GEOLOGIC MAP OF THE VAIL EAST QUADRANGLE, EAGLE COUNTY, COLORADO

By **Karl S. Kellogg, Bruce Bryant, and Margaret H. Redsteer**

Pamphlet to accompany
Miscellaneous Field Studies Map MF-2375
2003

U.S. Department of the Interior
U.S. Geological Survey

INTRODUCTION

The urban corridor along Interstate Highway 70, between Dillon and Grand Junction in Colorado, is one of the fastest growing areas in the State. The city of Vail, in particular, has undergone tremendous growth since 1962, the year of its founding. This rapid growth has required a new level of understanding concerning the geologic hazards inherent to a mountainous region, such as landslides, rockfalls, flooding, and snow avalanches. This geologic map of the Vail East quadrangle was completed in order to acquire an in-depth awareness of both the bedrock and surficial geology, as well as the geologic hazards, so that informed decisions can be made governing the growth of the Vail region.

Due to constraints in time and funding, ground-based mapping of the Vail East quadrangle was confined to the region southwest of the Gore Range drainage divide, which marks the boundary between Summit and Eagle Counties. East of the divide, surficial deposits and prominent fracture zones were mapped from aerial photographs, facilitated because much of this area is above timberline and the exposures are excellent. Most of the prominent fractures are faults, although without close examination of each fault or fracture zone, it is difficult to determine if there was significant displacement across them. Differences in the fracture pattern shown here and on published maps for both the Gore Range-Eagles Nest Primitive Area (Tweto and others, 1970) and the Minturn 15-minute quadrangle (Tweto and Lovering, 1977) are due to: (1) availability of a more accurate and larger-scale topographic basemap, (2) use of current, color aerial photographs (scale approximately 1:30,000), (3) use of a photogrammetric plotter to accurately transfer information on the photographs to the basemap, and (4) differences in judgement as to which fractures are more prominent. Most of the fieldwork for the Minturn 15-minute quadrangle (Tweto and Lovering, 1977) was done in 1942.

East of the Gore Range divide, attitudes in the Proterozoic rocks and contacts between rock units were obtained from the published maps (Tweto and others, 1970; Tweto and Lovering, 1977) and from notes taken during fieldwork for the Gore Range-Eagles Nest study (Bruce Bryant, unpub. data, 1969). In places west of the divide, observations made by the authors were supplemented by data from these earlier sources.

DESCRIPTION OF MAP UNITS

s	**Snowfield (latest Holocene)**—Larger snowfields (longest dimension greater than about 100 m) in higher cirques, mostly on eastern side of the Gore Range divide. Determined from aerial photographs taken September 11, 1983
af	**Artificial fill (latest Holocene)**—Compacted and uncompacted rock fragments, sand, silt, and clay derived from excavation for Interstate Highway 70. Composes roadbed and embankments along and adjacent to the Highway
Qa	**Alluvium (Holocene)**—Unconsolidated gravel, sand, and silt in lenses; composed of moderately sorted to well-sorted, stratified, clast-supported gray to tan sediment in channel and overbank deposits of the Gore Creek flood plain. Clasts are as long as about 2 m; clasts longer than about 10 cm are moderately rounded to well rounded. Clasts predominantly Proterozoic granite and gneiss; clasts of sandstone and conglomerate of the Minturn Formation appear downstream of intersection of Interstate 70 and Gore Creek; percentage of sedimentary rocks increases steadily downstream from this intersection. Alluvium mapped only along Gore Creek, although narrow, unmapped areas of alluvium underlie all stream channels. Maximum height of unit above Gore Creek about 3 m. Maximum thickness unknown, but probably greater than 10 m
Qlsy	**Recent landslide deposits (Holocene)**—Mostly unsorted, unstratified debris deposited by recent and potentially still-active landslides. Deposits commonly have hummocky topography. Some landslide scars are partially vegetated to unvegetated and indicate landsliding less than several tens of years old. One large earthflow 4 km east of lower Spraddle Creek, undercut by construction of Interstate Highway 70, is currently failing by a combination of deep rotation and shallow soil slumping (Jurich and Miller, 1987); this slide may be as thick as 40 m. Two other smaller recent landslide deposits mapped in southwest part of quadrangle probably less than 20 m thick

Qf **Fan deposits (Holocene and upper Pleistocene)**—Moderately well sorted to poorly sorted, tan to grayish-brown, stratified, sand to boulder gravel in fan-shaped deposits; sand matrix. Deposits are both clast and matrix supported, suggesting deposition by both alluvial and debris-flow processes. Clasts mostly subangular to subrounded and long dimension as much as about 2 m; most are considerably smaller. Deposited by side streams near where they join Gore Creek. Also mapped locally along Bighorn, Pitkin, and Booth Creeks. Include minor sheetwash deposits. All fan deposits grade to present stream level and probably began forming soon after deglaciation in late Pleistocene. As much as 15 m thick

Qt **Talus (Holocene and upper Pleistocene)**—Angular and subangular cobbles and boulders forming angle-of-repose deposits below steep valley walls or cliffs. Sandy matrix rarely exposed at surface. Boulders generally are as large as 2 m; in places as large as 10 m. All talus deposits are on valley walls previously occupied by Pinedale glaciers, so talus is as old as late Pleistocene. Talus forms more infrequently below Paleozoic units as compared to Proterozoic units because the former weathers into sand, silt, and clay which readily form colluvium (unit Qc) rather than talus. As much as 20 m thick

Qdf **Debris-flow deposits (Holocene and upper Pleistocene)**—Poorly sorted, poorly stratified, grayish-brown to tan deposits containing clasts as long as 2 m; composed entirely of Proterozoic crystalline rocks. Matrix not well exposed. Mapped at two localities, one in Pitkin Creek and the other in upper Gore Creek. Deposits form below gulleys and grade to streams in valleys previously occupied by Pinedale glaciers. As thick as 30 m

Qr **Rock-glacier deposits (Holocene and upper Pleistocene)**—Hummocky, lobate deposits of angular boulders and smaller clasts having a frontal slope near the angle of repose; locally active, indicating ice core. In places, grade into and include some talus (unit Qt) in their headward region. Form arcuate ridges in terminal area. Rock glaciers form in high cirques mostly east of Gore Range drainage divide, above about 12,000 ft (3,650 m) altitude, and extend as far as about 1 km from cirque headwall. Maximum thickness about 25 m

Qw **Wetland deposits (Holocene and upper Pleistocene)**—Dark-brown to black, organic-rich sediment (mostly silt and clay) in wetlands that commonly contain standing water and a variety of grasses and sedges. Below timberline (about 3,500 m altitude), commonly contain dense stands of willows. Maximum thickness estimated to be about 10 m

Qac **Alluvium and colluvium, undivided (Holocene and upper Pleistocene)**—Alluvium composed of unconsolidated, poorly to moderately sorted silt to boulder gravel in narrow channels that are too small to map separately. Alluvium is flanked by colluvial deposits composed of mostly poorly sorted, angular clasts, with longest axis typically as great as one meter, in a fine-grained weathered matrix as fine as clay that was derived from weathering of bedrock and transported directly downslope. Colluvium locally mantled by loess and contains a soil profile characterized by an “A” horizon that is typically 2-10 cm thick and a “B” horizon typically 5-20 cm thick that displays prismatic structures, indicating clay buildup. Generally less than 10 m thick

Qc **Colluvium (Holocene and upper Pleistocene)**—Unconsolidated to slightly indurated, mostly non-stratified, dark-brown to light-gray-brown deposits that mantle surfaces that slope less than about 50 degrees; rock clasts and fine-grained material are mixed by downslope movement. Contains angular pebbles, cobbles, and boulders derived from weathering of bedrock. Locally overlain by loess, as thick as about 50 cm, composed of very fine grained eolian sand, silt, and minor clay. Soil development characterized by an “A” horizon that is typically 2-10 cm thick and a “B” horizon typically 5-20 cm thick that displays prismatic structures, indicating clay buildup. Includes sheetwash and some landslides on slopes and minor alluvium in small channels. Commonly underlies areas covered by open meadows, sagebrush, and (or) aspen groves. Smaller colluvial areas are unmapped, particularly where unit is thin and discontinuous. Maximum thickness probably less than 15 m

Qls **Landslide deposits (Holocene and upper Pleistocene)**—Range from chaotically arranged debris to almost intact slump blocks of bedrock. Includes earth slides, earth flows, rock slides, and debris slides (Cruden and Varnes, 1996). Surface of deposits commonly hummocky, and relatively steep breakaway zone identifiable. The middle member of the Minturn Formation (unit ℙmm) is particularly susceptible to sliding (mostly earth and rock flows), although slides may occur in most units where oversteepening has destabilized slopes. Larger landslide deposits may be as thick as 60 m

Qfm **Felsenmeer (Holocene and Pleistocene)**—Deposits of angular blocks as long as about 3 m composed of Early Proterozoic gneiss or granitic rock. Formed by periglacial processes (largely freeze-thaw wedging) in non-glaciated areas of alpine zones above about 3,600 m. Active during Pleistocene periods of glaciation with minor felsenmeer formation probably extending into Holocene. At surface, blocks commonly have open spaces between them or contain a dark-brown gravelly soil that is a combination of material derived from mechanical weathering and eolian silt (loess). Composition of blocks same as immediately underlying bedrock. Mapped at two localities near eastern border of quadrangle, just north of Bighorn Creek. Smaller, unmapped areas of felsenmeer are common along some high ridges. Thickness probably less than 5 m

Qbf **Boulder field (upper Pleistocene?)**—Hummocky deposits of angular boulders of Proterozoic granite as long as 4 m (most less than 2 m) over large, horizontal to gently sloping area in Pitkin Creek valley. Matrix is absent at most places at surface, where deposit is devoid of vegetation; locally contains dark-brown silty matrix which hosts grass and small trees. Up-valley end is at distal end of landslide deposit on east side of Pitkin Creek valley. Near-horizontal attitude of deposit is enigmatic; preferred interpretation is that deposit formed as rock avalanche that flowed across glacier of late-Pinedale glaciation. Thickness probably less than 20 m

Qtp **Pinedale Till (upper Pleistocene)**—Unsorted and unstratified bouldery till that generally has hummocky topography. Commonly containing closed depressions and small ponds. In Gore Creek valley, however, development has altered many of these features. Subrounded to subangular clasts are matrix supported and composed mostly of Proterozoic gneiss and plutonic rocks; in Gore Creek and Middle Creek valleys, till contains small percentage of clastic and carbonate rocks of the Minturn and (or) Maroon Formations. Matrix light tan and sandy. Soil contains an “A” horizon less than about 5 cm thick and a “B” horizon that is poorly developed with little or no clay buildup; boulders are generally unweathered. Glacier of Gore Creek valley fed by ice caps in Vail Pass area, less than 12 km southeast of quadrangle, and large cirque less than 7 km east of quadrangle. The glacier flowed down Gore Creek valley to be joined by other glaciers on the south flank of the Gore Range. The terminus of the Pinedale glacier is indistinct, but believed to terminate about 3 km west of quadrangle (Scott and others, 2001). Age of Pinedale deposits in type area in Wyoming is 16-23 ka (Chadwick and others, 1997). Mapped as high as 300 m above present stream level in Gore Creek valley. Thickness at some places as much as about 30 m

Qtb **Bull Lake Till (middle Pleistocene)**—Unsorted and unstratified bouldery till that has been dissected; hummocky topography rarely preserved. Subrounded to subangular clasts as long as about 4 m are matrix supported and composed mostly of Precambrian gneiss and granitic rocks; south of Gore fault, locally contains clasts of sandstone, conglomerate, or limestone of Minturn Formation. Boulders of Proterozoic gneiss and plutonic rock have weathered rinds. Soil in Bull Lake Till contains an uppermost black, organic-rich zone (“A” horizon), typically 2-10 cm thick, that contains a component of eolian silt (loess). The “A” horizon overlies a pale-colored elutriation zone (“E” horizon), typically 5-20 cm thick, in which clay and iron have been leached. The “E” horizon overlies an orange-brown zone (“B” horizon), typically 20-50 cm thick, of clay and iron accumulation. The “B” horizon overlies unweathered till (“C” horizon). Small areas of alluvium and colluvium may locally overlie unit. Terminus of Bull Lake glacier about 6 km west of quadrangle boundary (Tweto and Lovering, 1977). Age of Bull Lake glaciation in type area in Wyoming is 95 ka to >130 ka (Chadwick and others, 1997). Mapped on flanks or ridges adjacent to Gore Creek as high as 425 m above present stream level. Lower reaches covered by Pinedale Till. Thickness may locally exceed 30 m

Qd **Diamicton (middle to lower Pleistocene)**—Red-brown to brown, mostly deeply weathered, bouldery deposits in which clasts composed entirely of Proterozoic crystalline rocks are commonly weathered and soft. Matrix generally poorly exposed and well indurated and clayey. Includes deposits previously mapped as Bull Lake Till and, on ridge between Gore and Bighorn Creeks, as high as 3,500 m (11,500 ft), as pre-Bull Lake till (Tweto and Lovering, 1977). However, glacial deposits this high, 900 m above present stream level, with glacial terminus glacier about 15 km to the west, brings into question whether all these high-level deposits are till (P.E. Carrara, written commun., 2001). In addition, two other deposits in quadrangle previously mapped as pre-Bull Lake till (Tweto and Lovering, 1977), near Spraddle Creek and in southwestern corner of quadrangle, contain only locally derived clasts and clearly are colluvium (Qc), which suggests other areas previously mapped as pre-Bull Lake till should instead be mapped as diamicton. Maximum estimated thickness about 30 m

Ti **Dike rocks of intermediate to felsic composition (Tertiary?)**—Dikes are steeply dipping and mostly strike north to northwest. Only one dike, in northwest part of quadrangle, was analyzed in detail. This dike dips steeply, trends northwest, and is as wide as 15 m. The rock is massive, fine grained, pinkish gray, containing about 15 percent pink, subhedral potassic-feldspar phenocrysts as long as 1.5 cm; 5 percent gray, rounded quartz phenocrysts as long as 3 mm; and about 4 percent fine-grained biotite-rich clots as long as 4 mm. The matrix contains 20-30 percent quartz, 30-40 percent altered (sausseritized) sodic plagioclase, 30-40 percent microcline, 2 percent muscovite, 2 percent biotite, 2-3 percent opaque minerals, and a trace of garnet. The rock is strongly sausseritized and weathers reddish brown. The analysis indicates the rock is an altered, fine-grained monzogranite porphyry (Streckeisen, 1976). The dike intrudes along a northwest-striking fault, parallel to faults or shear zones that were recurrently active since at least late Paleozoic time, so the age of the dike is problematic. Tweto and Lovering (1977) suggested that dacitic to latitic dikes in the map area are related to the Green Mountain intrusive center, about 10 km northeast of the quadrangle's northeast corner. A sanidine ^{40}Ar/^{39}Ar age of 31.51+.08 Ma was determined for the intrusive center (M. Kunk, written commun., 2000)

Pℙm **Maroon Formation (Lower Permian to Middle Pennsylvanian)**—Grayish-red, pale-reddish-brown, and orange-red, coarse-grained to medium-grained, micaceous, calcareous sandstone, muddy sandstone, pebbly to cobbly sandstone, and conglomerate. Contains minor lenses of red shale and shaly limestone. Some finer-grained beds are gray-green. Pebbles and cobbles are commonly quartz and granite; less commonly granite pegmatite, and rarely biotite schist and gneiss. Cobbles are subrounded and as much as 10 cm in diameter. On outcrop capping unnamed peak near southern border of quadrangle, basal 10 m are mostly red, micaceous, locally cross-bedded sandy shale in beds 1-10 cm thick. About 40 m above base at this locality unit contains an approximately 10-m-thick, cross-bedded, ledge-forming pebbly arkosic sandstone bed; pebbles include limestone and chert. Regionally, the formation coarsens and thins significantly eastward. Locally separated from unconformity above Jacque Mountain Limestone Member of the Minturn Formation (ℙmj) by an unconformity. About 750 m of section exposed along west border of quadrangle; top of unit not exposed in quadrangle

ℙm **Minturn Formation, undifferentiated (Middle Pennsylvanian)**—Gray, pale-greenish-gray, yellowish-gray, grayish-red, pale-red, and pale-gray calcareous, arkosic sandstone, siltstone, pebbly sandstone, conglomerate, and scattered beds of gray, marine limestone. About 950-1,275 m of upper part of Minturn Formation is exposed in quadrangle. Type section, about 9.5 km south of southwestern corner of quadrangle, is 1,923 m thick

ℙmj **Jacque Mountain Limestone Member**—Pale to medium-gray stylolitic limestone, sandy limestone, and calcareous sandstone. Gray, locally mottled pinkish-gray, fine-grained to medium-grained, fossiliferous, tabular-bedded stylolitic limestone, sandy limestone, and calcareous sandstone. Locally oolitic. Beds 5 cm to 2 m thick; bedding thickness decreases upward. Conformably overlies clastic rocks of upper sandstone and conglomerate member of Minturn Formation (ℙmu). Weathers to pale gray to medium gray and in places forms prominent ledges. Locally removed by erosion before deposition of overlying Maroon Formation. Forms the marker bed that defines the top of the Minturn Formation. Thickness 6-8 m (compared to 9 m at type section)

ℙmu	**Upper sandstone and conglomerate member**—Mostly orange-red to maroon, arkosic conglomerate, sandstone, siltstone, and shale. Color locally greenish-gray, especially in finer grained horizons. Beds typically 1-10 m thick and lenticular so that lateral extent is limited. Cross bedding and channel fill common. Coarser grained, thicker beds commonly form ledgy outcrops on hillsides. Clasts are moderately rounded to well-rounded, as long as about 30 cm, and consist of quartz, chert, Proterozoic felsic plutonic rocks (including pegmatite), and rare mafic plutonic rock. Silty and shaly beds are micaceous. Equivalent to clastic unit H of Tweto and Lovering (1977). Thickness south of Gore Creek about 235 m (compared to 293 m at type section)
ℙmwq	**White Quail Limestone Member**—Mostly gray, fine-grained limestone in beds 1 cm to 5 m thick; massive within each bed. Weathers pale yellowish brown to medium gray. Prominent ledge-forming unit. Not identified west of Middle Creek. About 10 m thick (compared to 15 m at type section)
ℙmm	**Middle member**—Pinkish-gray, grayish-brown, gray-green, and mottled maroon and gray-green arkosic conglomerate, sandstone, siltstone, and shale; more reddish hues nearer top. Fewer conglomeratic beds than in upper member and clast sizes smaller (generally less than 5 cm). About 50 m below top of middle member, a ledgy, dark-gray, locally sandy limestone bed as thick as about 10 m is correlated with Elk Ridge Limestone Member of Tweto and Lovering (1977). This limestone bed is thinly laminated in upper 4 m, massive in lower 6 m. Lower part of middle member contains flaggy, brown, medium-grained arkosic, micaceous sandstone containing about 20 percent interbedded dark-gray micaceous fissile shale; this sandstone and shale sequence weathers light brown. Middle member correlates with clastic unit G of Elk Ridge Limestone Member, and clastic unit F of Minturn Formation of Tweto and Lovering (1977). Thickness south of Gore Creek about 235-300 m; thins north of Gore Creek to about 50 m. Unit is 218 m at type section
ℙmml	**Individual limestone bed—Generally cliff-forming and greater than 3 m thick**
ℙmr	**Robinson Limestone Member**—Consists of at least four sequences, each as thick as 20 m, of gray to yellowish-gray, fine-grained to medium-grained, locally fossiliferous, medium-bedded to thick-bedded marine limestone and dolomitic limestone. Each carbonate sequence is interbedded with pinkish-tan and light-tan, cross-bedded, arkosic, micaceous pebbly sandstone and light-grayish-pink sandy siltstone and shale. The ratio of carbonate to clastic rocks is about 1:2.5. Most limestone and dolomitic limestone beds are 0.5 cm to 2 m thick; many of the beds extend for several kilometers. The lower 18-m-thick, gray-weathering limestone contains distinctive laminated, knobby beds and may represent a reef facies. A few of the other thicker carbonate beds (as much as 10 m thick) may also represent reefs and are massive, vuggy, and grayish-orange weathering. The dolomitic limestone weathers to pale yellowish brown; the limestone weathers pale gray. Clastic beds typically weather in rounded forms as compared to relatively angular weathered forms in the carbonate beds. Thickness north of Gore Creek about 120 m; south of Gore Creek as thick as about 180 m. Thickness 220 m at type section
ℙmrl	**Individual limestone bed**—Generally cliff forming and greater than 5 m thick
ℙml	**Lower member**—Pinkish-gray, grayish-brown, gray-green, and mottled maroon and gray-green arkosic conglomerate, sandstone, siltstone, and shale. Rocks very similar to those of middle member. About 400 m of section exposed on west side of Pitkin Creek beneath Robinson Limestone member. Base of member exposed about 0.6 km southwest of Bald Mountain, just north of Gore fault, where basal bed is a granite-clast, matrix-supported, massive conglomerate as thick as 5 m that forms channels into underlying Sawatch Quartzite. Clasts of Proterozoic granite are as long as 25 cm
ℙmls	**Individual limestone bed**—Generally cliff forming and greater than 5 m thick
ℙꞒu	**Pennsylvanian to Cambrian units, undifferentiated**—Shown on cross section B-B’ only
Pzcd	**Clastic dike (lower Paleozoic?)**—Fine-grained, maroon, equigranular, very well indurated 0.5-1.0-m-wide tabular body of quartz sandstone that fills a north-northwest-striking fault just northwest of unnamed lake in upper Piney River drainage. Interpreted as a clastic dike. Grains are 99 percent quartz, well rounded, unbroken, and as long as 1 mm. Contains about 1 percent carbonate cement and trace of iron oxide. Some pressure solution around

grain boundaries, creating near 120° angles. Unit is cut by numerous, thin (less than 1 mm), irregular microbreccia zones. Dike can be traced for about 100 m. Age of clastic dike unknown, but lack of grain deformation suggests fluidized injection of sand occurred before complete diagenesis of parent unit, which is probably Upper Cambrian Sawatch Quartzite. If so, age of clastic dike is probably Late Cambrian. Margins of dike are faulted, indicating recurrent faulting prior to and after dike emplacement

Dp **Parting Formation (Upper Devonian)**—White and pale-green, coarse-grained, well-indurated, locally crossbedded quartzite and pebbly quartzite. Beds 0.3-2 m thick. Pebbles consist entirely of white quartz and quartzite. Found in two places just north of Gore fault, just southwest and southeast of Bald Mountain. The western outcrop lies unconformably on Proterozoic basement and pinches out abruptly to the north. Approximately 700 m east, Parting unconformably overlies Peerless Formation and is mapped by Tweto and Lovering (1977) also as pinching out to the north. However, this possible pinchout in this eastern exposure is largely covered and viewed as speculative. Thickness 0-20 m

€p **Peerless Formation (Upper Cambrian)**—Brick-red, dolomitic, fine-grained, poorly sorted, bioturbated mudstone and sandstone containing a micaceous, muddy matrix. Poorly indurated. Contact with underlying Sawatch Quartzite gradational over about 1 m and conformable. Thickness 6 m

€s **Sawatch Quartzite (Upper Cambrian)**—Vitreous, white and greenish-white, well-indurated quartzite and pebbly quartzite. Pebbles, composed entirely of white quartz or quartzite, as long as 1 cm. Well exposed at only one place about 700 m southeast of Bald Mountain, where it unconformably overlies Proterozoic basement rock. Appears identical to mapped Parting Formation, but is probably Sawatch because it underlies Peerless Formation. Elsewhere, poorly exposed wedges of Sawatch Quartzite exist sporadically along Gore fault zone; mostly identified by float. Thickness less than about 40 m; locally totally removed prior to deposition of Parting Formation

Early Proterozoic rocks

[Grain sizes for both plutonic and metamorphic rocks follow Compton (1962): fine-grained, less than 1 mm; medium-grained, 1-5 mm; and coarse-grained, greater than 5 mm]

Xu **Early Proterozoic rocks, undifferentiated**—Shown only in cross section D-D’

Rocks of the Cross Creek batholith (Early Proterozoic)—Forms much of the central Gore Range and the northeastern part of the Sawatch Range, 20 km southwest of the Gore Range (Tweto and others, 1970; Tweto and Lovering, 1977; Tweto, 1984). A Rb-Sr date of 1,675 Ma (no analytical uncertainly given; recalculated using 1977 decay constants; Reed and others, 1987; Tweto and Lovering, 1977) was obtained from rocks near Cross Creek in the Sawatch Range. Rocks of the Cross Creek batholith are part of the Routt Plutonic Suite of Tweto (1987), which is 1,667-1,750 Ma

Xap **Aplitic granite**—Fine-grained to medium-grained, gray to pinkish-gray hypidiomorphic, equigranular to weakly foliated, monzogranite. Contains about 25 percent quartz, 30-40 percent both sodic plagioclase and microcline, 1-5 percent biotite, 0-2 percent muscovite, 1 percent opaque minerals, and trace of zircon, apatite, and garnet. Exists as small irregular-shaped bodies intrusive into Cross Creek Granite. Mapped only in southeastern corner of quadrangle but found locally throughout the Cross Creek Granite

Xg **Cross Creek Granite**—Medium to coarse-grained, gray to pinkish-gray, texturally diverse monzogranite, tonalite, and granodiorite (classification of Streckeisen, 1976) containing stringers, pods, lenses, and dikes of granite pegmatite and aplite and inclusions of migmatite, biotite gneiss, and sillimanite schist. Hypidiomorphic, xenomorphic, equigranular, inequigranular, and porphyritic textures are all common. Contains 35-50 percent oligoclase (commonly altering to sericite), 20-30 percent undulatory quartz, 15-30 percent microcline, 8-15 percent biotite, 0-2 percent muscovite (commonly as flakes in biotite), and 0-1 percent garnet. Accessory and trace minerals are opaque minerals, zircon, and apatite. Locally contains undeformed pink microcline crystals as long as 4 cm, commonly aligned parallel to regional foliation, that contain deformed biotite and plagioclase crystals, a relationship that led Tweto and Lovering (1977) to suggest the microcline crystals were porphyroblasts rather than phenocrysts. Contacts with migmatite (Xm) and diorite (Xdi), both of which it intrudes, mostly gradational but locally sharp

Xdi **Diorite**—Gray to dark-gray, medium-grained to coarse-grained, massive to moderately foliated biotite and hornblende-biotite granodiorite, tonalite, and quartz diorite (classification of Streckeisen, 1976). From three examined thin sections, contains 10-15 percent undulatory quartz, 40-55 percent andesine ($\mathrm{An}_{35\text{-}44}$), 0-10 percent microcline, 20-30 percent biotite, 0-10 percent hornblende, 1-5 percent opaque minerals, 0-2 percent apatite (as long as 0.2 mm), 0-1 percent garnet, and trace sphene. These compositions agree with those reported for diorite by Tweto and Lovering (1977). Unit forms irregular-shaped masses intruded by and commonly having gradational contacts with the Cross Creek Granite

Xgb **Gabbro**—Black, coarse-grained, equigranular biotite-hornblende gabbro. Contains about 50 percent hornblende, 15 percent biotite, 10 percent augite, 10 percent cordierite, 8 percent slightly undulatory quartz, 5 percent calcic plagioclase (very altered), 1-2 percent opaque minerals, and trace apatite. Found in central part of quadrangle, about 1 km west of Booth Lake, as small irregular-shaped bodies surrounded by Cross Creek Granite

Xm **Migmatitic biotite gneiss (Early Proterozoic)**—Gray, well-foliated, inequigranular to equigranular, medium-grained, hypidiomorphic to xenomorphic biotite gneiss alternating with varying amounts (commonly as much as 70 percent of rock) of very light gray to white granitic layers ranging from a fraction of a centimeter to about 10 centimeters thick. Rock contains 10-60 percent oligoclase, 0-30 percent microcline, 0-20 percent quartz, 0-50 percent brown biotite (commonly chloritized), 0-30 percent fibrous sillimanite, 0-5 percent phlogopite, 0-3 percent muscovite, and traces of opaque minerals, garnet, zircon, and apatite. Layers show much pinch and swell and in most places are strongly folded. Leucocratic layers due both to injection (igneous origin) and in-situ partial melting; the latter commonly have biotite-rich selvages adjacent to layers (Johannes, 1988)

Xbg **Biotite gneiss (Early Proterozoic)**—Gray, medium-grained, hypidiomorphic to xenomorphic, well-foliated gneiss containing approximately 25-50 percent quartz, 20-30 percent plagioclase (approximately An_{30}), 0-30 percent microcline, 10-15 percent biotite, 0-15 percent muscovite, 0-10 percent sillimanite, 0-5 percent hornblende, 1-2 percent opaque minerals, and a trace of zircon. Typically contains 5-20 percent leucocratic layers, so distinction with migmatite (Xm) somewhat arbitrary. Mapped at one locality near drainage divide between upper Pitkin Creek and Boulder Creek

LOCAL AND REGIONAL STRUCTURE

Part of the Vail East quadrangle lies along the southwest flank of the Gore Range, a north-northwest-trending basement uplift bounded on the east by the Blue River normal fault (Tweto and others, 1970; Kellogg, 1999) and on the west by the Gore fault zone (see index map). The latter, which traverses the quadrangle, has been active since at least the early Paleozoic and defines the approximate eastern boundary of the central Colorado trough, a depocenter that contains a thick Pennsylvanian and Permian section (for example, DeVoto, 1980). The Gore fault zone was also active during Laramide (Late Cretaceous to early Tertiary) contraction and uplift.

The Gore fault zone is a complicated array of intersecting high-angle faults, previously interpreted as having overall normal fault movement (Tweto and Lovering, 1977; Tweto and others, 1978). Our mapping, however, shows that most faults in the zone are high-angle reverse faults. En-echelon, right-stepping faults along the zone (including the section of the zone shown on the Vail Pass quadrangle of Bergendahl (1969) to the southeast of the Vail East quadrangle) suggest a left-lateral component of movement (Kellogg and others, 2000).

In the northwest part of the quadrangle, on the valley side south of the Piney River, the Gore fault is exposed in the scarp of a small, unmapped landslide (location A on map). There, medium- to coarse-grained grayish-red arkosic sandstone and granule conglomerate are overlain by fractured Cross Creek Granite. A thin slice of Sawatch Quartzite along the fault plane strikes N. 25º E. and dips 35º southeast. The arkosic sandstone beneath the fault dips subparallel to it and is probably overturned. Map relations indicate that this low-angle fault is cut by a high-angle fault (Sec. A-A').

The east-striking segment of the Gore fault is well exposed on both sides of Booth Creek valley where highly sheared limestone and clastic rocks of the Minturn Formation contain phacoids of quartzite (either Sawatch Quartzite or Parting Formation) as long as 1 m. The shear zone is as wide as 3 m and dips steeply to the north. Beds of the Minturn Formation are folded to vertical or overrturned orientations immediately south of the shear zone. This and other low- to moderate-angle contractional fault segments involving Pennsylvanian rocks are probably part of a compressive Gore fault system that was active along the west margin of the late Paleozoic ancestral Front Range in Late Pennsylvanian or Permian time.

Faults within Early Proterozoic basement in the central part of the range have two distinct strikes: east-northeast and north-northwest. Prominent joints in the basement mimic the fault trends. The east-northeast fault set is parallel to and exploited the widely distributed Homestake shear zone, a broad region of east-northeast-trending, Middle Proterozoic ductile shear that has been the locus for several subsequent deformational and intrusive events (Tweto and Sims, 1963; Tweto, 1984). Monazite dating of the shear zone in the Sawatch uplift, about 10 km south-southwest of the quadrangle, suggested that the main period of mylonitization was Early Proterozoic 1,710-1,630 Ma), with a period of early Middle Proterozoic (1,450-1,380 Ma) ultramylonitization (Shaw and others, 2001). The mylonitic zones in the Gore Range are commonly overgrown by secondary silica and muscovite, and are texturally unlike the wide, fine-grained mylonites and ultramylonites of the Homestake shear zone in the Sawatch Range (Tweto, 1984). However, well-developed S-C fabrics (Simpson and Schmid, 1983) generally give shear sense. Our reconnaissance data indicate that the mylonites in the Vail East quadrangle dip steeply to the southeast and that the lineations are mostly steep, but vary to nearly horizontal. Shears with steep lineations indicate predominantly normal slip (8 out of 9 determinations), and, of these, most had a component of sinistral slip.

The north-northwest set of faults cutting the Proterozoic basement had a very long history, with at least five periods of movement: (1) possible Precambrian movement, as the set follows the general foliation trends (Tweto and Lovering, 1977), (2) movement related to late Paleozoic uplift of the Ancestral Front Range (Tweto and Lovering, 1977), (3) uplift related to Laramide contraction (Tweto, 1975), (4) possible strike-slip movement related to a poorly understood mid-Tertiary period of deformation (Erslev and others, 1999), and (5) extension related to late Oligocene and younger normal faulting, crustal heating, and uplift of the rift flanks along the northern Rio Grande rift (Tweto 1979; Kellogg, 1999; Erslev and others, 1999).

Apatite fission-track dates from rocks on either side of the Gore fault in the central and southern parts of the quadrangle indicate that the Gore fault had no large vertical displacement in Neogene time because late Paleogene and early Neogene (37-17 Ma) fission-track ages of apatite, which represent times when the rock cooled below 110 ºC, are similar on both sides of the fault zone (Erslev and others, 1999). Speculatively, the north-northwest-trending faults in the Proterozoic rocks in the northwest part of the quadrangle had Neogene movement distributed among them associated with the uplift of the high part of the Gore Range. Mount Powell, the highest peak in the Gore Range, is only 0.8 km north of the quadrangle.

Lineations in the north-northwest faults fall into two distinct sets, one indicating strike-slip movement and the other dip slip. Most of the faults from the strike-slip set (11 out of 14, where sense could be determined) indicate sinistral movement. Most of the faults from the dip-slip set are normal (8 out of 9 observations) and are probably related to late Oligocene and younger regional extension associated with formation of the Rio Grande rift (Tweto, 1979). Of these dip-slip faults, most also had a component of sinistral slip.

Stratigraphic relationships and structures in the Paleozoic sedimentary rocks reveal important aspects of the regional tectonic history. Many Paleozoic units thin or pinch out adjacent to the Gore fault, reflecting the zone’s long history as a fundamental structural boundary. Significant differences in the stratigraphic section are preserved within two areas only 400 m apart, just north of the head of Spraddle Creek in the west part of the quadrangle. In the western of the two areas (section B-B’) the Upper Cambrain Sawatch Quartzite lies directly below the Pennsylvanian Minturn Formation. (Tweto and Lovering [1977] mapped the quartzite sequence as Devonian Parting Formation.) The Parting and Upper Cambrian Peerless Formation apparently are missing in the western area but are preserved in the eastern area (section C-C’) where they appear to pinch out northward. In both areas, the Mississippian section is completely missing. Tweto and Lovering (1977) suggested that a north-trending fault, active during the early Paleozoic, separated these two areas. A north-trending distributed shear zone between the two areas may have been responsible for the differing stratigraphy.

The thick Pennsylvanian and Permian section generally dips gently south to southwest about 5°-15°, except within about 200 m of the Gore fault where it is abruptly folded to a steep to overturned attitude (sections B-B’, C-C’, and D-D’). The gentle regional tilting may be coeval with Tertiary uplift and southwestward tilting of the entire Gore Range (Erslev and others, 1999), but the abrupt fold adjacent to the Gore fault is probably related to compressive deformation and movement along the fault by Laramide and (or) late Paleozoic deformation.

The Spraddle Creek fold is a north-trending structure just east of Spraddle Creek. The axial plane was mapped as faulted by Tweto and Lovering (1977), although our investigations showed at one locality only a thin zone of brecciation along the axial plane of a sharp, chevron-like fold with no discernable offset. The Spraddle Creek fold is suspected to be Laramide in age.

GEOLOGIC HAZARDS

The steep mountain landscapes in the quadrangle are settings in which geologic processes are particularly active. The urbanized valley bottom of Gore Creek faces a number of geologic hazards that have been studied, mostly by private contractors, to aid the city of Vail and guide development away from the more dangerous areas. Since 1961, when building began in the Gore Creek valley, debris flows and rockfalls have damaged a few buildings at the margins of the developed area.

Much of the land outside the bottom of the Gore Creek valley is in the White River and Arapaho National Forests, and the high country of the Gore Range is part of the Eagles Nest Wilderness. Hazards, such as avalanches and rockfall, also exist in these areas, and forest roads and campgrounds need to be designed with these hazards in mind. In the high mountains, only hikers, skiers, and mountaineers need to be concerned, but that concern is part of the challenge of back-country travel.

Potential geologic hazards in the Vail East quadrangle include landslides, rockfall, floods and debris flows, seismic hazards, expansive soil, elevated radon, and avalanches.

Landslides

Landslide deposits are on both sides of the Gore Creek valley in areas mostly underlain by rocks of the Minturn Formation, particularly in the middle and lower members. Landslides are relatively rare in areas underlain by Proterozoic crystalline rocks. All mapped landslides are considered as earth flows and earth slides (Cruden and Varnes, 1996). With one notable exception, most slides appear to be inactive. One large earth slide, about 2 km from the western boundary of the map and just north of Interstate Highway 70, was undercut by construction of the Interstate and is currently failing by a combination of deep rotation and more-shallow earth sliding (Jurich and Miller, 1987). Landslide deposits, some with hummocky topography reflecting Holocene movement, underlie large areas of the Vail ski area, although no evidence was found for ongoing landslide activity.

Conditions that contribute to landslides in the map area include: (1) oversteepening of slopes by such processes as fluvial erosion of toe slopes and human undercutting of slopes (Varnes and others, 1989), (2) bedding oriented parallel to slope, (3) deforestation by logging, fires, and (or) human activity, (4) high water content (by intense or prolonged rainfall, or rapid or protracted snowmelt), and (5) contrast in stiffness of materials (dense, stiff material over plastic material) (Cruden and Varnes, 1996).

Rockfalls

Rockfalls occur in areas having steep slopes and cliffs. In 1983, 1986, and 1987, large boulders fell from cliffs in the Robinson Limestone Member of the Minturn Formation (Ᵽmr) east of lower Booth Creek and damaged several residences (Stover, 1988). A combination of weak shale beds, thick sandstone and limestone beds, joints in the rocks forming the cliffs, and a regional dip towards the valley all make this cliff more prone to rockfalls than most. North of Interstate Highway I-70, a large berm and trench bulldozed along the side of the hill below the cliffs, visible from Interstate Highway 70, is an attempt to mitigate this hazard. In the high country of the Gore Range, rockfalls from cliffs in Early Proterozoic rocks occur frequently, especially in the spring when water from daytime melting of snow freezes at night in cracks in rocks. The freeze-thaw sequence tends to pry rocks from cliffs. Talus deposits (Qt) in most places result from this process.

Floods and debris flows

Intense summer rainstorms or rapid melting of deep snowpack during unusually warm spring thaws may cause flooding or debris flows and localized damage to roads and structures. Flooding during such conditions may be particularly intense along developed sections of Gore Creek. Debris flows generally form on fan deposits (unit Qf and smaller unmapped fan deposits) that form from side gullies of Gore Creek and can obstruct roadways, including Interstate Highway I-70.

Elevated radon

Most of Colorado has elevated radon values compared to other parts of the country (Otton and others, 1993). One in three homes in Colorado has radon values greater than 4 picocuries per liter (pCi/l), the maximum allowable value for household radon determined by the EPA; mitigating action is recommended for values higher than 4 pCi/l (EPA, 1993) because elevated radon in homes increases the risk for contracting lung cancer. Granite and felsic gneiss are relatively radiogenic compared to most other rocks, so surficial units, such as alluvium (Qa), till (Qtp, Qtb), and other rubbly deposits derived from felsic Proterozoic bedrock (units Qd and Qc in places) may have elevated radon values (Otton and others, 1993). The hazard increases with increased permeability, so younger, less weathered units may have higher radon risk. Testing for radon is relatively easy and inexpensive and steps can be taken to mitigate the hazard (EPA, 1993).

Snow Avalanches

Snow avalanches may occur where (1) slopes are steeper than about 25° (90 percent of avalanches are on slopes between 30°-45°), (2) snow accumulates to a sufficient depth, (3) a weak layer or layers develop at depth, and (4) a trigger initiates the snowslide (Colorado Avalanche Information Center, 2000). Prevailing westerly winds cause cornices and snowpack to accumulate on the eastern sides of ridges and that is where most avalanches occur. Triggers might be a skier, animal, or a sonic boom, but most avalanches are caused simply by the weight of accumulated snow, and avalanches may occur when shear stress exceeds shear strength along a weak snow layer. Avalanche tracks or run-out zones are commonly devoid of large trees and may be littered with broken logs and tree limbs. However, tracks that have not run for many decades may be overgrown with aspen and conifers, which may obscure evidence for potential avalanche hazards. Although not mapped in the Vail East quadrangle, debris cones and aprons, composed of unsorted and unstratified rock and wood fragments, commonly lie at the base of avalanche tracks. These debris deposits result from a combination of avalanche activity, debris flows, and rock falls. Large avalanches may cross a valley and move hundreds of meters up the opposite valley side. During times of unusually high snowfall, avalanches may run into mature forests, uprooting and shearing off trees and clearing a new avalanche track.

The south side of the Gore Creek valley, except for the western 2.8 km, has a number of avalanche tracks, any of which might be the site of avalanches in a year of very heavy snowfall or after single great storms. Many of the fan deposits (Qf) along the south side of Gore Creek are avalanche runout zones (Mears, 1979). Building has generally been avoided in these runout zones on the valley bottom. Backcountry winter travelers need to be particularly aware of the indications of high avalanche danger.

RESOURCES

Gravel

The principal gravel resources in the quadrangle are in alluvium (Qa) along Gore Creek. However, these resources are now covered by extensive development and thus are unavailable for exploitation in most places. Alluvium and colluvium (Qac) along the Piney River in the northwest corner of the quadrangle is a potential source of gravel.

Metals

Faults and fracture zones in the Proterozoic rocks of the Pitkin and Bighorn Creek drainages have locally been prospected for copper, lead, zinc, and silver. Those zones locally contain thin quartz and quartz-carbonate veins, which have sparsely distributed copper, lead, and zinc minerals. A geochemical and geologic study of the mineral resources of the Gore Range was conducted before it was designated a wilderness area (Tweto and others, 1970). The study showed that the fault and fracture zones contained geochemically anomalous quantities of a large suite of other metals compared to their content in the country rock but concluded that no economic resources of metals are likely to be found in these small veins.

REFERENCES CITED

Bergendahl, M.H., 1969, Geologic map and sections of the southwest quarter of the Dillon Quadrangle, Eagle and Summit Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-562, scale 1:24,000.

Chadwick, O.A., Hall, R.D., and Phillips, F.M., 1997, Chronology of Pleistocene glacial advances in the central Rocky Mountains: Geological Society of America Bulletin, v. 109, no. 7, p. 1443-1452.

Colorado Avalanche Information Center, 2000, Avalanche facts: Internet site http://www.caic.state.co.us/facts.html

Compton, R.R., 1962, Manual of field geology: John Wiley and Sons, New York, 378 p.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, *in* A.K. Turner and R.L. Schuster, eds., Landslides investigation and mitigation: National Academy Press, Washington, D.C., p. 36-75.

DeVoto, R.H., 1980, Pennsylvanian stratigraphy and history of Colorado, *in* Kent, H.C., and Porter, K.W., eds., Colorado Geology: Rocky Mountain Association of Geologists, Denver, p. 71-101.

EPA, 1993, Home Buyer’s and Seller’s guide to radon: U.S. Environmental Protection Agency Air and Radiation Pamphlet 6604J, 32 p.

Erslev, E.A., Kellogg, K.S., Bryant, Bruce, Ehrlich, T.K.,, Holdaway, S.M., and Naeser, C.W., 1999, Laramide to Holocene structural development of the northern Colorado Front Range, *in* Lageson, D.R., Lester, A.P., and Trudgill, B.D., eds, Colorado and Adjacent Areas: Boulder, Colorado, Geological Society of America Field Guide 1, p. 21-40.

Johannes, W., 1988, What controls partial melting in migmatites?: Journal of Metamorphic Geology, v. 6, p. 451-465.

Jurich, D.M., and Miller, R.J., 1987, Acoustic monitoring of landslides: Transportation Research Record 1119, Transportation Research Board, National Research Council, Washington, D.C., p. 30-38.

Kellogg, K.S., 1999, Neogene basins of the northern Rio Grande rift—partitioning and asymmetry inherited from Laramide and older uplifts: Tectonophysics, v. 305, p. 141-152.

Kellogg, K.S., Bryant, Bruce, Naeser, C.W., and Kunk, M.J., 2000, Structural history of the western Gore Range, Colorado—shears, faults, and uplifts spanning more than 1 billion years: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-233.

Mears, A.I., 1979, Colorado snow avalanche areas, studies, and guidelines for avalanche hazard planning: Colorado Geological Survey Special Publication 12, 124 p.

Otton, J.K., Gunderson, L.C.S., and Schumann, R.R., 1993, The geology of radon: U.S.

Geological Survey, Informational pamphlet, 29 p.

Reed, J.C., Jr., Bickford, M.E., Premo, W.R., Aleinikoff, J.N., and Pallister, J.S., 1987, Evolution of the Early Proterozoic Colorado province—constraints from U-Pb geochronology: Geology, v. 15, p. 861-865.

Scott, R.B., Lidke, D.J., and Grunwald, D.J., 2002, Geologic map of the Vail West quadrangle, Eagle County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2369, scale 1:24,000.

Shaw, C.A., Karlstrom, K.E., Williams, M.L., Jercinovic, M.J., and McCoy, A.M., 2001, Electron-microprobe monazite dating of ca. 1.71-1.63 Ga and ca. 1.45-1.38 Ga deformation in the Homestake shear zone, Colorado—origin and early evolution of a persistent intracontinental tectonic zone: Geology, v. 29, no. 8, p. 739-742.

Simpson, Carol, and Schmid, S.M., 1983, An evaluation of criteria to deduce the sense of movement in sheared rocks: Geological Society of America Bulletin, v. 94, p. 1281-1288.

Stover, B.K., 1988, Booth Creek rockfall hazard area, *in* Holden, G.S., ed., Geological Society of America Field Trip Guidebook 1988: Colorado School of Mines Professional Contribution 12, p. 395-401.

Streckeisen, Albert, 1976, To each plutonic rock its proper name: Earth-Science Reviews, v. 12, p. 1-33.

Tweto, Ogden, 1975, Laramide (late Cretaceous-Early Tertiary) Orogeny in the Southern Rocky Mountains, *in* Curtis, Bruce, ed., Cenozoic history of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 1-44.

Tweto, Ogden, 1979, The Rio Grande rift system in Colorado, *in* Reiker, R.E., ed., Rio Grande Rift—Tectonics and Magmatism: American Geophysical Union, Washington, D.C., p. 33-56.

Tweto, Ogden, 1984, Geologic map and sections of the Holy Cross quadrangle, Eagle, Lake, Pitkin, and Summit Counties: Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-830, scale 1:24,000.

Tweto, Ogden, 1987, Rock units of the Precambrian basement in Colorado: U.S. Geological Survey Professional Paper 1321-A, 54 p.

Tweto, Ogden, Bryant, Bruce, and Williams, F.E., 1970, Mineral resources of the Gore Range-Eagles Nest Primitive Area and vicinity, Summit and Eagle Counties, Colorado: U.S. Geological Survey Bulletin 1319-C, 127 p.

Tweto, Odgen, and Lovering, T.S., 1977, Geology of the Minturn 15-minute quadrangle, Eagle and Summit Counties, Colorado: U.S. Geological Survey Professional Paper 956, 96 p.

Tweto, Ogden, Moench, R.H., and Reed, J.C., Jr., 1978, Geologic map of the Leadville 1º x 2º quadrangle, northeastern Colorado: U.S. Geological Survey, Miscellaneous Investigations Series Map I-999, scale 1:250,000.

Tweto, Ogden, and Sims, P.K., 1963, Precambrian ancestry of the Colorado mineral belt: Geological Society of America Bulletin, v. 74, p. 991-1014.

Varnes, D.J., Radbruch-Hall, D.H., and Savage, W.Z., 1989. Topographic and structural conditions in areas of gravitational spreading of ridges in the western United States: U.S. Geological Survey Professional Paper 1496, 28 p.