activities. In fact, one feature that is still in the planning stage will serve to benefit them: A rest area located adjacent to the interchange at the top of the pass will provide toilet facilities and parking space at a strategic access point for snowmobiling and cross-country skiing and a trail head for hikers and backpackers. Also included in the architecturally attractive building that will house the toilet facilities will be a sizeable shelter room complete with seats and a large fireplace. The primary source of heat proposed for the buildings is to be solar energy. When excavations for the rest area were in progress, remains of ancient Indian campgrounds were found. An archaeological team recovered a number of Indian artifacts that date back 5000 years or more. It is the intent of the state to put these artifacts on display in the rest-area building as an added attraction.

CONCLUSIONS

The environmental restraints imposed on the design of the Vail Pass project necessitated the development of designs that would ameliorate the adverse environmental consequences so frequently associated with heavy construction. This became a challenge to all members of the team involved in the design and construction efforts. The measures taken on the project generally mitigated the disruption of the terrain in two ways: In some instances the design simply reduced the area affected by substituting a structure for a cut or a fill, and in other cases the terrain was restored by landscaping measures. With the passage of time, the massive construction should have less and less effect.

The measures taken were costly; how costly is hard to assess accurately. It will always be a matter of conjecture whether or not the additional expense was warranted. In my opinion, the extraordinary scenic qualities of the terrain justified the extraordinary measures taken to preserve them.

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Geologic Constraints on the Vail Pass Project

Charles S. Robinson, Charles S. Robinson and Associates, Inc., Golden, Colorado

The complexity of the geology in the Vail Pass area of Colorado and the many engineering problems it presented in the design and construction of I-70 are discussed. Precambrian igneous and metamorphic rocks and Pennsylvanian-Permian sedimentary rocks had been extensively folded and faulted. Glacial and stream erosion and deposition had modified the topography. Large, complex landslides that had developed in bedrock and surficial deposits and that could not be avoided by changes in highway alignment were the major geologic constraints. The engineering solution to the geologic problems and the integration of the engineering solutions with other environmental factors resulted in minimal environmental impact. The Vail Pass route of I-70 can serve as an example of the value of defining the geologic environment in an environmentally complex area and incorporating environmental constraints into the design and construction of a major highway to minimize environmental impact.

The geology of an area and the geologic processes operative within it determine the environment. The modification of this environment for any purpose must consider geology and geologic processes. Minimal environmental impact will occur when engineering design and construction practices are integrated with the geology and the geologic processes of an area. At Vail Pass every effort was made to integrate geology and geologic processes into the design and construction of I-70 in order to ensure a safe highway and minimize environmental impact and highway maintenance.

GENERAL GEOLOGY

I-70 across Vail Pass crosses terrain typical of the geology of the high mountains of Colorado (see Figure 1). The route follows the valleys of Black Gore Creek, which flows north from Vail Pass, and the west fork of Tenmile Creek, which flows south from Vail Pass. These streams flow along the west flank of the Gore Range, a northwest-trending mountain range bordered on the east by the Blue River. The Gore Range is an uplifted block of granite and metamorphic rocks, flanked on either side by sedimentary rocks—chiefly beds of sandstone, siltstone, shale, and some limestone. Figure 2 shows a generalized stratigraphic section of Vail Pass. Figure 3 shows a generalized geologic map of the area.

After the uplift of the Gore Range, the area was subject to glaciation and stream erosion. The deposits related to the glaciation, erosion, and weathering of the rocks are unconsolidated and locally, after their original deposition, slid to form extensive landslide areas. As a result of the extensive faulting of surficial materials and most of the areas of landsliding, the bedrock—with a few notable exceptions—is relatively stable. Construction across these deposits, however, could easily have caused new landslides or activated old landslides.

Previous geologic work done in the area was mostly

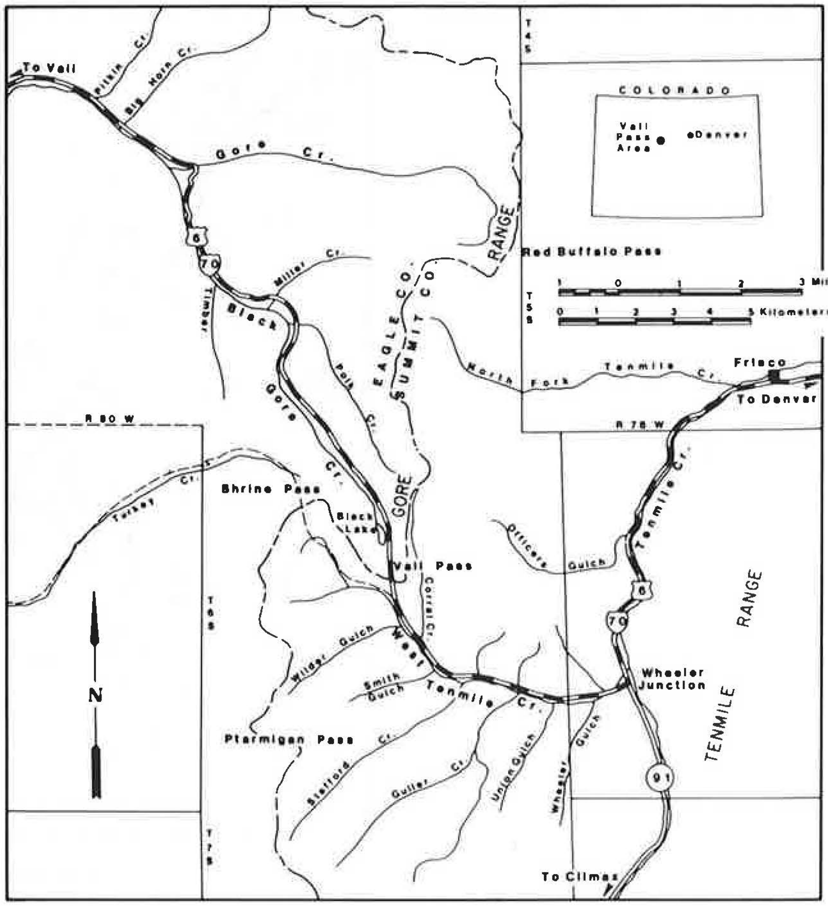


Figure 1. Index map of the Vail Pass area.

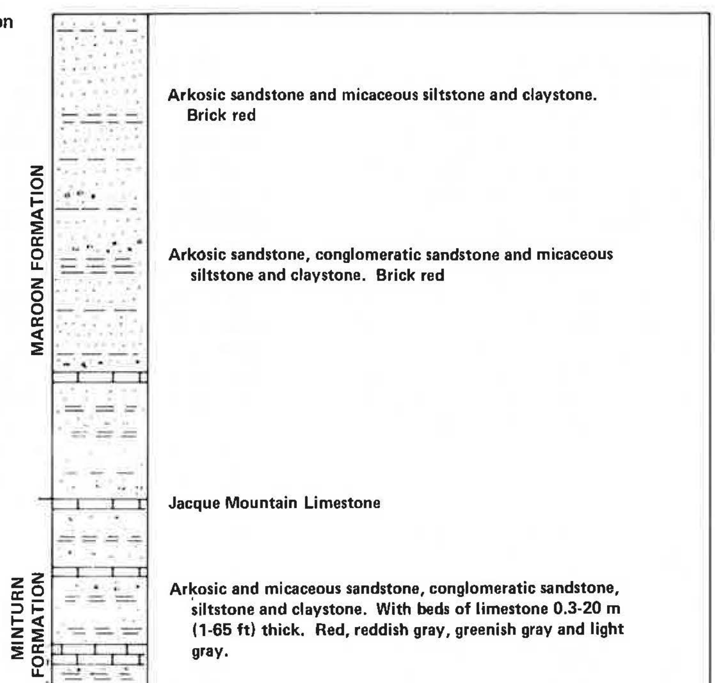
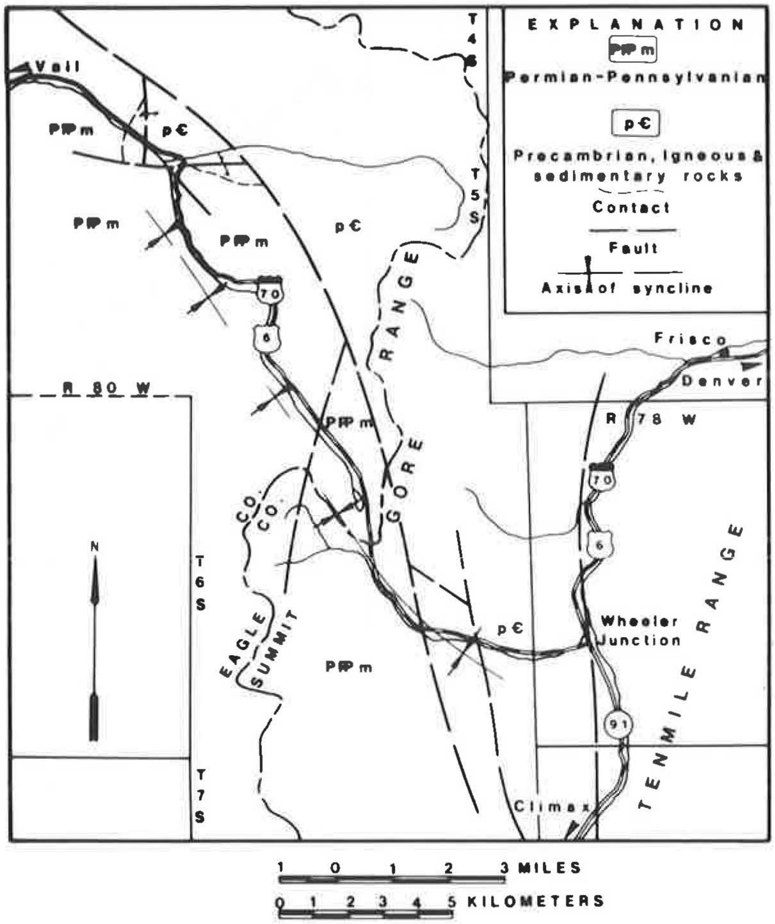


Figure 2. Generalized stratigraphic section of the Vail Pass area.

Figure 3. Generalized geologic map of the Vail Pass area.



general in nature and not specifically for engineering purposes. An exception to that is the work done by Wahlstrom, Warner, and Hornback for the Denver Board of Water Commissioners. They made geologic investigations in connection with proposed water collection, diversion, and storage projects in the vicinity of Miller and Black Gore Creeks, between Black Gore and Gore Creeks, and between Gore and Booth Creeks (Figure 1). Those data have been made available to me. General geologic studies that have included parts of the area of interest are those of Lovering and Tweto (1) on the geology and ore deposits of the Minturn quadrangle, Bergendahl (2,3) on the geology of the Tenmile Range and the Dillon quadrangle, and Tweto (4) on the geology of the Gore Range-Eagles Nest Primitive Area.

GEOLOGIC CONSTRAINTS

The intermediate geologic investigations defined the geologic conditions and processes that were to be considered in the location, design, and construction of I-70 through the Vail Pass area. Active landslides and the potential for reactivating old landslides or creating new landslides were the principal constraints in the location, design, and construction of the highway. The existence of groundwater and groundwater drainage, foundation conditions such as swamp areas, and suitable footings for structures were considered based on the intermediate and subsequent detailed geologic investigations.

LANDSLIDES

Geologic studies of the Vail Pass area showed that more than 50 percent of the alignment of US-6 north of Vail Pass and 10 percent of the alignment south of Vail Pass had been constructed on landslides (see Figure 4). It was recognized that I-70 could not be built across Vail Pass and avoid all the landslide areas. The initial geologic studies and later, more detailed studies were able to define the landslides and their activity, and an alignment was chosen to avoid the more active areas.

The area along the west flank of the Gore Range has long been subject to landsliding. Most of the landslides were not the result of human activity but of geologic processes. Landsliding has occurred in the area before and since glaciation. Most of the older landslides are now stable. The landsliding has involved the bedrock, which constitutes the larger and older of the landslides, and the surficial deposits, which constitute the younger and more active landslides.

Table 1 gives the locations and dimensions of the larger areas of landsliding along the highway alignment.

Bedrock

Large areas of bedrock in the Vail Pass region have failed, forming landslide areas. The failure of the areas of bedrock is related to faulting or to oversteepening of the valley walls as a result of erosion related to glaciation. The landslides in bedrock have involved igneous, metamorphic, and sedimentary rocks.

An area of landsliding in the igneous and metamorphic rocks occurs south of the Gore Creek Campground (see Figure 5). In this area, blocks of bedrock separated by arcuate faults form a series of steps from Gore Creek up the mountain to the south. The slope of the steps is

Figure 4. Map of Vail Pass landslide areas.

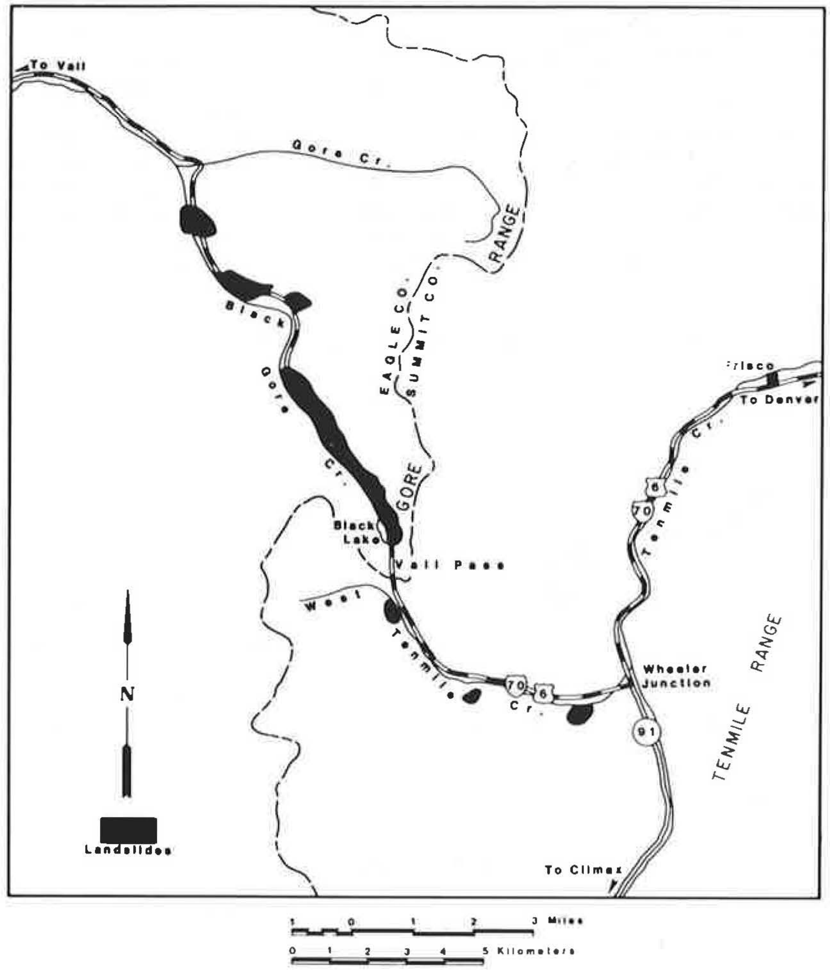


Table 1. Description of major Vail Pass landslide areas.

Approximate Stations	Description
380 to 390	Stabilized landslide in igneous and metamorphic rocks (not outlined as active landslide area)
415 to 440	Bedrock slide of sedimentary rocks with cover of moraine and colluvium; two slides, one on either side of Black Gore Creek
480 to 520	Bedrock slide of sedimentary rocks with cover of rocky colluvium
540 to 560	Surficial slide in moraine and colluvium; older slide with active segments
610 to 675	Bedrock slide of sedimentary rocks with cover of moraine and colluvium
735 to 775	Bedrock slide of sedimentary rocks with cover of moraine and colluvium; very active locally
785 to 800	Bedrock slide of sedimentary rocks with cover of moraine
845 to 855	Bedrock slide of sedimentary rocks with cover of rocky colluvium on alignment of eastbound lane
	Copper Mountain slide; talus material, south of proposed alignments

toward the mountain to the south. Undrained depression or small draws developed at the back of the steps as a result of erosion along the fault or landslide slip plane. The faults or landslide slip planes were formed before glaciation since the outcrops show evidence of glaciation. The southern limit of the steps is a major northeast-trending fault. There is no evidence that there has been any recent movement of the landslide blocks, and the landslide is considered to be stable.

The largest landslides in the Vail Pass area involve bedrock of sedimentary rock. These landslides developed as a result of faulting and the erosion of Black Gore Creek. Most of the sedimentary rock landslides occur on the west or north side of Black Gore Creek north of Vail Pass (Figure 1). Only one landslide in sedimentary rock occurs south of Vail Pass. Most of the bedrock landslides are covered by surficial deposits (see Figure 6). These surficial deposits are also moving locally because of movement in the bedrock or depositional instability. In such areas, landslides are sliding on landslides Most of the areas of sedimentary rock landslides are stable; only locally within an area of a landslide are blocks of bedrock sliding.

The upslope limit of the landslide areas is typically a fault scarp. The faults are generally parallel to the valley and are believed to be related to the Gore Fault to the east of the area (1). The downslope limit of the landslides is Black Gore Creek.

Typical of the areas of sedimentary bedrock landslides are large, undrained depressions that resemble sinkholes in a karst region. These depressions generally have an elongated, elliptical shape. They range from less than 0.5 m (1.6 ft) wide and 2 m (6.5 ft) long to tens of meters wide and hundreds of meters long. Some depressions represent very old movement since they have trees as large as 0.3 m (1 ft) in diameter growing within their limits (Figure 7). Other landslides show, as evidence of recent movement, cracks in the sod in the bottom of the depression. Some of these cracks have been probed to depths of more than 5 m (16 ft).

Blocks of sedimentary rock are exposed in the landslide masses. Some of the blocks are tumbled, but most are about parallel in strike to the beds of the undisturbed bedrock, although the dip is greater. The blocks within a landslide area move different amounts at different times, as the differences in age of the depressions indicate. The blocks of sedimentary rocks are like randomly oriented and shaped wooden shingles on a steep roof; if one shingle is moved, support is removed from one or more other shingles and they also move, which in turn allows others to move until equilibrium is again established.

For the sedimentary rock landslides, Black Gore Creek erodes away a piece of a sedimentary rock block, which allows the block to move toward the stream. Blocks upslope will then move downslope. This process has been going on over a long period of geologic time.

Figure 5. Cross section of bedrock landslide in igneous and metamorphic rock.

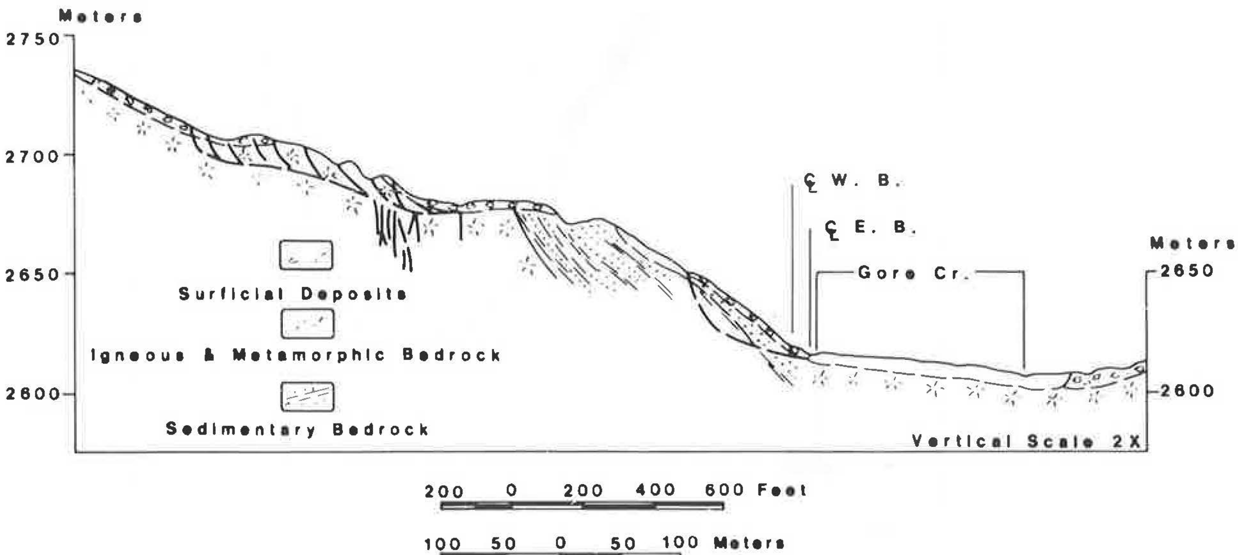
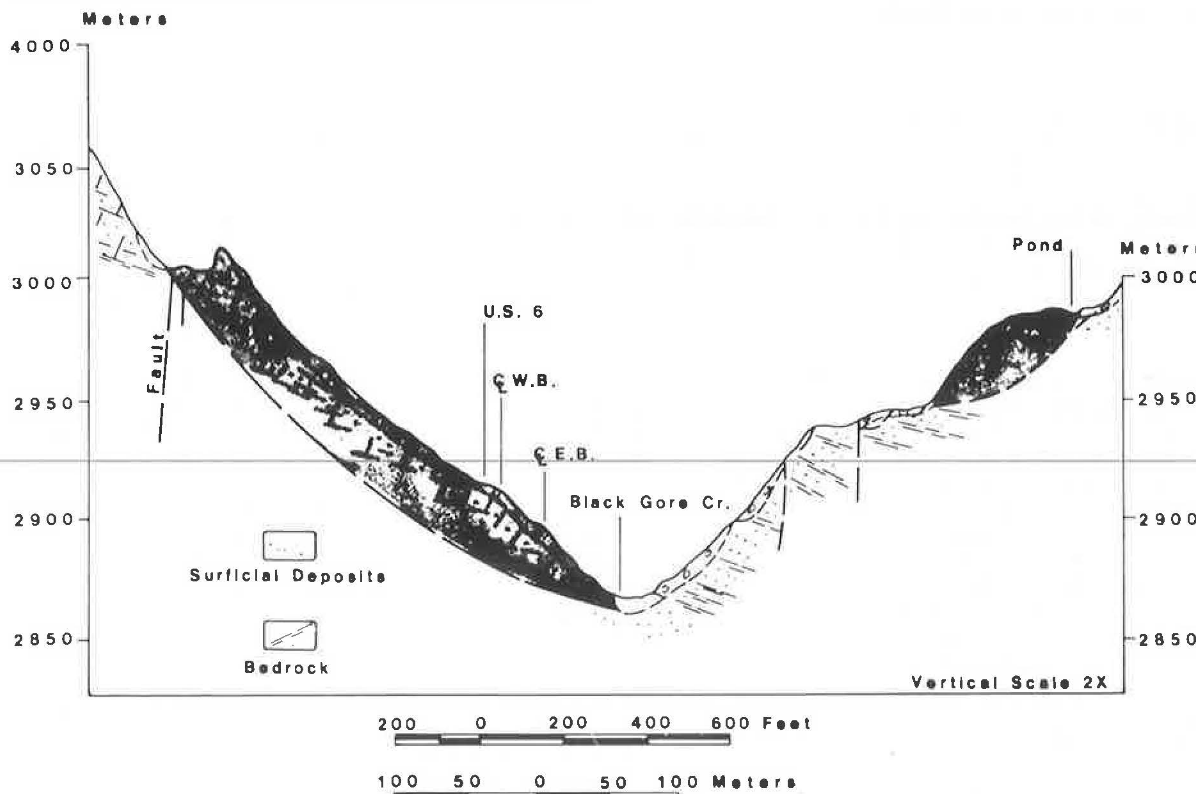


Figure 6. Cross section of bedrock landslide in sedimentary rock.



Because these landslides are composed of blocks of sedimentary rock, and the movement is generally along and about parallel to the bedding, the landslides are not thick. Drilling and the installation of instruments have indicated that the maximum depth of movement in this type of slide ranges from 6 to about 21 m (20-70 ft). Movement does not occur along a single slip plane; rather, there may be several parallel slip planes in a single area of a landslide. Movement occurs along weak bedding planes between beds in a single block of sedimentary rock or between overlapping landslide blocks of sedimentary rock.

Surficial Deposits

Landslides have developed in the surficial deposits on both sides of Vail Pass. The landslides are the result of the deposition or accumulation of surficial deposits on steep bedrock slopes and then the periodic movement of the deposits (Figure 8). Failure has been the result of steepening of the slopes by erosion, by changes in the groundwater regime, or by movement of the bedrock. All types of surficial deposits are involved in landslides, but most of the landslides are found in the moraine or colluvium.

Figure 7. Trees growing in landslide scarp depression.

The scarps of the individual slumped areas are recent. Most indicate movement of the surficial deposits during historic times; many show annual movement. The individual scarps range in length from 1 to about 150 m (3.3-500 ft). They average about 60 m (200 ft) in length. The vertical offset across the scarps ranges from less than a meter to several meters. The abundance of scarps in an area of landslides and their relative short length and small offset indicate that the depth of movement is relatively shallow. Drilling has shown that the individual landslides in the surficial deposits are generally less than 15 m (50 ft) thick.

The individual scarps may represent a single small landslide or an active segment of a large landslide area. The landslide area may be (a) a bedrock landslide in which the scarp represents slumping in the surficial material as a result of movement in the bedrock or (b) a large landslide in the surficial deposits. The individual scarps indicate the active segment of the large landslide.

A landslide in the surficial deposits is the result of the deposition of these deposits on a bedrock slope that was oversteepened by glacial erosion. The deposits were poorly drained at the time of deposition, and many swamps developed. The permeability of the surficial deposits is different in different areas, and numerous springs occur throughout. During much of the year when the surface is not frozen, the deposits are saturated with water. With the spring runoff there is a period of rapid erosion during the time of maximum saturation. This results in minimum stability in a mass of poorly sorted and unconsolidated material on a steep slope, the lower edge of which is at a stream channel. Along Black Gore Creek, downcutting of the creek has not been able to keep up with the movement of the landslides into the valley. The gradient of the creek above the landslides has been lowered and alluvial deposits have formed because the landslides have partially dammed the creek (Figure 9).

Figure 8. Cross section of landslide in surficial deposits.

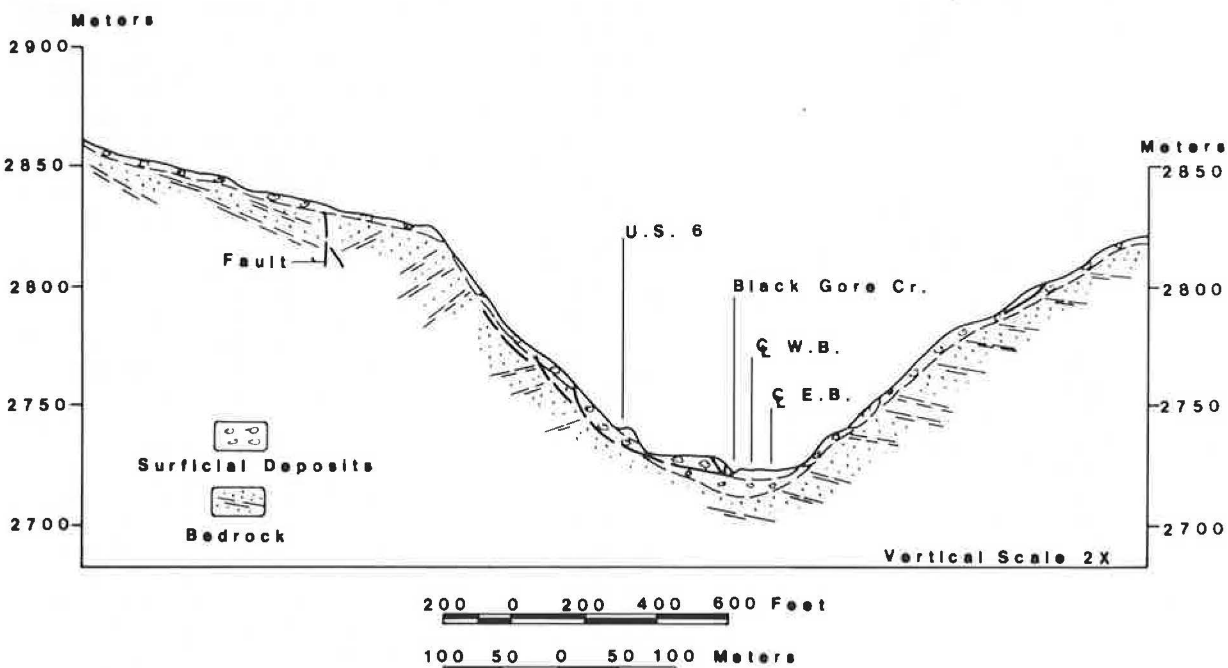


Figure 9. Alluvial deposits as result of damming of stream by landslides.

GROUNDWATER

In the Vail Pass area, snow accumulates to a depth of a meter or more during the winter months (generally November to April). Most of the snow melts in a relatively short time (April to July), and the streams are full from the spring runoff. Precipitation during the summer months is in the form of thundershowers—local, heavy precipitation during a short period of time and heavy runoff. Because of the accumulation of the snow pack, the ground is saturated with water part of each year. The time of total saturation depends on many factors, including source, porosity, permeability, and altitude.

Groundwater occurs in the fractures and the pore space of the bedrock and in the surficial deposits. The fractures and granular pores of the bedrock are probably saturated most of the time but the incidence of fractures and granular porosity in the bedrock is low. Most of the groundwater in the Vail Pass area is in the surficial deposits. Of particular importance is the groundwater in landslide areas.

The occurrence of groundwater was determined by mapping and by the use of drillholes. The locations of swamps and springs were mapped during the geologic investigations. The estimated flows of springs ranged from <1 to 265 L/min (<0.264 to 70 gal/min). The springs occur at the edges of surficial deposits and bedrock outcrops, at the margins of landslide areas, at the heads or toes of slump areas, along draws or stream valleys in surficial deposits where there is a thinning of the deposits, at contacts between different types of surficial deposits, and at the toes of surficial deposits adjacent to the major streams.

FOUNDATION AND SLOPE STABILITY

The foundation and slope stability of the geologic materials of the area was defined by the geologic studies, and this information was considered in the final location, design, and construction of the highway.

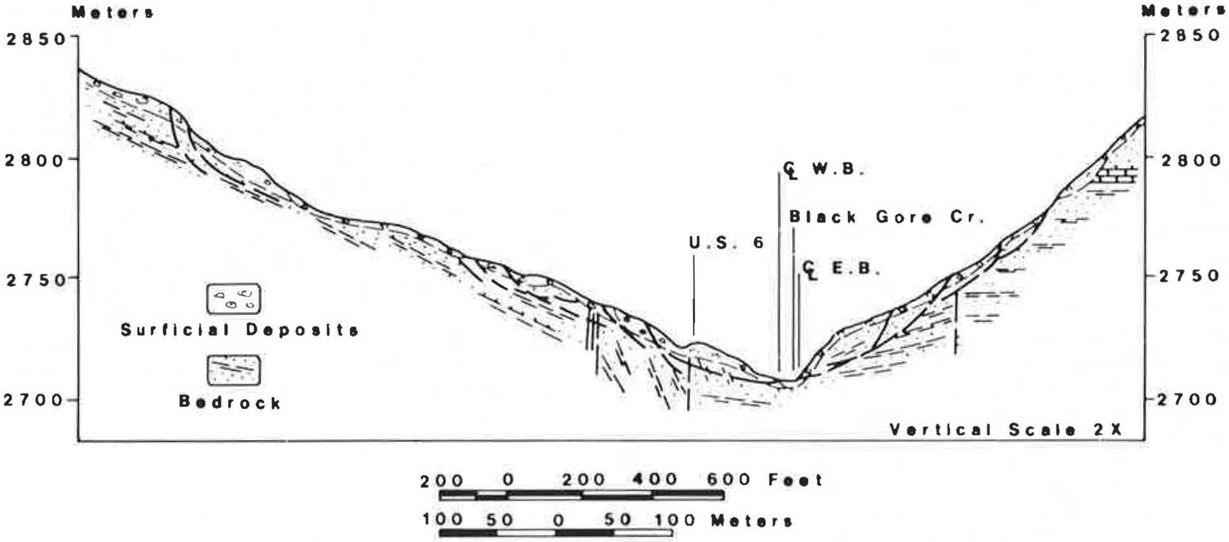
The igneous and metamorphic rocks include gneissic granite and migmatite. The gneissic granite is generally a massive, competent rock. The upper meter or so is rippable, but drilling and blasting were required for major cuts. Cut slopes in the gneissic granite stand vertically except where faults or joint systems approximately parallel the face of the cut. The excavated granite serves as excellent fill. Structures were founded on unfaulted and unaltered granite. Groundwater occurs in the faults and joints. In the placement of fill or the founding of structures on the gneissic granite, care was taken to ensure that the movement of groundwater through the fractures toward the streams was not impeded.

The migmatite is less competent than the gneissic granite because of the variation in composition of the layers. The biotite-rich layers, because of their micaceous structure, are weak compared with the granitic layers. Much of the migmatite is rippable. Drilling and blasting were required in some cuts where a high percentage of the rock was granite. The principal direction of weakness in the migmatite is the foliation. The rock is also jointed and locally faulted. Cut slopes in the migmatite were designed to the angle of dip of the foliation or the joint set that most closely parallels the direction of the cut. The migmatite excavated into tabular blocks, the longer dimensions of which paralleled the foliation.

The sedimentary rocks include a wide variety of lithologic types. These, in order of abundance, are sandstone, siltstone, shale, and limestone. The engineering characteristics of the sedimentary rocks are chiefly dependent on the grain size of the sand, the percentage of clay, and the structure. Sandstone constitutes about 75 percent of the sedimentary bedrock. The other types of clastic sedimentary rocks are interbedded and gradational with the sandstone. The sandstone is typically medium to coarse grained, conglomeratic [with pebbles of igneous or metamorphic rock to 0.15 m (6 in)], arkosic, micaceous, and poorly sorted. The rock is generally friable; calcium carbonate cementation does occur at the base of some beds. The typical sandstone grades into fine-grained sandstone and siltstone, which are micaceous and clayey and, in turn, grade into sandy and silty micaceous claystone or shale. Beds of limestone up to 10 m (30 ft) thick occur in the vicinity of stations 380 to 385 and stations 560 to 570.

The sedimentary rocks are generally massive, competent rocks. The rock is rippable at most locations but required drilling and blasting in high rock cuts. The design of cuts was dependent on the structure. The sedimentary rocks are jointed, and these joints form generally widely spaced sets [>0.5 m (>1.6 ft)]. Most joints are about vertical, and vertical cuts are possible. The alignment of the cuts was determined by the strike of the joint sets. Most cuts in sedimentary rocks ravel with time. The sedimentary rocks contain a small percentage of montmorillonite clay, which expands and contracts with changes in humidity and temperature. As a result, the rocks are repeatedly stressed, and small pieces work loose. The siltstone and shale beds, which contain a higher percentage of clay, ravel more, and overlying sandstone beds are undercut, which allows joint blocks of

Figure 10. Cross section through abutting landslides.



sandstone to fall. The sedimentary rock serves as excellent fill if properly placed. Structures on the sedimentary rock were founded on the massive sandstone or limestone beds. In the placement of fill on the sedimentary rock, particular attention was paid to the direction of the dip and to groundwater drainage.

The surficial deposits of the area include a wide variety of materials that have resulted from weathering of bedrock in place (colluvial deposits), transport and deposition by streams (alluvial deposits), transport and deposition by glaciers (morainal deposits), and residual deposits including terrace deposits, swamp deposits, and boulder trains.

Construction on the colluvial deposits presented problems. The deposits were at their natural angle of repose and, locally, were moving, if very slowly. Cut slopes of 1:1 in the dry material were possible, but allowance was made for continued raveling. The slopes ravel regardless of the angle if they are steeper than the natural slope because of continuing movement in the slope. Where the colluvial deposits were saturated with water, slopes of 2:1 or 3:1—depending on the average size of the rock fragments, the percentage of clay, and the height of the cut—were required for a relatively stable slope. In the maintenance of slopes, drainage was an important consideration, particularly in the colluvium derived from the sedimentary rocks that contain a relatively high percentage of clay.

The morainal deposits were also at their natural angle of repose, and cut slopes steeper than this angle would cause raveling and local failure. Slopes of 1:1 were relatively stable except for continued minor raveling in the dry morainal material derived from the igneous and sedimentary rock. Maximum slopes of 1.5:1 in the dry morainal material derived from the sedimentary rocks were relatively stable. When wet or subject to saturation, slopes of 2:1 or 3:1 would ravel and slump locally in either type of morainal material if they were not protected or planted. The control of drainage was important in the maintenance of stable cut slopes.

Construction on the alluvial deposits presented a few problems. The alluvial deposits in the major stream valleys had a limited bearing capacity. Test drilling and sampling were required to determine the suitability of these materials for footings for structures. Cuts intersected the toes of alluvial fans at the margins of the larger stream valleys. Most of these alluvial fans consisted of well-sorted and stratified granular materials that were saturated with groundwater. With adequate drainage control, slopes in these materials were stable at 1:1. Some raveling would be expected except that most of the slopes were laid back (flattened) and planted.

Classified as residual deposits were terrace deposits, swamp deposits, and boulder trains. The terrace deposits were characteristic of the alluvial deposits and presented similar problems in construction. The swamp deposits, which consist mostly of organic, rich, fine sand, silt, and clay, range from <0.1 to 3 m (<0.3-10 ft) in thickness. The swamp deposits were not suitable for use except as topsoil. These deposits were removed, and adequate drainage was developed before the placement of fill across a swampy area. The boulder-trains deposits range in thickness from 1 to 15 m (0.3-50 ft). Cuts through the boulder trains revealed a concentration of the finer material at depth. With adequate drainage, slopes of 1:1 were stable in the boulder trains.

ENGINEERING SOLUTIONS

The geologic environment and constraints were defined by the intermediate and detailed geologic investigations. These data were then integrated with the other environmental factors and constraints, and a preliminary alignment and design were established. This was chiefly the responsibility of International Engineering Company, with whom Charles S. Robinson and Associates worked closely.

It was not possible to avoid all landslide areas and still maintain highway standards. The studies, including the instrumentation, had indicated the landslide areas that were the most active and those that were relatively stable. The highway was designed to avoid the more active landslides. Where the highway crossed older landslides, the lanes were separated as far as possible in conformity with the requirements of standards for line and grade. The separation of the lanes allowed the height of cuts and fills to be held to a minimum. In several landslide areas, groundwater drainage was increased by drilling horizontal drains well below the level of the highway and the fills. The drainage across the old landslides was improved and carefully controlled to reduce infiltration into the landslide mass.

One landslide area was located between stations 415 and 425 (see Figure 10). Active bedrock landslides from either side of Black Gore Creek had their toes in the creek. The landslides on either side of the creek were instrumented, and their movement was monitored. The maximum movement occurred during the period of high groundwater levels, i.e., spring runoff. The solution to the stabilization of these two landslides was to fill the valley, transferring the thrust of one landslide against the other and putting the stream and the highway on the valley fill.

Slope stability was maintained by careful design of back slopes. The eastbound and westbound lanes were separated where space, line, and grade allowed, and the heights of back slopes and fills were kept to a minimum. Slopes in surficial material were laid back as far as was practical, contoured, covered with topsoil, and seeded. Particular care was taken to control surface and groundwater drainage on all cut-and-fill slopes. On bedrock slopes, the different types of material were treated differently depending on their ability to stand. The slopes in more competent units approached vertical, whereas those in less competent units were laid back and often seeded. The natural breakage of the rock—e.g., along joints—was followed, and the back slopes in bedrock conform in appearance to natural rock slopes.

One area of slope stability that was of particular concern was that between Gore and Bighorn Creeks. Along the alignment were surficial deposits, mostly glacial moraine, on Precambrian igneous rock. The surficial deposits were at their maximum angle of repose and were saturated with groundwater during most of the year. The choices for the placement of the highway were restricted by the presence of privately owned lands in the valley. Cuts in this area could have caused major slope failure. The solution was to put much of the highway on a structure.

ACKNOWLEDGMENT

In 1969, the Colorado Division of Highways entered into a contract with Charles S. Robinson and Associates, Inc., engineering geologists, and R.V. Lord and Associates, soils and foundation engineers, for an intermediate geologic study of the Vail Pass area. After completion of the geologic study in 1971, Charles S. Robinson and Associates were retained to work with International Engineering Company in the environmental studies of the Vail Pass area.

The geologic problems in the Vail Pass area were first recognized by R.K. Barrett of the Colorado Division of Highways (5). His report on the geology was the basis for the contract with Charles S. Robinson and Associates. The field investigations were conducted by Charles S. Robinson and Dale M. Cochran of Charles S. Robinson and Associates with the assistance of Gary T. Whitt of R.V. Lord and Associates. The contract was conducted under the supervision of Richard A. Prosence and Robert K. Barrett.

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U.S. Forest Service Involvement in and Overview of the Vail Pass Project

Charles H. Miller, U.S. Forest Service, Glenwood Springs, Colorado

The Vail Pass segment of I-70 was constructed across public land administered by the U.S. Forest Service. As the land-management agency, the Forest Service was responsible for ensuring that the construction would neither disrupt nor destroy the land's resources. The Forest Service carried out this responsibility by issuing environmental constraints for the construction, reviewing the construction plans and specifications in relation to these constraints, and periodically reviewing the construction work. A liaison officer was assigned to the project who, with the help of specialists, expressed the concerns of the Forest Service. This group assisted the Colorado Department of Highways in minimizing or eliminating the adverse environmental impacts caused by the construction of a highway to the standards of the Interstate system. Unique and innovative solutions to many sensitive environmental problems generated by the highway construction were found and applied through the effort and cooperation of many professionals and agencies. The result is an Interstate highway that lies lightly on the land and is compatible with the surrounding mountain environment.

The Forest Service of the U.S. Department of Agriculture is responsible for management of the national forests. This includes authorizing both occupancy and construction activities in these areas. This responsibility is carried out by issuing "stipulations" for the conduct of the work, reviewing the construction plans and specifications in relation to these stipulations, and periodically reviewing the work in progress. A right-of-way or ease-