COLORADO
DEPARTMENT OF NATURAL RESOURCES

ROCK TALK

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GRAVITY AT WORK

Rockfall in Colorado

GRAVITY AT WORK

Rockfall incidents will happen in Colorado, but in some cases rockfall can be avoided or mitigated. This issue of *RockTalk* covers the wide-ranging issues related to this geologic hazard.

A semi-truck collided with a fallen rock on Interstate 70 near Georgetown in April, 2004. Fallen rocks around bends in the highway or night-time rockfalls may not be visible to drivers, and can lead to accidents. (Photo by CDOT, 2004)

A large boulder the size of a small car was an uninvited guest at this residence in the Willow Springs area southwest of Denver. (Photo by LR Ladwig)

The large rock (right) fell from cliffs above before this home was built. A similar boulder falling on the house would do considerable damage; however the 1976 Big Thompson flood devastated the canyon and the house first. (Photo by V Matthews)

After parking near a rock cut along Clear Creek Canyon, the driver of this rental car returned from his afternoon rock climbing trip to a nasty surprise. Fortunately, no one was hurt; unfortunately, the motorist did not carry adequate insurance on the rental. (Photo by CDOT, 2006)

— See the back page for more rockfall photos —

From the Director, Vince Matthews—

A rockfall doesn't have to kill you to ruin your day.

You are much more likely to hit a rockfall, than to be hit by one on Colorado's highways. Although we all probably have concerns about a rock falling through the windshield of our vehicle, it is a much higher probability that our vehicle will be damaged by suddenly encountering rocks already lying on the roadway and not having time to avoid them.

The following is a personal example of how even a minor rockfall can be a hazard on Colorado's mountain highways: On the sunny afternoon of April 25th, 2006, I was driving over Monarch Pass on the way to delivering a speech in Gunnison. Descending the pass on the west side, I passed several cars with drivers blinking their headlights in an apparent warning. Having consequently slowed, I rounded a curve and saw the minor rockfall in the accompanying photo. I easily avoided the large boulder and straddled the small rocks on the center line. Unfortunately, being used to driving larger vehicles with high clearance, I forgot how low the clearance was on my MINI Cooper. I heard what seemed like a minor scraping as I drove over the smaller chunks of rock. Unfortunately, that "minor scraping" resulted in $1,400 damage to the radiator and air conditioner. There certainly are many of these lesser, but impactful, rockfall encounters throughout the state that cause damage and go unreported.

It is important to be extra alert during three particular times on Colorado's highways: spring thaw, after heavy rains, and at night. Be particularly alert during these times where you are approaching a blind curve in the road.

Random Acts of Gravity? When Rockfall Happens

Gravity never sleeps in Colorado's Rocky Mountains! Gravity's constant pull is actively operating on rocks high on steep slopes. When these rocks (both large and small) become destabilized, gravity causes them to roll, slide, or fall onto adjacent valley floors. When people, buildings, vehicles, or highways are in the path, these rockfall events can lead to tragedy—property loss, personal injury, or even loss of life.

Falling rocks are a special category of the large family of gravitationally-driven phenomena called landslides. What are commonly called rockfall events generally fall into four technical definitions: rockfall, rock topple, rock avalanche, and rock slide. Obviously nature doesn't always follow our pigeon-hole classifications, so rockfalls commonly grade into one another.

Rockfall is the fastest type of landslide and is common in mountainous areas near cliffs of broken, faulted, or jointed bedrock, on steep slopes of rocky soils, or where cliffy bedrock ledges are undercut by erosion or human activity. The loss of support from underneath, or detachment from a larger rock mass destabilizes the rocks and gravity does the rest. The criteria for rockfall is simply an exposure of broken rock, gravity, and a slope steep enough that when a rock detaches or dislodges from the ground surface, it will move down the slope rapidly. Complex interactions between physical parameters of both the rock and the slope cause the falling rocks to move down the slope in a high-velocity, seemingly random and erratic manner.

By their very nature, rocks are heavy—and when traveling at 60 feet per second or more, their energy upon impact is frightful to consider. Rockfall events can instantly demolish structures and kill people unfortunate enough to be in their way. Even a single baseball-sized falling rock has the potential for deadly consequences (Figure 1).

Figure 1: Rockfall accident in Glenwood Canyon. This hand-sized rock free fell 300 feet before striking the vehicle. The driver was unhurt and, luckily, there was no front seat passenger. (Photo by Jon White.)

How and Why Rocks Fall

It is important to note that rockfall is a natural, catastrophic process that has been occurring in steep terrain for as long as Earth has existed. Although we often think of mountains eroding away grain by grain (and some do); more often they tumble down in a punctuated, but perpetual, sequence of rockfalls, rockslides, landslides, and debris-laden floods over millions of years. In other words, our beautiful Rockies are basically falling apart (Figure 2).

Figure 2: The large deposits of fallen rock comprising this talus slope (coalescing talus cones outlined in red) at the base of the steep slopes demonstrate that the mountain is slowly falling apart and depositing the cones in continuous episodes of sudden rockfall. West Dyer Mountain east of Leadville. Vertical relief is 1,200 feet. (Photo by Vince Matthews.)

Source Areas

Typically, **source areas** of rockfall are topographically high, hard-rock formations; and to a lesser extent, unconsolidated deposits (soil) containing large fragments of solid rock. Discontinuities (cracks) in the rockmass, such as joints, fractures, faults, and bedding planes, are exposed to weathering processes that weaken the rockmass (Figure 3). The vast majority of rock units have discontinuities, or cracks. The orientation, length (persistence), spacing, and general condition of these cracks make a big difference as to the overall stability of the rockmass.

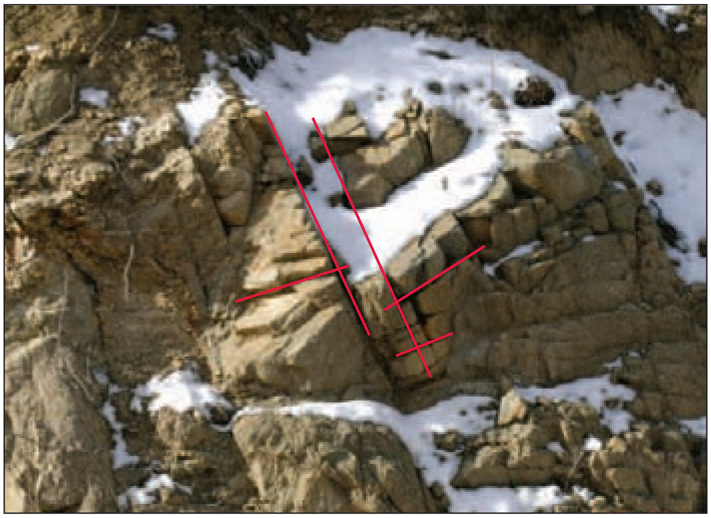


Figure 3: Discontinuities (cracks and fractures, some shown with red lines) in a Precambrian gneiss outcrop near Evergreen, CO. Weathering processes continually work to break apart the rock mass. The fractures are obvious zones of weakness. The orientation of the fractures is important in assessing rockfall hazard. (Photo by TC Wait)

A rockmass like a granite or hard sandstone is more resistant to erosion than soil or softer rock, such as mudstones, claystones, and shales. When softer materials are weathered and eroded away over time, these remaining resistant rocks create topographically high landforms such as mountains, ridges, and mesas. In the alpine areas of Colorado, glaciers created oversteepened valley walls by carving U-shaped valleys, cirques, and arêtes. These steep slopes are also now potential source areas for rockfall.

Table 1: Typical Forms of Rock Slope Failures Defined for the Purpose of this Discussion

Terminology	Relative Speed	General Definition*
Rockfall	Very rapid	Sudden dislodgement of a single or multiple blocks of rock of any size from a cliff or steep face, which descend in a relative free fall. Movement may be straight down, or in a series of leaps and bounds down the slope; it is not guided by an underlying slope surface.
Rockslide	Rapid	Sudden downward movement of an essentially coherent block or blocks of rock along some well-defined failure surface usually related to joints, fault shears, bedding, or preexisting structural feature surfaces. The moving mass is greatly deformed and usually breaks up into many small independent units.
Rock or Debris Avalanche	Rapid to very rapid	Movement of an incoherent mass of rock wherein the original structure of the formation is no longer discernible, occurring along a poorly-defined surface. Characteristic features include flow morphology, relative thinness in comparison to large aerial extent, and lobate form.

**Modified from Varnes, 1978 and AGI geologic glossary*

Rockfall initiates from high outcrops of more resistant rock that becomes unstable for a variety of reasons. The size of the falling rock depends on the source area geology (bedding thickness, bedding dip and dip direction, hardness, joint/fracture orientation), weathering, position, and steepness of the slope (Figure 4).

Weathering & Undercutting

Mechanical weathering in the source area is the primary actor in causing rockfall. It is a process whereby the rockmass is mechanically split and wedged apart along the discontinuities by water as it freezes and expands. The pressure exerted by the freezing of water forces the crack a bit wider with each cycle of freezing and melting, a process called **ice-jacking**. Shales are composed of clay minerals that take in water mineralogically and expand, but then shrink later as they dry out. This causes slaking wherein small shale flakes continually pop off of the exposed shale bed, causing accelerated erosion and potential undermining of harder rocks above. Biological activity (plants and wildlife) can also widen rock cracks. Tree roots seek the water found in rock fractures and the relentless pressure of a growing root can also widen these cracks.

Chemical weathering is a relatively slow process as rock minerals chemically change, causing a general decomposition of the rock. Hard, resistant minerals in a rock can chemically alter to softer, less resistant minerals during weathering. Some areas become susceptible to rockfall because hot waters from underground have chemically altered and weakened the rock (hydrothermal alteration). Weathering can eventually force a once-stable rock into an unstable position where gravity finally pulls it down.

Erosional undercutting, where supporting soft layers underlying a jointed resistant rock are slowly removed, can also turn a once-stable rock into an unstable one that suddenly falls when enough of its support is removed and gravity prevails.

Excavations, such as road cuts or those made during grading activities for developments, can remove support for overlying or overhanging rock and create rockfall hazards. Construction on talus slopes, considered potentially unstable slopes, can increase rockfall risks to areas above and below construction by increasing or renewing ground movements within the talus. Heavy rainfall or wind can move rocks on steep slopes.

Physical Triggers

Triggers for rockfall include precipitation (water lubricates rock joints and fractures, weakens them, and causes them to slip and/or separate), increased ground water pressures (water pressure in the rockmass can hydraulically "lift" the rock and decrease the normal rock friction at discontinuities) temperature extremes (ice-jacking forces rocks apart during freeze/thaw cycles), chemical weathering (decomposition of rock), seismic (earthquake shaking, blasting), erosion and undercutting (from rivers, glaciers, gullying, etc.), or adverse loading (snow loads, landsliding, etc.) that can loosen or overturn an unstable rock. Observers have even witnessed lightning trigger a rockfall in Colorado.

In addition to natural rockfall causes, source areas can also occur as a result of human activities such as steep cutslopes in rocky soils, oversteepened excavation in a rockmass with adverse properties, adverse drainage, and loading by structures. Occasionally, human activities can trigger rockfall or cause rocks to fall sooner than they would naturally. Vibration from roads or blasting can trigger rockfall, as can development-related changes in surface water and groundwater conditions. In Colorado, animals, even humans, can also dislodge rocks while burrowing, climbing, or walking in steep rocky terrain.

Runout Zones

The areas where fallen, rolling, or bouncing rocks accumulate are called **runout zones**. The size and shape of the runout zone depends greatly on the steepness of the slope, the size and quantity of the falling rock, and other factors like vegetation cover. A large quantity of loose fractured rock debris on a slope is sometimes called **talus** or **scree**. Talus on steep slopes is often the result of numerous small rockfall events. If the base of a slope or valley is littered with angular or block-shaped boulders and there is a high cliff up on the valley wall of the same rock type, then it is a rockfall runout zone (Figure 4).

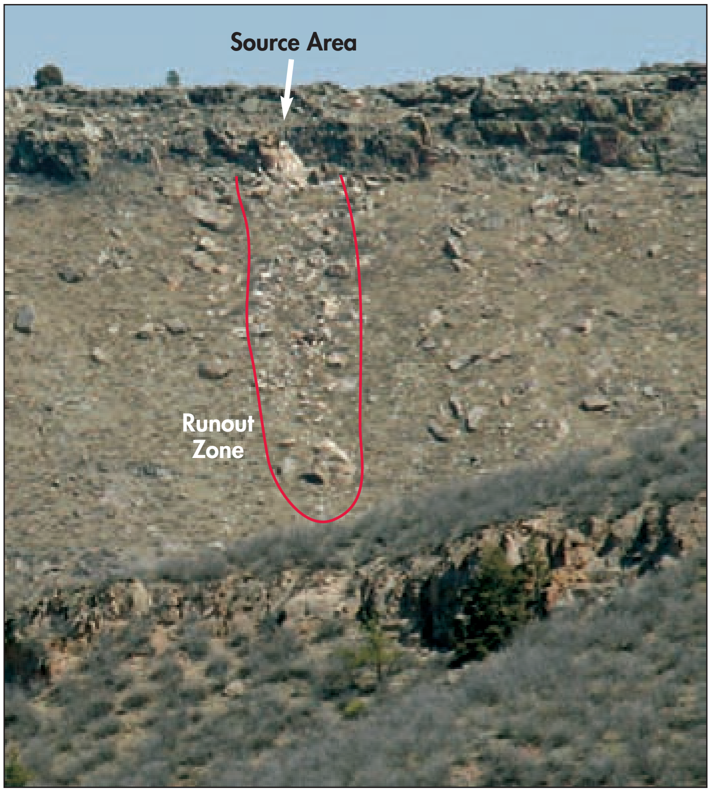


Figure 4: Rockfall source area and runout zone from a rockfall that was triggered by a lightning strike. The whiter rocks indicate the fresh rockfaces of the most recent rockfall event; however the slope is littered with large rocks from older events also. (Photo by Vince Matthews.)

Rockfall in the extreme form is a **rock avalanche** that completely buries the existing ground. When a rockslide occurs with enough mass and long steep slopes, such as a flank of an entire mountain, it quickly becomes a catastrophic landslide. Figure 5 shows the 1991 West Lost Trail Creek landslide in the San Juan Mountains. This gigantic landslide began as a rock avalanche on the flank of Pole Creek Mountain and quickly grew into a large avalanche as it accelerated down the steep slopes to "flow" onto the valley floor.

Figure 5: The July 1991 West Lost Trail Creek rockslide in Hinsdale County, Colorado. This estimated 10 million cubic-yard rock and debris avalanche began as a massive rockslide. (Photo from CGS archives.)

Rockfall Rating Systems

Rockfall rating systems are used to assess the hazard and risk associated with a wide range of rockfall situations including highway and railway transportation corridors, commercial and residential real estate development, and the mining industry. Rockfall rating schemes typically employ two major themes: the objective *hazard* of the rockfall itself and the subjective *risk* associated with that hazard. Rating systems are used for large-scale corridor evaluations, and is generally not appropriate for individual homes or sites.

The *hazard* component can be thought of as the potential for rocks to fall and includes aspects of geology and slope geometry. Geologic characteristics considered in hazard assessment include rock type, degree of fracturing and jointing, the size of the individual blocks resulting from fractures and joints, the relative "smoothness" of the rock, the presence of water, and the degree to which the rock has weathered. Slope geometry includes the overall height of the rock face as well as the rockfall source area, the angle (steepness) of the slope, the presence of launching features which could cause a falling rock to bounce or tumble, the exposure of the slope to the elements of weather, as well as the size and shape of any catchment area (runout zone) at the base of the slope.

The *risk* assessment component of rockfall rating schemes is more variable and reflects the context of the slope with its anticipated human interaction. In the case of a roadside rockfall area, risk assessment is based on the notion of a moving object in the rockfall zone and includes the amount of traffic, the speed of the traffic, and the sight distance available to drivers to avoid a falling or fallen rock. In the case of real estate, the risk component is tailored to that of a stationary object in the rockfall zone and includes aspects such as the location of the structure and its intended use, i.e. full time occupancy in the case of a residence, or scarce occupancy in the case of a utility building.

In order to characterize rockfall hazard areas and the risk associated with those areas, the many parameters of objective hazard and subjective risk are numerically rated and mathematically combined to produce the overall rating for the site. The method by which these components are combined is dependent on the context of the situation. In some cases the hazard and the risk are equally weighted, and in others one component may be more heavily weighted to produce a rating that is appropriate for the specific situation.

Slopes prone to rockfall are highly varied and so their assessment scheme needs to produce some means of comparison between areas and delineate hazard versus risk. A slope may be composed of highly fractured and crumbly old rock, but is located in such a way as to present no risk. Another slope may be composed of more "competent" rock, but is located directly above someone's home or a highway with very high traffic volumes. Which slope deserves more attention? Rockfall rating schemes allow rockfall areas to be compared to each other on an "apples to apples" basis.

Rockfall Investigation and Mitigation

Geologic forces have given rise to the beautiful landscape that is Colorado and part of that beauty is its high elevation and high relief. Rockfall-prone slopes are a part of this landscape, but we, as humans, need to be smart about how we interact with it. By studying rockfall events and understanding the terrain where they occur, geologists, engineers, and local decision makers can work to improve development planning by avoiding high risk rockfall areas, and providing rockfall protection and mitigation in lower risk areas.

Because steep slopes are more difficult to develop, many areas with rockfall hazards have historically been avoided except by road construction; however, as growth continues throughout the mountains and other steep slope areas in Colorado, more areas are being developed within potential rockfall hazard zones. Many mountain towns of Colorado are exposed to rockfall hazards, some of which are high risk and potentially very dangerous. Planning for avoidance or mitigation of the rockfall hazard is crucial in these areas.

Colorado Highways and Rockfall

CDOT has a Rockfall Program that is tasked with identifying, assessing, and mitigating rockfall hazards along Colorado's state highways. Colorado's mountainous terrain and variable geology combine to produce substantial challenges in terms of keeping rocks off the road. One doesn't have to spend much time driving in the mountains to notice the many rocky slopes along the side of the road. Given these many thousands of roadside rock slopes, which present the greatest risk to the traveling public?

CDOT uses a rockfall rating system to rank and prioritize roadside rock slopes for mitigation (See "Rockfall Rating" on page 5). As a first step, every Colorado highway was driven and a cursory visual inspection of the adjacent slopes was made by a geologist evaluating slope geometry and geologic character. This information was combined with traffic data and past rockfall activity at specific sites, as identified in interviews with CDOT maintenance personnel and state patrol accident reports. The combined data allowed CDOT to categorize the slopes into a qualitative ranking of high, medium and low rockfall risk. Of the thousands of roadside rock slopes in Colorado, approximately 750 were ranked as having a "high" rockfall risk. These slopes where then inspected and rated according to a more rigorous rockfall rating scheme. Periodically, these slopes are re-rated to reflect changes in road construction and traffic volumes. The ratings are then used to prioritize rockfall areas according to their relative risk.

Today, CDOT's Rockfall Program is focusing half of its funding for rockfall mitigation along I-70 at Georgetown Hill, which is a unique situation in terms of rockfall hazards and traffic volumes. The Georgetown Hill corridor has had several rockfall accidents over the years, some of which have resulted in fatalities. The slopes adjacent to Georgetown Hill are extremely long and steep and the rockfall source areas can be up to 2000 feet above the highway. Rocks falling from these source areas can attain very high velocities (in excess of 70 mph) and impact the roadway with significant force. This part of Interstate 70 lies between Denver and the major ski areas or other recreational destinations in the Colorado mountains, so traffic volumes can be extremely heavy.

Rockfall along a highway presents a unique problem, in that a rock falling directly on a moving car is relatively rare, although it does sometimes happen. More often the rock falls onto an empty highway and then a car comes along and runs into the rock, causing damage to the car and injury to the occupants.

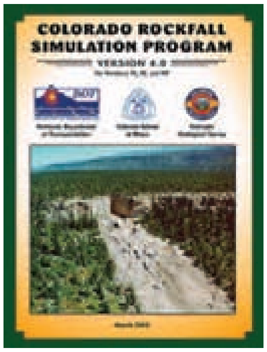
Another aspect of roadside rockfall is that many of the rockfall source areas are old cut slopes that were excavated into the mountainside to facilitate the preferred, most cost-effective, road alignment. In the past, rock blasting for road alignments was uncontrolled and resulted in what is called overbreak; the damaging cracking and fissuring of the rock face by the explosive energy of a blast. Some of these damaged rock faces, blasted years ago and exposed to 50 to 100 years of weathering, are a problem. Road construction methods have evolved in recent years to the point that blasting techniques to excavate rock slopes allow considerably more predictable results and create much less fracturing of the remaining rock slope. For all new highway improvements, rockfall potential and the long-term behavior and stability of an excavated rock slope is taken into consideration early in the project design stage, and mitigated during construction. CGS often works with CDOT to assess and study the rockfall potential on highway projects.

Identifying Potential Rockfall Hazard Areas

Specific rockfall occurrences are very difficult to predict, but it is possible for a geologist to identify areas that are prone to rockfall events, and to make judgments on the level of hazard and the level of risk to human development. Identifying areas that may be affected by rockfall involves looking at a number of geologic and topographic factors.

Before going into the field, the geologist might conduct an analysis to pinpoint where steep slopes are located. A geologist will examine the overall topography of the terrain to determine areas with enough relief and steep slopes that would allow gravitational forces to create rockfall. The types and condition of rocks and materials on or above a slope are evaluated to determine which formations might produce a falling rock. Slopes, vegetation, and valley floors are inspected for evidence of past rockfall activity. Current land use and human activity are also considered by the geologist, because these may enhance natural conditions for rockfall, or even directly induce rockfall. All of these factors are considered in order to determine whether any mitigation or protective measures should be developed.

Colorado Rockfall Simulation Program (CRSP)



COLORADO ROCKFALL SIMULATION PROGRAM

VERSION 4.0

Figure 6: Documentation and user's manual for the Colorado Rockfall Simulation Program, version 4.0, available from the CGS.

One example of a useful tool in assessing and modeling rockfall hazard is the Colorado Rockfall Simulation Program (CRSP). This computer program allows the user to simulate a rock rolling down a slope and to predict the speed and bounce heights of the rock. The CRSP software was first developed in 1988 by researchers at the Colorado School of Mines and the Colorado Department of Transportation (CDOT) who recognized the need to model rockfall during the I-70 Glenwood Canyon Construction Project. The Colorado Geological Survey (CGS) assisted CDOT with monitored rockfall testing that provided empirical data for CRSP calibration. The program is recognized worldwide as a useful and valuable tool for analyzing rockfall hazards and preparing mitigation designs.

CRSP has been revised and re-calibrated in later versions. Today, CRSP Version 4.0 is the current version available. CGS sells the program and a user's manual for $25 through the CGS online bookstore (**http://dnr.state.co.us/geostore/Search.aspx?Keyword=CRSP**) (Figure 6). Stay tuned, though. The CDOT Rockfall Program is financing the development of a wholly revised CRSP that should be available within a couple of years.

Instrumentation and Monitoring of Rocks in Source Areas

A wide variety of different types of tools are available that can measure the movement of an unstable rockmass or large block of rock. Some of these methods are extremely sensitive and can measure not only rock movement, but the expansion and contraction of rock as it warms in the sun and cools at night. Instrumentation and monitoring of large unstable rock features is prudent in many circumstances because observations show that rock movement usually accelerates prior to ultimate failure (i.e., sliding, toppling, etc.)

Some of the methods can be very simple but still effective. Crack gauges and other "tell-tales" are simple devices that are generally affixed to a rock face spanning a fracture or other discontinuity in the rockmass (Figure 7). As the rock moves, a gap begins to show between the two indicators that can be measured. A drawback of these old-fashioned types of devices is that they need to be visited to be read, not a pleasant thought if the crack gauge is anchored up on a 600-foot cliff and it's winter time.

Electronic devices are more sensitive than simple physical indicators and are able to report millimeters of movement, but are more complicated.

Figure 7: Close up view of tell-tale gauge. Two steel rebar segments (shown with arrow) have been cemented into small drill holes above and below the large crack in the rock. Any movement could be measured by the offset of the two bars that were touching when cemented. This rock has not moved since the gauge was installed in 2003. (Photo by Ty Ortiz, CDOT.)

Simple circuit tools can span a rock crack and initialize a warning if the circuit is broken when the crack widens. More complex transducers that measure frequency fluctuation in vibrating wires are used in crack or joint meters, tilt meters, and extensometers (Figure 8). These devices send electronic signals through cables that can be connected to a data-logging computer and telecommunication system. These systems allow near real-time observations of rock movements from any location with a computer (or a mobile device such as a Blackberry) and an internet connection.

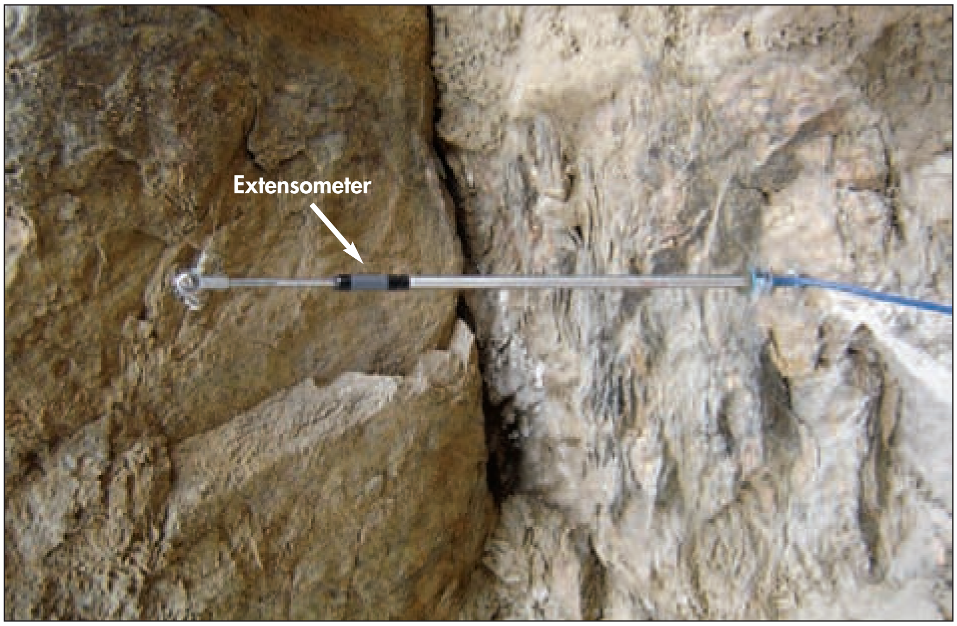


Figure 8: Close-up of a crackmeter sensor anchored across a rock joint near Idaho Springs, CO. A crackmeter is mounted to posts that are grouted into drill holes on each side of the rock crack. (Photo by Ben Arndt, Yeh and Associates, Inc.)

Figure 9: Installation of target prism anchored to a cliff to measure rock movement. Prism is screwed into a wedge anchor bolt that is installed into a drill hole. (Photos by Jon White.)

Survey equipment is also commonly used to monitor rocks and rockmasses. Target prisms or other reflectors can be affixed to a rock face (Figure 9) and periodically measured with a laser surveying instrument. More advanced survey equipment, called laser scans or 3D scans, has entered the market in recent years. These laser-distance tools “sweep” a rockface and the return laser beam scatter is measured and deciphered as 3D points in space. Thousands of these points create a three-dimensional “point cloud” that depict an accurate image of the rockface (Figure 10). Each sweep of the tool generates new 3D points at the same location. Each successive reading is compared to previous readings, and software can measure incremental movements of the rock face.

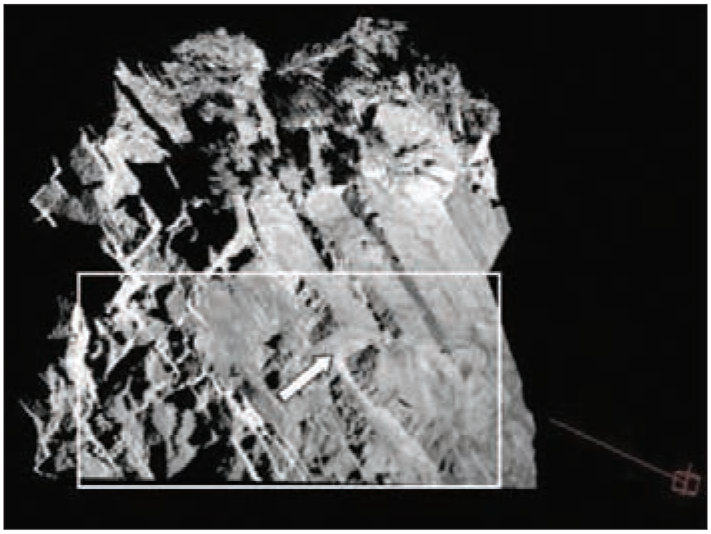


Figure 10: Point cloud generated by laser scan of rock face. These scans are capable of detecting minute changes of 3–10 millimeters in a rock face. The arrow points to the rock overhang that was of interest to CDOT in the survey. (Image courtesy of Ty Ortiz, CDOT.)

The electronic and survey data is plotted on graphs showing rock movement over time. Trends can be established that show no movement, steady state creep, seasonal fluctuations, and/or diurnal movements. If the rate of movement begins to increase markedly, then responsible entities can be notified to start further investigation, mitigation design, and mitigation construction as necessary. Electronic monitoring and real-time data collection can also be configured as an early warning system.

When a site has been identified as being exposed to rockfall hazards, there are three primary categories of mitigation alternatives: 1) avoidance of the hazard, 2) protection from the hazard, and 3) rock stabilization and slope-support techniques that include either removal of hazardous rock features and/or reinforcement of the rockfall source area. The mitigation design approach chosen is always dependant on a site-specific geologic investigation of the hazard area, access availability, and the economic reality for the type of structure(s) or land use proposed versus engineering and mitigation costs. In many situations, the final mitigation design is a combination of specific schemes from all three categories.

Avoidance

Avoiding the rockfall hazard area is the most basic method, albeit oftentimes the most difficult to accomplish. If land-use master plans are carefully prepared (by county and city governments) and in effect prior to development, high-risk areas can be designated as no-build zones, and therefore off limits to development. In the case of a pre-existing development or structures, the only other avoidance alternative is to move the structure out of the hazard zone, which is usually very problematic and costly, and therefore, rarely done. In the case of a new roadway, the planned road alignment simply avoids a rockfall hazardous zone. For existing roadways, moving the road alignment during highway improvement or widening projects, or by relocating the road into a tunnel, can often avoid the hazardous areas. Typically, avoidance of the hazard is the least expensive mitigation alternative when planning new construction or road alignments, but it is one of the most expensive for existing structures.

Protection

Protection concepts accept that rocks will fall in a hazardous area, but structures and roadways can be acceptably shielded from rockfall, or sufficiently reinforced to withstand the impact without adverse damage or loss of functionality. Rockfall protection designs come in many forms. Rockfall barriers are designed to stop falling or rolling rocks. They can be constructed in the form of a large earthen wall or berm, or specialty fences built with strong, steel cable netting. Earthen barriers often include a ditch in back to provide extra space to accommodate falling and rolling rocks and associated debris. A good example of both earthen rockfall berms and impact walls is at the Booth Creek rockfall site in Vail. Photos of these barriers are shown in the case history article. Rockfall fences can be seen at many locations around the state, the most notable of which can be seen alongside and above Interstate 70 on the Georgetown Hill (Figure 11). Rockfall fences are well suited in rugged terrain and very steep slopes where impact walls and rockfall catchment ditches are not feasible. Another method of protection from rockfall is constructing a rockfall shed over the road or structure, similar to an avalanche protection shelter. This technology is the most expensive protection option, but is well suited to locations where rockfall is consistently severe, and where other protection devices would likely fail under repeated rockfall events.

Figure 11: Wire rope rockfall fence installed on a rock slope at Georgetown Hill above Interstate 70. Exit ramps shown in the upper part of the photo are for the Silver Plume Exit. (Photo courtesy of Ty Ortiz, CDOT.)

Rock Stabilization

Rock stabilization is a common form of rockfall mitigation. Stabilization and controlled removal of loose or potentially loose rocks improves both the risk of falling rock and the exposed rock's ability to support itself. Removing a potential rockfall before it becomes a falling rock is the most direct way to address rockfall hazards. Removal may be as simple as knocking down loose rocks with a crowbar (known as scaling) or may consist of drilling, loading explosives in the hole, and blasting down potentially unstable rock features. Reducing the grade of a rocky slope (laying the slope back) will improve slope stability and can also prevent rocks from detaching from the rock outcrop and rolling down the slope. This technique was utilized at the large rockslide in Clear Creek Canyon in 2005. Removing the hazard is oftentimes difficult to accomplish where there are existing structures nearby that may be threatened or damaged in the process.

Figure 12: Installation of rockbolts on the rocky slope of Glenwood Canyon during the Interstate 70 highway construction project in 1991. The worker is spinning an epoxy-coated steel bar into the drill hole using a pneumatic drill. The protruding bars in the foreground (shown by arrows) are installed rockbolts. (Photo by Jon White.)

Stabilization of rockfall prone slopes is another preventive mitigation alternative. These methods are generally mechanical techniques that improve the strength of the rock and prevent failures along discontinuities, as explained in the overview article of this *RockTalk* issue. These techniques can be subdivided into techniques that further stabilize the rockmass internally and those that support the rock at the surface.

Rock bolts, or dowels, are long steel bars that are cemented into drill holes in the rock with a concrete or epoxy-like mortar (Figure 12). Many times these rock bolts are tensioned with a hydraulic ram and then a nut is tightened at the surface to lock the bolt, which puts the rockmass in compression (forces the rock together) and applies additional frictional forces at the discontinuity surfaces they cross, which counteract gravitational forces and hold critical planar or wedge "key blocks" in place. Many highway rock slopes have rock bolts in them. The only evidence at the surface is a small steel plate and a nut exposed on the rock face (Figure 13).

Because water in cracks can cause rocks to weaken and fail, it is common to drill inclined holes into the rockmass to allow better drainage of any water-filled fractures and thus stabilize the rock inexpensively.

Another emerging technology to stabilize rock slopes is through the use of an injected polyurethane resin. Holes are first drilled into the rock, and then a two part resin, similar to common epoxy, is injected into the rock. The resin hardens after a short time and the interior of the fractured rock is essentially "glued up" and held in place.

Figure 13: Pattern rock bolting to reinforce the rock cut along Highway 285. The threaded steel bars have been cemented into drill holes. The external evidence of rock reinforcement is shown by the steel plates and large nuts, four of which are indicated with arrows. (Photo by TC Wait.)

Surface retention of an unstable rockmass includes anchored concrete buttresses (Figure 14), and wire mesh (similar to chain-link fencing) or cable netting, either anchored to the rock face or draped down on a rock slope (which serves to redirect a falling rock into a ditch). Occasionally, large rocks can be stabilized by cable lashing, which also serves to hold the rock in place. Cable lashing is often employed to protect existing structures and roads from precariously balanced rocks that are too dangerous to remove or too unstable to drill into (Figure I, page 17). Another form of surface retention of rock is shotcrete, which is the pneumatic spraying of concrete onto a rock face or cut slope. Shotcrete can be very effective when applied on cut slopes in rocky soils (Figure 15) and in poor rock conditions such as slaking shale slopes that are undermining more resistant rock above.

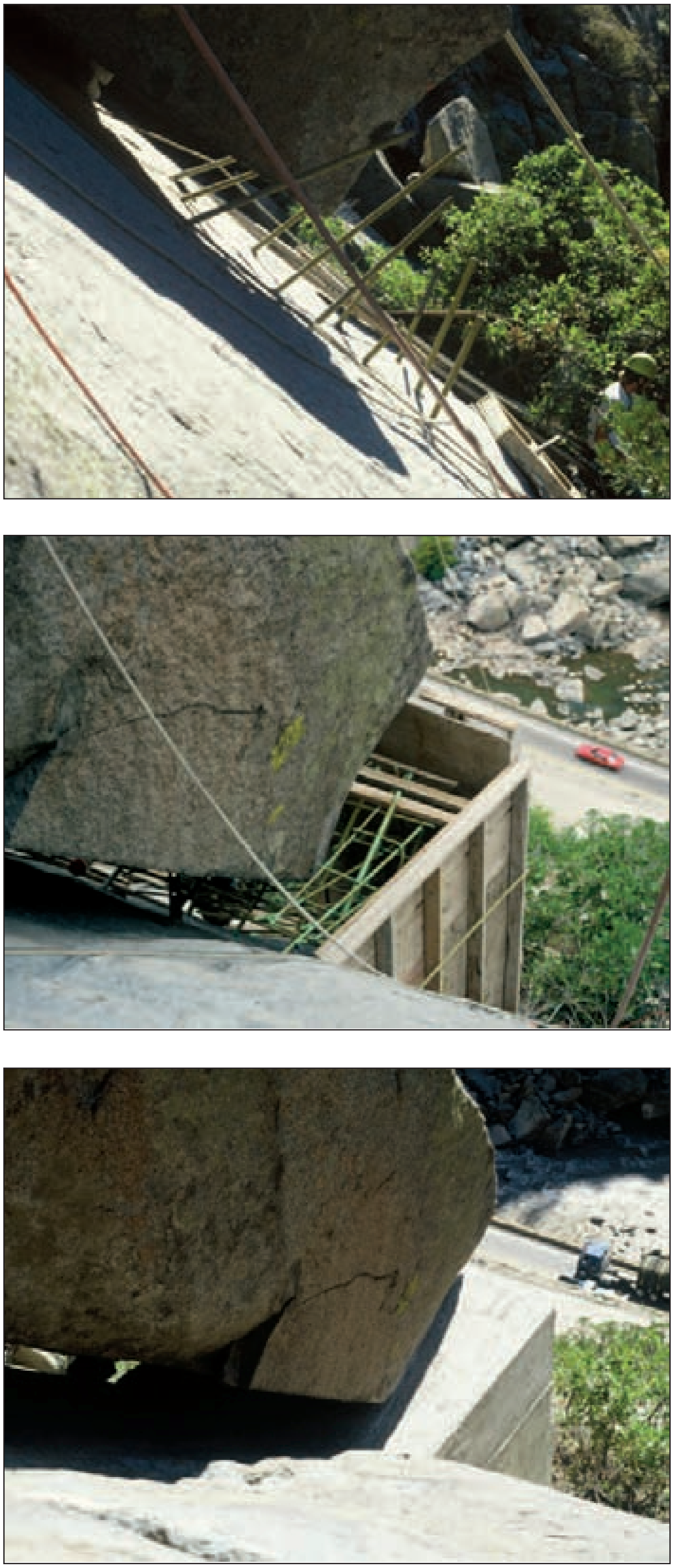


Figure 14: Smaller, upslope concrete buttresses are anchored to the rock face with rockbolts. Then, concrete rebar and wood forms are wired to the anchors in Glenwood Canyon. The concrete is carried in mud buckets by helicopter. The three photos show the progression of the installation. (Photos by Jon White.)

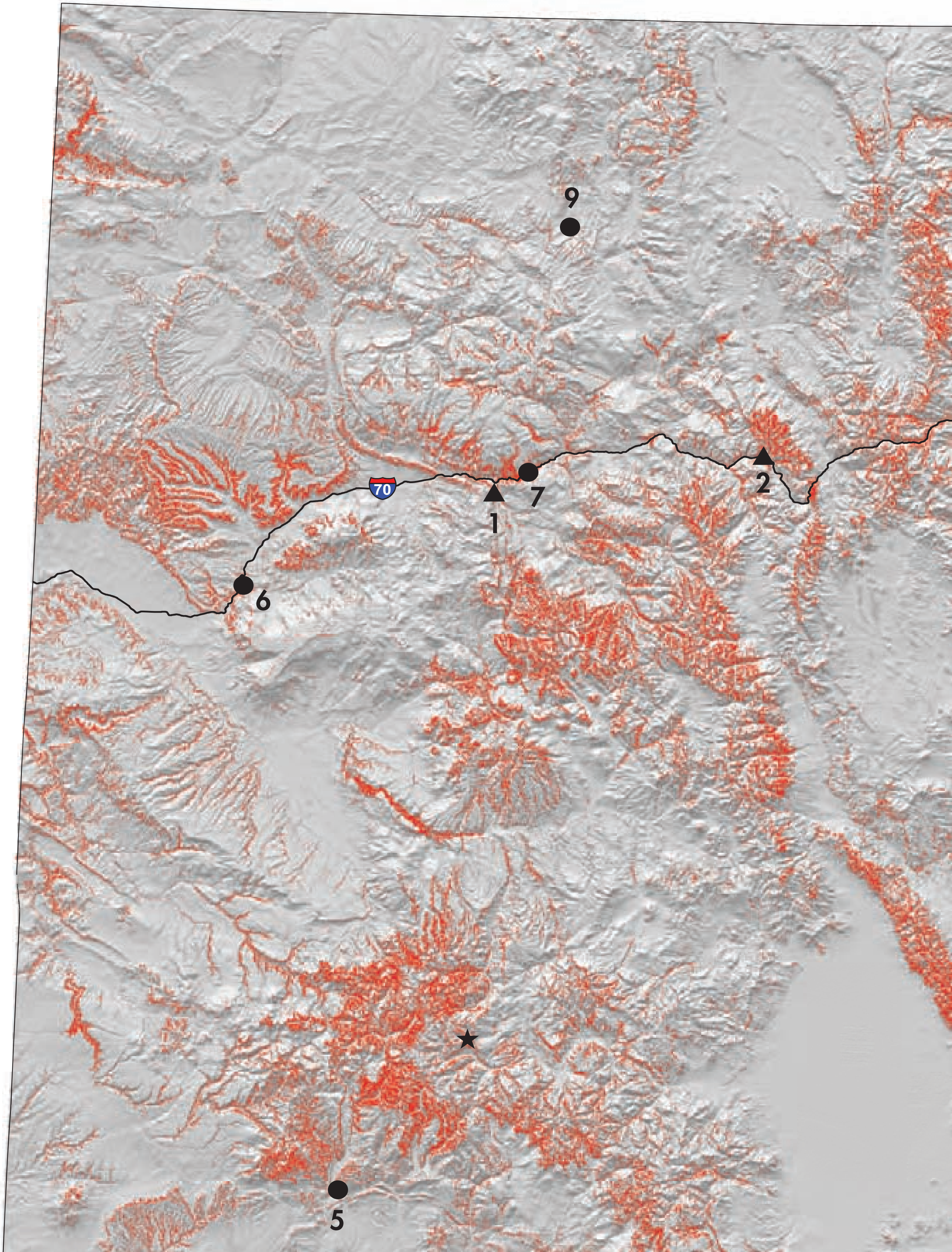
Figure 15: Application of shotcrete at a raveling cut-slope exposed in a rocky talus chute. The concrete has been dyed dark brown to better match the surrounding area. (Photo by Jon White.)

In most cases, rockfall mitigation is designed to incorporate a combination of these techniques. Common highway mitigation project scenarios include first removing loose rock by scaling and sometimes blasting, then reinforcing rocks with anchors that are installed and tensioned to improve the overall rockmass stability and prevent larger rockslide failures, then draping wire mesh or netting over the slope to control and direct smaller rock fragments that will loosen over time to fall between the mesh and the cliff face, and finally constructing a suitable containment ditch at the highway shoulder to retain these smaller rock fragments that may fall.

The Role of CGS in Colorado's Rockfall

One of the primary missions of the Colorado Geological Survey is to help reduce the impact of geologic hazards on the citizens of Colorado. To act in accordance with that mandate, the Colorado Geological Survey responds to Colorado's rockfall hazards in many ways:

- Emergency response to rockfall events when they occur throughout the state;
- Providing rockfall investigations and hazard evaluations to other state agencies and departments;
- Identifying and mapping specific areas of rockfall hazard in cooperation with local government planning agencies and the Colorado Division of Emergency Management;
- Recently completing rockfall hazard maps for the towns of Estes Park, Evergreen, and Colorado Springs;
- Providing the popular Colorado Rockfall Simulation Program computer software, including the user's guide, at government cost;
- Helping county and municipal planners and developers to identify and avoid, or mitigate hazardous areas through our land use review program;
- Providing comment and guidance for proposed rockfall mitigation;
- Providing educational resources, such as this issue of *RockTalk*, so that the people of Colorado can better understand rockfall and the risk associated with living in and traveling through mountainous terrain.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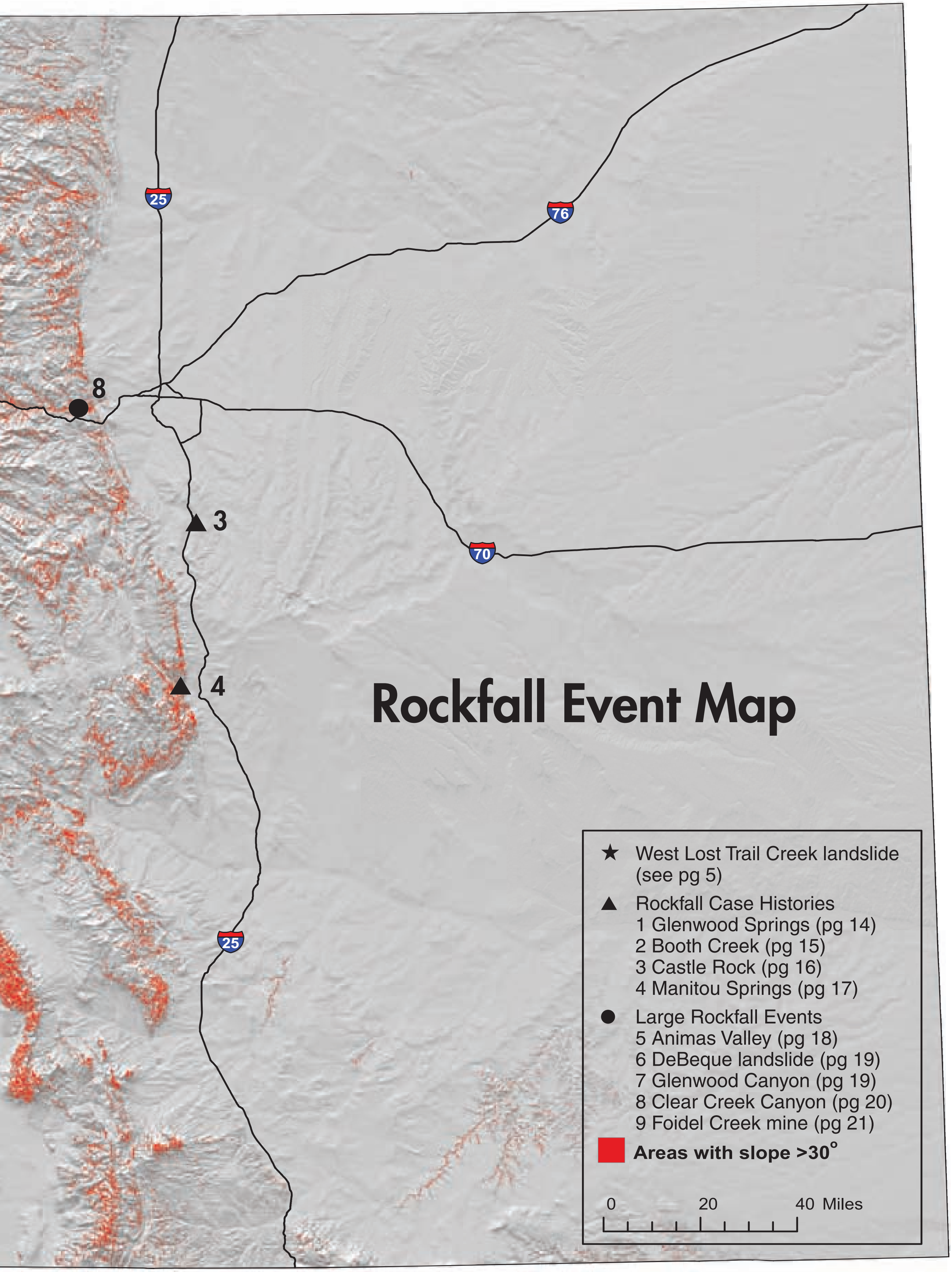


Rockfall Event Map

Figure A (above): *Valley rim west of the Roaring Fork River in Glenwood Springs looking north towards the confluence with the Colorado River. Note slumped (tilted) sandstone blocks in the exposed rock layer. Some of the rock blocks shown in this picture from 1994 have now fallen/rolled to the valley floor. (Photo by Jon White.)*

Rockfall Case Histories

The following case histories illustrate the hazards associated with rockfall areas and the resulting complexities and difficulties involved in land use planning and rockfall mitigation efforts. The locations of these sites are shown in the accompanying map of Colorado (preceding page). In most of these examples, the threat and high risk of rockfall was not appropriately addressed during the planning and building of homes in rockfall runout zones. Only after significant and repeated potentially lethal rockfall events, or later geologic hazard investigations was the threat fully understood and taken seriously by residents, developers, or local planning agencies. Simple avoidance of hazardous areas would have solved the rockfall problems in these situations.

Glenwood Springs

The town of Glenwood Springs in west-central Colorado lies at the confluence of the Roaring Fork and Colorado Rivers. The town is tightly constrained by the steep river valleys so land-development pressure is causing more residential growth to advance into rockfall hazard areas. In West Glenwood, on the west side of the Roaring Fork River, the valley is rimmed with sandstone outcrops (Figure A). The sandstone layers are being undercut by the erosion of underlying softer siltstone and shale so that large sandstone blocks are being actively undermined and destabilized. In this area, there have been several large rockfall events from the valley rim; some that have severely damaged homes on the valley floor, 1,100 vertical feet below (Figure B). Fortunately, there have been no injuries or fatalities. Rapids in the river are evidence of continuous rockfall over many centuries. While there has been rockfall mitigation in some locations (Figure C), the threat remains in other areas.

Figure B: In April 2004, this rock from the source area shown above smashed through the wall of a home and came to rest against an easy chair. The homeowner built a rockfall protection fence afterwards. (Photo taken in 2004 by Steve Vanderleest, City of Glenwood Springs.)

Figure C: This newer development in west Glenwood Springs constructed a rockfall impact wall above their townhomes to protect against both rockfall and mudslides (debris flows). (Photo by Jon White.)

Booth Creek Rockfall Events

Another example of a rockfall hazard and high risk affecting a neighborhood is in East Vail at Booth Creek. The north valley wall of Gore Creek is benched with two high rock cliffs. Above the two cliffs, the 1,100-foot high valley rim is composed of an eroding slope of glacial till, which is also composed of very large rocky material. All three of these areas periodically release large rocks. After several repeated, potentially lethal, rockfall events that damaged several homes in the early to mid 1980s, CGS was asked to provide assistance to the Town. The neighborhood created a special Geologic Hazards Abatement District (GHAD) affiliated with the Town of Vail. The GHAD funded a rockfall hazard study that included a mitigation design. The construction of a rockfall catchment ditch and berm above the homes on the valley slope was completed in 1990 (Figure D). Owners of adjacent condominiums elected to not participate in the GHAD, and that poor judgment was brought into sharp focus in March, 1997. Another large rockfall event fanned down the slope toward the residential areas at the property line between the homes and condominiums. The existing rockfall ditch and berm was 100% effective in catching the rocks, but several rocks impacted the unprotected condos (Figure E). After that incident, which luckily resulted in no fatalities, the condominium homeowners association petitioned the town for their own mitigation. In 2001, specially designed impact barriers (Mechanically Stabilized Earth wall) were constructed on the slope behind the condos to provide a similar level of protection (Figure F).

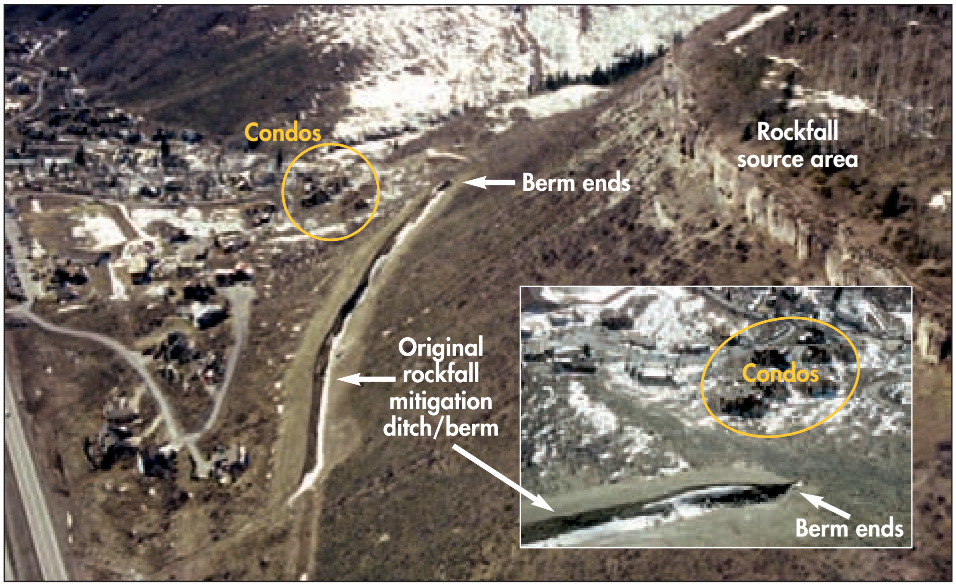


Figure D: Oblique aerial view, looking west, of Booth Creek debouching onto the Vail Valley floor. Interstate 70 highway is shown on the far lower left of the photo. The ditch and berm completed in 1990 is shown left of center. The termination of the berm and continued rockfall-hazard exposure of the condos (circled in yellow) is shown in the inset photo. (Photos by Jon White.)

Figure E (center row): Stunned condo occupant looking at exterior wall of her bedroom. Luckily, she wasn't home at the time of this event. The boulder demolished her bedroom crashing through two interior walls and the floor. The 5-foot boulder came to rest in the basement. (Photos by Jon White.)

Figure F (right): Three impact walls were built after the 1997 event to mitigate the threat of future rockfall at the condominiums. (Photo by Jon White.)

St. Francis of Assisi Rockfall Site, Castle Rock

The Colorado Geological Survey extensively studied the site of St. Francis of Assisi Church in Castle Rock after a block detached from the upper cliff face in January 1981. The block presented a risk to homes at the base of the slope south of the church, and was broken up using passive demolition methods. Other detached blocks continued to present a rockfall hazard to six homes located at the base of the bluff (Figure G). No consideration was made to address rockfall hazards at the base of the slope when the homes were originally built.

The church is planning a major expansion, and in 2005 CGS was asked by Douglas County to review the church's development plans. The church sits atop a bluff that is composed of hard, blocky Castle Rock Conglomerate overlying soft, erodible Dawson Arkose (a type of sandstone). Tension fractures in the cap rock conglomerate indicate that large blocks are actively detaching from the cliff face, and large fallen blocks are present on the slope below. Some of these large rocks have even been incorporated into the landscaping of homes below the bluff.

However, since the homes pre-date the proposed expansion, the church was required to make every effort to ensure that the expansion will not further destabilize the bluff. CGS and Douglas County were concerned that the proposed expansion would impose construction-related disturbances and vibrations that could increase the rockfall hazard. Post-construction runoff from the planned large roof and pavement areas could result in increased infiltration and seepage, further destabilizing the precarious blocks along the cliff.

A rockfall mitigation plan was developed for the site. The mitigation plan included (1) constructing a rockfall catchment trench, (2) cable-lashing a large pillar, (3) scaling unstable rocks, and (4) using rock bolts with wire mesh and shotcrete to anchor the larger areas of unstable rocks. The mitigation was completed in September 2008.

Figure G: St. Francis of Assisi Church in Castle Rock. Fractures in the cliff and large fallen blocks on the slope above these homes indicate an active rockfall zone. Red lines are property boundaries. (Photo from Douglas County Planning Department.)

Manitou Springs 1995 Rockfall Threat

Manitou Springs occupies a narrow valley where Fountain Creek emerges from the foothills northeast of Pikes Peak and west of Colorado Springs. The valley slopes are composed of interbedded resistant sandstone and conglomerates (i.e., gravelly sandstone), and weaker mudstones and shale. The outcropping sandstone is most prevalent on the steeper slopes on the north side of the valley.

During the wet Spring of 1995, incidents of rockfall and landslides increased throughout Colorado, some of which resulted in fatalities. In Manitou Springs, a fortunate set of circumstances occurred before the Memorial Day holiday weekend when local residents observed the movements of a large, dangerous block of rock before it could fall. This set into motion an emergency declaration by the town, which resulted in the compulsory evacuation of homes that were located below the rocky slope, the closing of the road in the area, and an immediate rock stabilization project. During this emergency situation, the Colorado Geological Survey was asked to provide assistance to the town to help stabilize the rock. The emergency evacuation decree remained in effect until the rock was stabilized and the area was declared safe.

A prominent 12-foot-thick ledge of strongly-jointed sandstone forms the rim of this slope. Two essentially vertical and intersecting joint sets produce large orthogonal sandstone blocks that are being undermined by the more easily weathered mudstone beds below the ledge. The blocks begin to topple as the underlying rock that supports them erodes, creating dangerous overhangs. At the time of discovery, this particular block had moved 5.5 feet from the back face of the sandstone ledge and tilted precariously over the next sandstone ledge below. Had the 70-ton block fallen, it would have certainly crushed a home below.

Figure H: A precarious rock above Manitou Springs started to move in 1995 after a period of wet weather. As an emergency measure, high-strength steel cables were wrapped around the rock and anchored to the surrounding ledge to arrest the movement. (Photo by Jon White.)

Figure I. After the rock was stabilized, additional cables were physically attached to the top of the rock block and secured to surrounding stable rock. (Photo by Jon White.)

The extremely unstable, tilted, rock could not be removed due to the proximity of homes directly below, so high-strength steel cables were wrapped around the rock and anchored to the surrounding ledge (Figure H). Once the block was safely restrained, additional cables were physically attached to the top of the block at anchor points that were cemented into drill holes to provide an additional level of support for the block and safety for the homes below (Figure I).

Large Rockfall Events in Colorado

For most of us, our immediate experience with rockfall events are encounters with minor episodes that leave small rocks lying on a highway before a maintenance patrol removes them. Media often report some of the larger rockfalls when a major highway is temporarily closed, a vehicular accident occurs, or a fatality results from the rock impact. Discussed below are some of the larger rockfall events and rockslides that have recently occurred in Colorado. Not all are along Colorado highways. Most are natural events, but some are caused by human activity. These large rockslides can be very dangerous because of the major impact on the terrain below when they fall. The common theme in the following examples is a rocky rim of a steep-walled valley or canyon, and/or a high cliff face of exposed bedrock. The following recent, large rockfall examples are located on the map of Colorado in the center of this *RockTalk*.

Animas Valley Rockfall

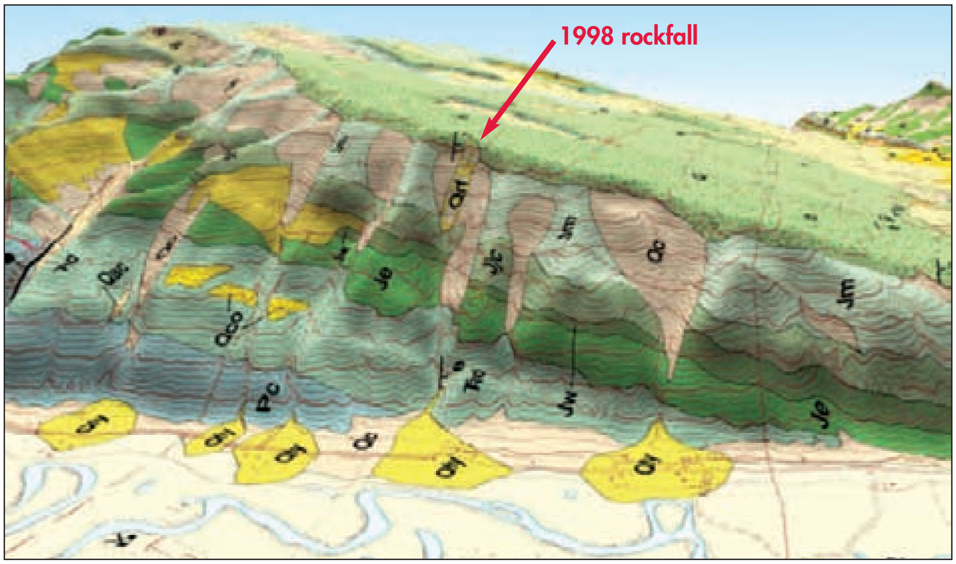
On July 5, 1998, a large rockfall event occurred about 4½ miles north of Durango along the cliffs marking the east rim of the Animas River Valley. Over 50,000 cubic yards of rock detached and toppled from the sandstone cliff face. The falling rocks rolled and slid down the valley wall to crash into lower bedrock outcrops where they came to rest in a narrow cleft in the cliff face. The cliff of the valley rim consisted of an angular promontory edge that was being actively undermined by the erosion of weaker shales below. Over time, fissures began to open along vertical rock joints that were 30 feet behind the cliff face. These fissures, roughly parallel to the cliff face, became increasingly separated from the hillside. Before the failure occurred, they had widened to the point where there was over three feet of separation. The rockfall event occurred over the July 4th holiday weekend just days after landowners on Missionary Ridge had visited the cracked edge. The landowners had videotaped the cracks and detached rocks, with family members even jumping back and forth, across them onto the detached rock block.

The rockfall scar is quite visible from Durango (Figure A). Fortunately the falling rock did not reach the valley floor where homes are located so no injuries or fatalities occurred. When it fell and crashed down the valley side, a plume of dust was created that completely filled the valley. At the time of the rockfall, CGS geologists were mapping the area and immediately responded by assisting La Plata County's assessment of the rockfall event.

Future geologic hazards related to this event include additional rockfall and the re-mobilization of the already fallen rock debris during intense rainstorms. The rockfall debris is composed primarily of sandstone blocks (up to 40 feet in length) with minor amounts of shale, silt, and clay that could become re-mobilized and carried down the narrow drainage and deposited on the alluvial fan on the eastern valley margin (Figure B). Based on recommendations made by CGS, county officials have assisted landowners living on the fan with the construction of a new channel to divert runoff away from their homes. To contain rock material from spilling out of the channel during mudslide (debris flow) events, below-grade catchment basins were constructed at the head of the fan, and both sides of the channel bank were bermed. In November of 2008, renewed activity on the upper rock face and large blocks of rotating rock were observed and are being closely monitored by the County.

Figure A: Aerial view of the Durango rockslide in 1998. White cliff at the top is the Dakota Sandstone and Burro Canyon Formation. Slope with the rockslide scar is the Morrison Formation. Lower red cliffs near the valley floor are the Entrada Sandstone and Dolores Formation. See geologic terrain model in Figure B. (Photo courtesy of the CDOT Aerial Reconnaissance Unit.)

*Figure B (below): Terrain model of the east side of the Animas River Valley north of Durango, draped with the 1:24,000 scale CGS geologic map. The rockfall event of July 5, 1998 is shown as the deposit **Qrf**. (Created with 10-m DEM from USGS; geology by Carroll and others, 1999).*



The Historic DeBeque Rockslide

The active landslide (Figure C) at milepost 51 of Interstate 70, 36 miles east of Grand Junction, began its life as a massive rockslide. A large, 900-foot long, 300-foot high, and possibly 400-foot wide chunk of the sandstone cliff that had fissured from the southern canyon wall in the recent geologic past, finally fell into the Colorado River. The date of this rockslide is uncertain but the event occurred prior to 1910. It is documented that the rockslide, with rock blocks the size of small homes, partially dammed the river and pushed the river course north towards the opposite bank. The historic records mention that part of the railroad was washed out, as well as a peach orchard and structures at Tunnel, a work camp that was located across the river from the rockslide. Fortunately, there was no road on this side of the canyon at the time of the rockslide. The entire fissured sandstone cliff did not fall, however. A remnant of the upper block in front of the fissure still remains and continues to creep towards the river and Interstate 70. This continued movement is monitored by the Colorado Geological Survey for the Colorado Department of Transportation.

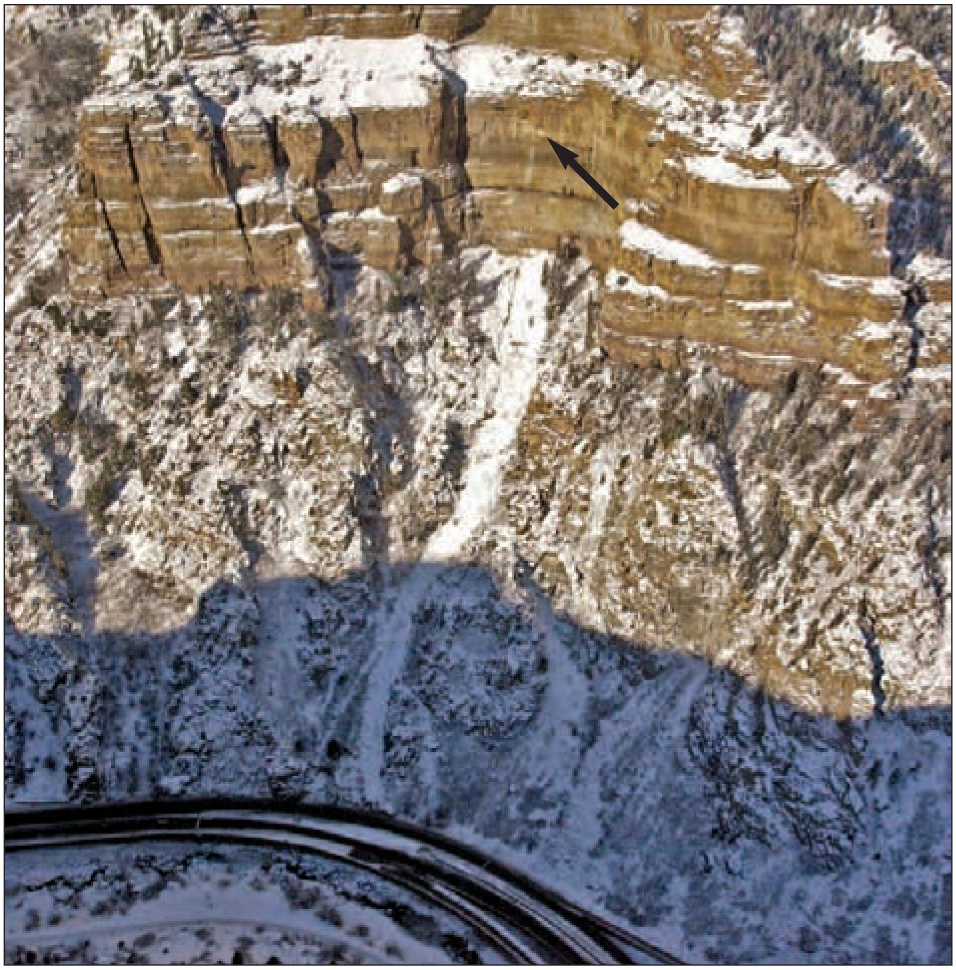


Figure D: The Thanksgiving 2005 rockslide area in Glenwood Canyon. Detachment location of rockfall is shown by black arrow. This 600-foot thick cliff of Sawatch Sandstone lies over Precambrian basement rocks at a major nonconformity. The rockslide path is well marked by the snow-filled chute in the underlying Precambrian rocks. (Photos by Ty Ortiz, CDOT.)

Figure C: Oblique view of the DeBeque Canyon rockslide. Note the large blocks in the rubble and how the river course has been diverted and narrowed. The ground fissure can be seen at the headwall of the landslide, left of center. Interstate 70 crosses the toe of the landslide. (Photo by Jon White.)

Glenwood Canyon Thanksgiving Day Rockslide

On Thanksgiving Day in 2005, a very large rockfall event occurred in Glenwood Canyon affecting a portion of Interstate 70. A segment of rock over 1,200 feet high on the canyon wall and 2,000 cubic yards in volume, detached from the cliff face, broke into many large blocks that rolled down a rockfall chute, and slammed into the highway at the valley bottom (Figure D). Thankfully, the westbound lanes were temporarily closed at the time. No vehicles were hit, but there was severe damage done to Interstate 70 highway structures, requiring the westbound lanes to be closed for almost three months for repairs.

The rockslide occurred near the Shoshone Interchange, which is a tightly constrained section of highway structures in one of the narrowest sections of the canyon. A series of bridges and retaining walls enable the highway to cross the Colorado River to the Hanging Lake Tunnel portal while still providing road and bicycle access to the Hanging Lake Rest Area. The rockfall was caught on the closed circuit video cameras used to monitor Interstate 70 traffic in the canyon. The video showed many rocks, up to 12 feet in diameter, impacting the on-ramp retaining wall of the rest area, as well as the bridges to the tunnel portal. A dust cloud generated by the rockslide filled the canyon afterwards.

When the dust cleared, the highway was littered with boulders of all sizes (See Figure E). Upon closer inspection, the true nature of the damage became apparent as large holes were punched though the concrete deck and the westbound retaining wall, demolishing a section of the bicycle path below, as well as damage to the bridge girder of the adjacent eastbound bridge (Figure F). Fortunately, no one was caught in this major rockfall event.

Figure E: Huge blocks of sandstone litter both east and westbound I-70.

Figure F: Westbound deck of I-70 with extensive damage.

Clear Creek Canyon Rockslide

A high-profile rockslide event occurred on June 21, 2005 along U.S. Highway 6 in Clear Creek Canyon, approximately 10 miles west of Golden, CO. Around 11 AM, 2,000 cubic yards of rock slid from a pre-existing road cut on the north side of the road and completely covered the road (Figure G). Two tractor-trailers were caught in the rockslide and were pushed off the road by the debris. The tractor-trailers were totaled, but only minor injuries were sustained by the drivers.

The geology at this location consists of Precambrian metamorphic schist and gneiss, which has been subsequently intruded (cut through by molten rock) by granitic pegmatite dikes. Unfortunately, one of these thin pegmatite dikes that had intruded into the metamorphic rocks was steeply inclined toward the roadway. When the dike intruded the metamorphic rocks the contact between the two rock types became "baked" and the mineralogy and texture of the rock was changed. This "baked" contact weathered to produce a zone

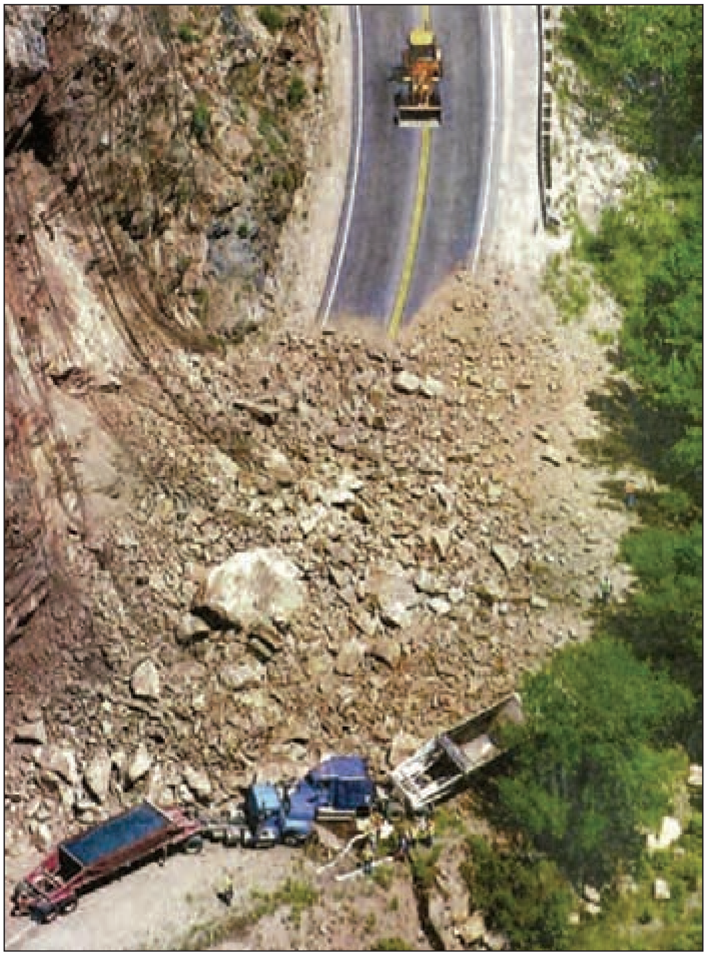


Figure G: Aerial view of the Clear Creek Canyon rockslide. Note how fallen rock pushed the blue and white haul truck across the roadway to hit, head on, with another haul truck (blue and red). Luckily the blue and white truck was not buried and crushed in the debris. Draped wire mesh shown hanging from the outcrop (upper left of photo) was not designed for such a massive rockslide. (Photo courtesy of the Denver Post.)

of clay-rich material. The clayey zone was structurally weak, providing a plane for the rocks above to detach from the underlying rocks and produce this large rock slide (Figure H).

To mitigate the unstable rock slope left after the slide, approximately 35,000 cubic yards of rock had to be excavated by blasting. The slope was laid back to an angle of 45 degrees, and rock reinforcement anchors were installed into the slope to enhance stability (Figure I). Wire mesh was then draped over the slope to help control any small rocks that will inevitably get loose. By the end of August 2005, after the longest full road closure in Colorado's history, the road was reopened to traffic.

Figure H: Oblique aerial photo of rockslide area after clean-up, before stabilization project. Note the overhanging, unstable rock. (Photo by CDOT.)

Figure I: Oblique aerial photo of rockslide area after rock excavation project. (Photo by CDOT.)

Foidel Creek Mine Subsidence Rockslides

A mile long stretch of rockfall-prone land in Colorado is entirely due to human activity! In the coal mining areas of Routt County in north-central Colorado, a technique called "long-wall mining" is often the most economical and preferred method for underground extraction of coal. Depending on thicknesses of the overburden (the rock and soil overlying the coal), long-wall mining and resulting collapse of the mined-out cavern can result in several feet of subsidence at the ground surface. At the Foidel Creek Mine in the mid to late 1990s, long-wall mining was extended below the surface exposure of the Twentymile Sandstone, a 100-foot thick, massively bedded, sandstone cliff that is exposed on the slope above Routt County Road 27. The strain from the ground subsidence fractured and broke almost 1½ miles of the exposed sandstone cliff, which resulted in several large rockfall events with some rock blocks the size of small homes (Figure J). The potential of rockfall was anticipated by the mine operator, the Colorado Division of Reclamation Mining and Safety, and the Colorado Geological Survey. A mile-long span of ditches and berms were constructed on the slope above Routt County Road 27 to mitigate the anticipated rockfall. Individual rock blocks in these rockfalls that rolled to the ditch have been completely contained by this mitigative design.

Figure J: Subsidence of the Foidel Creek Mine resulted in rockfall in the Twentymile Sandstone cliff face. Note rockfall ditch and berm above roadway. (Photo courtesy of Colorado Division of Reclamation, Mining, and Safety.)

Geology Then and Now

Fascinating photographic images documenting the splendor of Colorado were published by John Fielder in two books, *Colorado 1870–2000, Volumes I and II.* In these books, Mr. Fielder located and re-photographed locations and landscapes shown in historic photographs by William Henry Jackson in the 1870s. The photographs convey change over time. One can observe the growth of cities, the abandonment of work camps and mining town, the cutting and regrowth of forests, and the location of new roads and infrastructure; all put in a poignant record with the side-by-side black and white photography of 1870 and Fielder's recent color images. In one pair from Mancos Valley in Southwest Colorado, Fielder, with keen observation, comments on a new addition to a group of very large boulders. These images illustrate that in locations where very large blocks of rock litter a valley beneath steep slopes, they will in time be joined by others through continuing erosion and rockfall.

The Mancos Valley of Southwest Colorado. Top photo by William Jackson circa 1870s; bottom photo by John Fielder© 1999. Note the new rockfall block (right foreground) in the more recent picture.

Paleo-Rockfall

Rockfall has been occurring as long as Earth's crust has existed and is a normal weathering process in mountainous terrain where bedrock is exposed and the ground surface is steep. Geologists find evidence of ancient rockfall and rockslides in the landforms that are formed or sediments that are deposited. During the last ice age (about 16,000 years ago), the flanks of many mountains were steepened by the intense erosive action of hundreds of feet of glacial ice whose grinding and crushing action form the classic U-shape of many alpine valleys. As the glaciers in Colorado's alpine valleys melted, many mountain ridges were weakened by the loss of the lateral support from the glacial ice, and massive rockslides occurred. Boulder fields, rocky talus slopes, and large bulges of broken rock on valley floors remain today and serve as a geologic record of these ancient rockslide events.

One of the more interesting stories involving paleo-rockslides occurred in Glenwood Canyon in west-central Colorado. The incision rate of Glenwood Canyon in the last million years was very rapid as melt waters from several major ice age periods coursed through the canyon, carving the steep-walled gorge through heavily-fractured Precambrian basement rocks. In the last 10,000 years, rockfall from the canyon walls has filled the canyon faster than the Colorado River could remove the debris. Cottonwood Falls, also known as the "Barrel Springs" rapid, is located at the I-70 Shoshone Interchange. This is the location of a large rockslide that geologic evidence indicates fell 10,000 years ago, dammed the Colorado River, and created a lake that filled the entire east end of the canyon. The natural dam was never completely breached and much of it remains today. River gravel, fine-grained lake sediments with organic layers, and rockfall debris from the canyon walls simply filled in the paleo-lake to the point that the river flowed over the top of the rockslide dam, creating the river knickpoint and rapids seen today. The thick, soft, compressive lake sediments buried on the canyon floor, known locally as the "gray layer" by geologists and engineers, created significant engineering challenges for highway construction through the canyon. It was the organic material at the base of the gray layer that was dated at 9,820 (+/- 130) years before present using the carbon-14 radiometric method. Through Glenwood Canyon there are several other smaller ancient rockslides one can see on the canyon floor.

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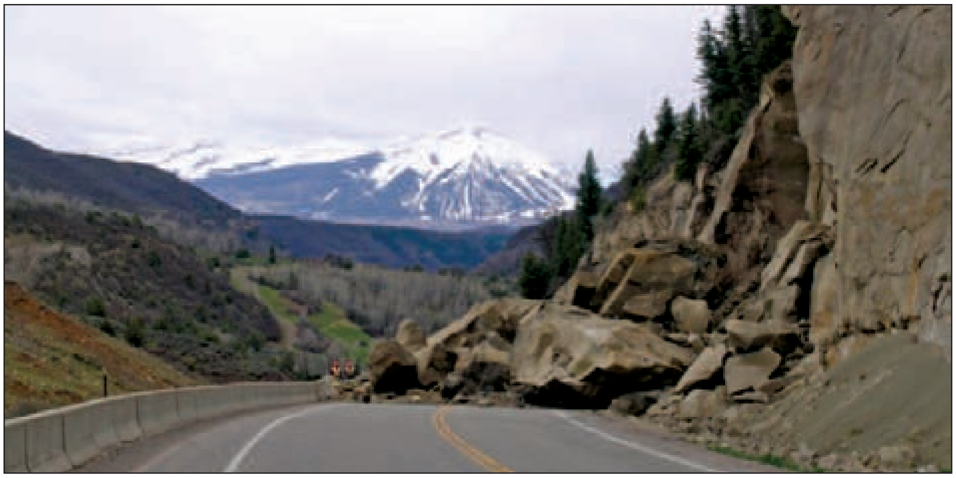
GEOLOGIC HAZARDS AREN'T NECESSARILY ACTIVE ALL THE TIME



Clockwise, from upper left: Rockfall debris on Highway 133 near Paonia that occurred in the spring of 2007 (Photo by Jon White); Large boulder that fell through an apartment in Glenwood Springs in the fall of 2005 (Photo courtesy of the Glenwood Springs Post Independent); Rivers can undercut banks and create rockfall hazards; Large rockslide on Missionary Ridge near Durango that occurred in 1998 (Photo by CDOT); Boulder that fell on a county road in Jefferson County in the spring of 2007 (Photo by Inter-Canyon Fire Department).

ROCKTALK

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