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GEOLOGIC CONTROLS ON COMPLEX SLOPE DISPLACEMENT AT THE PITCH RECLAMATION PROJECT

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ABSTRACT

Moment-driven, regressive slope deformation has been observed in many large open pits. The Homestake Pitch Mine provides another example of this type of pit slope instability. The North Pit of the Pitch Mine was developed in a geologic setting that led to moment-driven slope instability. Moment-driven slope movement is typically regressive and often manageable during mining operations. However, pit excavation, coupled with extreme climatic conditions, led to large-scale, rapid slope failures that eventually terminated mining in the North Pit. The Pitch site is currently in reclamation. The North Pit slopes are in a regressive state and displacement velocities continue to decline.

INTRODUCTION

The Homestake Mining Company (Homestake) Pitch Reclamation Project (Pitch) is located in the Sawatch Mountains, approximately 30 mi (19 km) east of Sargents, Colorado. Homestake began open pit uranium mining at the Pitch Mine in 1977. Reclamation activities have been ongoing since mining ceased at the property in 1984. Slope instability in the North Pit is directly related to the response of the geologic system to pit excavation.

During the spring and again in the fall of 1983, large-scale, rapid slope failures occurred in the northeast corner of the North Pit. These appear to be plane shear translational failures that occurred in response to oversteepening of the east wall, due to the moment-driven deformation at the east wall of the North Pit, coupled with particularly high precipitation and other meteoric effects.

THE NORTH PIT

The North Pit currently extends from a maximum elevation of about 10,900 ft (3323 m) above mean sea level (amsl) at the east wall, to the level of the North Pit Lake at about 10,320 ft (3146 m) amsl. The North Pit has a maximum length of about 1200 ft (366 m) and a maximum width of about 1000 ft (305 m). It is comprised of the east wall, north wall, south wall, west wall, and the northeast corner. A shallow pit lake (North Pit Lake) currently occupies the bottom of the North Pit. Figure 1 is a photograph of the North Pit.

During mining operations, the floor of the North Pit extended to a minimum elevation of 10,220 ft (3116 m) amsl, which corresponds to a depth that is about 100 ft (30 m) below the

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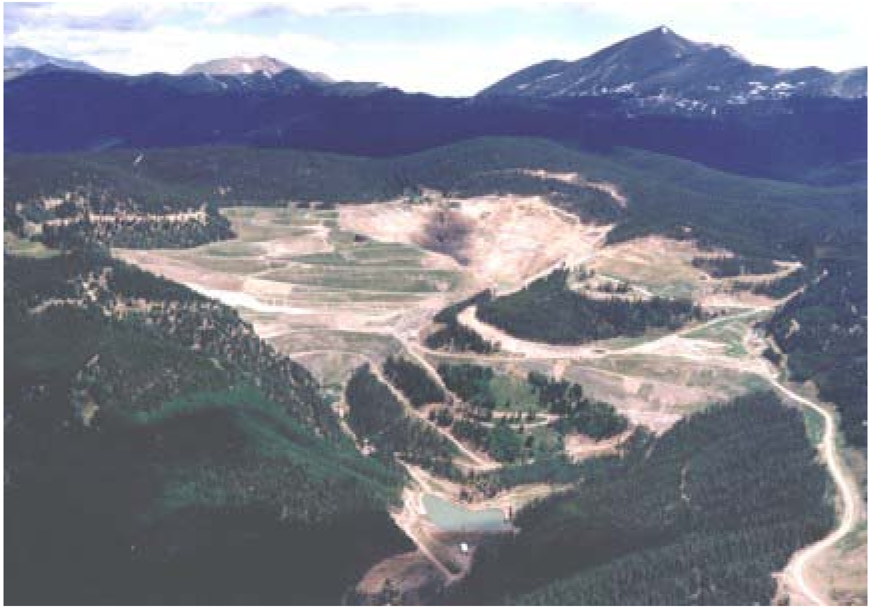


Figure 1. Photograph of North Pit looking north.

current surface of the North Pit Lake. Also during mining operations, the deepest and narrowest part of the North Pit was at the north end of the pit. The east wall and north wall were originally excavated at about 42 degrees from horizontal. The west wall was originally excavated to about 38 degrees from horizontal. The south wall was originally excavated to 30 degrees from horizontal.

As a result of slope re-grading in the North Pit in 1996, the overall slope angle of the east wall has been reduced from 42 degrees to 28 degrees from horizontal. Re-grading plans for the east wall involved first dozer-pushing the material off of the 10,600 bench, which lies at about mid-pit level, then grading the material to the level of the North Pit Lake. However, when deposition of the material below the 10,600 bench was nearly complete, the material failed and slid to the angle of repose. The failed material partially filled the North Pit Lake and translated to the opposite (west) side of the lake. The failed material resulted in significant buttressing of the east wall.

A geotechnical model of the east wall of the North Pit was developed for the purpose of slope stability analysis, as detailed in the Geotechnical Slope Model section of this paper. The lower roughly one-half of the east wall pit slope, which is comprised primarily of clay that is the result of intense sericitic alteration, is herein termed the Lower Block. The upper roughly one-half of the east wall slope, which is characterized by a series of high-angle faults that dip toward the pit, is herein termed the Middle Block. The herein termed Upper Block lies between the crest of the east wall and the prominent headscarp that lies above the east wall.

SITE GEOLOGY

The Pitch site is located on the west side of the southern flank of the Sawatch Range in the southern Rocky Mountain physiographic province. An erosional remnant of Paleozoic rocks underlies most of the site. The Paleozoic rocks extend past the western boundary of the site to a contact with volcanic rocks that are associated with Tertiary volcanism in the West Elk Mountains. The eastern boundary of the Paleozoic block is coincident with the Chester Fault Zone. The Chester Fault Zone is a roughly north–south trending, high-angle reverse fault zone of Laramide age. Igneous intrusive and metamorphic rocks extend from the Chester Fault Zone to the east flank of the Sawatch Range.

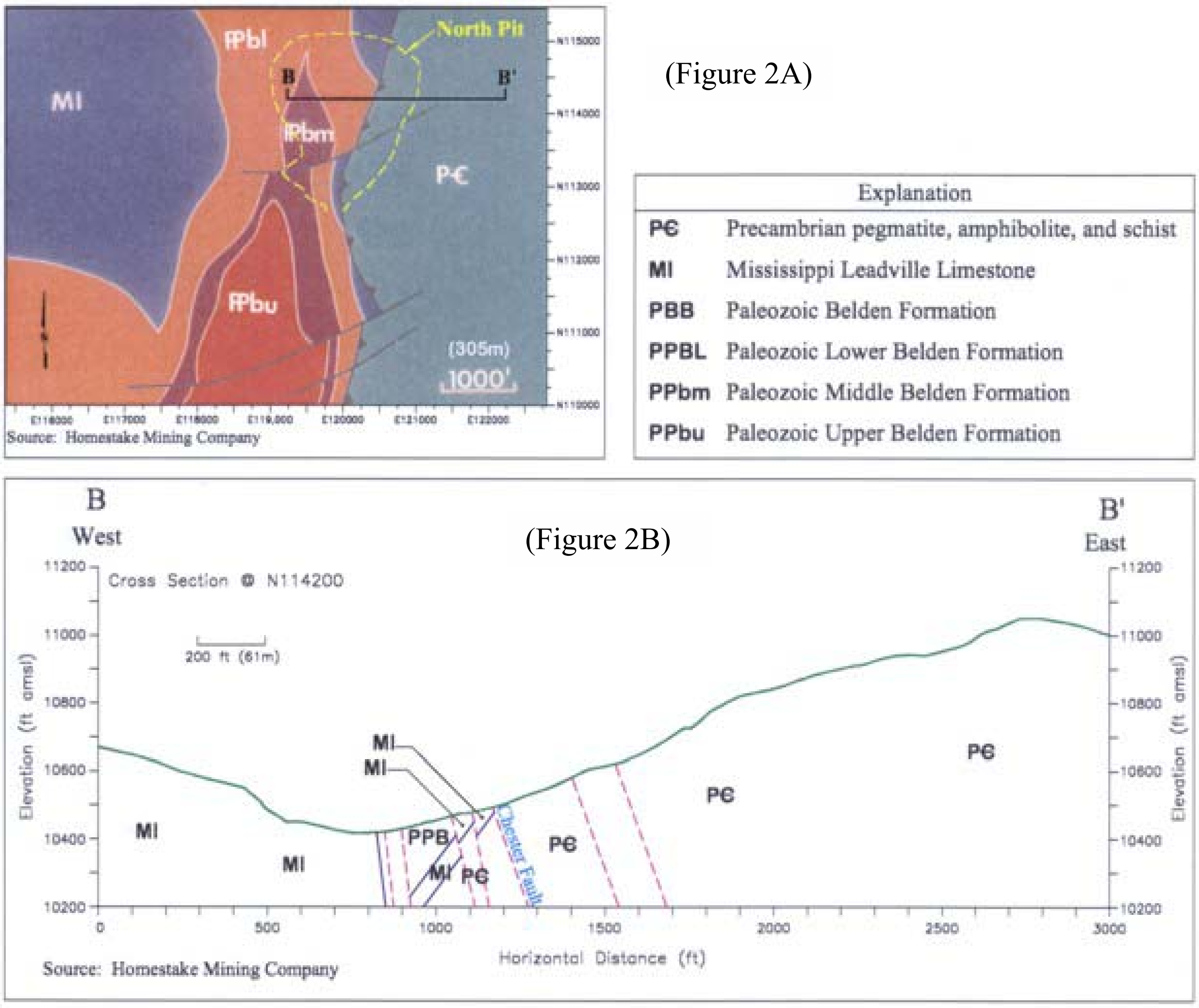
GEOLOGY OF THE NORTH PIT

Excavation of the North Pit revealed a complex geologic system. The North Pit lies along, and either side of, the Chester Fault Zone. Precambrian rocks, including pegmatite, amphibolite and schist, were thrust from east to west against a block of Paleozoic rocks, including dolomitic limestone of the Mississippian Leadville Limestone Formation (Fm), and sandstone, carbonaceous claystone, and siltstone of the Pennsylvanian Belden Fm.

The contact between the Precambrian block and the Paleozoic block is defined by the north–south trending Chester Fault. Westward thrusting of the Precambrian block against the Paleozoic block resulted in the folding, tilting, and overturning of the Paleozoic rocks. This deformation resulted in the formation of a plunging syncline in the Paleozoic block. The east limb of the syncline is overturned and was previously exposed in the north wall of the North Pit prior to pit re-grading. The west limb dips more gently to the east. The entire syncline plunges to the south at about 20 degrees. Figure 2 is a generalized geologic map and cross section of the Pitch site.

Maximum folding occurs in the North Pit area and the limbs of the syncline dip more gently to the north and south of the North Pit. The tight folding in the vicinity of the North Pit probably resulted in a greater degree of brittle fracturing in the very brittle dolomitic limestone of the Leadville Fm. The resultant increased permeability likely led to enhanced supergene mineralization and emplacement of the Pitch site pitchblende deposit in the Leadville Fm.

The Homestake exploration program revealed that the Precambrian block at the east wall of the North Pit was cut by a series of faults that strike roughly north–south and dip at high angles (60 to 70 degrees from horizontal) into the east wall of the North Pit. These faults display obsequent movement, such that the downslope side of the fault moves up, relative to the upslope side. These faulted blocks tend to restrict downgradient migration of ground water, due to low permeability fault gouge in the shear zones. In response to this dam effect, sag ponds and springs had formed on the east wall of the North Pit, with the greatest number of these features occurring at the contact between the Precambrian lithologies and the sericitic-altered block at the pit slope toe. When the east wall was re-graded in 1996, the sag ponds were drained, and the spring water was collected in a lined drainage, informally dubbed "Spring Creek," and channeled off of the east wall.



Source: Homestake Mining Company

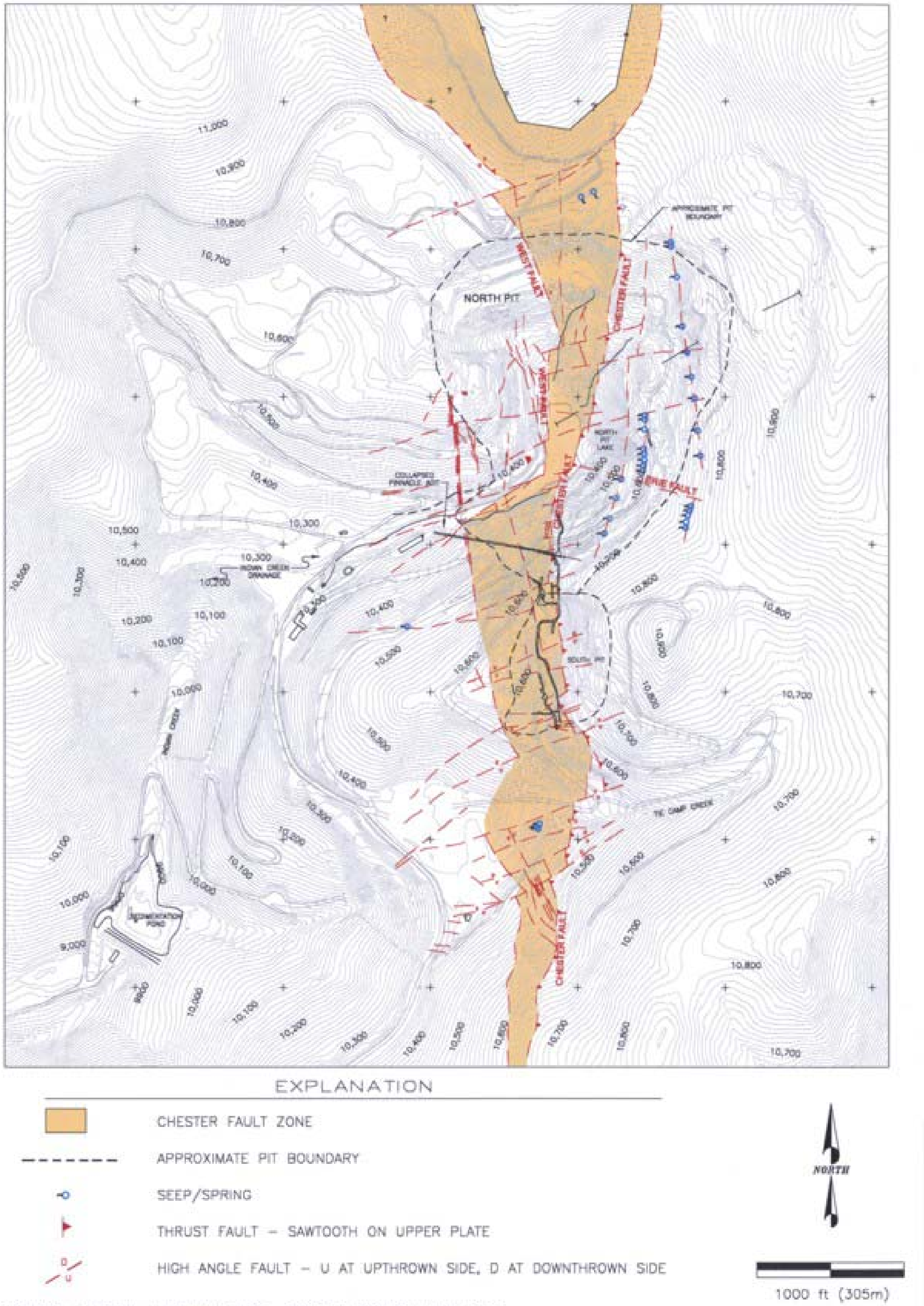
Explanation	
P€	Precambrian pegmatite, amphibolite, and schist
Ml	Mississippi Leadville Limestone
PBB	Paleozoic Belden Formation
PPBL	Paleozoic Lower Belden Formation
PPbm	Paleozoic Middle Belden Formation
PPbu	Paleozoic Upper Belden Formation

Source: Homestake Mining Company

Figure 2. (A) Generalized geologic map of the North Pit area, and (B) generalized east–west, pre-mining geologic cross section through the North Pit area.

The Chester Fault Zone is also cut by a series of transverse faults that trend northeast–southwest with a strike of about 075 degrees. Vertical offset and drag folding along these faults may be observed in the east wall of the North Pit. These transverse faults may have provided a side release mechanism for the north–south fault set. Figure 3 is a geologic structure map for the Pitch site, illustrating the trend of the Chester Fault Zone and the major transverse faults.

In the slopes that lie above the crest of the North Pit, weathering has resulted in a relatively shallow zone of weak, highly weathered granite. This zone has a maximum thickness of about 150 ft (46 m). A perched ground-water zone occurs at the base of the Upper Block, which is coincident with the transition to unweathered competent rock.



SOURCE: PINCOCK, ALLEN AND HOLT; BEDROCK GEOLOGY MAP 1979.

Figure 3. Structural geology map of the Pitch site.

HYDROGEOLOGY OF THE EAST WALL OF THE NORTH PIT

The Upper Block is comprised of weathered pegmatite and schist and is relatively free draining. At the Middle Block, the north–south oriented, high-angled faults create low-permeability barriers to ground-water flow. This is evidenced by north–south oriented linear patterns of springs, as shown on Figure 3. It appears that the linearity of these springs reflects the trace of high-angled, in-dipping faults. Movement along the northeast–southwest oriented transverse faults has resulted in additional barriers to ground-water flow in the north–south direction. The combination of north–south trending faults, coupled with the northeast–southwest trending faults, resulted in a compartmentalized ground-water system.

The intense alteration associated with ore deposition created a block of sericitic-altered clay at the Lower Block of the east wall of the North Pit. The sericite clay block at the toe of the east wall of the North Pit also appears to have contributed to inhibiting ground-water flow. Springs and seeps are abundant on the east wall, above the level of the contact with the sericitic clay block, but none are observed below the contact with the sericitic clay block. Piezometers installed in the sericitic clay block, which have been completed to about the level of the North Pit Lake, have been dry.

Compartmentalization of ground water in the Middle Block, due to the high-angle, in-dipping faults and the transverse faults, meant that dewatering holes (horizontal drain holes) only drained small, discrete portions of the pit wall. Dewatering of the Lower Block was ineffective because the block is comprised of low-permeability, low-strength clay. As a result, dewatering holes were often lost to collapse, and those that did drain prior to collapse yielded very little water.

HISTORY OF SLOPE INSTABILITY AT THE EAST WALL OF THE NORTH PIT

Homestake began mining operations at the Pitch Mine in 1977. By 1979, excavation of the North Pit was underway. Raveling and minor slope failures began to occur in the shallow pit walls during the first year of excavation. The first slope failure on the east wall occurred in March 1980. This was a bench-scale failure. In March 1983, a large-scale, rapid slope failure occurred in the northeast corner of the east wall. Figure 4 is an historic photograph of the March 1983 slope failure. In October 1983, a second large-scale, rapid slope failure occurred in the northeast corner of the east wall. The October 1983 failure involved about twice the volume of the March 1983 event. Figure 5 is an historic photograph of the October 1983 slope failure.

The year 1983 was a climatological anomaly, related to the El Niño weather phenomenon. The combination of warm fall temperatures (that caused the ground to remain unfrozen late into the year, enhancing infiltration), heavy winter snowpack, early and rapid snow melt and increased rainfall, resulted in optimum conditions for reducing shear strengths of slope materials in response to elevated pore water pressures. Slope displacement velocities reacted quickly to the increased infiltration of surface water and rising ground-water levels. On March 7, 1983, the slope displacement rates reached a non-recoverable velocity in the northeast corner of the North Pit and continued to increase until slope failure took place on March 13 and 14, 1983.

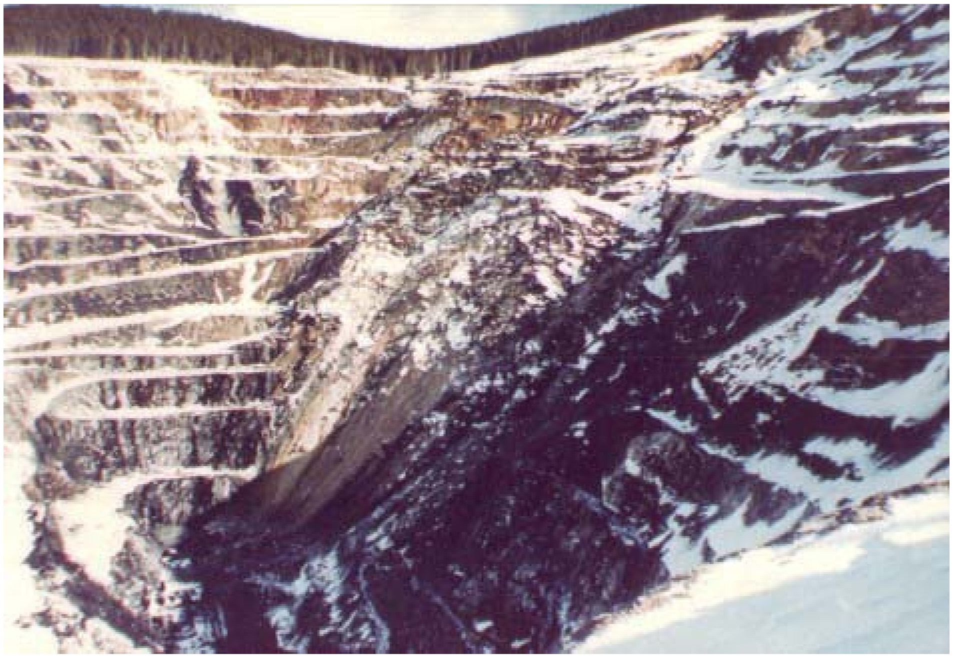


Figure 4. Northeast corner slope failure — March 1983.

Figure 5. Northeast corner slope failure — October 1983.

The east wall headscarp, which defines the eastern extents of the Upper Block, had developed as early as September 1981, and possibly earlier in pit development. The headscarp was referred to as the "tension crack" in earlier Homestake files. It is unclear from the available information whether the ground between the east wall pit crest and the headscarp (Upper Block) had developed tension cracks prior to the March 1983 event. The March 1983 slope failure in the northeast corner of the east wall resulted in about 60 ft (18 m) of vertical displacement at the headscarp. The slope failure mass appears to have originated primarily above the 10,600 bench, which traverses the North Pit at about mid-pit height. Large-scale, rapid slope failure was limited to the northeast corner of the North Pit, although headscarp development and tension cracking occurred throughout the Upper Block. The geometries of the shear surfaces of the northeast corner failures are characteristic of other slope failures in the weathered pegmatite at the site. These are characteristically circular in profile near the headscarp and roughly linear with little or no curvature at the toe.

As the North Pit slopes advanced north due to mining, following the March 1983 slope failure in the northeast corner of the North Pit, surveys of slope monitoring points revealed that all of the North Pit monitoring points were accelerating. The October 1983 northeast corner failure occurred in the same area as the March 1983 northeast corner slope failure, but progressed farther up the slope. The October event involved about twice the volume of the March event. The following account, quoted from the Homestake, October 1983, Monthly Report provides a dramatic account of the slope failure.

> "By October 13, 1983, the "swamp" area had reached over six inches a day in movement rates and failure was imminent…Friday morning, October 14, in an hour and a half, the North east (sic) corner came in…
>
> October 14, 1983: Storm front brings rain and snow to the mine during the night (0.5 inches of precip(itation))

5:00 a.m.	Sump pump in the north end of the pit moved because sump filling in with mud.
7:30 a.m.	Friday's crews arrive, snowing, pit shrouded in fog.
8:00 a.m.	Large cracks noted in fresh snow at tree line above the swamp.
8:30 a.m.	Slide well underway. Perimeter well defined by cracks in the fresh snow. Crews ordered to save equipment (pumps and light plants). Bulge noted in center of slide area.
9:00 a.m.	Slide toe advancing rapidly (one ft per minute) as crews scramble to move equipment.
9:30 a.m.	Crews and equipment safe. Photographs taken, slide toe stops advancing.
10:00 a.m.	Crews sent home, water from the (10)600 level of slide reworking slide material as it works it(s) way into the pit. Slide stable."

The October 1983 northeast corner failure completely filled the north end of the North Pit. The North Pit Lake began forming immediately after the slope failure. Displacement at the headscarp appears, based on photographic evidence, to have roughly doubled in magnitude to a total vertical displacement of about 120 ft (37 m).

Figure 6 is a Homestake photograph of the headscarp taken after the March 1983 event. Figure 7 is a photograph from a similar perspective that was taken after the October 1983 event. Comparison of these photographs reveals the magnitude of displacement at the headscarp initiated by the two 1983 slope failures.

The North Pit Lake currently obscures the toe of the northeast corner slope failure. The failure surface above the 10,600 bench has been excavated to the apparent failure plane. Material from the north wall was pushed onto the toe of the former slide during the 1996 re-grade of the east wall.

MOMENT-DRIVEN REGRESSIVE SLOPE FAILURE

A slope that accelerates to failure is termed a progressive slope failure (Zavodni & Broadbent, 1978). From a mining or reclamation perspective, progressive failures such as the 1983 northeast corner failures are unacceptable. However, the style of slope displacement that governs the entire east wall is more accurately termed regressive failure. A regressive failure is defined as a slope that is moving toward equilibrium and is continually decelerating as the mass is readjusted or forces contributing to instability are reduced (Zavodni & Broadbent, 1978; Call et al., 1993).

Moment-driven failures were described by Nieto and Matthews (1987) as a form of deep-seated toppling. Nieto and Matthews (1987) described the kinematic geometry of a moment-driven failure in similar terms to those used herein to describe the east wall of the North Pit. Nieto and Matthews (1987) describe a "passive wedge" at the toe of a slope, which is analogous to the sericitic Lower Block of the east wall of the North Pit. The term "toppling section" is used to describe what is herein called the Middle Block. An "active wedge" is defined as the block above the toppling section, which is analogous to the Upper Block of the east wall of the North Pit.

The characteristics of moment-driven slope deformation cited by Nieto and Matthews (1987) include tension cracks and headscarp development near the crest, shear fractures with obsequent faulting in the middle portion of the slope, and a bulging toe section. These characteristics have all been observed at the east wall of the North Pit of the Pitch site. Nieto and Matthews (1987) also suggest that because the deformation involves moments, the forces involved are less than those of a translational type failure. Nieto and Matthews (1987) proposed that the forces required to establish equilibrium would also be less than those expected for a translational type of failure.

Call and others (1993) described regressive slope failure in large open pits. Although Call and others (1993) did not use the term "moment-driven failure," the characteristics described are consistent with those described by Nieto and Matthews (1987), and have all been observed at the east wall of the North Pit. These characteristics include low-strength rock mass at the toe, in-dipping fault-bounded blocks oriented sub-parallel to the strike of the pit face with clay alteration of faults between the blocks, high-angle side release faults, and compartmentalized ground water.

Figure 6. East wall headscarp following the March 1983 northeast corner slope failure.

Figure 7. East wall headscarp following the October 1983 northeast corner slope failure.

Both Nieto and Matthews (1987) and Call and others (1993) promoted continued mining in a regressive slope environment, if slope displacement can be controlled by such means as dewatering, controlled production rate, and strategically placed stepouts. Slope monitoring is also cited as a key element to protecting personnel and equipment.

Limit equilibrium methods do not accurately represent moment-driven slope displacement because a discrete shear surface is not present. Numerical analysis is much better suited to analysis of moment-driven deformation. Cremeens and others (2000) used a two-dimensional distinct element model for the east wall of the North Pit that accounted for the rotation, bending, frictional sliding, and plastic deformation that occurred in the east wall, and allowed prediction of future slope performance.

GEOTECHNICAL SLOPE MODEL

A geotechnical model of the east wall of the North Pit was developed to facilitate numerical slope stability analyses. Details of the numerical slope stability evaluation are presented in a previous publication (Cremeens et al., 2000). The east wall of the North Pit was divided into three zones, based on rock strength and style of slope displacement. Intense, sericitic alteration associated with ore emplacement resulted in weak, plastic clay in the lower part (toe) of the pit slope, herein termed the Lower Block. The Middle Block contains a series of high-angle, in-dipping faults that strike parallel to the East Wall of the North Pit. Deformation of the Lower Block allowed rotation of the fault-bounded blocks of the Middle Block toward the pit. Weathering resulted in a contact between weak, weathered rock, and fresh, competent rock in the upper east wall of the North Pit. The ground above this contact is herein termed the Upper Block. The Upper Block appears to have displaced mostly as plane shear, but the obsequent style of faulting displayed in the Upper Block indicates that the failure was also influenced by rotation and shearing of in-dipping faults.

The low permeability sericitic clay at the toe of the slope, and low permeability fault gouge along in-dipping, north–south oriented faults, and northeast–southwest transverse faults, created a compartmentalized ground-water system that resulted in an elevated piezometric surface at the east wall of the North Pit, further exacerbating pit instability.

Figure 8 is a map of the North Pit, showing the northeast corner pit failure locations, the Upper, Middle, and Lower Blocks, and other components of the east wall of the North Pit. Figure 9 is a modeled pre-displacement profile through the most critical section of the east wall. Figure 10 is a modeled post-displacement profile showing bulging at the Lower Block, rotation of the Middle Block, and translation of the Upper Block.

CONCLUSION

The east wall of the North Pit of the Pitch Reclamation Project exhibits geologic features common to moment-driven, regressive slope deformation. These features include:

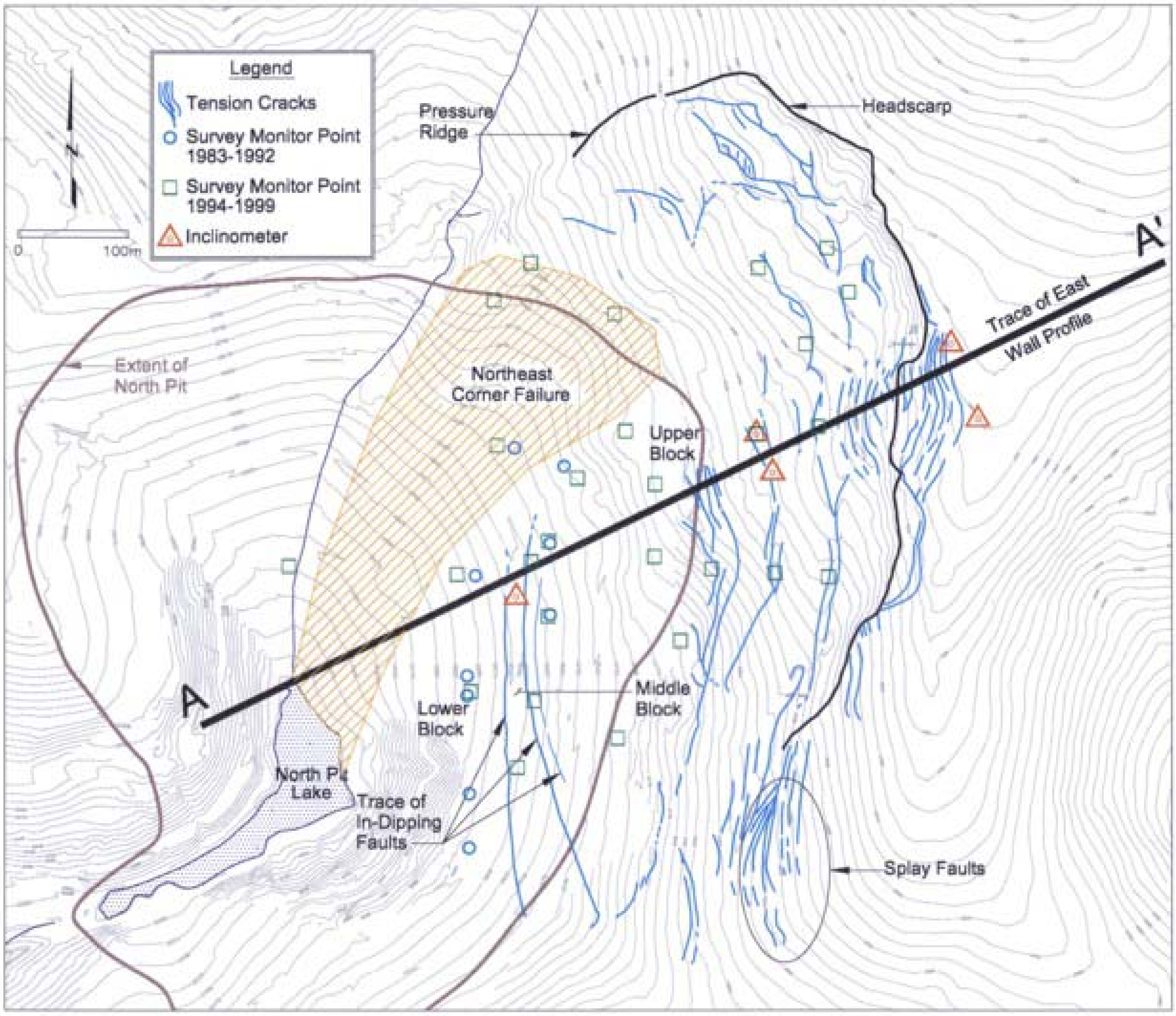


Figure 8. Map of the North Pit showing east wall components.

- A weak deformable toe
- A mid-pit section with high-angle, in-dipping faults oriented sub-parallel to the pit wall
- A fault set oriented transverse to the in-dipping faults
- Obsequent fault displacement
- Compartmentalized ground water

Moment-driven slope failures commonly display regressive behavior. However, the rapid, large-scale northeast corner failures of 1983 illustrate a case where a portion of a pit slope that was in a regressive mode failed suddenly in response to extreme weather-related events.

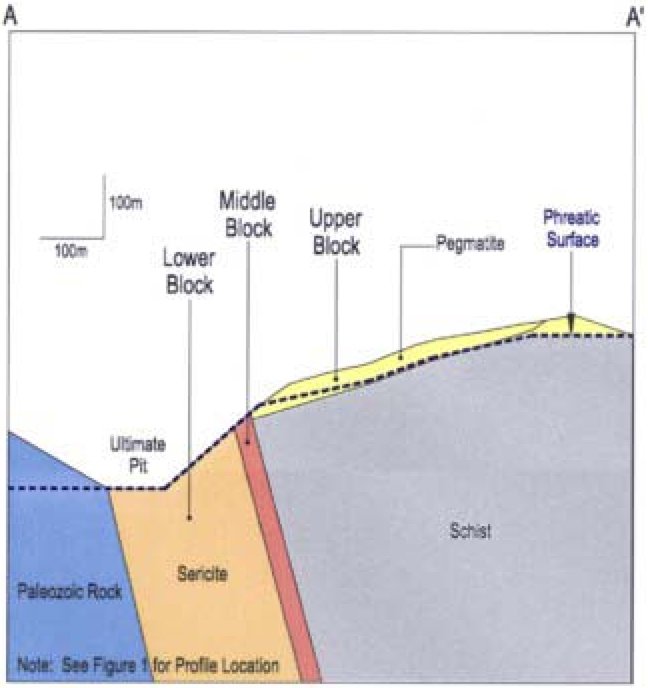


Figure 9. Pre-displacement geotechnical model profile.

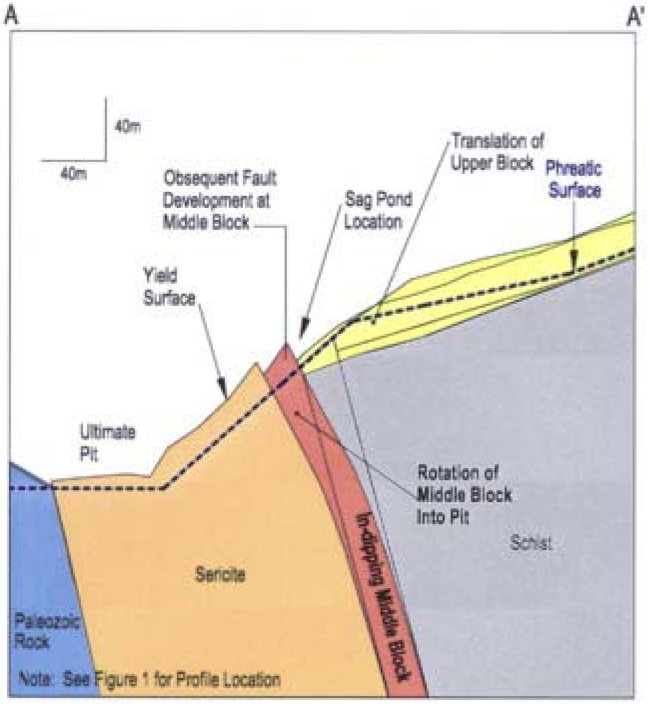


Figure 10. Post-displacement geotechnical model profile — deformation highly exaggerated.

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