Assessment, Monitoring and Ground Control Management of Rock Slope Stability at the Red Dog Open Pit Mine

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Abstract

Red Dog Mine is a zinc-lead-silver mine located in northwest Alaska. The Red Dog deposit consists of three sub-horizontally stacked, folded and faulted thrust sheets. The structural geology of the mine area is highly complex and extremely variable. Monitoring and failure mitigation measures have been implemented in the Main Pit at the Red Dog Mine. These measures include a revision of the structural geological model, daily field wall inspections and data collection, monitoring of slope movement, and on-going geotechnical stability assessment and analysis. Particular emphasis has been given to identifying potentially adversely oriented major faults and geologic contacts which may exist behind the proposed ultimate pit walls. Pit walls inspections, together with slope movement monitoring data, allows for small scale (bench size) to large scale (multi-bench) instabilities to be proactively identified. The monitoring of slope displacement is undertaken using a robotic total station prism monitoring system. Formerly, the updated structural geology interpretation has been used to update stability assessments, re-design certain areas of the Main Pit, and carry out hazards and risk assessment of the pit walls. Latterly, the interpretation of survey data has allowed for long term hazard assessments, stability assessments and analysis, and day-to-day geotechnical support for the on-going safe operation of the open pit. This paper briefly describes the geologic model that was developed to guide the forecasting, assessment, monitoring, and mitigation of geotechnical hazards and risks in the Main Pit at Red Dog Mine. A discussion is provided regarding the ground control management plan which has been implemented to mitigate the risks associated with potential slope instability. The identified zones of instability, known as geotechnical hazard zones (GHZ), are presented, including a geotechnical description, anticipated future behaviour, actual slope performance, required pit design modifications and remedial measures being implemented. Results of the stability analyses including the underlying assumptions, methodology, input data and limitations are also discussed.

1 Introduction

Red Dog Mine is one of the world's largest producer of zinc and a significant producer of lead. The deposit is hosted in the Kuna Formation in the western Brooks Range in Alaska, 90 miles north of Kotzebue. In 2010 the mine produced 538,000 metric tons of zinc and 109,900 metric tons of lead, after hauling a total of more than 11 million tons of rock. The reserve is exploited by open pit mining as a load-and-haul operation, using conventional drill and blast mining methods.

The hazardous nature of open pit mining presents unique challenges to the engineers, who have to provide a reliable design for safe and economic mining operations. Ground control management should be regarded as an essential instrument to manage the risks associated with deep excavations in complex geological settings. This paper illustrates the ground control management plan implemented at Red Dog Mine to respond to slope instability and allow for the continued safe operation of the mine. Various components of the ground control program are described, in particular:

- on-going geotechnical data collection;
- monitoring of ground movements;
- monitoring of surface and groundwater conditions; and
- definition of design changes and remedial measures.
2 Production history

The first official recorded notice of the presence of a mineral deposit in the Red Dog area was included in the 1955 report of the USGS geologist Irv Tailleur, who observed iron-oxide staining along Ferric Creek. In 1968 a “bush” pilot, named Bob Baker, who was engaged in part time prospecting, reported to Tailleur the presence of similar staining in a creek at the current Red Dog mine site. More than 2% Pb and more than 1% Zn were detected semiquantitatively in rock hand samples, and more than 10% Pb was analysed in stream sediment samples (Tailleur, 1970). In recognition of the assistance of the bush pilot in first recognizing the area and its potential significance, the USGS named Red Dog Creek after the pilot's pet red dog, Baker's frequent and faithful traveling companion (Mowatt et al., 1991).

Active exploration of the site and adjacent area began in 1975 and the first claims were staked in 1978. In 1980, Cominco Alaska drilled 9 holes that totaled 915 meters, to determine the size of the deposit. Geologic mapping at a scale of 1:12000 was done in the region from 1977 to 1984. The Red Dog deposit was mapped at a scale of 1:2400 in 1982 and 1983. One hundred core holes were drilled from 1981 to 1984 for a total of 9800 meters (Williams, 2000).

Four deposits have been determined in the Red Dog area: Qanaiyaq, Main, Aqqaluk, and Paalaaq. Proven and probable ore reserves in the four Red Dog deposits have been estimated at 55.3 million tones at 15.9% Zn and 4.0% Pb.

The Red Dog mine was developed in 1982 under an operating agreement between the Northwest Alaska Native Association (NANA) and Teck Alaska, Inc. (Teck), a U.S. subsidiary of Teck Resources Limited. NANA is a Native corporation owned by the Iñupiat people of northwest Alaska. NANA owns the land on which Red Dog Mine is situated. Under the negotiated agreement Teck would operate the Red Dog mine and fund further exploration and mining. The mine development began in 1986 and construction was complete by November 1989. Operations and production began in December 1989. Zinc and lead concentrates from the mill at Red Dog are trucked 84 km to the south to a port facility at tidewater where they are stored until loaded onto vessels. Red Dog has only a brief summer shipping season (July to September) during which the zinc and lead concentrates are shipped to markets in North America, Asia, and Europe. Mining of the ore reserves in the Main deposit are expected to be exhausted in 2011, however stripping of the Aqqaluk deposit, ahead of starting open pit mining, commenced in May 2010.

3 Site conditions

3.1 Geological settings

The four Red Dog deposits are located in the De Long Mountains in the northwestern Brooks Range Zn-Pb-Ag belt (Morelli et al., 2004). The Brooks Range is a broad, east-west trending, approximately 1,000-km-long, fold and thrust mountain belt that spans the width of northern Alaska.

Eight stacked and folded thrust allochthons have been recognized in the De Long Mountains. The stacked thrust slices were subjected to at least two directions of compression (Moore et al., 1986). The structurally lowest allochthons consist of Devonian through Cretaceous clastic and chemical sedimentary rocks. The uppermost allochthons contain Jurassic or older mafic and ultramafic igneous sequences (Kulas, 1992). The Endicott Mountains allochthon is the second lowest allochthon in the Brooks Range and includes the Kuna Formation (Moore et al., 1986).

The Kuna Formation of the Lisburne Group hosts the giant Red Dog and related Zn-Pb-Ag massive sulfide deposits (Mull et al., 1982). The Lisburne Group includes both deep and shallow water sedimentary facies and local volcanic rocks. The rocks have been extensively disrupted by thrusting. The Kuna Formation consists of black carbonaceous (organic-rich) siliceous shale, mudstone, chert, and locally abundant carbonate turbidites (Mull et al., 1982; Dumoulin et al., 2004; Young et al., 2004). The Kuna Formation is divided into two units, the
Kivilina unit and the Ikalukrok Unit. The Kivalina unit is the stratigraphic footwall to mineralization, which is contained in the Ikalukrok Unit. The Kuna Formation is overlain by chert and shale of the Siksikpuk Formation. In general, at Red Dog Mine the ore material occurs as massive sulfides and veins with complex assemblages of (in order of decreasing abundance) sphalerite, galena, pyrite, and marcasite. Textures include replacement, vein, breccia, and disseminated ores with various amounts of gangue minerals (e.g. barite, quartz) (Rombach & Layer, 2004). Several small intrusive bodies, including a felsic sill and a mafic diabase dike, are present at the southern and northern ends of the Main orebody, respectively (Moore et al., 1986; Werdon, 1999).

### 3.2 Structural geology

Mineralization is often controlled by geological structures and zones of weakness such as geological contacts, faults, fractures zones and dykes. Geological structures also control the stability of rock slopes. Mapping and understanding of the structural geology is a critical component for the development of an effective geological model, which can be used to address geotechnical concerns, to identify potentially unstable slopes and to drive the implementation of mitigation measures.

The structural geology of the Red Dog deposits is quite complex and is characterized by three subhorizontally stacked, internally imbricated, and regionally folded allochthons. These allochthons define a dominant northeast-southwest structural grain, which is offset by abrupt west-northwest/east-southeast along-strike structural changes that involve the entire allochthon stack. The allochthon stack is also offset by west-northwest/east-southeasterly trending to northwest/southeast trending extensional faults and by transverse zones of similar orientation in the contractional structures. Variations in the orientations of the contractional structures and in tectonic transport direction are interpreted in terms of underlying oblique and/or lateral ramps, which may have been controlled by inherited basin margin structures. Movement on these ramps resulted in antiformal stacking of the lower thrust sheets of the Endicott Mountains allochthon and folding and uplifting of the higher allochthons into a series of regional synforms and antiforms (Vera et al., 2004).

As shown in Figure 1, the Endicott Mountains allochthon, which contains all known strata-bound sulphide deposits in the Brooks Range, is divided into three fault-bounded structural plates (Young, 2004): the Red Dog Creek plate, the structurally lower Wolverine Creek plate, and the structurally higher Key Creek plate. The Red Dog and Key Creek plates contain all of the Zn-Pb-Ag mineralization. Large-displacement thrust faults have thrust the rocks of the Red Dog plate and stacked three repeating subplates of the stratigraphic sequence. These three subplates are referred to as Lower, Middle and Upper Red Dog plates.

![Figure 1. Thrust faults and plates at Red Dog Mine (Seago, 2010). The URDT1, URDT2, etc. indicate thrust splays off the URDT present in the Upper Red Dog Plate (URDP), which occur throughout the pit.](image-url)
The first geologic model, dated 2004, included four major thrust faults dipping south to south-east. From the top to the bottom of the Red Dog plate, these thrust faults were called LV, South Mélange, Median and Basal Fault.

To date, there have been more than 1,100 boreholes drilled within the Red Dog deposits, which add to more than 150 kilometers in total length. Pit wall mapping has been carried out in the Main pit since mining started. Structural cross sections have been constructed using the Red Dog’s extensive geological database and examining the pit wall mapping (Seago, 2010). The cross sections are oriented northeast/southwest and northwest/southeast, parallel to thrust movement direction. These structural cross sections have been digitized and a three-dimensional structural model has been built (Fig. 2).

The updated structural geology interpretation renames the thrust faults as Red Dog Roof Thrust (RDRT), Upper Red Dog Thrust (URDT), Median Red Dog Thrust (MRDT) and Lower Red Dog Thrust faults (LRDT) respectively. The RDRT occurs at the base of the Key Creek plate and constitutes the roof of the Red Dog plate. The URDT and MRDT are interpreted to occur within the Red Dog plate and to be located at the base of the Upper and Middle Red Dog plates respectively. The LRDT occurs at the top of the Wolverine Creek plate (Seago, 2010). The deposit has a bowl-shaped appearance, reflecting the structure of the footwall rocks. The URDT is interpreted as sub-horizontal with a gentle southerly to southwesterly dip in the centre of the Main Pit. The MRDT and LRDT are mainly considered as northeast/southwest trending. The MRDT exhibits a moderate northeasterly dip along the west side of the Main Pit, which decreases toward the centre of the pit. The LRDT is interpreted as shallow northeasterly and southwesterly dipping respectively along the west and east side of the Main Pit.

A northwest/southeast trending lateral ramp system, called the D2 Fault, is interpreted to dip steeply toward the northeast and the southwest along the west and east side of the Main Pit respectively. In some areas, mainly along the west side of the pit, thrust faults have been displaced along the lateral ramps, while in other areas, largely along the east side of the pit, the thrusts merge to form a single fault along this lateral ramp structure.

Figure 2. Three-dimensional model of the Main Pit (Feb 2010) and interpreted geological structures – Looking South.
3.3 Hydrogeology

Thermistors installed in the vicinity of the open pit indicate that the base of the permafrost varies from approximately the 600 to 700 ft elevations. According to the current mine plan, the ultimate pit will be mined down to the 475 ft elevation, below the base of the permafrost.

Piezometers installed below the permafrost in the vicinity of the pit indicate groundwater head elevations in the range of 850 and 950 ft, approximately 250 ft above the base of the permafrost. These head elevations are well above the base of the permafrost, and indicate that the permafrost is acting as a confining layer and that there are high groundwater pressures within the unfrozen rocks below the base of the permafrost.

A review of the thermistor data installed at the crest of the pit indicates that the depth of the active zone is relatively shallow at the crest of the pit (less than 12 ft). Thermistors installed in the Red Dog Creek valley bottom suggest that the ground is thawed to a depth of at least 50 ft and below this depth temperatures are below zero.

4 Ground control management

An open pit mine is a complex engineering system with many sub-systems that need to function in an integrated manner for the mine to operate safely and economically. Management of ground conditions in open pit mines is an essential element of mine planning and design. Ground control activities should include data collection, definition of excavation geometry and methods, drilling and blasting design, monitoring strategies and emergency action procedures. Geotechnical monitoring and inspection is required to identify instability issues of the pit walls and will allow for design modification and remedial measures to be implemented in a timely manner.

A ground control management program has been implemented at the Red Dog Mine since the early stages of mine development. This program included mapping of geological structure, monitoring of ground movements and recording general ground performance. A review of the pit slope stability was carried out between the end of 2009 and the beginning of 2010. This review comprised an update of the structural geology model, to guide the evaluation, monitoring and mitigation of geotechnical hazards and risks.

4.1 Data collection

Phase and final walls should be mapped after they are mined, but before access is affected by subsequent mining. The complete mapping format will depend on geological requirements. Particular attention should be given in the field to specific aspects which may potentially affect slope design and wall stability.

Mapping at Red Dog Mine was completed on a bench-by-bench scale. However, until the recent geology revision (2009/2010), these maps had never been compiled into a “master” map of the entire pit, in which discrete continuous structures are correlated across benches. Consideration has been given to the evaluation of occurrence, orientation and continuity of all the structures that may affect the slope performances throughout the pit and the verification of the assumed rock mass strength and hydrogeological conditions.

4.2 Monitoring program

A comprehensive slope monitoring program that includes visual inspection and slope stability monitoring is an essential part of a ground control management plan. The program should provide the following:

- a basis for maintaining safe operational procedures;
- general coverage of the open pit in order to provide “background” data and early indication of slope movements;
- specific coverage to delineate, track and manage moving slopes;
- input to short- and long-term planning with respect to areas of potentially unstable ground; and
- support for investigation of potentially unstable slopes.
4.2.1 *Visual inspection*

Regular visual inspection of the workings is an important responsibility of all personnel involved in a mining operation. Pit wall inspections allow for small scale (bench size) to large scale (multi-bench) instabilities to be proactively identified. Once identified, controls can be put in place and potential hazards can be communicated in a timely manner to all personnel.

The occurrence of rockfalls, crack observations and other hazards at Red Dog Mine is reported to the pit supervisor and to the geology/geotechnical engineering department for evaluation. Visual inspection of pit crests, active benches, general slope stability and shot surface conditions is conducted on a regular basis by engineering staff. Observations from these inspections are compiled in a consistent format to establish a formal record of pit slope performance over time. Additionally, photographs are taken during inspections. These include photographs of specific areas of interest along the slopes taken during regular site inspections and photographs taken from fixed stations around the pit. All these photographs contribute to maintaining a qualitative record of pit slope performance over time.

4.2.2 *Slope stability monitoring*

Slope stability monitoring programs for open pit mines are intended to assess the stability performance of the pit walls as the excavation progresses and to detect unexpected slope stability conditions in a timely manner so that remedial measures can be implemented before slope failure develops. In the case of marginally stable slopes, the monitoring data will assist in determining when it is no longer considered safe to be working below or near the pit walls and whether it is acceptable to re-enter the affected areas.

For this purpose, survey monitoring is typically implemented soon after the excavation of the pit begins in order to establish a baseline. Monitoring prisms or GPS monitors are installed on successive benches as the pit is excavated in order to monitor ground surface deformations as the pit walls are being excavated. Pit wall stability monitoring procedures are also typically integrated into the mine operating and health and safety procedures.

Slope movements have been monitored at Red Dog Mine using survey prisms. The monitoring program started in November 2002 with the installation of prisms on both the west and east walls of the South Pit. An automatic prism monitoring system was set up in the second quarter of 2010 and started working in June 2010. The system comprises two Leica robotic total stations integrated with the GeoExplore software, which includes effective data management of multiple monitoring systems. Initial operating problems and challenges due to survey distances, mining conditions and climatic conditions have been promptly resolved by employing rigorous surveying practices and modifying various components of the survey system.

All slope failures are unique, and each failure will exhibit different total displacements and velocities prior to accelerating toward a non-recoverable catastrophic failure state. Consequently, it is not possible to accurately pre-determine an absolute total displacement or velocity criteria for each individual failure for the purpose of determining if it is safe to continue to mine beneath a marginally stable slope. Therefore at the Red Dog Mine, a relative displacement or rate criterion is used according to which slope movement acceleration, interpreted from displacement versus time graphs, are used as the primary method for assessing the potential for catastrophic slope failure. Prism velocity is also used as an indicator of slope stability performance. Acceptable thresholds have been estimated based on the review of all available historical monitoring information concerning the Red Dog pit walls. A consistent monitoring velocity of approximately 2 inches per day (50 mm per day) is used as a threshold limit above which mining cannot be allowed to continue in specific locations of the pit. As the survey monitoring systems at Red Dog exhibited an accuracy of the order of 1 inch per day (25 mm per day), this threshold is considered large enough to prevent too many false alarms. Current policies require that mining below a slope is discontinued when the deformation rate exceed 2 inches per day and mining is not resumed until the observed velocity has decreased to less than 1 inch per day, or the given slope has been determined to be safe based on the assessment of the mine geotechnical department.

In addition to using a velocity threshold criterion, the rate of change of velocity or acceleration of the monitors has also been considered when determining safe procedures for mine operations in proximity of part of the walls
exhibiting relatively large deformations. For instance, if more than one prism, in an area with reasonable coverage, shows acceleration for three consecutive readings above the accuracy of the monitoring system, then mining below the unstable slope is generally stopped. Figure 3 qualitatively describes the procedures for assessing prism accelerations.

Operating procedures not only provide the assumed threshold criteria for slope stability, but they also include evacuation and re-entry scenarios which would need to be communicated to the workers, should the slope monitoring data exceed the defined threshold criteria. The real time monitoring system implemented at Red Dog Mine has proved to be successful in early detecting of incipient failures and in allowing mining to be safely and efficiently carried out under pit slopes that were experiencing significant displacements.

5 Geotechnical Hazard Zones

Slope failures pose a safety hazard to mine personnel and can significantly impact the recoverable reserves. As part of the ground control plan implemented at Red Dog, potentially unstable slopes have been identified in the Main Pit and named geotechnical hazard zones (GHZ). In these zones geological structures, hydraulic conditions and pit wall configuration have been recognized as such to have potential negative effect on the pit wall stability. The location of the geotechnical hazard zones and a description of the Main Pit areas, are given in Figure 4.

5.1 Geotechnical Hazard Zone 1

The Geotechnical Hazard Zone 1 (GHZ1) is located in the north wall of the North Pit (Fig. 4). Movement that has been observed in this area is assumed to have occurred along discrete structures/faults. Unravelling ground conditions in proximity of fault zones have also been observed. Potential movements in the GHZ1 are being monitored using survey prisms. Mining in this area was temporarily stepped-out in the second half of 2009 to allow for the completion of the structural geology review. Subsequently, slope re-design for this area was completed based on the identified potentially adversely oriented major faults and geologic contacts behind the ultimate pit walls.

Figure 5 highlights the significant geologic structures which have been identified along the north side of the North Pit. These structures include the URDT, MRDT and LRDT faults, which in this zone exhibit a southerly to southeasterly dip, and a southwesterly dipping lateral ramp fault (D2 fault), that is interpreted to exist to the south of the north wall. The MRDT and URDT faults have merged to form a single fault along this lateral ramp structure (Fig. 5). Bedding and geologic contacts with the Kivalina shale dip toward the southwest sub-parallel to the D2 fault.

![Figure 3. Prism data interpretation.](image-url)
The previous geologic interpretation indicated that a steep southwesterly-dipping fault was located behind the north wall, and it was previously thought that sliding along this fault was the cause of the ongoing monitored instability. The revised geologic interpretation indicates that major, unfavorably oriented faults are not expected to be encountered behind the north wall and that the observed slope movement is the result of planar failure and raveling along the undercut bedding. In order to provide catchment for the ravel debris a step-out was established along the toe of the north wall.

### 5.2 Geotechnical Hazard Zone 2

The Geotechnical Hazard Zone 2 (GHZ2) is located in the west wall of the North Pit (Fig. 4). A large (approximately 12,000m³) rock wedge failed in this zone in July 2009. The structural geology review indicated that the failure occurred as the result of a multi-bench failure along the northwest striking, steeply dipping D2 lateral ramp (55/062 dip/dip-direction) and a northeast/southwest striking fault (40/140 dip/dip-direction).

![Figure 4. Configuration of the Main Pit at Red Dog Mine and location of the geotechnical hazard zones (Base contour map supplied by Teck Alaska Inc.).](image-url)
As for GHZ1, slopes in GHZ2 are monitored using survey prisms and the pit walls have been permanently stepped out of design. The potential for similar structural conditions to occur in the area north of the failed wedge was recognized. By projecting the measured fault orientations behind the proposed ultimate wall, it was recognized that the line of intersection of the wedge that is formed by the faults is located behind the pit wall and that the fault does not daylight in the wall. However, this interpretation was uncertain as the D2 fault is very continuous and can be expected to extend to depth behind the ultimate wall, whereas the continuity of the northeast/southwest striking fault that formed the north limb of the wedge is doubtful. In order to confirm that a second wedge did not exist and that design modifications would not be required, monitoring prisms were installed on the wall within the limits of the potential wedge and wall mapping was carried out as mining progressed looking for evidence of both faults below the existing step-out. To date, no significant sign of movement has been recorded on the pit wall in GHZ2.

5.3 Geotechnical Hazard Zone 3

The Geotechnical Hazard Zone 3 (GHZ3) is located in the west wall of the South Pit (Fig. 4). Prism monitoring indicated that in this area slope movement has occurred since July 2007 from an approximate bench elevation of 1,025 ft (approximately 200ft below the pit crest) and extending to the pit floor. At that time, the geological interpretation, dating back to 2004, indicated the presence of a southeasterly dipping thrust fault (Basal Fault later renamed MRDT fault) behind the wall. The fault was interpreted to be undercut between approximately the 650 and 700 ft elevations. A back-analysis of the slope was carried out in order to evaluate the strength parameters for the shales in the area where instability had developed. Further stability analyses were carried out to assess the effectiveness of a toe buttress on the stability of the slope. The results of these analyses showed an increase in factor of safety between 20% and 40%, for various cross sections, with the addition of a toe buttress. A buttress was constructed between the 700 and 750 ft elevations (Fig. 6), and the prism monitoring data showed a decrease in movement rates after the buttress was built.

The review of the structural geology shows the presence in this zone of southeasterly to easterly dipping LRDT and MRDT faults, easterly to northeasterly dipping D2 fault and geologic contacts parallel to the LRDT and MRDT faults. The geologic structure in the GHZ3 area is quite complex: in some areas the thrust faults have been displaced along the lateral ramps, while in other areas the thrusts merge with the ramps.

Figure 5. Southwest/Northeast trending cross section indicating the dominant structural features in GHZ1 (Adapted from Seago, 2010).
5.3.1 Slope stability analysis, slope performances and pit design modifications

The new geological interpretation (2009/2010) differs substantially from the previous one carried out in 2004. Accordingly, back analysis of the slope using the most recent geological interpretation has been carried out in order to re-evaluate the strength parameters of the rocks.

The revised geologic interpretation indicated that as the southwest wall was mined deeper in the pit and approached the pit floor at the 500 ft elevation, the MRDT fault would have gradually been undercut. As a result, the necessity to step-out of design of the wall was recognized and the need to build a buttress in order to support the rock overlying the MRDT fault. Slope stability analyses were carried out in order to assess the stability of the existing slope and to confirm the magnitude of the intact rock step-outs and the waste rock buttress that were required to bring the factor of safety of this slope to an acceptable value.

Two-dimensional slope stability analyses have been carried out along cross sections perpendicular to the wall. The stability analyses have been carried out using the SLIDE® slope stability analysis software with the General Limit Equilibrium (GLE) method.

A pore pressure coefficient \( r_u \) of 0.2 was used in the stability analyses to simulate partially drained conditions that were expected to exist along the west side of the South Pit. Thermistor data together with considerable groundwater seepage along the west wall of the pit indicated that the base of the permafrost extended down to approximately the 700 ft elevation, and that the ground was not frozen below this elevation. Consequently, groundwater levels in the walls were expected to be high, particularly during the spring and early summer. The high ground water pressures can have an adverse impact on the stability of the walls with respect to sliding along undercut thrust fault exposures.

Figure 6. Looking southwest to GHZ3, showing the buttress constructed between the 700 and 750 ft elevations.
A sensitivity analysis was carried out to evaluate the responsiveness of the models, in terms of factor of safety, to slope configuration, fault location and fault thickness. The results indicated that the stability models could be very sensitive to small changes in any of these parameters. The results are also very sensitive to rock mass strength. Uncertainties in the rock mass strength parameters and in the fault location and thickness have been recognized. Therefore, a minimum design factor of safety in the order of 1.4 was used for the analyses that have been carried out to evaluate the required step-outs and buttresses.

The results of the slope stability analyses indicated that the As-built portion of the west wall in the GHZ3 was expected to exhibit marginal stability. In order to stabilize the existing wall, a buttress was built along the toe of the 625 ft bench.

In order to prevent failure of the ultimate overall slope and to ensure the safety of future mining operations, modifications were required also on the lower slope below the 650 ft bench to increase the factor of safety to a minimum of 1.4. Alternative slope configurations have been analysed along the cross sections in order to determine the magnitude and the configuration of the intact rock step-outs and waste rock buttresses that may be required along the toe of the slope. As a result, remedial pit design modifications have been implemented in the mine design. The prism monitoring has not indicated any further significant slope movement in this area.

5.4 Geotechnical Hazard Zone 4

The Geotechnical Hazard Zone 4 (GHZ4) is located in the southeast wall of the South Pit (Fig. 4). In the second half of 2009 localized instability occurred within low strength rock material exposed along the contact of the southeasterly dipping URDT fault, and accordingly the toe of the wall was temporarily stepped-out. No further signs of instability have been observed to date based on monitoring data by survey prisms.

5.5 Geotechnical Hazard Zone 5

The Geotechnical Hazard Zone 5 (GHZ5) is located in the northeast wall of the South Pit (Fig. 4). A multi-bench slope instability occurred at the end of 2009 in the eastern portion of GHZ5 (Fig. 7). A preliminary assessment was undertaken before monitoring of the wall movement commenced and the structural geology review was completed. Undercutting of the D2 fault, interpreted to exist behind the upper portion of the east side of the northeast wall, was recognized as the most likely cause of failure. The preliminary assessment also indicated that the probability of slope instability to further develop in this area would increase as the final pit walls were mined and an unfavorable thrust fault and geologic contacts were exposed in the northeast wall. In order to prevent further undercutting of the D2 fault along the slope, the wall in this zone has been permanently stepped-out of design on the 825 ft bench.

The structural geology re-interpretation has indicated that the southeasterly to easterly dipping LRDT and MRDT faults, and a south to southwesterly dipping D2 fault are present in the GHZ5. The geologic contacts are interpreted as sub-parallel to the D2 fault. In some areas the LRDT and MRDT faults merge with the D2 fault while in others they have been shifted along the D2 fault forming a varied and complex geological setting.

5.5.1 Slope stability analysis, slope performances and pit design modifications

The revised geologic interpretation indicated that as the stepped-out wall is mined deeper in the pit and approaches the pit floor, the D2 ramp fault would have gradually been undercut. It was recognized that the toe of the northeast wall in the GHZ5 needed to be stepped-out of design to buttress the wall. Slope stability analyses have been carried out in order to confirm the magnitude of the step-out that was required on the lower slope below the 825 ft bench in order to to bring the factor of safety of this slope to an acceptable value.

Two-dimensional slope stability analyses have been carried out along a series of northeast/southwest trending cross sections that have been cut through the GHZ5 portion of the proposed ultimate pit design. In the analyses, a pore pressure coefficient of 0.2 has been used to simulate partially drained conditions encountered along the east side of the Main Pit. Thermistors together with considerable groundwater seepage along the east and
northeast walls of the South Pit appear to indicate that the ground below a creek on the pit crest may not be frozen, and that relatively high groundwater levels may be expected in the pit walls.

The results of these stability analyses have indicated that the slope at GHZ5 in its ultimate pit configuration is not expected to exhibit adequate stability with respect to a failure along the faults that are inferred to exist behind the wall. In order to prevent failure of the wall, modifications, including slope step-out of design, were required on the lower slope below the 825 ft bench to increase the factor of safety to a minimum of 1.4. As for GHZ3, a target minimum factor of safety of the order of 1.4 has been used to account for the uncertainty in the fault location, fault thickness and rock mass strength. Further stability analyses have been carried out to determine the size of the intact rock step-outs that were required at the base of the slope. The prism monitoring has not indicated any further significant movement of the slope in this area.

6 Conclusions
Slope failures and ground instability at surface mining operations contribute to nearly 15% of surface mining fatalities (Girard, 2001). Mine safety can be drastically improved by employing a ground control management plan.

The difficult and extremely variable ground conditions make operations in the Main Pit at Red Dog Mine challenging and hazardous. In order to manage the risk associated with unanticipated ground conditions and consequent uncertainties in the pit design (such as rock mass strength, geologic structure location and persistence, hydraulic conditions, etc.) a ground control management plan has been implemented.

Figure 7.  Looking northeast to GHZ5 (December 2009).

The plan provides information for the development of safe operational procedures, the revision of the geological model, the optimization of pit slope design through identification of structural controls, the assessment of the
performance of the slope design and the identification of slope displacements. The information is collected through activities like on-going geotechnical data collection, hazard identification, geotechnical monitoring, comparison of actual with predicted slope performances, identification of threshold levels, definition of mitigation measures and design changes. The ultimate objective of the ground control management plan, achieved at Red Dog Mine, is to assist in providing the optimum return for the project in a safe working environment.

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8 References