A new approach to mine accident analysis: a case study of a mine cave-in

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Synopsis

In May of 1980, a mine operated by Belmoral Mines Ltd experienced a failed crown pillar, resulting in the death of eight miners and putting sixteen others in harm's way. The Ferderber mine was located in the Val d'Or region of the province of Quebec in Canada, and had been under development for 19 months and production for 9 months, since the opening of the portal. The crown pillar separating the 1–7 level from overlying overburden ultimately failed, permitting an estimated 1.5 million cubic feet of liquefied sediment to gain entry into the mine.

This paper back-analyses the cave-in by applying decision error theory, in an examination of the organizational culture and the collective decisions contributing to the cave-in disaster. A case will be made for a greater understanding of mining methodology, geomechanics and risk assessment when operating in such challenging geologic conditions. Boundary condition and decision (BCD) analysis will be introduced as an innovative new method for the analysis of mine accidents and incidents. It will also be shown that BCD analysis can be applied to any event in an enterprise for which standards, norms or legislation exists. A cognitive profile will be presented that provides insight into the safety ethos existing within the Ferderber mine organization at the time of the tragedy.

Introduction

The Belmoral mine disaster occurred at, or about 22:00 hours on May 20, 1980 in the Ferderber mine, located 10 km north-east of the town of Val d'Or, Quebec. The mine started development in October of 1978, and had been in production since August, 1979. The principal mining method was shrinkage stoping, with the possibility of sub-level stoping for wider ore zones. The development of the mine consisted of a trackless access ramp from surface at a grade of 17%, connecting four levels at 100, 200, 250 and 500 feet depth. There were eight stopes at the time: four in production on the 200 level; two in production on the 350 level; and two in development on the 350 level. Twenty-four miners were working underground during the evening of the disaster, eight of whom lost their lives; sixteen narrowly escape serious injury or death.

The event

The event that tragic day was a failure of the crown pillar directly above the 1–7 stope consisting of 55 feet of bedrock, followed by nearly 50 feet of water saturated varved clays, silts and gravels. The failure produced 100 000 tons of water-borne sediment that infiltrated the mine through a conical shaped penetration of the crown pillar (Beaudry, 1981). The failure in geomechanical terms has been described as a 'chimney failure', (Betournay, 1994) and can be considered behaving analogously to mixed granular material within a large hopper (Kvapil, 1965) passing through a narrow opening. There appeared to be ample warning to mine management of an impending disaster, as the ingress of fluidized sediments had been observed in previous days, as the decision analysis will show. However, on the part of the underground miners, the only warning of the crown pillar failure was an air blast, followed by a wall of fluidized sediments and debris two metres high that swept away materials, rolling stock and miners alike. The time taken for the mud and sediments to reach the 350 foot level was estimated to be in the order of fifteen minutes. The funnel shaped crater remaining was later measured 200 feet in depth parallel to the axis of the orebody. In plan view, the crater was oval in shape and 185 feet wide at the long axis.

Regional geology

The general geology of the region is characterized as part of the Abitibi greenstone belt, of Archean age (2.7 million years), within the Canadian Shield. Within this geologic province, lays the Malartic group of complex rocks of

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volcanic origin. These rocks tend to be intruded by many igneous plutons consisting of mafics, ultramafics and basalts. The Ferderber mine is situated central to one such igneous intrusion known as the Bourlamaque batholith, within the Lower Malartic group (Figure 1). The Bourlamaque batholith consists of massive quartz diorite, with a surface area of the order of 160 square kilometres. The Ferderber mine is unique insofar as being situated well inside the boundaries of this intrusion; whereas all other mines in the Val d'Or region are located along its contact with the undifferentiated volcanic Upper Malartic rock, pervasive within the region. The prospect was first discovered in 1974, when a prospector reasoned that gold-bearing quartz-filled fractures and faults would be found within the batholiith, given the extent of metamorphic alteration (green schist facies), and the fact that the batholith had undergone extensive tectonic and structural activity early in its geologic history (Beaudry, 1981).

Local geology

The gold-bearing ore zone occupies a one to fifteen metre shear zone within the quartz diorite, consisting of moderate to strongly altered chlorite schists. Within these schists are boudinaged and foliated vein structures containing mineralized quartz, varying between several centimetres to tens of metres in length. The shear zone is oriented at east to west, as are most of the intrusions within the region, and dips steeply to the south (Figure 2). The dip varies between 50 and 65 degrees, depending upon the depth. The shear zone is by definition highly structurally controlled, by at least two tectonic events of different ages (Vu *et al.*, 1985). The schists also show signs of strong foliation, parallel and sub-parallel to the shear zone, depending on depth. The displacement along the shear zone is indicative of reverse vertical thrust movement.

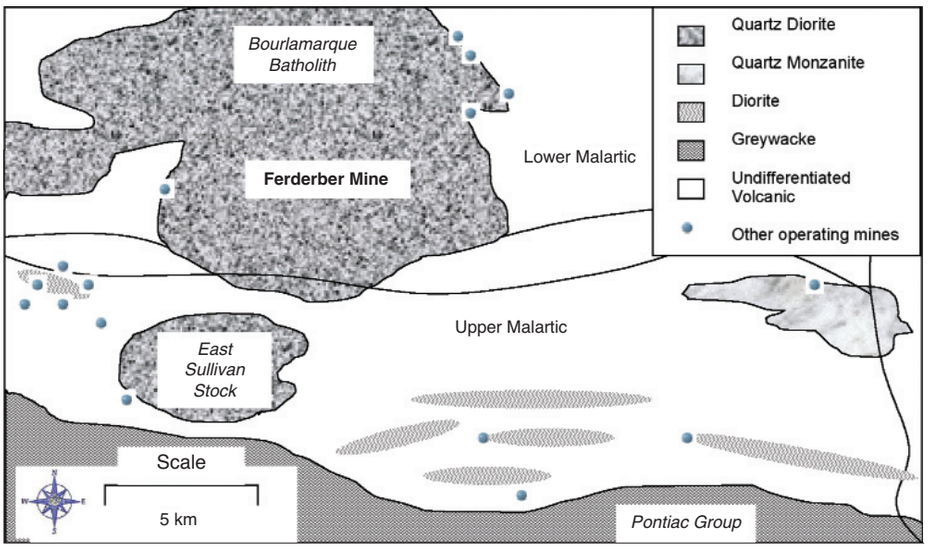

Figure 1—Geology of the Val d'Or area showing the location of the Ferderber Mine (Vu *et al.*, 1987)

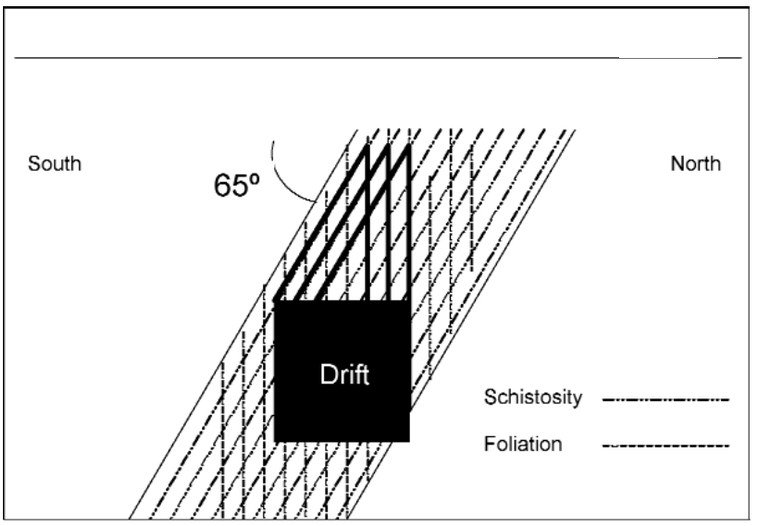

Figure 2—Schematic illustration of foliation and schistosity within the ore zone (Beaudry, 1981)

The boudinaged quartz veins comprise 70% of the quartz veins, and are most often mineral bearing (pyrite and gold). The gold is finely disseminated within the quartz. The folded veins comprise 25% of the quartz veins and are often mineralized. There are many faults and fractures that cut the shear zone, in some cases intersecting with the inclosing quartz diorite. In the latter instances, the quartz-filled faults and fractures are not mineralized and are considered post contemporaneous to the shear zone. The ore within the shear zone is considered to have no structural competency, and the altered contact with the quartz diorite low structural competency (Beaudry, 1981).

Mine workings

The mine underground development was designed in 1978. The layout was predicated upon the application of shrinkage stoping as the mining method, with two possible phases of production. The first phase involved four levels of development and production down to a depth of 510 feet (155 metres). The proposed levels were at 100 feet, 200 feet, 350 feet and 500 feet (Figure 3). They were accessed by a ramp driven at a grade of 17% with two 180 degree 'switch-backs'. The choice of a ramp access over a production shaft was made on the basis that production could start earlier, and consequently, so would the cash flow. Each level was designed with one ventilation shaft and an escape way at 70 degrees to vertical, following the general dip of the orebody. The second phase was to go to 650 feet (198 metres), incorporating a second escape way and ventilation raise. There was consideration for the possibility of changing the mining method to sub-level stoping, should the orebody thicken. Ironically, no decision had been made about the size of the horizontal pillar separating the 200 and 350 levels at the design stage of the underground workings.

At the time of the disaster, phase one was well underway, having been in development since October 1978, and production since August 1979. The 100 level had a single abandoned stope and exploration drift, connected with cross-cuts to a haulage drift and the access ramp. The 200 level, where most of the production was taking place, was complete with four stopes in production (2–5, 2–7, 2–9 and 2–11); and the development of cross-cuts, ventilation raise, stope raises, pillar raises and haulage ways were complete (Figure 3). The 350 level was in the process of completion of stope development, with two stopes in production and two more underway. The ramp, haulage way, cross-cuts, ventilation raise and escape way were all completed. The sumps were completed on all levels and two lunchrooms were in place off the ramp on the 200 and 350 levels.

The 500 level was in the early stages of development. There were no stopes in production or development. At the time of the disaster, there were two crews working on the 500 level, one diamond drill crew, and a second crew—an Alimak raise crew completing the ventilation raise. The Alimak raise crew was nearing completion of the ventilation raise with 40 feet to complete before joining the existing raise at the 350 foot level. There was no secondary escape way at the 500 level. The ramp was the only means of egress from the 500 level (Figure 3).

Chronology of events

The events leading up to the Belmoral mine disaster were numerous, well documented (Beaudry, 1981) and, in some cases, predictable. The first warnings of geologic and geomechanical problems occurred in May and June of 1979, when the mine flooded as the driving of the ventilation raise was underway. This was the first hint of a broader context for the disaster: a lack of understanding and respect for the

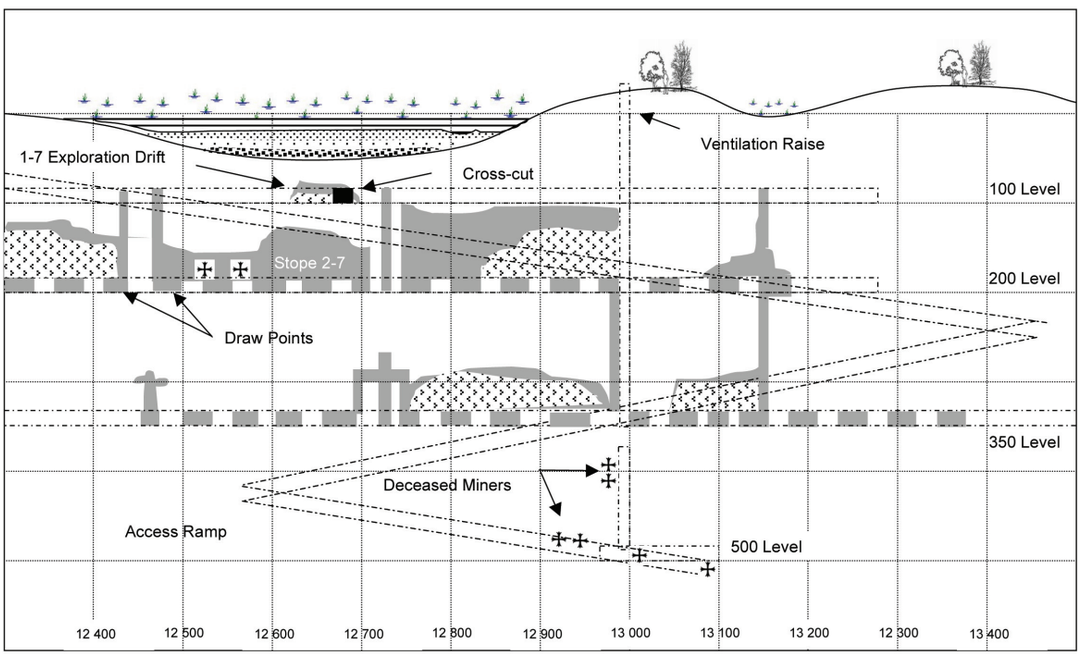

Figure 3—Modified sectional view of the Ferderber Mine depicting the mine workings and failed crown pillar at the time of the tragedy (Beaudry, 1981)

large amounts of stored water within the overlying surface soil materials in the region. Not long after, in July of 1979, an exploration drift that was being driven on the 100 level had to be abandoned after just fifty feet of advance, due to ground instability problems. In November a second attempt was made to advance the exploration drift, which also met with incipient ground failure. Concurrently, the 2–7 stope was put into production, some of which was below the 1–7 drift. As a precaution, a 25 foot (8 m) high horizontal pillar was left between the 2–7 stope and the 1–7 drift. It is not clear how this dimension was calculated, or by whom. December saw the tragic death of a miner within the 2–9 stope, a fatality that apparently did not galvanize mine management into action concerning the deteriorating condition of the 2–7 stope. It is not clear as to what the circumstances were concerning this fatality, only that it was a tragic harbinger of events yet to come.

By February of 1980 the falls of ground within the 2–7 stope were sufficient to erode the 25 foot pillar to just 8 feet (2.5 m). By March of 1980, ore was being pulled from the 2–7 sporadically, as dictated by production targets (Figure 4a). The sporadic production contributed to the instability in the back of the stope by permitting void space to develop. Succeeding days to weeks would see a continuous dilution of the muck from the 2–7 stope, with respect to ore grade. This was another clear indicator of the failure of the pillar between the 2–7 stope and the 1–7 exploration drift above. On May 13 of 1980, it was common knowledge among the mine workforce that the pillar was failing, to the extent that mine supervision explicitly cautioned the miners about ground conditions (Figure 4a). On May 15 of 1980, it was decided to isolate the 2–7 stope from the remainder of the mine, and bulkheads were installed for this purpose.

Owing to a lack of monitoring instrumentation and geomechanical expertise, the 2–7 stope and the 1–7 exploration drift were now without means of inspection. Regardless, the production of sediment laden groundwater and the poor condition of the backs and walls of mine workings near the 2–7 stope suggested that a catastrophic failure of the crown had in fact occurred. What was not expected was that during the long weekend of May 17 through 19, the crown pillar between 1–7 and the overburden would also be in the process of incipient failure (Figure 4b). The following day of May 20, witnessed a heavy mobile crane travel over the very spot where in a matter of hours, a 185-foot crater would exist. The operator reported no unusual ground effects during his transit; nor did anyone else. At approximately 22:00 hours, the crown pillar above the 1–7 exploration drift failed admitting 100 000 tons of sediment laden water into the mine, taking the lives of eight underground miners, and causing the closure of the mine for months to come.

Boundary condition and decision analysis

The analysis of decision errors contributing to accident/incident scenarios is both a novel and an overdue method of forensic analysis of events within the workplace.
It is based upon a decision error theory (Sweeney, 2004), which states that notwithstanding acts of malfeasance, all decisions contributing to an accident scenario can be considered to fall into one of three mutually exclusive error classes: errors of commission, errors of omission, and errors of mistaken belief. Each will be considered in turn.

Errors of commission

Errors of commission are errors made by a person, who is fully cognizant that a standard, rule or norm applies, but transgress the standard—for reasons known only to himself. Typically, persons likely to make errors of commission are those that are more senior in age or job experience, belong to a militant collective bargaining unit, or are in a position of

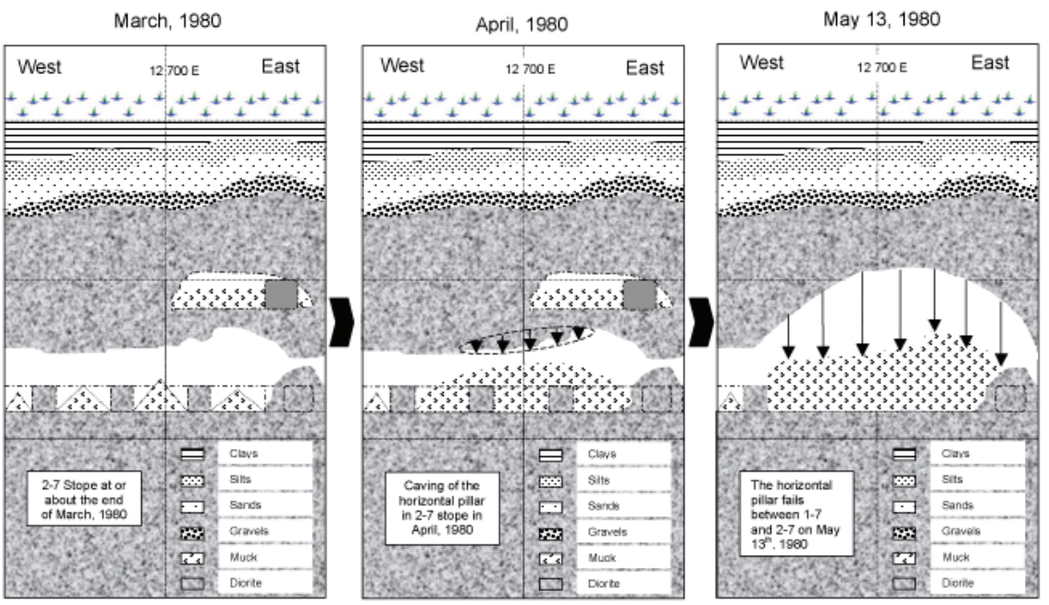

Figure 4a—A progression of thumb-nail sketches over time illustrating the progressive loading and failure of the crown pillar in stope 2–7

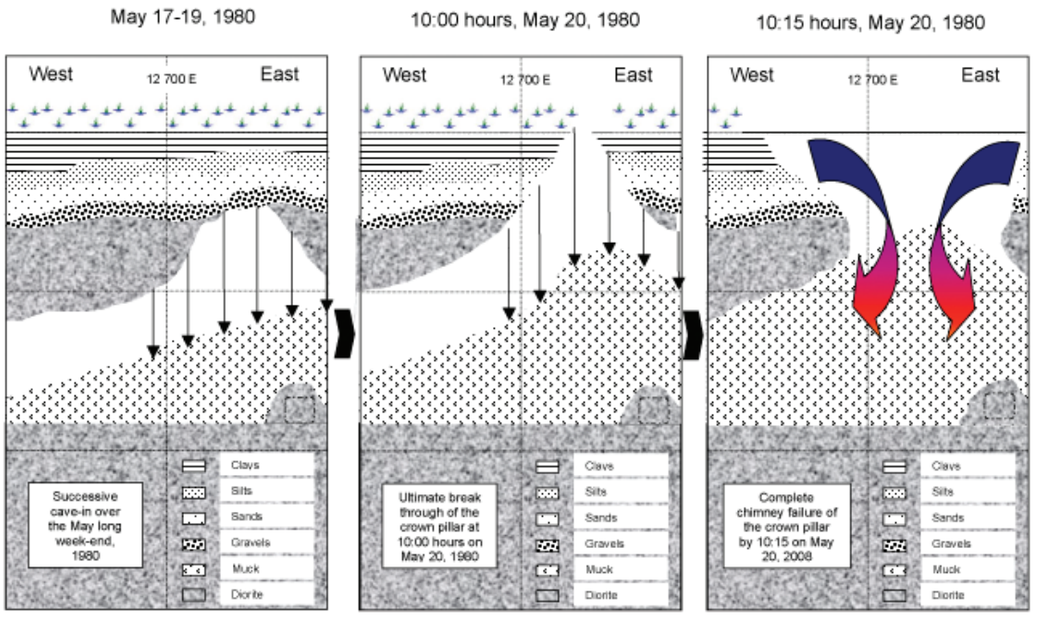

Figure 4b—A progression of thumb-nail sketches over time illustrating the progressive loading and failure of the crown pillar in stope 2–7

perceived power or authority over others. A classic example is that of the Westray Mine disaster in which management condoned the operation of welding torches and sources of ignition in the underground coal environment—the standard being the rule of law, and the consequences being an underground mine explosion killing 27 (Richard, 1996).

Errors of omission

Errors of omission are errors made by a person who is fully cognizant that a standard, rule or norm exists, but defers complying with the standard until it is too late. Most often, this can be attributed to human factor reasons (fatigue, exhaustion, panic, fear) or environmentally factored reasons (ambient heat, noise, humidity). In any case, they transgress the standard due to competing priorities. Persons likely to make errors of omission are in scenarios that are generally degrading with respect to time and for which they are unable to cope or compensate. The typical example is a control room operator who is confronted with too many sources of stimulus (lights, buzzers and gauges) and misses a cue to make a decision as a result of sensory overload.

Errors of mistaken belief

Errors of mistaken belief are errors made by a person who either does not know that a standard, rule or norm exists, or makes a decision based upon a decision or assumption that had it been true, would have rendered the error innocent. Persons making errors of mistaken belief are those that lack experience or training, or lack the cognitive processing skills to make a correct decision, or both. Typically such a person is an entry-level worker, a worker in a temporary assignment or someone who is called upon to function in a job setting beyond his level of competence. An example is that of the Sunshine Mine disaster in which all concerned believed that there was little, if anything combustible underground. As a result, the response within and without the mine was lacking and inappropriate to the inferno raging below that took the lives of 91 (Olsen, 2005).

Boundary condition and decision analysis

The Belmoral mine disaster is an example of an event in which many decision errors were made over a considerable period of time by all of the workplace parties. The merit of this analysis is that it does attribute cause to effect, regarding decisions, and yet, does so in a blame-averse manner. Based upon the Commissioner's Report of the Belmoral mine disaster (Beaudry, 1981), there were at least 21 decision errors contributing to the event, distributed among five parties at the enterprise level (Table I). That is, the decision errors that are considered are made by those in the day-to-day operations of the mine, as well as those in authority with the mine—Belmoral corporate management and the mine inspectorate. In total, there were 41 decision errors, and they are enumerated in Table I; plotted in Figure 5; and, profiled in Figure 6.

Observations

Of the 41 decision errors (Table I, Figure 6), 22 (59%) were errors of mistaken belief, 15 (37%) were errors of commission, and 2 (4%) were errors of omission. Boundary condition and decision analysis reveals that both errors of omission were on the part of mine management, ostensibly under pressure from the corporate management to meet production targets and generate cash flow. In so doing, they acted expediently to pull muck from the 2–7 stope and continue operations in the face of mounting geomechanical challenges. Also, strongly disposed to mistaken belief were the mineworkers, who were collectively of the belief that they did not have the right to know, the right to participate, or the right to refuse hazardous work (Figure 5).

Table I

Chronology of decision errors contributing to the Ferderber Mine crown pillar failure

No	Aggravating condition contributing to tragedy	Actor	Error
O	The choice of mine method was not appropriate for working of this orebody under the known geologic conditions. Regulatory agency not fully up to speed as to mine status. Regulatory Agency	Belmoral Mines Ltd Mine Management EOC	EMB EMB
N	Belmoral Mines Ltd operated the mine without safety management systems, a designated safety officer or any individual responsible for health, safety and training. Mine Supervision	Belmoral Mines Ltd Mine Management EMB	EOC EOC
M	Unusual flow of water flooding mine while driving ventilation raise wasn't investigated, or fully mitigated by management. Management motivated to complete development (May '79). Regulatory Agency	Belmoral Mines Ltd Mine Management EMB	EOC EOC
L	Unstable conditions in 1-7 exploration drift requires it to be abandoned. No attempt was made to discern why, such as diamond hole drilling or exploration work (July '79). Mine Supervision	Mine Management Regulatory Agency EMB	EMB EMB
K	Management decided to re-enter and advance 1–7 drift with the belief that the back of the drift was stable (Oct '79). Supervision acquiesced to management.	Mine Management Mine Supervision	EMB EMB
J	Decision to mine the 2-7 stope under 1–7 in an effort to exploit ore before the situation in 1–7 worsened, but no instrumentation installed to monitor/assess ground (Nov '79)	Mine Management Mine Supervision	EOO EMB
I	A fatality occurred in the 2-9 stope that should have triggered a review of ground and geologic conditions by the regulatory agency, mine management and mine supervision (Dec '79). Mine Supervision	Regulatory Agency Mine Management EOC	EMB EOC
H	There was a lack of emergency egress on the 350 level. The Mine Inspectorate provided a wrong interpretation of statute.	Mine Management Regulatory Agency	EMB EMB
G	The 25' crown between 1-7 and 2-7 was only 8', yet no means for this to be known to ground techs (Feb '80).	Mine Management Mine Supervision	EMB EMB
F	The mine openings were not designed within generally accepted mine standards—or factors of competence.	Mine Management Mine Supervision	EMB EMB
E	Mine Management was inappropriately influenced by Belmoral Mines Ltd to increase cash flow, as per contract, and consider production over development (March, '80) Mine Supervision	Belmoral Mines Ltd Mine Management EMB	EOC EOC
D	Production supervisors spoke often of the failing stope, and that it was worsening—workers did not refuse work (May 13)	Mine Supervision Mine Workforce	EOC EMB
C	The grade of ore in 2-7 was in steady decline. The mine geologist underestimated dilution. A decision was made to draw muck from 2-7 stope, on a sporadic basis (May 14).	Mine Management Mine Supervision	EMB EMB
B	Decision was made to ignore the condition of the back and walls of 2-7 and the flow of muddy water as indicative of imminent danger (May 17–19) Mine Workforce	Mine Management Mine Supervision EMB	EOC EOC
A	None of the workplace parties had been trained in, or prepared for an underground crisis of the order of the tragedy, in spite of the predictability and a previous fatality. Mine Supervision Mine Workforce	Belmoral Mines Ltd Mine Management EOC EMB	EOC EOC

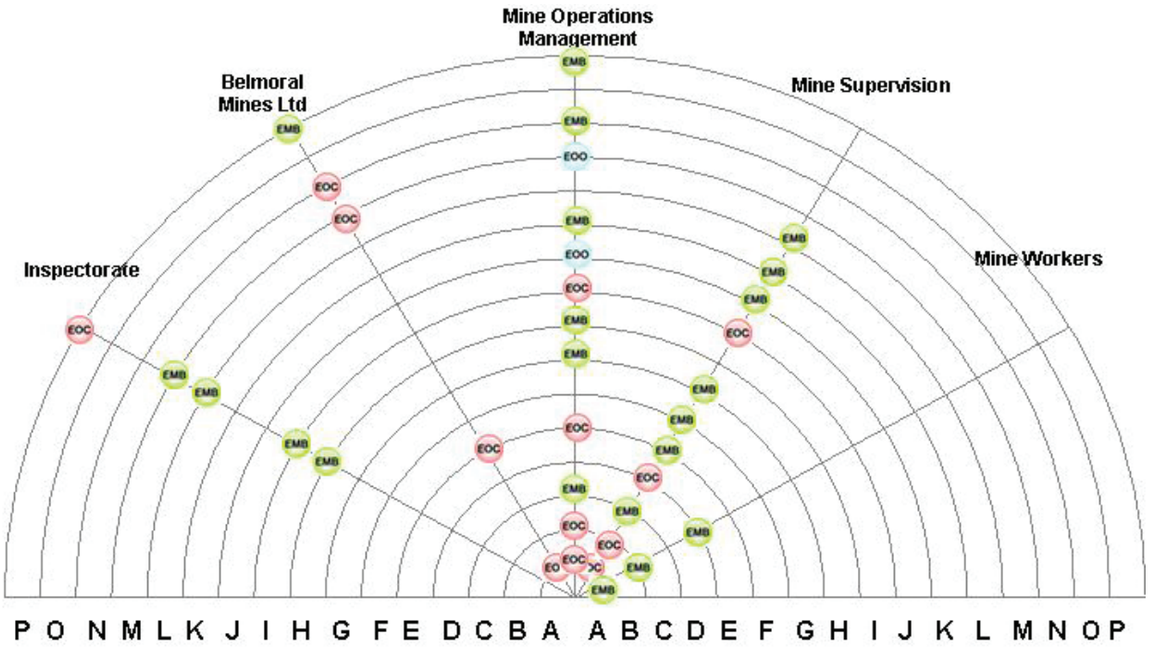

Figure 5—Semi-polar diagram applying boundary condition and decision analysis to the Ferderber Mine tragedy, illustrating the decison errors

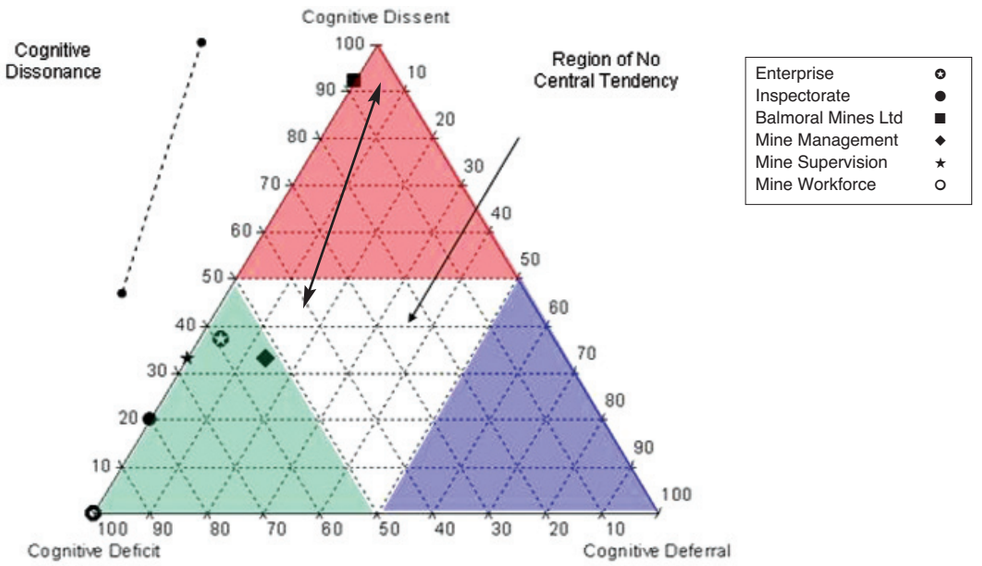

Figure 6—Cognitive ternary diagram illustrating distribution of the Belmoral Mine disaster decision errors

Cognitive profiling

Cognitive profiling is a method of considering decision errors within the culture of safety, or ethos of the enterprise in which they occur. The distribution of decision errors determined by BCD analysis (Table I, Figure 5), are plotted on a ternary diagram (Figure 6) to determine where each of the workplace parties' decision errors reports. The three cognitive regions are cognitive dissent, cognitive deferral, and cognitive deficit (Figure 6), with a region of no central tendency being in the middle of the diagram.

Belmoral mine overall cognitive profile

The cognitive profile of the Ferderber mine disaster, at the enterprise level, reports to the cognitive deficit region of the ternary diagram, with 59% per cent errors of mistaken belief, 37% errors of commission and 4% errors of omission (Figure 6). The contribution for each workplace party is tabulated below (Table II) and it is noted that with the exception of Belmoral Mines Ltd, all parties were strongly disposed to errors of mistaken belief. Mine management contributed to 36% of the decision errors, followed by mine supervision at 30%, corporate management at 15%, the mines inspectorate at 12%, and the mineworkers at 7% (Table II).

Cognitive profile of the mines inspectorate

Boundary condition and decision analysis reveals that the mines inspectorate made five decision errors, four of which were errors of mistaken belief. The mistaken belief in nearly every case was that Belmoral mines were actively and competently managing the geomechanical problems, a belief that was not based upon first-hand knowledge. The one error of commission was the lack of oversight that the inspectorate demonstrated in terms of approval of the mining method, at the design stage. The inspectorate has a fiduciary responsibility to the public and to the mining community through the issuance of licenses, to ensure that mine plans meet the standard of sound engineering principles and generally accepted industry practice.

Cognitive profile of corporate management

On the part of Belmoral Mines Ltd, corporate management were disposed to 84% errors of commission, and 16% errors of mistaken belief. It is noted that in each of the five errors of commission, the standard that was violated was the requirement imposed upon all directors of organizations—the duty of care to ensure competent supervision within the workplace, a standard for which there is no argument of ignorance of fact or circumstance. Corporate directors vicariously assume accountability for the workplace and the health and safety of all who work therein.

Cognitive profile of the mine management

Mine management at the Ferderber Mine were ultimately responsible for the day-to-day operational decisions at the mine. It is expected therefore that the majority of decisions would be made by mine management. It is not expected that the majority of the decision errors would be made by

Table II

Summary of decision error distribution tabulated according to workplace party

Workplace party	Count	EOC(%)	EOO(%)	EMB(%)	%
Inspectorate	5	20%	0%	80%	12%
Belmoral Mines Ltd	6	83%	0%	20%	15%
Mine management	15	33%	13%	55%	36%
Mine supervision	12	33%	0%	67%	30%
Mineworkers	3	0%	0%	100%	7%
Enterprise totals	41	59%	4%	37%	100%

management. Clearly, the latter was the case (Table II); and 55% were errors of mistaken belief. The mine management at the Ferderber Mine were not competent to manage the affairs of the mine, by this measure. Specifically, they lacked knowledge and the capacity for decision making about geomechanical matters, the very matters that would become so critical to the operation of the mine during the days to weeks antecedent to the May 20 crown pillar failure.

Cognitive profile of the mine supervision

The mine supervision includes all mine personnel directing the activities of others, as well as those professionals and technologists with whom the responsibility resides for technical matters such as mine ventilation and ground control. Mine supervision has an onerous and presiding obligation to ensure the health and safety of workers in the workplace. They have the authority, opportunity, and by definition, the competence to direct the work. The mine supervision was disposed to 67% errors of mistaken belief and 33% errors of commission (Table II). Typically, the errors of mistaken belief demonstrated by mine supervisors were violations of their duty of care in the workplace and to the workforce. An example in point was the imminent danger present in the 2–7 stope on May 13th. The supervisors spoke openly as to the hazard associated with the failing crown pillar, but did not take action appropriate to the threat.

Cognitive profile of the mineworkers

The mineworkers at the Ferderber mine made three errors of mistaken belief. Each one was related to their right of refusal of unsafe work, which they failed to exercise. Whereas an argument can be made that legislation may not have existed in 1980 that specifically empowered them with this right, surely a higher order standard did exist—that of self preservation. One miner had already been killed in December of 1979, and there was sufficient reason to form the belief that they were working in deteriorating mine conditions. Add to this the lack of safety training and standards, and the conditions were such that any number of mine emergency scenarios presented unacceptable future liabilities to the Ferderber underground miners.

Conclusion

The presiding ethos of the Ferderber mine enterprise was one of risk taking. All parties contributing to the day-to-day operation of the mine were disposed to errors of mistaken belief. They were, to various degrees, not competent to work in such a high-risk setting as presented by the Ferderber mine in May of 1980. The workers did not have the requisite knowledge of hazard assessment, safety or emergency response. The mine supervision lacked an understanding of their roles, responsibilities and geomechanical acumen. Mine management was motivated and influenced by production targets at the expense of prudent and considered ground control strategies.

It is evident that mine management were suffering from cognitive dissonance, as their competing priorities of production and safe development resulted in tension between themselves and the Belmoral Mines Ltd. This is illustrated by their cognitive profiles (Figure 6). The decision errors of mine management reported to the cognitive deficit region of the ternary diagram, and those of corporate management to the cognitive dissent region. In other analyses of disasters (Sweeney and Scoble, 2007) this signature has been shown as indicative of dissonance on the part of at least one of the workplace parties.

The enterprise at the Ferderber mine would have benefited from greater expertise and leadership by Belmoral Mines Ltd, and much greater dialogue and oversight by the mines inspectorate. That this was not the case is tragic in its consequences, and serves as a lesson to all mining enterprises as to the value of consultation, collaboration and caution when mining challenging geologic conditions.

Epilogue

Officers of Belmoral Mines Ltd. were charged with manslaughter by the office of the Attorney General of Quebec, Canada. The verdict of that trial was acquittal. The verdict was overturned in 1987 by the Quebec Court of Appeal, ordering a new trial on the basis of judicial error. The decision of the Quebec Court of Appeal was appealed to the Supreme Court of Canada in 1989, and the decision of the Quebec Court of Appeal was upheld.

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