thereafter, a series of Job, Safety and Environment Analyses (JSEA’s) were developed to detail a framework of agreed steps to be followed. Using the JSEA’s OZ Minerals was able to identify and control hazards and provide a plan for each work component.

The risk assessment was undertaken within six days of the failure and within a week equipment had been moved back into the pit and remediation had begun. The construction of the lower buttress was completed in three days and the construction of the upper buttress in six days. A time series of photographs taken of the construction is shown in Figures 13a to 13f.
Eighteen days after the failure the remediation was complete and the pit was re-opened, with access to the ore and pit production resuming.

Table 1. Summary of the risk assessment undertaken for the NO3 ramp remediation.

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<th>Hazards</th>
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<td>Personal injury</td>
<td>Personal injury and illness e.g. serious injury (LTI) to single fatality</td>
<td>Prism monitoring (focus area and increase frequency by switching off alarms, collect data between moving equipment over potentially unstable ground)</td>
<td>During remediation: All other mining activities to cease in Stage 2 (e.g. blasting for material to be used in construction of buttress). Restrictions to prevent non-critical personnel entering the pit below a specified berm level.</td>
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<td>Damage to equipment</td>
<td>Financial e.g. loss or damage to machinery including production losses caused by loss or damage</td>
<td>Visual inspections</td>
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<td>Further ramp failure</td>
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<td>Crack monitors</td>
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<td>Changes in environmental conditions</td>
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<td>Experienced operators</td>
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<td>Day shift work only</td>
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<td>Slope movement thresholds (no work unless 0mm/24hr on ramp surface and no accelerating movement on 10076RL berm)</td>
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<td>Dry weather only</td>
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<td>Dedicated radio channel for team involved in remediation</td>
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<td>Area controller assigned</td>
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<td>Develop a JSEA for dumping, hauling and construction</td>
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<td>Windrows to direct truck operations and restrict access to open edge of crest</td>
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<td>Spotters for the dozer</td>
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<td>Installation of prisms along new ramp crest windrow as developed</td>
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<td>JSEA for design of toe buttress and method of construction of buttress</td>
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5 Conclusions

An over cautious pit design is undesirable. As a result there are frequent instability events occurring in open pits throughout the mining industry. These events are acceptable, provided they can be managed safely and without threat to the business. At OZ Minerals’ Prominent Hill Operation the ramp failure on the only access to the ore supply heightened the already demanding pressures on the pit production. The acute fall of ground occurred over a period of hours but the instability in the lead up to the failure began almost two weeks before. The difficulty during this period was in maintaining pit production as the instability developed and whist confronted with uncertainties over the extent and magnitude of the pending instability. Remedial plans could not be developed or actioned until there was confident data indicating the failure had ceased. Just over a week elapsed before the remediation initiated, during which time the options for the corrective work were considered, the risks assessed and a work plan developed. The reconstruction of the ramp and slope was completed within ten days of commencing the work and eighteen days after the multi-butter failure event closed the pit, pit operations and production were restored. This swift and successful management of the failure event was facilitated through the knowledge of the skarns’ historical mining performance and through the collection of data, using the prism monitoring system, visual inspections and crack monitors. These tools enabled OZ Minerals to manage the failure by limiting the impacts, and as a consequence they provided a control over the instability.
Figure 13. Time series photographs of the buttress construction: 13a - Slope and ramp after the failure, the material at the toe of the slope is from the failed 10076RL and 10052RL batters, 13b - The completed lower buttress, 13c,d - Partially constructed buttress, 13e,f - The completed buttress.

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7 References
