U.S. DEPARTMENT OF THE INTERIOR
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GEOLOGIC MAP OF THE VAIL WEST QUADRANGLE, EAGLE COUNTY, COLORADO

By

Robert B. Scott, David J. Lidke, and Daniel J. Grunwald

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Pamphlet to accompany
MISCELLANEOUS FIELD STUDIES MAP
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DESCRIPTION OF MAP UNITS

INTRODUCTION

Surficial deposits shown on the map are estimated to be at least 1 m thick; they were not mapped where deposits are thin, small in area, or discontinuous. Ages for surficial deposits are estimated from their height above modern drainage and on measurements of rates of downcutting, from degree of change in original landform by erosion, and from the stage of soil formation. However, downcutting rates are irregular because new studies show that tectonic changes, climatic changes, and (or) stream capture have greatly influenced downcutting rates. The rate of downcutting by major streams west of the map area is as little as 0.13 m/ky (ky, thousand years) based on 80–85 m of downcutting since deposition of the 640±4-ka (ka, thousands of years ago) Lava Creek B volcanic ash (M.A. Lanphere, U.S. Geological Survey, written commun., 2000) measured at the White River near Meeker, Colorado (J.W. Whitney, oral commun., 1992; Whitney and others, 1983). In contrast, about 396 m of downcutting below a 1.5-Ma basalt (Larson and others, 1975; Kunk, in press) at Triangle Peak along the Roaring Fork River, about 50 km southwest of the map area, provides a significantly higher rate of about 0.26 m/ky. Also, about 145 m of downcutting below a 0.6-Ma basalt (Larson and others, 1975) along Rock Creek, which is 0.2 km north of the Colorado River, about 28 km northwest of the map area, provides another high rate of about 0.24 m/ky. The Lava Creek B ash 90 m above the Colorado River near the east end of Glenwood Canyon (Izett and Wilcox, 1982) cannot be used until the amount of aggradation by the river behind a landslide in the canyon is precisely known (R.M. Kirkham, Colorado Geological Survey, oral commun., 2000). Also the same ash, about 88 m above the Roaring Fork River near Carbondale, Colorado (Piety, 1981), cannot be used because that area has probably experienced unknown amounts of subsidence related to evaporite dissolution since deposition of the ash (Scott and others, 1999; Kirkham and others, in press). A rate of 0.16 m/ky is based on about 1,600 m of downcutting by the Colorado River after eruption of 10-Ma (Ma, million years old) basalt on Grand Mesa (Marvin and others, 1966) about 170 km to the southwest of the map area. Although this rate is commonly cited, this average downcutting rate considerably downstream may have little bearing on rates over much shorter time periods in the late Cenozoic where known tectonic events probably changed downcutting rates significantly (Naeser and others, in press).

Correlation of units **Qty** and **Qto** with alluvial units near Wolcott (Lidke, 1998) and near New Castle, Colorado (Scott and Shroba, 1997; Shroba and Scott, 1997) is determined by the elevation of these units above stream level. Also the age of unit **QTdi** is estimated from the projected elevation above Piney River.

The Soil Survey Staff (1975), Guthrie and Witty (1982), and Birkeland (1999) defined the soil-horizon designations used. Stages of secondary calcium carbonate morphology (Gile and others, 1966) are referred to as stages I through III Bk and K horizons in this report. Terminology for grain sizes for surficial deposits and bedrock follow the modified Wentworth scale (American Geological Institute, 1982). Clasts are defined as the fraction greater than 2 mm in diameter, whereas the term “matrix” is defined as the fraction less than 2 mm. The Munsell Soil Color Charts (Munsell Color, 1973) define dry matrix colors of the surficial deposits and the Geological Society of America Rock-Color Chart (Rock-Color Chart Committee, 1951) defines bedrock colors.

Metric units are used in this report; a conversion table is provided for those more familiar with English units (table 1). A review of the divisions of geologic time used in this report is also provided (table 2)]

Table 1. Factors for conversion of metric units to English units to two significant figures

Multiply	By	To obtain
centimeters (cm)	0.39	inches
meters (m)	3.3	feet
kilometers (km)	0.62	miles

Table 2. Definitions of divisions of geologic time used in this report

EON	ERA /	Period /	Epoch /	Years
PHANEROZOIC	CENOZOIC	Quaternary	Holocene	0 to 10 thousand
			[1]Pleistocene	10 thousand to 1.65 million
		Tertiary	Pliocene	1.65 to 5 million
			Miocene	5 to 24 million
	MESOZOIC	Cretaceous		66 to 138 million
		Jurassic		138 to 205 million
		Triassic		205 to ~240 million
	PALEOZOIC	Permian		~240 to 290 million
		Pennsylvanian		290 to ~ 320 million
		Mississippian		~320 to 360 million
		Devonian		360 to 410 million
		Ordovician		435 to 500 million
		Cambrian		500 to ~ 570 million
PROTEROZOIC	EARLY PROTEROZOIC			1,600 to 2,500 million

After Hansen (1991) except for the Pleistocene. Subdivisions of [1]Pleistocene time are informal and are as follows: late Pleistocene is 10–132 thousand years, middle Pleistocene is 132–788 thousand years, and early Pleistocene is 788–1,650 thousand years (Richmond and Fullerton, 1986).

SURFICIAL UNITS

Artificial-fill deposits—Mostly compacted rock, sand, and silt debris placed under and adjacent to highways, earthen dams, urban streets, buildings, and landscaped areas

af **Artificial fill (latest Holocene)**—Mostly compacted rock, sand, and silt debris placed under and adjacent to highways and earthen dams. Unit was mapped under Interstate 70 (I-70) in the southern part of the map area and at several minor dams for ponds on private land. Unmapped artificial fill was used in construction of paved roads within the town of West Vail and of dirt roads outside of the town. Maximum thickness of unit is about 3 m

mls **Modified land-surface deposits (latest Holocene)**—Mostly compacted rock, sand, and silt added during extensive landscaping of building grounds in the urban area of the town of Vail West. In many localities, the deposit includes a cover of grass sod and decorative boulders that have been moved from their original sites. In the Vail West area, unit mls covers Pinedale and Bull Lake Tills (Qtp, Qtb), probably covers minor alluvium (Qal), younger terrace alluvium (Qty), younger fan-alluvium and debris-flow deposits (Qfy), colluvium (Qc), and Minturn Formation (IPm); the map unit probably includes poorly exposed, small unmapped outcrops of all these deposits. Landscaping covers natural exposures that might provide means of determining the thickness of the map unit

Alluvial deposits—Silt, sand, and gravel in stream channels, floodplains, and terraces along Gore Creek, Piney River, and tributaries

Qal **Alluvium (Holocene)**—Stream-channel deposits along Gore Creek and Piney River. The map unit probably also contains colluvial deposits (Qc) and wetland deposits (Qw) that are too small to be mapped separately. Commonly alluvium contains thick (1–2 m) beds of poorly sorted cobble to pebble gravel interbedded with thin (0.1–0.4 cm) beds of sand and pebbly sand. Typically, the unit is clast supported but locally it is matrix supported. Clay and silt are sparse except in marshy areas where vegetation trapped finer material. No secondary carbonate was observed. Areas underlain by the unit are frequently flooded during spring snowmelt and during or after heavy summer thunderstorms. Exposed thickness of unit is 1–3 m

Qty **Younger terrace alluvium (late Pleistocene)**—Stream alluvium that underlies terraces that are about 6–8 m above Eagle River. The unit consists of moderately well sorted, clast-supported, rounded to well-rounded, pebbly to cobbly gravel with a pale-brown silty sand and sand matrix. Gravel is commonly overlain by about 1 m of massive, light-brown to light-reddish-brown silty fine sand and fine sand. Clasts consist predominantly of very light gray and pinkish-gray, coarse-grained granite; very light gray and medium-light-gray, fine-grained granite and granodiorite; dark-gray gneiss and schist; very light gray, pink, and light-brown quartzite; and fine- to medium-grained, moderate-red sandstone. Clasts are not cemented. Younger fan alluvium and debris-flow deposits (Qfy) overlie younger terrace alluvium. Unit is probably equivalent in part to outwash of the Pinedale glaciation, which is about 12–35 ka (Richmond, 1986, chart 1A). Note that this Pinedale range of ages does not match well with the 43- to 57-ka age range calculated from the downcutting rate of 0.14 m/ky, but overlaps with the 24- to 32-ka age range calculated from the downcutting rate of 0.25 m/ky. Unit occurs in the southwestern part of the map area in Eagle Valley. Unit is a potential gravel resource. Thickness of map unit is commonly 5–10 m

Qto **Older terrace alluvium (late middle Pleistocene)**—Stream alluvium that underlies small terrace remnants about 25–30 m above the Eagle River. Unit consists of moderately well sorted, clast-supported, rounded to well-rounded, pebble to boulder gravel with a pale-brown silty sand matrix. Gravel is commonly overlain by about 1 m of massive, light-yellowish-brown silty fine sand. Clasts consist mostly of very light gray and pinkish-gray, coarse-grained granite; medium-light-gray, fine-grained granite and granodiorite; dark-gray gneiss and schist; very light gray, moderate-pink, and light-brown quartzite; and fine- to medium-grained, moderate-red sandstone. Clasts are poorly cemented to locally well cemented by fine-grained calcium carbonate. Older fan alluvium and debris-flow deposits (Qfo) commonly overlie older terrace alluvium. Unit probably is equivalent in part to outwash of the Bull Lake glaciation, which is about 140–150 ka (Pierce and others, 1976). Note that this Bull Lake range of ages does not match well with the 178- to 214-ka age calculated from the assumed downcutting rate of 0.14 m/ky or with the 100- to 120-ka age calculated from the assumed downcutting rate of 0.25 m/ky. The unit is a potential gravel resource. The map unit occurs in the southwestern part of the map area in Eagle Valley. The preserved thickness of the map unit is commonly 3–5 m

Alluvial and colluvial deposits—Generally gravel, sand, and silt in fans deposited where high-gradient tributaries join Piney River and Gore Creek

Qfy **Younger fan alluvium and debris-flow deposits (Holocene and latest Pleistocene)**—Generally consists of poorly sorted, bouldery to cobbly sand and silt that includes minor lenses of sandy to cobbly gravel and debris-flow deposits. The map unit also includes exposures of colluvium (Qc) and stream-channel alluvium (Qal) that are too small to map separately. Unit commonly is matrix supported but is locally also clast supported. Most of the boulders are less than 1 m in diameter, but local debris-flow deposits contain boulders as great as 2 m in diameter. Where exposed, the map unit is nonbedded to poorly bedded. Clasts consist of subrounded to angular sandstone and limestone, largely derived from the Maroon and Minturn Formations (PIPm and IPm). Flooding during or after major thunderstorms is common and presents a hazard to the town of Vail; the map unit may be subject to channel modification and debris flows during intense or prolonged rainstorms. Fine-grained deposits may be susceptible to hydrocompaction and piping-related subsidence. Deposits occur at the junctions of intermittent streams with the Piney and Eagle Rivers and with Gore Creek. The surface of the map unit has been extensively covered and disturbed by construction in West Vail and Vail, but the fan-shaped landforms still presist. Maximum thickness of the map unit is estimated to be about 5–10 m

Qfo **Older fan alluvium and debris-flow deposits (middle Pleistocene)**—Light-brown, poorly sorted silt, sand, and clay to pebbly to cobbly gravel of locally derived sandstone, limestone, and siltstone. Gravels are matrix supported and clasts are subangular to rounded. The map unit forms a low-gradient fan in Eagle Valley in the southwestern part of the map area and overlies older terrace alluvium (Qto). Unit includes some unmapped younger fan alluvium and debris-flow deposits (Qfy), alluvium (Qal), and colluvium (Qc) that are too small to be mapped separately where unit Qfo is being reworked. Channel modification and debris flows during intense or prolonged rainstorms commonly rework the map unit. Fine-grained deposits may be susceptible to hydrocompaction and piping-related subsidence. Maximum thickness of the map unit is estimated to be about 5 m

QTdi **Older diamicton (middle Pleistocene? to Pliocene?)**—Unsorted(?) and unstratified(?) bouldery gravel of basaltic rock and Dakota Sandstone (Kd), finer gravel, sand, and silt. Two areas are underlain by very poorly exposed older diamicton in the northwestern part of the map area; a larger area is northeast of Piney River, and a smaller area is southwest of Piney River. The larger area contains subangular to subrounded boulders of basaltic rock at least 1.5 m in diameter and subangular to subrounded boulders of Dakota Sandstone as much as 0.5 m in diameter. The smaller area contains only angular to subangular boulders of basaltic rock as large as 1 m in diameter. The clasts in the smaller deposit consist of a mixture of vesicular and massive basaltic rock. The best exposures are those at the base of uprooted trees, and it is unclear from these poor exposures whether the deposits are clast or matrix supported. The most likely means of deposition of the older diamicton is some form of mass wasting, probably debris flows.

In this report, the slope of older colluvium (QTc) is interpreted as an old landslide that was deposited on a slope that averages about 7°. If that were also the slope of deposition of the older diamicton, then the smaller and larger areas of older diamicton project about 182 and 260 m above the modern Piney River, respectively. Using the assumed downcutting rate of 0.14 m/ky, the time of deposition of the older diamicton may range between 1,300 and 1,900 ka, but at the rate of 0.25 m/ky, the time of deposition may range between 730 and 1,000 ka. Given this large range and the imprecision of the assumptions used, the older diamicton was probably formed sometime between early Pleistocene and late Pliocene. No potential sources of basaltic flows exist in the map area; the closest basaltic flow is 6 km north of the northern exposure of the map unit. The thickness of the smaller area is no more than about 10 m, but the larger area of the map unit may be as thick as 35 m

Colluvial deposits—Silt, sand, and rock debris that were transported by gravity and deposited on hill slopes

Qc **Colluvium, undivided (Holocene and late Pleistocene)**—Chiefly layers of pebble to boulder gravel that is clast supported and contains a sand to clayey silt matrix, deposited on or at the base of steep slopes. Colluvium is commonly unstratified to poorly stratified, unsorted to poorly sorted, and angular to subrounded. The map unit locally contains younger fan alluvium and debris-flow deposits (Qfy), sheetwash deposits, stream channel alluvium (Qal), talus, and landslide (Qls) deposits that are too small to be mapped separately. Colluvium may include debris flows, rock falls, small slumps, and landslides. The unit thickness is commonly about 5 m, but locally may reach 15 m

Qls **Landslide deposits (Holocene to late Pleistocene)**—Largely unsorted and unstratified rock debris having a hummocky upper surface. Landslides commonly formed on unstable slopes that are underlain by the Dakota Sandstone (Kd) and the Morrison Formation (Jm), the Maroon Formation (PℙPm), the Eagle Valley Formation (ℙev), the Minturn Formation (ℙm), and older colluvium (QTc). Crescent-shaped headwall scarps and lobate toes are present only on younger landslide deposits; somewhat older landslides retain a hummocky topography, but more ancient deposits of probable landslide origin such as older colluvium (QTc) have been so altered by erosion that landform evidence of their origin no longer exists. The landslide deposits of unit Qls include debris-slide, rock-slide, debris-slump, slump-earth-flow, earth-flow, and debris-flow deposits, as defined by Varnes (1978). Slopes that are underlain by the Morrison Formation are particularly prone to landslides because the expansive clays in the formation lose shear strength when saturated with water. Landslides may be reactivated by natural processes, but also may be reactivated or initiated by disturbance by human-induced processes such as construction of home sites or roads. Construction of large homes at the base of major landslides on the south side of Gore Creek threatens to reactivate landslides. Although the deposits at the toes of these landslides do not show signs of young movement, the upper parts of many of them do have very youthful morphologies. The exposed thickness of the map unit is as great as 10 m; the maximum thickness is possibly 45 m

Qef **Earth-flow deposit (Holocene to late Pleistocene)**—Largely unsorted and unstratified rock debris having a distinctive elongate and lobate landform. Earth-flow deposit consists largely of matrix-supported, angular clasts of the Maroon Formation (PℙPm) that are as large as 3 m in diameter. The matrix consists of sand, silt, and clay. The single earth-flow deposit occurs at the base of a landslide deposit and is about 1 km long and locally as narrow as 0.2 km in the west-central part of the map area in an area characterized by periglacial features. The map unit increases in thickness downhill to a maximum height of about 25 m near the toe of the deposit. Smaller, probable earth-flow deposits were not mapped, but were included in periglacial deposits (Qpg). Roads constructed across this feature have the potential of reactivating the earth flow, particularly during prolonged periods of heavy precipitation. The map unit is between about 5 and 25 m thick

QTc **Older colluvium (middle Pleistocene? to Pliocene?)**—Largely unsorted and unstratified rock debris consisting of material from the Dakota Sandstone (Kd) and Morrison Formation (Jm) in a matrix of sand, silt, and clay. The map unit appears to range from clast to matrix support. Angular to subangular clasts of the Dakota are as great as 3 m in diameter, and recognizable fragments of the Morrison are generally less than cobble size. Tweto and Lovering (1977) reported clasts of the Entrada Sandstone but none were observed in this study. The clay in the matrix has expansive qualities that were probably inherited from the smectitic clay of the Morrison Formation. The surface of older colluvium is not hummocky; except for boulders of Dakota Sandstone, the surface forms a uniform gentle slope dipping northeastward at an average of about 7°. The unit covers three large areas of bedrock, two in the northwestern part of the map area and one in the central part of the map area. The Morrison clay matrix of the ancient landslide debris makes the older colluvium highly prone to landslide reactivation to form landslide deposits (Qls) along its downslope margins. The maximum exposed thickness of the older colluvium along young landslide scarps is at least 12 m and may be as much as 25 m. However, an even greater original thickness may be inferred by boulders of the Dakota Sandstone, similar to those in unit QTc that litter the top of hill 10,325 (about 1 km south of the map center), which is underlain by the Maroon Formation (Pℙm). That hill stands about 80 m above surrounding deposits of unit QTc that cover the lower parts of the hill. Deposits may have originated from strata once above the hill, and, therefore, the deposits may been much thicker on the flanks of the hill, perhaps as thick as 80 m

Glacial deposits—Ice-deposited gravel, sand, and silt in glacial till along Piney River and its tributaries and along Gore Creek

Qtp **Pinedale Till (late Pleistocene)**—Bouldery deposits that form steep-sided hummocky lateral, end, and ground moraines in the Piney River valley and its tributaries chiefly in the northern part of the map area. Also a critical exposure of the map unit that defines the extent of the Pinedale Till along Gore Creek crops out on the southern cut of frontage road south of I-70 in the central southern part of the map area. Generally, the unit is matrix-supported, unsorted, unstratified boulders to granules in a matrix of silty, poorly sorted sand. Clasts range from rounded to angular and consist largely of foliated granite (Cross Creek Granite, Xc), migmatitic gneiss and schist (migmatite, Xm), and less abundant clasts of the Maroon and Minturn Formations (Pℙm and ℙm). Clasts are essentially unweathered, and the surface of the deposit is bouldery. Boulders of Proterozoic rocks are as great as 23 m in diameter. Although unmapped landslide deposits (Qls) and abundant colluvium (Qc) were shed from steep slopes of Pinedale Till, these colluvial deposits are either too small to map or too heavily covered with vegetation to distinguish them from till.

Landforms typical of Pinedale Till include closed depressions containing wetland deposits (Qw), elongate, smooth, streamline lateral moraines parallel to the valleys, and remnants of short arcuate terminal moraines perpendicular to the valleys. Terminal moraines have been breached by streams, but little other erosional modification is obvious. Along Piney River, about 5 km downstream from the Proterozoic-Paleozoic rock contact at the Gore fault zone, exposures of Pinedale Till at higher elevations consist largely of Proterozoic clasts (Xc and Xm) derived from cirques within Proterozoic bedrock in the adjacent East Vail quadrangle (Kellogg and Bryant, in press). However, at the base of steep valley walls of the Maroon Formation on the south side of the river, about 90% of the clasts in the till are Maroon, and toward the center of the valley, a higher contribution of Proterozoic clasts is present. Soil A horizons are thin and poorly developed, and B horizons are nonexistent to very poorly developed (pinkish gray, 5R7/1, to pale red, 5R7/2, where Proterozoic clasts dominate) and contain little clay. These B horizons acquire a deeper red color at elevations above 3,050 m (pale red, 5R7/4, to light red, 7.5R6/6). Where abundant clasts of the Maroon are in the till, the unit has a strong red color throughout, regardless of soil development. A weak E horizon at lower elevations becomes more pronounced at elevations above 3,050 m in fir and spruce forests. Pinedale Till probably includes local unmapped exposures of Bull Lake Till (Qtb).

The Pinedale Till is probably about 12–35 ka (Richmond, 1986, chart 1A). The lower limit of Pinedale glaciation is about 2,750 m along Piney River, but is as low as 2,450 m in the town of West Vail along Gore Creek. Much of West Vail is built on deposits of Pinedale and Bull Lake Tills but these are nearly completely covered by modified land-surface deposits (mls). Thickness of the map unit is difficult to determine because till is commonly draped over bedrock highs, but its maximum thickness is estimated to be about 175 m

Qtb **Bull Lake Till (late to late middle Pleistocene)**—Remnants of matrix-supported, unsorted, unstratified boulders to granules in a matrix of silty, poorly sorted sand principally in the northeastern part of the map area and along the sides of the valley that contains the town of West Vail and Gore Creek in the southeastern part of the map area. Bull Lake Till also exists north of the headwaters of Indian Creek in the central part of the map area. A probable remnant of a terminal moraine exists on the south side of Piney River 1 km upstream from the junction with Meadow Creek. Geomorphic expression of these remnants has been greatly modified by erosion, particularly along Gore Creek. Soil A and B horizons are well developed where preserved and the B horizon (weak red, 10R5/3 to reddish brown, 2.5YR5/4) has a significant clay content. Much of the town of West Vail is built on both the Pinedale Till (Qtp) and the Bull Lake Till. Locally, Bull Lake Till is also covered by thin, unmapped colluvium (Qc), stream alluvium (Qal), and small younger fan alluvium and debris-flow deposits (Qfy). Construction and landscaping have almost completely removed clear evidence of tills by covering the map unit along the Gore Creek valley floor by modified land-surface deposits (mls). On the southern side of Gore Creek below a dipslope of the Minturn Formation (ℙm), the map unit is commonly covered by massive landslide deposits (Qls) and colluvium (Qc). Bull

Lake Till is probably about 140–150 ka (Pierce and others, 1976; Pierce,1979). Bull Lake Till extends to an elevation of about 2,410 m, where it is about 2 km downstream from the only exposure of the Pinedale Till (Qtp) in the Gore Creek valley. In the Piney River valley, Bull Lake Till extends to an elevation of about 2,610 m, where it is about 1 km farther downstream than Pinedale Till. Thickness of the map unit is estimated to be as great as 25 m

Qti **Till, undivided (late to late middle Pleistocene)**—Remnants of matrix-supported, unsorted, unstratified boulders to granules in a matrix of silty, poorly sorted sand. On the steep sides of the Gore Creek valley, either erosion has modified soil profiles or colluvial deposits have covered till making distinction between Pinedale (Qtp) and Bull Lake (Qtb) deposits impossible. Locally, the thickness of the map unit may be as great as 20 m

Unsorted deposits of uncertain origin—Unsorted and unstratified boulders, sand, and silt that is both matrix and clast supported

Qpg **Periglacial deposits (Holocene and late Pleistocene)**—Bouldery deposits that form steep-sided hummocky terrain that resembles lateral, end, and ground moraines in the U-shaped valleys of Moniger Creek and Dickson Creek drainages at elevations less than 3,290 m in the northwestern part of the map area. Generally, the unit is matrix-supported, unsorted or poorly sorted, unstratified boulders to granules in a matrix of silty, poorly sorted sand. The clasts consist chiefly of debris from the Maroon Formation (PIPm) and minor debris from Mesozoic formations (Kd, Jm, Je, and ₹c) that are present at higher elevations than the map unit. Landforms typical of these periglacial deposits include closed depressions perpendicular to valley axes that contain unmapped, small wetland deposits (Qw), arcuate ridges (5–10 m high) roughly perpendicular to valley axes, and small (10–20 m high) elongate streamline ridges parallel to valley axes. Some of these elongate ridges may include small, unmapped earthflow deposits (Qef). These features are similar to many features that are common in Pinedale Till deposits (Qtp), but the Qpg deposits and landforms are at elevations that are probably too low to have formed glaciers and where there is no adjacent high-elevation area large enough for snow and ice accumulation. The possible source for snow and ice accumulation does not exceed 3,400 m and the area above 3,350 m is only about 1 km^2, probably inadequate for an ice-accumulation zone for glaciation. But these periglacial deposits were probably formed under stagnant snow and ice fields. Unit Qpg probably is partly time equivalent to Pinedale glaciation based upon youthful morphology. The map unit is about 5–20 m thick

Qdi **Younger diamicton (Holocene to middle? Pleistocene)**—Unsorted and unstratified bouldery gravel, finer gravel, sand, and silt. The map unit is both matrix and clast supported. Deposits of younger diamicton are commonly found adjacent to areas of suspected till deposits of Pinedale glaciation (Qtp), abundant landslide deposits (Qls), or colluvium (Qc). The map unit is very poorly exposed and does not display soils, weathering, or landforms that distinguish it from debris-flow deposits, landslide deposits, or glacial till; the map unit probably contains deposits of all these origins. Some Qdi deposits probably have been modified by periglacial processes and some have youthful morphologies. Thickness of younger diamicton may be as great as 35 m

Moderately sorted deposits of uncertain origin—Moderately sorted and stratified gravel, sand, and silt deposits covered in places by silty sand (loess?) deposits found downstream from periglacial deposits (Qpg)

Qo **Outwash of periglacial deposits and Pinedale Till (Holocene? and late Pleistocene)**—Moderately sorted and stratified gravel, sand, and silt deposits covered locally by 1–2 m of silty sand (loess?). Deposits occur downstream from periglacial deposits along lower reaches of Moniger Creek and Meadow Creek. Locally along Meadow Creek, some small, unmapped debris-flow deposits may also form part of the outwash deposits of Pinedale glaciation. The map unit is probably involved in small, unmapped landslides along both creeks. Unit is very poorly exposed. Maximum thickness of the map unit is about 10 m and the exposed thickness is about 3 m

Qbf **Boulder-field deposits (Holocene to late Pleistocene?)**—Moderately sorted deposits of angular to subangular boulders that contain no matrix and commonly support little or no vegetation. The most abundant boulder field deposits are found in the northwestern part of the map area where landslides have reactivated the older colluvium (QTc). The largest boulders are 3 m in diameter. These boulder fields consist entirely of Dakota Sandstone (Kd) clasts; the largest boulder field is about 100 m long. Although most of these boulder fields do not occur below steep slopes at present, they may have formed by falling off steep slopes onto thin ice or snowfields under periglacial conditions. Subsequent landslides along the margins of older colluvium (QTc) formed newer steep slopes uphill from the boulder fields, leaving boulder fields as much as 0.5 km from the modern margins of older colluvium (QTc). In the northeastern part of the map area, a few boulder fields occur along the upper part of Marugg Creek drainage; these may be related to rock falls from exposures of Cross Creek Granite (Xc) onto either glacial ice or snowfields. The thickness of the map unit may be as much as 5 m

Wetland deposits—Organic-rich, silt and sand deposits in boggy areas

Qw **Wetland deposits (Holocene)**—Organic-rich, silt, sand, and clay deposits in boggy areas and small lakes, generally formed in areas affected by glacial, periglacial, or landslide processes. Only the surface of the map unit is exposed, and that surface is commonly covered with willows, alders, and grasses. Thickness of the unit is unknown

Spring deposits—Calcareous deposits at springs

Qtu **Tufa deposits (Holocene)**—Porous, weakly to moderately indurated carbonate deposits formed by evaporation of spring water at the base of cliffs of limestone and dolomite in the Minturn Formation (ℙm) on the southwestern side of Piney River northeast of Flagstone Park. Vertically oriented tubes in the tufa are actively forming by deposition of calcium carbonate on plant stems. Unit Qtu locally includes dense, well-indurated travertine and tufa-cemented sand and gravel. The maximum exposed thickness is about 2 m

BEDROCK UNITS

Tst **Tuffaceous sedimentary rocks (Miocene)**—Very pale orange to grayish-orange-pink, poorly lithified to well-lithified, moderately well sorted to poorly sorted, calcareous silty sandstone and minor pebbly sandstone that contain minor volcanic ash and local pumice fragments as much as 3 cm long. Most of the unit has minor cement but it locally is highly cemented by both calcareous and siliceous material. Pebbles include 1- to 3-cm-diameter subrounded to angular limestone, chert, silicified siltstone, and pumice fragments; sand-size material consists of quartz, feldspar, weathered volcanic ash, and biotite. Subangular pumice fragments are suggestive of short transport, are weathered, and appear to be aphyric. Bedding is massive to thin (20 cm thick). The unit is preserved at and under the margins of older colluvium (QTc) and is locally deformed by normal faulting and tilting. The age of unit Tst is being determined, but the unit is certainly Miocene as silicic volcanism is common in the region, both within the Miocene Browns Park Formation and in other units (Mutschler and others, 1987). The thickness of the map unit is at least 60 m, but the unit has been tilted and faulted during Tertiary deformation and an unknown part of the unit is covered by older colluvium (QTc); therefore, a maximum thickness cannot be determined

Kd **Dakota Sandstone (Upper and Lower? Cretaceous)**—Crossbedded, pale-yellowish-brown, white to grayish-yellow, and light-greenish-gray, medium- to coarse-grained, silica-cemented, well-sorted sandstone and orthoquartzite interbedded with brownish-black, yellowish-gray, and sparse, pale-red-purple shale. Contains scattered lenses of chert- and quartz-pebble conglomerate; commonly a thin conglomerate bed is present at or near base of unit. Where well exposed along the small exposures on the western side of the map area, the Dakota is divisible into three unmapped parts. The upper part consists of pale-yellowish-brown, well-sorted, well-cemented, medium- to coarse-grained, blocky to massive-bedded sandstone and orthoquartzite. The middle part is interbedded, lenticular, dark-gray to brownish-black and yellowish-gray shale and lenticular, pale-yellowish brown, light-greenish- to yellowish-gray, and white sandstone. Lower part is crossbedded, thin- to medium-bedded, light-gray to pale-yellowish-brown sandstone interbedded with thin, lenticular, gray shale and sparse lenses of pebble conglomerate; conglomerate consists of black chert and quartz clasts in an iron oxide-stained matrix of medium-grained to very coarse grained, silica-cemented sand. The stratigraphic position of the boundary between Upper and Lower Cretaceous rocks is not known in this region; existing data suggest that the boundary may be present within the Dakota Sandstone (Wanek, 1953; W.A. Cobban, U.S. Geological Survey, oral commun., 1998). The map unit is highly resistant to weathering and where it is involved in mass wasting, it forms blocky landslide deposits and other blocky colluvial deposits. Commonly the Dakota is jointed, and areas below local cliffs are susceptible to rock falls. The Dakota Sandstone is present at two localities along the central western part of the map area. The uppermost part of Dakota has been removed by erosion, and the map unit thickness is about 70 m

Jm **Morrison Formation (Upper Jurassic)**—Interbedded calcareous sandstone, siltstone, mudstone, shale, and limestone. Upper 90–120 m is predominantly interbedded and lenticular moderate-red, pale-green, and grayish-purple siltstone, mudstone, and shale interbedded with greenish-gray calcareous sandstone and medium-gray limestone. Lower 30 m consists of four or more 1- to 3-m-thick, very light gray, lenticular, calcareous, fine-grained, crossbedded sandstone beds interbedded with light-greenish-gray, sandy siltstone and shale. Very light gray to white, thinly crossbedded sandstone beds in lower part can be distinguished from the white to pinkish-gray sandstone at top of Entrada Sandstone (Je) by the larger cross beds of the Entrada. Basal contact with underlying Entrada Sandstone (Je) is mapped beneath lowermost greenish-gray siltstone or shale of sandy lower part. The map unit commonly weathers to rounded slopes covered by bouldery colluvium derived from the overlying Dakota Sandstone. Shale in the map unit contains expansive smectitic clays that are conducive to landsliding. Unit is poorly exposed in map area and is present in the central western part of the map area. Total thickness of the map unit is about 130 m

Je **Entrada Sandstone (Middle Jurassic)**—Fine- to medium-grained, well-sorted, crossbedded, calcareous sandstone. Frosted, well-rounded sand grains and large-scale, low- to moderate-angle, tangential cross bedding are suggestive of dune deposits. The map unit weathers to form distinctive moderate-orange-pink, blocky to rounded cliff faces in which cross bedding is commonly obscured. Contact with the underlying moderate-red to grayish-red shale and siltstone of the Chinle Formation (₮c) is sharp and unconformable; it locally shows slight angular discordance 15 km west of the map area in the Wolcott quadrangle (Lidke, 1998). Exposures of the Entrada Sandstone are restricted to the central western part of the quadrangle. Total thickness of the map unit is about 30 m

₮c **Chinle Formation (Upper Triassic)**—Moderate-reddish-brown, grayish-red-purple, and moderate-reddish-orange, calcareous shale, siltstone, mudstone, and very fine grained sandstone. Limestone-pebble conglomerate and paleosols were not seen in the map area but are present 15 km west of the map area near Wolcott, Colo. (Lidke, 1998). The basal part of the Chinle, expressed by the blocky ledges of the Gartra Sandstone Member, consists of about 15 m of grayish-red-purple, dark-reddish-brown, moderate-orange-pink, and white, medium-grained to very coarse grained, silica-cemented sandstone that commonly contains lenses of pebbly conglomerate. The Gartra thins and becomes finer grained and less conglomeratic west of the map area (Lidke, 1998;, in press). The sharp contact of the Chinle with the underlying Maroon Formation is poorly exposed but appears to be a slight angular unconformity, along which the State Bridge Formation has been removed by erosion. The State Bridge Formation pinches out beneath the Gartra Sandstone Member several kilometers west of the map area (Lidke, in press). The Chinle Formation is present only in the western part of the map area and is generally poorly exposed. The map unit has a total thickness of about 115 m

P₽m **Maroon Formation (Lower Permian to Middle Pennsylvanian)**—Consists mostly of moderate-red, pale-red, moderate-reddish-brown, and moderate-reddish-orange, micaceous, fine-grained to very coarse grained and pebbly, arkosic sandstone interbedded with siltstone, shale, local lenses of arkosic conglomerate, and beds of light-gray to medium-dark-gray and light-brownish-gray, sandy limestone (ls). Shale is sparse and present mainly as thin beds and partings at silty tops of blocky sandstone beds. Locally, sandstone interbeds are light greenish gray to white. The Schoolhouse Member of the Maroon Formation forms the top of the Maroon Formation in the Wolcott quadrangle several kilometers west of the map area, but this grayish-orange-pink to white sandstone member pinches out abruptly in that region (Lidke, 1998) and is absent from the map area. The upper part of the formation is principally silty to fine-grained sandstone in contrast to the coarser middle and lower parts of unit. Pale-green spots and mottles are locally common in the sandstone. Toward the northeastern part of the map area closer to the Gore fault zone, the abundance, coarseness, and angularity of clasts increases. Within 1 km of the fault zone, the predominant rock is a highly arkosic conglomerate containing cobble-size clasts of Proterozoic rocks, chiefly foliated granitic rock, migmatitic gneiss, and pegmatite. Locally, the map unit forms cliffs and weathers to blocky or massive exposures. Sedimentary structures include ripple cross-laminations, low-angle parallel and tangential cross bedding, and mud cracks in siltstone and shale. Limestone interbeds are confined to lower part of unit. Generally, limestone beds were not mapped by walking out the beds because following limestone beds is difficult in the dense vegetation. Therefore, limestone beds are shown where they were observed on traverses or on aerial photographs. Limestone beds within the Maroon Formation contained no megascopic fossils. Limestone beds commonly contained conglomerate and sand clasts, but did not contain significant quantities of silt and clay particles, and these beds range from 1 to about 10 m thick. One dolomite bed (dol) less than 1 m thick is present near the base of the Maroon Formation in the southeastern part of the map area.

The Maroon Formation overlies and intertongues with the Eagle Valley Formation (₽ev) in southwestern part of map area where the base of the Maroon thickens to the northeast at the expense of the upper part of the Eagle Valley. The basal contact with the underlying Eagle Valley Formation is gradational and approximately located at the change from predominantly moderate-red, crossbedded sandstone typical of the Maroon Formation, to more tabular interbeds of pale-reddish-brown, light-brown, and pale-green fine-grained sandstone, siltstone, shale, and dark-gray limestone characteristic of the Eagle Valley Formation.

The Maroon Formation also spans the underlying 2-km-wide lateral facies change from the Eagle Valley Formation to the Minturn Formation (₽m), and rests on the Minturn Formation east and north of that facies change. The Maroon is interpreted to continue to increase in thickness across the facies change at the expense of the upper part of the Minturn toward the northeast to the projected position of the Jacque Mountain Limestone Member

(ℙmj) of the Minturn. In the eastern and northern parts of the map area, the top of the Jacque Mountain Limestone Member of the Minturn Formation marks the base of the Maroon. In the southern and southwestern parts of the map area, the Jacque Mountain Limestone is absent, making the base of the Maroon difficult to define.

The thickness of the map unit is difficult to determine because the base and the top of the unit are nowhere clearly defined without intervening folds and probable, but unrecognized, faults. Clearly, the Maroon Formation thins significantly to the northwest based on the geometry of cross section ***B–B***'. Our estimate of a maximum thickness of 1,070 m is based on the geometry of cross section ***A–A***' and the projection of the top of the unit from the R & W triangulation point south of the southern end of cross section ***B–B***'; Tweto and Lovering (1977) estimated a maximum thickness of 1,280 m near Red and White Mountain just west of the western boundary of the map area

ℙev **Eagle Valley Formation (Middle Pennsylvanian)**—Pale-reddish-brown, pale-red, medium-light-gray, light-greenish-gray, and light-brown shale, siltstone, and fine-grained to very fine grained sandstone interbedded with distinctive, dark- to light-gray, micritic to finely crystalline limestone and lenses of pinkish-gray to light-greenish gray, very coarse grained to pebbly and conglomeratic grit beds. Unmapped limestone beds range from about 5 cm to 2 m thick and are present throughout formation, but are particularly common in middle and lower part of unit. One mapped limestone bed (ls) is shown in the Eagle Valley Formation. Lenses of grit are as much as several meters thick and may represent tongues of the Minturn Formation (ℙm). Locally, the map unit contains evaporite interbeds, most of which are near the base of the map unit and are part of a 50- to 90-m-thick basal transition into thick evaporite of the underlying Eagle Valley Evaporite (ℙee) (Lidke, 1998; in press). Tweto and others (1978) first mapped the Eagle Valley Formation in this region and defined it as fine-grained clastic rocks transitional between coarse-grained clastic rocks of the Minturn and Maroon Formations and evaporitic rocks of the Eagle Valley Evaporite. Precise correlation among these Pennsylvanian and Permian formations remains unresolved. In the map area and directly west of the map area in the Edwards quadrangle (Lidke, in press), the Eagle Valley Formation and Maroon Formation intertongue at various scales. In the Edwards quadrangle west of the map area, rapid west to east thickness changes of both the Eagle Valley and Maroon Formations occurs by large-scale intertonguing across several kilometers (Lidke, in press). In part, western exposures of the upper Eagle Valley Formation are laterally equivalent to eastern exposures of the lower Maroon Formation across this region, resulting in thickening of the Maroon and thinning of the Eagle Valley Formations toward the east. In the map area, the Eagle Valley Formation changes facies to the east and north by intertonguing to become the Minturn Formation over a distance of at least 1 km, but probably less than 3 km. One tongue of that facies change occurs about 1.5 km west of West Vail as shown on the map. The maximum thickness of the Eagle Valley Formation exposed in the map area is estimated to be about 400 m

ℙee **Eagle Valley Evaporite (Middle Pennsylvanian)**—Chiefly a white to dark-gray evaporitic sequence of gypsum and anhydrite, which contains interbeds of pale-yellowish-brown-weathering, light- to dark-gray shale and argillaceous, light- to dark-gray limestone, pale-yellowish-brown very fine grained sandstone, and sparse pale-red silty sandstone. The only exposure of the evaporite occurs just east of the southwest corner of the map area, but in areas west of the map area and in the southwestern part of the map area, the Eagle Valley Formation is underlain and diapirically intruded by the Eagle Valley Evaporite. Collapse-related brecciation of evaporitic rocks and of interbedded limestone that resulted from dissolution of halite and other evaporitic rocks is common. The map unit is also commonly folded and faulted both by flow related to evaporite diapirism and by volume changes related to hydration and dehydration reactions of anhydrite and gypsum. A diapir is inferred at depth beneath the southwestern part of cross section ***A–A***' to explain chaotic deformation of the overlying Eagle Valley Formation and Maroon Formation. Map unit thickness cannot be determined from the small exposure in the southwestern part of the map area, but a minimum of 500 m is present in the Edwards and Wolcott quadrangles (Lidke, 1998; in press)

ℙm **Minturn Formation (Middle Pennsylvanian)**—Interbedded arkosic grit, sandstone, conglomerate, siltstone, shale, and volumetrically small, but stratigraphically significant, limestone and dolomite. The grit is coarse grained (coarse sand to granule), poorly sorted, subangular, and quartz rich, but it also contains abundant feldspar, muscovite, and biotite and rock fragments. Sandstone is similar to grit except by having finer grains. Conglomerate is common and contains poorly sorted, subrounded to angular, granules to cobbles of chiefly Proterozoic rocks, which include granitic rock, migmatitic gneiss, and pegmatite. It also contains minor lower Paleozoic carbonate rock and quartzite clasts. Siltstone and shale contain abundant mica and sand besides illitic clays (Raup, 1966). Colors of these clastic units differ greatly both locally and regionally. Although colors cannot be used as dependable diagnostic mapping tools, some generalizations can be made. Grayish-orange-pink, pale-yellowish-brown, brownish-gray, and light-brownish-gray sandstone and grit are common. Conglomerate colors are predominantly light brownish gray to grayish pink whereas siltstone and shale colors are predominantly pale brown to grayish red. In the more proximal facies of the Minturn Formation of the eastern part of the quadrangle, red and pink colors are relatively common near the top of the unit although brown and gray colors are dominant lower in the unit. In the western map area, gray and brown colors are the rule in the more distal facies of the map unit.

Numerous carbonate rocks occur in the Minturn in the map area. (1) The Jacque Mountain Limestone (IPmj) and White Quail Limestone (IPmwq) Members form widespread, relatively continuous limestone members. (2) The Robinson Limestone Member (IPmr) of Tweto and Lovering (1977) consists of a complex sequence of discontinuous limestone and minor dolomite beds separated by clastic rocks. (3) Numerous, thinner, less continuous, unnamed limestone beds are present in the upper part of the Minturn Formation. (4) At least one dolomite member (IPmd) is present in the lower part of the Minturn in the northwestern part of the map area. These carbonate members and beds are described separately below. Locally within the Minturn Formation, unnamed limestone beds (ls) are mapped, but unnamed dolomite beds are too discontinuous to be mapped separately. Also, because the limestone and dolomite members and beds are not continuous in many parts of the map, subdivision of the Minturn Formation into members was not attempted. In the southern part of part of the map area, only the upper part of the map unit contains limestone beds (ls) and only rarely contains thin, unmapped dolomite beds. In the southeastern part of the map area, an estimated 820 m of the map unit is exposed without exposure of thick dolomitic beds characteristic of the lower Minturn. In the southwestern part of cross section ***A–A'***, the Minturn is shown as thinning to the northeast across a facies change with the overlying Maroon Formation (PIPm), which thickens at the expense of the Minturn. At the Minturn type section about 1.7 km south of the map area (Tweto and Lovering, 1977), the thick dolomite beds are about 1,050 m below the top of the unit. Therefore, the Minturn appears to thin significantly toward the northeast where the lower dolomite beds are exposed only 380 m below the Jacque Mountain Limestone Member (IPmj). In the northern and eastern parts of the map area where the Jacque Mountain Limestone Member defines the top of the Minturn, further thinning of the Minturn toward the northeast must occur below the Jacque Mountain. Tweto and Lovering (1977) estimated the thickness of the Minturn Formation to be about 1,800 m near the intersection of Red and White syncline and line of cross section ***A–A'*** in this map area

IPmj **Jacque Mountain Limestone Member**—Light-gray to light-bluish-gray, fine-grained, partly oolitic limestone, which contains some micaceous, quartzose, and feldspathic sand-size clasts that locally are cross bedded. Where the clastic-biotite content is high, the limestone has grayish-pink mottling. The map unit contains sparse cephalopods, gastropods, and pelecypods and is the highest fossiliferous limestone in the Minturn-Maroon sequence. The Jacque Mountain is discontinuous and does not define the top of the Minturn Formation everywhere. In the Gore Creek valley, the limestone member could be traced only 1.3 km from the east border of the map area. The map unit was continuously mapped on either side of Piney River except where covered by younger deposits. Thickness of the unit ranges from 0 to about 10 m

IPmwq **White Quail Limestone Member**—Medium-dark-gray, fossiliferous and locally oolitic limestone. The map unit was recognized along the northwest side of Gore Creek near the town of West Vail and on the north and south sides of Gore Creek in the southeastern part of the map area. The unit could be traced westward only to within 1 km of the facies change from the Minturn Formation to the Eagle Valley Formation. The thickness of the White Quail Limestone Member is difficult to determine as the lower part of the unit is poorly exposed, but it is at least 2 m thick

IPmr **Limestone beds of the Robinson Limestone Member**—At least two, if not three, locally thick, light-bluish-gray to light-gray, fossiliferous limestone beds. The upper and lower limestones that belong to this member are identified on the map. Because these limestones are not continuous enough to recognize the Robinson Limestone Member in all parts of the map area, only the individual limestone beds of the member are identified. These limestone beds include intervals of clastic rocks between the limestones as defined by Tweto and Lovering (1977). The beds contain fossils of brachiopods, fusulinids, and pelecypods. Thicknesses of individual beds change considerably in relatively short lateral distances, and the beds appears to pinch out locally. The best exposures of the unit are present on the southwest side of Piney River at Flagstone Park. The thickness of individual limestone intervals of the map unit may locally be as great as 25 m

IPmd **Dolomite member**—A light-gray, light-brownish-gray- to grayish-orange-weathering, coarsely crystalline dolomite that forms bold cliffs on the southwestern side of Piney River below Flagstone Park and on either side of Moniger Creek. The unit dips to the northeast and is down dropped by a northwest-dipping normal fault so that on the northeast side of Piney River the unit is exposed just at one locality. The dolomite bed may also pinch out to the northeast. The map unit is at least 20 m thick, but its base is poorly exposed

IPb **Belden Formation (Middle and Lower Pennsylvanian)**—Shown in cross section ***A–A'*** only

Ml **Leadville Limestone (Lower Mississippian)**—Shown in cross sections only

Dc **Chaffee Group (Upper Devonian)**—Includes the Dyer Dolomite and the Parting Formation. Shown in cross sections only

O€ **Ordovician and Cambrian units, undivided**—Includes the Manitou Formation (Lower Ordovician), the Dotsero Formation (Upper Cambrian), and the Sawatch Quartzite (Upper Cambrian). Shown in cross sections only

Xc **Cross Creek Granite (Early Proterozoic)**—Grayish-orange-pink to pinkish-gray, medium- to coarse-grained, slightly foliated, somewhat porphyritic granite or granodiorite consisting of plagioclase, microcline, quartz, and biotite. Microcline phenocrysts reach 3 cm long and groundmass crystals are less than 1 cm in diameter. In the Dillon quadrangle, a granite that is not part of the Cross Creek batholith, but is similar to the Cross Creek Granite, has been dated at 1,725±Ma (Kellogg, 1997). A U-Pb zircon date of the Cross Creek Granite is being determined

Xm **Migmatite (Early Proterozoic)**—Dark-gray to medium-light-gray, migmatitic gneiss that consists of alternating, irregular-shaped, quartz- and feldspar-rich and biotite-rich layers and lenses. Although the migmatite is older than the Cross Creek Granite (Xc), its age has not been determined

Ɐ **Early Proterozoic rocks, undivided**—Shown in cross sections only

STRATIGRAPHY

Glacial deposits: In the map area, glacial deposits consist exclusively of late Pleistocene Pinedale Till (Qtp) and late middle Pleistocene Bull Lake Till (Qtb). The age of glacial deposits shown in this map is based principally on semi-quantitative estimates of the amount of clay in B horizons, the degree of weathering of clasts within the tills, and the degree of erosional modification of glacial landforms. Much of the Bull Lake Till mapped by Tweto and Lovering (1977) appears to be Pinedale Till based on the till's youthful landforms, lack of significant B horizons, and lack of weathered clasts. In the Piney River valley, Pinedale Till is present about 11 km down gradient from the major cirques in the Vail East quadrangle; the Bull Lake Till is found about 12 km down gradient from these cirques (Kellogg and Bryant, in press). In the Gore Creek valley, Pinedale Till extends about 18 km down gradient from cirques in the Vail East quadrangle, and the Bull Lake Till extends about 20 km down gradient from the cirques. We mapped minor exposures of Pinedale Till considerably farther down gradient than did Tweto and Lovering (1977), who did not recognize Pinedale Till in the Vail West part of the Gore Creek valley. Also, we found no evidence of pre-Bull Lake Till in the Vail West map area as mapped by Tweto and Lovering (1977), particularly north and northwest of Red and White Mountain in the Edwards quadrangle and south of Piney River. In the northeastern part of the map area, most of Tweto and Lovering's pre-Bull Lake Till probably is Bull Lake Till. In the northwestern and central western parts of the map area, these deposits commonly have very youthful morphologies and are interpreted as young deposits such as periglacial deposits (Qpg), landslide deposits (Qls), earth-flow deposits (Qef), and younger diamicton (Qdi).

Periglacial deposits: Near the western border of the Vail West map area, directly east of Red and White Mountain, which is 0.6 km west of the western boundary of the map area in the Edwards quadrangle, periglacial deposits cover valley floors below shallow, sloping, cirque-like landforms. These deposits must have originated from the very limited highlands (about 1 km^2) of the 3,400-m-high Red and White Mountain. The floors of these shallow cirque-like landforms at the heads of Moniger and Dickson Creeks are at 3,230 m and slope at least 8° rather than having nearly flat floors of true cirques. In contrast, in the Gore Range in the Vail East quadrangle, the average elevation of true cirques is 3,440 m and vast highlands surpass 3,950 m. Thus, the highlands of the Gore Range are as much as 550 m higher than Red and White Mountain, and the true cirques of the Gore Range are at least 200 m higher than the shallow, sloping, cirque-like landforms on the eastern flanks of Red and White Mountain. Therefore, the unsorted boulder deposits of Moniger and Dickson Creeks are probably not glacial tills, but deposits formed by periglacial or solifluction processes, perhaps under stagnant ice fields or snowfields (R.F. Madole, emeritus USGS, written commun., 2000). The sides of Moniger and Dickson Creeks contain numerous landslide deposits (Qls), colluvium (Qc), and younger diamicton deposits (Qdi) that have greatly modified or covered the map unit leaving only remnants in the center of the valleys.

Earth-flow deposit: One of the many landslide deposits in Dickson Creek is a classic example of an earth-flow deposit (Qef) as classified by Varnes (1978). The map unit landform is similar to landforms reported in historic landslides near Manti, Utah (Fleming and others, 1988), at Ephraim

Canyon, Utah (Baum and others, 1993), and near Lake City, Colo. (Varnes and Savage, 1996).

Older colluvium: The source of Dakota Sandstone (Kd) and Morrison Formation (Jm) debris that forms the older colluvium (QTc) presents an interesting problem. Two small exposures of the Dakota and Morrison form the stratigraphically highest bedrock units in the map area; these exist uphill from several, relatively large areas of older colluvium. Along the western border of the map area, a small 0.02-km^2 exposure of Dakota Sandstone exists uphill from an exposure of unit QTc, which has an area of about 2.5 km^2. A few kilometers to the east, another small 0.04-km^2 exposure of Dakota is found uphill from an exposure of unit QTc, which has an area of about 3 km^2. But a third exposure of unit QTc, which has an area of about 2 km^2 in the central part of the map area, has no uphill source of Dakota Sandstone or Morrison Formation. Clearly, the first two source areas presumably represent small remnants of more extensive source areas, where landsliding caused by failure in weak smectitic-rich Morrison under the Dakota progressively diminished source areas. This process has progressed further in the central part of the map area, destroying nearly all evidence of the source area. The highest topographic and stratigraphic feature in the central part of the map area is hill 10,325, which is partly surrounded by an apron of older colluvium. The top of the hill is underlain by the upper part of the Maroon Formation (PIPm). This hilltop and its upper slopes are littered with large Dakota Sandstone boulders similar to those within the older colluvium. It is likely that when the last vestiges of Dakota and Morrison above hill 10,325 were carried away by landslides, leaving a blanket of QTc on the flanks of the hill, erosion left only a lag of Dakota boulders. Unit QTc is old enough so that no landslide landforms remain; the deposits form a 10- to 25-m-thick veneer above an early Pleistocene or late Pliocene pediment surface, which dips at 7° toward Piney River. Before the older colluvium was dissected into its three remnants, it probably covered an area of at least 25 km^2.

Older diamicton: The older diamicton (QTdi) contains clasts of basaltic rock and Dakota Sandstone (Kd) on the north side of Piney River and clasts of basaltic rock on the south side of Piney River. No basaltic rock exposures exist in the map area that might have been the source of the old diamicton on the south or north side of Piney River. The closest uphill exposures of the Dakota Sandstone occur 5.5 km northwest of Piney River in the adjacent Piney Peak quadrangle. The closest exposures of basaltic rocks are only 6 km to the north of the northern exposure of QTdi in the map area. These lava flows are probably continuous with those 21- to 24-Ma basaltic rocks in the vicinity of State Bridge, Colo. (York and others, 1971).

Chert deposits: Locally at the exposed surface of the Maroon Formation, unusual chert deposits are found at elevations between 3,050 and 3,200 m. At one locality the chert appears to underlie the older colluvium (QTc). Areas that contain abundant, but scattered remnants of these chert deposits are found on a flat ridge near the southern half of Red and White anticline and on a flat area east and south of the centrally located hill 10,325. Although these chert deposits are unmapped because of their discontinuous and disrupted remnants, their limits are shown on the map by the dotted enclosures. Although these chert deposits replace limestone locally, most of them are associated with surfaces that are essentially horizontal and, therefore, do not coincide with sparse limestone strata that dip 5°–10°. The chert deposits appear to have formed by pedogenic processes because they are found only on flat, mature surfaces that have well-developed soils. Remnants of massive, very light gray to pinkish-gray chert layers as much as 16 cm thick are common. Age of chert deposits has not been independently determined, but the deposit underlies the older colluvium (QTc) that is probably middle Pleistocene to Pliocene in age. The formation of the chert deposits may be related to silica released during alteration of volcanic ash that underlies the chert at one locality. Another potential source of silica could be crushed quartz created during emplacement of landslides that formed the older colluvium (QTc). The flat surfaces on which chert deposit remnants are found are probably as old as middle Pleistocene or late Pliocene. If the surfaces are this old, then processes similar to those that create silcrete could have formed the deposits.

Volcanic ash: A silicic volcanic ash containing phenocrysts of sanidine and biotite was found at one locality where it is partially exposed at a road cut in the central part of the map. That locality is marked "ash" in an area of older colluvium (QTc) near the center of the map. The ash underlies the old colluvium (QTc), appears to underlie remnants of the chert deposit, and overlies the Maroon Formation (PIPm). Although its age is likely to be Miocene, similar to the ages of many silicic volcanic rocks in the region, the unit is being dated because its age will provide a maximum age for the older colluvium and possibly the silica deposits. Alteration of this ash may have supplied the silica to form these chert deposits.

Tuffaceous sedimentary rocks: Because these tuffaceous sedimentary rocks are the youngest tilted and faulted rocks in the map area, their age will provide a critical maximum age of that deformation in the area. The age of siliceous volcanic ash and pumice is probably about 22 Ma, based on the inferred age of silicic volcanism bracketed between basalts dated at 21 and 24 Ma on Yarmony Mountain, 37 km to the northwest of the map area (York and others, 1971; Larson and others, 1975). Some of these strata dip at attitudes as great as 24° to the southwest, and the faults are consistent with those northwest-striking normal faults that appear to be related to extension of the Rio Grande system.

Facies change at the base of the Maroon and the tops of the Eagle Valley and Minturn Formations: From southwest to northeast, the base of the Maroon Formation is shown to thicken by facies change by about 740 m at the expense of the tops of the Eagle Valley and Minturn Formations. This facies change is restricted to the southwestern part of the map area where the Jacque Mountain Limestone Member of the Minturn is absent. Evidence of this facies change is seen where the strike of strata in the lower part of the Maroon abuts the contact with the Minturn at a high angle about 4 km east of the southwestern corner and about 0.2 km north of the southern boundary of the map area. Farther to the northeast, the Jacque Mountain Limestone defines the top of the Minturn.

Facies change from the Eagle Valley Formation to the Minturn Formation: Only at one locality can the change from the distal facies of the Eagle Valley Formation to the proximal facies of the Minturn Formation be mapped. About 5 km eastward from the southwestern corner of the map area, a tongue of the Eagle Valley Formation that is at least 1 km long pinches out toward the northeast within the Minturn Formation.

Limestones in the Maroon and Minturn Formations: At numerous localities, mapping was unable to confirm the presence of limestone beds reported by Tweto and Lovering (1977) in both the Maroon and the Minturn Formations. The basal contact of the Maroon Formation (PIPm) with the Minturn Formation (IPm) has previously been placed at the top of the Jacque Mountain Limestone Member of the Minturn Formation (IPmj) (Tweto and Lovering, 1977). Furthermore, Lovering and Mallory (1962) used this relationship to correlate the relations of the Eagle Valley, Minturn, and Maroon Formations in northwestern Colorado. However, the Jacque Mountain Limestone Member is absent from the south-central part of the map area on the well-exposed, south-facing slope above Gore Creek. Therefore, in this area, the contact was placed with less certainty above a mottled pale-red and very pale orange sandstone zone that contains only local discontinuous 10- to 20-cm-thick lenses of limestone and one local lens of 5-cm-thick dolomite. This horizon is close to the estimated stratigraphic position of the Jacque Mountain Limestone Member. Although the Jacque Mountain Limestone Member caps the Minturn Formation under the Maroon Formation on the eastern border of the map area, the Jacque Mountain pinches out 6.5 km east of the transition between the Minturn and Eagle Valley Formations. This demonstrates the necessity of careful field mapping in addition to measuring sections to draw regional stratigraphic conclusions.

The limestone members of the Minturn Formation are not everywhere readily mappable and, therefore, there are no mappable horizons by which the Minturn can be subdivided in the map area.

Lower Paleozoic strata: Numerous exposures of lower Paleozoic strata are found in fault slices along the Gore fault zone in the Vail East quadrangle (Kellogg and Bryant, in press). Where these fault slices preserve the tops and bottoms of these strata, it is clear that lower Paleozoic strata thin appreciably and irregularly near the Gore Range from greater thicknesses found southwest of the map area, which confirms the conclusions of Tweto and Lovering (1977). Cross section ***A–A'*** shows this relationship.

STRUCTURE

The Ancestral Front Range east of the Gore fault supplied sediments that formed the Minturn and Maroon Formations indicating that the Gore fault zone was active at that time. In fact, the region east of the fault was probably uplifted periodically from the Precambrian through the entire Paleozoic Era (Kellogg and others, 2000) relative to the region southwest of the fault. Even the Triassic and Permian State Bridge Formation, which is present in the Edwards quadrangle to the west, thins and pinches out before reaching the map area (Lidke, in press). But other Mesozoic strata are present in the northern part of the Gore Range, which indicates that during most of the Mesozoic, both sides of the Gore fault were covered by nonmarine and marine sediments.

During the Late Cretaceous, the Gore fault zone became active again in the Laramide (Tweto, 1975). The folds shown in cross section ***A–A'*** (Nottingham anticline, Red and White syncline, Dickson anticline, and an unnamed anticline and syncline) and the Red Sandstone syncline that is not shown all have northwest-trending axes subparallel to the Gore fault zone and are attributed to Laramide compression. A probable monoclinal limb of a fold is well exposed in a distinct gulch cut into the Maroon Formation south of Piney River about 1 km west of the Gore fault zone. At this locality, gently southwest dipping strata closer to the fault zone roll over at the head of the gully to dip at 48° southwest. Dense vegetation cover and colluvium prevent accurately tracing the extent of this limb, but along strike on the northern side of the Piney River valley, dips change abruptly from 10° to 26°. This monoclinal limb may be a fault-propagation fold related to a small blind thrust in the Gore fault zone of deformation. The poorly defined, gentle East Meadow anticline that trends northeast has no obvious genetic relation to any tectonic event.

In the Miocene, the Rio Grande rift system broke into a series of offset extensional basins in Colorado, such as the Blue River Valley, east of the Gore Range (Tweto, 1975; Kellogg and others, 2000). During the Late Cenozoic, the Gore Range rose rapidly and was subjected to an increase in the geothermal gradient as indicated by apatite fission track ages as young as 6 million years (Naeser and others, in press). Also the range and basin experienced extension by normal faulting. Naeser and others assumed that these events are related to the rift-tectonic process that operated in Blue River Valley. This extension created a pattern of northeast-dipping normal faults in Blue River Valley in the Gore Range of the Vail East quadrangle (Kellogg and Bryant, in press). In the northwestern part of the map area (cross section ***B–B'***), relatively thin distinctive Mesozoic strata define three northeast-dipping normal faults, and at least two other normal faults that cut thick limestone and dolomite beds in the Minturn Formation in that area have the same attitudes, similar to faults in the Gore Range and Blue River Valley.

Where there is a lack of thin, distinctive Mesozoic horizons in the central part of the map area, these faults could not be projected with certainty because of the scarcity of definitive stratigraphic horizons within the Maroon (Pℙm) and the Minturn Formations (ℙm) and because of heavy vegetation and extensive thin colluvium. Only sparse limestone beds can be used to correlate strata within these redbeds. The cover makes it difficult to trace limestones except where they are several meters thick. This inability to trace thin beds may also be related to discontinuous limestone horizons. For these reasons, limestone beds are commonly shown by dashed lines except where they were well defined on aerial photographs or could be walked out. Although along cross section ***A–A'*** in the thick and monotonous Maroon Formation no normal faults were recognized with certainty, one northeast-dipping normal fault was projected from cross section ***B–B'*** to the southeast along the northeast slope of a northwest-trending ridge. We suspect that instead of this one fault shown with a large displacement along cross section ***A–A'***, it is more likely that the strain was actually distributed on numerous smaller offset faults in the central and southeastern parts of the map that have not been recognized. During mapping in the Basin and Range, abundant small-scale normal faults that cumulatively represent a great deal of distributed strain in thin strata cannot be traced through thick, monotonous units (Scott and Bonk, 1984; Scott and others, 1995).

The amount of displacement on such faults in the map area may decrease to the southeast, but at least one northeast-dipping normal fault of unknown displacement exists south of Gore Creek. A projection of this fault toward the northwest to connect with the fault along cross section ***A–A'*** was not feasible because no break was obvious in the approximately located Maroon-Minturn contact.

Deformation related to evaporite tectonism such as evaporite diapirism or evaporite dissolution and collapse is present in the Eagle Valley area (Lidke, 1998, 2001, in press). Some of the deformation and folding of the Eagle Valley and Maroon Formations in the southwestern part of the map area suggests evaporite diapiric tectonism of the underlying Eagle Valley Evaporite, as portrayed in cross section ***A–A'*** . Specifically, note that attitudes of the overlying Eagle Valley Formation are highly irregular in the areas surrounding the small exposure of the Eagle Valley Evaporite.

GEOLOGIC HAZARDS

A summary of the map units that are associated with various geologic hazards is shown in table 3.

Landslides are common on steep slopes in the map area. South of Gore Creek, the dip slope of the Minturn Formation (ℙm) is largely covered by extensive landslide deposits (Qls) and by colluvium (Qc). Only small isolated exposures of bedrock protrude through the cover of colluvium and landslide deposits, both of which have been modified by erosion. Some of the landslides are very young, particularly those that are below the landslide scarp at exposures of the Robinson Limestone Member of the Minturn Formation near the southern border of the map area. Construction of roads and houses at the toes of landslide deposits may reactivate these landslides. In some cases, multistory houses are being built against cuts in the toes of these landslide deposits.

The steep slopes on the southwestern side of Piney River downstream from the junction with Dickson Creek also contain both young landslides and older landslides. Because the dense cover of vegetation obscures landslide features in aerial photographs, younger landslides can be distinguished from older only by direct field observation. The steep sides of Moniger Creek, Dickson Creek, and the South Fork of Dickson Creek in the west-central part of the map area have numerous landslide deposits that involve periglacial deposits. In one example, a debris-slump landslide is above the head of an earth-flow landslide deposit. In another case, abrupt drops of 4–15 m commonly mark the down-

Table 3. Geologic hazards and related map units in the Vail West quadrangle, Eagle County, Colorado

Erosion				Volume change		Debris-flow deposition	Flooding	Evaporite-related collapse
Mass wasting		Gullying	Piping	Hydro-compaction	Expansive materials			
Qls	Qc	Qfo	Qfo	Qfy	Jm	Qfy	Qfy	ℙee
Qef	Qpg	Qfy			QTc	Qfo	mls	ℙev
Qdi	Qfo	Pℙm			Qls	Qls	Qal	
Qfy	QTc	ℙm				Qc	Qc	
Kd	Jm							
Pℙm	ℙm							

slope contacts between older colluvium (QTc) and landslide deposits (Qls) in the northwestern part of the map area. Contours do not reflect these topographic features because they are hidden by extensive vegetation. Areas underlain by landslide deposits (Qls) can be recognized in aerial photographs by the presence of aspen groves whereas older colluvium (QTc) is usually covered by conifers. Scarp symbols are not shown at these localities because of the absence of topographic expression on maps and aerial photographs and because of the impracticability of walking out all scarps. Much of the area containing landslides is part of the White River National Forest, where activities such as construction of logging roads have the potential of reactivating preexisting landslides or triggering new landslides in older colluvium and periglacial deposits.

Steep slopes on either side of the town of West Vail create the potential of rock falls that can transport large boulders into the town. Also, steep slopes that are relatively free of large trees have the potential of snow avalanches during the winter and may have the potential of debris flows during periods of heavy snow melt or during prolonged heavy rain.

In the town of West Vail, houses and apartments have been built adjacent to creeks where they exit from steep terrain to the north into the Gore Creek valley. At these localities, particularly at Red Sandstone Creek, serious hazards from flash floods exist. The lower parts of Buffer Creek and Nottingham Gulch are also areas of potential flash flooding. Significant debris flows may occur on higher slopes in these drainages, particularly if wildfires destroy vegetation.

Piping occurs in the fine-grained material in older fan alluvium and debris-flow deposits (Qfo) and hydrocompaction may occur in younger fan alluvium and debris-flow deposits (Qfy).

Smectitic clays in the Morrison Formation (Jm) expand when saturated with water, and landslide deposits that contain Morrison clays have the same properties. The older colluvium (QTc) has a matrix containing Morrison clays. All these units have the potential to disrupt foundations of structures and create hazardous, slippery, dirt roads during wet periods.

In Eagle Valley in the southwestern part of the map area, the Eagle Valley Evaporite (ℙee) probably underlies surficial deposits as indicated in cross section ***A–A'***. Ground subsidence related to dissolution of evaporite is a potential geologic hazard in this area underlain by the evaporite and the Eagle Valley Formation (ℙev). The highly erratic attitudes of strata in the southwestern part of the map area are indicative of past subsidence.

ECONOMIC RESOURCES

The most valuable geologic resource in the Vail West area is the intrinsic beauty of the mountains that attracts many tourists to the map area during the summer months in addition to those that use the ski area south of Gore Creek in the winter. The younger terrace deposits (Qty) in the southwestern part of the map area are being used as gravel resources. Although local gravel deposits in the Gore Creek valley are associated with tills and reworked tills that contain gravel and large Proterozoic boulders, housing and commercial development cover most of these deposits. Pinedale Till (Qtp) on either side of Piney River is a potential source of gravels.

The potential for an economic mineral deposit is suggested by the presence of chrysocolla in small veins in altered Minturn Formation (ℙm) southwest of the end of the East Meadow anticline on the south side of Piney River; the locality is marked by a prospect pit symbol. Also in the bottom of the narrow valley to the northwest of the prospect pit, a short adit was dug on the northwest side of a stream into an extensive complex of gossan, but no zone of nonoxidized mineralization was encountered. This area has been broken by numerous small Tertiary(?) faults that are probably related to the extension in Blue Valley, part of the breakup of the Rio Grande rift system in Colorado. Possibly this hydrothermal alteration is related to thermal events associated with the higher geothermal gradient proposed by Naeser and others (in press) for the Gore Range. Therefore, the mineralization is probably Tertiary.

ENVIRONMENTAL ISSUES

Clear-cutting in the White River National Forest has created several environmental issues. First, clear-cut areas increased exposure of Maroon Formation (Pℙm) to erosion that added significant silt and clay loads to stream systems in the map area to the detriment of aquatic life. Much of the added sediment load forms terraces along stream courses. The soil and loose rock in the exposed clear-cut areas and the greater abundance of loose terrace deposits adjacent to streambeds have the potential to be removed as debris flows during periods of heavy precipitation. Numerous wetlands have been disturbed by vehicle and log tracks made during clear-cutting. Also, the resulting enhanced erosion has degraded wetlands by clogging them with fine sediment. Similar erosion and degradation of steep slopes of the Maroon Formation is likely where excessive grazing of sheep herds has occurred.

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