Avalanche Hazard "Risk Management" for the Yule Marble Quarry

Christopher C. Landry
President, Yule Creek Avalanche Services, Inc.

Introduction

Snow avalanches may have been the least anticipated and most tragically underestimated natural hazard faced by the rapidly-spreading Colorado mining boom of the late 1800's. Mostly newcomers with little or no mining experience, let alone mountain experience, successive waves of hopeful men and their attendant boom towns established patterns of industrial and community development during summer months with inadequate regard for the harsh realities of high alpine winters.

The inevitable consequences were grim: men were routinely lost in avalanches traveling to and from their mines, entire mine crews were lost sleeping in their bunkhouses, and even schoolhouses were wiped out.[1]

The discovery in 1873 and eventual development in the 1890s of the Yule Creek marble deposits was no exception to this litany of harrowing stories. Located some three miles up the rugged Yule Creek valley from Marble, access to the quarry was difficult enough during summer months, and numerous transport systems were tried before an electric tram proved reasonably reliable. Still, winter often thwarted the best technology these determined men could throw at it. After heavy snowfalls—and frequent and sometimes massive avalanches—snow removal was accomplished with men wielding shovels.

Living at the quarry site was a marginal solution at best, and not without peril. And even the enormous millworks in the town of Marble fell victim to itself as slopes were logged and denuded of timber, exacerbating an already significant avalanche hazard. Men were lost, operations were interrupted, and facilities suffered heavy damage. It was clear, as the operation grew, that simply dealing with the snow and avalanches in Yule Creek required an enormous "industrial" effort comparable to operating the quarry itself.[2]

Gradually, the business failed until, in 1941, all operations ceased. But, while the quarry and millworks had become uneconomic to operate, a substantial portion of the high-grade deposit remained to be recovered. Fifty years after it had fallen silent, in the summer of 1990 the Yule Quarry was being revived by the newly formed Colorado Yule Marble Company (CYMC). The underground quarry caverns were cleared of debris, a new floor-level portal opened, and the access road rebuilt. The modest operation would rely on modern heavy equipment to move the men and material to and from the quarry. As in the past, quarry operations expertise was imported from Italy. But, unlike the past, this time the new company sought out avalanche expertise as well.

CYMC hired consultant Arthur I. Mears, P.E., to assess avalanche hazards to the modern operation of the quarry and to recommend mitigation measures. By the fall of 1990, Mears had mapped eight major avalanche paths and numerous bank slide areas capable of reaching the 3.4 mile road leading to the quarry. Potential for avalanching at the new portal was also noted. Mears explained the concept of hazard as a function of exposure in his report and recommended a stability evaluation/closure approach to hazard mitigation. A stability evaluation and hazard forecasting program was outlined and professional avalanche forecasting assistance was recommended. Numerous safe-travel recommendations were presented and preparation for self-rescue was emphasized.

Mears stated in his report, "during particularly bad winters the access road may be closed...as much as 10 to 20 days." Certainly, compared to their predecessors of 1890, the miners undertaking this diffi-

[1] *Living and Dying In Avalanche Country,* by J. Marshall & J. Roberts, pp. 54-60.

[2] *Marble – A Town Built on Dreams, Vol. II,* O. McCollum, Jr., pp. 45, 95-102, 251, 266-267 and *Marble, Colorado – City of Stone,* D. Vandenbusche and R. Myers, pp. 71-72.

cult venture in 1990 were armed with vastly superior information about the avalanche hazard. By late fall, quarry operations were in full swing—just in time for the first snows.

The spring of 1993/94 marked the fourth complete winter of avalanche accident-free operation. Yule Creek Avalanche Services, Inc. (YCAS) has provided avalanche consulting to CYMC for the three full winters of 91/92, 92/93, and 93/94.

This paper will elaborate on the Yule Creek avalanche path attributes, the "avoidance" approach to "risk management" applied to this operation, and on the application of that approach in the month of February '94.

The Avalanche Potential of the Lower Yule Creek Valley

The following map (Figure 1) of the lower Yule Creek valley and those avalanche paths which affect quarry operations is a compilation of the original mapping done by Mears in 1990 along with additions made by the author over the succeeding years.

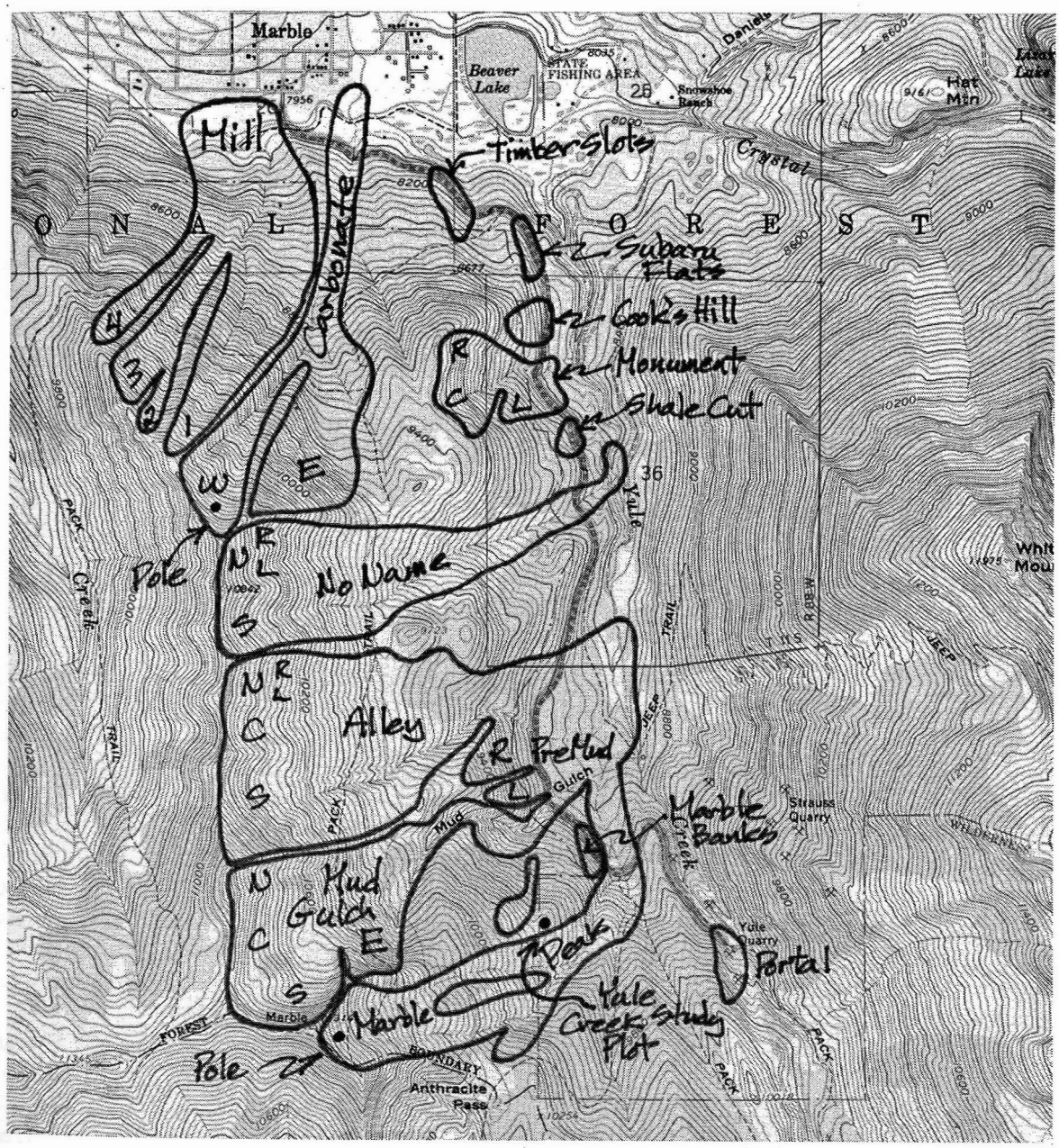


Figure 1. Lower Yule Creek valley.

Additions to Mears' work include the plotting of the Mill #1-#4 paths. Although the Mill paths do not threaten the quarry access road itself, they do threaten a parking area and material storage yard now used by the quarry operation. Other additions include the Subaru Flats, Cook's Hill and Shale Cut paths, all of which buried the road with significant events during Feb '94. The bank slides noted by Mears in 1990 have been renamed "Marble Banks," and the Portal slide path has been plotted and named. Also noted on the map are the sites of two starting zone poles and the location of the "Yule Creek Study Plot" (YCSP).

Three primary physical characteristics seem to shape the avalanche potential of the lower Yule Creek valley: 1) the relatively low elevation of the starting zones, 2) the terrain configuration vis-a-vis orographic effects, and 3) the relatively homogeneous aspects and other characteristics of the starting zones.

None of the slide paths can be considered equivalent to the more stereotypical high alpine starting zones common to the Colorado Rockies. The Marble Peak path starting zone at 11,300' is the highest to threaten the quarry road, and some starting zones are as low as 9,000'. In spite of the relatively low elevation, though, the Yule Creek valley does collect substantial moisture, generally comparable to the Schofield Pass, Gothic, and Irwin Lodge study plots near Crested Butte. Some 1,081 mm (42.5") of H_2O equivalent snowfall was measured at YCSP in the period from 10/27/92 through 5/23/93. The 1993/94 total from 10/7/93 through 5/10/94 was 757 mm (29.8") of H_2O equivalent.

Winter storms typically track into Colorado out of the SW-to-NW quarter; late-storm wraparound moisture generally approaches from the N/NE, and even E. Yule Creek seems to prosper best from storms tracking into the area on a WSW flow. As storms approach from the WSW, crossing the 6,000' elevation west-central valleys, they encounter an abrupt mountain front formed by the Raggeds ridge (12,641') and the Treasure Ridge massif (13,528'). Convective activity enhancement of the already substantial orographic effect on storms following this track is not uncommon and can be substantial in late winter and spring.

Storms approaching Colorado out of the NW are generally less productive in Yule Creek than SW'ly storms. Yule Creek is the easternmost and lowest in a series of four parallel, north/south axis valleys. Each ridge to the west of Yule Creek rises higher than the previous, culminating in the Chair Mountain and Raggeds complex at 12,700' some seven miles "upstream." Much farther upstream to the WNW, the 10,500' Grand Mesa rises dramatically out of the 4,500' Grand Valley and captures heavy snowfalls from NW'ly storms. Similarly, wraparound moisture on a N'ly flow is a sparse precipitation producer in Yule Creek, shadowed by the upstream higher terrain of the Elk Range.

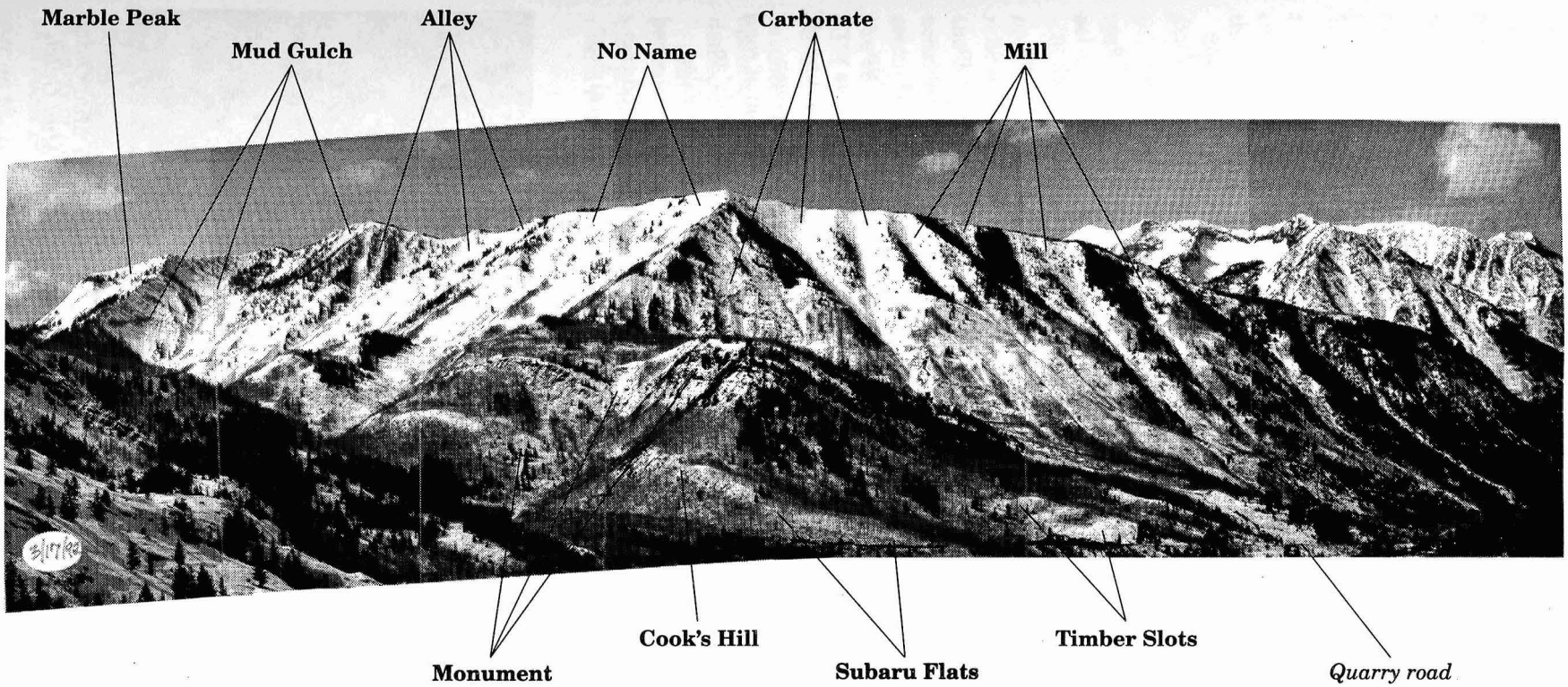
Taken together, the low elevation starting zones combined with relatively mild (frequently convective) and moisture rich SW'ly storms introduce intermountain-like aberrations into the typical continental snow climate and depth-hoar snowpack for which Colorado is best known.

Seen together, as shown on the map and presented on the following page in Table 1, the largest of these slide paths present a number of common traits. Starting zone ground cover in all of these paths is quite similar with nothing but "grass" typical on all of the SE, E, and most of the NE aspects; some pockets in the higher NE aspects contain young coniferous trees of less than 2 meters in height. Exposed rock is present in the steepest areas of the Mud Gulch starting zones.

The similarity of alpha angles among these large paths reflects the morphology of this ridge with its beds of sandstones and shales capped by igneous material. And, as the map reveals, all of these paths share starting zone aspects from SE to E to NE (except for Carbonate and the Mill paths, which have no SE components). In short, due to their generally similar altitudes, slope angles, and aspects, these paths tend to share similar snowpack characteristics.

The remaining set of slide paths (Table 2) that affect the road is characterized by steeper alpha angles, shorter vertical runs, and lower elevation starting zones. All of these paths have produced events capable, at a minimum, of pushing a passenger vehicle off of the road; the Monument and Pre Mud paths are capable of significant damage to vehicles and heavy equipment.

Although Timber Slots, Pre Mud, and Monument contain some open areas free of trees or bushes, the ground cover in these paths generally consists of thin to moderately-thick aspen groves, with trees from 3-10" in diameter, and occasional conifers up to



Not shown: Shale Cut, Pre Mud, Marble Banks, Portal

Table 1. Avalanche paths originating at ridgetop.

Path Name	Max SZ Elev.	SZ Angle	SZ Acres	Alpha Angle	Max Vertical	Width at Road
Mill #1-4	10,500'	40°	30	27°	2,600'	NA
Carbonate	10,800'	40°	20	25°	2,900'	480'
No Name	10,800'	35-40°	50	23°	2,400'	320'
Alley	11,200'	35-45°	70	25°	2,600'	1,250'
Mud Gulch	11,300'	35-50°	40	27°	2,600'	370'
Marble Peak	11,300'	35-40°	20	24°	2,600'	430'

Table 2. Avalanche paths originating on lower slopes.

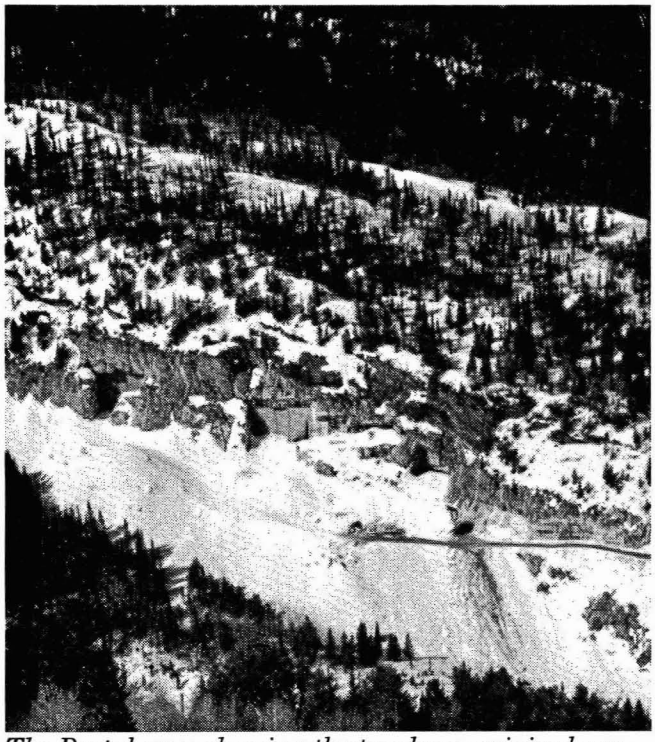
Path Name	Max SZ Elev	SZ Angle	SZ Acres	Alpha Angle	Max Vertical	Width at Road
Timber Slots	8,400'	35°	3	30°	200'	650'
Subaru Flats	8,400'	35°	3	30°	200'	600'
Cook's Hill	8,600'	35°	3	28°	300'	200'
Monument	9,200'	40°	10	33°	800'	600'
Shale Cut	8,600'	45°	2	45°	100'	550'
Pre Mud	9,500'	35°	5	35°	700'	670'
Marble Banks	9,200'	40°	3	40°	200'	530'
Portal	9,600'	45°	5	45°	300'	650'

18-24" in diameter. The low elevations of these paths enables rain precipitation to occur at the same time that snow is falling in the higher starting zones. These paths share E and NE aspects; none faces SE.

These lower elevation paths also tend to behave similarly to each other, yet they behave differently than their higher elevation counterparts. And, because of their quite steep alpha angles, smaller events are capable of reaching the road.

The Portal path area, due to the nature of the operational activity and facilities there, presents a different potential for an avalanche incident. Having once been entirely denuded of tree cover, the very steep, rocky face above the two large, historic portals has partially recovered, leaving a few open, steep pockets surrounded by moderately dense coniferous tree cover. The old portals are now curtained in an effort to minimize freezing of the open water ponds inside the quarry. Unfortunately, one of these curtains needs routine shoveling to prevent damage from accumulated snow.

The new portal tunnel bored in 1990 was placed to enable vehicles to drive into the floor level of the underground quarry "rooms." Like the old portals, the new portal entrance is also cut into a steep rock face. The quarry's electrical generator and radio transmitter are located in a semi-trailer next to the new portal, as is its fuel tank. After the generator trailer was nearly knocked over during the winter of 92/93, it was moved some twenty-five feet away from the slope before the 93/94 winter. Gasoline-fueled crew passenger vehicles are parked outside of the new portal due to mine safety regulations.

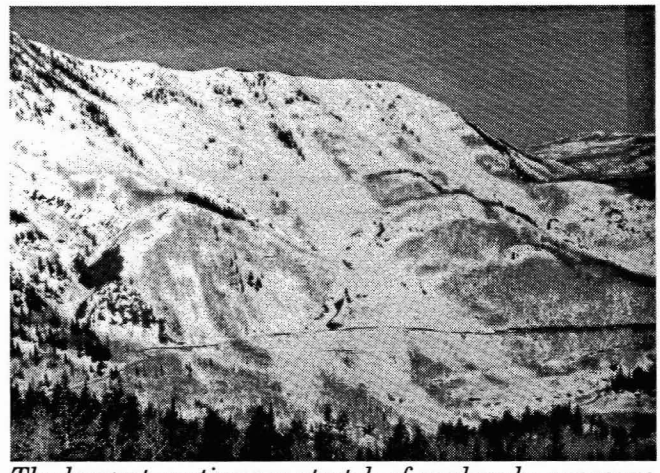


The Portal area showing the two large original portals, now curtained, and the new portal down and right. The generator trailer is visible to the left of the new portal.

The Avalanche Hazard in Yule Creek

Operating the Yule Creek marble quarry during winter months (ie., from late October thru late May) requires extensive exposure of workers and equipment to the impressive avalanche potential of the lower Yule Creek valley.

As is evident from the slide path map, traveling the 3.4 mile road to and from the quarry requires significant exposure to thirteen distinct avalanche paths. Based on field observations of the four winters from 1990/91 to 1993/94, and of flank trim lines, it is now estimated that some 7,300' (1.4 miles), or 40% of the length of the road lie within avalanche path tracks or runouts. Travel times vary, of course, with direction, conditions, and the type of vehicle. In good conditions, the crew's passenger vehicles may traverse in 30 seconds a section of road which requires two minutes for the "hill truck" to cross when loaded with a 15 ton block of marble. Road plowing operations require the most prolonged exposure, from a minimum of two hours round trip travel time following a small storm, to several days following a major avalanche cycle.



The longest continuous stretch of avalanche exposure on the quarry road runs for 2,300' under Mud Gulch (far left), Pre Mud (lower knob between Mud Gulch and Alley), and the Alley (center).

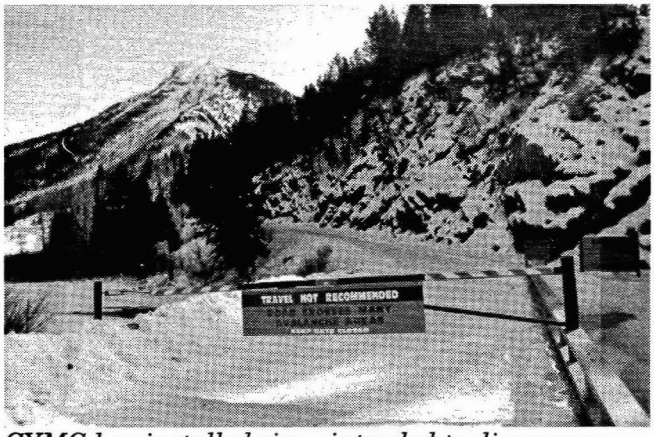
In addition, as mentioned above, the vehicle parking and material storage activities in the Mill paths runout area are another opportunity for exposure. Likewise, approaching the quarry portal, parking, entering and leaving the portal, generator maintenance, and curtain maintenance all require exposure in the Portal path.

And, of course, performing the field work necessary to adequately monitor and predict avalanche conditions requires backcountry travel, on skiis, by the avalanche professional(s).

Unfortunately, in addition to these exposures experienced by the quarry workers, the reopening of the quarry has also created a quantum leap in opportunities for the general public to place themselves in harm's way. Although CYMC rebuilt and now maintains the road, the quarry road is considered a public road by Gunnison County. Since the road is usually in plowed condition (by CYMC, not the County), and because the quarry has received considerable publicity since reopening, winter sightseeing travel is increasing. And, as mine claims in the Yule Creek valley are sold, new cabins are being built which depend on the quarry road for access. A bible camp recently applied to the County for permission to expand its facilities in Yule Creek and to operate during the winter. (The application was denied.)

During periods when the road is unplowed and CYMC operations are suspended, ski tourers, snowboarders, snowmobilers, snowshoers, and a year-round resident continue to travel the road. Because of its status as a public road, CYMC cannot lock the gate at the bridge at the beginning of the road or prohibit the public from accessing Yule Creek. Signs on the bridge gate designed to discourage public travel are only partially effective.

A party of unknown backcountry skiers triggered this event in S. No Name while ascending the shoulder on the left. No one was caught in the slide.



CYMC has installed signs intended to discourage public use of the road, but the effort has produced only limited success.

This public exposure to the Yule Creek avalanche potential has grown substantially since the winter of 1990/91 and may now match or surpass the exposure to CYMC operations. In the unfortunate event that an avalanche accident occurs, whether it involves CYMC or the public or both, the prospect of a rescue operation represents yet another significant form of exposure to these slide paths.

Risk Management

Based on its interpretation of its Wilderness Act management policies, the Sopris District office of the U.S. Forest Service has determined that no explosive avalanche intervention work may be performed within the federally-designated Raggeds Wilderness area. Since the Wilderness boundary generally parallels the quarry road just uphill of the road, this ruling precludes active "control" of virtually all of the slide paths affecting the road.

Given that ruling, and following CYMC's first unsuccessful attempts in 1990/91 to self-implement Mears' safety program, a program of measured exposure to the Yule Creek avalanche hazard has evolved. The program, as recommended by YCAS and "adopted" by CYMC, is based on a four-part, progressively more restrictive series of operating rules based on the avalanche hazard rating provid-

ed by YCAS. The rating system, with the corresponding operational rules, is presented below:

- LOW—generally stable snowpack; avalanche activity is unlikely in the Yule Creek valley. Operating rules: no restrictions on travel; radio communication recommended.
- MODERATE—pockets of instability; avalanche activity in the higher elevations of the valley is possible but should not pose a hazard to the quarry road or quarry portal. Small-scale road-bank and portal area activity is also possible. Operating rules: no restrictions on travel but vehicles should maintain spacing; radio communication required; plowing operations must maintain radio communications; transceivers required.
- HIGH—generally unstable snowpack; widespread avalanche activity has not begun or is winding down, but isolated avalanche activity capable of reaching the quarry road and/or portal area is (still) currently possible. Operating rules: CYMC travel restricted to shift change trips only—no hauling; multiple vehicles and spotting required—one vehicle at a time through all slide paths; plowing operations must be spotted; radio communication of exact position required; transceivers required.
- EXTREME—imminent, or actual widespread avalanche cycle in progress during which many avalanche paths will run and any/all paths have the capability of reaching the quarry road and portal or have already hit the road or portal. Operating rules: all operations cease, including plowing.

(CYMC uses an UHF radio system with mobile and hand-held units distributed among their various vehicles and in the quarry, a hand-held unit with YCAS, and a base station/repeater installation downvalley. Radio procedures during travel consist of declaring that a given vehicle is entering or clear of each slide path as the vehicle travels the road.)

The purpose of the program is to assure that CYMC is operating within the boundaries of what seems, from both YCAS's and CYMC's points of view, to be an acceptable level of risk to the employees and equipment. Clearly, elements of the operation such as plowing or material hauling could place some individuals at higher risk than others. The operating rules attempt to minimize that disparity in exposure. Under this program, presuming that an EXTREME hazard isn't declared while the crew is in the quarry, the nominally worst risk to CYMC operations occurs during HIGH hazard periods in the form of minimized and carefully managed travel to and from the quarry. Hauling, plowing, and other extraneous travel (other than by the avalanche professional) is halted.

The following schematic (Figure 2) relating risk to exposure presents this "risk management" program graphically and reveals a shortcoming inherent in these kind of incremental measures. (The "graph" represents an intuitive interpretation of the relationships).

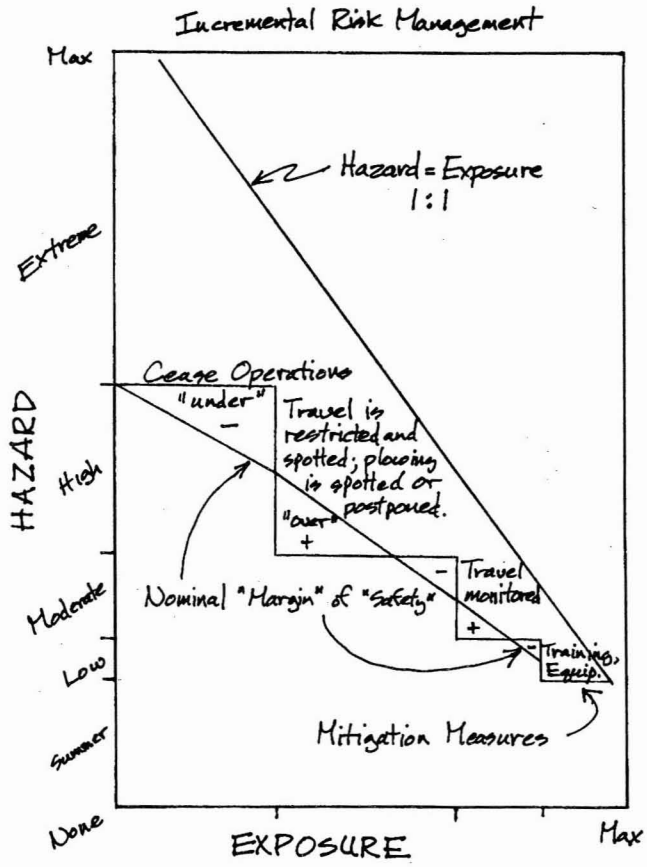


Figure 2. Incremental risk mitigation measures.

The vertical axis in the graphic represents avalanche hazard in a weighted scale intended to reflect the gravity of the ratings. The horizontal axis indicates a continuum of exposure, from "none" to "maximum." This scale is also weighted to emphasize the nature of exposure during increasing hazard. The line "Hazard = Exposure" refers to a theoretically possible relationship where a person's "odds" of being hit by a natural avalanche while

traveling the quarry access road are something like 50/50, or "even."

The "Margin of Safety" line below and left of that H=E line represents the hypothetical "reasonable risk" produced by the mitigation measures shown as the stepping line. Mitigation at LOW hazard does not include any travel restrictions but does include basic avalanche awareness, rescue training, and rescue equipment. Under MODERATE, in addition to that basic awareness and equipment, basic travel procedures and radio monitoring add to the "margin" of safety. As the hazard increases to HIGH, and the "stakes" (as well as the consequences of underestimating the hazard) increase, exposure is reduced to the bare minimum. Finally, when the hazard is either perceived or seen to be "EXTREME" per our definition (avalanche cycle is imminent or in progress), the margin of safety is intended to be total and all operations (exposures) cease.

For the sake of illustration, the "Margin of Safety" line is drawn through the stepping Mitigation Measures line at the midpoint along the vertical portion of the step, the midpoint being the moment when those measures are implemented. That midpoint designates the "center" of each rated hazard level within the continuum from None to Maximum Hazard. The symbols "-" and "+", labeled "under" and "over," indicate a shortcoming in applying incremental mitigation measures to a hazard continuum. This is well illustrated during a HIGH hazard.

Even assuming that conditions are actually identical among the slide paths, and that the forecaster is able to consistently modify the rating in precise synchronization with actual conditions, a particular set of mitigation measures could represent an over-mitigation during the initial phase of a hazard level or they could be less than sufficient to maintain the desired extra margin beyond H=E during and until the transition into the next higher level.

In the event that the hazard is underrated by a level, or the mitigation measures are not employed in step with the hazard, the result may be that the actual margin of safety collapses all the way back to the H=E line, or worse. If, for example, operational procedures were lax and exposure during HIGH hazard periods was mitigated by only radio monitoring of unrestricted travel, then nothing like the desired margin of safety would be achieved.

Given CYMC's imperative to "do business" in the Yule Creek valley during the winter and their reliance on a technical consultant for hazard analysis, operational decision-making is necessarily triggered by information gathered by the consultant and then compressed and communicated as a summarized rating. That rating, in turn, triggers a predetermined set of operational responses. This approach toward what is essentially equivalent to backcountry travel differs significantly from the behavior of, for instance, a skier who makes decisions and "risk management" choices from moment to moment in a continuous, iterative process driven by personal observation and analysis.

When indicated by the conditions, YCAS often provides a hazard rating which indicates a worsening trend, such as "MODERATE trending HIGH," in order to indicate that 1) conditions may warrant immediately implementing the stricter set of operational rules in order to avoid being caught "under-mitigating" and 2) conditions are likely to worsen and an appropriate planning response needs to be developed. When the hazard is rated "HIGH trending EXTREME" at 0600 hours, that rating will often be viewed by CYMC as sufficient to cancel operations for the day, thus precluding the necessity to evacuate the quarry and travel the road at some later time during the day under conditions that exceed the "worst acceptable case" risk contemplated under this program (where the "worst acceptable case" is that all operations will have ceased just prior to the moment when the hazard becomes EXTREME).

This risk management program, it must be noted, is considered appropriate for daylight operations only. In the view of the author, the program provides an insufficient margin of safety for night operations. The inability of travelers to observe the slide paths above the road, and the extreme difficulty entailed in a night rescue operation, not to mention the ratcheting effect that darkness can have on so many other problems which would be considered minor in daylight but which may result in prolonged exposure to the avalanche hazard at night, all offer strong arguments against conducting any operations during the night or, at a minimum, dropping each set of operational rules "down" one hazard rating. Under that approach all night operations would cease during HIGH hazard periods.

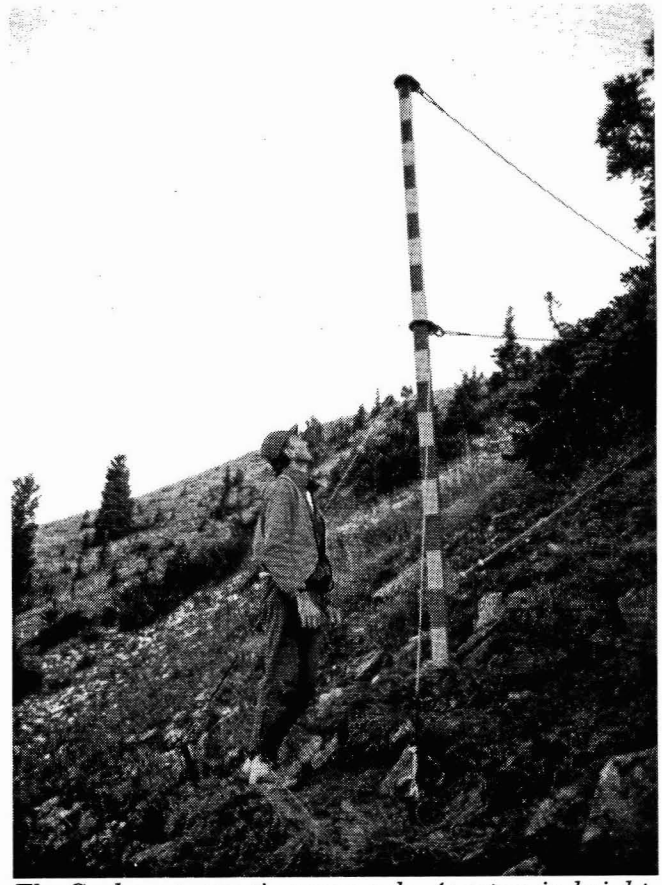
Avalanche Hazard Evaluation Methods and Tools

During the summer of 1992, YCAS installed an "automated weather data acquisition system" at the Yule Creek Study Plot location identified on the map. The station is at 9,700' on the highest elevation private property accessible from the quarry access road. YCSP is just a few yards from the Marble Peak slide path track. The station consists of a Campbell Scientific CR10 datalogger, a single sonar unit, a Noah II precipitation (water equivalent) gauge, air temperature and relative humidity gauge, three snow temperature sensors, an anemometer, a pyranometer, and radiotelemetry equipment. The system is photovoltaically-powered. The radiotelemetry base station/phone link is located at a private residence near Marble.

The automated weather data acquisition system at Yule Creek Study Plot. The anemometer, pyranometer, and photovoltaic panel are located on another mast some 200' south of here.

Data is logged in the CR10 for one hour, three hour, and 24 hour intervals and is retrieved via modem from YCAS's Carbondale office, some thirty miles from Marble. Retrieved data is transcribed to a loose leaf "Day Log," a "Month Log" wall chart, and, during storms, to a "Storm Log" using the three hour interval data. Examples of the Month and Storm Logs will be presented below.

YCAS also obtained a Special Use Permit from the U.S. Forest Service in order to (seasonally) install static depth-indicating poles in the starting zones of the Marble Peak and Carbonate slide paths inside the Raggeds Wilderness. These 3" × 3" square aluminum poles are marked in 20 cm increments



The Carbonate starting zone pole, 4 meters in height.

and are now 5 and 4 meters tall, respectively. (In February '93 the Marble Peak pole, then at 4 meters, was covered by the snowpack and didn't reemerge until mid-May). The poles are read from the quarry road using a 45X spotting scope.

Field work includes observations made from Marble and the quarry road of avalanche activity in Yule Creek and in the vicinity, observations of the starting zone depth poles, and snowpack profiles. In 1993/94, YCAS made 92 site visits; over 100 trips were made the previous winter. Most trips up the quarry road are made in a passenger vehicle but conditions sometimes require traveling the road via snowmobile.

In 1993/94, 25 documented snow profiles were conducted, most of them at the Yule Creek Study Plot. When conditions permit, profiles will be performed in other locations. But, as a general rule, YCSP is the only meaningful site that a solo snow worker can access safely. As a result, the field work concentrates on conducting a series of snowpack profiles at YCSP.

Avalanche activity greater than Class 1 is documented and significant storms (of at least 0.5" H_2O) are scored utilizing an avalanche activity index calculation recommended by Mears (unpublished).

At 0600 hours every day of the season (from 10/7/93 through 5/10/94 in '93/94), YCAS provides CYMC with an updated avalanche hazard rating and the current National Weather Service (NWS) forecast. These are transmitted in the form of a telephone call and a written copy via fax. As circumstances warrant, YCAS updates the hazard rating during the day by telephone from Carbondale, or by radio or in person while onsite.

NWS forecasts for the central and southern mountain zones are obtained via modem from a vendor and include the technical discussions by the NWS forecasters. A NOAA weather radio station located in Grand Junction, Colorado, is also monitored, as are several television weather information sources. Weather forecasts and avalanche advisories are also received from the Colorado Avalanche Information Center (CAIC), and YCAS provides frequent field observation updates to CAIC.

February 1994 Case Study

The winter of 1993/94 began with 113 mm of H_2O (as snow) in early October followed by three dry weeks, then another 134 mm H_2O in November from two storms separated by a dry and clear week. December produced another 75 mm of H_2O in a series of small storms. In December, the snowpack reached, then hovered around the 1 meter mark at YCSP. January produced only 29 mm of H_2O with a two week period mid-month of virtual drought, mild temperatures, and clear skies day and night. The month-end brought plunging temperatures.

The February Month Log of 24-hour summary data is presented below (Figure 3). Storms are numbered and their liquid equivalent (as measured by the Noah II) is shown, at 5 mm per square, next to the snowfall estimate during the 24 hour period, shown at 5 cm per square. Starting zone pole depth readings are shown, as is the daily maximum snow depth at YCSP (as measured by the sonar device). Wind is shown as a triangle where the 24 hour average speed forms the base, and the peak gust the apex, of the triangle; "average" direction is represented just below as the standard deviation from the mean. Air temperature, snow temperatures and solar flux data are presented in the middle grid. The slightly arcing horizontal line across the grid represents the estimated nominal total solar flux, in kJ, at YCSP on a given day under perfectly clear skies. The lower grid logs the number of Class 2 or larger avalanches, their aspects, the largest class of event, and the types of avalanches. Avalanches which reach the road are listed. The AM and PM hazard ratings are noted, as are site trips (as a Snow Profile number or observer initials).

(February 1994 Case Study text continues on the page after next)

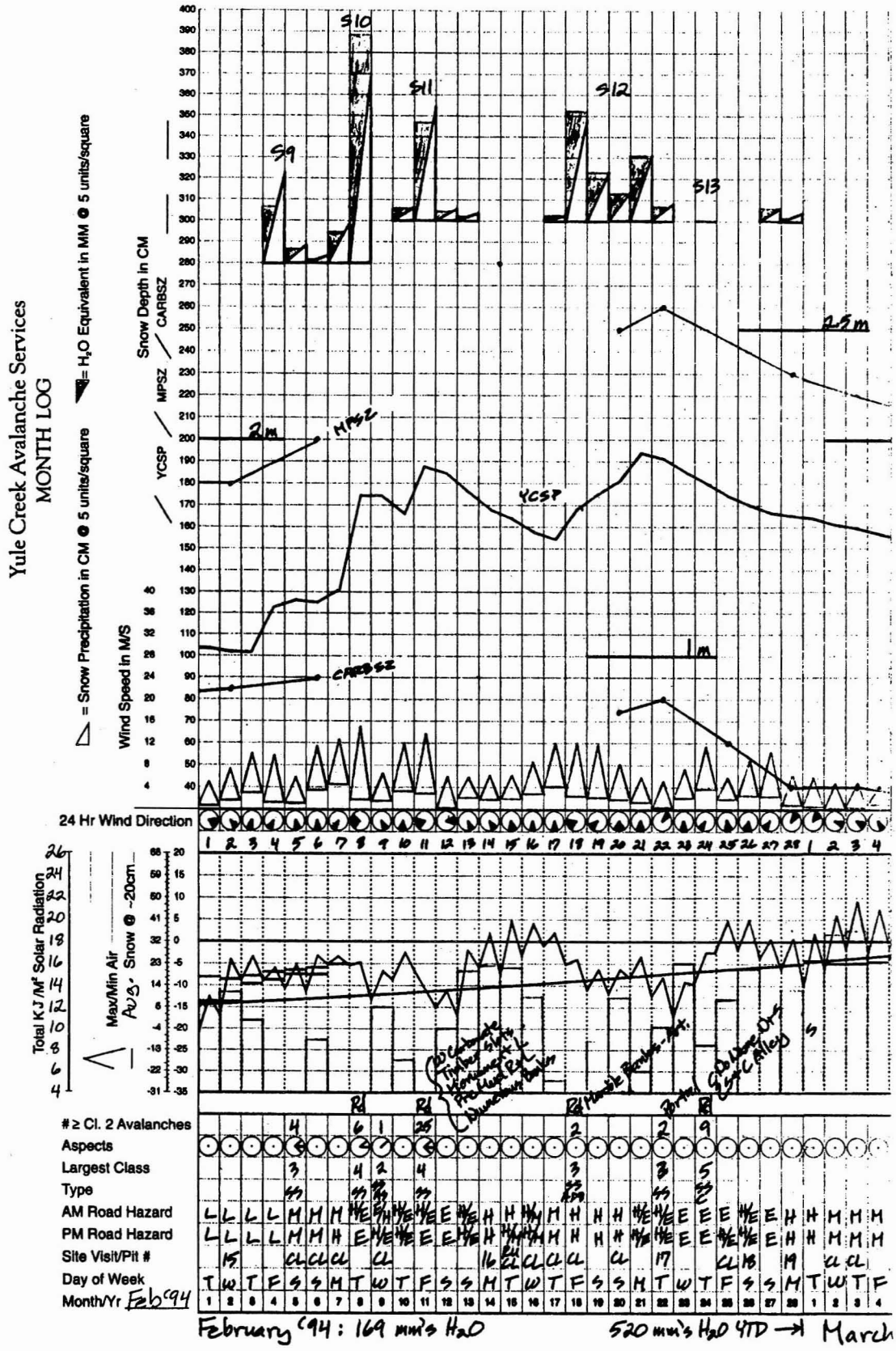


Figure 3. February 1994 Month Log.

February Highlights:

2/2/94—*Profile #15 at YCSP (Figure 4 below):* note that the top (Storm #8, 1/26) layer seems to have skipped any intermediate ET reduction and went, instead, directly from new snow to kinetic crystal form. Note densities ≤ 250 kg/m³. On the Month Log, note the 6.5° C gradient across 20 cm in the snow temperature sensors just below the surface at YCSP. Snowpack has deteriorated dramatically since Profile #14 on 1/22.

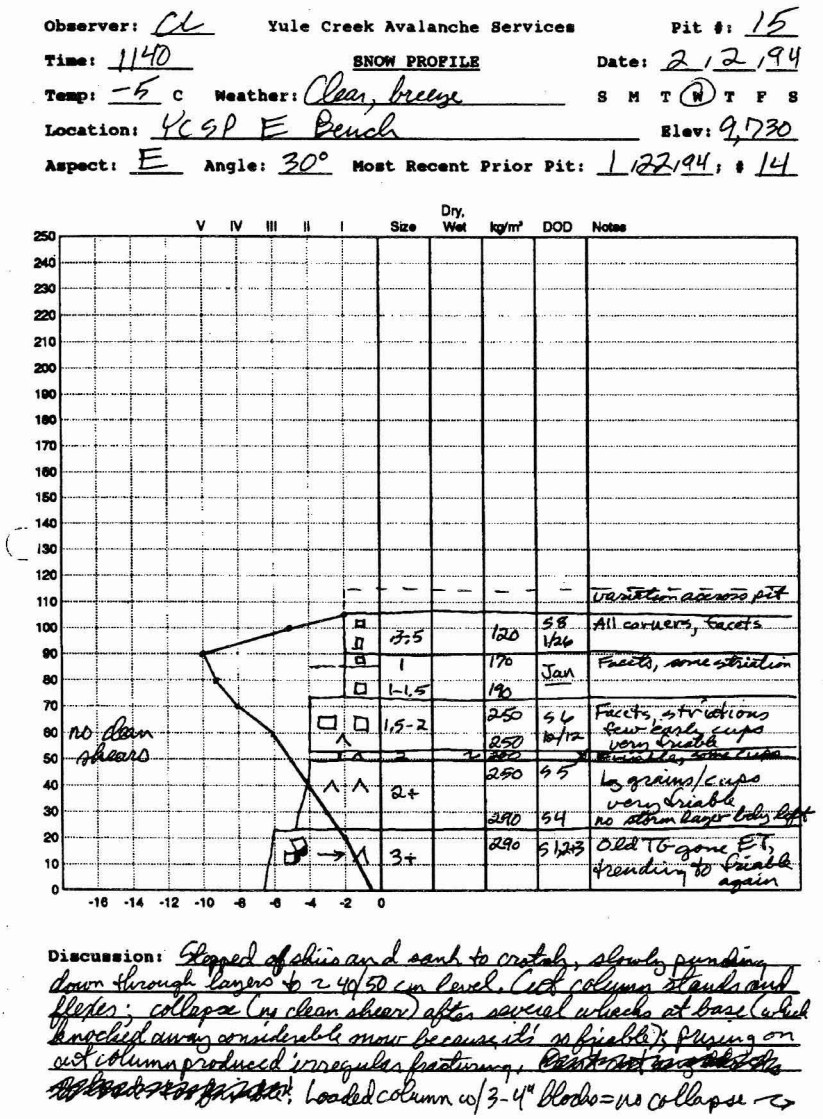


Figure 4. 1993/94 Snow Profile #15.

2/5/94—*Storm #9:* at 16 mm H_2O, produced mostly Cl 2 shallow, very soft slabs and loose sluffs. Ran into two women on snowshoes at No Name track road crossing; typically, they were unaware of having already traveled under several potentially deadly paths.

2/6/94—*0600 fax:* hazard is rated "MODERATE trending HIGH in Pre Mud path...just a few tenths of an inch of H_2O could...produce a road strike (and) the rest of the paths aren't far behind." Snow likely Monday through Wednesday. The Carbonate starting zone pole is at 90 cm, approaching 1 meter in depth for the first time this season.

2/6/94—*Rumor:* CYMC is discussing running a swing (night) shift for the next two weeks!

2/7/94—*0600 fax:* "...hazard will go to HIGH as precip begins. Winter Storm Watch starting late afternoon." CYMC cancels swing shift plans on YCAS's "strong" recommendation.

2/8/94—*Storm #10 (shown below):* as is often the case, precipitation intensity from midnight to 0600 hours this morning was exceptional; windspeed averages (factored by 2x to estimate ridgetop winds) are at or close to 4 mps, considered a critical threshold. At 0600 the hazard is rated at HIGH trending EXTREME; CYMC cancels operations.

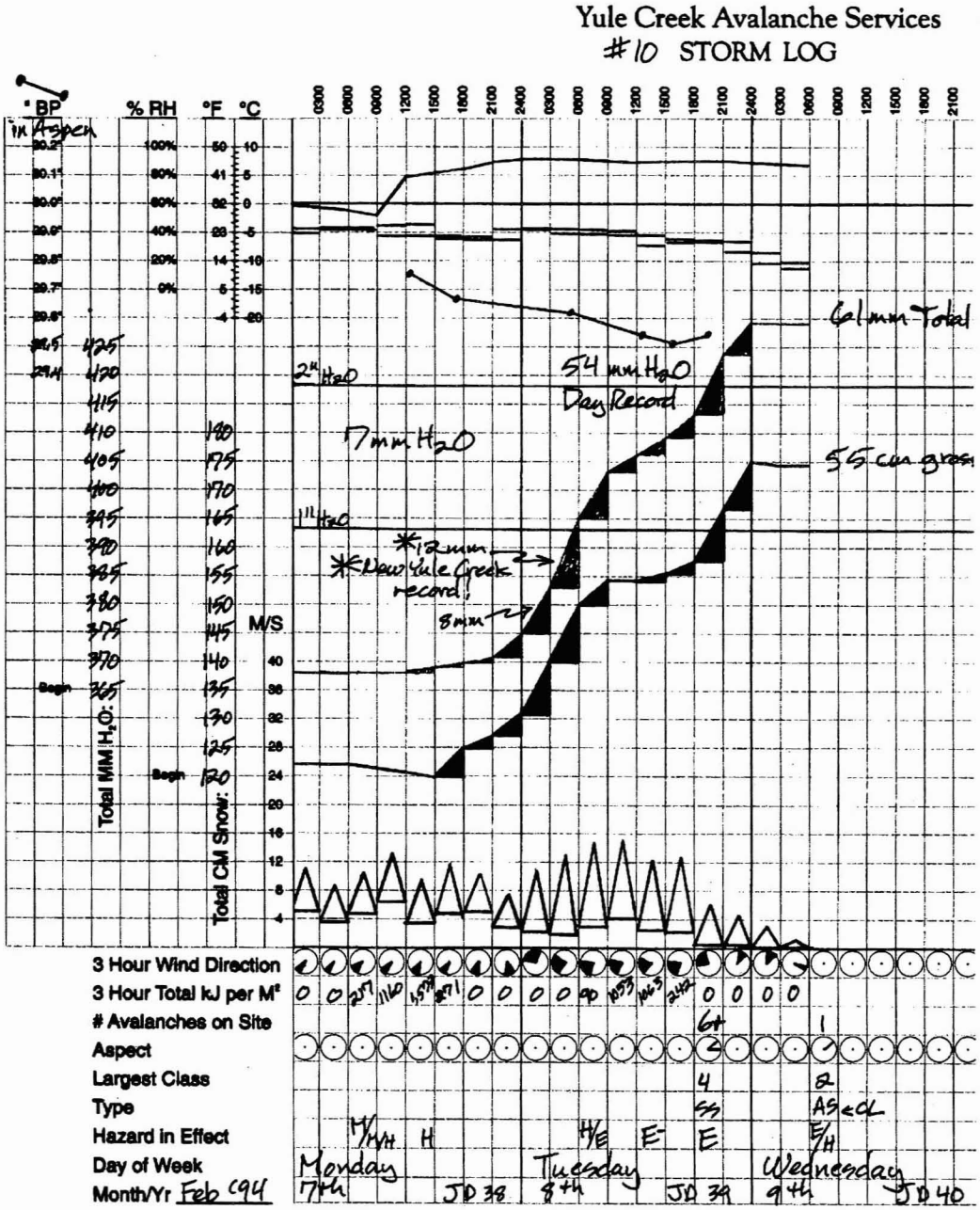


Figure 5. 1993/94 Storm #10 Log.

2/9/94—*Post-storm obs:* see major activity on McClure Pass paths on Hwy 133 driving up-valley. Excellent visibility in Marble. Cl 4 SS in Mill #1 reached flats at river, W Carbonate ran Cl 3 SS to transition, well short of road. From town can see fairly large event in Marble Peak, but nothing yet in No Name or Alley on NE aspects (can't see some E or any SE aspects). Take snowmobile up to Timber Slots, solo. Step up off road into flat area for pit and trigger massive collapse and Cl 2 event through trees nearby which puts 3' of debris on road. Retreat, much chagrined at having come even that far up the road.

2/10/94—*0600 fax:* hazard rated "HIGH verging on EXTREME. Hair-trigger instability...in 50 cm new slab may have diminished slightly with some 10 cm settlement in last 24 hrs (at YCSP) but not enough to warrant the triggering potential of plowing operations. Several large delayed action events were observed in Aspen area yesterday." CYMC cancels all operations.

2/11/94—*Storm #11:* moderate precip intensity and quantity (28 mm) with some moderately strong winds. 0600 hazard rating is "HIGH verging on EXTREME, EXTREME later (today)"; operations canceled. Drove into Marble in virtual whiteout; bank activity all along Marble road.

2/14/94—*Storm #11 Avalanche Activity Index Worksheet (Table 3):* note that W. Carbonate hit road with Class 4 event in spite of running at Class 3 only three days earlier. Cook's (year-round resident of cabin next to Monument) Subaru partially buried by "new" slide; amazing low elevation activity through trees—any steep slope suspect if not already down; secondary collapsing common.

Yule Creek Avalanche Services
STORM AVALANCHE INDEX AND ROAD COVERAGE WORKSHEET

Storm & Date: #11, 2/11/94 — 26 mm Total H2O for Storm

	Starting Zone	Event Class	Avalanche Debris on Road: Dm	x	Lm	x	Wm	x .66 =	Vm3
1	Mill #4	0							0
2	Mill #3	0							0
3	Mill #2	3							0
4	Mill #1	3							0
5	Carbonate W - R	3							0
6	Carbonate W - L	4	1.8		60		6		428
7	Carbonate E - R	3							0
8	Carbonate E - L	0							0
9	Timber Slots	4	2.5		225		5		1,856
10	Forest Lawn	3	1.5		210		5		1,040
11	Cook's Hill	2	1		15		5		50
12	Monument R	0							0
13	Monument C	3							0
14	Monument L	4	4		190		7		3,511
15	Shale Cut	3	1.5		180		5		891
16	No Name N - R	3							0
17	No Name N - L	3							0
18	No Name S	3							0
19	Alley N - R	3							0
20	Alley N - L	3							0
21	Alley C	3							0
22	Alley S	3							0
23	Pre Mud R	4	4		200		7		3,696
24	Pre Mud L	3	2.5		35		7		404
25	Mud N	3							0
26	Mud C	0							0
27	Mud S	0							0
28	Mud E	3							0
29	Marble Banks	3	4		150		5		1,980
30	Marble Peak	3							0
31	Portal	0							0

Avalanche Index
- Sum of Class Values 75
- Total Possible Score 155 (31 known paths @ Class 5)
- Avalanche Index Ratio 48%

Avalanche Debris On Road
- Total Debris Volume in Cubic Meters 13,855 m3
- Total Debris Volume in Cubic Yards 18,122 y3
- Mean Density of Avalanche Debris 60%
- Total Weight of Debris Removed in Metric Tons 8,313 mt
- Total Weight of Debris Removed in Pounds 18,327,525 lbs

Notes: Storm #10 preceded this storm by three days with 61 mm h2o and 55 cm's snow; Cl 3 SS's in Carbonate W and Marble Peak then also.

Table 3. 1993/94 Storm #11 Avalanche Activity Index using Mears' (unpublished) method.

2/15/94—*Cleanup:* even with CYMC spotters on both sides of the debris, the D-6 slipped off the road in Carbonate yesterday. Got D-8 and made slow progress to Monument today.

2/16/94—*Cleanup:* got to the entry into Alley today.

2/17/94—*Cleanup:* spent the afternoon in the D-8, with the operator, clearing debris from Pre Mud.

2/18/94—*Cleanup proceeding under HIGH hazard:* D-8 triggered Cl 1 pocket onto road in Marble Banks just as I arrived; operator explained to me that his wife was pregnant and that he'd like to get to know his child! Determined that D-8 probably could safely knock down the balance of the Marble Banks pockets and proceeded, spotted from Windy Point and behind, successfully triggering a larger pocket without hitting the D-8 but putting 12' of debris on the road. Storm #12 now in progress.

2/19/94—*Storm #12 continues:* precipitation and wind continue at what seem to be sub-critical rates per a working "critical precipitation intensities and critical wind thresholds" model developed based on conventional wisdom and observations.

2/22/94—*Storm #12 ends:* 0600 hazard is described as, "somewhere between HIGH and EXTREME" with a lengthy discussion regarding long duration storms; precipitation by 0600 at 58 mm storm total, over 56 hours. CYMC elects to proceed with operations under HIGH hazard rules. A fresh Cl 4 event on NW aspect of Mt. Justice is observed upon arrival at 0730 that morning, but no new activity in "our" paths. Profile #17 dug at YCSP at 1030. At 1330 hours a Cl 3 SS ran, observed by author from a distance, in the Portal path—giving the crew quite a thrill as it swept over and through the curtains, dusting them inside the quarry. Carbonate starting zone pole is back up to 80 cm following 2/11 Class 4 event.

2/23/94—*0600 fax:* "EXTREME hazard. Snowpack remains hypersensitive...due to...warm snow temperatures in the new slab causing creep strain...." And, noting the air temperature trend shown on the month log, a cycle of deep or climax activity seemed imminent. All paths were substantially reloaded and all aspects, especially SE, seemed suspect for climax events. CYMC cancels operations; gate at the bridge is swung shut (but can't be locked).

2/25/94—*AM field observations:* from safety of Town could see that No Name and Alley had produced very large events on the 24th and Carbonate had also repeated with yet another large Class 3. Drove up quarry road (a trace of spindrift) to encounter Class 5 event in No Name; debris estimated 10-12' deep on road. Virtually 100% of all aspects of the 50 acre starting zone had released, much of it to the ground; additional volume was entrained throughout the track all the way to the road; debris clods suggested a "damp" slab event. Fortunately, no one is looking for missing tourists, or snowshoers, etc. Alley had produced a similar Class 4 event covering a substantial length of road but not comparing to the Class 5 event of 2/20/93. Unfortunately, Marble Peak has not performed and does not, in spite of my best efforts to "will" it down. Plowing operations begin on No Name debris at 1300 hours.

2/28/94—*0600 fax:* hazard rated, "MODERATE up to Alley, HIGH from Alley up." CYMC's crew is back to work in the quarry having been out of the quarry for 19 of 28 possible days this month. Some of the crew were able to work, on some of those days, as spotters during plowing operations. But now everyone, particularly management, is "hungry" to work as much as possible. Plans are underway for the crew to camp in the quarry for the next week or two and run the quarry around the clock.

Thus ended a challenging month, but not the winter. March proved abnormally dry, and late April provided its own unusual weather. The entire season is summarized in the Season Log (Table 4) showing each storm and its avalanche index score.

Yule Creek Avalanche Services
SEASON AVALANCHE LOG AND STORM AVALANCHE INDEX

Season of: 1993/94

As of: 10-May-94

Starting Zone	Storm # & Class of Event																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Total
Total H20	57	9	40	52	61	25	12	12	16	61	26	58	0	33	17	12	14	13	19	13	71	621
Mill #4										2												
Mill #3										2												
Mill #2										2	3											
Mill #1										4	3											
Carbonate W - R						2				3	3											
Carbonate W - L				2.5						3	4		3									
Carbonate E - R										3	3		3									
Carbonate E - L				2					2													
Timber Slots											4											
Cook's Knob											2											
Monument R																						
Monument C											3											
Monument L											4											
No Name N - R											3		5									
No Name N - L									2		3		5									
No Name S				2						2	3		5									
Alley N - R											3		4									
Alley N - L											3		4									
Alley C				2		2					3		4									
Alley S				2		2					3		4									
Pre Mud R								2			4											
Pre Mud L						2			2		3											
Mud N					2		2		3		3		3									
Mud C					3				2		3											
Mud S				3						4												
Mud E				2.5							3											
Marble Banks						2		2	2		3											
Marble Peak				3				2		4	3											
Portal												3										
Avalanche Index	0%	0%	0%	13%	3%	7%	1%	4%	9%	20%	48%	2%	28%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 4. 1993/94 Season Log.

Conclusion

Managing Colorado Yule Marble Company's exposure to the avalanche hazards in Yule Creek, using a system of hazard-based mitigation measures, has been "successful" for the past three full winters in that no avalanche incidents involving injury to workers or damage to property have occurred. This approach requires close communication between the client (CYMC) and the consultant (YCAS) as well as a diligent implementation effort by the client. Intrinsic shortcomings in an incremental program of mitigation measures sharply focus attention on what constitutes an acceptable "margin of safety" from both the client's operational and the consultant's avalanche hazard evaluation standpoints.

Substantial improvements in the consultant's information collecting, analysis, and communication have enhanced both client and consultant confidence in the hazard evaluations. Site-specific hazard evaluation methodologies, such as the "critical precipitation intensity and wind thresholds" model, and the application of starting zone pole data, will require continued development. Likewise, the quarry operator has gained a great deal of hands-on experience in winter operations under rather severe circumstances and sees opportunities to improve efficiency and safety with improved equipment and procedures. In the meanwhile, the increasing public exposure to the Yule Creek avalanche hazard, made possible by CYMC's operation of the quarry, remains an unresolved dilemma.

In the longer term, it remains to be seen how well the risk management program will perform over time and whether or not the unpredictable and expensive nature of winter operations remains viable for CYMC.

References

Mears, A., 1990, (unpublished) "Snow Avalanche Hazard, Forecasting, and Safety Procedures—Colorado Yule Marble Quarry, Gunnison County, Colorado", 17 pp.