GEOLOGIC MAP OF THE SILVERTON AND HOWARDSVILLE QUADRANGLES, SOUTHWESTERN COLORADO

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INTRODUCTION

The Silverton and Howardsville 7.5-minute quadrangles (Luedke and Burbank, 1996a,b) are located in the western San Juan Mountains of southwestern Colorado (fig. 1 and map sheet). Together they include about 305 km^2 (110 mi^2) of rugged mountainous terrain at altitudes ranging from about 9,000 ft in the Animas River canyon, at the south edge of the map, to 13,552 ft on Tower Mountain in the north-central part. The Continental Divide crosses the southeastern corner of the map area with the headwaters of the eastward-flowing Rio Grande in the basin just east of Canby Mountain; most of the map area, however, is a part of the westward-draining Colorado River system. Steep valley walls below timberline (about 11,500 ft), particularly many north-facing slopes, usually are covered with dense timber and underbrush; geologic features may be obscured by this cover and, locally, by a veneer of iron-cemented rock debris and overlying soil.

Howardsville, the first of the very few towns to be sited within the map area, is located in the Animas River valley at its confluence with Cunningham Creek. For a short period of time in the middle 1870's, it was the county seat of the newly formed La Plata County in southwest Colorado. In its heyday in the 1880's, the town had a population of about 300 people, most of whom were engaged in mining and related industries (Ayers, 1951). A few kilometers to the west, also in the Animas River valley at its junction with Mineral Creek and located on the flats locally known as Bakers Park, is the town of Silverton, which now is the only commercial center within the map area. Silverton became the county seat of San Juan County when formed from La Plata County in 1878 (Henderson, 1926). In the ensuing years, the town survived the fluctuating economics of the mining industry. Although mining activity is currently at a low ebb, the town today is a thriving, active community. During the summer months, it is the midday terminal of the Durango-Silverton narrow-gauge railroad, a popular tourist excursion.

The earliest areal geologic mapping in this area, done by Cross and others (1905), subsequently was included in more comprehensive reports of the entire San Juan Mountains region by Cross and Larsen (1935) and Larsen and Cross (1956). Prior to that time, most articles and reports on the geology of the area were of a general nature only, but included a few notable reports (Endlich, 1876; Comstock, 1883; Rickard, 1903). The first detailed geologic mapping was by Burbank (1933) which later was augmented by Varnes (1963); academic studies include those of Schwarz (1967) and Spoelhof (1974). Our geologic map includes modifications of all of those reports, and is a part of a larger study of the western San Juan Mountains (fig. 1).

GEOLOGIC SETTING

Exposed pre-Tertiary bedrock, consisting of Paleoproterozoic (Plumb, 1991) igneous and metamorphic rocks and Paleozoic sedimentary rocks, is found mainly in the southern part of the map area. A thick assemblage of Paleozoic and Mesozoic sedimentary rocks that at one time covered the western San Juan Mountains region was mostly removed by extensive erosion in part during the Rocky Mountain orogeny at the close of the Paleozoic Era and in part during the Laramide orogeny at the end of the Mesozoic Era. The resultant early Tertiary erosional surface is unconformably overlain by a thick and widespread sequence of predominantly Tertiary volcanic rocks. Throughout the area, the entire rock assemblage was intruded by Tertiary igneous dikes, sills, and irregularly shaped plutons. The area was extensively eroded and glaciated in Pleistocene time, and now is locally blanketed by a variety of surficial deposits.

The metasedimentary and metavolcanic rocks, representative of the Paleoproterozoic units exposed more extensively in the Needle Mountains and vicinity to the south of the map area, consist dominantly of thin to thick bands of foliated plagioclase-quartz-biotite gneisses, thinner bands of mica schists, and garnet-bearing amphibolites. This metamorphic rock complex was intruded by dikes and small bodies of so-called granite and dikes of diabase.

The Paleozoic stratigraphic section ranges in age from Cambrian through Permian and consists of mainly clastic, but with some carbonate, sedimentary rocks. The layered sedimentary rocks regionally dip westward except south of the entrance to the Animas River canyon south of the town of Silverton, and in the down-dropped block (graben) near the south end of Cunningham Creek gulch.

Except for limited outcrops of a sedimentary unit at the base, rocks of Tertiary age consist predominantly of (1) a thick assemblage of volcaniclastic rocks of intermediate composition in the lower part; (2) volcaniclastic rocks, lava flows and breccias, and both air-fall and ash-flow tuffs of mafic to silicic composition in the middle part; and (3) welded ash-flow tuffs of silicic composition in the upper part. Sources for most of the volcanic rocks were volcanic centers in or near the western San Juan Mountains.

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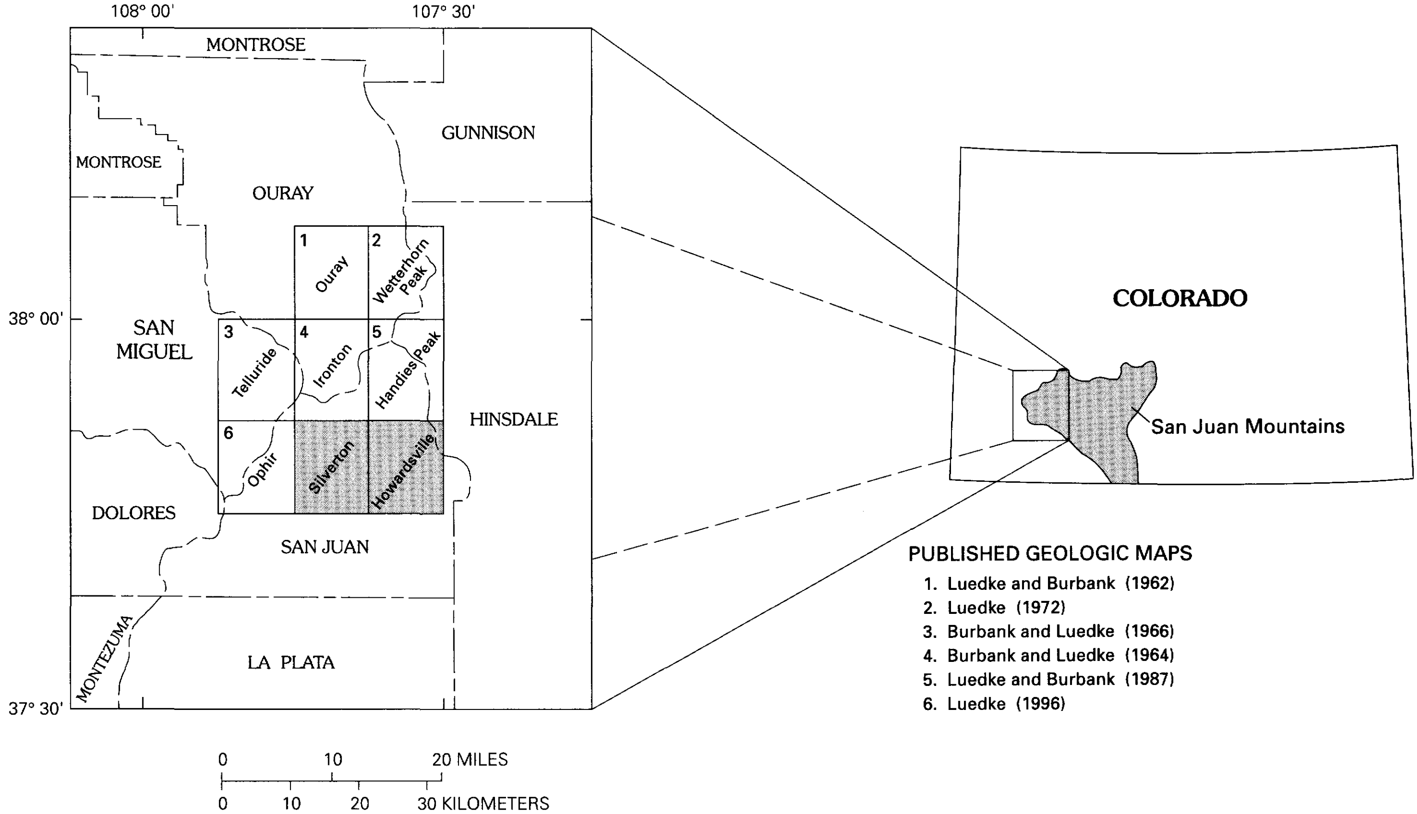

Figure 1.—Index map showing the location of the Silverton and Howardsville 7.5-minute quadrangles (shaded) with respect to related quadrangles studied in the western San Juan Mountains of southwestern Colorado

Middle to late(?) Tertiary igneous dikes, sills, and small round to irregularly shaped bodies of mafic to silicic, but dominantly intermediate, compositions have intruded the bedded sedimentary and volcanic rock sequence. The larger intrusive bodies are all located within or near the ring-fault zone of the Silverton caldera (fig. 2 and geologic map); they include the Sultan Mountain stock (D, fig. 2), an unnamed stock in the west-central part of the map, and the dike east of Howardsville. These igneous masses were emplaced about 26 Ma (McDowell, 1971; Jackson and others, 1980). The Sultan Mountain stock is a composite intrusive mass, but was not differentiated in the field, the rocks are mainly intermediate in composition. The unnamed stock is more silicic in composition and composed of more uniformly textured rock. Contact metamorphism of the country rock adjacent to the intrusive bodies varies in extent and intensity, but is more common next to the two stocks.

During Pleistocene time, the region was extensively glaciated, resulting in typical U-shaped valleys, sharp peaks, narrow ridges, and many steep-walled, bowl-shaped cirques of which several contain tarns. The alpine topography created by the glacial, interglacial, and postglacial erosion locally is covered by a variety of differentiated surficial deposits.

STRUCTURE

Exclusive of the profound Precambrian deformational events, the structural features within the map area are typical of the western San Juan Mountains and are characteristic of deformation associated with two early mountain-building periods and the later eruptive volcanic and caldera-related activities. Domal uplift, folding, and faulting of the ancestral San Juan Mountains region occurred during the late Paleozoic Rocky Mountain orogeny and again during the late Mesozoic to early Cenozoic Laramide orogeny. However, these orogenic events locally are poorly represented. Structural features that best reflect these two major orogenic events are vividly displayed by the Paleozoic and Mesozoic strata in the nearby Ophir, Telluride, and Ouray quadrangles to the west and north (fig. 1) where the strata were not as extensively eroded prior to the beginning of the widespread middle Tertiary extrusive and intrusive igneous activity.

Voluminous ash-flow eruptions about 28 Ma in the western San Juan Mountains resulted in the simultaneous development and collapse of the San Juan caldera and the comparable Uncompahgre caldera to the northeast, both of which were

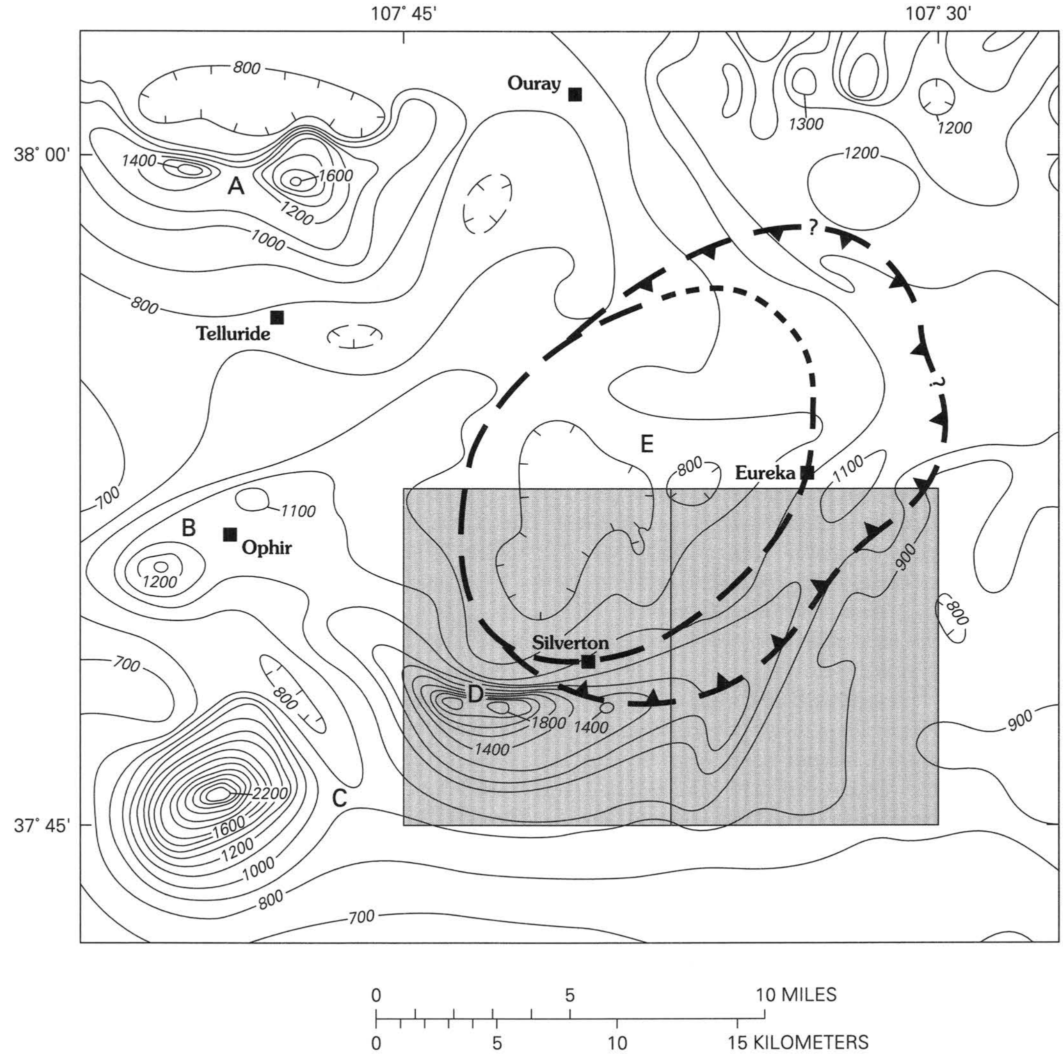

Figure 2.—Aeromagnetic map of part of the western San Juan Mountains region showing location of the Silverton and Howardsville 7.5-minute quadrangles (shaded) in relation to position of major intrusive masses and the San Juan and Silverton calderas. Contours show total intensity of the Earth's magnetic field relative to an arbitrary datum, with a contour interval of 100 gammas; hachures indicate closed areas of lower magnetic intensity. Points of reference: A, Mount Sneffels stock; B, Ophir stock; C, Grizzly Peak stock; D, Sultan Mountain stock; E, Silverton caldera (heavy dashed line); F, San Juan caldera (barbed heavy dashed line). Modified from U.S. Geological Survey (1972).

centered within a cluster of central-vent volcanoes of early Oligocene age (Luedke and Burbank, 1968; Steven and Lipman, 1976). Resurgent doming of these two calderas occurred as post-collapse lavas and volcanic sediments filled the calderas; this resurgence resulted in local angular unconformities, radial and concentric fracturing of the rocks both within and marginal to the central domal uplift, and the beginning of the development of longitudinal distention along the crest of the dome. Renewed ash-flow eruptions about 27 Ma resulted in an apparent trapdoor subsidence of the Silverton caldera (Steven and Lipman, 1976) within the older San Juan caldera, and the subsequent formation of the deeply faulted Eureka graben. This graben extends northeastward from about the center of the western calderas to where it was cut off 4 m.y. later by the much younger Lake City caldera nested within the Uncompahgre caldera (Lipman, 1976; Steven and Lipman, 1976).

Within the map area, the principal structural features are those associated with the nested San Juan and Silverton calderas; these features are continuous into the Ironton and Handies Peak quadrangles to the north (fig. 1). The caldera margins consist of zones of faults and fractures enclosing fault-block segments, many of which are semicircular or scallop shaped; the highly fractured and broken country rock provided an easily penetrable route for intrusive igneous material such as the dikes, stocks, and other plutons as well as for hydrothermal fluids. This extensively fractured country rock also was more easily eroded by the Pleistocene glacial activity that resulted in the U-shaped valleys of the Animas River and Mineral Creek. Structural control of the ring-fault zone, particularly along the upper Mineral Creek valley south of Chattanooga, is suggested in part by the alignment of iron-rich spring (bog) deposits.

The structural margins of the two calderas (the older, less obvious San Juan caldera and the younger Silverton caldera) are situated more or less together along the north-trending valley of Mineral Creek. The Sultan Mountain stock occupies the site where the structural walls of the calderas diverge; the Silverton caldera wall trends northeasterly along the Animas River valley, whereas the San Juan caldera wall trends southeasterly through Kendall Mountain and Kendall Peak, approximately in line with the Titusville dike and vein system, into Arrastra Basin and then easterly through Royal Tiger Basin. It then curves northward to intersect the valley of Cunningham Creek near the mouth of Dives Basin where a near-vertical wall of Tertiary welded ash-flow tuffs against Paleoproterozoic metamorphic rocks is exposed. The structural wall of the caldera, perhaps in part a topographic wall, can be seen underground in the workings of the Highland Mary mine (Varnes, 1963, pl. 3). The vertical to steeply dipping contact between Paleoproterozoic metamorphic rocks and Tertiary volcanic rocks trends northerly along the valley of Cunningham Creek and is traceable underground from within both the Green Mountain mine (Hagen, 1951) and the Pride of the West mine (Cook, 1952; Varnes, 1963, pl. 5), to surface exposures in Stony and Rocky Gulches, and again underground in a crosscut tunnel to the Gary Owen mine in the upper workings of the Old Hundred mine. The projection of the structural wall can only be surmised northeastward to exposures in the valley of Snare Creek and Cuba and Boulder Gulches beyond the northeast corner of the geologic map. The wall probably is located about where the 10,000-ft contour line intersects the creek in Maggie Gulch and about where flows and tuffs in the Henson Member and unnamed pyroxene andesite member of the Silverton Volcanics dip steeply northwest on the east side of Minnie Gulch; it may be reflected by the northeast-trending mineralized fault from the Kitti Mack mine towards the map corner. The unconformable and depositional topographic wall of the San Juan caldera is as much as 1.5 to 5.0 km outside the probable trace of the structural wall.

The valley trend of Cement Creek, north from the town of Silverton to the map edge, parallels the valley trend of Mineral Creek to the west. The block of ground that forms the ridge of Anvil Mountain between the two valleys is extensively silicified and altered; this block is reflected partly by the magnetic low in the southwest portion of the caldera (fig. 2). Cement Creek valley probably is in part structurally controlled, but no significant structures were discernible in the field.

An east-west-trending fault with at least 120 m of displacement (north side down) is aligned with the Middle Fork of Mineral Creek in the west-central part of the map area. This fault cuts the ridge of Anvil Mountain just south of Ohio Peak. Another east-west-trending fault that partially cuts the ridge, but with less displacement and with the south side down, trends along Mill Creek in the northwest corner of the map. The lopsided graben block defined by these two bounding, east-west-trending faults is in general alignment and with similar displacement to the major zone of weakness that controls the east-west trend of the valley of Howard Fork described in the adjoining Ophir quadrangle to the west (Luedke, 1996).

Numerous, mostly mineralized faults and fractures with varying, but usually small, displacements occur throughout the map area and are believed to be mostly related to formation of the younger Silverton caldera; they are principally radial or concentric to that caldera. The complex fracture systems developed within the map area, particularly in the volcanic rocks, have been analyzed in two different places: (1) Varnes (1962) described and discussed the structural patterns in the south-central part of the area, southeast of Silverton between the valleys of the Animas River and Cunningham Creek that includes the Arrastra Basin area previously described by Burbank (1933). (2) Schwarz (1968) discussed similar structural patterns in the Minnie Gulch area in the northeastern corner of the map.

GEOCHEMISTRY

Whole-rock chemical analyses for major oxides and trace elements were obtained for 29 rock samples (table 1) collected from the Silverton and Howardsville quadrangles. All analytical determinations (see Baedecker, 1987) were done in laboratories of the U.S. Geological Survey as follows: major oxides by rapid-rock analysis (analysts, L. Artis, S.D. Botts, G. Chloe, P.D.L. Elmore, J. Glenn, J. Kelsey, and H. Smith); trace elements by semiquantitative spectrographic analysis (analysts, J.L. Harris, R.T. Hopkins, and B.N. Rait). These 29 chemical analyses are in addition to 23 other analyses from these two quadrangles that previously were published in Van Horn (1900), Cross and others (1905), Varnes (1963), and Barker (1969).

Intrusive rocks within the map area may be included within two principal lithologic groups or types: (1) dominantly medium grained, equigranular to locally porphyritic rocks such as granite (Tig), quartz monzonite (Tip (field classification)), and granodiorite (Tim) in the form of stocks, irregularly shaped plutons, dikes, and sills; and (2) dense to very fine grained, locally porphyritic rocks mapped as andesite (Tia), dacite (Tid), and rhyolite (Tir) in the form of small irregularly shaped masses and dikes. Most of the analyzed samples of the first group of intrusive rocks, classified according to the system of the International Union of Geological Sciences (IUGS) (Streckeisen, 1976), cluster in the lower right part of the monzogranite field (fig. 3). Sample 23 represents a mafic inclusion within the Sultan Mountain stock and plots as a quartz monzodiorite. Analyzed sample 29 from a rhyolite dike (Tir), or small intrusive plug, in the southeastern corner of the map area actually plots in the granodiorite field in figure 3 or as a trachyte (a trachydacite because normative quartz is greater than 20 percent) in figure 4.

The volcanic rocks range in composition from basaltic andesite to rhyolite (fig. 4) and were classified also according to the IUGS system (Le Bas and others, 1986); as indicated, they are mostly subalkaline according to Irvine and Baragar (1971). All of the volcanic rocks in table 1 are high-potassium andesites, dacites, and low-silica rhyolites (Peccerillo and Taylor, 1976). Most of the analyzed samples cluster near the trachyandesite-andesite boundary, and represent lava flows and breccias from the Burns Formation (Tsb) and the pyroxene andesite member

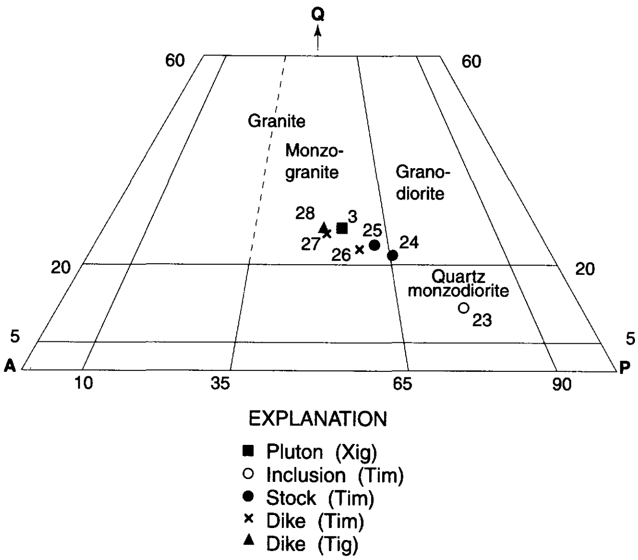

Figure 3.—Ternary variation diagram of quartz (Q), alkali feldspars (A), and plagioclase (P), according to International Union of Geological Sciences classification and nomenclature (Streckeisen, 1976), showing analyses of intrusive rocks from the Silverton and Howardsvillle quadrangles. Numbers correspond to samples in table 1. See Description of Map Units for explanation of map-unit symbols.

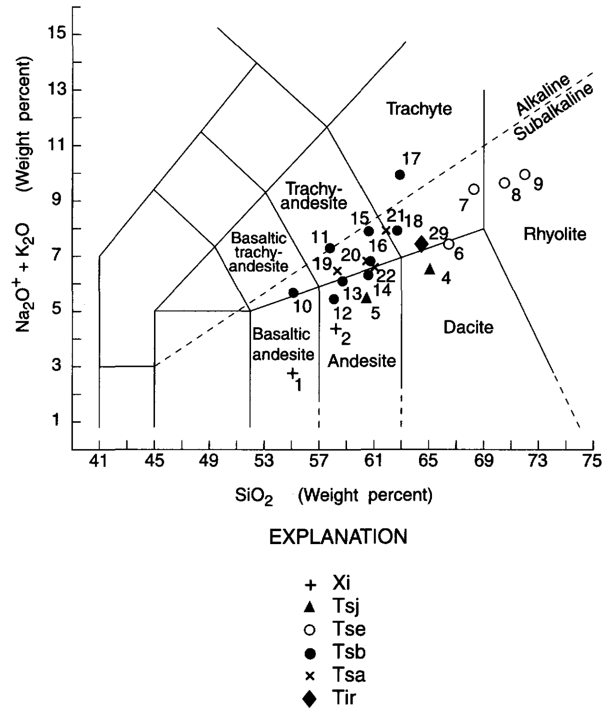

Figure 4.—Total alkali-silica variation diagram with International Union of Geological Sciences classification grid (Le Bas and others, 1986) showing analyses of extrusive rock samples from the Silverton and Howardsville quadrangles. Alkaline-subalkaline division is that of Irvine and Baragar (1971). Major-element oxides were recalculated to 100 percent volatile free. Numbers correspond to samples in table 1. See Description of Map Units for explanation of map-unit symbols.

(Tsa) of the Silverton Volcanics. Samples 7 to 9 are welded ash-flow tuffs from the Eureka Member (Tse) of the Sapinero Mesa Tuff; sample 6, also an ash-flow tuff from the Eureka Member, is slightly more mafic, probably because of the numerous lithic inclusions.

Included in figure 4 with the volcanic rocks are two samples (1 and 2) of metamorphic rocks. Both samples, collected south of Silverton, are of almandine-bearing amphibolite units interlayered with metasedimentary rocks of the Precambrian Irving Formation (Xi). These amphibolites are believed to be of igneous origin, but field relations here were not clear. To determine whether these rocks were of igneous or sedimentary origin, the chemical analyses were tested statistically using the technique of discriminant functions discussed by Shaw and Kudo (1965). The discriminant function using trace elements gave positive (igneous) values for both samples, but the discriminant function using major oxides gave a positive (igneous) value for one sample and a negative (sedimentary) value for the other. Thus the statistical results did not overwhelmingly confirm the proposed igneous origin. However, a volcanic origin was suggested for similar amphibolites that exhibit relict pillow structure (Barker, 1969) where exposed within the map area in the vicinity of the Highland Mary Lakes.

MINERAL DEPOSITS

This map includes the Animas (Silverton) mining district and part of the Eureka mining district, both of which have been integral parts of the mining and milling activities in the western San Juan Mountain metal-mining region. These districts yielded mostly base- and precious-metal ores and were very prominent early in the history of prospecting, mining, and milling in the western U.S. The first group of prospectors, the Baker party, was in the current Silverton area in 1860–61 primarily in search

Table 1.—Chemical analyses of igneous rocks from the Silverton and Howardsville quadrangles

[Major oxide data in weight percent. Trace element data in parts per million; data prior to 1968, reported in percent, recalculated to agree with later analytical data. N, not looked for; bdl, below detection limit. See Description of Map Units for explanation of map-unit symbols.]

Map No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Map-unit symbol	Xi	Xi	Xig	Tsj	Tsj	Tse	Tse	Tse	Tse	Tsb	Tsb	Tsb	Tsb	Tsb	Tsb
Sample No.	67S2	63S8	67S1	69H15	65H10	92S4	69H9	92H2	92S1	62S5	62H1	68S2	84H6	67H3	91H4
Laboratory No.	W173359	W162212	W173358	W173369	W174237	W257000	W173367	W256995	W256999	W162211	W172386	W170926	W255495	W169348	W255497

SiO_2	53.70	57.70	69.70	63.60	55.20	63.40	68.20	69.50	71.00	54.50	56.40	56.80	58.00	58.70	59.30
Al_2O_3	15.00	12.50	16.40	14.80	16.40	15.50	16.00	15.20	14.80	18.10	16.40	17.00	17.10	17.20	16.80
Fe_2O_3	2.80	6.10	.60	3.50	4.60	3.20	1.60	1.50	.94	3.80	4.50	4.70	3.80	3.40	3.90
FeO	8.60	8.30	1.60	1.70	2.40	.88	1.40	.80	.60	4.60	4.10	3.60	3.60	2.60	2.30
MgO	6.00	3.10	.64	1.5	2.5	1.3	.70	.61	.48	3.60	2.40	3.20	3.10	2.10	2.40
CaO	7.90	5.40	1.20	5.40	4.10	3.10	2.00	.77	.68	6.80	5.20	5.80	5.60	5.60	4.00
Na_2O	1.30	3.80	3.70	2.90	1.80	2.60	4.50	3.00	3.80	3.00	3.50	2.70	3.30	3.40	4.10
K_2O	.63	.50	5.10	3.40	3.10	4.60	4.90	6.60	6.00	2.70	3.60	2.60	2.90	2.70	3.60
H_2O^+	1.30	.53	1.10	1.30	3.80	1.60	1.10	1.00	.48	.90	1.90	1.70	1.20	1.40	1.30
H_2O^-	.08	.23	.04	.43	1.70	.23	.02	.15	.14	.30	.21	.25	.15	.21	.40
TiO_2	.10	1.10	.30	.61	.77	.68	.39	.44	.26	1.00	1.00	.88	.87	.70	.84
P_2O_5	.17	.48	.11	.26	.35	.19	.11	.11	.05	.53	.41	.40	.36	.36	.41
MnO	.20	.20	.04	.08	.11	.08	.08	.07	.03	.16	.15	.14	.14	.14	.12
CO_2	.06	.05	.36	1.90	2.80	1.50	.04	.38	.01	.05	.05	.08	.01	1.50	1.00
Total	99.00	100.00	101.00	101.00	100.00	99.00	101.00	100.00	99.00	100.00	100.00	100.00	100.00	100.00	100.00

Ba	200	200	3000	2000	700	700	2000	1000	700	1000	1000	1000	700	700	1000
Be	0	0	0	0	0	1	0	1	1	0	1	2	1	1	1
Ce	500	0	0	300	200	N	0	0	N	0	300	500	0	200	0
Co	70	20	0	15	15	10	0	0	0	30	10	30	20	0	20
Cr	1000	5	1500	150	15	15	300	0	0	2	bdl	15	30	10	20
Cu	30	50	0	50	15	7	20	15	5	70	10	100	30	30	20
Ga	15	20	20	20	15	30	20	30	30	20	10	15	30	10	50
La	200	0	70	100	70	50	70	50	70	0	70	100	50	100	50
Mo	5	7	0	0	3	0	7	0	0	3	3	5	5	3	0
Nb	0	0	0	15	7	20	15	20	20	0	5	10	20	7	20
Ni	0	50	0	0	0	7	150	5	5	50	0	bdl	15	30	7
Pb	0	20	20	15	7	30	20	30	15	20	30	10	20	7	20
Sc	0	50	0	0	15	10	0	7	5	30	10	20	20	15	15
Sr	1000	500	1000	2000	500	500	1500	200	200	2000	700	1500	300	200	500
V	500	50	0	100	100	50	20	30	15	300	20	200	150	100	150
Y	50	50	30	70	30	20	70	20	20	30	50	50	20	50	20
Yb	5	5	2	7	3	0	5	0	0	3	5	5	0	5	0
Zr	0	200	0	0	100	200	0	150	100	200	200	150	150	200	200

Table 1.—Continued

Map No.	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Map-unit symbol	Tsb	Tsb	Tsb	Tsa	Tsa	Tsa	Tsa	Tim	Tim	Tim	Tim	Tim	Tig	Tir
Sample No.	61H1	92H5	69H13	92H6	62S4	68H16	69H27	63S5	63S4	62S1	62H2	91H1	69H5	69H8
Laboratory No.	W172363	W256996	W173368	W256997	W172390	W170922	W173370	W172391	W164779	W162210	W172387	W255496	W173365	W173366
SiO_2	59.50	61.20	62.20	56.70	58.30	58.80	60.70	58.50	64.00	64.20	66.00	66.00	72.00	64.60
Al_2O_3	17.40	17.30	17.00	16.30	16.10	17.20	16.20	16.60	15.50	15.10	15.10	15.70	14.70	16.40
Fe_2O_3	3.00	2.10	3.50	5.40	3.20	3.50	3.70	3.80	2.50	3.50	2.50	2.30	1.10	5.00
FeO	2.30	1.90	1.90	2.20	3.00	1.40	3.40	3.30	2.80	2.60	1.80	2.20	.84	.96
MgO	1.80	1.20	1.70	2.70	2.90	1.40	2.40	3.20	2.00	1.90	1.30	1.70	.35	.70
CaO	6.00	2.70	3.90	6.00	5.10	4.00	5.00	6.40	4.00	3.60	2.90	1.00	.90	3.70
Na_2O	3.40	3.80	4.10	3.20	2.60	3.00	3.10	3.80	3.30	3.00	3.30	3.50	3.80	3.80
K_2O	3.20	6.10	3.80	3.10	3.90	4.50	3.50	2.70	3.90	4.20	4.80	5.10	5.80	3.70
H_2O^+	1.40	1.40	1.30	.80	2.00	1.60	1.50	.62	.75	.61	1.50	1.60	.86	.65
H_2O^-	.25	.15	.16	1.00	.07	.77	.07	.00	.08	.26	.03	.03	.03	.15
TiO_2	.70	.61	.75	.87	.52	.66	.87	.54	.57	.60	.34	.58	.33	.80
P_2O_5	.34	.26	.32	.40	.32	.36	.38	.28	.37	.42	.25	.24	.08	.38
MnO	.18	.10	.08	.14	.18	.11	.08	.15	.10	.07	.15	.09	.04	.04
CO_2	1.40	1.50	.56	.49	1.80	2.60	.26	.05	.05	.05	.05	.01	.12	.08
Total	101.00	100.00	101.00	99.00	100.00	100.00	101.00	100.00	100.00	100.00	100.00	100.00	101.00	101.00
Ba	700	700	2000	700	1000	1500	1500	700	700	1000	700	700	2000	1500
Be	1	1	0	1	2	2	0	1	1	2	2	1	0	0
Ce	300	0	500	0	300	500	0	300	0	500	300	0	0	500
Co	10	10	15	30	15	15	30	20	15	50	10	15	0	10
Cr	7	10	70	30	15	100	50	7	10	15	7	15	100	150
Cu	30	15	20	30	15	30	50	50	30	70	20	20	5	20
Ga	10	30	20	50	10	20	15	10	15	20	10	30	20	20
La	100	50	100	50	70	150	70	70	0	70	100	50	0	100
Mo	5	0	0	5	3	3	0	3	0	3	5	5	0	10
Nb	3	20	15	20	7	10	0	3	0	0	10	20	20	0
Ni	bdl	5	0	20	bdl	0	150	bdl	0	30	bdl	7	0	10
Pb	30	30	20	30	30	30	0	30	20	30	30	50	15	15
Sc	10	7	0	20	15	15	30	15	15	15	7	10	0	0
Sr	1000	500	1500	700	1000	1000	2000	1000	700	1500	500	300	1000	2000
V	50	50	70	150	70	70	150	100	70	150	70	100	0	150
Y	30	20	70	30	30	50	50	30	30	30	30	20	70	70
Yb	3	0	7	0	3	5	5	3	3	5	3	0	5	5
Zr	150	70	0	150	150	200	200	150	200	1500	200	150	0	0

of placer gold. They followed the Rio Grande upstream to its headwaters, an arduous but accessible route, then continued via Stony Pass to the valleys of Cunningham Creek and the Animas River; this route became the principal way into and out of the area for a number of years. After the first incursion, no further prospecting was done in this area until 1870 (Cooper, 1945).

Lode mining, rather than placer mining, was quickly established to be the method for obtaining mineral wealth within this area. The Little Giant gold lode (not labeled on base map), located in 1871 northeast of Arrastra Creek gulch, was the first reported mine in the area (Raymond, 1877; Ransome, 1901, p. 19); the district's first shipment of gold ore was from this mine. However, minimal prospecting and very little new mining occurred until the spring of 1874 when the region was officially opened following ratification of a treaty between the U.S. Government and the Ute Indians. With the settlement of that agreement, prospecting began in earnest with many claims being located and mining activity increased at a rapid pace. Green & Co.'s Works established the first smelter in Bakers Park in 1875 (Raymond, 1877, p. 284). Only high-grade, near-surface, supergene-enriched ores, however, could be mined profitably because of the lack of methods for concentrating the lower grade ores, the inability to process deeper unoxidized ores, and, particularly, the high transportation costs to the nearest railhead. Ransome (1901, p. 22) reported "...ores running less than $100 per ton could seldom be handled with profit...." The mining industry was restricted in part by the lack of cheaper transportation until the narrow-gauge railroad was extended from Durango to Silverton in 1882. Also of major importance to the mining industry in the area was the simultaneous development in 1890 of milling methods by E.G. Stoiber at the Silver Lake mine in the Animas district and by J.H. Terry at the Sunnyside mine in the nearby Eureka district that permitted successful treatment by concentration and amalgamation of low-grade ores (Burbank and Luedke, 1968, 1969). Reduced shipping costs and more profitable handling of lower grade ores resulted in more mines becoming productive. Further improvement to the milling processes occurred in 1917 with the introduction of the world's first commercial lead-zinc selective flotation plant, located in Eureka (fig. 2), for the Sunnyside mine. The greater part of the area's production undoubtedly was from silver-bearing lead ores, but gold always has been an important byproduct; Prosser (1911) reported on numerous properties that produced some gold. Although the area was extensively prospected and explored, most mines have produced sporadically and only small quantities of ore. The industry, however, maintained economic viability until recently (1990's) despite the boom-and-bust periods typical of mining regions.

Many mines within the map area were inaccessible for examination, but most are believed to have been small and explored only to shallow depths; many were closed and inaccessible even at the turn of the century (Ransome, 1901). A few mines, however, did develop into major producers and were representative of the region as a whole; this was possible in part through a consolidation of properties, or as previously stated, by improvements in mining and milling methods and a reduction in transportation costs. The area's rugged topography was conducive principally to adit and tunnel-type construction and to gravity tram lines for transporting ore from mines high on the mountain slopes to the mills below in the valleys. A few mines were described and discussed in some detail by Ransome (1901), Henderson (1926), Burbank (1933), Mining World (1942a,b), King and Allsman (1950), Varnes (1963), and Musgrave and Thompson (1991). The geologic settings and ore deposits of several mines also have been the subject of academic studies (Hagen, 1951; Cook, 1952; Schwarz, 1967; Hardwick, 1984). The most recent data available on mining activities, for mainly the western part of the map area, have been summarized by Neubert (1992).

Metal-production records from mines within the map area for the early years of mining activity were included within the annual San Juan County totals. Henderson (1926, p. 216) reported the county production from 1873 to 1923 of gold, silver, copper, lead, and zinc in terms of recoverable metals totaling about $70.4 million; however, that total probably included some early ore figures from the Red Mountain district to the north. Vanderwilt (1947, p. 197) added to and extended the county total, through 1945, to more than $117 million; he (1947, p. 198) also reported metal production for the Animas district, the principal mining district within the map area (the northernmost part of the map area is a part of the Eureka district and figures for it are not included here), for the period of 1932 to 1945: 283,351 oz gold, 4,985,029 oz silver, 11,837,400 lb copper, 44,345,700 lb lead, and 10,496,700 lb zinc with a total value of $17,301,543. Based upon many sources, Varnes (1963, p. 35) updated and reported production in terms of total metals for 1901 through 1957 (with an estimate for ore produced prior to 1901) to be approximately $61 million for only the so-called South Silverton part of the mining district, and suggested that this total may be low by several million dollars. Bergendahl (1964, p. 80) estimated for the entire Silverton area a total production through 1964 of about $80,935,000, exclusive of placer production, which here is negligible. Recent literature has reported production data we consider questionable and, therefore, is not repeated here. In addition to the precious and base-metal ores, an estimated 350,000 lb of WO_3 (tungsten trioxide) was produced between 1900 and 1954 from about 24 mines within the Cement Creek drainage area in both the Animas and Eureka districts and from the Maggie Gulch area (Belser, 1956, p. 3).

Most ore production in the area was from vein deposits in Tertiary volcanic rocks within and peripheral to the Silverton caldera. Ransome (1901) described the veins as consisting of silver-bearing base metals or gold-bearing pyrite and chalcopyrite occurring in gangues of quartz, barite, carbonate minerals, and, locally, fluorite. These deposits are characteristic of veins elsewhere in the western San Juan Mountains. Varnes (1963) described the veins in the South Silverton part of the area as a complex-sulfide type and classified the ore deposits as upper mesothermal or epithermal. The mineralogy of ore and gangue samples examined from mine dumps on the Anvil Mountain-Ohio Peak ridge between Cement and Mineral Creeks indicates some production possibly was from deposits similar to the chimney or pipe deposits in the Red Mountain district to the north (Burbank, 1941). Several veins on Sultan Mountain, in the Cement Creek area, and in Maggie Gulch contain huebnerite (Prosser, 1910; Belser, 1956), and some veins on the north flank of the Animas River valley in the vicinity of Howardsville contain notable quantities of specular hematite. Exploration for porphyry-type molybdenum deposits also was conducted in the

1970's and 1980's within the areas adjacent to the granitic stock north of Sultan Mountain and northwest of the townsite of Chattanooga.

ALTERATION

Most, if not all, of the volcanic rocks within the San Juan and Silverton calderas and peripheral to them have been propylitically altered to varying degrees. This rock alteration (Burbank, 1960), caused by effusions of water and carbon dioxide, intensifies with depth, and ranges from weakly carbonatized and chloritized to locally albitized and epidotized types. The alteration probably occurred during and shortly after the magmatic resurgence of the Silverton caldera and simultaneous emplacement of igneous intrusive rocks within and near the caldera ring-fault zone. This alteration preceded vein formation and the general introduction of sulfur and metals.

Typical epithermal quartz-sericite-pyrite alteration was coextensive with the numerous stages of vein-forming solutions that yielded the many siliceous and often compound sulfide veins in the caldera area, and is generally restricted to within 1.5 m of the veins and ore bodies. This alteration was more or less associated with the introduction of ores and gangues in the vein deposits.

Several episodes of more intense hydrothermal, near-surface alteration of an advanced argillic or acid-sulfate type were then superimposed upon the earlier propylitic alteration that leached and redistributed the rock bases (Burbank and Luedke, 1961). These highly altered rocks occur in much of the Anvil Mountain-Ohio Peak ridge area between Cement and Mineral Creeks and along the Animas River valley northeast of Silverton. They consist of quartz, various clay minerals, alunite, zunyite, and pyrite. The so-called metamorphism of the country rocks and the acidic waters issuing from them were discussed at some length by Ransome (1901, p. 113–131). The mineral association of dickite, alunite, and pyrophyllite with enargite and pyrite in the chimney or pipe ore deposits is characteristic of areas that have undergone acid-sulfate alteration (Burbank, 1941; Burbank and Luedke, 1969; Luedke and Hosterman, 1971). The association of arsenical minerals in leached and oxidized ore deposits, and of arsenic and other metals in acidified mine and surface waters has long been recognized. A geochemical study by Burbank and others (1972) explored the possibility of using arsenic as an indicator element in the search for chimney or pipe ore deposits in an area where the rocks were subjected to acid-sulfate alteration and leaching. Preliminary field tests for residual arsenic proved to be a useful geochemical prospecting tool as long as the tests were intended to define specific areas, such as the relatively small pipe localities, and not to show anomalous broad halos. In addition to arsenic residuals, residual values of lead, silver, and mercury generally conform to the residual arsenic values, but copper and zinc do not as these elements are more easily leached by the acid surface waters.

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