Cenozoic geology of the Arkansas Hills region of the southern Mosquito Range, central Colorado

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CENOZOIC GEOLOGY OF THE ARKANSAS HILLS REGION OF THE SOUTHERN MOSQUITO RANGE, CENTRAL COLORADO

by

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INTRODUCTION

Location

The Arkansas Hills area is located northeast of Salida, Colorado, in the southernmost portion of the Mosquito Range. The study covers about 100 square miles within the southern half of the Cameron Mountain 15-minute quadrangle. Elevations range from about 6,800 feet at Salida to 10,993 feet atop Cameron Mountain. The major geologic features bounding the area include the upper Arkansas segment of the Rio Grande depression on the west, the Thirtynine Mile volcanic field on the north and east, and the canyon of the Arkansas River on the south. Adjacent communities include Salida, Wellsville, Howard, Cotopaxi, and Guffey. Accessibility is provided mainly by the Ute Trail, which connects Salida with Colorado State Highway 9, and by numerous mining and logging roads which branch from it (see figure 1).

Pre-Cenozoic Rocks

The pre-Cenozoic rocks in the Arkansas Hills area range in age from Precambrian to Permian and include rocks from all periods of the Paleozoic Era except Cambrian and Silurian. The Precambrian rocks consist, for the most part, of metamorphics which have been intruded by granitic and gabbroic bodies and invaded by their associated dikes and sills. Unconformably overlying the Precambrian erosion surface is a Paleozoic section which includes, from bottom to top; Manitou Dolomite (Early Ordovician), Harding Sandstone (Middle Ordovician), Fremont Dolomite (Late Ordovician), Chaffee Formation (Devonian), Leadville Limestone (Mississippian), and a very thick sequence of Permo-Pennsylvanian strata. Preservation of blocks of Paleozoic strata is largely due to down faulting during Late Paleozoic and Late Cretaceous-Early Tertiary orogenies and subsequent burial by Cenozoic sediments and volcanic rocks. Pre-Cenozoic stratigraphic and structural features are shown on the enclosed geologic map, (see back pocket).

Pre-volcanic Erosion Surface

The Arkansas Hills are located on the western edge of an extensive pre-volcanic erosion surface described by Epis and Chapin (1968, p. 56-59). This surface covers an area of about 5,000 square miles and extends from the foot of Kenosha Pass in northeastern South Park to the northern Wet Mountains and the Wet Mountain Valley. In an east-west direction it stretches from the upper Arkansas
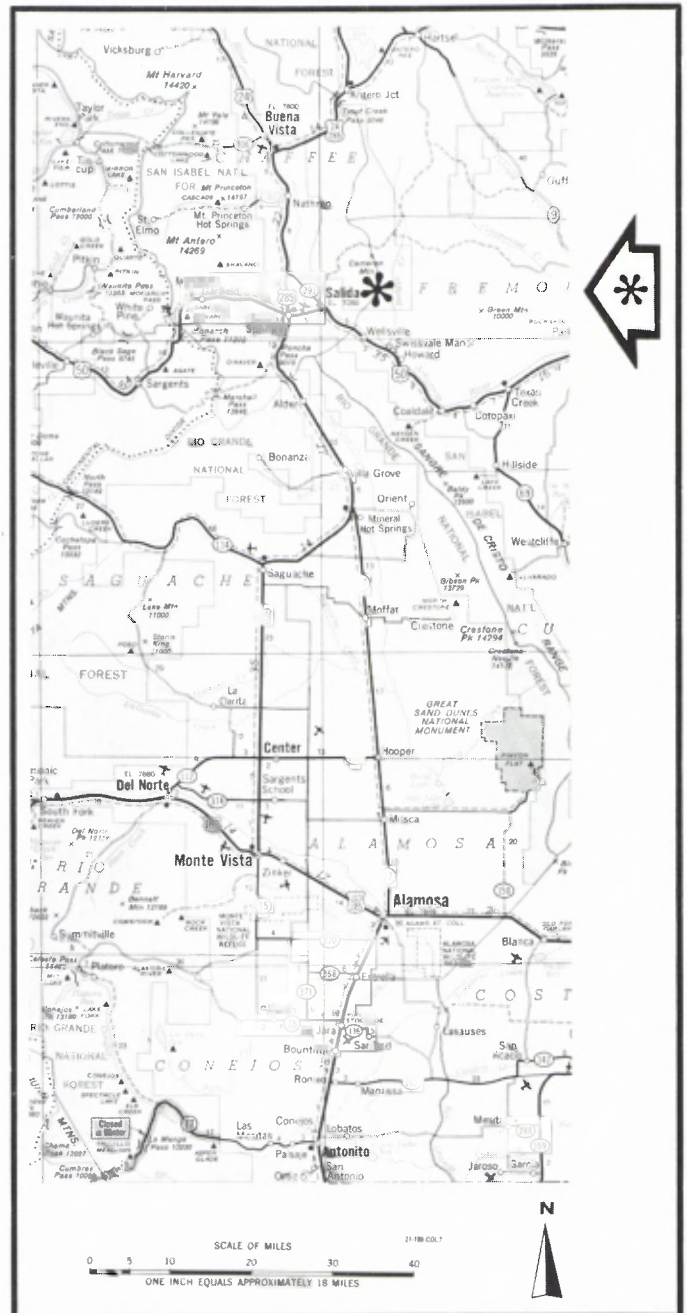

FIGURE 1.

Location map.

Valley to the Cripple Creek area, a distance of about 50 miles. According to Epis and Chapin (1968, p. 57) the pre-volcanic erosion surface was a relatively smooth plain of low relief upon which small hills, as much as 800 feet high, were present. The surface slopes southward from an elevation of about 9,500 feet in South Park to about 8,500 feet in the northern Wet Mountains. The erosion surface appears to have formed by Middle to Late Eocene time and was subsequently broken by Late Cenozoic faulting (Chapin, Epis, and Lowell, 1970).

In the area of investigation, volcanic rocks preserve an anomalous drainage pattern which trends east-west and crosses the Laramide structural grain and the present drainage at nearly a right angle. The Salida-Waugh Mountain and Gribbles Run paleovalleys are remnants of east-flowing paleodrainages incised in the pre-volcanic erosion surface and later filled by Early Oligocene volcanic rocks (see geologic map, back pocket). The Salida-Waugh Mountain paleovalley has been traced for 11 miles from near Salida eastward to Waugh Mountain. It averages 2 miles in width and has a maximum depth of about 1,000 feet (Lowell, 1969, p. 62-63; Chapin, Epis, and Lowell, 1970). The Gribbles Run paleovalley is about 4 miles long, ¼ to ½ mile wide, and about 500 feet deep. Both paleovalleys trend east-west, have westward or northwestward-forking tributaries, and are cut by steep north-trending post-volcanic faults.

CENOZOIC ROCKS

A composite table of stratigraphic units with corresponding ages and thicknesses is shown in Table 1. A brief description of the various lithologies is given together with other pertinent data.

WHITEHORN STOCK

Prior to the onset of volcanism, granodioritic magma was intruded along the axial plane of the asymmetric Pleasant Valley syncline to form the Whitehorn stock. Sills, dikes, and apophyses pierce the inclosing rocks, particularly the Permo-Pennsylvanian strata within which laterally-continuous sills are common. The nature and significance of the dikes and abundant xenoliths have been discussed by Osborn and Rainwater (1934, p. 33-35) and Bhutta (1954, p. 85). Pyrometasomatic iron-ore deposits which formed along the contacts of the stock were described by Behre, Osborn, and Rainwater (1936).

The central portion of the Whitehorn stock is characterized by knobby, bouldery outcrops, whereas towards the periphery massive, sheeted zones are common. The rock typically has a bluish "salt and pepper" appearance on fresh surfaces and a dull greenish-gray cast on weathered or altered surfaces. The rock is holocrystalline and the grain size varies from fine to coarse. Quartz and orthoclase surround and embay the earlier-formed plagioclase and ferromagnesian minerals. Accessory apatite, zircon, and sphene are prominent in hand specimens and thin sections. A detailed petrographic analysis is given by Bhutta (1954, p. 89).

The Whitehorn stock is younger than all of the Paleozoic rocks and much of their deformation is older than the last phase of Laramide tectonism. By Late Eocene time the stock had been unroofed and beveled by an erosion surface of moderate relief.

ASH FLOW 1

The basal volcanic unit in the Arkansas Hills is an extensive (chemically rhyolitic), mineralogically latitic to trachytic, ash-flow sheet which is the earliest major extrusive rock in the adjacent Thirtynine Mile volcanic field It is a multiple-flow, simple cooling unit informally designated as Ash Flow 1 by Epis and Chapin (1968). Member flows of the cooling unit are indistinguishable in the field and generally form prominent, ledgelike exposures with a striking eutaxitic fabric. The fabric is made conspicuous by the

TABLE 1.

Cenozoic stratigraphic units in the Arkansas Hills region of the southern Mosquito Range, central Colorado.

AGE	LITHOLOGIC UNIT	THICKNESS
Quaternary	Alluvium	—
	Landslides, slump blocks, and colluvial deposits	—
Late Miocene-Pliocene	Boulder gravels	—
	Dry Union Formation	—
	Tenderfoot Hill Facies of Dry Union Formation	±450′
Oligocene-Miocene	Silicic Felsite of Section 36	0-200′
	Andesite of Big Baldy	0-200′ (?)
	Upper Andesite (18.9 ± 1.2 m.y.)*	300-1200′
	Latite of Waugh Mountain	200-700′
	Ash Flow 7 (34.8 ± 1.4 m.y.)*	+600′
	Latite of East Badger Creek	250-300′
	Tuff of Badger Creek	+313′
	Antero Formation	+368′
	Ash Flow 1 (40.0 ± 1.4 m.y.)*	Pre-volcanic Erosion Surface
	(37.3 ± 1.9 m.y. and 35.4 ± 1.1 m.y.)†	
Late Cretaceous-Late Eocene	Whitehorn stock	

* Epis and Chapin (1968)
† Van Alstine (1969)

presence of subparallel pumice lapilli. Where these lapilli have been removed by weathering, a distinctive "drill hole" appearance is imparted to the rock. The unit weathers to gray, buff, and dark-brown colors but when freshly exposed the rock has a reddish-brown to purplish, aphanitic matrix which contains large fractured phenocrysts of sanidine and plagioclase. The clear, unaltered, and often zoned sanidine phenocrysts range upward in size to a maximum of about 7 mm. Zoned plagioclase phenocrysts are usually smaller and are frequently altered to a dull white or yellowish color. Tiny flakes of oxidized biotite, 2 mm or less in diameter, are also present in minor amount. The matrix consists of devitrified glass shards and dust, irregular granophyric intergrowths, and patches of extremely fine-grained feldspar, tridymite, and cristobalite. Lithic inclusions are rare even in the basal member of the cooling unit. Welding ranges from moderate to dense within the cooling unit and a black vitrophyric zone about 3 feet thick is exposed in the east end of the Gribbles Run paleovalley. The maximum thickness of the cooling unit is about 100 feet.

Antero Formation

Overlying the Ash Flow 1 rocks throughout much of the project area is the Lower Tuff Member of the Antero Formation (Johnson, 1937; De Voto, 1964). Two major lithologic types of Antero tuff are recognized by the author in the Arkansas Hills. These are both andesitic in mineralogical composition and are termed the ash-flow tuff facies and the sedimentary tuff facies.

The ash-flow tuff facies forms the base of the Lower Member of the Antero Formation and has a measured thickness of 368 (Lowell, 1969, p. 27) east of Black's cabin (SE ¼, Sec. 7, R. 11 E., T. 50 N.). At this locality, the ash-flow tuff facies exhibits striking pinnacles of unwelded, pumice-rich, ash-flow tuff. These unwelded ash flows consist of phenocrysts of plagioclase, biotite, very minor sanidine, hornblende, and sphene in a whitish-gray matrix of glass shards. Lithic fragments, generally less than 3 inches in diameter, comprise about 1 percent of the rock and include Precambrian quartzite Paleozoic sandstones and carbonates, and porphyritic volcanic rocks of intermediate composition. Subrounded, uncollapsed pumice lumps which range in size from ¼ inch to 14 inches in diameter and contain abundant fresh biotite and plagioclase crystals may constitute as much as 60 percent of the rock. Two types of pumice are present, one pinkish orange in color, and the other white. The average size of the lithic inclusions and pumice lumps tends to increase upward through the section. Commonly, the pumice lumps are slightly flattened which imparts a very crude compaction foliation to the rock with which the lithic fragments roughly conform. The ash-flow tuffs of the lower facies weather to buff or light reddish-brown in color and often show a distinctive sheeting in weathered outcrop. Further petrographic and stratigraphic details have been compiled by Lowell (1969, p. 24-29).

The lower ash-flow tuff facies is overlain by, and grades into, the sedimentary tuff facies which consists of well-stratified, locally cross-bedded, pumice-rich and biotite-rich, tuffaceous sediment. The character of this facies varies from indurated, bluish sandstone containing altered biotite and rock fragments to extremely friable pumice beds which nearly lack clastic matrix. The sedimentary tuff facies is the predominant facies in the Gribbles Park area (northeast portion of geologic map, back pocket). It represents a combination of reworked, air-fall material and erosional debris derived from the colder, unwelded, Antero ash-flow tuffs.

Tuff of Badger Creek

The tuff of Badger Creek is the informal name proposed for the most extensive volcanic formation in the project area (Lowell 1969, p. 25). The unit overlies the Antero Formation and Ash Flow 1 in the east-trending Salida-Waugh Mountain paleovalley (see geologic map, back pocket). A compaction foliation defined by collapsed pumice is pervasive and it occasionally contains a lineation formed by the stretching of pumice lapilli. Six, dark-gray to black, vitrophyric zones have been observed at various horizons within the unit indicating a multiple-flow origin and a compound cooling history. The vitrophyric zones grade upward into moderately and slightly welded zones where pumice is more conspicuous and thin streaks of pink, siliceous spherulites are present. Where pumice has been removed by weathering, numerous tubular cavities about 1 inch in diameter present a distinctive "Swiss cheese" appearance. The weathered rock takes on a buff to yellowish-gray color. A few Precambrian lithic fragments have been observed, but the most common inclusions are angular to subrounded volcanic rock fragments of intermediate composition which average less than 2 inches in diameter. Pumice, showing all degrees of welding, may form as much as 5 to 10 percent of the unit above the vitrophyric zones. The unwelded pumice is of two colors, pinkish-orange and white in about equal abundance, both rich in biotite and plagioclase crystals.

Mineralogically, the tuff of Badger Creek is andesitic and consists of phenocrysts of plagioclase, biotite, very minor sanidine, hornblende, and sphene combined with flattened pumice and a few lithic fragments in a matrix of cuspate glass shards. The glass shards show a wide range of welding and devitrification features. The unit has a measured thickness of 313 feet (Lowell, 1969, p. 35) north of East Badger Creek (Sec. 12, R. 11 E., T. 50 N.). The tuff of Badger Creek and the unwelded ash-flow tuffs of the Antero Formation are remarkably similar in mineralogy, lithic constituents, and pumice content. Kinship probably exists between the two units even though their respective emplacements were separated by an interval of erosion and reworking.

Latite of East Badger Creek

The latite of East Badger Creek is a distinctive, cliff-forming lava flow which overlies the tuff of Badger Creek along the eastern end of the Salida-Waugh Mountain paleovalley (see geologic map, back pocket). The bow is 2 to 3 miles long, about ½ mile wide, and 250 to 300 feet thick.

The rock is holocrystalline and aphanophyric, ranges in color from gray to purple, and weathers to a yellowish-brown cast. Seriate, microcrystalline feldspars comprise about 80 percent of the rock and form a pilotaxitic texture. Plagioclase phenocrysts display splotchy, irregular zoning and comprise about 10 percent of the rock. Sanidine or anorthoclase (average $2V = 49°$), forms about 8 percent of the rock and partially-oxidized biotite phenocrysts comprise the remaining 2 percent.

Ash Flow 7

A thick sequence of mineralogically trachytic to latitic ash-flow tuffs, correlated with the Ash Flow 7 cooling unit of the Thirtynine Mile volcanic field (Epis and Chapin, 1968) was mapped along the eastern margin of the Cameron Mountain quadrangle. In this region, Ash Flow 7 is a multiple-flow, compound cooling unit which forms massive cliffs along south-facing slopes.

The rock varies from dark purplish-brown to gray in color and shows a moderate to well-developed compaction foliation. Phenocrysts of sanidine, plagioclase, biotite, hornblende and sphene are contained in a glassy matrix which may variously be purple, orange, gray, or red depending upon the stratigraphic horizon (Lowell, 1969, p. 40). Pumice lumps, welded and darkened in varying degrees, are flattened into lenses averaging ¼ inch by 3 inches in cross section and may form as much as 10 percent of the rock. Angular, lithic inclusions up to 1 inch in diameter and consisting of red to black, aphanitic to porphyritic, volcanic rocks of intermediate composition are abundant. Bronzy, oxidized biotite and chatoyant sanidine phenocrysts are characteristic of the entire formation. A stratigraphic section measured north of Two Creek (Sec. 5, R. 11 E., T. 50 N.) revealed the presence of at least 4 member flows with an aggregate thickness of over 600 feet (Lowell, 1969, p. 73).

Latite of Waugh Mountain

Waugh Mountain (11,718 feet), whose western flank lies along the boundary between the Cameron Mountain and the Black Mountain quadrangles, is the dominant topographic feature in the southwestern part of the Thirtynine Mile volcanic field. A poorly exposed volcanic center near the middle of Waugh Mountain is thought to be the source of a sequence of rhyolitic to latitic flows and flow breccias 200 to 700 feet thick which occur along its western flank (Epis and Chapin, 1968, p. 73). This flow sequence, termed the latite of Waugh Mountain, overlies Ash Flow 7 and caps the ridges at the head of Two Creek along the eastern margin of the map area. The upper surface of this unit forms discontinuous patchy outcrops of resistant knobs and boulders. The formation consists of gray to pinkish-gray flows and autoclastic flow breccias which are commonly silicified. Flow bands, 1 to 4 inches thick, generally parallel the crudely-oriented breccia clasts within the framental zones.

Phenocrysts comprise 10 to 20 percent of the rock and consist of plagioclase, sanidine, and oxidized biotite in a glassy microcrystalline matrix. Trace amounts of anortho-

clase, hornblende, and sphene may also be present. Lensoid axiolitic and spherulitic zones, more or less conformable with tabular and lath-shaped minerals, define the flow structure. Where brecciation has occurred, thin stringers of calcium carbonate may envelop some of the breccia clasts. Accidental lithic inclusions are rare, but types ranging from Precambrian gneiss to Tertiary volcanic rocks have been observed.

Upper Andesite

Overlying the latite of Waugh Mountain is a sequence of andesitic and basaltic flows, flow breccias, and minor laharic breccias and tuffs which have been informally named Upper Andesite by Epis and Chapin (1968, p. 76). The estimated thickness of the unit ranges from a maximum of about 1,200 feet near Waugh Mountain, the presumed source, to less than 300 feet in the southern part of the Thirtynine Mile volcanic field. Upper Andesite rocks are present along the eastern boundary of the map area (Secs. 10, 15, and 16, R. 11 E., T. 50 N.), which is a densely-wooded region, nearly barren of outcrops, where formational contacts are largely inferred from rock fragments in colluvium. A brownish-purple, aphanophyric andesite (?) which weathers to a buff color and contains a few phenocrysts of plagioclase, pyroxene, and biotite, crops out on hill "10,660 feet." These rocks display prominent but erratic sheeting. Overlying the andesite (?) is a black, vesicular olivine basalt which contains a few pinkish-white amygdules of calcite. The thickness and areal extent of these rocks could not be accurately determined from the available outcrops.

Andesite of Big Baldy

In the southwestern portion of the map area, a number of isolated patches of similar-appearing basaltic andesites are grouped under the informal designation of andesite of Big Baldy. These rocks are younger than the Antero Formation but complete stratigraphic information is lacking. Because of dissimilar petrologic characteristics and appreciable geographic separation, no direct genetic relationship to the Upper Andesite is postulated. The relative ages of these two formations are unknown. The best exposures of the andesite of Big Baldy are in the vicinity of Big Baldy Mountain (Sec. 21, R. 10 E., T. 50 N.), where andesitic lava flows, autobrecciated and silicified in part, are interstratified with minor, variegated, andesitic boulder breccias. The breccias contain red and black porphyritic andesite (?) boulders up to 4 feet in diameter and are restricted to two small outcrops west and south of the summit of Big Baldy Mountain.

The major portion of the unit consists of purplish, aphanophyric basaltic andesite which weathers brown to black. Phenocrysts of altered and zoned plagioclase containing numerous, minute apatite inclusions form 25 to 40 percent of the rock. Small amounts of altered hypersthene, basaltic hornblende, clinopyroxene, and opaque grains comprise the remaining phenocryst portion. The matrix elements are brownish glass and plagioclase microlites

which vary in textural arrangement from hyalopilitic to pilotaxitic.

Silicic Felsite of Section 36

A highly silicified lava flow which rests upon pre-volcanic rocks or upon the andesite of Big Baldy is present in the southwest portion of the map area (Sec. 36, R. 9 E., T. 50 N.). This flow, previously described by Bhutta (1954, p. 109) as pitchstone, is referred to as the Silicic Felsite of Section 36 in the present study. The massive, purplish-gray flow is locally fractured and brecciated and forms resistant cliffs along its 1 mile length. In outcrop, flow structures and phenocryst foliations are vague and extremely erratic. Fractured, white phenocrysts of zoned plagioclase comprise less than 10 percent of the rock and are usually accompanied by a few scattered phenocrysts of oxidized biotite and opaque grains. Most of the rock consists of pinkish-brown glass which in thin section displays crude banding with which the phenocrysts do not conform. A few faintly birefringent, arborescent microlites are usually visible in thin section.

Miscellaneous Extrusive or Intrusive Rocks

Three different igneous rock types of unknown stratigraphic position occur in very small isolated outcrops within the area of investigation. For convenience, these rocks appear on the geologic map (see back pocket) under the symbol Tm (Tertiary miscellaneous). Along the upper reaches of Dead Horse Gulch (NE ¼, Sec. 22, R. 9 E., T. 50 N.) a pinnacle-forming, tuffaceous body crops out. The lithic content of this body consists of: (1) extremely abundant yellow chert; (2) numerous cognate Paleozoic fragments of all shapes, sizes, and formations; and (3) angular blocks of amygdaloidal and vesicular porphyritic rock up to 1 foot in diameter which closely resembles the andesite of Big Baldy. The rock is iron stained to a bright yellow color and displays no evidence of stratification or sorting. Probably this exposure is a portion of a small, localized laharic breccia which was emplaced during, or following, the eruption of the andesite of Big Baldy.

A small body of intrusive breccia has been mapped within the Whitehorn stock (Sec. 31, R. 10 E., T. 49 N.). The breccia consists of angular fragments of gray porphyritic rock of intermediate composition and granodiorite from the Whitehorn stock in a matrix of yellowish clay. The breccia may have formed during movement along the post-Laramide Maverick fault.

Slightly less than a mile south of the intrusive breccia and on strike with the Maverick fault is an isolated body of altered felsite. The felsite has a pinkish-orange, flow-banded matrix which contains a few altered feldspar phenocrysts. Greenish-yellow hydrothermal alteration pervades the entire outcrop. The rock is extensively brecciated and incloses abundant quartz-filled vugs. The outcrop may be either a small intrusion or a flow remnant.

Dry Union Formation

Northeast of Salida, Precambrian igneous and metamorphic rocks are unconformably overlain by sediments thought to be correlative with the Dry Union Formation of Tweto (1961, p. B-33). Van Alstine and Lewis (1960), and Van Alstine (1969) studied these sediments and their fossils in the Salida vicinity and concluded that they were of Late Miocene and Early Pliocene age. The formation consists of friable, poorly consolidated, tuffaceous and arkosic silts, sands, and gravels with thin, intercalated clays and calcareous zones. Pumice and biotite are present in the tuffaceous horizons and pebble to sand-size clasts of Precambrian metamorphic and Tertiary volcanic rocks are abundant.

Tenderfoot Hill Facies of the Dry Union Formation

The basic volcanic rocks in the Tenderfoot Hill area, just east of Salida, have been previously described by Bhutta (1954, p. 106) as intrusive andesite porphyry. In an earlier study, the writer described these rocks under the name Tenderfoot Hill Volcanic Sequence (Lowell, 1969). The same rocks are now viewed as a volcanic facies within the Dry Union Formation.

The rocks in question are part of a steep, west-dipping, interstratified sequence of basic lava flows and unconsolidated boulder gravels of Late Tertiary age. Mapping and stratigraphic measurements indicate the presence of 6 basaltic lava flows and 5 interflow boulder gravel deposits with an aggregate thickness of at least 450 feet. Stratigraphic measurements are complicated by the presence of steep faults, landslides, and alluvium so that the true thickness, as suggested in section B-B′ (see geologic map, back pocket), may be several times this value.

The lower flow members of the facies (Flows-1 and -2) are similar, black, porphyritic basalts which weather reddish brown. Approximately 25 percent of the rock is composed of phenocrysts of plagioclase, clinopyroxene, and opaque minerals. The plagioclase phenocrysts form about 20 percent of the rock and are pitted, altered, strongly zoned, and frequently contain a few tiny apatite inclusions. The clinopyroxene phenocrysts, probably augite, may reach a length of 1 inch and are often twinned and rimmed by hornblende. The matrix is pilotaxitic in texture and is composed of subequal amounts of brown glass and plagioclase microlites.

Flow-3 consists of several thin, gray to bluish gray, porphyritic flows separated by yellowish-brown soil horizons. The rock weathers to a brownish-black color and contains coarse, grayish-white, altered plagioclase phenocrysts.

Flow-4 is a thin flow of andesitic basalt whose outcrops are less resistant to weathering than other flows in the sequence. The rock varies from bluish-gray to black in color and weathers to dark brown. Conspicuous greenish and purplish altered zones pervade the outcrops. Phenocrysts of plagioclase and pyroxene (?), visible in hand specimens, are nearly always highly altered.

Flow-5 is an aphanitic, gray to black basalt which weathers to a reddish-brown color and is characterized by rubbly outcrops. The rock is strongly jointed and sheeted and exhibits numerous, small, discontinuous, red and yellow breccia zones. This flow member possesses only a few phenocrysts (less than 5 percent) of plagioclase, clinopyroxene, and opaque grains. The plagioclase crystals com-

monly display combined Carlsbad-albite twinning and may contain a few tiny apatite inclusions. The matrix is hyalo-pilitic with subequal quantities of brownish glass and pla-gioclase microlites. The cap of Tenderfoot Hill is probably a remnant of Flow-5.

The upper member of the sequence, Flow-6, is a reddish-brown to black, porphyritic, amygdaloidal, autobreccia of basaltic composition. The breccia clasts range in size up to 1.5 feet in diameter. Yellowish-white amygdules and thin stringers of calcium carbonate are abundant through-out the flow. Large, highly altered and zoned phenocrysts of plagioclase are very prominent.

The sediments interbedded with these flows are poorly sorted, crudely stratified, unconsolidated boulder gravels apparently of fluvial origin. Boulders of Precambrian meta-morphic rocks and Tertiary volcanic rocks, ranging up to 4 feet in diameter, form as much as 60 to 70 percent of the interbeds. Some of the volcanic fragments can be recog-nized as belonging to the underlying member flows of the Tenderfoot Hill facies but most are of unknown deriva-tion. The matrix is composed of greenish-gray to yellowish-gray silt and sand. The similarity of these sediments to those described by Van Alstine (1969, p. 21), and Tweto (1961) suggests that they are correlative with the Dry Union Formation.

BOULDER GRAVELS

Subsequent to the major phases of volcanism in the Ar-kansas Hills region, boulder gravels were deposited in the Salida-Waugh Mountain paleovalley where they occur as isolated, erosional remnants resting upon tuff of Badger Creek, Antero Formation, or pre-volcanic rocks. The gravels consist of unstratified, angular to rounded, boulders as large as 4 feet in diameter of various rocks of Precambrian, Paleozoic, and Tertiary age. Post-depositional erosion has removed the original matrix material so that only rounded knobs of boulder-strewn debris remain.

QUARTERNARY DEPOSITS

For the purposes of this study, landslides, slump blocks, and colluvial deposits were mapped collectively. A number of such deposits are shown on the geologic map under the symbol Qls. The landslide associated with the feature named "The Crater" (Sec. 24, R. 9, T. 50 N.) on the Cameron Mountain 15-minute topographic quadrangle is worthy of individual mention. At this locality, the dark-purplish andesite of Big Baldy overlies the white, unwelded ash-flow tuff facies of the Antero Formation with striking color contrast. The downslope area west and southwest of "The Crater" is covered by loose andesite debris which has a decidedly hummocky and rubbly appearance. The writer views the scooped-out depression adjacent to the in situ volcanic rocks as a landslide scar rather than a vol-canic crater as implied by the topographic nomenclature.

Alluvium, in this report, refers to detrital deposits of recent origin including sediments in stream beds, alluvial fans, flood plains, and valley fill. In the interest of map clarity, only a small number of such deposits are shown on the geologic map.

CENOZOIC AND LATE MESOZOIC STRUCTURES

The Arkansas Hills are a southern extension of the Mosquito Range, one of a series of north- to northwest-trending uplifts bounded by steeply dipping faults and separated by down-faulted intermontane basins or parks. Like those of other mountain ranges in central Colorado, the present structural features of this uplift are the result of three superimposed phases of Phanerozoic tectonism. The first phase occurred during Late Paleozoic and Early Mesozoic time when the ancestral Rocky Mountains were uplifted. The structural history of this orogeny is recorded in the Permo-Pennsylvanian sediments which filled the Central Colorado trough. In the faults and unconform-ities within these sediments, and in the stripping of Paleo-zoic rocks from areas to the east, and in the preservation of Paleozoic rocks in down-faulted blocks. The second phase of deformation occurred during Late Cretaceous and Early Tertiary time and consisted of uplift, folding, thrust-ing, and intrusion of stocks. The third phase, characterized by uplift, block faulting, and development of the Rio Grande depression, began in Middle Miocene time and is continuing today.

PRE-VOLCANIC FOLDING AND THRUSTING

Several Laramide structures of regional importance pass through the extension of the southern Mosquito Range. These are the Pleasant Valley syncline, Pleasant Valley thrust, and Wellsville-Orient thrust (see geologic map, back pocket). The Pleasant Valley syncline is a major north-northwest-trending synclinal fold in Paleozoic strata in the southern Mosquito Range. Along Badger Creek, the east-ern limb of the fold is steeply dipping to slightly over-turned and is truncated by the high angle Pleasant Valley thrust. The western limb dips less steeply and is cut by the northern extension of the Wellsville-Orient thrust (Gableman, 1952, p. 1580; De Voto, 1961, p. 204). The Whitehorn stock was intruded along the eastward dipping axial plane of the syncline and obliterates most of the major structure in the map area. From the Arkansas Hills, the Pleasant Valley syncline extends northward through Bas-sam Park almost to Trout Creek Pass (Gableman, 1952, p. 1590), and southward into the Spread Eagle Peak area on the eastern flank of the northern Sangre de Cristo Moun-tains (Munger, 1965, p. 6).

The Pleasant Valley thrust is a north-trending, east-dipping, high-angle reverse fault which brings Precambrian metamorphic and igneous rocks into contact with sedimen-tary rocks of Permo-Pennsylvanian age along most of its length. The fault extends north from the southern bound-ary of the map area along Badger Creek and Willow Creek and crosses the northern boundary west of Gribbles Park. The dip varies from about 60 degrees east to vertical along this trace. Precambrian rocks are in fault contact with steeply dipping Manitou Dolomite in most of this region and the trace of the major fault is offset by numerous min-or cross faults. Apparently, the fault dies out north of the map area before reaching South Park (De Voto, 1961, p.

204) rather than connecting with the London-Weston fault zone as proposed by Gableman (1952, p. 1596). Munger (1965, p. 4) shows the fault continuing south from the southern Mosquito Range across the canyon of the Arkansas River and into the northern Sangre de Cristo Mountains as far south as the Spread Eagle Peak area.

The western limb of the Pleasant Valley syncline is truncated by a steeply dipping fault that displays both normal and thrust fault characteristics. This fault is thought to be the northward continuation of the Wellsville-Orient thrust described by Gableman (1952, p. 1596). Within most of the mapped area, the fault appears to have a nearly vertical attitude. However, in some localities such as the upper reaches of Cottonwood Gulch (Sec. 28, R. 9 E., T. 49 N.), Precambrian metamorphic rocks are thrust eastward over the Manitou Dolomite along a thrust plane which dips about 15 degrees west. Similar variations in attitude have been described along the Mosquito-Weston fault north of the map area by Gableman (1952, p. 1597), and De Voto (1961, p. 206). Apparently, these variations arose when post-Laramide vertical faults, accompanied by local cross faulting and rotation, broke the former Laramide thrust plates. It is suggested here that the northward extension of the Wellsville-Orient thrust into the Arkansas Hills provides the link postulated by Burbank and Goddard (1937, p. 938) between the Wellsville-Orient fault and the Mosquito-Weston fault.

POST-VOLCANIC BLOCK FAULTING AND FORMATION OF THE UPPER ARKANSAS GRABEN

A series of parallel, north-trending, vertical faults offset the volcanic pile in the Arkansas Hills with step-down displacements toward the west. Reconstruction of the pre-volcanic drainage patterns indicates that these faults have played an important role in the formation of the upper Arkansas Valley segment of the Rio Grande rift zone (Chapin, Epis, and Lowell, 1970).

The Badger Creek fault is the easternmost of the major, north-trending, post-volcanic faults in the map area. It is a post-Laramide, vertical fault which was reactivated, in part, along the pre-existing Pleasant Valley thrust zone. At the confluence of Willow Creek and Badger Creek (Sec. 15, R. 10 E., T. 50 N.), the Badger Creek fault branches north-northeast and follows Badger Creek. The fault crosses the Gribbles Run paleovalley but appears to die out before reaching the Paleozoic strata bordering Gribbles Park. East of the fault, the pre-volcanic surface dips from 9,800 feet at the eastern boundary of the map area to 8,200 feet at Badger Creek in a distance of about 4 miles. It appears that block faulting, and perhaps doming associated with the Waugh Mountain volcanic center, has caused westward rotation of the block east of the Badger Creek fault. This rotation caused a dramatic reversal of gradient in the eastern portions of the Salida-Waugh Mountain and Gribbles Run paleovalleys which previously drained to the east (Chapin, Epis, and Lowell, 1970; Lowell, 1969, p. 73).

The Maverick fault is a vertical, north-trending fault which accounts for the presence of similar volcanic rocks differing in elevation by 600 to 1,000 feet in a distance of 1 to 2 miles. Rotation of the block west of the Maverick fault has tilted the volcanic rocks down toward the upper Arkansas Valley and produced an overall decrease in elevation of about 1,000 feet in 3 to 4 miles. The Maverick fault follows a pronounced topographic lineament along which occur intrusive breccia, altered felsite, hydrothermal alteration landslides, numerous mineral prospects, and fresh-water springs.

Dead Horse fault is similar and parallel to the Maverick fault. It offsets the pre-volcanic surface at least 400 feet in a distance of ½ mile. The block west of the fault was stepped down and rotated to the west causing a gradient inversion in the western tributaries of the Salida-Waugh Mountain paleovalley (see geologic map, back pocket). The fault coincides with a prominent topographic lineament and marks the westernmost exposure of Paleozoic strata in the map area.

Dead Goat fault is a north-trending, vertical fault with minor step-down displacement on the west side. The fault is characterized by a strong topographic lineament, truncation of Tertiary rocks as young as Late Miocene-Pliocene (Dry Union Formation), severe disruption of adjacent exposures of Ash Flow 1, and landslides.

The formation of the upper Arkansas Valley appears to have been accomplished by downfaulting between the Sawatch Range on the west and the Mosquito Range on the east by recurrent movement along steep, north-trending faults such as those mapped in the Arkansas Hills. Such movements began after Oligocene volcanism and before Late Miocene time and have probably persisted intermittently into Holocene time (Chapin, Epis, and Lowell, 1970). They are thus conformable in style and timing with Basin-Range tectonism.

SUMMARY

PRE-VOLCANIC EVENTS

Late Cretaceous time marked the beginning of the Laramide Orogeny in central Colorado and early deformation produced the Pleasant Valley syncline and its bounding faults, the Pleasant Valley thrust and the Wellsville-Orient thrust in the Arkansas Hills. These early Laramide structures were partially obliterated by the subsequent emplacement of the Whitehorn stock in Early Tertiary time. The final phase of Laramide tectonism was followed by a prolonged period of erosion in central Colorado and the development of an extensive Late Eocene erosion surface. Incised in this surface were east-flowing drainages, such as the Salida-Waugh Mountain and Gribbles Run paleovalleys, which probably headed in the ancestral Sawatch Range prior to the formation of the upper Arkansas graben (Chapin, Epis, and Lowell, 1970; Lowell, 1969, p. 91).

VOLCANIC EVENTS

Volcanism in the Arkansas Hills and adjacent portions of the Thirtynine Mile volcanic field commenced in earliest Oligocene time with the deposition of Ash Flow 1 (Ash

Flow 1, 40.0 ± 1.4 m.y., Epis and Chapin, 1968, p. 52; 37.3 ± 1.9 m.y. and 35.4 ± 1.1 m.y., Van Alstine, 1969, p. 15). A thick sequence of ash-flow tuffs, lavas, and breccias were erupted from several volcanic centers. The youngest volcanic rocks dated in the adjacent Thirtynine Mile field are Middle Miocene in age (upper andesite, 18.9 ± 1.2 m.y., Epis and Chapin, 1968, p. 52), hence nearly the entire volcanic episode in the Arkansas Hills, including the time of interformational erosion, took place in about 15 to 20 million years. The bulk of this volcanic pile, however, was emplaced during 2 to 6 million years of Early Oligocene time.

The Early Oligocene eruption of Ash Flow 1 consisted of the emplacement of at least 3 member ash flows. These ash flows were probably erupted from a volcanic center in the Sawatch Range and spread eastward over the Late Eocene erosion surface at least as far as the Cripple Creek (Tobey, 1969) and Florissant areas (Niesen, 1969). The Salida-Waugh Mountain paleovalley was probably a major route by which ash flows were funneled eastward onto the erosion surface. The Gribbles Run paleovalley was probably filled by Ash Flow 1 and subsequently overrun by younger ash flows. Differential compaction and erosion led to the re-establishment of much of the pre-eruption topography following Ash Flow 1 deposition. The basal, unwelded ash flows of the Antero Formation were then erupted and these deposits filled the Salida-Waugh Mountain paleovalley and overflowed onto the adjacent erosional plateaus. Subsequent erosion of these friable, unwelded tuffs led to widespread deposition of tuffaceous sediments on the plateaus and rapid exhuming of the Salida-Waugh Mountain paleovalley.

Renewal of volcanism in the vent area of the Antero tuffs (locality uncertain but probably in the Sawatch Range), refilled the Salida-Waugh Mountain paleovalley with a sequence of at least 6 welded ash flows which comprise the tuff of Badger Creek. These welded tuffs were sufficiently resistant to erosion to preserve the Salida-Waugh paleovalley until the present time.

Initial activity at the Waugh Mountain volcanic center, east of the Arkansas Hills, began after the emplacement of the tuff of Badger Creek. With the deposition of the latite of East Badger Creek over the (then-filled), eastern end of the Salida-Waugh Mountain paleovalley. A thick sequence of ash flows correlated with the Ash Flow 7 unit of the Thirtynine Mile volcanic field, was deposited in the eastern and northeastern portion of the map area during Waugh Mountain activity. These ash flows have also been identified at Poncha Pass, Tallahassee Creek, the northern Wet Mountain Valley, and the upper Badger Creek drainage but their vent area is as yet unknown. They bear some resemblance to the Bonanza Tuff which occurs southwest of Salida and may possibly have come from the Bonanza volcanic center (see Epis, Bruns, and Weimer, this guidebook). The age of the Ash Flow 7 rocks is about 34.8 ± 1.4 m.y. (Epis and Chapin, 1968, p. 52). Continued eruptions from the Waugh Mountain volcanic center deposited the latite of Waugh Mountain above the Ash Flow 7 rocks along the eastern border of the map area. The andesitic and basaltic lavas, breccias, and tuffs of the Upper Andesite (18.9 ± 1.2 m.y.), then covered the latite of Waugh Mountain and marked the close of Waugh Mountain extrusive activity.

At approximately the same time that Waugh Mountain volcanism was occurring, the andesite of Big Baldy was deposited in the southwestern portion of the map area from an unknown eruptive source. The Silicic Felsite of Section 36 was emplaced some time after the deposition of the andesite of Big Baldy and may have been extruded from the same vent area.

The Tenderfoot Hill facies of the Dry Union Formation which is exposed along the outskirts of Salida represents the most recent phase of volcanic activity in the Arkansas Hills. The basaltic flows of the facies are interstratified with sediments which are thought to correlate with the Dry Union Formation of Late Miocene-Pliocene age. The volcanic rocks of the Tenderfoot Hill facies have been tilted steeply westward by the steep, north-trending, border faults of the upper Arkansas graben. These faults may have provided local conduits for the rise of basaltic magma during the period of crustal extension responsible for the Rio Grande rift zone.

POST-VOLCANIC EVENTS

Late Tertiary time was a period of profound structural and geomorphic modification in central Colorado. Uplift and block faulting formed the San Luis Basin and the upper Arkansas Valley segments of the Rio Grande rift zone and their bordering mountain ranges. In the Arkansas Hills, step faulting related to the formation of the upper Arkansas graben reversed stream gradients from eastward off the ancestral Sawatch Range to westward into the graben. The Salida-Waugh Mountain paleovalley was broken into 3 segments and the Gribbles Run paleovalley was broken into 2 segments. Deposition of the Dry Union Formation occurred contemporaneously with the down faulting. The basalt flows of the Tenderfoot Hill facies were emplaced within the basal portion of these sediments. The boulder gravels in the Salida-Waugh Mountain paleovalley probably represent pediment gravels deposited on a southwest-sloping, Late Tertiary, pediment surface (Van Alstine, 1969, p. 28) across which the Dry Union sediments were transported to the graben.

In Quaternary time, continued uplift and resultant erosion caused deep dissection of the Late Tertiary topography. Several periods of glaciation occurred in the Sawatch Range during the Pleistocene Epoch and extensive outwash gravels were deposited over the Dry Union Formation along the west side of the upper Arkansas Valley (Van Alstine, 1969, p. 22); however, no evidence of glaciation has been observed along the east side of the valley in the Arkansas Hills. Fault scarps cutting Late Miocene-Pliocene sediments of the Santa Fe and Dry Union Formations and Pleistocene gravels as young as Pinedale (Scott, 1970; Tweto, 1961; and Van Alstine, 1969) testify to continued tectonism along the Rio Grande rift zone.

ACKNOWLEDGMENTS

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