STATE OF COLORADO

RICHARD D. LAMM
GOVERNOR

JOHN W. ROLD
DIRECTOR

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
715 STATE CENTENNIAL BUILDING — 1313 SHERMAN STREET
DENVER, COLORADO 80203 PHONE (303) 866-2611

HAZ-1983-01

PRELIMINARY EVALUATION OF ROCKFALL HAZARD IN THE BOOTH CREEK AREA

DOI: https://doi.org/10.58783/cgs.haz198301.chml2341

PREPARED BY THE COLORADO GEOLOGICAL SURVEY
FOR THE TOWN OF VAIL, COLORADO
1983

TABLE OF CONTENTS

Figures

BOOTH CREEK AREA ROCKFALL INVESTIGATION

Summary

Rockfall Hazard in the study area is determined to be extremely high. Rockfall events can generally be divided into two categories; 1) those involving massive toppling slab failures of the cliff faces, and 2) those involving smaller individual boulders falling off the edges of the vertical cliffs due to downslope creep.

1) Boulders and slabs shed downslope during toppling failures are on the order of 4 to 10 tons and may be traveling at 70 mph or more as they enter the upper runout zone, where numerous residential structures are located. It is thought that events of this nature probably occur every 40 to 100 years. It is not economically or technically feasible to arrest, deflect or stop rocks of this size in the present physical situation. The only alternative solution is to prevent toppling failures by securing the jointed unstable cliffs through wiremesh, gunnite application, and rockbolting methods. Costs for stabilizing the cliffs above the area may run as high as two to three million dollars or more.

2) Smaller individual boulders falling off the vertical cliff edges are generally on the order of 500 to 1000 lbs and are expected to be traveling at speeds of 50 to 60 mph as they enter the upper runout zone. This type of rockfall is more frequent and is expected to occur periodically every one to three years. Most are triggered by unusually extreme weather conditions or ground motions. It appears probable that these frequent events might be controlled through the construction of energy-absorbing protective structures built on the subdivision property. Such structures would have little or no effect on larger boulders derived from toppling failures. Costs for several individual or one large area-wide structure are estimated to be on the order of 0.75 to one million dollars.

Rockfall boulders at the base of steep slopes in the study area were examined and used to map the limits of the runout zone and delineate several hazard zones. Disturbance of many rockfall boulders causes difficulty in accurately determining the maximun extent of the runout zone. All areas within the runout zone are subject to significant though varying amounts of rockfall hazards.

Scope and Methodology

This report presents the results and conclusions of a rockfall investigation conducted near the mouth of Booth Creek for the Town of Vail, Colorado. The study area shown in Figure 1 includes all of Vail Village Filing No. 12, and those lots in Vail Village Filing No. 13 east of Booth Creek.

Analysis of the rockfall problem was accomplished through aerial-photogeologic interpretation, examination of topographic maps, interviews with local residents, and field studies of rockfall source areas and runout zones.

The cliffs and steep slopes above the residential area were traversed and examined for evidence of instability, degree of hazard, and to investigate the particular mechanisms responsible for causing rockfalls. Each large boulder in the runout zone was examined to determine whether it was of rockfall origin or glacially deposited, and to verify whether or not it had been moved or

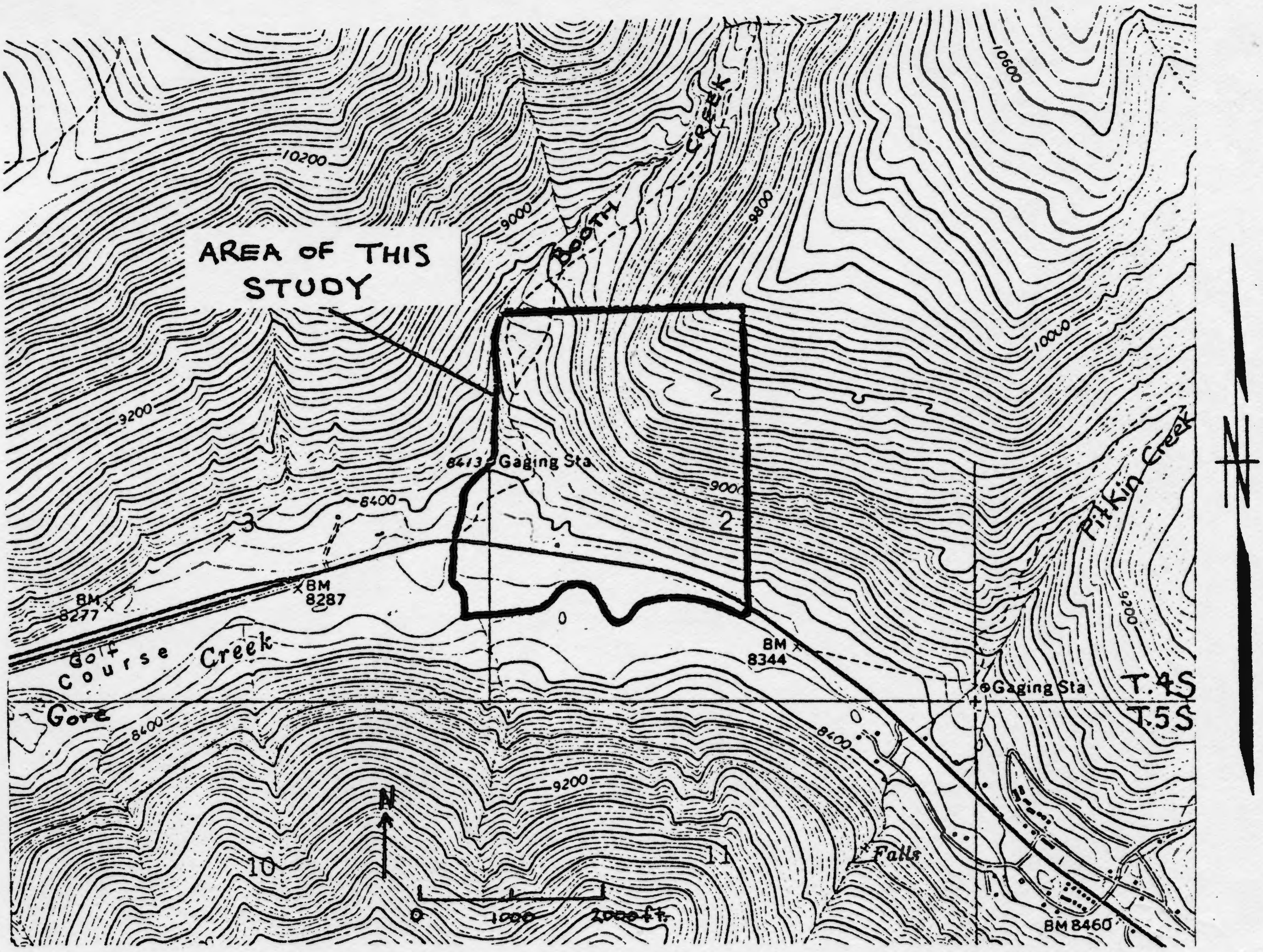


Fig. 1 Location Map of Study Area, scale 1:24,000.

disturbed by the actions of man during development of the area. Additionally, weathering patterns, lichen growth, and surface position of boulders and slabs in the runout zone were analyzed to provide a preliminary estimate of recurrence intervals for large rockfall events.

Site Description

The steep southwest-facing slopes and rocky cliffs investigated in this report tower 1,000 ft (305 m) above Vail Village Filing 12 on its northern boundary. These heights are attained within a horizontal distance of 1,700 ft (520 m) resulting in an average slope of 58 percent. The slope can be divided into several zones which combine to produce the rockfall known to occur along this portion of the Gore Creek Valley as follows: (Refer to Fig. 2)

A) Runout zone - slopes of 28 percent to 45 percent along the foot of the valley wall. This area is moderately wooded with fairly young aspen and has been developed as a residential subdivision. The majority of rocks falling from the cliffs come to rest in this zone.

B) Acceleration zone - slopes of 55 percent to 65 percent and steeper immediately below source area. No boulders of significant size can remain at rest on these slopes due to the steepness. Sparse, stunted aspen occur in small stands, but generally the slopes do not support much vegetation. Rocks traversing this portion of the slope will continue to gain energy and momentum as they roll and skitter downslope.

C) Lower vertical cliff source area - A 50 ft high (16 m) cliff of jointed sandstone and limestone outcrops 560 vertical ft (10m) above the runout zone. Large slabs 15 to 20 ft (4.5 to 6 m) in diameter periodically detach from the cliff face and tilt outwards until they topple over and shatter, showering boulders onto the accleration slopes below. (Fig. 3)

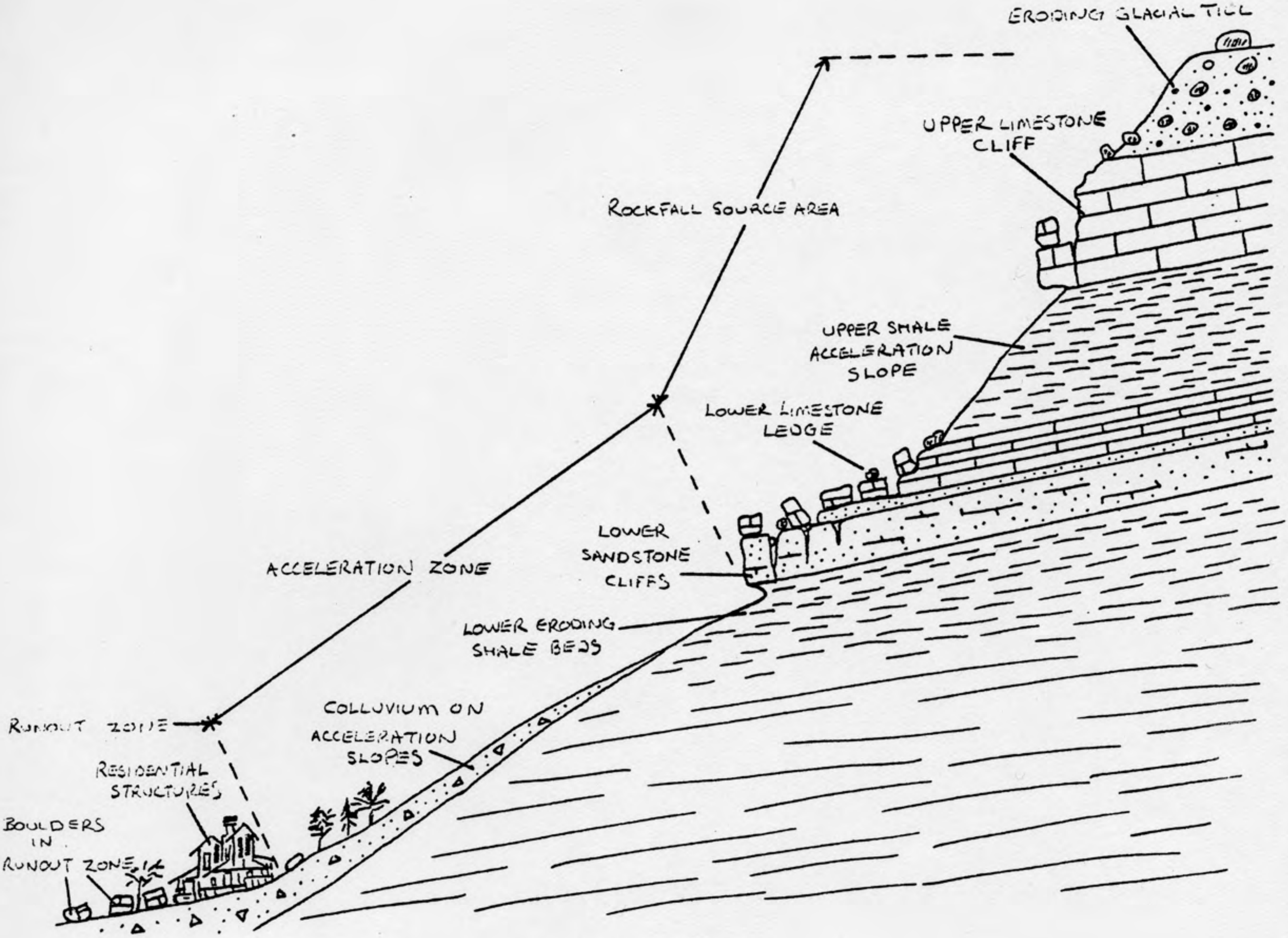
D) Upper shale-slope acceleration zone - A steep (68%) shale slope above the lower vertical cliff allows boulders from a higher cliff to gain momentum before becoming airborne at the cliff edge.

E) Upper vertical cliff source area - jointed slabs and boulders 1,000 vertical ft (305 m) above the runout zone periodically detach from the cliff and free fall and bound downslope and off the lower cliff. Most rocks do not shatter, but remain as intact approximately 8x5 ft (2.5x1.5m) limestone boulders which are capable of reaching the farthest limits of the runout zone. (Fig. 4)

F) Eroding upper till slope - Glacial till resting on top of the upper cliff sheds smooth 2ftx3ft (0.5x1m) diameter granitic boulders downslope which roll and fall off the cliffs. This till slope is considered to be a part of the upper source area.

Geology of Rockfall Source Areas

The geologic make-up of the cliffs above Vail Village Filing 12 is shown diagramatically in Figure 2. Sedimentary strata exposed in the cliffs are part of the Minturn Formation of Middle Pennsylvanian Age, and include beds of sandstone, shale, grit, conglomerate, and limestone. The beds strike N85°W and dip 15° to 18° into the valley axis. The lower cliff consists of shaley sandstone beds about 40 ft thick resting on a weak, fissile, rapidly eroding



Scale 1 in = 200 ft

Fig. 2 Geologic diagram of compound rock-fall slopes in study area. Drawn to scale with no vertical exageration. Note dip of strata toward valley.

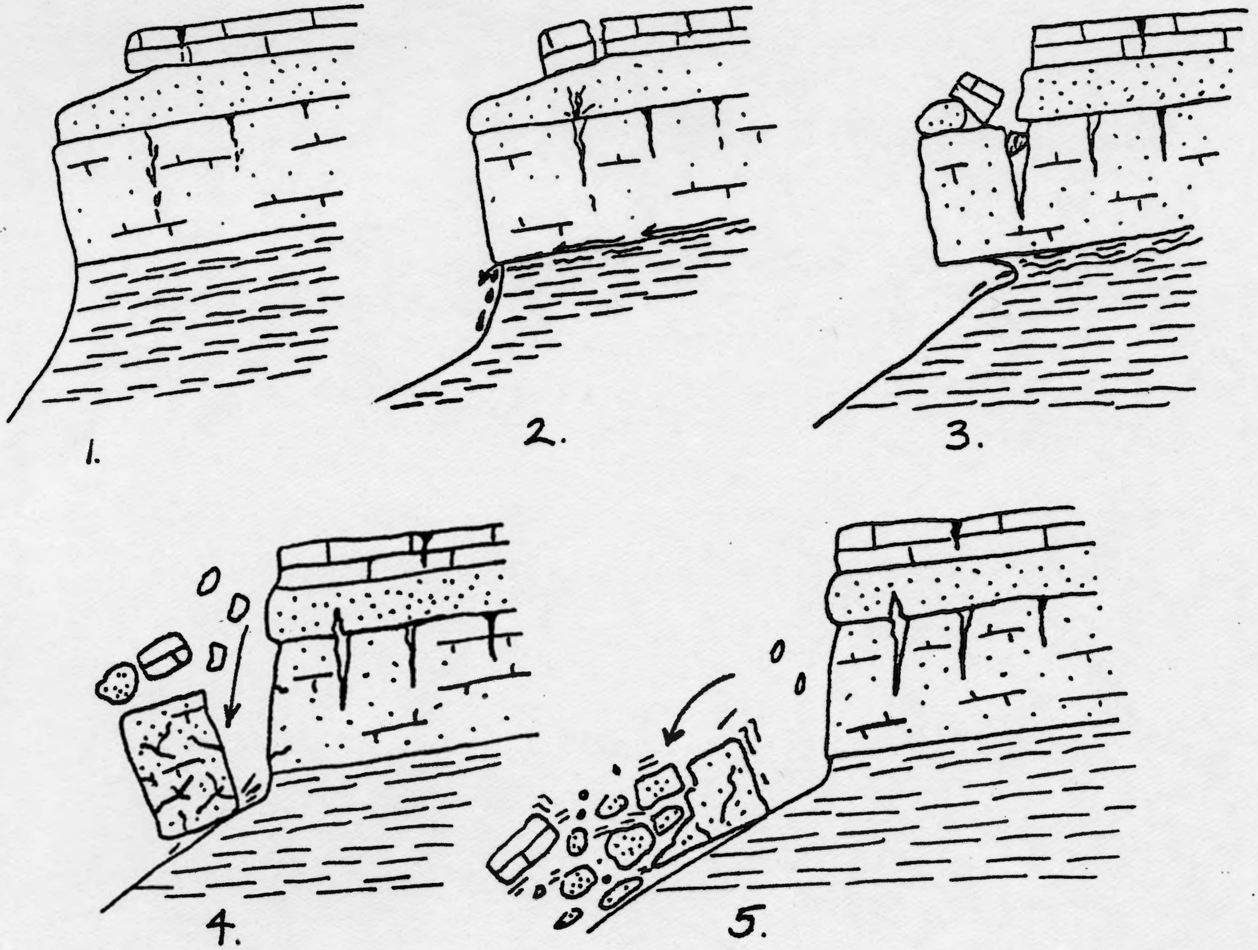


Fig. 3 Toppling Slab-failure Sequence

1. Initial cliff configuration
2. Differential weathering of soft shale begins to undercut massive cliff forming slabs. Joints open and widen due to slope creep and frost wedging. Springs issue from contact beneath cliff.
3. Undercutting continues. Joints widen and are wedged open by smaller rocks, causing slab to tilt outwards.
4. Slab falls from cliff face onto acceleration slopes, bringing down overlying rocks.
5. Slab topples and shatters, showering runout zone below with boulders, and exposing new cliff face to erosion.

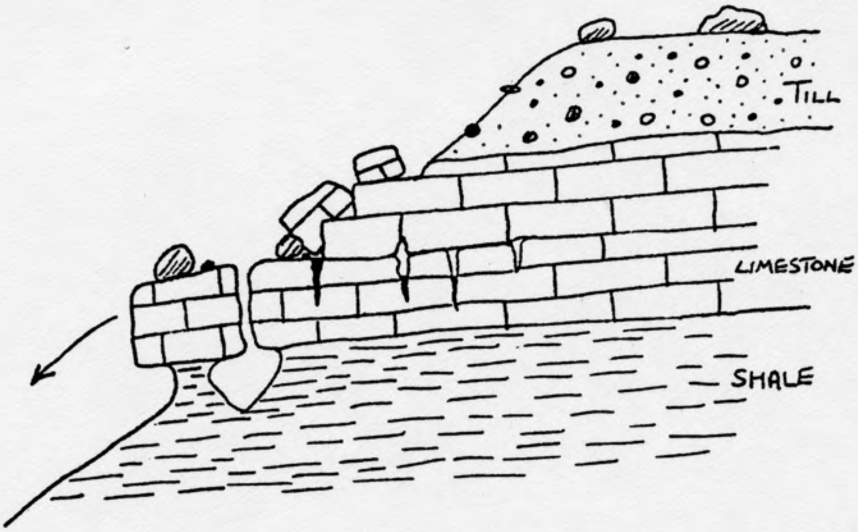


Fig. 4 Limestone slabs resting on weak shale pedestals, upper cliff source area.

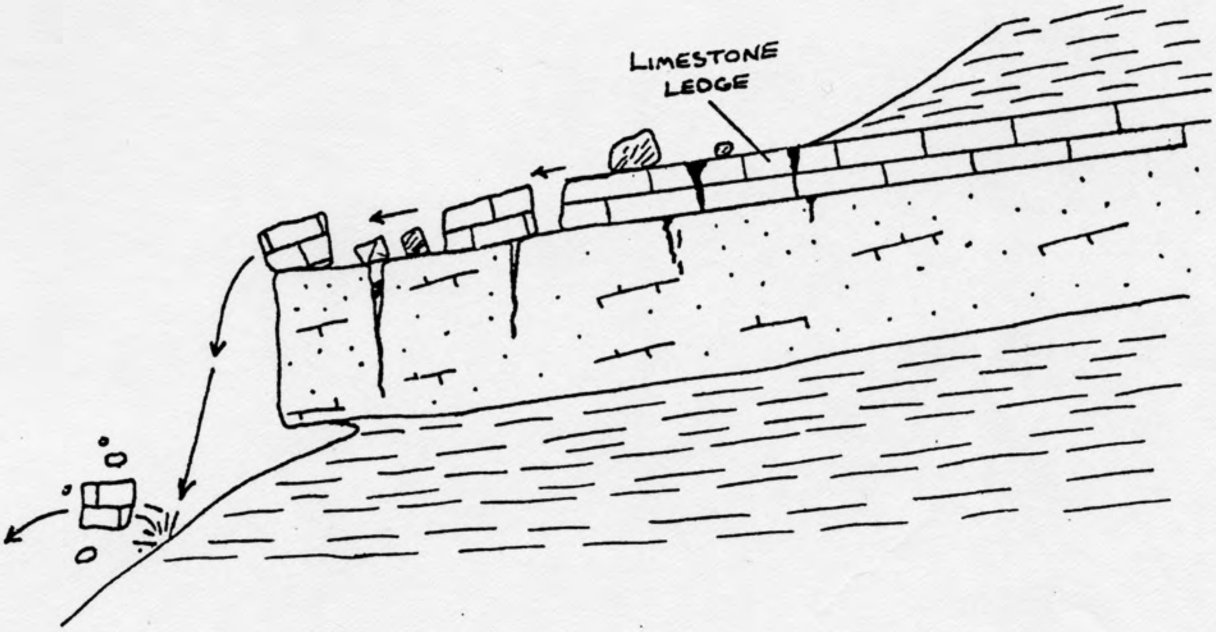


Fig. 5 Slope creep causing limestone blocks to move down bedding planes and off lower cliff edge. Blocks are generally 2 ft X 3 ft. This mechanism is responsible for frequent rock falls in the study area.

black to gray shale. The sandstone unit has two prominent joint sets striking N85°W and N55°W. These joints combine to separate large slabs and define the cliff face angle visible from the valley below. Above the sandstone is a soft friable course sandy conglomeratic bed 3 ft thick which weathers to a smooth rounded ledge and continually undercuts a 2 to 3 ft thick dense, hard gray limestone unit resting above it. The limestone is jointed so that subangular chunks 2ftx3ft (.5x1m) continuously detach from the bed and fall off the sloping cliff edge. It is these limestone blocks that are commonly involved in the more frequently recurring events that can often cause damage to structures in the runout zone, such as the event in early May of 1983.

A thick shale unit between the upper and lower cliffs has weathered back to a 68 percent slope. The shale is soft, clayey, and shows evidence of localized slippage and small slope failures that probably occur during intense rainstorms or heavy snowmelt. Very small mudflows appear to start on this steep slope and spill over the lower cliff edge. They are capable of disturbing or initiating rockfalls if boulders happen to be in their paths, or resting near points of initial failure.

Resting on this soft eroding shale is a thicker cliff-forming unit of the Robinson Limestone. This bed of dense, hard, gray limestone varies from 5 to approximately 30 ft thick (1.5 to 10m) in the study area and is the source for the largest rockfall boulders encountered in the runout zone. The limestone boulders that detach from the cliff are quite resistent and tend not to break up or shatter on their way downslope. The largest boulders found in the runout zone appear to be derived from this upper cliff-forming limestone.

The shale zone upon which the upper limestone cliffs rest is weak and by erosion undercuts the massive limestone ledges, creating pedestal-like blocks which eventually topple off their perches. The limestone is jointed such that blocks approximately 9ftx5ft are separated from the cliff and tilt outward toward the cliff edge. Thinner beds within the limestone cliff produce more slabby rocks that if not turned onto their edges by chance during the initial fall, remain flat-side down on the steep slopes.

An eroding slope in glacial till rests directly above the cliff-forming upper limestone in the northern part of the study area. The eroding slope periodically sheds 1ft to 2ft dia. smooth, rounded granitic boulders which tumble down the cliff into the runout zone. Other areas of this till farther east along the cliff appear relatively stable, and are not actively shedding large rocks to the slopes below.

Above this till, slopes flatten dramatically to grades of 0 to 35 percent. Large stands of mature aspen indicate that these gentle upper till slopes are relatively stable. No other rockfall sources pertinent to this study exist above these gentle slopes, which start at an elevation of approximately 9,450 ft.

Rockfall Mechanisms

Several natural geologic and topographic factors combine to cause rockfalls from the cliffs exposed on the north valley wall of Gore Creek in the study area. These factors include joint patterns, differential weathering of various rock types, dip of strata, and the slope of cliffs and acceleration zones.

Jointing and Differential Weathering of Cliff Faces

Joint patterns in the cliff forming rocks are caused by stress relief and physical properties of the rock. The joints so formed define the planar vertical cliff faces and act to separate large sections of the cliff into slabs along joints subparallel to the cliff face. Once a slab has detached from the sedimentary bed, it begins to creep outwards due to gravity and frost wedging in the joints. The joints widen with time, and are often wedged farther apart by tree roots or smaller rocks that fall into the cracks formed by the joints (Fig. 3).

Differential weathering is the process by which soft weak rock types, such as shale and claystone, erode away faster than adjacent beds of limestone or sandstone. As time passes, the rapidly eroding shales and clay begin to undercut the more resistant overlying sandstones or limestones creating a horizontal groove or crack at the base of the cliff which removes support for the rocks above. Eventually, the overhanging ledge becomes incapable of supporting its own weight, and falls or topples from the cliff. If the overhanging slab has already detached from the cliff along joints and is resting precariously on the shale, undercutting and differential weathering accelerate the process which finally results in the inevitable toppling of the slab. As the large slabs topple onto the acceleration slopes below, they usually shatter into many smaller boulder sized chunks which accelerate downslope to the runout zone. The toppling may trigger adjacent unstable parts of the cliff to fall as well.

Topography and Dip of Strata

The dip of the rock ledges making up the source area also contributes to rockfall along cliffs in the study area. The strata in the two cliffs dip approximately 15 degrees into the valley, causing any loose stones, cobbles, or boulders on the ledges to inevitably move down to the edge of the 50 ft vertical drop. Limestone blocks separated from their beds by jointing and weathering creep down toward the valley along these dipping bedrock surfaces (Fig. 5). Precipitation and snowmelt run directly off the cliffs, forming many small waterfalls. Rounded glacial cobbles and gravel move down along the dip slopes and fall into the open cracks formed by joints, wedging slabs farther apart.

The glaciated valleys of Gore and Booth Creeks both possess relatively flat bottoms and steep nearly vertical sides. The slopes are so steep that once a boulder or slab topples from the cliffs, it cannot come to rest until it reaches the lower footslopes of the valley wall, where the runout zone begins. An examination of the runout zone shows that large boulders and slabs have travelled onto and across parts of the valley floor due to the tremendous energy and momentum they acquire through the steeply sloping acceleration zone.

Factors Triggering Rockfalls

Heavy precipitation and alternating freeze-thaw conditions often trigger rockfalls. Large amounts of water may weaken or saturate clayey shale beds reducing the strength necessary to support the weight of overlying sandstones or limestones. Excess groundwater also creates a lubricating effect and causes slippage along cleavage planes in the shale. These effects may trigger rockfalls from the cliffs as movement and creep of the slabs and boulders is accelerated or reactivated during thunderstorms or heavy snowmelt. Periods of snowmelt followed by hard freezes overnight often combine to trigger rockfalls. The water in cracks, joints, and beneath boulders expands during freezing, and may move a slab or boulder just enough to trigger a rockfall.

The rocky slopes above the two cliffs are so steep and unstable that any cobble or rock knocked loose will roll and bound downslope, knocking other rocks loose, often starting small cascades of loose cobbles which shower off the lower cliff edge. These small cobbles are capable of striking a larger unstable boulder and initiating a rockfall event. Residents report that they often hear these smaller rocks bounding and rattling through the brush in the upper reaches of the runout zone, where they sound much like animals running through the underbrush. Examination of the rockfall source area revealed that many heavily travelled game trails criscross the steep slopes and cliffs. It is evident that deer and bighorn sheep often dislodge smaller cobbles along the trails which may trigger larger precariously perched boulders to fall from the cliffs.

As jointed slabs continue to tilt farther out from the cliff face, and boulders become precariously perched at the cliff edge, ground motion resulting from thunder, sonic boom or earth tremors is capable of dislodging boulders and triggering rockfall. An earthquake of magnitude three or four in the immediate vicinity could certainly dislodge many large boulders and slabs which are presently perched precariously on steep slopes in the study area.

Hazard Classifacation and Zonation

The rockfall hazard associated with geologic and topographic conditions and the proximity of dwellings as described above is considered to be severe. The majority of large boulders found among structures in the runout zone have fallen from the cliffs. Field study indicates that the question is not, "will rockfall occur?", but rather, "what is the recurrence interval between significant rockfall events?"

Acceleration slopes are so steep and smooth that rocks traversing them are free to deflect and skitter laterally in any direction radiating from the point of initial fall. The pattern or trajectory a given boulder could follow is so unpredictable that it is impractical to delineate individual hazard zones based on the physical conditions of various segments of the cliff faces. In the present situation, hazard zones are more practically related to horizontal distance from the source areas, zones farther away experiencing a smaller probability of being encompassed by a given event. This approach yields a series of zones radiating out from the source area, the more severe hazards existing closest to the cliffs. It should be pointed out, however, that any area within the extent of the runout zone is subject to some degree of rockfall hazard.

Hazard Zone Delineation

Varying degrees of rockfall hazard severity can be approximated by examination of the nature and positions of boulders and slabs in the runout zone. Each large boulder was examined to determine several factors which were used to approximate the extent of the runout zone, and estimate the time spans since each rockfall boulder came to rest. These factors are:

1) Whether or not a boulder was of rockfall origin or glacially deposited.

2) Whether or not a rockfall boulder was resting undisturbed in its original position or had been moved by human activities.

3) The physical nature of undisturbed rockfall boulders with respect to basal contact, (resting on surface, imbedded, partially covered, etc.) and lichen, moss, and weathering patterns on exposed surfaces.

4) The comparative size distributions of boulders within the runout zone.

Rockfall Versus Glacial Origin of Boulders

In order to determine the extent of the rockfall runout zone, it is necessary to determine whether boulders encountered below the cliffs in Vail Village have fallen from one of the source areas and come to rest on the surface, or if they were transported in and deposited by ice or outwash during Pleistocene glacial periods. This distinction can be made by comparing the character of boulders found imbedded in undisturbed glacial deposits with the limestone and sandstone boulders derived from the cliffs (Fig. 6). Glacially deposited boulders are mostly rounded to subrounded smooth granite or metamorphic rocks which are imbedded in the surrounding glacial drift. The exposed surfaces of these boulders are almost totally covered with lichens and moss, making it difficult to determine lithology of the boulders without close inspection. The heavy lichen cover and other well developed surface rock weathering features such as pits and etched relief of individual mineral grains suggest that these boulders have been in place for 20 to 40 thousand years. The glacially deposited cobbles and boulders are 85 to 90 percent granitic and metamorphic rock types, and very few limestone or sandstone cobbles or boulders can be found in the till. This is due to the fact that the only source area where valley glaciers could scour up limestone is a narrow band of rock one mile upstream from the runout zone. The extensive upper basin which spawned the glaciers is composed of Precambrian igneous and metamorphic lithologies, which make-up the vast majority of the rock types encountered in till deposits in the runout zone. In contrast, large boulders and slabs of rockfall origin are angular or poorly rounded, rest directly on the ground surface, do not show an equal amount of weathering on all exposed surfaces, and are almost exclusively limestone or sandstone. A few granitic rockfall boulders are also present, being derived from till in the upper source area. These differences were used to map the locations of large boulders of rockfall orgin and determine the approximate limits of the runout zone, as shown on the map accompanying this report.

Disturbed Versus Undisturbed Rockfall Boulders

Once a specific boulder was identified as being of probable rockfall origin, its position on the foot slopes could be used to predict the nature and extent of the runout zone. A problem with using the positions of rockfall boulders in the subdivision and adjacent areas to delineate the runout zone is that many have been disturbed and moved from their original positions during development and construction activities. Most of the boulders are too large (8ftx5ft, weighing up to 15 tons) to be moved easily, even by heavy equipment, and it is assumed that they were moved only a few feet to several tens of feet from their original position in order to carry out construction of roads and foundations. The accuracy of this assumption is not easily determined, and the present positions of the disturbed boulders as indicators of runout zone and hazard zone characteristics is not entirely reliable, and is used accordingly.

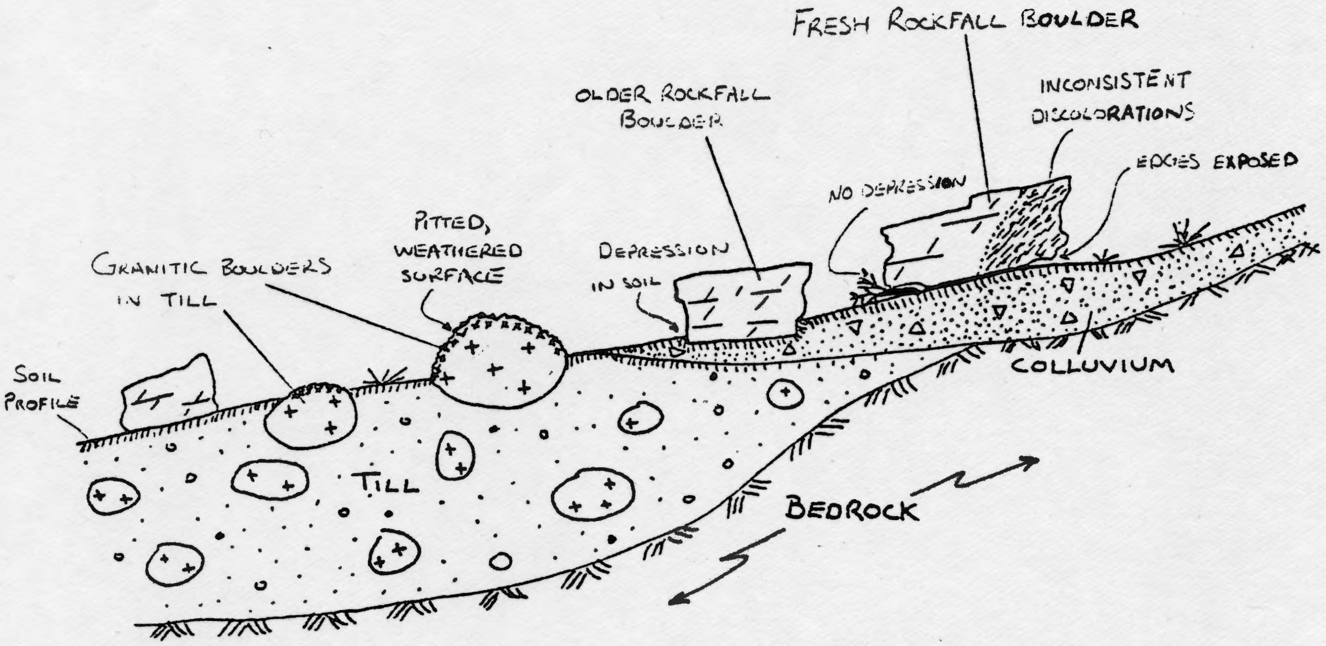


Fig. 6 Physical differences between rockfall and glacially deposited boulders in runout zone. Rockfall boulders are all limestone or sandstone, while glacial boulders are mostly rounded granite or metamorphic lithologies. Note that soil exists below rockfall boulders, while it is absent beneath glacial boulders.

Disturbed or transported rockfall boulders always show fresh gouges and abrasions caused by heavy earth moving equipment. Additionly, the moss and lichen growth patterns, if any, are not consistent with the present orientations of the boulders, indicating that they have been moved after the patterns were established. Discolorations of the disturbed boulders caused by soil contact can be observed on the sides or top of those which have been pushed over and moved. The boulders often leave trails or marks where they have been pushed along the ground, creating a small berm of scraped up soil along one of their basal edges. Undisturbed rockfall boulders do not show fresh gouges or scrapes, have consistant lichen and moss growth patterns, do not show soil discolorations on their sides or tops, and are often surrounded by young bushes, aspen trees, or natural vegetation, which has obviously not been disturbed. The positions of these boulders can be used to more accurately project the minimum limits of the runout zone, since they can be inferred to have come to rest in their present positions after falling from the cliffs.

Factors Used To Approximate Ages and Recurrence Intervals of Major Rockfall Events

Certain characteristics exhibited by undisturbed rockfall boulders and slabs in the runout zone suggest approximate or relative time spans since they came to rest after falling, and give a rough estimate of the recurrence intervals between large slab-failure events. The contact made by a boulder with the surface suggests how long the rock has been resting in its present position. As the length of time increases, the rock will tend to press into the ground, and slope wash, soil creep, and frost wedging will act to fill in around the base of the rock with soil materials. Rocks which have been sitting for long periods tend to be somewhat imbedded in the soil, and if moved, would reveal an indentation in the ground. Rocks which have recently fallen rest directly on the ground surface, and may lie on brush or small trees they have crushed beneath them. One can place a stick beneath the edges of such a the rock in certain spots.

Older rocks also have more consistent lichen growth patterns than fresh rocks which have recently detached from the cliff. Fresh rocks may possess differentially weathered surfaces, as a result of their former positions on the cliff. If the boulder aquired a surface weathering and color pattern while on the cliffs, it is unlikely to roll to a stop in the same position, and the surfaces which were previously against the ground or facing joints may still posess a characteristic coloration contrasting with older exposed weathered surfaces. Considerable time is necessary for natural weathering processes to remove this discoloration and create a new uniform surface color on the rock. These weathering factors and the nature of undisturbed rockfall boulders were used as a guide in determining hazard zones within the runout area.

Distribution of Rockfall Events

Examination of the source area and runout zone reveals that two basic types of rockfall event take place in the study area. The first and most common involves smaller individual boulders generally in the 2ftx3ft(0.5x1m) size range, which detach from sedimentary beds and eventually fall off the cliffs. These falls commonly involve several boulders, many of which are set in motion after being struck by the initial falling rock. This type of minor rockfall is common and based on examination of the runout zone and cliffs above can be expected to occur every one to three years. This is the type of rockfall which occured in the spring of 1983 and damaged several structures. The area which is most susceptible to these frequent events is shown on the Runout Zone Map, and includes the upper two rows of structures.

The second type of rockfall is much less frequent, but of far greater danger and destructive potential. It involves massive slab failures of the cliff faces, along joints w hich liberate large 15ftx20ft(4.5x6m) slabs and 8ftx5ft(2.5x1.5m) limestone boulders, showering them onto the acceleration slopes below. The next rockfall of this magnitude will almost certainly result in extensive destruction in the runout zone.

A rough preliminary estimate of recurrence intervals for these large slab-failure events, based on examination of the source area and undisturbed rockfall boulders in the runout zone, is on the order of 40 to 100 years. Large boulders set in motion during these events can travel through the runout zone as far as the maximum probable limit. An estimate of the last occurrence of this type of event, based on the freshest, undisturbed rockfall boulder in the runout zone, and weathering patterns on the cliffs, is on the order of 40 to 60 years ago.

Potential Solutions to Rockfall Hazards

The feasibility of protective structures and other preventive measures were evaluated during the study. The two types of rockfall events discussed above were considered separately, and potential solutions for both types are outlined below:

Rockfall Events Involving Smaller Boulders

Smaller boulders commonly falling off the lower cliff could probably be arrested by protective stuctures built near the lower acceleration zone on property within the platted subdivision. The structures must be capable of absorbing the energies of one ton boulders traveling at 50 mph, and would probably involve energy absorbing materials held within timber or rock cribbing. Maintainence of the structures would be necessary each time a boulder is stopped, since the energy dissipation will damage or deform that part of the structure involved. It is probably not feasible to build an armoring wall or other type of structure which attempts to arrest the boulders through rigid strength, due to the extremely high momentum rocks gain through the acceleration zone. The unpredictable paths and patterns followed by rocks skittering down slope makes it difficult to determine the best places to site the protective structures. One approach would be to construct individual protective structures for each building within the runout zone. Alternatively, a single large structure above the subdivision might provide as much protection and create less overall disturbance to the area. The structure would have to be carefully designed and constructed to be free draining and to prevent adverse snow or ice accumulations from forming above the protective barrier. Siting a community type protective structure appears to be feasible on the slopes immediately above the uppermost row of residences, however, more detailed siting studies are necessary to determine the most suitable location. In either case, costs for these structures are preliminarily estimated to be on the order of 0.75 to one million dollars, and could run higher. Unfortunately, these structures would do little to prevent larger boulders or slabs derived through toppling failures from destroying structures in the runout zone. The energies possessed by such slabs or boulders are simply too great to contain within the restricted space available between the source areas and existing residences.

Large Slab-failure Rockfall Events

Due to the close proximity of structures to the source area, the steep acceleration slopes, and the large sizes of boulders and slabs involved in this type of failure, there is no economically or technically feasible way to arrest, deflect, or stop four to ten ton boulders or slabs from traveling through the runout zone, and destroying structures, which happen to be in their paths. A conservative estimate of the energies such boulders are expected to have in the upper runout zone is approximated by the impact of a 10,000 lb truck striking a structure at a speed of 140 mph. Defensive structures capable of stopping 10 ton limestone boulders traveling an erratic, unpredictable path at up to 70 mph are technically and economically infeasible due to the extremely limited space available between the source area and the structures situated in the runout zone. The only viable alternative is to prevent the boulders and slabs from falling, and this may only be accomplished through extensive meshing, gunnite application, and rockbolting of the jointed unstable cliffs. Such an alternative may prove economically infeasible due to the magnitude of the problem and the extreme danger of inadvertently starting a massive rockfall during abatement work. The operations would probably include extensive meshing and gunnite application to stabilize the cliffs sufficiently to allow rock-bolting operations. Access to the cliffs would be difficult, and could involve helicopter support. Preliminary estimates suggest that costs could run on the order of two to three million dollars, considering the insurance which would be needed, and the potential for unforseen contingencies which could arise. Another consideration is the Federal wilderness designation of the area, which includes the cliff source areas. Obtaining permission and legal jurisdiction to allow extensive modification and remedial work on the cliffs may literally require an act of Congress.

Cliff Scaling

Cliff scaling was considered, but after examination of the cliffs and positions of structures in the runout zone below, it was deemed too dangerous and risky. There is a high probability that extensive damage to several structures would result from dislodging boulders or slabs from the 50ft vertical cliffs. Scaling is generally considered feasible only when used prior to construction of improvements in an area. The danger of damaging existing structures is usually too great to warrant scaling after development.

Snow Avalanche Hazards

Several relatively small snow avalanche tracks exist on the slopes above the subdivision, as shown in (Fig 7). They are narrow gulleys which generally start below the lower cliff and conduct mostly dry powder avalanches during or shortly after heavy snows. The overly steep south facing aspect of the cliffs and limited starting zones is not conducive to large destructive avalanches. Structures are generally not in the paths of these minor avalanche gulleys. The danger of rockfall far exceeds the concerns for avalanches.

Conclusions

Rockfall Hazard in the study area is considered to be extremely high. Rockfall events can generally be divided into two categories; 1) those involving massive toppling slab failures of the cliff faces, and 2) those involving smaller individual boulders falling off the edges of the vertical cliffs due to downslope creep.

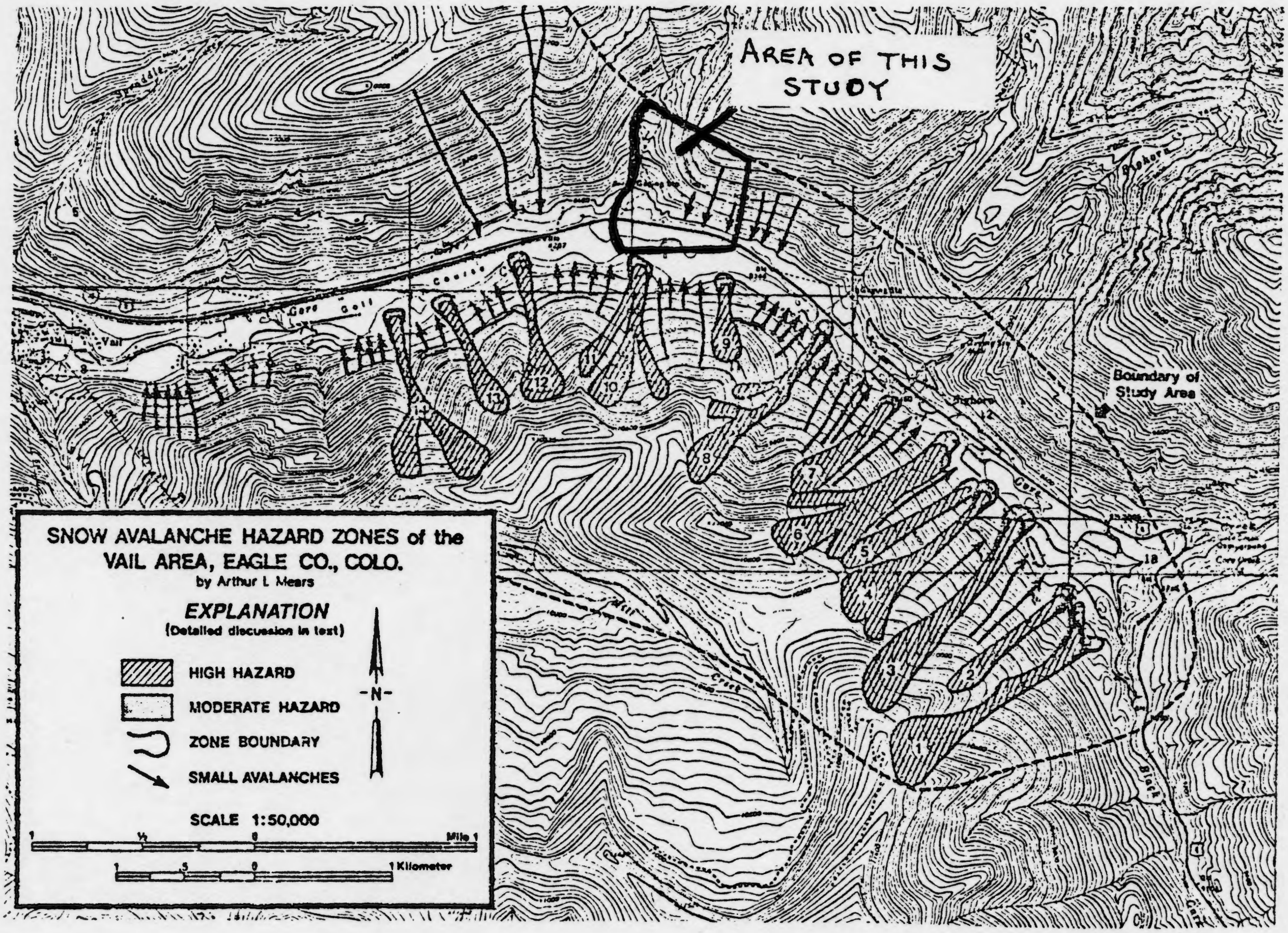


Fig. 7 Snow avalanche hazard zones in study area, from Mears, 1979. Three small avalanche tracks are present in the area of this investigation.

1) Boulders and slabs shed downslope during toppling failures are on the order of 4 to 10 tons and may be traveling at 70 mph or more as they enter the upper runout zone, where numerous residential structures are located. It is thought that events of this nature probably occur every 40 to 100 years. It is not economically or technically feasible to arrest, deflect or stop rocks of this size in the present physical situation. The only alternative solution is to prevent toppling failures by securing the jointed unstable cliffs through wiremesh, gunnite application, and rockbolting methods. Costs for stabilizing the cliffs above the area may run as high as two to three million dollars or more.

2) Smaller individual boulders falling off the vertical cliff edges are generally on the order of 500 to 1000 lbs and are expected to be traveling at speeds of 50 to 60 mph as they enter the upper runout zone. This type of rockfall is more frequent and is expected to occur periodically every one to three years. Most are triggered by unusually extreme weather conditions or ground motions. It appears probable that these frequent events might be controlled through the construction of energy-absorbing protective structures built on the subdivision property. Such structures would have little or no effect on larger boulders derived from toppling failures. Costs for several individual or one large area-wide structure are estimated to be on the order of 0.75 to one million dollars.

Rockfall boulders at the base of steep slopes in the study area were examined and used to map the limits of the runout zone and delineate several hazard zones. Disturbance of many rockfall boulders causes difficulty in accurately determining the maximun extent of the runout zone. All areas within the runout zone are subject to significant though varying amounts of rockfall hazards.

Recommendations

This preliminary rockfall hazard study is not intended to be a technical design study, but rather a preliminary evaluation of the magnitude and extent of the rockfall problem in the Booth Creek area. If rockbolting and securing the cliffs in the source area is found to be economically or technically infeasible, the decision of whether or not to build protective barriers designed for smaller, more frequent events must be made. This will be difficult, because these structures can not be expected to protect residences from large slab failures, particularly those occurring on the higher cliff source area. In this light, the considerable cost of protection from smaller events becomes difficult to justify.

If construction of protective structures is contemplated, we recommend that an experienced Civil engineer or geotechnical engineer, skilled in evaluation of dynamic geologic processes for design criteria, be retained to conduct detailed design and siting studies for the structures. This report should be used as a guide to plan further studies of specific protective structure designs and sites.

Bruce K. Stover
Bruce K. Stover, Engineering Geologist

1-17-84
Date

William P. Rogers
William P. Rogers, Chief,
Engineering and Environmental Geology Section

1-17-84
Date

References

Mears, A.I., 1979, Colorado snow-avalanche area studies and guidelines for avalanche-hazard planning: Colo. Geol. Survey Spec. Pub. 7, 124 p.

Robinson, C.S., and Associates, Geological Consultants, 1975, Geologic hazard maps for environmental and land-use planning, Eagle County, Colorado.

Rogers, W.P., et al, 1974, Guidelines and criteria for identification and land-use controls of geologic hazard and mineral resource areas: Colo. Geol. Survey Spec. Pub. 6, 146 p.

Shelton, D.C., 1974, Rockfall: variables which determine the hazard: Unpublished report, Colo. Geol. Survey Geologic hazard files, Denver, Colorado.

Tweto, Ogden, and Lovering, T.S., 1977, Geology of the Minturn 15-minute Quadrangle, Eagle and Summit Counties, Colorado: U.S. Geol. Survey Prof. Paper 956, 96 p.