GEOLOGY OF THE HACKBERRY MOUNTAIN VOLCANIC CENTER, YAVAPAI COUNTY, ARIZONA

Thesis by

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I had many useful discussions concerning this project with George Ulrich and Ed Wolfe of the U.S. Geological Survey. Fellow graduate students also contributed helpful advice; they include Cleve Solomon, Bob Criss, Alan Gillespie, Peter Larson, Henry Shaw, Kris Meisling, and Jim Quick. I also had several entertaining discussions with Gary Scott of Woodward Clyde Consultants concerning the local geology.

E.H. McKee of the U.S. Geological Survey promptly determined a potassium-argon age that was pivotal in interpreting the geologic history. D.P. Elston, also of the U.S. Geological Survey, graciously supplied a copy of his geologic map which included part of the area studied. Jan Mayne furnished supplies and helpful suggestions while figures were drafted.

I am grateful to Professor Barclay Kamb for providing support when other funds evaporated. Martha Stough, who opened her home to me, greatly enriched my years in Camp Verde which have been some of the most enjoyable of my life.

Most of all, I wish to thank my parents. I could always depend upon them for support, both moral and financial. Without them this thesis would have been much more difficult. Thanks.

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ABSTRACT

The Hackberry volcano in central Arizona, is a large dacitic volcano of late Miocene age. Most of the Hackberry Mountain area is underlain by Miocene volcanic rocks, primarily basalt and dacite. The oldest are a heterogeneous group of basalt flows, the Hickey Formation, erupted from local cinder cones. They were superseded by a homogeneous group of basalt flows, the Thirteenmile Rock Basalt, erupted from vents east of the area. Pyroclastics from the Hackberry volcano intertongue with the upper part of the Hickey Formation and all of the Thirteenmile Rock Basalt. There were seven episodes of these pyroclastics, collectively termed the Towel Creek Tuff, that were formed early in the history of the Hackberry volcano. This unit contains numerous dacitic ignimbrites and air-fall tuffs. Coarse, interstratified breccias occur in the upper parts of these deposits; they are capped by reworked tuffs. The sequence of air-fall tuff, ignimbrite, and breccia suggests a Peléan style of eruption.

After cessation of the pyroclastic activity, the volcano was intruded by a dacite stock, the Sally May Dacite. The stock probably extruded above the ground surface; because of its location, size (diameter of 8 km), petrography, and chemisty, the stock is believed to be the material of the magma chamber for the Towel Creek Tuff. The stock reached the surface without producing an attendant pyroclastic deposit. The fact that the stock rose to the surface without an accompanying paroxysmal eruption indicates that it was volatile-poor though still hot. Application of Stokes Law shows that it was unable to rise by buoyant forces alone; its upward migration apparently was facilitated by regional extension. The stock was hydrothermally altered at low temperature after its emplacement.

Two rhyolite plugs intruded the stock. One was apparently the conduit for a rhyolite flow nearly eight kilometers in length. This plug was later disrupted, possibly by an eruption driven by fluids in the altered stock. The volcanic activity culminated with the extrusion of a thick dacite flow, the Hackberry Mountain Dacite.

The Hackberry volcano was active for 2.2 to 3.9 m.y. The presence of basic xenoliths in the dacitic rocks suggests that its long life was the consequence of the injection of basaltic magma into the dacitic magma chamber. The dacite in all deposits of this volcano are petrographically similar.

The Hackberry Mountain area forms the southeastern margin of the Verde Valley, a sedimentary basin in which the Verde Formation accumulated. Fluviatile sandstones of the Verde Formation intertongue with the upper Hickey and lower Thirteenmile Rock Basalt in the northwestern part of this area, and the Verde grades upward into lacustrine sediments younger than all the volcanic rocks, but still of Miocene age. The Verde Valley formed primarily by subsidence along northwest-trending normal faults, many of which occur in the area studied. The faults in the Hackberry area are commonly interconnected and have a net offset of 400 meters, downdropped southwest. The margin of the basin occurs here because the amount of subsidence decreases, and, more importantly, the Hackberry volcano formed a topographic boundary.

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[Plates in pocket]

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INTRODUCTION

Purpose of investigation

The Hackberry Mountain area contains a large dacitic eruptive center of Miocene age, here called the Hackberry volcano. The purpose of this investigation was to determine the geologic history of this volcanic center.

Synoposis of volcanoes

The Hackberry Mountain area consists primarily of volcanic rocks of Miocene age, and many of which were erupted from volcanoes within the area. The oldest of these rocks are basaltic and were extruded from cinder cones exposed in the mapped area (figure 1) and adjoining regions. While the basalt flows accumulated, a large dacitic volcano, about eight kilometers across, emerged in the central part of this area. This dacitic volcano, the Hackberry volcano, was active for at least 2.2 m.y. (million years). The early period of activity was characterized by eruptions of dacitic pyroclastic rock. There were seven periods of pyroclastic activity of which the basal four were most voluminous. During each cycle a blanket of dacitic pyroclastic material was erupted which spread over the adjoining basaltic rocks but did not extend great distances from the vent, rarely farther than 10 kilometers. In periods of quiescence the Hackberry volcano was eroded extensively, so that much of the edifice was degraded, only to be rebuilt during the next period of activity. During each eruptive episode the Hackberry volcano was probably cone-shaped and had considerable relief (>500 meters); its central portion commonly contained a large dome. The erupted dacitic pyroclastic deposits interfingered with the

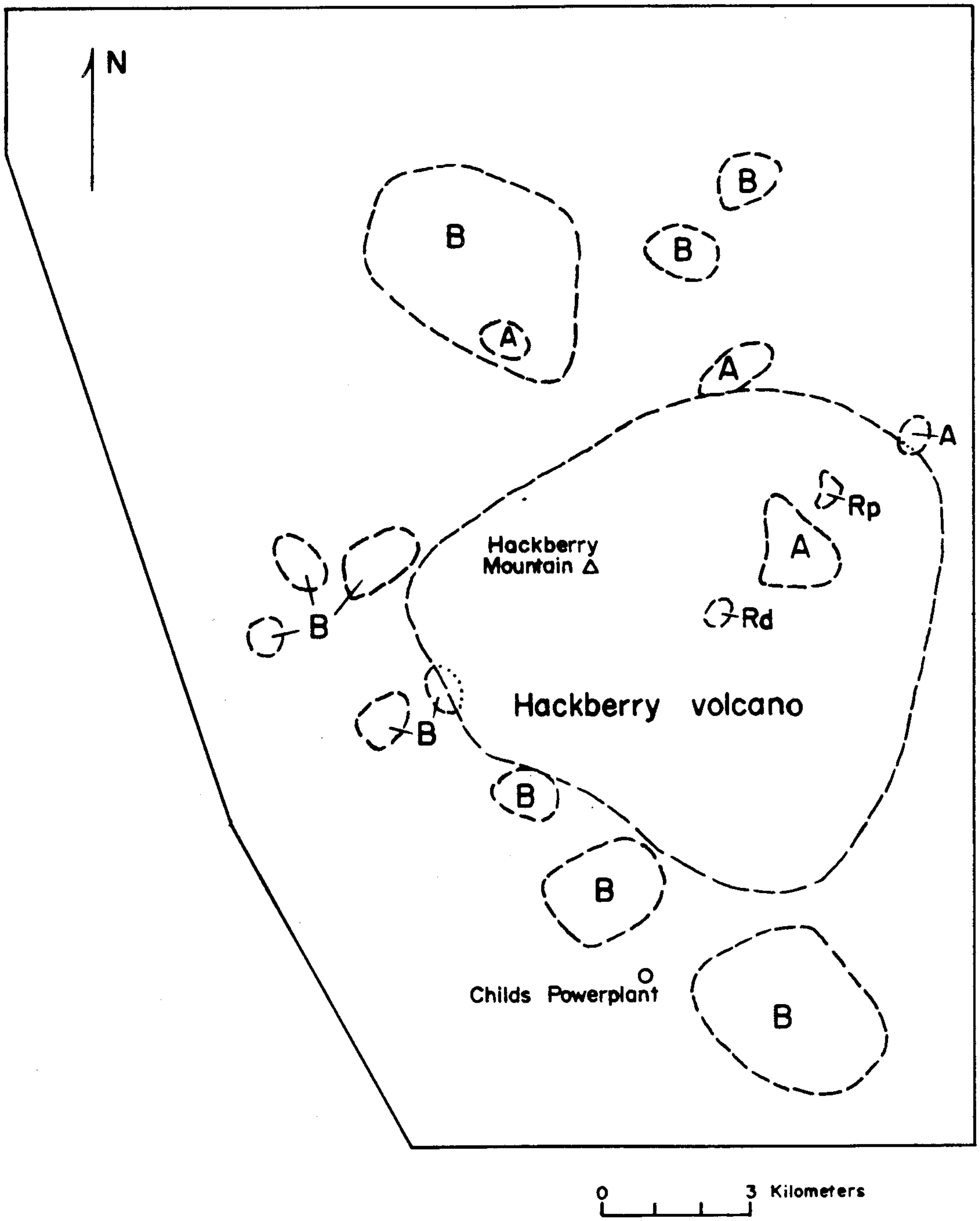

Figure 1.--Map of the Hackberry Mountain area showing location of volcanoes.

A Andesitic cinder cones

B Basaltic cinder cones

Rd Rhyolite diatreme

Rp Rhyolite plug

basaltic rocks around the periphery of the Hackberry volcano.

Shortly after the last voluminous cycle of pyroclastic activity, the basaltic rocks changed in character and were erupted from unknown vents, possibly fissures, exposed east of the Hackberry Mountain area. These flows covered all the older basaltic cinder cones and butted up against and eventually locally overtopped the Hackberry volcano. Several andesite flows were extruded contemporaneously from parasitic cinder cones adjacent to and on the flanks of the Hackberry volcano, and they interfingered with the basalts. Also, some silicic pyroclastic rocks were erupted from other unknown volcanoes possibly east of this area. These rocks plus others erupted from the Hackberry volcano interfingered with the mafic flows.

After the cessation of the mafic volcanic activity, the Hackberry volcano was forcibly intruded by a large circular dacite stock (about eight kilometers in diameter) which locally breached the surface. This intrusion transformed the Hackberry volcano from a cone-shaped mass composed primarily of pyroclastic deposits into a large, rugged body of massive dacite that rose above the surrounding rocks. As the intrusion cooled it was hydrothermally altered. This stock was extensively eroded and thick deposits of rubble accumulated around the volcano. Shortly after intrusion of the stock, a small rhyolite flow was erupted from the Hackberry volcano. The conduit for this flow was later disrupted and transformed into a diatreme. The volcanism then culminated with the extrusion of a very large, thick dacite flow which covered much of the Hackberry Mountain area including the Hackberry volcano. This flow was extruded from several vents located within the dacitic volcano and peripheral to it.

Location, culture, and accessibility

The Hackberry Mountain volcanic center is in central Arizona in eastern Yavapai county, close to the geographic center of the state (figure 2). The area mapped in the course of this investigation includes most of the Hackberry Mountain quadrangle bounded by longitude 111°37'30" to 111°45' W., and latitude 34°22'30" to 34°30' N. A small part of the Walker Mountain and Campe Verde quadrangles to the north and northwest were also mapped, and parts of the Horner Mountain and Verde Hot Springs quadrangles to the west and south.

The term "Hackberry Mountain area" is here used to include all the area in which geologic mapping was done for this report. The term probably should include only a small part of the mapped area, that around Hackberry Mountain, but no satisfactory geographic term is available for the entire mapped area. The location of geographic features within this area are shown in plate 5.

The small community of Childs is located along the Verde River at the southern boundary of the area. A small hydroelectric powerplant is located at this site, and it is operated by the Arizona Public Service. The powerplant was built in 1908 to provide electricity for the city of Prescott and the mines at Jerome and Iron King. The water is brought by flume from Fossil Springs which are located along Fossil Creek 18 kilometers east of the powerplant. Masson (1910) described the design and construction of the powerplant and associated structures. At present, Childs is populated by the powerplant operators and their families, fewer than 25 people.

The Verde Hot Springs, located 1.3 kilometers upstream from the Childs powerplant, was once the site of a spa and resort. The resort

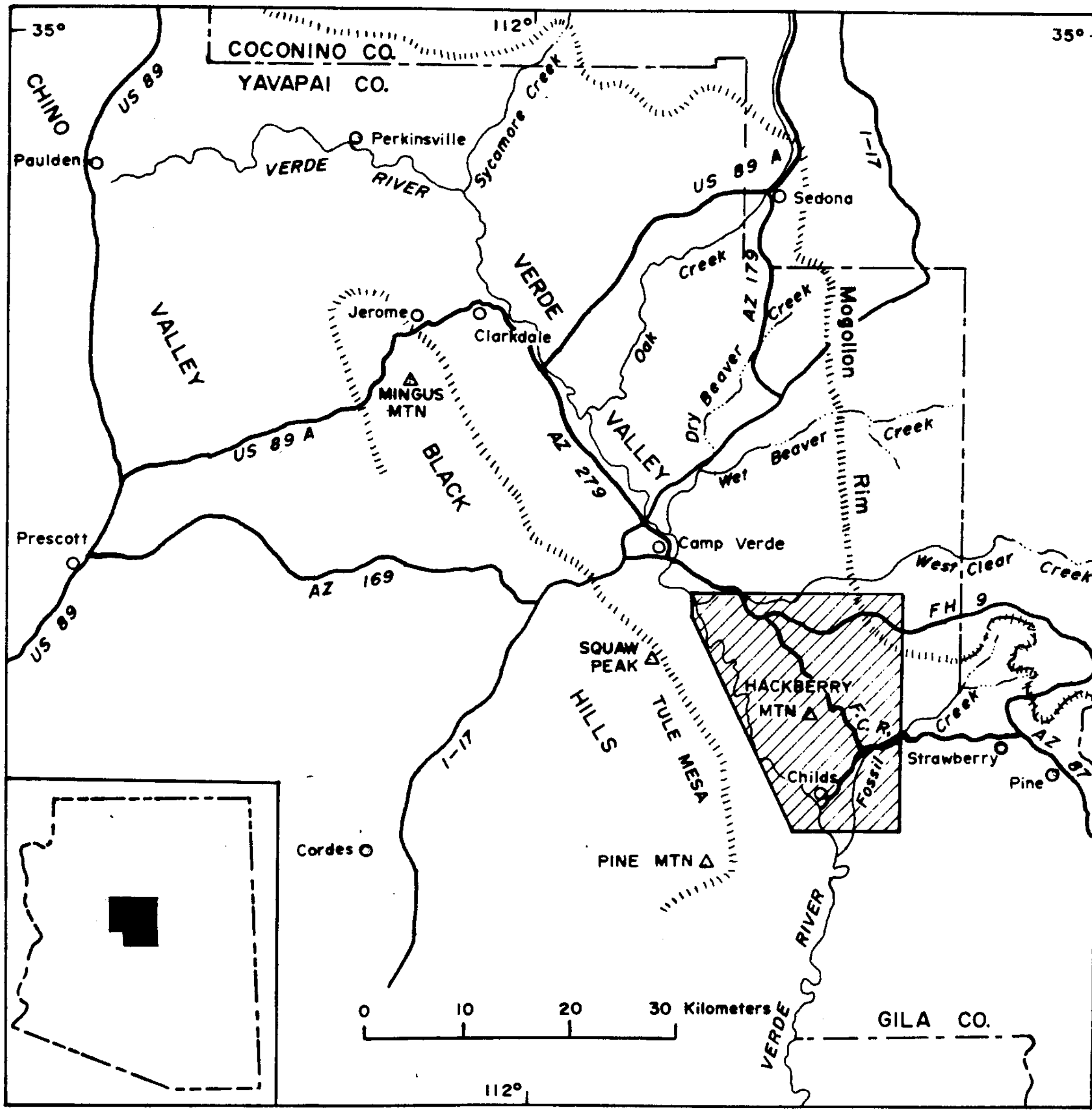

Figure 2.--Index map of central Arizona showing location of Hackberry Mountain area.
F.C.R.--Fossil Creek Road
FH-9--Forest Highway 9

burned down in the late 1950's (Clarence Ross, personal commun., 1979); it was never rebuilt. Nevertheless, the hot springs are still an attraction for visitors.

Indian ruins occur throughout the Hackberry Mountain area. The largest and best preserved occur along the Verde River and Towel Creek, in Sycamore Canyon, and within Hackberry Basin. Several of the ruins have been described in the thorough report of Mindeleff (1896). Both he and Mearns (1890, p. 748) have rough location maps for some of the larger ruins.

The Hackberry Mountain area, as defined above, is rugged and served by few roads. Fossil Creek Road crosses the area from its northwestern to southeastern boundary and provides access to a major part of the area. It is a very good gravel road that, until relatively recently, was the principal route from the Verde Valley to the Mogollon Rim region. A graded, but rough, gravel road connects Fossil Creek Road, near its intersection with Boulder Canyon, with the the Verde Hot Springs and the Childs powerplant. This road gives access to the southern part of the area. The northern boundary of the Hackberry Mountain area is delineated by Forest Highway 9; a paved road that is now the chief route to the Mogollon Rim region. Several jeep trails branch off Fossil Creek Road and provide access to Hackberry and Cottonwood Basins. Salt Mine Road runs from Camp Verde to Gap Creek near its confluence with the Verde River, and it terminates about one kilometer from the western boundary of the Hackberry Mountain area, near the confluence of Towel Creek with the Verde River. The entire southwestern quadrant of the area studied is not accessible by road.

Physical features

Regional-Fenneman (1931) divided Arizona into two physiographic provinces, the Colorado Plateau and the Basin and Range provinces. The Mogollon Rim defines the boundary between these two provinces. He further divided the latter province into the Mexican Highland and Sonoran Desert sections as shown in figure 3. The Colorado Plateau province comprises several plateaus together with valleys, buttes, and mesas; this region, in general, lies above 1750 meters in altitude (Wilson, 1962, p. 96). The Mexican Highland section is characterized by numerous nearly parallel short ranges, separated by valleys deeply filled with lacustrine and fluviatile deposits. The Sonoran Desert section is characterized by numerous short mountain ranges separated by broad desert plains underlain by fluviatile and lacustrine deposits of late Cenozoic age.

The Hackberry Mountain area lies along the boundary between the Colorado Plateau and Basin and Range provinces in an area where their boundary is poorly defined (Wilson, 1958, p. 97; Peirce and others, 1979, p. 13-15). East of the Hackberry Mountain area there are several basalt covered mesas that are within the Colorado Plateau province. To the west there is a plateau, the Black Hills, which rises precipitously from the Verde River. The Hackberry Mountain area lies along the southern boundary of the Verde Valley, a large intermontane valley typical of the Basin and Range province.

Local--The Hackberry Mountain area is dominated by several peaks formed of a resistant dacite flow: Hackberry Mountain, Towel Peaks, Buzzard Peaks, and Buckskin (hill 5296). Many landslides with their characteristic hummocky topography occur beneath these peaks. The area is drained by

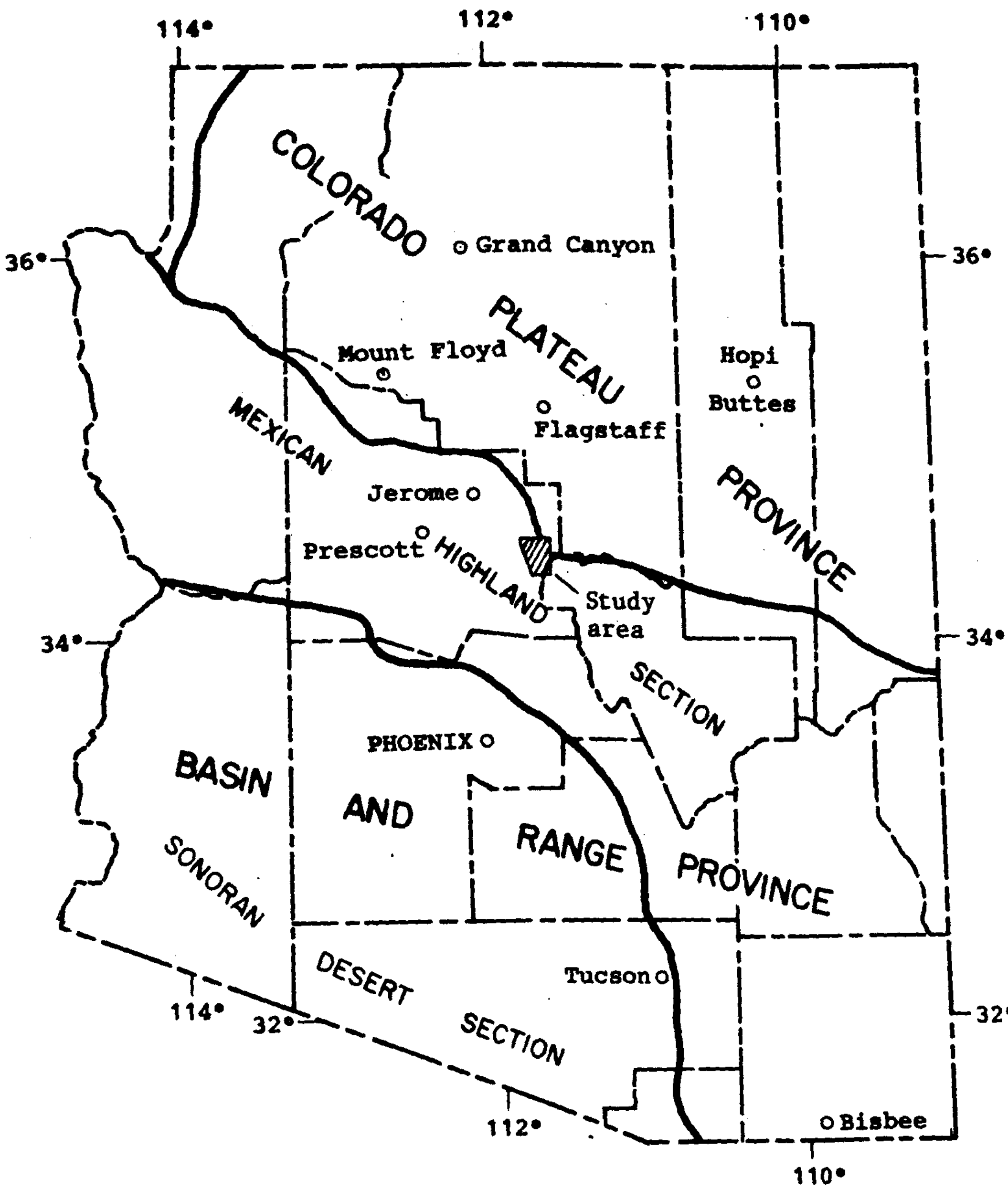

Figure 3.—Index map of Arizona showing location of study area and physiographic divisions of Fenneman (1931).

two perennial streams, the Verde River and Fossil Creek. The southeastern margin of the Verde Valley occurs in Cottonwood Basin, an area of low relief in the northwestern part of this area. The boundary of the valley occurs where the underlying and more resistant basaltic rocks emerge to the surface. Hackberry Basin is an area of low relief surrounded by steep cliffs of mafic volcanic rocks (figure 4).

The elevation in the area ranges from 820 meters (2696 feet) at the Childs powerplant to 1775 meters (5831 feet) above sea level at Hackberry Mountain.

Climate and vegetation

Climatological data for various localities in the Verde Valley including Camp Verde are presented in Twenter and Metzger (1963, p. 12). The values for average precipitation and temperature per month for Camp Verde are, in general, quite close to those of the Hackberry Mountain area. However, the higher elevations of this area have a climate more akin to that of the Sedona Ranger Station in Twenter and Metzger's data.

The Hackberry Mountain area typically receives around 33 centimeters (13 inches) of rain annually. The wettest months are July and August where the precipitation is from afternoon thunderstorms. June is the driest month. Minor amounts of snow may fall in the winter, especially at the higher elevations; it usually melts within several days.

The temperature is highest in June, July, August, and September when the daily high is commonly greater than 38°C (100°F). The temperature is lowest in January. During the winter, the daily low is commonly below 0°C (32°F). The most pleasant months for field work are April and October.

The vegetation is typical of the transition zone between the desert

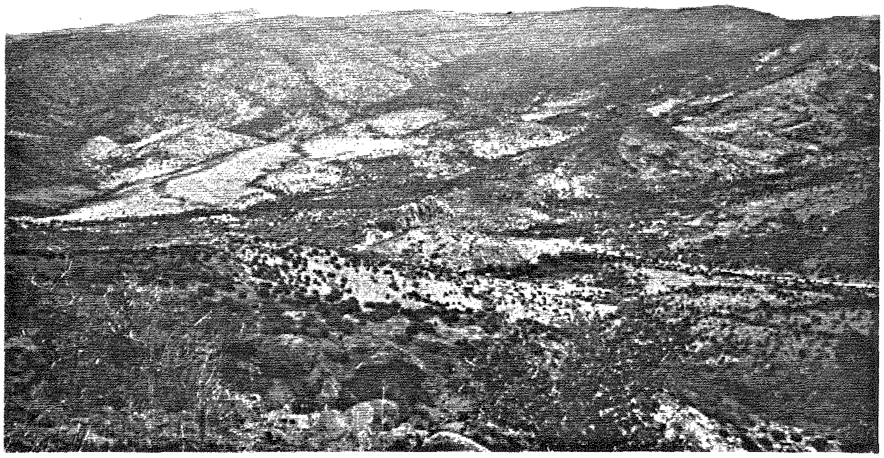

Figure 4.--Hackberry Basin. View northeast.

and the high plateaus that are forested with pine. It is somewhat variable depending on elevation and nature of bedrock. Utah juniper is the most conspicuous and occurs throughout the area. Pinon pine and alligator-bark juniper are found in the higher elevations. Many types of cacti grow in the area including barrel, cholla, hedgehog, prickly pear, and pincushion. They are concentrated in the lower elevations; prickly pear is most common and occurs at all elevations. Numerous thorny shrubs, such as mesquite, catclaw, ocotillo, century plant, and yucca, are typical of the location. Brushy thickets of scrub oak and manzanita are common. Manzanita is especially abundant where there are exposures of hydrothermally altered dacite. Cottonwood and sycamore trees occur along the larger watercourses. Cottonwood trees are also found adjacent to many springs.

Previous work

The following articles, listed chronologically, have been published concerning geologic features in the Hackberry Mountain area:

1923. Jenkins, O.P. Verde River lake beds near Clarkdale, Arizona: American Journal of Science, 5th series, v. 5, no. 25, p. 65-81.
Suggested that a lava dam in the Hackberry Mountain area was responsible for a lake in which the Verde Formation was deposited.

1949. Mahard, R.H. Late Cenozoic chronology of the upper Verde Valley, Arizona: Dennison University Science Laboratory Bulletin, v. 41, p. 97-127.
Recognized thick sequence of silicic tuffs and breccias within the Hackberry Mountain area. Suggested that lava-tuff dam in this area was responsible for lake in which the Verde Formation was deposited.

1958. Arizona Bureau of Mines. Geologic map of Yavapai County, Arizona: scale 1:375,000.
Reconaissance geologic map that includes the Hackberry Mountain area.

1960. Sabels, B.E. Late Cenozoic volcanism in the San Francisco volcanic field and adjacent areas in north-central Arizona: Unpublished Ph.D. Thesis, University of Arizona, Tucson, 345 p.
Described section of volcanic rocks exposed near Thirteenmile Rock. Described dacitic tuffs in Hackberry Basin and determined a potassium-argon age for one of them. Correlated silicic tuffs in Hackberry volcano with tuff deposits throughout central and northern Arizona.

1962. Peirce, H.W., Cooley, M.E., Johnson, P.W., and Breed, W.J. Road Log--Globe to Flagstaff, Arizona, in Weber, R.H., and Peirce, H.W., eds., Guidebook of the Mogollon Rim Region, east-central Arizona: New Mexico Geological Society Guidebook, Thirteenth Field Conference, p. 31-49.
Guide to geology along Fossil Creek Road plus a rough geologic map of the region.

1962. Sabels, B.E. Mogollon Rim volcanism and geochronology, in Weber, R.H., and Peirce, H.W., eds., Guidebook to the Mogollon Rim Region, east-central Arizona: New Mexico Geological Society Guidebook, Thirteenth Field Conference, p. 100-106.
Synopsis of his Ph.D. Thesis.

1963. Feth, J.H., and Hem, J.D. Reconaissance of headwater springs in the Gila River Drainage Basin, Arizona: U.S. Geological Survey Water Supply Paper 1619-H, 54 p.
Brief description of the Verde Hot Springs.

1963. Twenter, F.P., and Metzger, D.G. Geology and groundwater in Verde Valley--the Mogollon Rim region, Arizona: U.S. Geological Survey Bulletin 1177, 132 p.
Excellent account of the geology and groundwater of the Verde Valley area, includes northwestern portion of the Hackberry Mountain area.

1965. Teichert, Curt. Devonian rocks and paleogeography of central Arizona: U.S. Geological Survey Professional Paper 464, 181 p.
Briefly describes outcrops of Devonian Martin Formation located adjacent to the Hackberry Mountain area.

1972. Wadell, J.S. Sedimentation and stratigraphy of the Verde Formation (Pliocene), Yavapai County, Arizona: Unpublished Masters thesis, Arizona State University, Tempe, 111 p.
Detailed description of the lithology and history of the Verde Formation. Brief description of the volcanic rocks in the Hackberry Mountain area; considered these flows responsible for damming of the Verde River that allowed deposition of the Verde Formation.

1973. Elston, D.P., and Scott, G.R. Geologic map of part of the Hackberry Mountain Volcanic Center, southeastern Verde Valley, Arizona: unpublished U.S. Geological Survey map, scale 1:5000.

Excellent, very detailed geologic map of volcanic rocks exposed along the Verde River. Map is the basis of stratigraphy developed in this report. Information from map is used in all articles written by Elston.

1973. Elston, D.P., and Scott, G.R. The Hackberry Mountain Volcanic Center, A Miocene-Pliocene dacite volcano in central Arizona: Geological Society of America Abstracts with Programs, v. 5, p. 612.

Very brief description of Hackberry Mountain area. Determined a paleomagnetic reversal chronology for the volcanic rocks and correlated it with the oceanic anomaly pattern.

1974. Elston, D.P., McKee, E.H., Scott, G.R., and Gray, G.D. Miocene-Pliocene volcanism in the Hackberry Mountain area and evolution of the Verde Valley, north-central Arizona, in Karlstrom, T.N.V., Swann, G.A., and Eastwood, R.L., eds., Geology of northern Arizona with notes on archaelogy and paleoclimate, Part II, Area studies and field guides: Geological Society of America, Rocky Mountain Meeting, Flagstaff, Arizona, p. 602-610.

Brief description of Hackberry Mountain area. Presents generalized stratigraphic sections of the volcanic rocks and preliminary potassium-argon ages.

1974. Elston, D.P., Nations, J.D., and Gray, G.D. Field guide for southeast Verde Valley--northern Hackberry Mountain area, north-central Arizona, in Karlstrom, T.N.V., Swann, G.A., and Eastwood, R.L., eds., Geology of northern Arizona with notes on archaelogy and paleoclimate, Part II, Area studies and field guides: Geological Society of America, Rocky Mountain Meeting, Flagstaff, Arizona, p. 630-645.

Guide to geology along Forest Highway 9, along Fossil Creek Road south to Hackberry Basin, and within Cottonwood Basin.

1974. Scott, G.R. Geology, petrology, Sr-isotopes and paleomagnetism of the Thirteenmile Rock Volcanics: Unpublished Master's Thesis, University of Texas, Dallas, 71 p.

Brief but well done study of Hackberry Mountain area. Contains geologic map of the volcanic center and adjoining areas. Also contains numerous chemical data.

1978. Bressler, S.L., and Butler, R.F. Magnetostratigraphy of the late Tertiary Verde Formation, central Arizona: Earth and Planetary Science Letters, v. 38, p. 319-330.

Determined age of the Verde Formation including section exposed in Cottonwood Basin.

1980. McKee, E.H., and Elston, D.P. Reversal chronology from a 7.9 - to 11.5 - m.y.-old volcanic sequence in central Arizona: Comparison with ocean floor polarity record: Journal of Geophysical Research, v. 85, no. B1, p. 327-337.
Detailed potassium-argon age and paleomagnetic study of volcanic rocks in Hackberry Mountain area. Age data were invaluable in determining geologic history of the area.

1980. Ross, P.P., and Farrar, C.D. Map showing potential geothermal areas, as indicated by the chemical character of ground water, in Verde Valley, Yavapai County, Arizona: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-13, scale 1:250,000.
Indicates that the southern part of the Hackberry Mountain area has a low to medium geothermal potential.

Field work

Field work began in the Hackberry Mountain area in the fall of 1978. A portion of the area previously mapped by Elston and Scott (1973b) was remapped using stratigraphic units based on theirs. This stratigraphy was continually refined and expanded as the area was mapped. This process consumed the months of April through November of 1979 and April through October of 1980. Following this period of detailed mapping, 19 stratigraphic sections were measured during November and December of 1980 and during widely interrupted periods in the spring and summer of 1981.

Air photographs were used for field compilation. The geology was compiled on the U.S. Geological Survey photographs that were initially flown for the production of the 7 1/2 minute topographic maps of the region. These photos have a scale of about 1:36,000 and were enlarged two times for an effective scale of about 1:18,000. During the winter of 1980-1981, the geology was compiled photogrammetrically by the author using an Analytical Plotter Civilian manufactured by O.M.I. at the U.S. Geological Survey Center of Astrogeology at Flagstaff, Arizona. This compilation was at the scale of 1:20,000 and was subsequently reduced to

1:24,000 so the map would be compatible with those prepared for the adjoining areas under consideration for inclusion in the Wilderness system.

STRATIGRAPHIC GEOLOGY

GENERAL FEATURES

The rocks of the area range in age from Precambrian (?) to Miocene. The pre-Tertiary rocks include a basalt of probable Precambrian age and three sedimentary formations of early Paleozoic age. Miocene rocks, chiefly basaltic through rhyolitic flows and pyroclastic deposits and minor volcanoclastic rocks, underlie most of the area mapped. The pre-Tertiary and Miocene rocks have been divided into 13 different formations and informal units. The stratigraphic relationships between the principal units are schematically represented in figure 5.

PRE-TERTIARY ROCKS

General features

The pre-Tertiary rocks consist of an altered basalt of probable Precambrian age; the Tapeats Sandstone and Chino Valley Formations of Cambrian age and the Martin Formation of Devonian age. The contacts between all four units are unconformable. A regional study by Hereford (1975) has shown that the contacts between the three Paleozoic formations are disconformities.

The pre-Tertiary rocks are exposed only in small areas along the Verde River. The best exposure is located at the mouth of the drainage from Gospel Hollow (see in Section 15 of the appendix). Another principal exposure is along the northeastern bank of the Verde River 2.8 kilometers northwest of the Verde Hot Springs.

Figure 5.--Generalized diagrammatic section illustrating the principal rock formations and their age relations in the Hackberry Mountain area. Symbols refer to units listed in table 1.

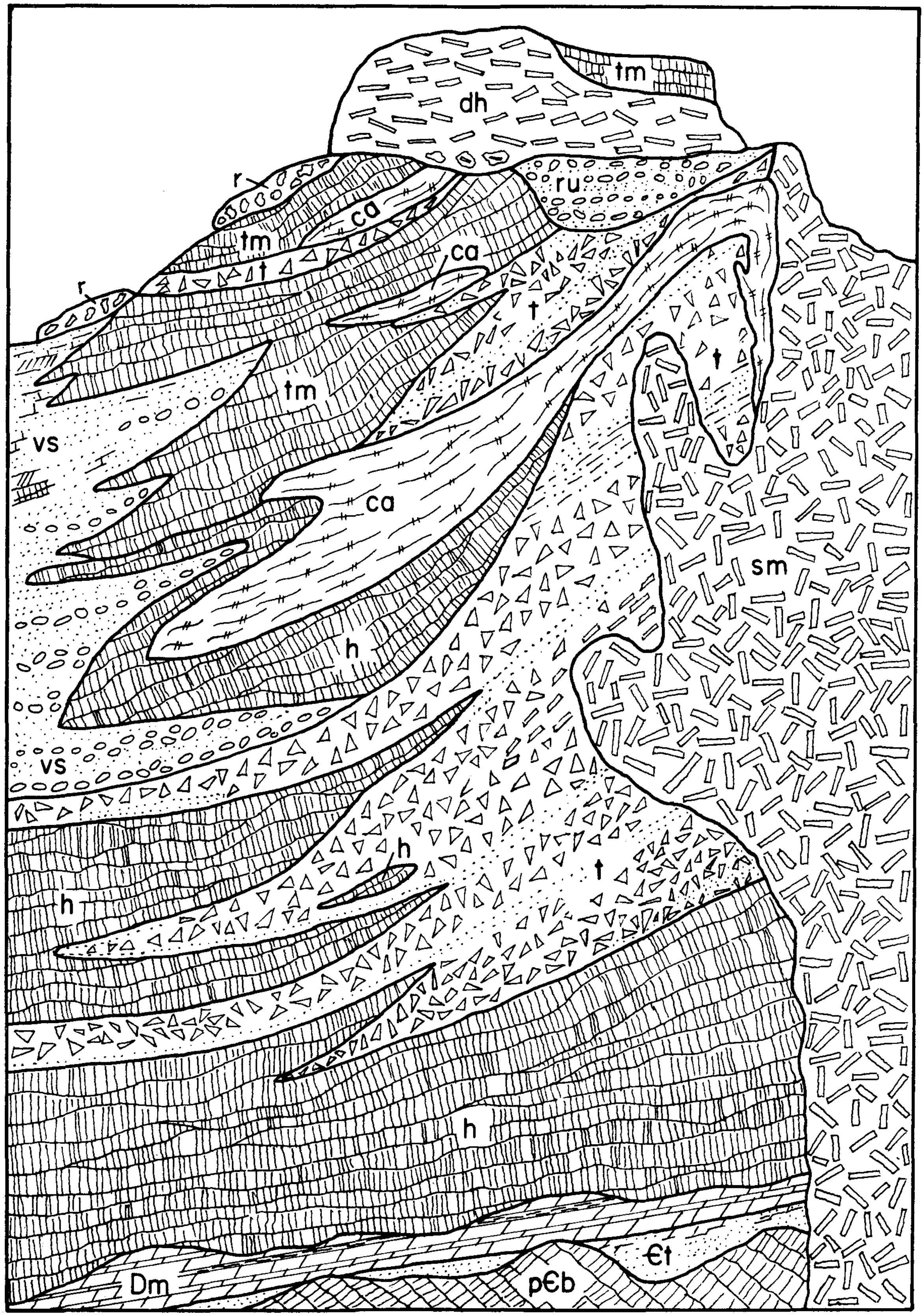
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Table 1.--Generalized stratigraphic column of pre-Quaternary rocks, Hackberry Mountain area, Yavapai County, Arizona

Symbol	Formation	Thickness (Meters)	Lithology and remarks	Age
vs	Verde Formation	185	White coarse- to fine-grained sandstones that grade upwards into siltstones, limestones, and evaporites	Miocene to Pliocene
dh	Hackberry Mountain Dacite	0-320	White and red, columnar-jointed dacite flow that commonly has an autobrecciated base. Unit also includes several dacitic intrusive bodies	Miocene
r	Rhyolite	15	Autobrecciated, bluish-gray, flow-banded rhyolite flow. Unit also includes a rhyolitic dome and diatreme	
ru	Rubble	0-210	Buff, thick-bedded sandy conglomerate and coarse-grained sandstone consisting exclusively of dacitic debris	
sm	Sally May Dacite		Large body of hydrothermally altered dacite that intruded the Hackberry volcano	
tm	Thirteenmile Rock Basalt	280	Lithologically homogeneous sequence of basalt and olivine basalt flows extruded from vents to the east of the Hackberry Mountain area. Minor amounts of basaltic tuff are intercalated with the flows in the eastern part of the mapped area	
ca	Cimarron Hills Andesite	0-470	Red and bluish-gray, plagioclase-bearing andesite flows and breccias. Unit includes several exhumed cinder cones with associated tuffs and dikes	
t	Towel Creek Tuff	0-930	Sequence of interbedded, white dacitic ignimbrites, pyroclastic breccias, air-fall tuffs, flows, base-surge tuffs, and reworked tuffs extruded from the Hackberry volcano. Unit is interbedded with the Hickey Formation	
h	Hickey Formation	550	Lithologically heterogeneous sequence of basalt and olivine basalt flows and tuffs of local origin. Unit includes several exhumed cinder cones with associated dikes, agglomerates, and breccias	
Dm	Martin Formation	6-52	Gray, thick-bedded, aphanitic dolomite with claystone interbeds. A zone of breccia occurs near the base of the unit	Devonian

Table 1.--Generalized stratigraphic column of pre-Quaternary rocks, Hackberry Mountain area, Yavapai County, Arizona--Continued

Symbol	Formation	Thickness (Meters)	Lithology and remarks	Age
Ct	Chino Valley Formation	8	Pale red and buff, finely crystalline, laminated dolomite	Cambrian(?)
	Tapeats Sandstone	0-13	Reddish-brown and buff, cross-bedded, coarse-grained sandstone	Early to Middle Cambrian
pCb	Precambrian Basalt	37 +	Gray, plagioclase-rich, sericitized basalt. Uppermost portion of basalt is hematized and pale red	Precambrian (?)

Precambrian Basalt

Topographic expression and lithology

The oldest rock exposed in the study area is a greenish-gray, altered basalt of probable Precambrian age. The Precambrian basalt is very resistant and forms steep cliffs along the Verde River at two localities (figure 6).

In hand specimen the Precambrian basalt is a dark greenish-gray aphanitic rock which contains subhedral plagioclase phenocrysts as long as 5 millimeters. Under the microscope the phenocrysts average 1.5 millimeters across; they are zoned and range in composition from An_{37} to An_{83}. The plagioclase phenocrysts originally composed 50 percent of the mode, but only 5 percent remains because their interiors have been altered to sericite ± chlorite ± epidote. The groundmass is pilotaxitic and composed primarily of zoned plagioclase microlites with minor amounts of intersertal chlorite, opaque minerals, clinozoisite, and sparse amounts of epidote, leucoxene, quartz, and rutile. The rock contains a small amount of amygdaloidal calcite. The upper surface of the basalt, 0 to 15 meters thick, has been altered to earthy hematite.

The designation of this unit as a basalt is arbitrary and is based chiefly upon the lack of hydrous mafic minerals. Because it is altered, a chemical analysis was not performed upon this unit. It could possibly be an altered andesite.

Thickness and relations

The maximum exposed thickness of the Precambrian basalt is approximately 40 meters. Its base is not exposed. It is unconformably overlain in places by the Tapeats Sandstone and in other places by the Chino

Figure 6.--Contact between Tapeats Sandstone (€t) and underlying Precambrian basalt (p€b) on west bank of Verde River near Gospel Hollow.

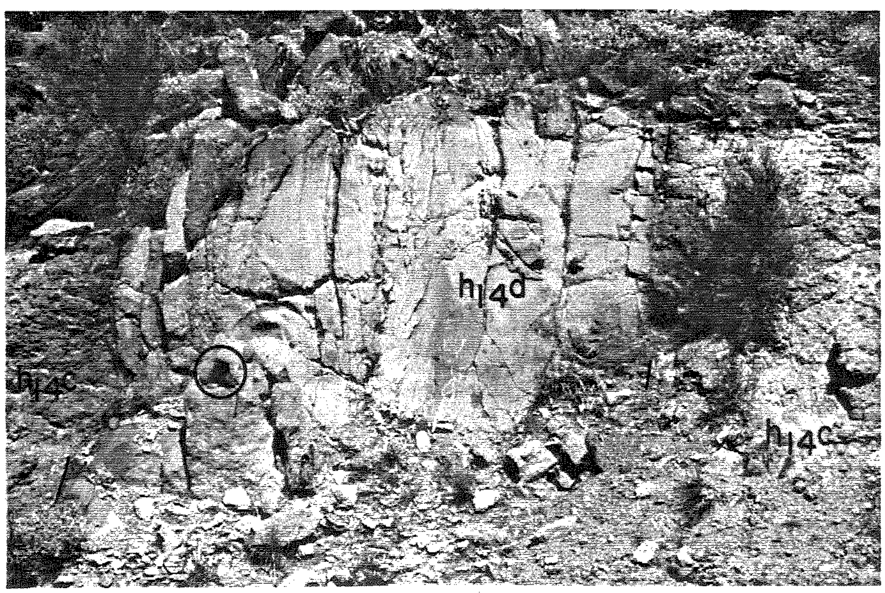


Figure 7.--Basaltic dike ($h_{14}d$) that has intruded basaltic cinder ($h_{14}c$). Both units are assigned to Member 14 of the Hickey Formation. Outcrop along Fossil Creek Road, and view is to west. Boot circled for scale.

Valley Formation, both of Cambrian age. The Tapeats Sandstone is of variable thickness and locally pinches out indicating that the Precambrian basalt underlay a surface of low relief on which this sedimentary unit was deposited.

The Precambrian basalt has two well-developed joint sets that dip 45° to the north and south, respectively (figure 6). If this basalt was a flow then the joints may have resulted from its extrusion, and they would normally be parallel and/or perpendicular to the top or bottom of the flow (MacDonald, 1972, p. 98). Therefore, if the basalt was a flow and the joints are related to the emplacement, it would have been rotated significantly prior to the deposition of the overlying sedimentary formations. Another possible cause for the joints would be structural deformation of the basalt long after its emplacement. The overlying sedimentary rocks have no joints with similar orientations. Thus, in either case, the orientations of the joint sets in the Precambrian basalt suggest that a major hiatus separates the basalt and the overlying sedimentary rocks.

Hematization of the upper surface of the Precambrian basalt was probably caused by by subaerial exposure of the basalt prior to the deposition of the overlying sedimentary units. According to Blatt and others (1972, p. 231, 257), thick iron-rich weathered zones are common atop basaltic rocks today and form fairly rapidly, but prior to the Devonian and the spread of profuse terrestial vegetation, iron-rich weathered zones were not common.

Age and correlation

The Precambrian basalt has been assigned a probable Precambrian age. The basalt can be no younger than Early to Middle Cambrian since it is unconformably overlain by the Tapeats Sandstone. The orientation of the joints within the basalt suggest that it may be considerably older than the Tapeats Sandstone.

Basalts of Precambrian age are not uncommon in central Arizona. They can be divided in two age groups--older and younger Precambrian. The younger Precambrian basalts consist of both flows and intrusive bodies (diabase); they have been described in the Sierra Ancha which is 70 kilometers southeast of the Childs powerplant (Shride, 1967, p. 42-44, 53-58). The older Precambrian basalts consist of flows, and they crop out in the Cordes area (Anderson, 1972) and in the northern Bradshaw Mountains (Anderson and Blacet, 1972a). Both areas are approximately 40 kilometers west of the Childs powerplant.

The basalts of older Precambrian age are quite similar petrographically to those in the Hackberry Mountain area. In both areas, the basalts have plagioclase phenocrysts that contain granules of clinozoisite, epidote, and sericite set within a pilotaxitic groundmass containing albitic laths separated by interstitial chlorite, sericite, clinozoisite, leucoxene, and sparse quartz grains (Anderson, 1972, p. 6-7; Anderson and Blacet, 1972a, p. 17). The younger Precambrian basalts are not petrographically similar to those of the Hackberry Mountain area. On the basis of these petrographic similarities, a correlation between the Precambrian basalt of this study and the basalts of older Precambrian is more likely. The petrographically similar basalts are part of the Spud Mountain Volcanics and belong to the Big Bug Group of the Yavapai Series. Their age is between 1,770 ± 10 and 1,820 + m.y. (Anderson and others, 1971, p. C15).

Rocks of Precambrian age have been described in the Pine Mountain area (Canney and others, 1967, p. J12) which is 10.5 kilometers southwest of the Childs powerplant. These rocks consist of metamorphosed mafic extrusive rocks that are dark gray to dark grayish-green to greenish-black on fresh surfaces. Unfortunately, the authors do not describe the rocks in any greater detail, so a correlation with the Precambrian basalt is not possible.

Tapeats Sandstone

Topographic expression, thickness, and stratigraphic relations

The Tapeats Sandstone is very resistant and forms cliffs atop the outcrops of Precambrian basalt along the Verde River (figure 6). The Tapeats Sandstone ranges from zero to 13 meters in thickness. The thickest and best exposed section occurs where the stream draining Gospel Hollow intersects the Verde River.

The Tapeats Sandstone rests unconformably upon the Precambrian basalt. The sandstone was deposited on a surface of low relief. There was, however, enough relief to cause this sandstone to pinch out in two areas: (1) within a splayed fault system northeast of the Verde River 2.8 km upstream from the Verde Hot Springs; (2) on the northeastern bank of the Verde River 3.7 kilometers upstream from the Verde Hot Springs.

The Tapeats Sandstone is overlain by the Chino Valley Formation. The contact is sharp and is marked by a change in lithology from resistant sandstone to non-resistant laminated dolomite. Although there is regional evidence of a disconformity, there is no angular discordance.

Lithology

The Tapeats sandstone is a buff to pale yellowish-orange medium- to coarse-grained sandstone. The sandstone has well developed parallel beds that range in thickness from one to 50 centimeters and also has well developed cross-beds. The parallel beds differ in grain size. Grains in the coarser beds range from medium sand to pebble size and average coarse sand size; grains in the finer beds range from very fine sand to granule size and average medium sand size. In all beds the grains are subangular to subrounded and are poorly sorted. The sandstone is very well indurated and is bonded primarily with a ferruginous cement; there are also minor amounts of siliceous and calcareous cement.

The Tapeats Sandstone is a subarkose according to the classification of Pettijohn (1975, p. 211). Quartz in the Tapeats Sandstone comprises 80 percent of all the grains. The remainder are orthoclase, plagioclase, and microcline plus sparse chert and muscovite. The Tapeats Sandstone does not contain any fragments derived from the underlying Precambrian basalt.

Age, correlation, and origin

The age and correlation of the Tapeats Sandstone in central Arizona has been problematical and was resolved only relatively recently. The Tapeats Sandstone was recognized and named by Noble (1914) based upon exposures in the Grand Canyon region of Arizona. There the Tapeats is fossiliferous and its age is Early to Middle Cambrian (McKee, 1945, p. 35). In the Jerome area of central Arizona (50 kilometers northwest of Hackberry Mountain) a sandstone, believed to be unfossiliferous, crops out beneath dolomite of the Devonian Martin Formation. Anderson and Creasey (1958, p. 49) suggested that this sandstone was correlative with the Tapeats Sandstone on the basis of its lithologic similarities with the fossiliferous Tapeats in the Grand Canyon. However, this sandstone is also lithologically similar to a basal unit of the Martin Formation designated the Beckers Butte Member by Teichert (1965). He (1965, p.

25) was able to correlate the sandstone of the Jerome area with the Tapeats Sandstone of the Grand Canyon region based upon the occurrence in both units of "Corophioides", an index fossil of Cambrian age for rocks in Arizona. Elston and Bressler (1977, p. 429) were able to confirm this correlation by paleomagnetic methods.

The sandstone that overlies the Precambrian basalt in the Hackberry Mountain area is unfossiliferous and lithologically similar to both the Tapeats Sandstone and the Beckers Butte Member of the Martin Formation. However, this sandstone is overlain by a thin sequence of laminated dolomite that has been identified by Hereford (oral commun., 1980) as the Chino Valley Formation, which occurs between the Tapeats Sandstone and the Martin Formation (Hereford, 1975). Therefore, the sandstone overlying the Precambrian basalt is the Tapeats.

According to Hereford (1974), the widespread occurrence of marine trace fossils and the textural and mineralogical maturity of the Tapeats indicate that the sandstone was deposited in a marine environment. He further states that many aspects of the sedimentary structures are comparable to those found in modern tidal sand bars.

Chino Valley Formation

Topographic expression, thickness, and stratigraphic relations

The Chino Valley Formation is non-resistant and forms slopes that generally are covered with colluvium. However, it is well exposed at the mouth of the Gospel Hollow drainage.

The Chino Valley Formation is about 8 meters thick. Because it is so thin, it was grouped with the Tapeats Sandstone as one map unit.

The upper contact is sharp and is defined by a change in lithology from finely laminated buff dolomite of the Chino Valley Formation to buff thick-bedded dolomite of the Martin Formation.

Lithologically, the Chino Valley Formation appears to be a transitional unit between the Tapeats Sandstone and the Martin Formation. However, a regional study by Hereford (1975) indicates that the contact with the Martin is disconformable.

Lithology

The Chino Valley Formation is a pale reddish-purple or buff, very fine-grained dolomite. The basal part is pale reddish-purple; the upper one meter is buff, the same color as the overlying dolomite of the Martin Formation. The Chino Valley Formation has moderately developed laminae, one to five millimeters thick, that are discontinuous and commonly lensoid. The laminae are expressed by differences in the average size of the dolomite grains: the finer-grained laminae, which form most of the rock, contain grains that average 0.01 millimeter across; the coarser-grained laminae contain grains that average 0.3 millimeter across. All dolomite grains are subrounded. This unit also contains quartz grains (10 modal percent) and trace amounts of plagioclase and muscovite grains. These terrigenous constituents are subangular to subrounded and average 0.03 millimeter across and are as large as 0.3 millimeter. Because of the presence of fine laminae and the absence of recrystallized dolomite grains, this unit may be a clastic dolomite. According to the classification scheme proposed by Folk (1959), the rock of Chino Valley Formation is a sandy dolomicrite (Ts IIIm:D2).

Age, correlation, and origin

The Chino Valley Formation was recognized and named by Hereford (1975) for exposures in the Chino Valley region which is 110 kilometers northwest of Hackberry Mountain. This formation is unfossiliferous and its age is based on stratigraphic position. It rests locally upon an irregular surface of Bright Angel Shale of Middle Cambrian age and regionally underlies the Martin Formation of Devonian age. Hereford (1975) assigned the Chino Valley Formation a probable age of Late Cambrian because there are no rocks of Silurian or unquestioned Ordovician age in northern Arizona. Hereford (oral commun., 1980) has looked at the outcrops of the Chino Valley Formation in the Hackberry Mountain area and has confirmed that they indeed belong to this formation.

Hereford (1975, p. 682) states that "from the extremely fine grain size and the local presence of mud cracks that the dolomite [of the Chino Valley Formation] may have accumulated on a mud flat in the supratidal zone. The mud flat probably developed in an embayment that formed on the eastern margin of the upwarped Precambrian terrain."

Martin Formation

Distribution, topographic expression, thickness, and stratigraphic relations

Outcrops of the Martin Formation were recognized in the Hackberry Mountain area by Teichert (1965, p. 5) and Scott (1974, p. 7). The Martin Formation has the greatest areal exposure of any pre-Tertiary unit; it is moderately resistant and forms distinct white step-like cliffs or slopes.

A section exposed atop hill 3061 (2.6 kilometers northwest of the Verde Hot Springs) is the only section of Martin Formation in the Hackberry Mountain area where its upper contact is not truncated by a fault or obscured by Quaternary deposits. Here the Martin Formation is approximately 60 meters thick and is overlain by the Hickey Formation of Miocene age. In nearby parts of central Arizona, where it is overlain by the the Redwall Limestone of Missippian age, the Martin Formation has a fairly uniform thickness of 120 to 155 meters (Stoyanow, 1936, p. 497; McNair, 1951, p. 518; Anderson and Creasey, 1958, p. 49; Lehner, 1958, p. 524; Krieger, 1965, p. 57; Huff and others, 1966, p. F7). Probably at least 60 meters of the Martin was eroded from the exposed section near the Verde Hot Springs prior to the accumulation of the Hickey Formation.

Lithology

The Martin Formation consists primarily of dolomite with a subordinate amount of dolomitic breccia and claystone. The basal part of the Martin Formation, approximately three meters thick, is a well indurated buff, laminated, aphanitic dolomite. It has well developed beds one to 50 centimeters thick; beds become thicker toward the top of the unit. Well developed, wavy laminae commonly occur within the beds. The laminae average one millimeter thick and are expressed by slight differences in color.

A stratum of cherty dolomitic breccia approximately one meter thick overlies the basal dolomite beds. It is composed about half of angular fragments of dolomite that range about four millimeter to 20 centimeters across and smaller subrounded to subangular fragments of chert. About one-tenth of the fragments are chert. The dolomite fragments are identical to those of the unit below except that their laminae are more contorted. The clasts are set in a finely crystalline calcareous matrix.

The remaining 55 meters of the Martin Formation consists of pinkish-gray, thick-bedded, aphanitic dolomite. The aphanitic dolomite consists of well defined parallel beds 0.2 to 1.5 meters thick. Beds of pale green claystone two millimeters to four centimeters thick occur between some of the dolomite beds. The dolomite is very well indurated and commonly has perfect conchoidal fracture. Rare subrounded to rounded quartz sand grains are present. Under the microscope the rock can be seen to consist primarily of crystalline subhedral to anhedral dolomite grains that average 0.1 millimeter across. There is a subordinate amount of anhedral, finely crystalline dolomite grains that average 0.02 millimeter across. The dolomite has about three percent porosity. Pore spaces generally are surrounded by coarser dolomite grains. No pore spaces occur in the finer-grained dolomite. The rock is a medium crystalline dolomite (V:D4) according to the classification of Folk (1959).

Age and correlation

The Martin Formation was named by Ransome (1904, p. 33) for outcrops on Mount Martin near Bisbee in southeastern Arizona. Much work has been been performed by many geologists in correlating the Martin Formation throughout Arizona (Teichert, 1965). Teichert (1965) divided the Martin Formation into two members. The lower member is the Beckers Butte, a channel-filling sandstone with discontinuous distribution. It is conformably overlain by the Jerome Member which consists of dolomite with minor amounts of limestone, sandstone, and shale. Teichert and Schopf (1958) assigned the Beckers Butte Member an Early or Middle Devonian age on the basis of fossil psilophytes. The Jerome Member is largely nonfossiliferous but richly fossiliferous horizons do occur locally within the uppermost part of the member. These fossils place the uppermost beds in the late Frasnian stage of the Late Devonian (Teichert, 1965, p. 90).

Teichert (1965) divided the Jerome Member into three units: a fetid dolomite unit, an aphanitic dolomite unit, and an upper unit. The fetid dolomite unit is a "fine- to medium-grained gray laminated dolomite that generally emits a strong fetid odor when struck with a hammer. ...Lithologically, it is closely related to the overlying aphanitic dolomite unit" (Teichert, 1965, p. 29). From his detailed description it is clear that the basal aphanitic dolomite of the Martin Formation in the Hackberry Mountain area corresponds to Teichert's fetid dolomite. However, this dolomite is not fetid in the Hackberry Mountain area. The dolomite breccia described in this report is similar to brecciated rock that commonly occurs at the top of the fetid dolomite unit. According to Teichert (1965, p. 29-30), the average thickness of the fetid dolomite unit is 6.5 meters, and the thinnest section is 2.5 meters thick. The fetid dolomite exposed in the Hackberry Mountain area is approximately 3.5 meters thick.

Teichert's (1965, p. 33-34) lithologic description of his aphanitic dolomite unit matches the characteristics of the upper thick-bedded aphanitic dolomite in the Hackberry Mountain area. In most sections measured by Teichert the aphanitic dolomite unit is 30 to 45 meters thick; it is about 55 meters thick in the section on hill 3061.

The preserved beds of the Martin Formation in the Hackberry Mountain area correspond to the nonfossiliferous lower part of the Jerome Member. The age is within the range Early or Middle Devonian to mid Late Devonian.

Origin

According to Teichert (1965, p. 81-82) the fetid dolomite unit was deposited upon a sandy, featureless plain dotted with claypans. The aphanitic dolomite unit was deposited after a sudden change in the conditions of sedimentation marked by the cessation of the supply of organic matter and increase in supply of terrigenous sediment. The aphanitic dolomite was probably deposited upon a vast mudflat.

UNCONFORMITY AT THE BASE OF THE CENOZOIC ROCKS

Within the study area, the Martin Formation of Devonian age is unconformably overlain by the Hickey Formation of Miocene age. This major unconformity is exposed throughout central Arizona; it separates rocks of Paleozoic and Mesozoic age from those of Cenozoic age. McKee (1951) prepared isopach maps of the Paleozoic and Mesozoic units in Arizona and postulated a combined accumulation of 900 to 1200 meters in the Hackberry Mountain area. Only 70 meters of Paleozoic sediments remain; the rest was eroded prior to accumulation of the Hickey Formation.

Gravels containing clasts of Paleozoic sedimentary and Precambrian crystalline rock occur along the Mogollon Rim north and east of the Verde River (Price, 1950) atop outcrops of the Paleozoic sediments. The composition of the enclosed clasts suggests that their source was from the southwest implying a northeastern drainage direction while they accumulated (Price, 1950, p. 503). Subsequent to the deposition of these gravels, there was a drainage reversal which resulted in a southern drainage direction and the excavation of an ancestral Verde Valley (Mahard, 1949, p. 111). This excavation formed a steep escarpment along the eastern side of the present Verde Valley, an ancestral Mogollon Rim. This ancestral rim is exposed at West Clear Creek (Peirce and others, 1979, p. 14-15; Ulrich and Bielski, in preparation) and at Fossil Creek where there is approximately 610 meters of relief (Twenter, 1962a; Pierce and others, 1979, p. 14). Peirce and others (1979), in a regional study of the Mogollon Rim, suggest that this erosional event possibly occurred in the Oligocene (?).

In the early Miocene (?) a thick section of sedimentary rocks, the Dry Beaver Creek rocks, accumulated within the ancestral Verde Valley (Twenter, 1961, p. C154). The sediments consist chiefly of conglomerate with lesser amounts of sandstone, mudstone, and limestone. The clastic components were derived primarily from the Precambrian rocks exposed to the west (Mahard, 1949, p. 112). Most of the sediments were removed by erosion during the middle Miocene (?) (Twenter, 1961, p. C155). Only a few outcrops remain in the Verde Valley region, and they have been described by Mahard (1949, p. 112-113), Twenter and Metzger (1963, p. 35-39), and Wadell (1972, p. 10-14). Deposits equivalent to the Dry Beaver Creek rocks are not exposed in the Hackberry Mountain area.

MIOCENE ROCKS

Rocks of Miocene age are exposed over the majority of the mapped area. They include basaltic, andesitic, dacitic, and rhyolitic volcanic rocks, and sedimentary rocks. The concurrent accumulation of the various lithologies resulted in complex interfingering relationships. The basaltic rocks comprise the majority of the stratigraphic units in Hackberry Mountain area; they have been divided into the Hickey Formation and the overlying Thirteenmile Rock Basalt. The Cimarron Hills Andesite and dacitic Towel Creek Tuff interfinger with the basaltic formations. This section is overlain,in ascending stratigraphic order, by local outcrops of a rubble unit, a rhyolite flow, the Hackberry Mountain Dacite, and the Verde Formation. Other than the Verde and Hickey Formations, all the above mentioned units are defined in this report. The Thirteenmile Rock Basalt is a redefinition of a name used previously (Elston and Scott, 1973b; Elston, McKee, Scott, and Gray, 1974).

McKee and Elston (1980) obtained 26 potassium-argon ages from a stratigraphically controlled section of the Miocene rocks exposed along the Verde River in the northwestern part of the Hackberry Mountain area. Except for the Verde Formation, the apparent ages of all the Miocene units are well constrained by the potassium-argon data. The apparent age of the Verde Formation is also well constrained from the paleomagnetic study of Bressler and Butler (1978). The Miocene rocks exposed within the study area accumulated from about 12 to 6 m.y. ago. This span of ages lies within the Miocene epoch according to the time scale proposed by Sohl and Wright (1980).

Hickey Formation

The basaltic rocks of the Hackberry Mountain area, which include the Hickey Formation, were first reported by Jenkins (1923, p. 66); they were undifferentiated and labeled as lava flows of Tertiary age. Mahard (1949, p. 118) also mentioned these volcanic rocks; they were undifferentiated and labeled as lava, tuffs, and breccias that underlie the Verde Formation. Twenter and Metzer (1963, p. 39-41) included the Hickey Formation exposed in the northwestern portion of the study area within their Tertiary volcanic rocks of Miocene (?) and Pliocene (?) age. Elston and Scott (1973a, b) were the first to correlate the lower section of basaltic rocks of the Hackberry Mountain area with the Hickey.

Distribution and topographic expression

The Hickey Formation is a sequence of heterogeneous basalt and olivine basalt flows with intercalated basaltic tuffs, breccias, agglomerates, and dikes about 355 to 550 meters thick. The major exposure of the Hickey occurs in a strip along the Verde River, up to three kilometers wide, that extends from near Sycamore Canyon to the southern boundary of the mapped area. The formation is also exposed along the cliffs below Deadman Mesa and in the area bounded by upper Sycamore Canyon and the Cottonwood Spring fault. Many small discontinuous exposures of the Hickey occur along the northern and western margins of Hackberry Basin and between Hackberry and Sycamore Canyons. In general, the Hickey forms steep cliffs along the major drainages, but away from the drainages it forms low, rounded hills. The Hickey Formation is the least resistant of the major volcanic units.

Stratigraphic relations

The Hickey Formation rests on an irregular surface eroded on the Martin Formation. In the few outcrops where the contact is exposed the two units appear to be structurally concordant.

The contact between the Hickey Formation and the overlying Thirteen-mile Rock Basalt is structurally concordant. Approximately the basal two-thirds of the Hickey Formation consists exclusively of mafic volcanic rocks; the upper one-third of the Hickey Formation is intercalated with the Towel Creek Tuff, the Cimarron Hills Andesite, and the Verde Formation. The complex stratigraphic relationships within the upper one-third of the Hickey Formation are schematically represented in figure 5 and are also depicted in Sections 1 and 2 of plate 4. Details of some of these stratigraphic relationships can also be gleaned from the measured sections in the appendix to this report, in particular, Sections 1, 2, 4, 5, 6, 11, 12, 13, 14, 16, 18, and 19.

In previous studies of this area (Elston and Scott, 1973b; Elston, McKee, Scott, and Gray, 1974), the upper contact of the Hickey was placed at the base of the stratigraphically lowest dacitic tuff (Member 1 of the Towel Creek Tuff). All volcanic rocks above this contact were assigned by them to the Thirteenmile Rock Volcanics. However, the basalt flows that occur in the basal portion of the Thirteenmile Rock Volcanics of Elston and Scott (1973b) are lithologically similar to those of the Hickey. In this report the upper contact of the Hickey Formation has been placed at a higher stratigraphic level where there are substantial changes in the basaltic rocks. The overlying basaltic unit has been defined in this report as the Thirteenmile Rock Basalt and the differences between this unit and the Hickey Formation are listed in table 2. The major difference between the two formations is that the basalts of the Hickey were erupted from local cinder cones, and those of the Thirteenmile Rock Basalt were not. The contact between the Hickey Formation and the Thirteenmile Rock Basalt occurs at the base of a basalt designated B 1 by Elston, McKee, Scott, and Gray (1974), Scott (1974), and McKee and Elston (1980). Andesitic, dacitic, and rhyolitic rocks previously assigned to the Thirteenmile Rock Volcanics have all been placed in different units described later in this report.

The upper portion of the redefined Hickey Formation interfingers with the lowest four Members of the Towel Creek Tuff. Locally, a fifth member of the Towel Creek Tuff occurs between the Hickey Formation and the Thirteenmile Rock Basalt. These dacitic rocks were extruded from the Hackberry volcano, a positive topographic feature at that time. As a result, the members of the Hickey Formation that are interstratified with the Towel Creek Tuff pinch out as they approach this ancient dacitic volcano. This relationship is very well exposed along Towel Creek. Conversely, the basal members of the Towel Creek Tuff pinch out away from the dacitic volcano.

The upper part of the Hickey Formation locally interfingers with

Table 2.--Lithologic contrasts between the Hickey Formation and the Thirteenmile Rock Basalt

Hickey Formation	Thirteenmile Rock Basalt
Petrographically heterogeneous, noticeable variations in phenocryst content and average grain size of groundmass	Petrographically homogeneous, very little varia- between individual flows
Numerous local source vents	No local source vents, probable source is to the east of the study area
Vents are all cinder cones	Vents unknown, may be fissures
Numerous intercalated basaltic tuffs	Basaltic tuffs are rare except in easternmost exposures
Moderately resistant	Extremely resistant
Flows are shades of gray, brown, and red	Flows are various shades of gray only
Usually more olivine than pyroxene phenocrysts	Greater concentration, in general, of pyroxene phenocrysts
Irregular joints, columnar joints are rare	Well developed joints, columnar joints are common
Brecciated and vesiculated flows are common	Brecciated and vesiculated flows are not common

the lowest member of the Cimarron Hills Andesite. The upper two members of the Hickey Formation each contain several flows, as does the lowest member of the andesite. Individual flows from the three units were erupted intermittently during the same period of time and, consequently, they have complex interfingering relationships. The Hickey Formation and the overlying Thirteenmile Rock Basalt are similar in the northeastern part of the mapped area but a flow of the lower member of the Cimarron Hills Andesite commonly occurs between the two basaltic formations and helps to delineate their contact.

In the west-central part of the mapped area, the Hickey Formation has two small tongues of the sedimentary Verde Formation. The stratigraphically lower of the two is the oldest outcrop of the Verde exposed in the area studied and may possibly be the oldest in the entire Verde Valley.

Thickness

The average thickness of the Hickey Formation is approximately 550 meters. This figure is the sum of the thicknesses of all the individual members that are included within the composite section depicted in Section 1 of plate 4A. This thickness is greater than that reported in any other study of the Hickey or similar rocks in central Arizona (table 3). It is probably thickest in the Hackberry Mountain area because the volcanism lasted longer here (see following section on the age of the Hickey Formation). Also, the Hickey may also be thickest in the study area because here the section is complete. In the other areas studied, the Hickey is the highest formation preserved (Anderson and Creasey, 1958, p. 56; Lehner, 1958, p. 550; Canney and others, 1967, p. J15) and has been subjected to an unknown amount of erosion, or it is unconformably

Table 3.--Reported thicknesses of the Hickey Formation and equivalent rocks in central Arizona

Unit	Location	Geographic relationship to Hackberry Mountain	Thickness (meters)	Reference
Hickey	Woodchute Mountain	58 kilometers northwest	440	Anderson and Creasey (1958, p. 56) Lehner (1958, p. 550)
Hickey	southern end of Lonesome Valley	49 kilometers west-northwest	315	Anderson and Creasey (1958, p. 56)
Hickey	Antelope Hills	59 kilometers northwest	30 to 90	Lehner (1958, p. 550)
Hickey	Casner Mountain	63 kilometers north-northwest	75 +	Lehner (1958, p. 550)
TVR*	Hidden Valley Ranch	45 kilometers northwest	110	Twenter and Metzger (1963, p. 44)
TVR	Pine Mountain	16 kilometers southwest	300	Canney and others (1967, p. J15)

* Tertiary volcanic rocks

overlain by a younger unit (Lehner, 1958, p. 550).

Lithology

The Hickey Formation consists primarily of a heterogeneous group of basalt and olivine basalt flows with minor amounts of intercalated basaltic tuff and breccia. The formation also includes several exhumed basaltic cinder cones with associated dikes.

The physical character and mineralogic composition of the basalt flows of the Hickey Formation are highly diverse. Individual basalt flows range from less than two to greater than 120 meters thick in some compound units. The average flow is 10 to 30 meters thick. The basalt flows range in color from moderate red to very dark gray in both fresh and weathered samples. The most common colors are gray on a fresh surface and gray or brownish-gray on a weathered surface. Most flows have a massive interior with a brecciated top and bottom. Some flows are brecciated throughout, especially where close to their vents. Normally the uppermost and lowermost part of the flows are vesicular, especially if the flows are not heavily brecciated. The central parts of many flows are vesicular; vesicles constitute up to 40 percent of the volume of the flows. The vesicles are spheroidal to irregular in shape and range in size from less than one millimeter to several centimeters across. They are commonly filled or lined with calcite or, less commonly, with chalcedony or zeolites. Massive parts of the flows generally are jointed; brecciated parts rarely are jointed. Most jointed flows have two sets of joints. One set is parallel to the base of the flow and is best developed in the basal part, probably it is caused by shearing at the base of the flow (Williams and McBirney, 1979, p. 116). The other set is perpendicular to the base of the flow and commonly trends in several different directions.

Columnar joints are also common and are best developed in the thicker and more massive flows.

Essentially all the flows are porphyritic. They contain phenocrysts of olivine and pyroxene set in an aphanitic groundmass. The phenocrysts average about one millimeter across and range from less than one to five millimeters across. The olivine phenocrysts are typically subhedral; pyroxene phenocrysts are typically euhedral. Olivine phenocrysts are more abundant that pyroxene. Glomerophyres of olivine and pyroxene microphenocrysts are common. Olivine phenocrysts generally are totally altered to iddingsite; less commonly, only their rims are altered to iddingsite. A fresh olivine was not observed. The pyroxene phenocrysts in most cases are green; a few flows have black pyroxenes. The pyroxene phenocrysts are most commonly clinopyroxene. Orthopyroxene was observed only in one unit. No reaction relations between the olivine and pyroxene crystals were observed. Phenocrysts of plagioclase are common but are rarely an important constituent. Corroded quartz phenocrysts are rare. The groundmass of Hickey flow rocks generally is holocrystalline and pilotaxitic. It contains microlites of labradorite with intergranular, anhedral clinopyroxene, olivine (altered to iddingsite), and opaque mineral grains. Rarely the groundmass contains intersertal chlorite. Intersertal glass was observed in one flow. Commonly, basalt flows change lithologically with distance from their eruptive vents; changes in the abundance of phenocrysts are common.

Many of the basalt flows are separated by thin basaltic tuffs. The tuffs range in thickness from less than one to greater than 50 meters and are commonly between five and 15 meters. Thickness of the tuffs depends upon proximity to their source vent. In general, the tuffs are non-resistant and poorly exposed; commonly, only the uppermost beds that have been baked by the overlying basalt flow are exposed. The tuffs are usually buff, but they are moderate red where they have been baked. The basaltic tuffs are usually well bedded. However, a substantial number are massive. The bedding is typically expressed by differences in the grain size of the ash and lapilli of the individual beds. It is also shown by differences in porosity. The beds are usually parallel to the base of the tuff. Cross-beds or other fluviatile sedimentary structures were not recognized in any tuff, which suggests that few, if any, had been reworked, contrary to the reports of Elston and Scott (1973b), Elston, McKee, Scott, and Gray (1974), and Scott (1974, p. 9).

The tuffs consist primarily of basaltic lithic lapilli and ash. Minor amounts of basaltic vitric lapilli and ash plus olivine and pyroxene crystals occur in some tuffs. Many tuffs contain substantial amounts of calcite. The calcite fills the pore spaces within the tuff and fills the vesicles in the enclosed lapilli. Most tuffs are mineralogically similar to the basalt flows that overlie them.

At least nine exhumed basaltic cinder cones that were the source vents for individual flows or group of flows assigned to the Hickey Formation occur in the Hackberry Mountain area. The cones average about two kilometers across, and their exposure ranges from fair to good depending primarily upon the amount of dissection. The exhumed cinder cones contain massive or bedded deposits of basaltic tuff and subordinate basaltic dikes, agglomerate, and flows. Tuffs exposed within the exhumed cinder cones are similar to those interstratified with the basalt flows but commonly contain larger lapilli, up to four centimeters in diameter, and thicker beds.

Most of the exhumed cinder cones contain basaltic dikes. The dikes are vertical or nearly so. They are generally one to two meters thick and locally can be as thick as 50 meters. The dikes are five to over 600 meters in length and commonly crop out in an en echelon pattern. Most trend towards the northwest, parallel with the average trend of faults in the area. The mineralogy of the dikes is similar to that of the associated basalt flows. The dikes have a finer-grained groundmass and smaller phenocrysts. The dikes are rarely vesicular, have chilled glassy borders, and have baked the basaltic cinder they intrude (figure 7).

Basaltic agglomerate exposed in small outcrops at a few of the exhumed cinder cones is composed of red or blue basaltic bombs with interstitial basaltic lapilli and ash. These deposits are interstratified with the tuff beds. The bombs are fusiform in shape, indicating that the eruptions were Strombolian (MacDonald, 1972, p. 219). The bombs are generally aphanitic and rarely contain phenocrysts. Olivine is the most common phenocryst.

Basalt flows commonly are interstratified with the basaltic tuffs within the exhumed cinder cones but never constitute more than 10 percent of the volume of a given cone. The flows rarely are thicker than five meters, and form discontinuous and irregular outcrops.

Pyroclastic deposits were mapped separately in areas close to but outside of the exhumed cinder cones. These deposits consist of red or purple basaltic tuffs, lapilli tuffs, and agglomerate with subordinate amounts of scoriaceous, brecciated basalt flows.

Most of the thicker and more continuous basalt flows can be traced to source vents in the Hackberry Mountain area. All the identified vents for the basalt flows are exhumed cinder cones. The number of basalt flows and intercalated tuffs and the thickness of the Hickey

Formation increase as the Hickey is traced along the main outcrop from the southern to the western part of the mapped area.

The mineralogic heterogeneity of the basalt flows of the Hickey permitted the formation to be divided into 15 mappable informal members. Mapped members that occur in the basal two-thirds of the Hickey Formation (those which occur below the basal member of the Towel Creek Tuff) consist either of a distinctive basalt flow or a group of flows and intercalated basaltic tuffs and breccias that occur stratigraphically between easily mapped marker units. The members mapped in the upper one-third of the Hickey are packets of basalt flows with intercalated basaltic tuffs and breccias that interfinger with the Towel Creek Tuff. Rocks of the cinder cones are mapped as separate facies of the various members.

Elston and Scott (1973b) also divided the Hickey Formation into many separate units. The correspondence between their units and the informal members used in this report is presented in table 4.

Brief descriptions are given below of the members of the Hickey Formation. More detailed descriptions of the rocks that comprise each member are given in the stratigraphic sections in the appendix.

Member 1, the stratigraphically lowest member of the Hickey Formation, rests unconformably upon the Martin Formation of Devonian age, and consists of one distinctive basalt flow. The flow is dark olive, has well developed columnar jointing, and contains abundant green pyroxene and olivine phenocrysts set in an aphanitic groundmass. In the vicinity of the Verde Hot Springs the flow is locally overlain by a mineralogically similar basaltic tuff that was mapped as a separate facies. The basalt flow is underlain by a purple, aphanitic, structureless basaltic ash that crops out along the Verde River adjacent to Gospel Hollow.

Table 4.--Assignation of informal members of the Hickey Formation

This Report		Elston and Scott (1973b) and McKee and Elston (1980)
Member 15	(Th_{15})	Ttb_{2-5}; $Tts_{3,4}$
Member 14	(Th_{14})	----
Member 13	(Th_{13})	Ttb_{7-11b}; Tts_{7-11b}
Member 12	(Th_{12})	----
Member 11	(Th_{11})	Ttb_{12-13b}; Tts_{12}
Member 10	(Th_{10})	Ttb_{14}
Member 9	(Th_9)	Thb_{15}; Ths_{15}
Member 8	(Th_8)	$Thb_{16,17}$; $Ths_{16,17}$
Member 7	(Th_7)	Thb_{18a-19}; Ths_{18}
Member 6	(Th_6)	Thb_{20}; Ths_{20}
Member 5	(Th_5)	Thb_{21-24}; Ths_{21-24}
Member 4	(Th_4)	Thb_{25}; Ths_{25}
Member 3	(Th_3)	Thb_{26-30}; Ths_{26-29}
Member 2	(Th_2c, Th_2p)	Tha_{31}
Member 2	(Th_2)	Thb_{31}
Member 1	(Th_1)	----

Member 2 consists of one to three petrographically similar basalt flows that form columnar-jointed cliffs along long parts of the Verde River. The flow contains a sparse olivine phenocrysts that have been altered to iddingsite. Distinct haloes of hematite surround the olivine phenocrysts. A part of the cinder cone associated with this flow crops out along the eastern bank of the Verde River due east of Brown Springs.

Member 3 consists of a packet of slope forming basalt flows with intercalated basaltic tuffs bounded by the distinctive basalt flows of Members 2 and 4. This member contains as many as seven individual flows.

Member 4 consists of a very dark gray, very resistant basalt flow that has well developed columnar joints, and contains fairly abundant green pyroxene and olivine phenocrysts. A large exhumed cinder cone that was the source for this flow is exposed along the cliffs east of the Verde River just north of the Verde Hot Springs.

Member 5 is a sequence of basalt flows with intercalated basaltic tuffs and occurs between Members 4 and 6. It includes a scoriaceous, brecciated andesite flow at the base. A large, exhumed basaltic cinder cone exposed at the southern end of Deadman Mesa has also been assigned to this member.

Member 6 consists of a distinctive, usually thick, very dark gray, and aphyric basalt flow.

Member 7 is a sequence of basalt flows with intercalated basaltic tuffs and breccias.

Member 8 contains two separate basalt flows and a part of a cinder cone associated with the lower flow. The cinder cone is exposed along the Verde River just south of the mouth of Bull Run Creek. A possibly related northwest-trending basaltic dike crops out 500 meters south of the mouth of Bull Run Creek. The dike has discontinuous exposures and is close to and parallel to a fault; it was also recognized west of the Verde River (E.W. Wolfe, oral commun., 1980).

Member 9 includes several flows and one has a well exposed cinder cone located in Gospel Hollow. This unit is generally overlain by Member 2 of the Towel Creek Tuff; it is locally overlain by Member 1 of the Towel Creek Tuff. Several small outcrops of a basalt flow that occupy the same stratigraphic position along Fossil Creek west of Deadman Mesa have also been assigned to this member.

Member 10 consists of a thin basalt flow of very limited exposure and a well exposed cinder cone located along Bull Run Creek. The flow is stratigraphically bound by Members 1 and 2 of the Towel Creek Tuff and is exposed between Bull Run Creek and Gospel Hollow. Another flow at the same stratigraphic level, exposed along Fossil Creek west of Deadman Mesa, is tenatively assigned to this member.

Member 11 is a series of basalt flows and intercalated basaltic tuffs that occur between Members 2 and 3 of the Towel Creek Tuff.

Member 12 contains various basalt flows that occur within thick exposures of Member 3 of the Towel Creek Tuff. The flows are exposed along Towel Creek, east of Gospel Hollow, southwest of the Towel Peaks, and along the west side of Deadman Mesa. The basalt flow exposed along the south side of Towel Creek is characterized by euhedral plagioclase phenocrysts in a blue aphanitic groundmass. This flow is petrographically similar to the Cimarron Hills Andesite, but chemically it is closer to a basalt (sample RL-79-13 in table 5). This flow is also unique because it thickens as it approaches the Hackberry volcano.

Member 13 consists of a packet of basalt flows and intercalated tuffs bounded by Members 3 and 4 of the Towel Creek Tuff that is in a strip over a relatively large portion of the mapped area from Sycamore Canyon southeast to Deadman Mesa. The cinder cone associated with one of the flows is exposed beneath the northwestern tip of the Towel Peaks.

Member 14 has many separate flows which are interbedded with associated basaltic tuffs and Member 1 of the Cimarron Hills Andesite. Included are several distinctive very dark gray to bluish-gray basalt flows and several large associated cinder cones. These flows are characterized by abundant phenocrysts of green pyroxene and olivine. No other basalt flow in the Hackberry Mountain area has as high a concentration of phenocrysts. The basalt flows of Member 14 were mapped only near their cinder cones. A large exhumed cinder cone located along Fossil Creek Road was one of the vents for these flows. A satellite cinder cone which contains a substantial amount of basaltic agglomerate occurs to the east along upper Sycamore Canyon. Both cinder cones have many basaltic dikes.

Member 15, the youngest member of the Hickey Formation, consists of basalt flows and intercalated basaltic tuffs that lie between Member 4 of the Towel Creek Tuff and the Thirteemile Rock Basalt. This member also intertongues with the Verde Formation and the Cimarron Hills Andesite. Its upper contact commonly occurs at the base of the uppermost flow of Member 1 of the Cimarrron Hills Andesite. In the northeastern part of the mapped area, where there is no andesite flow, it is difficult to define the contact of this member with the Thirteenmile Rock Basalt. Basaltic cinder assigned to this member occurs along upper Sycamore Canyon.

Chemistry

The chemistry of the Hickey Formation is quite variable, and it reflects the heterogeneity of this formation (table 5). Most of the rocks are basalts according to the classification scheme of Streckeisen (1979, p. 332). Two flows, one in Member 5 and the other in Member 7, are andesite. The majority of the basaltic rocks lie in the alkalic basalt field as defined by MacDonald and Katsura (1964, p. 87) (figure 8); two analysed rocks are in the tholeiitic field close to the alkalic basalt boundary. There is no correlation between chemistry and stratigraphic position for the various flows.

McKee and Anderson (1971) determined the chemistry of basalts from the Hickey Formation from rocks collected in central Arizona. They reported that the majority of the samples were alkalic basalt as defined by MacDonald and Katsura (1964).

Age

The Hickey Formation was named by Anderson and Creasey (1958, p. 56) based upon exposures of basalts with intercalated tuffs atop Hickey Mountain (55 kilometers northwest of Hackberry Mountain). They assigned this formation to the Pliocene (?) based primarily on lithologic similarities between gravels within the Hickey and others of known age in central Arizona.

Lehner (1958) studied the Hickey Formation in the Clarkdale quadrangle and also assigned it a Pliocene (?) age but concluded that the Hickey Formation could possibly be of Miocene age. In a regional study of the upper Tertiary rocks of central Arizona, Twenter (1961) noted that the late Tertiary histories of the sedimentary basins in central Arizona were all similar. In all of these the Hickey or an equivalent unit is

Table 5.--Major-element and normative compositions, in percent, of the Hickey Formation

Member	2	3	4	5	5	5	5	6	7	7	7	8
Sample No.	[1]RL-78-3	[1]RL-79-54	[2]B24a-1	[2]B24b-1	[2]B23b-1	[2]B22-1	[2]B21b-1	[2]B20-1	[2]B19a-1	[2]B19b-1	[2]B18b-1	[2]B16-1
Major oxides (weight percent)												
SiO_2	48.8	44.9	56.1	56.1	50.5	48.3	50.4	47.2	53.5	50.6	49.1	47.4
Al_2O_3	13.8	17.2	14.2	14.2	15.5	18.4	14.2	16.2	16.8	15.7	12.9	16.3
Fe_2O_3	8.07	10.5	3.61	3.75	9.01	8.4	5.07	6.44	6.02	4.89	3.37	3.82
FeO			3.38	2.97	1.05	1.26	3.74	3.69	1.49	3.06	6.53	6.03
MgO	3.5	5.84	6.2	5.8	5.1	3.5	9.3	5.9	3.3	6.3	12.3	7.0
CaO	8.36	12.1	7.5	7.5	10.0	10.0	9.4	11.8	7.7	10.1	8.7	10.6
Na_2O	2.5	2.2	3.5	3.4	3.3	3.4	3.2	2.7	3.5	3.3	2.7	2.9
K_2O	1.51	0.92	1.7	2.1	1.2	1.4	1.2	1.2	1.5	1.3	0.8	0.9
TiO_2	1.29	1.45	0.87	0.89	1.18	1.83	1.18	1.60	1.32	1.40	1.03	1.31
MnO	0.07	0.13	0.12	0.11	0.11	0.10	0.15	0.14	0.10	0.11	0.16	0.17
P_2O_5	0.4	1.0	0.29	0.28	0.49	0.52	0.47	0.90	0.56	0.62	0.41	0.65
CO_2			0.20	0.62	0.33	0.32	0.31	<0.05	0.09	0.46	0.06	0.26
H_2O+			0.64	0.73	0.79	0.81	1.11	1.04	1.76	1.22	0.97	1.87
H_2O-			1.38	1.53	2.05	1.82	0.92	1.25	2.64	1.62	0.49	0.84
[3]Loss	10.29	3.09										
Total	97.6	99.3	99.7	100.0	100.6	100.1	100.7	100.1	100.3	100.7	99.5	100.1
CIPW Norms[4]												
q	7.2		5.0	5.0					6.2			
or	10.2	5.7	10.3	12.8	7.3	8.6	7.2	7.3	9.3	7.9	4.8	5.5
ab	24.1	19.5	30.4	29.7	28.9	29.8	26.8	23.0	31.0	28.8	23.3	25.3
an	25.1	36.0	18.5	17.9	24.8	32.0	21.8	29.3	27.0	24.9	21.2	29.7
ne								0.2				
di	15.9	16.5	14.4	15.1	19.1	13.3	18.4	20.3	7.6	18.3	16.3	16.5
hy	11.6	2.2	17.0	15.3	10.6	0.1	7.9		12.9	8.6	11.1	1.6
ol		12.5			3.4	9.2	12.5	12.2		5.4	17.9	14.9
mt	2.0	2.2	1.8	1.8	2.3	2.2	2.1	2.3	1.9	1.9	2.4	2.3
il	2.8	2.9	1.7	1.7	2.3	3.6	2.3	3.1	2.6	2.7	2.0	2.6
ap	1.1	2.5	0.7	0.7	1.2	1.3	1.2	2.2	1.4	1.5	1.0	1.6

Footnotes explained on last page of table.

Table 5.--Major-element and normative composition, in percent, of the Hickey Formation--Continued

Member	9	10	10	11	11	11	12	13	13	13	13	13	13
Sample No.	[2]B15-1	[2]B14-1	[2]B14-2	[2]B13-1	[2]B13a-1	[2]B13-2	[1]RL-79-13	[2]B11-1	[2]B11a-2	[2]B11-2	[2]B11	[2]B10-M2	[2]B9-1
Major oxides (weight percent)													
SiO_2	46.7	44.6	47.6	44.4	42.8	46.7	50.8	51.8	47.0	45.7	46.6	47.0	48.9
Al_2O_3	14.8	14.7	14.9	13.9	15.4	17.3	14.0	15.4	16.6	15.5	16.4	16.9	16.3
[1]Fe_2O_3	8.23	8.1	3.77	6.80	8.5	7.6	7.25	6.3	8.7	7.9	7.3	7.8	4.84
FeO	2.93	1.89	5.54	3.06	2.97	2.61		2.70	2.40	2.61	2.70	2.21	4.19
MgO	7.0	7.4	9.9	7.4	7.0	5.1	6.94	7.3	4.3	6.0	5.4	4.6	7.7
CaO	11.5	14.8	10.2	14.9	14.9	12.6	9.96	9.3	11.9	12.6	12.3	11.9	9.8
Na_2O	2.7	3.1	2.7	2.6	2.5	3.0	2.8	3.3	2.3	2.7	2.3	3.4	3.1
K_2O	0.7	1.2	0.9	1.7	0.9	1.1	1.67	1.3	0.8	1.3	1.2	1.1	1.0
TiO_2	1.12	1.16	1.16	1.40	1.12	1.08	1.14	1.08	1.47	0.96	1.07	1.35	1.16
MnO	0.17	0.15	0.16	0.15	0.14	0.12	0.15	0.10	0.11	0.12	0.11	0.09	0.15
P_2O_5	0.43	0.84	0.42	0.99	0.75	0.46	0.83	0.35	0.54	0.83	0.54	0.60	0.51
CO_2	1.05	<0.05	0.13	0.33	0.06	0.22		<0.05	<0.05	0.22	<0.05	0.65	0.26
H_2O+	1.45	0.99	1.62	1.43	0.73	1.41		1.01	1.41	1.41	1.42	1.32	1.06
H_2O-	1.25	1.18	0.80	1.12	1.40	1.18		1.46	2.27	1.23	1.97	1.25	0.72
[3]Loss							3.39						
Total	100.0	100.1	99.8	100.2	99.2	100.5	98.9	100.4	99.8	99.1	99.3	100.2	99.7
CIPW Norms[4]													
q							0.3						
or	4.3	7.3	5.4	10.4	5.5	6.7	10.4	7.8	5.0	8.0	7.4	6.7	6.1
ab	23.1	3.1	23.5	1.4	1.6	17.0	24.9	28.3	20.4	15.5	20.3	21.2	26.9
an	27.4	23.3	26.7	21.9	29.2	31.4	21.8	23.7	34.2	27.5	32.4	28.7	28.4
ne	0.4	12.9		11.6	11.0	5.0					0.05	4.7	
di	24.0	37.9	18.3	38.9	34.8	24.7	19.8	16.9	19.9	26.4	23.0	23.6	14.7
hy			0.8				16.7	11.7	12.1				4.7
ol	14.9	9.1	19.7	8.5	11.3	9.8		6.5	1.7	11.6	11.1	8.	13.6
mt	2.5	2.1	2.2	2.1	2.4	2.3	1.7	2.1	2.5	2.3	2.3	2.2	2.1
il	2.2	2.3	2.3	2.7	2.2	2.1	2.3	2.1	2.9	1.9	2.1	2.7	2.3
ap	1.1	2.1	1.0	2.5	1.9	1.1	2.1	0.9	1.4	2.1	1.4	1.5	1.3

Footnotes explained on last page of table.

Table 5.--Major-element and normative compositions, in percent, of the Hickey Formation - Continued

Member	13	15	15	15
Sample No.	[2] B8-1	[2] B4-1	[2] B4ee-1	[2] B3-2
Major oxides (weight percent)				
SiO_2	46.1	47.6	49.1	50.7
Al_2O_3	15.2	15.0	14.7	15.0
Fe_2O_3	4.29	7.3	5.3	5.6
FeO	5.40	2.43	4.32	2.52
MgO	8.1	5.9	9.3	3.9
CaO	12.5	10.8	9.1	10.2
Na_2O	2.5	3.7	3.3	4.2
K_2O	0.8	1.8	1.0	2.2
TiO_2	1.16	1.69	1.01	1.36
MnO	0.19	0.15	0.15	0.14
P_2O_5	0.70	0.80	0.30	0.70
CO_2	0.21	0.47	0.07	1.15
H_2O+	1.53	0.72	1.12	0.60
H_2O-	0.77	1.20	1.19	0.96
[3] Loss				
Total	99.5	99.6	100.0	99.2
CIPW Norms[4]				
or	4.9	11.0	6.1	13.5
ab	17.7	20.4	28.7	28.7
an	28.8	19.7	23.0	16.2
ne	2.3	6.5		4.5
di	24.8	24.8	17.3	26.1
hy			0.3	
ol	15.2	10.1	19.6	4.6
mt	2.2	2.2	2.3	1.9
il	2.3	3.3	2.0	2.7
ap	1.7	2.0	0.7	1.8

[1] Chemical analyses by x-ray fluorescence methods with all iron calculated as Fe_2O_3. Locations of samples shown in plate 7. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg

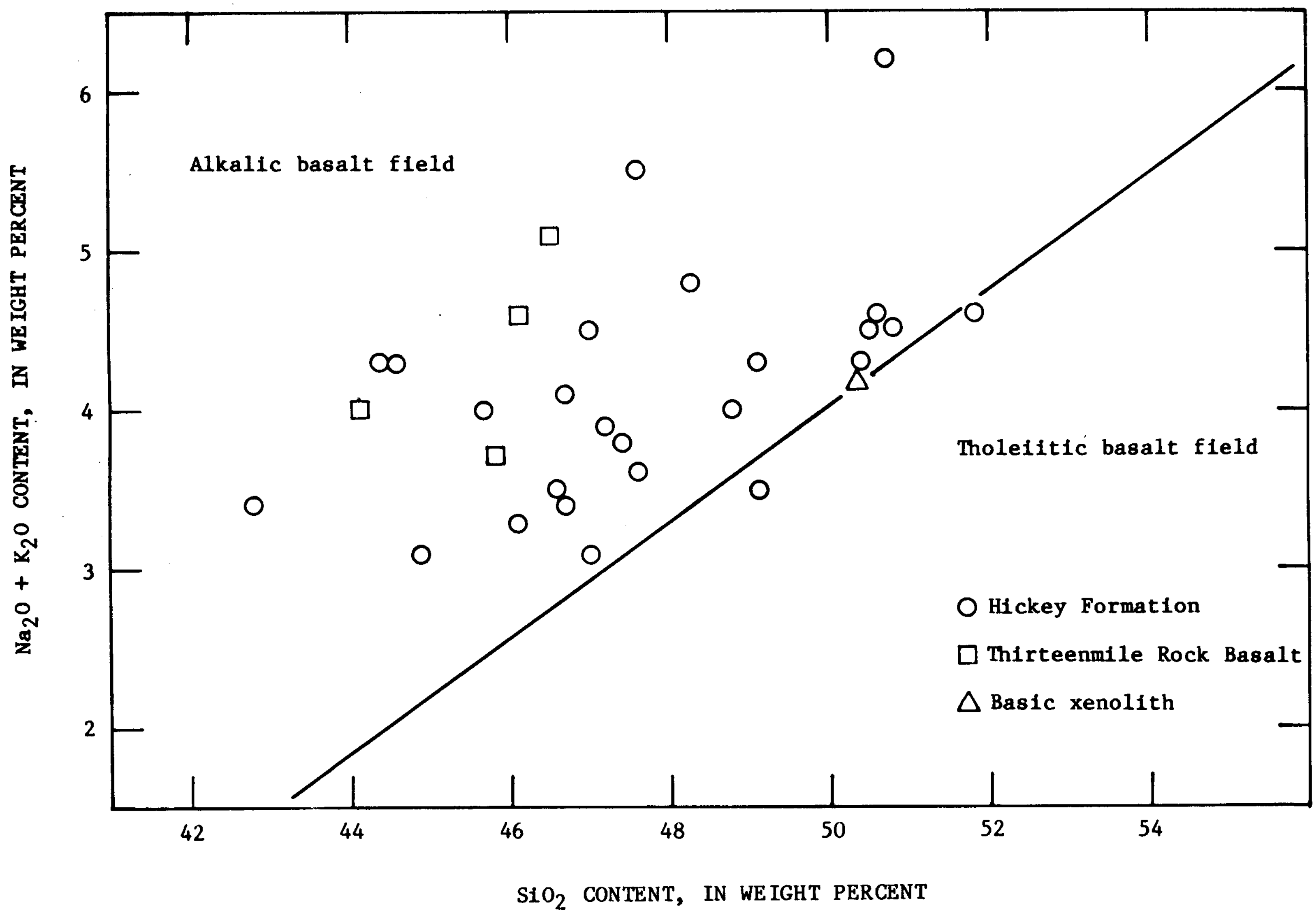
Table 5.--Major-element and normative compositions, in percent, of the Hickey Formation--Continued

[2] Chemical analyses from Scott (1974). Alphanumeric characters preceding the hyphen for each sample number refer to flow, in their terminology, that analyzed rock is from. Table 4 equates his terminology with that used for the informal members in this report.

[3] Loss on Ignition.

[4] In the analyses determined for this report all iron was calculated as ferric iron. The ratio between the ferric to ferrous iron was calculated using an equation determined by Wolfe and others (in preparation) in their study of the San Francisco volcanic field. The equation ($FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$) is a least squares fit between the silica content and the ferric to ferrous iron ratio of the least oxidized of the numerous major-element chemical analyses performed. For consistency and because they are typically highly oxidized, the ferric to ferrous iron ratios for the analyses from Scott (1974) were recalculated for the determination of their normative mineralogy.

Figure 8.--Alkali-silica diagram depicting boundary between tholeiitic basalt and alkalic basalt fields (after MacDonald and Katsura, 1969, p. 84).


Alkalic basalt field
Tholeiitic basalt field
Hickey Formation
Thirteenmile Rock Basalt
Basic xenolith
6
5
4
3
2
42
44
46
48
50
52
54
$Na_2O + K_2O$ CONTENT, IN WEIGHT PERCENT
SiO_2 CONTENT, IN WEIGHT PERCENT

overlain by and interfingers with lacustrine and fluviatile rocks. In Walnut Grove Basin (80 kilometers west-southwest of Hackberry Mountain) Hickey-equivalent tuffaceous rocks are overlain by fossiliferous lacustrine and fluviatile rocks. These fossiliferous rocks contain diagnostic fossils of early Pliocene age (Lance, 1960, p. 156). Therefore, Twenter (1961) concluded that the Hickey Formation accumulated in late Miocene to early Pliocene times.

Krieger and others (1971) obtained a potassium-argon age of 14.6 ± 1.1 m.y. for the stratigraphically lowest flow within the Hickey Formation on the east side of the Black Hills. McKee and Anderson (1971) collected ten samples of the Hickey formation from central Arizona and obtained potassium-argon ages ranging from 14.0 ± 0.6 to 10.1 ± 0.4 m.y.

McKee and Elston (1980) dated 19 stratigraphically controlled flows from the Hickey Formation in the Hackberry Mountain area by potassium-argon methods (table 6). The dated flows occur in Members 4 to 15 of the Hickey and they range in age from at least 11.4-11.7 to 7.4-8.5 m.y. The basal three members of the Hickey were not dated. However, it is unlikely that the basal three members are older than about 14.6 m.y., the oldest age reported for the unit (Krieger and others, 1971). The upper units of the Hickey Formation in the Hackberry Mountain area have younger potassium-argon ages than have been reported from other localities.

Correlation

Anderson and Creasey (1958, p. 56-58) defined the Hickey Formation and divided it into two facies--volcanic and sedimentary. The volcanic facies comprises chiefly flows and subordinate amounts of basaltic sediments and breccia. The flows are generally basaltic and contain olivine

Table 6.--Potassium-argon ages of volcanic rocks from the Hackberry Mountain volcanic center from McKee and Elston (1980) and this report

Unit designation used in this report	Unit designation of McKee and Elston (1980)	Age and Precision at σ (Reproducibility of Analysis)	Estimated age accuracy *
dh		8.3 ± 0.5	7.8 - 8.4
t_6	T -1	7.9 ± 0.5	7.8 - 8.4
tm_1	B -1	8.5 ± 1.3	7.8 - 8.5
	B 1	8.3 ± 2.2	7.8 - 8.5
h_{15}	B 2	7.4 ± 1.9	7.8 - 8.5
	B 3	8.3 ± 0.8	7.8 - 8.5
ca_1	A 4a	7.7 ± 0.8	7.8 - 8.5
h_{15}	B 5	8.3 ± 0.5	7.8 - 8.8
t_4	T 6	9.3 ± 0.4	8.9 - 9.6
h_{13}	B 7	9.2 ± 0.4	8.9 - 9.6
	B 8	10.0 ± 0.7	8.9 - 10.6
	B 9	10.0 ± 0.7	9.3 - 10.6
	B 10	10.4 ± 0.8	9.6 - 10.6
	B 11	10.2 ± 0.4	9.8 - 10.6
h_{11}	B 12	11.3 ± 2.6	9.8 - 11.3
t_2	T 13	10.7 ± 0.6	10.1 - 11.3

Unit designation used in this report	Unit designation of McKee and Elston (1980)	Age and Precision at σ (Reproducibility of Analysis)	Estimated age accuracy *
t_1	T 14	11.3 ± 0.7	10.6 - 11.7
h_9	B 15	12.0 ± 1.3	10.7 - 11.7
h_8	B 16	12.0 ± 1.3	10.8 - 11.7
	B 17b	11.6 ± 0.3	11.3 - 11.7
h_7	B 18	11.6 ± 0.6	11.3 - 11.7
	B 19	11.6 ± 0.2	11.4 - 11.7
h_5	B 21	13.1 ± 2.2	11.4 - 11.7
	B 22	11.5 ± 1.8	11.4 - 11.7
	B 23	11.3 ± 1.8	11.4 - 11.7
	B 24	11.5 ± 0.4	11.4 - 11.7
h_4	B 25	11.4 ± 0.3	11.4 - 11.7

All ages are given in millions of years.

* McKee and Elston (1980, p. 331) were able to further refine the age data because of stratigraphic control. Their method was as follows:

*** the K-Ar determinations were arranged in stratigraphic succession and shown as bars, the lengths of which represent the limits of analytic uncertainty at one standard deviation. Because the relative ages of the rock units are known from

Table 6.--Potassium-argon ages of volcanic rocks from the Hackberry Mountain volcanic center from McKee and Elston (1980) and this report--Continued

the stratigraphic sequence, it is possible to evaluate the individual radiometric ages by comparing them with ages from overlying and underlying rocks. The lengths of many of the uncertainty bars become shortened because of constraints imposed by samples with comparatively small analytical errors (±).

A potassium-argon age was determined for the Hackberry Mountain Dacite by E.H. McKee of the U.S. Geological Survey (table 17). The Hackberry Mountain Dacite stratigraphically overlies the units dated by McKee and Elston (1980). Using their method it was possible to further refine the ages of some of the units previously dated.

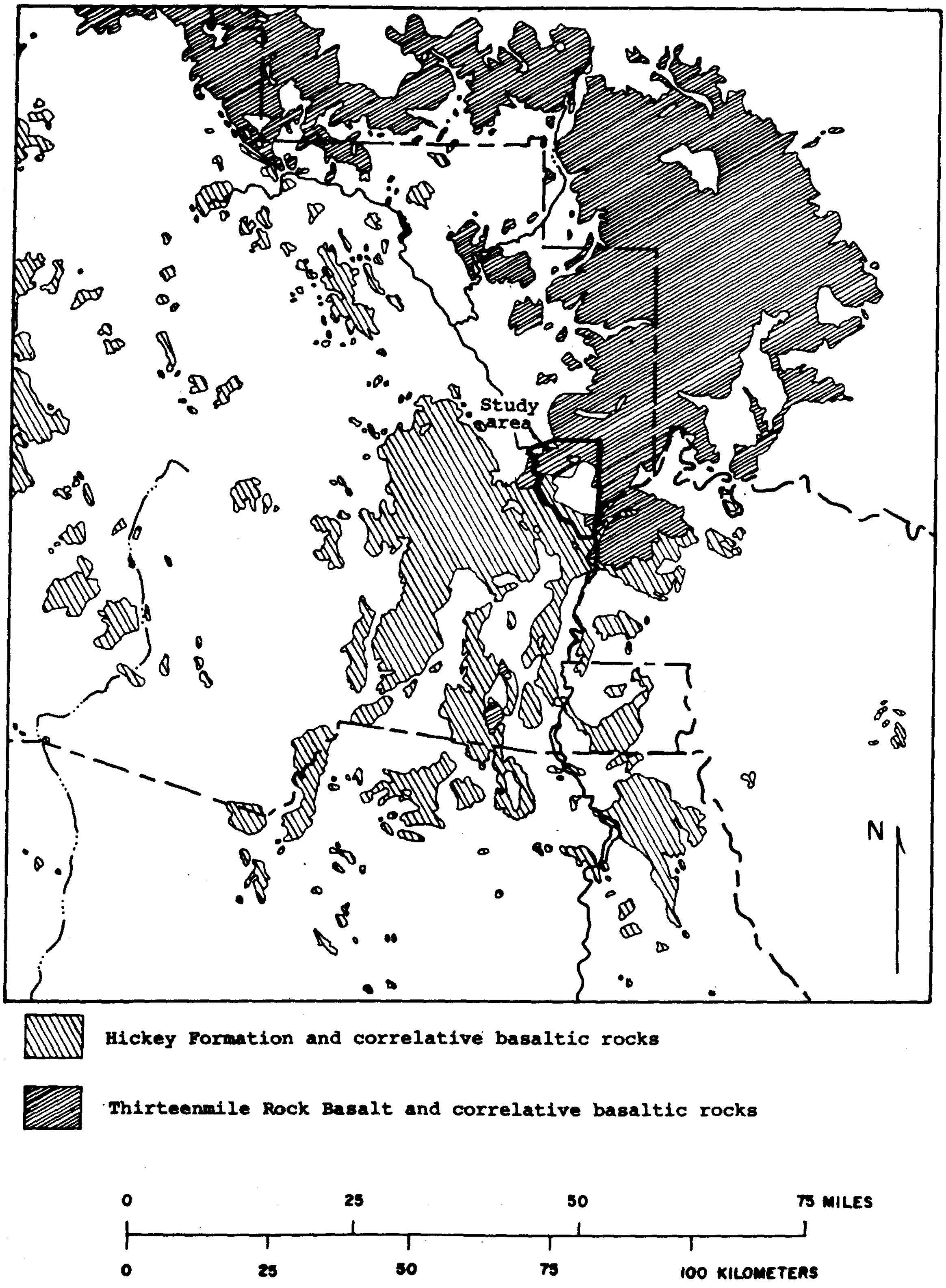
(altered to iddingsite) and, less commonly, augite phenocrysts in a microcrystalline groundmass, composed of labradorite needles in a base of mafic material. Vesicles are abundant. The basaltic sediments are widespread; they are well-bedded, fairly sorted, non-resistant, and are composed partly of red to pink basaltic lapilli. The sedimentary facies of the Hickey Formation ranges from fine marl or silt to coarse gravel and conglomerate.

The basaltic rocks of the Hackberry Mountain area described in this section are lithologically similar to the Hickey as defined by Anderson and Creasey (1958, p. 56-58); therefore, a correlation between the two is proposed. The basaltic sediments they described are probably equivalent to the basaltic tuffs intercalated within the basalt flows in the mapped area. Elston and Scott (1973a, b) had previously correlated the lower portion of the Hickey Formation in the Hackberry Mountain area with the type section at Hickey Mountain.

Continuous outcrops of the Hickey Formation have been traced from its type section in the Jerome area north into the Clarkdale quadrangle by Lehner (1958, p. 549) and south into the Mayer and Mount Union quadrangles by Anderson and Blacet (1972b, c). Unfortunately, the lithologies of most of the Cenozoic volcanic rocks in central Arizona have not been described so other correlations with the Hickey Formation are not possible.

Basaltic rocks with similar ages as the Hickey occur throughout central Arizona (figure 9). Those that cap the Black Hills west of the Hackberry Mountain area have a potassium-argon age of 13.1 ± 1.6 m.y. (Shafiquallah and others, 1980, p. 257) indicating that they and the Hickey are equivalent in age.

Figure 9.--Map of central Arizona showing outcrop pattern of Hickey-equivalent and Thirteenmile Rock-equivalent basalts (modified from Luedke and Smith, 1978).


Study area
N
Hickey Formation and correlative basaltic rocks
Thirteenmile Rock Basalt and correlative basaltic rocks
0
25
50
75 MILES
0
25
50
75
100 KILOMETERS

Thirteenmile Rock Basalt

Thirteenmile Rock is a large boulder that was used as a marker on the Crook Trail in the section from Fort Verde to Fort Apache. The trail was built in 1872 and was in constant use until 1928 (Bowman, 1978, p. 4). This boulder is 20 kilometers (13 miles) east of Fort Verde along the trail. Today most people do not associate Thirteenmile Rock with the boulder that occurs next to a turnout along Forest Highway 9; rather they associate it with the large prominent mesa that occurs to the north, Thirteenmile Rock Butte.

The name Thirteenmile Rock was first used in a geologic context by Sabels (1960, 1962) who proposed the name Thirteen Mile Rock Volcano for the source of the vitric tuff defined in this report as the Towel Creek Tuff. He (1962, p. 100) considered Hackberry Mountain to be the crater of this volcano and the topographic highs surrounding the basin to be the remnant crater rim.

The name Thirteenmile Rock Volcanics was applied to basaltic through rhyolitic volcanic rocks that occur above the base of the stratigraphically lowest member of the Towel Creek Tuff. In this report the Thirteenmile Rock Volcanics of Elston, McKee, Scott, and Gray (1974, p. 607) are divided into several different formations. The basaltic rocks above Member 15 of the Hickey Formation have been assigned to the newly named Thirteenmile Rock Basalt. Basaltic rocks stratigraphically below the top of this member have been assigned to the Hickey Formation.

The type section of the Thirteenmile Rock Basalt is readily accessible and occurs within the canyon south of the turnout for Thirteenmile Rock along Forest Highway 9. At this type section there is a sequence, about 200 meters thick, of generally resistant, well exposed basalt flows with subordinate intercalated basaltic tuff. This section overlies a thick basaltic tuff which occurs in the canyon bottom and is overlain by a landslide. The section interfingers with volcanic rocks of the Towel Creek Tuff and the Cimarron Hills Andesite. A composite stratigraphic section for the formation at this location is given in Sections 2 and 3 in the appendix. Sabels (1960), who also described the rocks at this location, assigned them to the Hickey Formation.

Distribution and topographic expression

The major outcrop of the Thirteenmile Rock Basalt occurs in the eastern and west-central parts of the Hackberry Mountain area. Its southwestern boundary follows Fossil Creek north to its intersection with Boulder Canyon and then follows this drainage north to Hackberry Basin. The contact skirts around the margin of this basin to Hackberry Mountain where it follows a westerly trend to the Verde River. Cottonwood Basin forms the northwestern boundary of this large outcrop of the Thirteenmile Rock Basalt. A small outcrop of this formation crops out along the crest of the eastern Towel Peaks.

The flows within this formation are typically resistant, and many of the steeper cliffs in the Hackberry Mountain area consist of flows assigned to this unit. The intercalated basaltic tuffs are slope-formers and generally are poorly exposed.

Stratigraphic relations

The Thirteenmile Rock Basalt typically rests on the Hickey Formation. Commonly these two formations are separated by thin outcrops of other volcanic units: Member 5 of the Towel Creek Tuff in the western part of the mapped area; the uppermost flow of Member 1 of the Cimarron Hills in the northern and northeastern parts; the Hackberry Basin Member of the Towel Creek Tuff along the margins of Hackberry Basin.

Locally the Thirteenmile Rock Basalt interfingers with Members 2 and 3 of the Cimarron Hills Andesite and Members 6 and 7 of the Towel Creek Tuff. The lowest flows of the Thirteenmile Rock Basalt intertongue with and are buried by the sandstone beds of the Verde Formation in Cottonwood Basin. At the northern margin of Hackberry Mountain, this formation is unconformably overlain by the Hackberry Mountain Dacite. The Hackberry Mountain Dacite is overlain by the Thirteenmile Rock Basalt at the eastern end of the Towel Peaks. Adjacent to Hackberry Mountain the Thirteenmile Rock Basalt is unconformably overlain by the rhyolite flow. The stratigraphic relationships of the Thirteenmile Rock Basalt are diagramatically represented in Plates 4A and 4B. The upper part of the Thirteenmile Rock Basalt contains the youngest volcanic rocks exposed over much of the Hackberry Mountain area.

Thickness

In the western part of the Hackberry Mountain area (Sycamore Canyon south to the northern boundary of Hackberry Mountain) the Thirteenmile Rock Basalt is approximately 240 meters thick. At Thirteenmile Rock, the section is 170 meters thick. Member 3 of the Cimarron Hills Andesite is exposed in both sections, and the thickness of Thirteenmile Rock Basalt exposed beneath this andesite is 160 meters in the eastern section and 180 meters in the western. These surprisingly close values suggest a rather uniform accumulation for this unit throughout the region. Differences in the thickness may simply be due to erosion.

Lithology

The Thirteenmile Rock Basalt consists of basalt and olivine basalt flows that are relatively uniform lithologically, in contrast to those of the Hickey Formation. A few intercalated basaltic tuffs and basaltic dikes that intrude units higher than the Hickey Formation also have been assigned to this formation. No vents for the flows occur in the area mapped.

Individual basalt flows range in thickness from less than two to more than 35 meters; compound flows are as thick as 100 meters. The thickness of most flows is between five and 20 meters. Normally they are massive and devoid of vesicles. Rarely they are brecciated at the top and base and very rarely throughout. The flows have well developed horizontal and vertical joints similar to those in the flows of the Hickey Formation. Only rarely does a flow have more than five percent vesicles. Vesicles are generally spheroidal averaging about one millimeter in diameter, and are commonly filled with calcite. The flows are medium to very dark gray in color.

Essentially all the flows are porphyritic and contain olivine and/or pyroxene phenocrysts in a dense aphanitic groundmass. The olivine phenocrysts are subhedral and usually are 1.5 millimeter or less in diameter. They constitute from zero to 25 percent of the mode but, most commonly, are between four and seven percent. Iddingsite occurs along the rims and fractures in all the olivine phenocrysts, and some phenocrysts are totally altered to iddingsite. The pyroxene phenocrysts are usually green, in a few flows they are black. All are clinopyroxene. They are subhedral to euhedral and average one millimeter across. Pyroxene phenocrysts constitute from zero to 25 percent of the mode and usually constitute one to five percent. Glomerophyres of pyroxene microphenocrysts are common in some flows. Cumulophyres of olivine and pyroxene microphenocrysts are also common. In several flows, phenocrysts of olivine that have been altered to iddingsite are enclosed within a rim of clinopyroxene. Rare subhedral plagioclase phenocrysts occur in a few flows. Corroded quartz xenocrysts occur in one basalt flow (see unit 7 of Section 5 in the appendix). Overall, the flows of the Thirteenmile Rock Basalt contain more phenocrysts, especially pyroxene phenocrysts, than those of the Hickey.

The groundmass of the basalt flows of the Thirteenmile Rock Basalt is holocrystalline and commonly pilotaxitic. It is composed chiefly of subhedral labradorite microlites, anhedral intergranular clinopyroxene, and opaque mineral grains. Some flows have intergranular olivine crystals which are altered to iddingsite. Intersertal chlorite occurs in a few flows, and apatite inclusions in plagioclase microlites are common.

Basaltic tuffs are intercalated with the flows of the Thirteenmile Rock Basalt. In the eastern part of the area, tuff beds constitute up to 40 percent of the total volume of the formation, but they thin and pinch out towards the west. Less than one percent of the section west of Fossil Creek Road is composed of tuff. Tuff units were mapped only where they are either very thick or very well exposed. Tuff sequences are generally between two and 10 meters thick but locally are as thick as 80 meters. Most of the interflow pyroclastic deposits are unconsolidated yellow and red massive ash, although a few deposits are well bedded. The major constituents of the tuffs are orange basaltic vitric lapilli and ash and brown basaltic lithic lapilli. Free crystals of pyroxene and olivine and sparse basaltic bombs are present in some units. All the tuffs are very porous, and the pore spaces are commonly filled or lined with calcite.

Basaltic dikes assigned to the Thirteenmile Rock Basalt intrude the Sally May Dacite; a few were recognized that intrude the flows of the Thirteenmile Rock Basalt. Probably many more dikes intrude the flows of the Thirteenmile Rock Basalt but were not recognized because they are in contact with lithologically similar rocks. Some dikes near Sycamore Buttes are 800 meters long and 60 meters wide. The majority of the dikes trend northwest.

West of Fossil Creek Road, the Thirteenmile Rock Basalt was divided into four members. Member 1, at the base of the section, is about 180 meters thick and is widely exposed north and south of Sycamore Canyon. This member intertongues with and is overlain by the Verde Formation in Cottonwood Basin. Member 1 consists chiefly of a thick compound basalt flow (unit 22 of Section 4 and unit 10 of Section 5), individual flow units are five to 10 meters thick. The flow is characterized by olivine phenocrysts and microphenocrysts (18 modal percent) that are altered to iddingsite, and varying amounts of green clinopyroxene phenocrysts (trace to eight modal percent) set in a gray aphanitic groundmass consisting of labradorite microlites with intergranular clinopyroxene and opaque mineral grains. Calcite amygdules are common. East of the Verde River fault zone several additional basalt flows occur between the compound flow and the underlying Cimarron Hills Andesite.

Member 2 of the Thirteenmile Rock Basalt rests on Member 1, or Member 3 of the Cimarron Hills Andesite, or Member 7 of the Towel Creek Tuff. It is a compound flow approximately 40 meters thick. This basalt contains phenocrysts of olivine (three modal percent) and green clinopyroxene (three modal percent) in a grayish-black aphanitic groundmass consisting of labradorite microlites with intergranular olivine, clinopyroxene, and opaque mineral grains. All olivine crystals are altered to iddingsite. Glomerophyres of clinopyroxene and cumulophyres of olivine + clinopyroxene microphenocrysts are common.

Member 3 of the Thirteenmile Rock Basalt overlies Member 2 and is exposed only in a small area on the northern side of Hackberry Mountain, where it is unconformably overlain by the Hackberry Mountain Dacite. It consists of a poorly exposed basalt flow at least 20 meters thick. The flow contains labradorite microphenocrysts (five modal percent), olivine phenocrysts (five modal percent) that are altered to iddingsite, and green clinopyroxene phenocrysts (three modal percent) in a vesicular, medium-gray groundmass consisting of labradorite microlites with intergranular clinopyroxene, olivine, and opaque mineral grains. Cumulophyres of plagioclase + olivine + pyroxene microphenocrysts are present.

Member 4 of the Thirteenmile Rock Basalt is a basalt flow that overlies the Hackberry Mountain Dacite along the eastern crest of the Towel Peaks. This member also includes several mafic dikes that intrude the brecciated base of the Hackberry Mountain Dacite on Hackberry Mountain. Although they are lithologically dissimilar, the dikes and the flow have been assigned to the same member as the only volcanic units demonstrably younger than the Hackberry Mountain Dacite. The preserved thickness of the basalt flow is about 40 meters. It contains olivine (10 modal percent) and clinopyroxene microphenocrysts (five modal percent) in a grayish-black aphanitic groundmass consisting of bytownite microlites with intergranular clinopyroxene and opaque mineral grains. The rims of the larger olivine microphenocrysts are altered to iddingsite. The mafic dikes assigned to Member 4 are nearly vertical and less than one meter thick. They contain ragged labradorite phenocrysts (two modal percent) and glomerophyres of clinopyroxene phenocrysts (one modal percent) in a vesicular, medium gray, aphanitic groundmass consisting of labradorite microlites with intergranular clinopyroxene, olivine (altered to iddingsite), and opaque mineral grains.

Chemistry

Four chemical analyses are available for the Thirteenmile Rock basalts, three from Member 1 and one from Member 4 (table 7). Chemically, these rocks resemble the basalts of the Hickey Formation; they lie in the alkalic basalt field on the alkali-silica diagram (figure 8).

Age

The ages for Members 1, 2, and 3 of the Thirteenmile Rock Basalt from the section west of Fossil Creek Road are constrained by the potassium-argon ages reported by McKee and Elston (1980, p. 334) (table 6) and a potassium-argon age for the overlying Hackberry Mountain Dacite (table 17) to lie in the range 7.8 to 8.5 m.y. This places the Thirteenmile Rock Basalt in the late Miocene. Elston, McKee, Scott, and Gray (1974, p. 608) reported preliminary potassium-argon ages of 3 to 5 m.y. for samples from the section exposed along Forest Highway 9 near Thirteenmile Rock. However, both Member 7 of the Towel Creek Tuff and Member 3 of the Cimarron Hills Andesite can be traced from beneath the Hackberry Mountain Dacite in the western section to the Thirteenmile Rock section where Member 3 of the Cimarron Hills Andesite occurs almost at the top. The andesite is overlain by one basalt flow (unit 15 of Section 3 in the appendix). Therefore, the section at Thirteenmile Rock will be considered

Table 7.--Major element and normative compositions, in percent, of the Thirteenmile Rock Basalt

Member	1	1	1	4
Sample No.	[1]Blb-bl	[1]Blb-ml	[1]Blb-m2	[2]RL-79-51
Major oxides (weight percent)				
SiO_2	45.8	46.5	46.1	44.1
Al_2O_3	16.9	17.4	17.5	16.6
Fe_2O_3	10.1	4.7	5.7	11.9
FeO	1.89	6.48	5.13	
MgO	4.0	5.6	5.8	6.58
CaO	11.1	9.9	10.2	12.2
Na_2O	2.6	3.9	3.4	2.9
K_2O	1.1	1.2	1.2	1.10
TiO_2	1.70	1.69	1.64	1.69
MnO	0.14	0.21	0.19	0.19
P_2O_5	0.86	0.84	0.84	1.1
CO_2	<0.05	0.20	0.24	
H_2O+	1.13	1.40	1.34	
H_2O-	2.02	0.70	0.62	
[3]Loss				0.610
Total	99.3	100.7	99.9	98.4
CIPW Norms[4]				
or	6.8	7.2	7.3	6.7
ab	23.0	22.7	22.4	13.3
an	32.7	26.9	29.7	29.8
ne		5.9	3.8	6.4
di	16.0	14.5	13.7	20.5
hy	4.3			
ol	8.9	14.9	15.3	14.8
mt	2.6	2.5	2.4	2.5
il	3.4	3.3	3.2	3.3
ap	2.2	2.1	2.1	2.7

[1] Chemical analyses from Scott (1974).
[2] Chemical analysis by x-ray fluorescence method with all iron calculated as Fe_2O_3. Location of samples shown in plate 7. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg.
[3] Loss on Ignition.
[4] All norms calculated with $FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).

the same age as the western section which is no younger than 7.8 m.y. old, the minimum age of the Hackberry Mountain Dacite (table 6).

The age of Member 4 of the Thirteenmile Rock Basalt is not well constrained. This basalt flow is younger than the Hackberry Mountain Dacite, but how much younger is not known. This flow is petrographically similar to those that crop out beneath the dacite flow and will also be considered late Miocene.

Correlation

The flows within the Hackberry Mountain area assigned to the Thirteenmile Rock Basalt are part of an extensive group of basaltic rocks that occurs along the eastern margin of the Verde Valley from Fossil Creek north to Oak Creek Canyon. Luedke and Smith (1978), in their compilation of the volcanic rocks of late Cenozoic age in Arizona and New Mexico, assigned basalt flows that crop out along the southern margin of the Colorado Plateau from Oak Creek Canyon west to the Mount Floyd area to the same potassium-argon age category as those flows exposed along the eastern margin of the Verde Valley. Figure 9 was modified from their map, and it shows the outcrops of basaltic rocks with ages similar to the Thirteenmile Rock Basalt. In general, none of these basaltic rocks have been assigned to a formation. They are commonly referred to as "rim basalts." Robinson (1913) assigned them to the first of his three general periods of volcanic activity in the San Francisco volcanic field.

Potassium-argon ages from the basalt flows that occur along the southern margin of the Colorado Plateau west from Oak Creek Canyon range from about 4.3 to 8.7 m.y. (Damon, 1965, 1968; Damon and others, 1974; Elston, McKee, Scott, and Gray, 1974; McKee, 1973; McKee and Anderson, 1971; McKee and McKee, 1972). The older of these basalts are equivalent in age to the Thirteenmile Rock Basalt but their lithologies have not been described in enough detail to permit a correlation with the Thirteenmile Basalt. The younger potassium-argon ages for some of these basaltic rocks suggest that either there has been erosion of the younger basaltic rocks from the Hackberry Mountain area, or the locus of the basaltic eruptive centers migrated northwards with time.

The drainage basin of Beaver Creek, whose southern boundary occurs about 12 kilometers north of Thirteenmile Rock, contains basaltic rocks of Tertiary age named the Beaver Creek Volcanics by Scholtz (1969) which intertongue and overlie the Verde Formation. She considered these basalts to be younger than and not correlative with the Hickey Formation. However, potassium-argon ages of several of the basalt flows within the Beaver Creek drainage (Damon, 1968; Peirce and others, 1979, p. 15) indicate that flows equivalent in age to the Hickey occur there. Basalt flows that overlie these Hickey-equivalent units have yet to be dated, but they may be equivalent to the Thirteenmile Rock Basalt.

Wadell (1972, p. 88-89) assigned the basalt flows interbedded with the Verde Formation in Cottonwood Basin, primarily Member 1 of the Thirteenmile Rock Basalt, to the Verde Formation. He claimed that these basalt flows unconformably overlie the Hickey Formation. I found no evidence of any unconformity.

Sources of the flows

The thickening of intercalated tuffs to the northeast suggests that the Thirteenmile Rock Basalt flows were extruded from vents located east of the mapped area. Some of the flows may also have been extruded from fissures. Scott (1974, p. 22) reported a large number of basaltic dikes exposed just east of the mapped area in the Sycamore Buttes. These very thick basaltic dikes intrude the Thirteenmile Rock Basalt and could possibly be conduits for some of its basalt flows.

Basaltic dikes of unassigned age

Basaltic dikes of unknown age are exposed in Hackberry Basin, the Cimarron Hills, along Fossil Creek, and south of Thirteenmile Rock Butte. The basaltic dikes are lithologically diverse. Most are similar to the dikes of the Hickey Formation and the Thirteenmile Rock Basalt. All dikes are normally much finer-grained than the basalt flows. The unassigned dikes typically have a dark gray aphanitic groundmass that consists of lar-radorite microlites with intergranular clinopyroxene ± olivine ± opaque crystals ± chlorite. Some are aphyric and others contain phenocrysts of olivine and/or clinopyroxene. Cumulophyres of olivine + clinopyroxene are common.

The unassigned dikes are nearly vertical, one to two meters thick, as long as 300 meters, and commonly arranged in an en echelon pattern. The majority strike towards the northwest. Baked zones around the intruded country rock are common, especially where the country rock is silicic. The dikes are generally no more resistant than the rock they intrude.

Most of the dikes intrude the Hackberry Basin Member of the Towel Creek Tuff; a lesser number intrude Member 1 of the Cimarron Hills Andesite, Member 3 of the Towel Creek Tuff, and cinder deposits of Member 15 of the Hickey Formation. The dikes are probably related either to the Thirteen-mile Rock Basalt or Members 14 or 15 of the Hickey Formation. No dikes assigned to this unit were observed within the Hackberry Mountain Dacite or the Verde Formation.

Cimarron Hills Andesite

Sabels (1960) was the first to report the existence of andesitic rocks in the Hackberry Mountain area. Elston and Scott (1973b) recognized and mapped andesite flows and assigned them to their Thirteenmile Rock Volcanics. Scott (1974, p. 13-14) stated that the andesite flows accounted for approximately one-quarter of the basic lavas in the Thirteenmile Rock Volcanics.

The Cimarron Hills Andesite consists primarily of andesite flows and subordinate plugs, cinder cones, pyroclastic flows, and dikes. It is named for exposures in the Cimarron Hills.

Distribution and topographic expression

The andesite flows of the Cimarron Hills Andesite are intimately associated with the Thirteenmile Rock Basalt in the northern and western parts of the mapped area. The andesite flows are more resistant than most of the basalt flows and form ledges. Intrusive bodies of andesite in the northern Cimarron Hills form low dark hills in an otherwise light-colored terrain. Andesitic cinder deposits and pyroclastic flows are usually non-resistant and occur in areas of low relief. Andesitic dikes occur within the andesitic cinder and commonly form ridges.

Stratigraphic relations and thickness

The Cimarron Hills Andesite has been informally divided into three members on the basis of stratigraphic relations with the Hickey Formation, the Thirteenmile Rock Basalt, and the Towel Creek Tuff. Member 1 contains as many as three flows which interfinger with the uppermost members of the Hickey Formation (Members 14 and 15) and also occurs between the Hickey and the overlying Thirteenmile Rock Basalt. This member was designated A 4 by

Elston and Scott (1973b) and McKee and Elston (1980). Adjacent to the Hackberry volcano, along Ike's Backbone, this member interfingers with the Hackberry Basin Member of the Towel Creek Tuff. Member 1 is the thickest along the northwestern margin of Hackberry Basin, where it is about 160 meters thick.

Two vents for the flows of Member 1 are exposed in the Hackberry Mountain area. The larger and better exposed vent is in the Cimarron Hills where a plug and several dikes of andesite intrude the Hackberry Basin Member of the Towel Creek Tuff and are, in turn, intruded by the Sally May Dacite. The other vent occurs along the northern margin of Hackberry Basin. It is a large but poorly exposed cinder cone. Both the younger Thirteenmile Rock Basalt and Member 3 of the Cimarron Hills Andesite butt up against it. Poor exposure prevents tracing the flows of Member 1 directly into this deposit. Both of these andesitic vents were parasitic cones which grew on the flanks of the Hackberry volcano. These cones were emplaced during the final stages of pyroclastic activity of the Hackberry volcano which is typical of parasitic cones (Williams and McBirney, 1979, p. 83). An andesitic breccia and lapilli tuff that occurs within the Hackberry Basin Member of the Towel Creek Tuff was mapped as a pyroclastic deposit of Member 1.

Member 2 of the Cimarron Hills Andesite consists of two cinder cones and many andesite flows interstratified with the Thirteenmile Rock Basalt. It is stratigraphically higher than the Sally May Dacite and lower than Member 7 of the Towel Creek Tuff. In most outcrops it consists of one thin flow.

There are two vents assigned to Member 2 in the Hackberry Mountain area. One is a well exposed andesitic cinder cone exposed at the eastern terminus of Doren's Defeat Canyon where the flows within Member 2 are thickest, 160 meters thick. Several individual flows can be traced directly into this deposit. Another cinder cone is exposed northwest of the confluence of Sycamore and Hackberry Canyons. It consists of a large cinder deposit with associated andesitic dikes that adjoins the large basaltic vent of Member 14 of the Hickey Formation.

Member 3 of the Cimarron Hills Andesite contains many flows and local tuff deposits that occur between Members 1 and 2 of the Thirteenmile Rock Basalt and locally above Member 7 of the Towel Creek Tuff. It is up to 150 meters thick along the northern flank of Deadman Mesa. An andesitic lapilli tuff occurs between the flows of Member 3 on the northern flank of Deadman Mesa.

Lithology

Cimarron Hills Andesite flows are fairly uniform lithologically. Contrasts between the flows of different members are no greater than the differences within an individual member. More detailed descriptions of the individual andesite flows are in the stratigraphic sections in the appendix.

Individual andesite flows range in thickness from two to 35 meters with an average of 10 to 20 meters. Although most flows are massive both their basal and upper contacts are commonly brecciated. The massive part of the flows are medium to very dark gray, and the brecciated portions are usually moderate red. Most flows are slightly vesicular (five to 10 percent vesicles) although some are extremely vesicular (up to 30 percent vesicles). The vesicles are either spheroidal or stretched and average one to three millimeters in width. They are commonly filled or lined with calcite or chalcedony. The massive parts of the flows typically have poorly to well developed vertical and horizontal joints. Poorly developed columnar joints are rare. The brecciated portions are not jointed, and the vesicular portions have poorly developed joints or none at all.

All andesite flows contain plagioclase phenocrysts (five to 10 modal percent) and generally some of the flows contain olivine and pyroxene phenocrysts or microphenocrysts in an aphanitic or very fine-grained groundmass. The plagioclase phenocrysts are white, euhedral to subhedral, commonly lath-shaped, sieved, and typically have a thin orange rim. They are up to six millimeters and average two millimeters in length. They range in composition from calcic oligoclase to andesine and characteristically contain numerous inclusions of opaque minerals, glass, pyroxene, and sericite. The boundaries of the phenocrysts are commonly ragged except where they have a thin (average 0.05 millimeter) rim of inclusion-free plagioclase. Generally these rims are not optically continuous with the remainder of the phenocryst. Slight zoning occurs in most phenocrysts, and oscillatory zoning is common.

Subhedral olivine phenocrysts in the andesites (five modal percent) range in width from 0.5 to 1.5 millimeters. Most are altered to iddingsite plus opaque minerals. Subhedral to euhedral green pyroxene phenocrysts or microphenocrysts (one to two modal percent) range in size from 0.2 to one millimeter. All are clinopyroxene. Cumulophyric groupings of pyroxene ± plagioclase ± olivine microphenocrysts are common and average two millimeters in diameter. The holocrystalline, intergranular groundmass is composed of andesine microlites (40 to 60 percent), clinopyroxene (10 percent), opaque grains (seven to 10 percent), and iddingsite after olivine (zero to 10 percent).

The cinder cones of the Cimarron Hills Andesite are composed of lapilli and blocks or bombs of andesite in a consolidated ash matrix. The matrix constitutes about one-half of each cone. The clasts contain plagioclase phenocrysts or microphenocrysts in an aphanatic groundmass. The deposits are red or brown. They are commonly well bedded. The cinder deposit assigned to Member 1 in the Cimarron Hills contains a accidental of dacitic blocks and lapilli (10 modal percent), some of which are pumiceous.

Andesitic dikes assigned to Members 1 and 2 either intrude the cinder cones or adjacent rocks. Typically the dikes are vertical and narrow (one to three meters thick), but a few are wider than 30 meters. The dikes are lithologically similar to the andesite flows but are commonly finer-grained. Other andesite dikes which intrude the Sally May Dacite and strike to the northwest, are similar to the dikes assigned to Members 1 and 2. One small andesite dike located along Fossil Creek Road just west of bench mark 3822 has a unique mineral assemblage. It contains hornblende phenocrysts and has no olivine phenocrysts.

Chemistry

Eight major-element chemical analyses of the Cimarron Hills Andesite are given in table 8; seven are from Member 1, and one is from Member 3. All analyzed rocks are andesites according to the guidelines proposed by Streckeisen (1979, p. 332). The samples are transitional from basaltic andesite to andesite according to Ewart's scheme (1982, p. 26).

Age

McKee and Elston (1980, p. 334) determined a stratigraphically controlled potassium-argon age of 7.8 to 8.5 m.y. for Member 1 of the Cimarron

Table 8.--Major-element and normative compositions, in percent, of the Cimarron Hills Andesite

Member	1	1	1	1	1	1	1	3
Sample No.	[1]RL-79-60	[2]A4-1	[2]A4a-1	[2]A4-2	[2]A4a-2	[2]A4b-ml	[2]A4b-ul	[1]RL-79-65
Major oxides (weight percent)								
SiO_2	54.3	55.7	55.8	54.6	54.7	54.9	54.8	53.4
Al_2O_3	15.4	16.1	15.9	15.7	15.7	15.0	15.7	16.5
Fe_2O_3	7.73	5.40	4.4	5.77	5.7	3.4	7.1	8.61
FeO		2.39	2.43	1.26	1.8	3.69	0.63	
MgO	5.2	3.4	4.5	4.1	4.5	5.6	5.1	4.7
CaO	8.52	8.2	8.2	8.4	8.0	7.8	8.5	8.76
Na_2O	3.1	3.9	4.0	3.7	4.0	4.0	4.0	3.4
K_2O	1.55	2.0	1.8	1.8	1.7	1.9	1.6	1.34
TiO_2	1.06	1.10	1.07	1.09	1.04	1.07	1.14	1.18
MnO	0.11	0.10	0.12	0.09	0.11	0.11	0.13	0.13
P_2O_5	0.4	0.41	0.37	0.43	0.40	0.38	0.39	0.5
CO_2		0.07	0.10	<0.05	<0.05	<0.05	<0.05	
H_2O+		0.37	0.66	0.81	0.59	0.55	0.38	
H_2O-		0.69	1.13	1.74	1.43	1.19	0.88	
[3]Loss	1.56							0.410
Total	98.9	99.8	100.5	99.5	99.7	99.6	100.4	98.9
CIPW Norms[4]								
q	5.4	3.9	3.1	4.0	2.3	0.9	1.2	3.2
or	9.5	12.0	10.8	11.0	10.3	11.5	9.6	8.1
ab	27.1	33.6	34.4	32.4	34.8	34.6	34.3	29.4
an	24.3	20.9	20.5	21.7	20.4	17.8	20.5	26.4
di	13.6	14.7	15.1	15.2	14.5	15.7	16.1	12.1
hy	15.1	9.8	11.4	10.7	12.7	14.6	13.2	15.3
mt	1.9	2.0	1.7	1.8	1.9	1.8	1.9	2.0
il	2.1	2.1	2.1	2.1	2.0	2.1	2.2	2.3
ap	1.0	1.0	0.9	1.1	1.0	0.9	1.0	1.2

[1] Chemical analyses by x-ray fluorescence methods with all iron calculated as Fe_2O_3. Location of samples shown in plate 7. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg.
[2] Chemical analyses from Scott (1974).
[3] Loss on ignition.
[4] All norms calculated with $FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).

Hills Andesite (table 6). Members 2 and 3 of the Cimarron Hills Andesite occur between Member 6 of the Towel Creek Tuff and the Hackberry Mountain Dacite which have both been dated, and these stratigraphic constraints indicate an apparent age of 7.8 to 8.4 m.y. for these two members (table 6).

Correlation

Anderson and Creasey (1958, p. 57) and Lehner (1958, p. 553) reported small andesite flows near the northwestern margin of the Verde Valley and assigned them to the Hickey Formation. They are lithologically distinct from the Cimarron Hills Andesite, they contain biotite and/or hornblende phenocrysts.

Scholtz (1969, p. 2681) reported small andesite flows within the Beaver Creek Volcanics that crop out at the southern margin of the Beaver Creek drainage basin. These flows may be correlative with the Cimarron Hills Andesite.

Towel Creek Tuff

The Towel Creek Tuff, defined here, consists primarily of numerous dacitic ignimbrites. It contains a subordinate amount of dacitic breccias and reworked tuffs, and it includes minor amounts of dacite flows, air-fall tuffs, base-surge tuffs, and fine-grained sediments. These units were erupted from or, in the case of the sediments, deposited within or adjacent to the Hackberry volcano, a large dacite volcano (see figure 1 for rough outline of volcano). Deposits close to and within the Hackberry volcano contain all or most of these different units. Many units pinch out with distance from the volcano, and the most distal exposures typically contain only dacitic ignimbrites and air-fall tuffs.

Distribution and topographic expression

The Towel Creek Tuff is extensively exposed in and around the Hackberry volcano. The most complete exposures occur in canyon walls along Towel Creek. The thickest sections are in Hackberry Basin, the Cimarron Hills, and Boulder Canyon. The tuff is also exposed in a large area bounded by Bull Run Creek to the north, Hackberry Mountain to the east, and the Towel Peaks to the south. Small outcrops occur atop the Buzzard Peaks and Ike's Backbone, on the flanks of Deadman Mesa, south of the Towel Peaks, and within the northeastern part of Cottonwood Basin. Discontinuous outcrops are also found throughout the northeastern part of the mapped area.

The Towel Creek Tuff is well exposed, sparsely covered by vegetation, and easily mapped. The ignimbrites, breccias, reworked tuffs, and flows form cliffs; air-fall tuffs, base-surge tuffs, and fine-grained sediments form slopes.

Stratigraphic relations and thickness

The Towel Creek Tuff intertongues with the Hickey Formation, the Thirteenmile Rock Basalt, the Cimarron Hills Andesite, and the Verde Formation (figure 10). The formation is informally divided into eight members on the basis of their stratigraphic relations to the intertonguing mafic volcanic units. The members cannot be distinguished by lithology alone. All members have variable thickness and pinch out away from the Hackberry volcano. The maximum exposed thickness for each is listed in table 9. Members 1 through 6 were recognized previously as map units by Elston and Scott (1973b) and McKee and Elston (1980), although they used a different terminology (table 10).

Members 1 through 4 of the Towel Creek Tuff interfinger with the

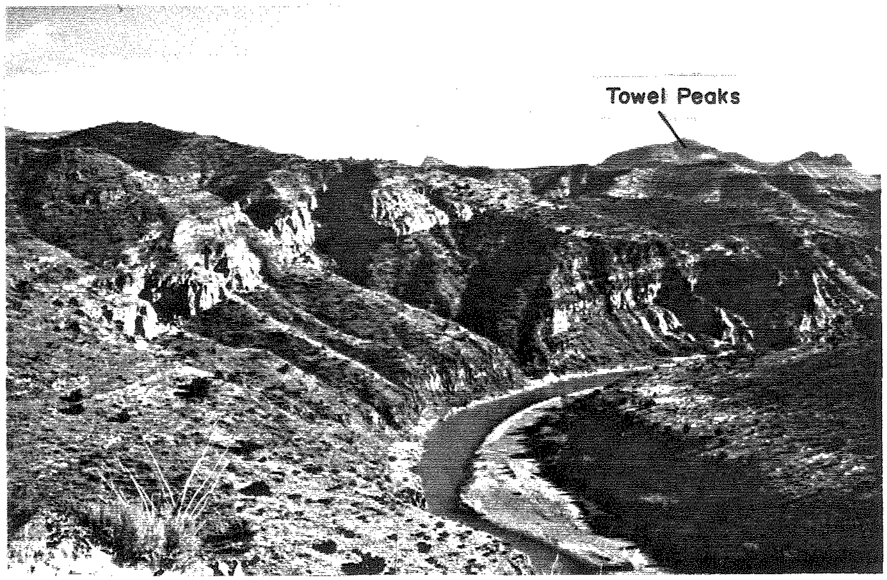


Figure 10.--Interstratified Towel Creek Tuff and Hickey Formation along east side of Verde River south of the Grotto.
t_4 - Member 4 of the Towel Creek Tuff

Figure 11.--Ignimbrites in the Hackberry Basin Member of the Towel Creek Tuff near Willow Spring. Each band on the rod is 0.1 meter.

Table 9.--Maximum exposed thickness of members of the Towel Creek Tuff

Member	Maximum exposed thickness (in meters)	Location
1	25	Towel Creek
2	75	Towel Creek
3	150	Towel Creek
4	145[1]	Towel Creek
5	50	Hackberry Canyon
6	30	Cottonwood Basin
7	110	upper Sycamore Canyon
Hackberry Basin	245[2]	Boulder Canyon

[1] Top of section not exposed.

[2] Base of section not exposed.

Table 10.--Nomenclature and symbols used for members of the Towel Creek Tuff

This Report		Elston and Scott (1973) and McKee and Elston (1980)
Member 7	(Tt_7)	----
Member 6	(Tt_6)	$Ttt_{-2,-1}$
Member 5	(Tt_5)	Tts_1
Member 4	(Tt_4)	Ttt_{5a-6}; Tts_{5a-6}
Member 3	(Tt_3)	Ttt_{11}
Member 2	(Tt_2)	$Ttt_{13a,b}$; $Tts_{13a,b}$
Member 1	(Tt_1)	Ttt_{14}

upper Hickey Formation. Member 1 is a tongue bounded by Members 9 and 10 of the Hickey; Member 2 of the Towel Creek Tuff occurs between Members 10 and 11 of the Hickey; Member 3 of the Towel Creek Tuff is bounded by Members 11 and 13 and contains Member 12 of the Hickey; Member 4 of the Towel Creek Tuff extends as a tongue between Members 13 and 15 of the Hickey and elsewhere underlies Member 1 of the Cimarron Hills Andesite.

Members 2, 3, and 4 can be traced continuously along the outcrop, whereas Member 1 is only intermittently exposed. These four members thicken as they approach the Sally May Dacite stock, a younger intrusive body. (This relationship is depicted in plate 4B.) As they become thicker the number of beds within each member increases, and the individual beds thicken. This relationship indicates that the source vent or vents for these members were located within the area of the present outcrop of the Sally May Dacite stock.

Each member of the Hickey that intertongues with the Towel Creek Tuff pinches out as it approaches the Hackberry volcano. Where the interstratified basaltic rocks pinch out, separating the members of the Towel Creek Tuff is difficult because of their lithologic similarity. Where all the mafic rocks pinch out is considered the boundary of the Hackberry volcano. Where Member 10 of the Hickey Formation pinches out Members 1 and Member 2 of the Towel Creek Tuff were mapped as one unit--the lower member.

Members 5, 6, and 7 of the Towel Creek Tuff occur stratigraphically above the Hickey formation. Member 5 occurs as a tongue between the basal flow of Member 1 of the Cimarron Hills Andesite and the Thirteenmile Rock Basalt. Member 6 is interstratified with Member 1 of the Thirteenmile Rock Basalt and the Verde Formation. Member 7 comprises a tongue bounded by Members 1 and 2 of the Thirteenmile Rock Basalt and several separate units interstratified in the undifferentiated Thirteenmile Rock Basalt. Member 7 occurs either between Members 2 and 3 or above Member 3 of the Cimarron Hills Andesite.

Neither Members 5 or 6 of the Towel Creek Tuff could be traced to a vent. The discontinuous outcrops of Member 5 apparently thicken as they approach the Hackberry volcano suggesting that it was erupted from this edifice. The location of the vent for Member 6 is unknown.

Member 7 of the Towel Creek Tuff contains several ignimbrites and a dacite flow that were apparently erupted from two separate vents. Ignimbrites within Member 7 thicken dramatically and have more continuous outcrops in the northeastern part of the mapped area, near the Sycamore Buttes. Reconnaissance beyond the area mapped suggests that a vent from which a part of this member erupted lies east of Sycamore Buttes. In exposures adjacent to their apparent source these ignmbrites contain lapilli of flow-banded rhyolite which suggests that this vent is more silicic than the Hackberry volcano. Chemical analyses of an ignimbrite and an enclosed pumiceous clast by Ulrich and Bielski (in preparation) support this interpretation (samples UMW 36 and 52 of table 11); they are rhyolites according to Streckeisen's (1979, p. 332) scheme. The occurrence of a rhyolite flow along Forest Highway 9 just north of the Sycamore Buttes (Elston, McKee, Scott, and Gray, 1974, p. 607; Elston, Nations, and Gray, 1974, p. 641) provides further evidence of a vent in this area that is more silicic than the Hackberry Volcano. Part of Member 7, however, was erupted from the Hackberry volcano. This part includes a thick, stubby dacite flow and an ignimbrite exposed north and east of Hackberry Mountain. All units within Member 7 were included within one mapped unit, even though they were erupted from two separate vents, because they all occur at the same stratigraphic level, and they could not be readily differentiated except where they contained coarse lithic lapilli, a condition met in only a few outcrops.

In the east-central and southeastern parts of the Hackberry Mountain area thick, lithologically monotonous sequences of Towel Creek dacitic pyroclastic and sedimentary rocks are exposed. They occur within the flank of the Hackberry volcano. These sequences cannot be readily correlated with the other members because their outcrops are separated by large landslides and the Sally May Dacite stock. Most importantly, they lack mafic volcanic interbeds which are useful for correlation. These sequences are informally named the Hackberry Basin Member of the Towel Creek Tuff for the excellent exposures within that basin. The thickest sequence exposed is an incomplete section in Boulder Canyon 245 meters thick.

The Hackberry Basin Member is overlain in places by the undifferentiated Thirteenmile Rock Basalt and in other places by Member 2 of the Cimarron Hills Andesite. Flows assigned to Member 1 of the Cimarron Hills Andesite and Member 15 of the Hickey Formation occur within the upper part of the Hackberry Basin Member. The base of the Hackberry Basin Member is exposed only along Ike's Backbone where it is underlain by Member 13 of the Hickey Formation, the same unit that underlies Member 4 of the Towel Creek Tuff.

In Boulder Canyon the Hackberry Basin Member occurs at a similar elevation as an outcrop of Member 3 exposed on the northern slopes of Deadman Mesa to the south. Their similar elevations suggest a possible correlation. Part of the Hackberry Basin Member occurs stratigraphically above Member 1 of the Cimarron Hills as does Member 5 of the Towel Creek Tuff. Part of the Hackberry Basin Member is correlative with Member 4 of the Towel Creek Tuff, and other parts may be correlative with Members 3 and 5.

The Hackberry Basin Member is intruded by a plug and several dikes assigned to Member 1 of the Cimarron Hills Andesite and by the Sally May Dacite. The Hackberry Basin Member is also intruded by various basaltic, andesitic, and dacitic dikes and by a rhyolitic diatreme.

At Chalk Springs there is a thin section of dacitic air-fall tuff and reworked tuff that overlies the Sally May Dacite stock and is unconformably overlain by the rubble unit. This tuff is younger than the other members of the Towel Creek Tuff. It contains numerous lapilli of altered dacite which indicates that its vent passed through the Sally May Dacite.

Lithology

This section of the report consists of general descriptions of the various lithologies. For detailed descriptions please refer to the stratigraphic sections in the appendix. The Towel Creek Tuff is described in all sections except 2, 5, 11, 14, 15, and 18.

Ignimbrites--White, structureless pyroclastic deposits that contain abundant dacitic pumiceous fragments within a matrix of dust-size glass grains (figure 11) are the major constituent of the Towel Creek Tuff. These pyroclastic rocks are ignimbrites, and unlike most, they are never welded. However, paleomagnetic work by Scott (1974, p. 32-34) indicates that they were emplaced at fairly high temperatures, greater than 425°c. Other than the rare squashed pumice, there is no evidence of compaction.

The ignimbrites are generally concentrated in the basal part of each member.

The number of ignimbrite sheets within each member of the Towel Creek Tuff depends upon its proximity to the Hackberry volcano. The Hackberry Basin Member has as many as 20 separate sheets, and five to 10 sheets is a typical value for the other members in outcrops around the periphery of the volcano. If the Hackberry Basin Member is indeed correlative with Member 4 of the Towel Creek Tuff, then as many as 100 separate ignimbrite sheets may have been erupted from the Hackberry volcano.

The ignimbrite sheets all have sharp contacts, and they generally overlie dacitic air-fall tuffs. The sheets are overlain chiefly by air-fall tuffs and, less commonly, by other ignimbrites or reworked tuffs. Where two ignimbrites are in stratigraphic contact, it is difficult to recognize their boundary.

The individual ignimbrite sheets are from 0.2 to 30 meters thick and average eight meters thick. The sheets within the basal four members of the Towel Creek Tuff thin gradually and pinch out at distances from three to 11 kilometers from the center of the Hackberry volcano (considered to occur at the center of the Sally May Dacite stock); the majority pinch out within six kilometers. Tracing out several sheets assigned to Member 4 of the Towel Creek Tuff near Bull Run and Towel Creeks led to a very rough estimate of 2.5 kilometers for their later extent. Assuming that this value is the average width of an ignimbrite sheet and that the average sheet extends about five kilometers from its vent and is about 12 meters thick leads to a volume of 0.15 cubic kilometer for each sheet.

A thick ignimbrite (up to 30 meters thick) occurs in the basal part of all outcrops of Member 4 of the Towel Creek Tuff. If this is the same ignimbrite in all exposures and if radial symmetry about Hackberry volcano is assumed (it is exposed within an arc of 270°), then its estimated volume is 1.7 cubic kilometers. This sheet also has the greatest areal extent of any ignimbrite erupted from the Hackberry volcano. It extends from seven to 11 kilometers from the center of the volcano.

The typical ignimbrite contains dacitic pumiceous and lithic lapilli and blocks in a matrix composed primarily of glassy dust with lesser amounts of plagioclase, hornblende, biotite, and opaque mineral crystals. The most conspicious constituents are white, rounded lapilli and blocks of dacitic pumice (30 modal percent). They range from 0.05 millimeter to greater than one meter in diameter and average four millimeters across.

The pumiceous clasts are all lithologically similar. They contain plagioclase (10 to 25 percent), brown biotite (one to two percent), green hornblende (one to three percent), magnetite (one percent), and rare quartz phenocrysts in a glassy groundmass that contains plagioclase microlites (10 modal percent). Plagioclase phenocrysts average one millimeter across, are subhedral, commonly broken, and have ragged boundaries. Glomerophyres of plagioclase are common. The phenocrysts are zoned and oscillatory zoning is common. Their average composition is An_{35}. The plagioclase phenocrysts have inclusions of apatite ± hornblende ± opaque minerals ± biotite. Biotite phenocrysts are euhedral and are as large as three millimeters in diameter. Inclusions of plagioclase and opaque minerals in the biotite are common. Hornblende phenocrysts average 0.3 millimeter across and are as large as 0.6 millimeter. They are subhedral to euhedral. Inclusions of opaque minerals in the hornblende are ubiquitous. The opaque mineral phenocrysts are subhedral and average 0.02 millimeter in diameter. Corroded quartz phenocrysts average one millimeter in diameter. The glassy groundmass generally is vesicular. The vesicles are commonly stretched.

Subrounded to subangular dacitic lithic lapilli and blocks are also major constituents of the ignimbrites (up to 20 modal percent). They are white, blue, and red, range from less than one millimeter to greater than one meter in diameter and average one centimeter. They are petrographically similar to all other dacitic clasts which are described on pages 159-164.

Many of the ignimbrites contain accidental clasts of basalt (zero to two modal percent). They average two millimeters in diameter and are as large as 10 centimeters. These clasts contain phenocrysts of olivine in a pilotaxitic groundmass composed primarily of plagioclase laths.

Plagioclase is the most common (10 modal percent) free crystal component of the clastic matrix of the ignimbrites. The plagioclase crystals are subhedral and commonly broken. They average one millimeter in diameter and are as large as five millimeters. Oscillatory zoning is common. Sanidine crystals are a conspicious component of the matrix of Member 6. Biotite and hornblende crystals constitute two to three percent of the groundmass. They are subhedral and average one millimeter or less in diameter. The biotite crystals are commonly altered to hematite (?) and goethite (?). Trace amounts of anhedral quartz and sanidine are also present. All quartz phenocrysts are corroded. Both average 0.2 millimeter across and are as large as one millimeter. Xenocrysts of clinopyroxene and altered olivine are present in trace amounts in a few ignimbrites. The remainder of the ignimbrites is a light brown glass dust matrix.

Dacitic pyroclastic breccias--Members 2, 3, and 4 of the Towel Creek Tuff commonly contain one or more structureless, wedge-shaped deposits of dacitic lithic blocks within a glassy groundmass (figure 12). These deposits generally occur within the Hackberry volcano. In this report they are called dacitic pyroclastic breccias. Those within Members 2 and 3 occur only in the Towel Creek and Brushy Prong areas, and those in Member 4 occur in all exposures west of Hackberry Mountain.

These breccias generally occur within the uppermost part of each member and are interbedded with the ignimbrites. Unlike the ignimbrites, they do not have associated air-fall tuffs. The dacitic pyroclastic breccias vary greatly in thickness. They are exceedingly thick in deposits within the flanks of the Hackberry volcano, one such deposit within Member 3 is at least 160 meters thick and was mapped separately, but thin rapidly around the periphery of the volcano. The typical deposit is wedge-shaped within four kilometers of the center of the Hackberry volcano (assumed to be the geographic center of the Sally May Dacite stock) beyond which their thickness is more constant, typically between 10 and 25 meters. They extend as thinner deposits for considerable distances from the vent, up to seven kilometers, although they are not as extensive as the ignimbrites. The members of the Towel Creek Tuff can have as many as three pyroclastic breccias within deposits on the flank of the volcano; in exposures away from the volcano, there is usually no more than one breccia within each member.

The dacitic pyroclastic breccias are chaotic, structureless deposits composed entirely of subangular dacitic lithic blocks and lapilli (45 modal percent) within a fine-grained matrix. These clasts are either white or pink. They average 15 centimeters in diameter and generally

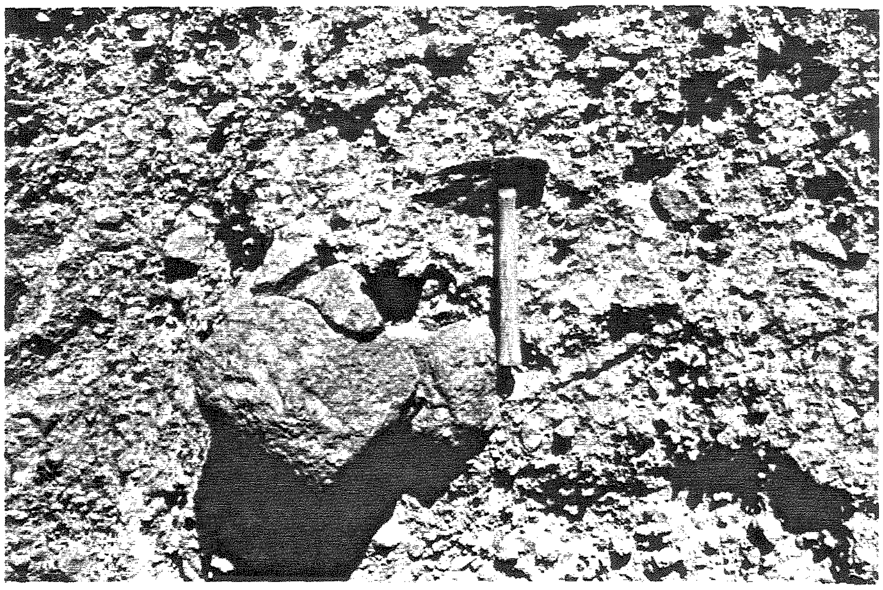


Figure 12.--Part of thick mapped dacitic pyroclastic breccia within Member 3 of the Towel Creek Tuff.

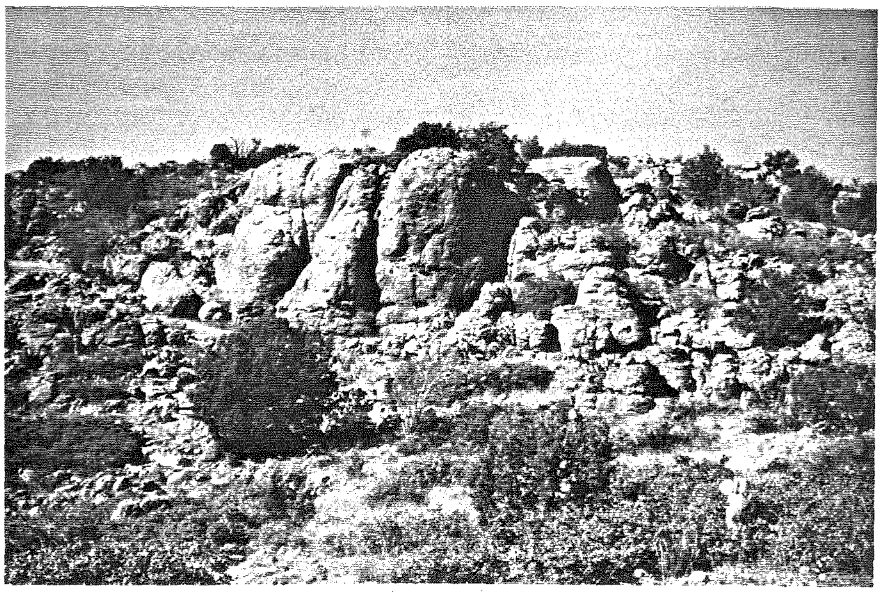


Figure 13.--Dacite flow in Member 7 of the Towel Creek Tuff. Outcrop is west of Hackberry Basin. Tree in left foreground is about three meters high.

are as large as four meters. However, thicker parts of the mapped breccia within Member 3 contain several blocks that are as large as 30 meters across. The petrography of the dacitic lithic clasts is similar to that of all other dacites (pages 159-164). Rounded blocks and lapilli of basic xenoliths (pages 164-166) occur in trace amounts. The remainder of these breccias is a fine-grained matrix. A major constituent of the matrix is ash-sized dacitic lithic grains (16 modal percent). They are subangular and are as small as 0.3 millimeter in diameter. Subangular plagioclase crystals (nine modal percent) are scattered throughout the matrix. They are broken, anhedral, and are 0.04 to 3.5 millimeters in diameter. Oscillatory zoning within the plagioclase crystals is common, as are inclusions of glass. Subhedral crystals of green hornblende (one modal percent) and brown biotite (trace) also occur in the matrix. Both average 0.3 millimeter across. The hornblende phenocrysts commonly have biotite inclusions and the biotite phenocrysts have plagioclase and opaque inclusions. Rounded, ash-sized particles of tuff are commonly present (one modal percent). The remainder of the matrix is composed of a pale brown glass dust.

The pyroclastic breccias contain insignificant quantities of dacitic pumice, whereas other dacitic pyroclastic deposits contain appreciable pumice. Silicic pyroclastic deposits devoid of pumiceous clasts are generally either autobrecciated lava flows or are the remnants of collapsed domes (Parsons, 1969, p. 270-274). The dacite breccia lenses at the Hackberry volcano closely resemble deposits formed by the collapse of domes. These deposits typically are formed from incandescent debris released by simple gravitational collapse of a growing dome (Williams, 1957, p. 60). This kind of pyroclastic flow is commonly referred to as the Merapi type (Williams, 1957, p. 60; Williams and McBirney, 1979, p. 142-153; Walker and others, 1980, p. 320-321) or as block and ash flows (Perret, 1935, p. 63-64). Perret (1935) provides several graphic descriptions of the eruption of these gas-poor pyroclastic flows.

Reworked tuffs--The reworked tuffs are coarse fanglomerates composed entirely of dacitic detritus deposited within and adjacent to the Hackberry volcano. These deposits are readily distinguished from the pyroclastic rocks of the Towel Creek Tuff by color (they are buff and most pyroclastic deposits are white or pink) and by the presence of well developed beds. The reworked tuffs occur in Member 3 along Towel Creek, in all outcrops of Member 4 west of Hackberry Mountain, in Member 7 north of Hackberry Mountain, and in all outcrops of the Hackberry Basin Member.

The reworked tuffs generally are the uppermost unit within each member. Typically there is only one such deposit within each member, and there are rarely more than two. The deposits are thickest in exposures around the periphery of the Hackberry volcano; the thickest section of reworked tuffs, 50 meters thick, occurs within Member 4 of the Towel Creek Tuff west of The Rocks. The reworked tuffs gradually thin as they recede from the volcano and generally pinch out within six kilometers of the vent. Deposits of reworked tuff are more extensive than those of the pyroclastic breccias but less extensive than those of the ignimbrites.

Most reworked tuffs have moderately developed thin beds that are two to 30 centimeters thick. These beds are expressed by differences in the average size and concentration of the enclosed lithic dacite clasts. Some of the finer-grained beds are laminated; cross-beds are not uncommon. The reworked tuffs are poorly sorted. Their grain size ranges from very fine sand to boulder. These deposits have sharp contacts and are well indurated and are well exposed.

The reworked tuffs are composed primarily of dacitic lithic clasts (25 modal percent) and plagioclase grains (20 modal percent). They contain minor pumice (five modal percent), hornblende and biotite grains (one modal percent), opaque mineral grains (two modal percent), and trace amounts of quartz grains, mafic lithic clasts, and pyroxene grains. The lithic clasts are subrounded, range from coarse sand to cobble size, and average pebble size. The groundmass of the dacitic clasts is commonly devitrified. The mineral grains are subangular and range in size from fine to very coarse sand. The plagioclase grains average fine sand size, and the other mineral grains average coarse sand size. The remainder of the deposits (30 to 35 modal percent) is too fine-grained to be resolved optically.

The reworked tuffs are thickest, coarsest-grained, and their enclosed clasts are most angular in outcrops adjacent to the present exposure of the altered Sally May Dacite. These attributes indicate that the reworked tuffs were derived from erosion of the Hackberry volcano and from the reworking or underlying pyroclastic deposits.

The internal characteristics of the reworked tuffs suggest that they were deposited as alluvial fans. These characteristics include 1) poor sorting, 2) angularity of clasts, 3) fairly constant thickness of beds, 4) variability of thickness, particle sorting, and particle size in adjacent beds, 5) pink color of outcrops which typify an oxidizing environment during deposition (Bull, 1972). The only characteristics of alluvial fans that these deposits lack are channel-fill structures, which may have simply not been recognized.

Dacite flows--Four dacite flows occur in the Towel Creek Tuff. One is found within Member 7 northeast of Hackberry Mountain (figure 13), and a group of three flows are within Member 3 near Brushy Prong. In both members the flows are adjacent to their probable vents. The flows are composed of the typical dacite (pages 159-164), and they are similar to the flow of the Hackberry Mountain Dacite, although they are thinner. The flow assigned to Member 7 is about 70 meters thick, and the group within Member 3 has an aggregate thickness as great as 150 meters.

Air-fall tuffs--Thin deposits of well bedded dacitic air-fall tuffs occur in all members of the Towel Creek Tuff. They form extensive deposits that are present in most exposures of this formation. They are, however, generally not as extensive as those of the ignimbrites. Most members contain between one and three separate air-fall tuffs, and the number increases towards the Hackberry volcano. They are especially prevalent in outcrops on the eastern flank of the volcano; there are at least 10 separate air-fall tuffs within the incomplete section of the Hackberry Basin Member at Boulder Canyon. The individual tuffs are generally about one meter thick. However, they thicken dramatically on the flanks of the Hackberry volcano where they are as thick as 40 meters. Most air-fall tuffs are concentrated at the base of the individual members and are everywhere overlain by ignimbrites.

The air-fall tuffs are white and weather the same color. They have well developed parallel beds that average two centimeters thick and mantle the underlying surface. The beds are expressed by contrasts in both the size and abundance of dacitic pumiceous or lithic lapilli. They have no impact structures. Clast characteristics and average grain size depend upon proximity to the vent. As vents are approached, the tuffs become coarser-grained and generally contain more dacitic lithic clasts. The typical air-fall tuff contains dacitic pumiceous lapilli (50 modal percent), plagioclase phenocrysts and microphenocrysts (20 modal percent), dacitic lithic lapilli (0 to 20 modal percent), biotite and hornblende microphenocrysts (trace to two modal percent), opaque mineral grains (one modal percent), and trace amounts of quartz microphenocrysts and basaltic lithic fragments. The lithic and pumiceous lapilli are subrounded and average two millimeters across, but may be as large as 2.5 centimeters. The mineral grains are subhedral and average one millimeter across.

Base-surge tuffs-A few thin surge deposits occur in the Hackberry Basin Member within Hackberry Basin (see Section 9 of the appendix). The surge deposits are light gray to grayish-pink and weather the same colors. They are about 10 meters thick and have very well developed laminae two to three millimeters thick which are expressed by slight differences in average grain size. The laminae generally are undulatory with wavelengths up to one meter and amplitudes as great as 20 centimeters. Cross-bedding (figure 14) and bomb sags are common. These deposits have sharp contacts with ignimbrites that both overlie and underlie them.

The base-surge tuffs are composed of dacitic lithic grains (20 modal percent) and blocks (one modal percent), basaltic lithic grains (11 modal percent), dacitic pumiceous grains (eight modal percent), plagioclase crystals (eight modal percent), and a trace amount of hornblende and biotite crystals in a brown glass dust matrix. The lithic and pumiceous grains are rounded and average one millimeter in diameter. The dacitic lithic blocks are rounded, average six centimeters across, and are as large as 30 centimeters. The mineral grains are subangular, average

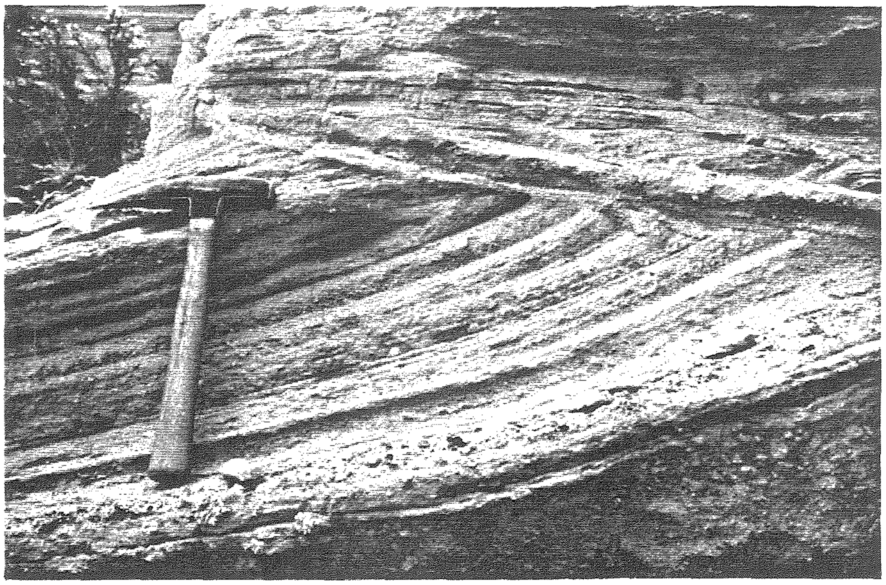


Figure 14.--Cross-beds in base-surge tuff in Hackberry Basin Member of the Towel Creek Tuff.

Figure 15.--Fine-grained sediments within Hackberry Basin Member of the Towel Creek Tuff. Slump structure due to soft-sediment deformation is left of the hammer.

0.15 millimeter in diameter, and are as large as 1.5 millimeters.

Surge deposits can form in at least two different types of environments: 1) phreatic eruptions; 2) eruptions that produce a nuee ardente (Sparks and Walker, 1973, p. 63). Fisher (1979, p. 306) called the deposits from phreatic eruptions base-surge deposits and the deposits associated with nuée ardentes ground-surge deposits. He also described a third type of surge deposit which mechanically segregates from the top of a pyroclastic flow and occurs above it. This type of deposit is also a ground-surge.

Base-surge deposits have different characteristics than the other two types of surge deposits because they are deposited in a wet and relatively cool environment. Features characteristic of the water-rich base-surge deposits include: (1) more accidental fragments than in the other types of surge deposits (Walker and others, 1980, p. 326); (2) vitric ash fragments that have straight or slightly curved grain edges caused by their contraction and shattering when quenched by water (Heiken, 1971, p. 5623); (3) accretionary lapilli (Heiken, 1971; Waters and Fisher, 1971); (4) cohesive bedding caused by presence of water. The best evidence for cohesive bedding is provided by bomb sags (Heiken, 1971, p. 5623; Waters and Fisher, 1971, p. 5612; Crowe and Fisher, 1913, p. 668). Walker and others (1980, p. 326) suggest that the other types of surge deposits are rarely thicker than one meter.

The surge deposits of the Towel Creek Tuff have many bomb sags and are commonly thicker than one meter, which suggests that these deposits are base-surge deposits associated with phreatic eruptions. Also, these deposits contain only minor amounts of dacitic pumiceous clasts. Pumice clasts generally occur in much greater abundances in deposits associated with ignimbrites.

Phreatic eruptions of the Hackberry volcano apparently were rare. Moreover, lahars, which are also indicative of abundant surface water, are almost totally absent in the Towel Creek Tuff. The only unit which suggests the presence of ponded surface water on the Hackberry volcano are fine-grained sediments that occur near the base-surge deposits in Hackberry Basin and in about the same stratigraphic position.

Fine-grained sediments--The Hackberry Basin Member contains one exposed unit of lacustrine sedimentary rocks which occurs in the southwestern part of Hackberry Basin. This deposit consists of distinctive laminated siltstone and conglomeratic sandstone and is labeled fine-grained because all other sedimentary deposits within the Towel Creek Tuff are much coarser.

The fine-grained sediments occur near the base of the exposed section within Hackberry Basin. It is about 35 meters thick and is underlain by a dacitic ignimbrite of unknown thickness; it is overlain either by reworked tuff or dacitic ignimbrite. The extent of this deposit is not known because it is covered by landslides along its southern and western margins. The sediments apparently butt up sharply against pyroclastic deposits to the north. The basal part consists primarily of conglomeratic sandstone with a minor amount of interbedded siltstones. The section grades upward into siltstone which, in turn, grades into sandstone at the top. The deposit has a ferruginous cement that is poorly indurated.

The sandstone beds are very light gray and weather the same color. They are poorly sorted and contain thin, discontinuous stringers of dacitic pumiceous pebbles and granules. The grains range from fine sand to cobble size. They are composed of lithic dacite grains (27 modal percent), plagioclase (17 modal percent), mafic minerals (seven modal percent), and basalt (one modal percent). The groundmass consists of clay minerals and glass. The lithic grains are subrounded and the mineral grains are subrounded to subangular.

The siltstone is very pale orange and weathers grayish-orange. It has well-developed laminae one millimeter to one centimeter thick. They are expressed by differences in color--orange versus white. A few interbeds of sandstone, each about five centimeters thick, occur in the siltstone. The laminae and beds are commonly disrupted by small faults and slumps (figure 15), which evidently are a result of soft-sediment deformation. The siltstone is composed chiefly of subangular silt size particles of devitrified glass and goethite (?) with minor amounts of plagioclase (four modal percent) and mafic mineral grains (three modal percent).

Chemistry

Chemical analyses of the Towel Creek Tuff are given in table 12. All samples analyzed expressly for this report are from ignimbrites. The samples are either from the groundmass or from pumiceous clasts. No significant differences were found in the analyses from groundmass or pumice where collected from the same outcrop. The remaining analyses are from Scott (1974); the units represented by his samples are not known.

The composition of the majority of the analysed rocks lies in the dacitic field of Streckeisen (1979, p. 332). A few specimens have less than 20 percent normative quartz and are andesites according to his scheme. However, they are petrographically indistinguishable from the samples in the composition field of dacites and will be considered dacites in this report. The chemical composition of the samples collected by Ulrich and Bielski (in preparation) from Member 7 plot in the rhyolitic

Table 11.--Major-element and normative compositions, in percent, of the Towel Creek Tuff

Member	1	1	1	2	2	2	2	2	3	3	3	3
Sample No.	[1,6]RL-79-77	[1,7]RL-79-76	[2]T14-1	[1,6]RL-79-80	[2]T13-1	[2]T13a-1	[2]T13b-1	[2]T13-3	[1,6]RL-79-83	[1,6]RL-79-46	[2]T11-1	[2]T11A-1
Major oxides (weight percent)												
SiO_2	61.8	63.0	62.8	62.5	66.7	66.0	64.2	65.8	60.6	62.0	64.3	65.3
Al_2O_3	16.0	15.3	15.5	16.2	15.8	15.4	15.2	15.5	17.3	15.8	15.5	15.7
Fe_2O_3	3.97	3.76	2.94	3.82	2.6	2.6	2.5	2.6	4.73	3.75	2.7	3.05
FeO			0.95		0.72	0.72	0.81	0.63			0.99	0.63
MgO	2.0	2.1	2.2	1.8	1.4	1.6	1.8	1.3	2.1	1.7	1.7	1.4
CaO	4.11	4.16	4.20	4.00	3.1	3.4	3.4	3.3	4.93	3.88	4.1	3.7
Na_2O	2.8	2.6	3.2	3.2	3.8	3.8	3.1	4.0	3.6	3.2	3.8	3.2
K_2O	2.4	3.03	2.6	2.45	2.7	2.6	2.7	2.7	2.40	2.35	2.7	2.7
TiO_2	0.49	0.49	0.45	0.46	0.39	0.37	0.38	0.40	0.58	0.43	0.46	0.40
MnO	0.05	0.07	0.06	0.05	0.06	0.08	0.07	0.05	0.07	0.06	0.07	0.10
P_2O_5	0.2	0.3	0.22	0.3	0.19	0.20	0.20	0.17	0.3	0.2	0.25	0.22
CO_2			<0.05		0.10	<0.05	<0.05	0.10			0.53	<0.05
H_2O+			2.41		1.82	1.56	2.47	1.68			1.73	1.75
H_2O-			1.79		1.16	1.41	2.50	1.21			1.42	1.38
[4]Loss	4.51	3.62		3.78					2.00	4.12		
Total	98.3	98.3	99.3	98.6	100.5	99.7	99.3	99.4	98.6	97.5	100.3	99.5
CIPW Norms[5]												
q	24.9	24.7	21.8	23.6	25.2	24.1	26.4	23.1	16.0	24.0	20.6	26.2
or	15.2	18.9	16.2	15.3	16.4	15.9	16.9	16.6	14.7	14.9	16.6	16.6
ab	25.3	23.2	28.5	28.6	33.0	33.3	27.8	35.1	31.6	29.0	33.3	28.1
an	20.4	19.8	20.4	18.9	14.5	16.1	16.5	15.9	23.4	19.3	17.9	17.6
c	1.9	1.0	0.3	1.8	1.5	0.7	1.6	0.4	0.6	1.5		1.4
di											1.2	
hy	9.6	9.5	10.1	8.8	7.0	7.7	8.5	6.7	10.5	8.7	7.7	7.6
mt	1.1	1.1	1.2	1.1	1.0	1.0	1.0	1.0	1.3	1.1	1.1	1.1
il	1.0	1.0	0.9	0.9	0.8	0.7	0.8	0.8	1.1	0.9	0.9	0.8
ap	0.5	0.8	0.6	0.8	0.5	0.5	0.5	0.4	0.8	0.5	0.6	0.6

Footnotes explained on last page of table.

Table 11.--Major-element and normative compositions, in percent, of the Towel Creek Tuff - Continued

Member	4	4	4	4	4	4	4	Hackberry Basin		5	6	6
Sample No.	[1,6]RL-79-86	[1,7]RL-79-84	[1,7]RL-79-85	[2]T6-1	[2]T6-2	[2]T5b-1	[2]T4-1	[1,6]RL-79-73	[1,7]RL-79-72	[1]RL-79-64	[2]T (-)1-3a	[2]T (-)1-3p
Major oxides (weight percent)												
SiO_2	61.8	61.7	65.9	60.9	60.8	63.1	60.3	64.9	66.2	60.4	65.1	64.8
Al_2O_3	16.4	15.6	16.1	16.7	15.8	16.1	17.1	15.4	15.4	16.6	15.6	15.4
Fe_2O_3	3.94	3.56	3.93	3.26	3.72	1.80	3.4	3.19	3.01	4.78	2.4	2.0
FeO				1.44	0.81	2.25	1.17				0.81	0.81
MgO	2.0	1.8	1.0	2.0	2.4	1.8	2.2	0.96	1.1	2.5	1.6	1.5
CaO	4.40	4.40	4.05	4.7	4.7	4.4	4.9	3.43	3.32	5.53	3.4	3.6
Na_2O	3.2	3.1	3.8	3.8	3.7	3.9	4.4	3.2	3.6	3.5	3.3	3.4
K_2O	2.30	2.68	2.63	2.5	2.5	2.6	2.2	2.49	2.51	1.84	2.7	2.9
TiO_2	0.52	0.47	0.54	0.57	0.53	0.53	0.63	0.36	0.33	0.64	0.31	0.31
MnO	0.06	0.06	0.03	0.08	0.07	0.07	0.08	0.04	0.05	0.07	0.07	0.17
P_2O_5	0.3	0.3	0.3	0.35	0.31	0.28	0.31	0.2	0.2	0.4	0.15	0.15
CO_2				<0.05	0.17	<0.05	0.06				0.10	0.36
H_2O+				1.62	1.90	1.71	1.38				2.34	2.53
H_2O-				1.07	1.82	1.08	1.10				1.53	1.08
[4]Loss	4.25	4.74	0.540					4.32	2.49	2.81		
Total	99.2	98.4	98.8	99.0	99.2	99.6	99.2	98.5	98.2	99.1	99.4	99.0
CIPW Norms[5]												
q	22.2	22.0	23.2	15.5	16.0	18.0	12.0	28.8	27.3	17.2	26.0	24.2
or	14.4	17.0	15.9	15.4	15.5	15.9	13.5	15.7	15.5	11.4	16.7	18.1
ob	28.6	28.1	32.8	33.4	32.9	34.1	38.6	28.8	31.9	30.8	29.3	30.3
an	21.0	21.3	18.5	21.9	20.1	19.4	21.2	16.7	15.9	25.2	16.7	17.8
c	1.4	0.3	0.4	0.04				1.8	1.3		1.5	0.5
di					1.9	1.1	1.6			0.6		
hy	9.4	8.6	6.3	10.4	10.4	8.6	9.8	5.9	6.0	11.2	7.8	7.3
mt	1.1	1.0	1.2	1.3	1.3	1.2	1.3	1.0	0.9	1.3	1.0	0.9
il	1.0	1.0	1.0	1.1	1.1	1.0	1.2	0.7	0.7	1.3	0.6	0.6
ap	0.8	0.8	0.7	0.9	0.8	0.7	0.8	0.5	0.5	1.0	0.4	0.4

Footnotes explained on last page of table.

Table 11.--Major-element and normative composition, in percent, of the Towel Creek Tuff - continued

Member	6	7	7	7
Sample No.	[1,6]RL-79-61	[1,7]RL-79-66	[3]UWM 52	[3,7]UWM 36
Major oxides (weight percent)				
SiO_2	65.0	60.3	69.71	73.77
Al_2O_3	15.7	17.1	15.22	14.96
Fe_2O_3	3.19	4.08	0.57	0.28
FeO			2.03	0.89
MgO	1.2	2.1	2.67	0.74
CaO	3.58	4.40	3.21	1.76
Na_2O	3.2	3.0	2.78	3.61
K_2O	2.63	1.77	3.27	3.80
TiO_2	0.32	0.43	0.32	0.16
MnO	0.05	0.05	0.06	0.00
P_2O_5	0.2	0.2	0.11	0.04
CO_2				
H_2O+				
H_2O-				
[4]Loss	3.65	5.09		
Total	98.7	98.5	100.0	100.01
CIPW Norms[5]				
q	27.4	23.8	29.2	33.0
or	16.4	11.2	19.3	22.5
ab	28.5	27.3	23.5	30.5
an	17.4	22.0	15.2	8.5
c	1.6	2.9	1.5	1.8
di				
hy	6.6	10.2	9.5	2.9
mt	1.0	1.1	0.9	0.4
il	0.6	0.9	0.6	0.3
ap	0.5	0.5	0.3	0.1

[1] Chemical analyses by x-ray fluorescence methods with all iron calculated as Fe_2O_3. Location of samples shown in plate 7. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg.
[2] Chemical analyses from Scott (1974).
[3] Chemical analyses from Ulrich and Bielski (in preparation).
[4] Loss on ignition.
[5] All norms calculated with $FeO/Fe_2O_3 = 9.027 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).
[6] Groundmass of ignimbrite.
[7] Pumiceous clast from ignimbrite.

field.

Scrutiny of the analyses for this formation suggests that each member may have its own chemical fingerprint. There appear to be consistent differences in both CaO and MgO content exhibited between the members of the Towel Creek Tuff. Although these differences are minor they might have possibilities as a tool for correlation.

The dacites of the Towel Creek Tuff are slightly less silicic than those of the Sally May and Hackberry Mountain Dacites. The Towel Creek Tuff has a mean anhydrous silica content of 66.6 ± 2.5 percent in contrast to 69.5 ± 2.0 percent for the other two formations.

Age

Mahard (1949, p. 118) was the first to mention the Towel Creek Tuff. He commented upon the thick section of tuffs and breccias exposed along Fossil Creek Road, and suggested that there might be correlative volcanic rocks exposed at the northeastern margin of the Verde Valley which he had assigned to the late Pleistocene.

Twenter and Metzger (1963) included the lower members of the Towel Creek Tuff within their Tertiary volcanic rocks. They assigned these rocks a Miocene (?) or Pliocene (?) age. This age was based on a possible correlation with the volcanic rocks of the Jerome area that were assigned to the Pliocene (?) by Anderson and Creasey (1958, p. 58-59). Twenter and Metzger's assignment was also influenced by the suggestion of Cooley (1961) that some of the early volcanism in this region was of Miocene age.

Sabels (1962, p. 100) determined a potassium-argon age of 14.3 m.y. for a coarse tuff-breccia exposed in the floor of Hackberry Basin. This sample is undoubtedly from the Hackberry Basin Member. Wadell (1972, p.

18) noted the discrepancy between Sabels' date and those obtained by McKee and Anderson (1971, p. 2770) for the Hickey Formation (14.0 ± 0.6 to 10.1 ± 0.4 m.y.). Wadell considered it doubtful that the units dated by McKee and Anderson were only from the upper part of the Hickey Formation and suggested that Sabels' date might be wrong.

Elston and Scott (1973a) determined a paleomagnetic reversal sequence for a volcanic section along the Verde River they had mapped previously (Elston and Scott, 1973b). From a preliminary correlation of their reversal pattern with the oceanic anomaly pattern they estimated that the major phase of dacitic volcanism (probably Members 1 to 4 of the Towel Creek Tuff) occurred from 7.9 to 8.8 m.y. ago. They reported that this phase was followed by sporadic ash eruptions (probably Members 5 to 7) to perhaps 4.5 m.y. ago or less.

Elston, McKee, Scott, and Gray (1974, p. 608) reported preliminary potassium-argon ages for volcanic rocks sampled from the Verde River and Forest Highway 9 near Thirteenmile Rock. These preliminary ages include one of 9.7 m.y. for Member 3 and another of 8.5 (?) m.y. for Member 4. They reported preliminary ages of 3 to 5 m.y. for the Thirteenmile Rock section which includes Member 7.

Potassium-argon ages for several members of the Towel Creek Tuff were determined by McKee and Elston (1980). Their data are summarized in table 6. They dated Members 1, 2, 4, and 6 and obtained stratigraphically controlled apparent ages of 10.6-11.7, 10.1-11.3, 8.9-9.6, and 7.8-8.4 m.y., respectively. They also dated units that bracket Members 3 and 5 stratigraphically. The resulting apparent ages for these two members are 9.3-11.3 and 7.8-8.5 m.y. The potassium-argon age of the Hackberry Mountain Dacite (table 17) was necessary for the age determination of

Member 7, 7.8-8.4 m.y. Therefore, the Towel Creek Tuff accumulated over a maximum time span of 11.7 to 7.8 m.y. b.p. (before present) and over a minimum time span of 10.6 to 8.4 m.y. b.p.

Because of the abundant data and stratigraphic control, the ages of the Towel Creek Tuff published by McKee and Elston (1980) are taken to be correct, and the age cited by Sabels (1962, p. 100) for the Hackberry Basin Member is too old. The ages obtained by the preliminary paleomagnetic correlations of Elston and Scott (1973) are too young for all the members. The preliminary potassium-argon ages reported by Elston, McKee, Scott, and Gray (1974, p. 608) are close to the accepted values for Members 3 and 4 but are much too young for Member 7.

Two and possibly three of the five major hiatuses recognized by McKee and Elston (1980, p. 331) in the time record of the volcanic rocks of the Hackberry Mountain area occur after eruptions of a basal member of the Towel Creek Tuff. One such hiatus separates Members 1 and 2 of the Towel Creek Tuff, and another separates Member 4 of the Towel Creek Tuff from the overlying Member 15 of the Hickey Formation. Another major break separates Members 11 and 13 of the Hickey Formation; Member 3 of the Towel Creek Tuff was erupted during this hiatus. Therefore, the history of the volcanic rocks within the Hackberry Mountain area can be characterized by the relatively continuous accumulation of basalt flows that culminates with the eruptions of dacitic pyroclastic rocks from the Hackberry volcano. These eruptions are followed by a period of repose before the basaltic volcanism continues.

Correlation

The Towel Creek Tuff is exposed over an area larger than that studied in this report. Scott (1974) identified exposures to the southeast at

Hardscrabble Canyon. Ulrich and Bielski (in preparation) mapped several discontinuous outcrops of silicic tuff, probably Member 7, near Thirteen-mile Rock and two kilometers to its north. Wolfe (in preparation) mapped the basal members of the Towel Creek Tuff along the west side of Verde River in the region adjoining the Hackberry Mountain area.

Sabels (1962) attempted to correlate the Towel Creek Tuff with other silicic tuffs exposed in northern and central Arizona. He proposed that tuffaceous beds within the Bidahochi Formation of northeastern Arizona were derived from the Hackberry volcano. The Bidahochi Formation is a sedimentary and volcanic unit of late Tertiary age exposed within the Hopi Indian Reservation and located 160 kilometers northeast of Hackberry Mountain (figure 3). This formation consists chiefly of flat-lying beds of claystone, siltstone, sandstone, and tuff with an aggregate thickness of more than 100 meters (Shoemaker and others, 1962, p. 330). Shoemaker and others (1957) divided the Bidahochi Formation into six members. The lower members consist primarily of lacustrine sediments which also contain twelve individual thin beds of white, waterlaid tuff that is chiefly rhyolitic (Shoemaker and others, 1962, p. 330) believed by Sabels (1962) to have been erupted from the Hackberry volcano.

Sabels' (1962) proposed correlation is supported by potassium-argon ages for both the Towel Creek Tuff and the Bidahochi Formation. Scarborough and others (1974) obtained a potassium-argon age of 6.7 ± 0.16 my. for a trachybasalt that overlies the silicic tuff beds. A mammalian fauna occurs in beds that are probably equivalent in age to one of the lower four members of the Bidahochi (Shoemaker and others, 1962, p. 331). This fauna is of Clarendonian or Barstovian age (Lance, 1954) which corresponds to the period of time between 15.6 and 10.7 m.y. ago (Evernden and others, 1964, p. 164). Therefore, the silicic tuff beds of the Bidahochi Formation were deposited between 15.6 and 6.7 m.y. ago. This span of ages includes those reported previously for the Towel Creek Tuff.

The deposition of silicic tuffs at substantial distances downwind from their vents is not uncommon (e.g. Mullineaux, 1974). Studies of eolian deposits within the Bidahochi Formation indicate that wind movement during the time of their accumulation was from the southwest (Akers, 1964; Cooley and others, 1969, p. 40). Therefore, the Hackberry volcano was located in the prevailing upwind direction from the Bidahochi Formation at the time of its deposition, which is consistent with Sabels' (1962) proposed correlation.

Rubble

Distribution and relation to other rocks

The rubble unit is exposed at Chalk Springs and along slopes adjacent to Brushy Prong. This unit is very resistant and forms steep cliffs that are noticeable at quite some distance. Its thickest exposure is at Chalk Springs, and it is 210 meters thick.

This flat-lying unit unconformably overlies Members 3 and 4 of the Towel Creek Tuff along Brushy Prong (figure 16), and it overlies the Sally May Dacite and the Towel Creek Tuff at Chalk Springs. In all its exposures the rubble is overlain with structural concordance by either the Hackberry Mountain Dacite or Member 4 of the Thirteenmile Rock Basalt.

Lithology

This unit consists almost exclusively of a moderately indurated

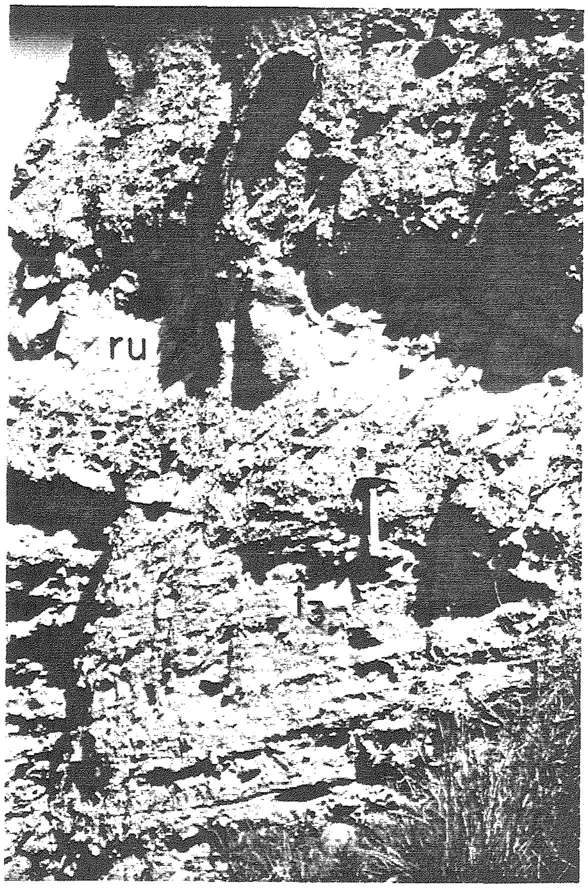


Figure 16.--Unconformable contact between the rubble unit (ru) and the underlying Member 3 of the Towel Creek Tuff (t_3). Outcrop is east of Brushy Prong. View east.

sandy conglomerate. It is grayish-orange-pink in contrast to the white or very pale gray of the underlying dacitic pyroclastic deposits. It has well developed beds with variable thickness (20 centimeters to four meters thick). Individual beds are fairly uniform and continuous, especially near Chalk Springs. The beds are expressed by differences in the abundance of coarse dacite clasts. In general, the thicker the bed, the coarser the material in it is. The long axes of the clasts are commonly aligned with the beds. At the exposure near Chalk Springs some of the coarser beds are graded. Lenticular concentrations of lithic clasts are common in the exposures adjacent to Brushy Prong.

This unit is very poorly sorted. It contains lithic clasts (40 modal percent) that consist exclusively of subangular, white or blue, unaltered dacite. These clasts range from granule to boulder size and average pebble size. The remainder of the rock consists of a silt to coarse sand size matrix that is composed of varying but subequal proportions of altered dacitic grains, unaltered dacitic grains, plagioclase crystals, and sparse hornblende and biotite crystals. The matrix is fairly porous (15 percent). The unit is bonded by a ferruginous cement. The outcrop of rubble near Chalk Springs contains several thin beds of basaltic and dacitic tuff.

Age and origin

The rubble unit is younger than the Sally May Dacite which, in turn, is younger than Member 6 of the Towel Creek Tuff, and the rubble is older than the Hackberry Mountain Dacite. Therefore, it is stratigraphically limited to an age of 7.8 to 8.4 m.y. (table 6).

The total absence of mafic or rhyolitic clasts and olivine or pyroxene crystals within the rubble indicates that it was derived exclusively from dacitic rocks. Furthermore, the scarcity of pumiceous fragments indicates that its source was probably not chiefly pyroclastic material. The most probable source is the Sally May Dacite, which was probably a positive topographic feature at the time of deposition. This conclusion is strongly supported by the presence of altered dacite grains within the matrix of the rubble. The Sally May Dacite is the only altered dacitic body in the vicinity. Chemical analyses of two samples from the rubble unit are in table 12, and there are no appreciable differences between these analyses and those of the Sally May Dacite (table 19). Because the Sally May Dacite probably breached the surface when intruded (see section on Sally May Dacite), the rubble was deposited soon after emplacement of the stock.

The coarse beds and lenticular concentrations of coarser clasts indicate that this unit was deposited in a fluvial environment. The presence of graded beds and the uniform thickness of the beds at Chalk Springs suggest that portions of this unit may have been deposited by debris flows (Bull, 1972, p. 70-71).

Rhyolite flow

Distribution and stratigraphic relations

Discontinuous remnants of a rhyolite flow occur on the northern side of Hackberry Mountain and extend west-northwest to the Verde River. Theses remnants form low, light colored mounds. The flow unconformably overlies Member 3 of the Cimarron Hills Andesite, Member 7 of the Towel Creek Tuff, and Member 1 of the Cimarron Hills Andesite. It rests on progressively older units towards the west. These units were exposed by erosion prior to the eruption of the rhyolite. The flow also overlies a tongue of Verde Formation along the Verde River.

Table 12. Major-element and normative compositions, in percent, of the rubble unit

[Chemical analyses by x-ray fluorescence methods. Analyst: S. Ramage]

Sample No.	RL-80-7	RL-80-4
Major oxides (weight percent)		
SiO_2	63.46	62.61
Al_2O_3	15.07	15.66
[1] Fe_2O_3	4.24	4.07
MgO	1.9	2.3
CaO	3.92	4.27
Na_2O	3.5	4.06
K_2O	1.46	2.52
TiO_2	0.48	0.52
MnO	0.065	0.083
P_2O_5	0.21	0.26
Total	94.3	96.4
CIPW Norms[2]		
q	26.5	16.8
or	9.2	15.5
ab	31.5	35.8
an	19.2	17.8
c	1.2	2.1
hy	9.6	9.2
mt	1.3	1.2
il	1.0	1.0
ap	0.5	0.7

[1] All iron as Fe_2O_3.

[2] Norms calculated with $FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).

See plate 7 for sample locality.

The rhyolite flow is overlain by the flow of the Hackberry Mountain Dacite at its easternmost outcrop. Both silicic flows unconformably overlie the same units and appear to rest on the same surface. The rhyolite flow has a maximum thickness of 15 meters.

Lithology

The rhyolite flow is thoroughly autobrecciated in all exposures (figure 17). Approximately 55 percent of the flow consists of subangular to angular rhyolitic blocks and fragments, and the remainder consists of white, comminuted rhyolitic groundmass. The blocks average 5 centimeters across at the outcrop along the Verde River and are progressively coarser in outcrops to the east. The blocks and fragments have well developed flow-banding expressed by contrasts in color. Thinner bands are commonly one millimeter thick and are buff to white while the thicker bands are up to five millimeters thick and are blue. The thinner bands have irregular outlines. They also have a darker groundmass and a greater concentration of crystals than the thick blue bands. Elongate mineral grains are usually aligned with the bands.

The rhyolite contains abundant subhedral feldspar phenocrysts and sparse biotite and hornblende phenocrysts set in a glassy groundmass. All phenocrysts are substantially smaller and less abundant than the phenocrysts of the typical dacitic rocks. Plagioclase phenocrysts (two modal percent) range in composition from calcic oligoclase to andesine. They are subhedral, lath-shaped, and average 0.4 millimeter in length. Apatite, hornblende, and biotite inclusions are common. Groundmass plagioclase crystals (20 to 30 modal percent) are also subhedral, lath-shaped, and average 0.05 millimeter in length. Sanidine phenocrysts (one modal percent) are approximately the same size and shape as the

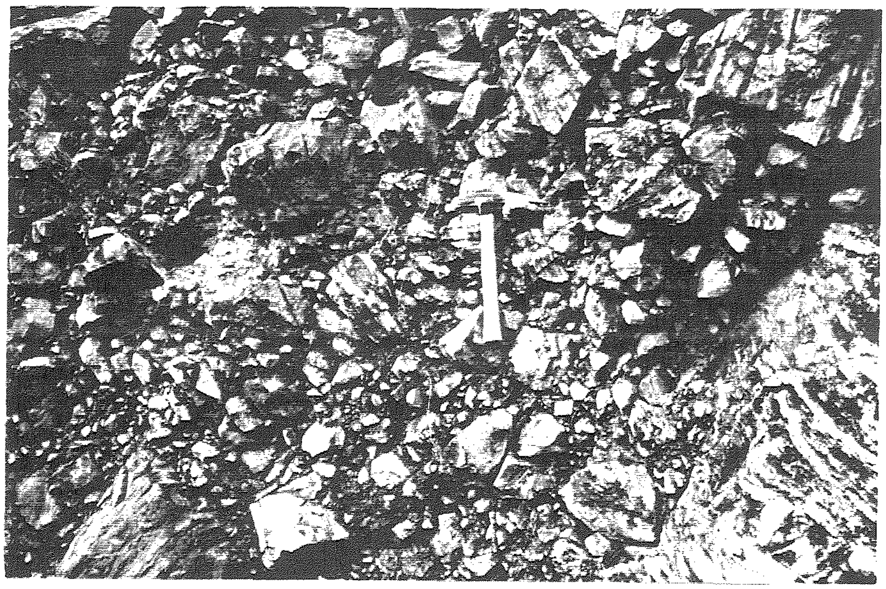


Figure 17.--Autobrecciated rhyolite flow.

plagioclase phenocrysts. Brown, euhedral to subhedral biotite crystals (one modal percent) and green, subhedral hornblende crystals (trace to two modal percent) occur within the groundmass and as phenocrysts. The phenocrysts average 0.1 millimeter across. Plagioclase and magnetite inclusions are common in the biotite crystals. Magnetite inclusions are common in the hornblende crystals. A chemical analysis of a hornblende phenocryst from the rhyolite flow is in table 13. Anhedral magnetite grains (0.5 modal percent) occur in the groundmass and average 0.05 millimeter across. The remainder of the rock is composed of a clear glassy groundmass that commonly contains small vesicles averaging 0.1 millimeter across. A chemical analysis of the glass from the rhyolite flow is given in table 14.

Chemistry and age

Two chemical analysis of the rhyolite flow are given in table 15. Using the classification scheme of Streckeisen (1979) based upon normative mineralogy, the flow and intrusive body both plot in the rhyolitic field.

The rhyolite flow is older than the Hackberry Mountain Dacite and younger than Member 6 of the Towel Creek Tuff. These two units have been dated (table 6) and they define an apparent age of 7.8 to 8.4 m.y. for the rhyolite flow.

Correlation

Twenter and Metzger (1963, p. 58) described rhyolite flows and intrusions in the southern Verde Valley which lies about 10 kilometers northwest of the westernmost rhyolite outcrop in the Hackberry Mountain area (figure 18). These rhyolite flows unconformably overlie the Verde Formation and the associated intrusive bodies intrude it. As the rhyolite flow exposed

Table 13.--Chemical analyses of hornblende phenocrysts in silicic rocks

[Analyses performed with MAC-5-SA3 electron microprobe using energy-dispersive method described by Albee and others (1980)]

Sample No.	RL-79-5	RL-79-80	RL-79-83
Major oxides (weight percent)			
Na_2O	1.86	1.09	0.98
MgO	13.20	15.06	15.10
Al_2O_3	10.62	6.44	6.70
SiO_2	45.73	48.38	50.41
Cl	0.08	0.08	0.05
K_2O	0.51	0.70	0.60
CaO	11.12	11.48	11.64
TiO_2	1.39	1.26	1.16
Cr_2O_3	0.08	0.06	0.07
MnO	0.32	0.54	0.53
FeO	14.45	12.19	13.15
Total	99.32	97.26	100.44

SAMPLE DESCRIPTIONS

RL-79-5	Rhyolite flow
RL-79-80	Groundmass of Member 2 of the Towel Creek Tuff
RL-79-83	Groundmass of Member 3 of the Towel Creek Tuff

Location of samples shown in plate 7.

Table 14.--Chemical analyses of glass from rhyolitic rocks

[Analyses performed with MAC-5-SA3 electron microprobe using energy-dispersive method described by Albee and others (1980)]

Sample No.	RL-79-5	RL-79-90	RL-79-94	RL-79-106
Major oxides (weight percent)				
Na_2O	1.74	2.52	2.24	1.60
MgO	0.00	0.00	0.00	0.00
Al_2O_3	11.80	12.17	12.11	12.07
SiO_2	80.18	77.11	76.27	75.48
P_2O_5	0.29	0.00	0.00	0.09
SO_3	0.02	0.00	0.00	0.00
Cl	0.04	0.00	0.11	0.06
K_2O	4.36	4.66	4.58	3.90
CaO	0.32	0.60	0.59	0.83
TiO_2	0.28	0.30	0.14	0.21
Cr_2O_3	0.00	0.00	0.02	0.01
MnO	0.04	0.15	0.00	0.02
FeO	0.66	0.47	0.56	0.57
NiO	0.13	0.00	0.02	0.00
Total	99.85	97.97	96.63	94.82

SAMPLE DESCRIPTIONS

RL-79-5	Rhyolite flow
RL-79-90	Rhyolitic plug
RL-79-94	Rhyolitic dike-shaped body from diatreme
RL-79-106	Silicic tuff-breccia matrix from diatreme

Location of samples shown in plate 7.

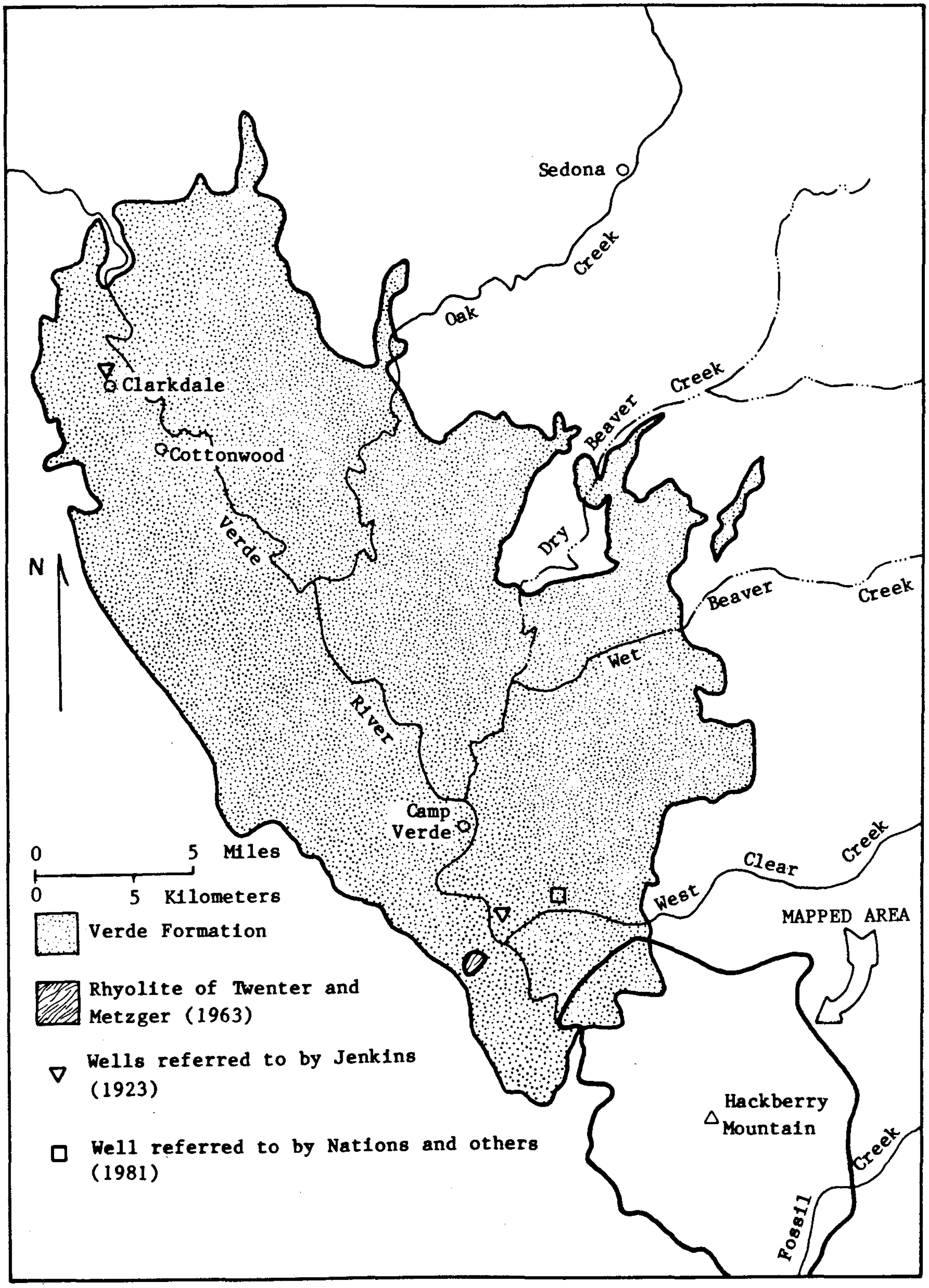
Table 15.--Major-element and normative compositions, in percent, of the rhyolitic rocks

Sample No.	[1]RL-79-5	[2]R (-)1-2	[3]RL-79-90	[3]RL-79-106
Major oxides (weight percent)				
SiO_2	71.7	71.1	72.79	66.88
Al_2O_3	14.1	14.2	13.87	14.71
Fe_2O_3	1.61	1.0	1.2	3.27
FeO		0.54		
MgO	0.52	0.6	0.5	0.9
CaO	1.89	2.0	1.22	2.66
Na_2O	3.1	3.3	3.87	3.61
K_2O	3.59	3.1	3.74	2.77
TiO_2	0.17	0.18	0.08	0.38
MnO	0.03	0.05	0.064	0.046
P_2O_5	<0.1	0.10	0.05	0.16
CO_2		<0.05		
H_2O+		2.29		
H_2O-		0.53		
[4]Loss	1.96			
Total	98.8	99.0	97.4	95.4
CIPW Norms[5]				
q	35.9	35.8	33.1	28.6
or	21.9	19.1	22.7	17.2
ab	27.1	29.0	33.6	32.1
an	9.0	9.6	5.9	12.8
c	2.0	2.1	1.4	1.4
hy	2.9	3.2	2.6	5.7
mt	0.6	0.5	0.4	1.0
il	0.3	0.4	0.2	0.8
ap	0.2	0.3	0.1	0.4

[1] Chemical analysis by x-ray fluorescence methods with all iron calculated as Fe_2O_3. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg.
[2] Chemical analysis from Scott (1974).
[3] Chemical analyses by x-ray fluorescence methods with all iron calculated as Fe_2O_3. Analyst: J. Ramage.
[1,3] Location of samples shown in plate 7.
[4] Loss on Ignition.
[5] All norms calculated with $FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).

RL-79-5	Rhyolite flow
R (-)1-2	Rhyolite flow
RL-79-90	Rhyolitic plug
RL-79-106	Tuff-breccia of rhyolitic diatreme

Figure 18.--Outcrop of the Verde Formation (modified from Wilson and others, 1969) and location of rhyolite flow described by Twenter and Metzger (1963, p. 58). Approximate position of wells cited by Jenkins (1923, p. 71) and Nations and others (1981, p. 134) depicted.


Sedona
Oak Creek
Clarkdale
Cottonwood
Verde River
Beaver Creek
Dry
Beaver Creek
Wet
Camp Verde
West Clear Creek
MAPPED AREA
Hackberry Mountain
Fossil Creek
N
0 5 Miles
0 5 Kilometers
Verde Formation
Rhyolite of Twenter and Metzger (1963)
Wells referred to by Jenkins (1923)
Well referred to by Nations and others (1981)

within the Hackberry Mountain area also overlies the Verde Formation at its westermost outcrop, the geographic proximity of the various rhyolites suggests that they are correlated. Although Twenter and Metzger assigned their rhyolite to the Pleistocene because it is younger than the Verde Formation which they (1963, p. 58) considered to be of Pliocene (?) or Pleistocene age, later work (Bressler and Butler, 1978) documents that the Verde accumulated during the Miocene and Pliocene epochs. The Verde at the rhyolite locality of Twenter and Metzger may be Miocene. It is possible that the rhyolitic rocks described by Twenter and Metzger could be the same age as those exposed in the Hackberry Mountain area.

Several small intrusive bodies of rhyolite were described by Canney and others (1967, p. J16) in the Pine Mountain area. These outcrops are about 20 kilometers south-southwest of Hackberry Mountain. They intrude granitic rocks of Precambrian age, and their relationship to the Tertiary units in that area is unknown. They were assigned a possible Quaternary age on the basis of their fresh appearance and a possible correlation with the rhyolitic rocks described by Twenter and Metzger (1963, p. 53). However, the rhyolitic rocks of the Pine Mountain area may also be correlative with the rhyolites of the Hackberry Mountain area.

Origin

All outcrops of the rhyolitic flow are assumed to be related and if the outcrops are indeed from one flow, it is at least 4.5 kilometers long and was extruded upon a surface that sloped 4° west. The most likely vent for this flow is the rhyolitic diatreme which intrudes the Sally May Dacite stock. The rhyolite in the diatreme is petrographically similar to that of the flow, and both are of the same approximate age. If the diatreme was the source, the flow extends for nearly eight kilometers, longer than any other silicic flow previously reported (Williams and McBirney, 1979. p. 99).

Hackberry Mountain Dacite

Distribution

The name Hackberry Mountain Dacite is used for the rocks exposed on the summit of Hackberry Mountain. This formation consists primarily of a dacite flow that caps all the high peaks in the central and south-central parts of area--Hackberry Mountain, the Towel Peaks, the Buzzard Peaks, and Buckskin (hill 5296). The basal part of the flow is typically brecciated, and where the breccia is particularly thick, beneath Hackberry Mountain and The Rocks, it was mapped separately. A large associated dike occurs along the crest of the Buzzard Peaks, and an associated plug occurs along Sally May Wash near Fossil Creek. Scott (1974) originally recognized the Hackberry Mountain Dacite, and he identified most of its outcrops.

The name Hackberry Mountain Dacite was used previously to denote all the dacitic rocks contained within their Thirteenmile Rock Volcanics (Elston, Scott, McKee, and Gray, 1974, p. 607; Scott, 1974, p. 12). However, their dacite unit has been divided in this report into three separate dacitic formations--the Towel Creek Tuff, the Sally May Dacite, and the Hackberry Mountain Dacite.

Stratigraphic relations

The flow of the Hackberry Mountain Dacite unconformably overlies all rocks beneath it except for a rubble unit and a rhyolite flow. The dacite flow overlies progressively older units in outcrops to the west of Hackberry Mountain. In this area the flow was emplaced upon the extensively eroded western flank of the Hackberry volcano; a surface with greater than 350 meters of relief. The dacite flow atop Buckskin (hill 5296) overlies the same units as those exposed on the northern flank of Hackberry Mountain. This relationship indicates that a relatively minor amount of erosion occurred north of Hackberry Mountain prior to the extrusion of the dacite, in contrast to the area west of the mountain. Because the rhyolite flow was also extruded upon an erosion surface inclined to the west, the contact between it and the overlying flow of Hackberry Mountain Dacite is believed to be concordant. The flat-lying rubble unit also was deposited upon an erosion surface and its contact with the overlying Hackberry Mountain Dacite is believed to be structurally concordant.

At most localities the Hackberry Mountain Dacite is the highest volcanic unit. At the eastern end of the Towel Peaks, however, it is overlain by Member 4 of the Thirteenmile Rock Basalt. The two flows appears to be structurally concordant. Mafic dikes assigned to Member 4 also intrude the brecciated base of the dacite flow atop Hackberry Mountain.

A large vertical dike intrudes the Sally May Dacite and the Hackberry Mountain Dacite along the crest of the Buzzard Peaks, and a rectangular plug of unaltered dacite intrudes the altered Sally May Dacite along Sally May Wash near Fossil Creek. The plug has vertical contacts and locally is brecciated at the contact. Well developed horizontal and vertical joints are present. Both of these intrusive bodies have been assigned to the Hackberry Mountain Dacite.

Thickness and lithology

Along the western Towel Peaks the Hackberry Mountain Dacite is a single flow unit up to 320 meters thick; it pinches out between a very thick section of the rubble unit and overlying Thirteenmile Rock Basalt at the eastern end of the Towel Peaks. At Hackberry Mountain the unit consists of two separate flows both 70 meters thick.

These flows are composed of the massive dacite described on pages 159-164. The basal parts of the flows north of Towel Creek are commonly autobrecciated. The breccia typically contains subangular dacite blocks up to five meters across set in a groundmass of comminuted dacite. The massive part of the flow generally has well developed columnar joints which extend, in places, into the brecciated portion below.

Along the northern margin of Hackberry Mountain, the Hackberry Mountain Dacite flow is underlain by a poorly exposed dacitic air-fall tuff. This tuff has well developed beds parallel to the overlying dacite flow. The tuff is composed of pink lithic dacite lapilli and ash-size fragments. No pumiceous lapilli are present. Another dacite air-fall tuff separates the two flow units on Hackberry Mountain; this tuff is exposed at the southeastern margin of Hackberry Mountain and pinches out towards the northwest. This tuff consists of subangular lithic dacite lapilli set in an ash-size groundmass. Some of the lapilli are hydrothermally altered. The tuff has poorly developed northwest dipping beds that are expressed by contrasts in the abundances of the lithic lapilli. Bomb sags occur beneath some of the larger dacitic blocks. This tuff also contains no dacitic pumiceous lapilli.

The large dacite dike exposed along the crest of the Buzzard Peaks resembles, in hand specimen, the rhyolitic rocks of the area. It is bluish-white, is finer-grained than the typical dacite, and has well developed flow bands that are vertical and strike parallel to the long axis of the dike. However, its chemical composition (sample RL-80-10 of table 16) plots in the dacitic field of Streckeisen (1979) and it was was assigned to the Hackberry Mountain Dacite. The dike is resistant and protrudes above the adjoining dacite flow.

Chemistry, age, and correlation

Chemical analyses of the Hackberry Mountain Dacite are given in table 16. The normative mineralogy for the three rocks plot within the dacitic field of Streckeisen (1979, p. 332).

A potassium-argon age for the flow of the Hackberry Mountain Dacite has been determined for a sample obtained from the summit of Hackberry Mountain; it is 8.3 ± 0.5 m.y. old (table 17). The range in age can be further limited to 7.8 to 8.4 m.y. on the basis of stratigraphically lower units that have been dated previously by McKee and Elston (1980).

The Hackberry Mountain Dacite is not exposed outside of the Hackberry Mountain area. Little pyroclastic material is associated with this formation, and it is doubtful that any silicic tuffs occurring within the Verde Formation or found elsewhere are correlative with the Hackberry Mountain Dacite.

Source

The dip of the two flows on Hackberry Mountain suggests that the conduit for these flows is exposed to the southeast, probably in the adjacent area now covered by recent landslide deposits. The presence of altered dacitic lapilli in the intercalated tuff suggest that the vent may have penetrated the Sally May Dacite.

The rocks exposed below the flow on Buckskin are not structurally disturbed, and there is no evidence that the vent for this flow occurs beneath it. The outcrops atop Hackberry Mountain and Buckskin may be

Table 16.--Major-element and normative compositions, in percent, of the Hackberry Mountain Dacite

[Chemical analyses by x-ray fluorescence methods]

Sample No.	[1]RL-79-74	[1]RL-79-50	[2]RL-80-10
Major oxides (weight percent)			
SiO_2	68.3	63.7	68.95
Al_2O_3	14.7	15.4	14.59
[3]Fe_2O_3	3.36	3.69	2.78
MgO	0.55	1.9	1.3
CaO	3.08	3.47	2.55
Na_2O	3.3	3.3	3.74
K_2O	2.82	2.59	2.63
TiO_2	0.42	0.46	0.28
MnO	<0.02	0.06	0.052
P_2O_5	0.4	0.3	0.08
CO_2			
[4]Loss	1.24	3.35	
Total	98.2	98.2	97.0
CIPW Norms[5]			
q	31.6	24.8	29.7
or	17.2	16.2	16.1
ab	28.9	29.5	32.7
an	13.1	16.1	12.5
c	1.6	1.7	1.2
hy	4.6	8.9	6.2
mt	1.1	1.1	0.9
il	0.8	0.9	0.5
ap	1.0	0.8	0.2

[1] Analysts: J. Baker, J. Taggart, and J.S. Wahlberg.
[2] Analyst: S. Ramage
[3] All iron as Fe_2O_3.
[4] Loss on ignition.
[5] All norms calculated with $FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).

SAMPLE DESCRIPTIONS

RL-79-74	Flow atop Hackberry Mountain
RL-79-50	Flow atop Towel Peaks
RL-80-10	Dike along crest of Buzzard Peaks

See plate 7 for sample localities.

Table 17.--Potassium-argon age determination of the Hackberry Mountain Dacite

[Potassium-argon analysis by E.H. McKee]

Sample Number	Mineral dated	K_2O	$^{40}Ar^*$	$^{40}Ar^*/^{40}Ar\ \Sigma$	Apparent Age m.y. ± σ
RL-81-76	Hornblende	0.913%	1.08655×10^{-11}	12.6%	8.3 ± 0.5

$^{40}K/K\ \Sigma = 1.167 \times 10^{-4}$ g/g; $\lambda_\varepsilon = 0.572 \times 10^{-10}\ yr^{-1}$; $\lambda_\beta = 4.963 \times 10^{-10}\ yr^{-1}$

Sample location is shown in plate 7.

remnants of the same flow. If this is true, this flow would have traveled nearly five kilometers down a gradient of about 3°. Although this is a fairly great distance for a siliceous, glass-rich flow to travel, slightly greater distances, up to 5.5 kilometers, have been reported elsewhere for similar flows (Anderson, 1941, p. 375-376).

The source of the flow that caps the Towel Peaks is problematical. There are no intrusive bodies of dacite adjacent to the flow, but many intrusive bodies of dacite crop out in the Gospel Hollow area. These bodies are primarily large dikes that are parallel to the crest of the Towel Peaks. As these dikes are similar in lithology and chemistry to the dacite flow (table 20), they may have been conduits for the flow. The dacite at The Rocks is intrusive at the northwestern part of outcrop and extrusive at the southeastern part.

Verde Formation

The Verde Formation was named by Jenkins (1923) for a sequence of lacustrine deposits with minor amounts of fluviatile deposits confined to the Verde Valley. According to Twenter and Metzger (1963, p. 46), the Verde Formation underlies a generally elliptical area of about 340 square kilometers with the northwest-trending axis of deposit about 55 kilometers long and subparallel to the Verde River (figure 18). The Verde Formation was deposited in an ancient valley whose boundaries were very close to those of the present Verde Valley. These boundaries are the Mogollon Rim to the north and east, the Black Hills to the west, and the volcanic rocks of the Hackberry Mountain area to the south. Outcrops of the Verde Formation in the area mapped are confined primarily to Cottonwood Basin. This area contains the southeasternmost exposures of the Verde Formation. However, several thin beds of Verde intercalated with the basalt flows of the Hickey Formation and Thirteenmile Rock Basalt occur farther south. They are exposed in discontinuous outcrops along the Verde River from Cottonwood Basin south to Bull Run Creek.

Topographic expression

The Verde Formation consists of easily eroded beds; its largest area of outcrop in Cottonwood Basin is one of low relief. Within Cottonwood Basin the surfaces cut on the Verde are generally flat and featureless and are commonly mantled by pebbles and cobbles of mafic volcanic rocks derived from sources to the south and east. The best exposures are along the foors of small canyons within Cottonwood Basin. Cliffs of the Verde Formation occur along the northern boundary of Cottonwood Basin where the Verde is capped by the gravel deposit atop Wingfield Mesa. The formation also crops out along the Verde River, where the Verde beds are interstratified with basalt flows of the Hickey Formation and Thirteenmile Rock Basalt.

Thickness

Jenkins (1923, p. 71) obtained two minimum estimates for the thickness of the Verde Formation by combining logs of wells (figure 18) and exposed stratigraphic sections above each well head. Near Clarkdale the estimated thickness is 425 meters, and south of Camp Verde the estimated thickness is 610 meters. Mahard (1949, p. 104) measured an exposed section of 230 meters of the Verde Formation near Clarkdale and another section of 315 meters near where Highway 89A crosses the Verde River. Nations and others (1981, p. 134) reported a minimum thickness for the Verde Formation of 956 meters. This was obtained by taking the difference between the highest exposure of the Verde Formation reported by Twenter and Metzger (1963, p. 55) and the lowest reported occurrence of the formation in the Arizona Verde Oil Well No. 1 (see figure 18 for well location).

The Verde Formation is at least 185 meters thick in the Hackberry Mountain area. This thickness includes the Verde exposed in Cottonwood Basin plus tongues within the basaltic rocks along the Verde River to the south.

The highest preserved deposits of the Verde Formation are 1530 meters above sea level (Nations and others, 1981, p. 133). Probably the Verde Formation was deposited to this level within the area mapped, but the highest preserved beds are at 1160 meters above sea level. The highest preserved outcrop consists of beds of marl adjacent to the Verde River that is overlain by the rhyolite flow. This outcrop was recognized by Elston and Scott (1973b).

Stratigraphic relations

The lowest beds of the Verde Formation intertongue with the volcanic rocks of the Hickey Formation, the Towel Creek Tuff, and the Thirteenmile Rock Basalt. The lowest recognized tongue, which occurs between Member 4 of the Towel Creek Tuff and Member 15 of the Hickey Formation, is exposed along Sycamore Canyon, 2.5 kilometers upstream from the Verde River. Another tongue occurs within Member 15 of the Hickey Formation along the Verde River near The Grotto. This tongue occurs stratigraphically above Member 1 of the Cimarron Hills Andesite. Tongues of the Verde within basalt flows of Member 1 of the Thirteenmile Rock Basalt and Member 15 of the Hickey Formation are exposured along the Verde River adjacent to Cottonwood Basin. Member 6 of the Towel Creek Tuff extends as a tongue into the Verde Formation along the eastern margin of Cottonwood Basin. A small tongue of Verde occurs between Member 1 of the Thirteenmile Rock Basalt and the overlying rhyolite flow along the Verde River north of Bull Run Creek.

Lithology

The Verde Formation in the area mapped consists of two distinct lithologic units. The contact between the two is gradational, however, and they were not differentiated in the geologic map.

Basal unit--The basal unit comprises 120 of the 185 meters of the exposed Verde. It consists of conglomeratic sandstone interbedded with finer-grained sandstone. The beds vary substantially in thickness, from two millimeters to greater than four meters. The thicker the bed, the coarser the material contained within it. The thinner beds contain concentrations of granule sized particles while the thicker beds contain concentrations of larger clasts, pebble size and larger. Well developed planar cross-beds characteristic of a fluviatile environment are common in the finer-grained sandstones; the cross-sets average five centimeters thick. Cut-and-fill structures are also common in both the conglomeratic and finer-grained sandstones.

These beds are typically very poorly sorted with the constituents ranging from silt to boulder size. The constituents can be divided into two size groups: 1) the coarse clasts, which range from granule to boulder size; 2) the matrix which ranges from silt to very coarse sand size. The coarse clasts are subrounded and average pebble size. In general, about 85 percent of these clasts are mafic volcanic rocks; the remainder consists primarily of dacite lithic clasts and sparse dacite pumice and clasts of basic xenoliths. Locally, dacite pumice accounts for up to 80 percent of all coarse clasts; the abundance of pumice diminishes towards the northwest. Most clasts are derived from readily recognized flows and tuffs exposed in the Hackberry Mountain area.

The matrix in all beds is similar and constitutes from 85 to 100 percent of their volume. It consists predominantly of plagioclase grains, subordinate lithic grains, and sparse olivine, pyroxene, hornblende, and biotite grains.

Upper Unit--The upper unit, exposed on the southwestern flank of Wingfield Mesa, consists primarily of mudstone and subordinate siltstone, gypsum, limestone, sandstone, and claystone. Most individual beds are buff or white. The gypsum beds contain coarse selenite crystals. This unit contains well developed thin beds and laminae which, in conjunction with the presence of gypsum and limestone beds, indicates depostion in a lacustrine environment.

This unit also contains a glass-rich silicic tuff bed described previously by Twenter and Metzger (1963, p. 53-54) and used by Bressler and Butler (1978, p. 324) for correlation of their paleomagnetic section measured in Cottonwood Basin with another measured near West Clear Creek. The tuff is about 6 m.y. old (Bressler and Butler, 1978, p. 324). It is doubtful that it was derived from the Hackberry Mountain volcano because it is younger than any silicic rocks exposed in that area.

Age

Jenkins (1923, p. 76-77) recognized that the Verde Formation was of Cenozoic age and assigned it to the very late Tertiary or early Pleistocene based upon structural and lithologic evidence. Mahard (1949, p. 126) considered the Verde Formation to be the same age or younger than igneous activity associated with the San Francisco Mountain area to the north.

This activity was believed by Robinson (1913) to be of late Pliocene or Pleistocene age. Anderson and Creasey (1958, p. 60-61) and Lehner (1958, p. 561-563) assigned the Verde Formation a probable Pliocene or Pleistocene age. Their assignment was based primarily upon stratigraphic relations between the Verde and Hickey Formations in the areas studied by them. Based on fossil elephant tracks Brady and Seff (1959) suggested that the Verde is of late Tertiary or early Pleistocene age. Taylor (1966) restricted the age of the Verde to Blancan (late Pliocene - early Pleistocene), and he suggested that it is probably early Pleistocene on the basis of the similarity of mollusk fossils in the Verde Formation with those found near Benson, Arizona. Nations (1974) determined from invertebrate fossils exposed in the upper one-third of the Verde Formation that it is late Pliocene to late Pleistocene in age.

McKee and Anderson (1971, p. 2773) obtained potassium-argon ages for two separate basalt flows found within the Verde Formation. One was from a flow described by Lehner (1958, p. 559). It is exposed in Sycamore Creek and has an apparent age of 4.5 ± 0.2 m.y. The other basalt was described by Mahard (1949, p. 108). It is exposed 13 kilometers north of Camp Verde and has an apparent age of 5.5 ± 0.2 m.y. On the basis of these two ages, McKee and Anderson (1971, p. 2773) considered the Verde Formation to be of Pliocene age.

Bressler and Butler (1978), in a magnetostratigraphic study of the Verde Formation, sampled a fairly complete composite section of the unit, including one section from Cottonwood Basin. Using the potassium-argon ages determined by McKee and Anderson (1971, p. 2773), they were able to correlate their magnetostratigraphic section with the sea floor records of Talwani and others (1971), Opdyke (1972), Opdyke and others (1974), and McDougall and others (1977). Their best correlation was with the sections of Opdyke (1972) and Opdyke and others (1974). The upper age of the Verde Formation for the beds sampled, based on a correlation with all the time scales, is 3.1 m.y. However, Bressler and Butler did not sample the upper 56 meters of their composite section. They estimated an upper age for the Verde of 2.5 m.y. based on an extrapolation of their calculated sedimentation rate. The lower age of the Verde Formation for the beds sampled ranges from 8.0 to 7.2 m.y. depending upon the polarity time scale used. The oldest beds were sampled in Cottonwood Basin. However, Bressler and Butler (1978) did not sample the basal sandstone unit within Cottonwood Basin which is about 125 meters thick.

The stratigraphically lowest outcrop of Verde Formation recognized within the Hackberry Mountain area occurs between Member 4 of the Towel Creek Tuff and the overlying Member 15 of the Hickey Formation. From the age data of McKee and Elston (1980) (table 6) this outcrop has an age of 7.8 to 9.6 m.y. Therefore, the Verde Formation accumulated from at least 7.8 to about 2.5 m.y. ago and is of Miocene and Pliocene age. Bressler and Butler (1978) sampled a section of the Verde Formation exposed within Cottonwood Basin. Correlation of this section with the sea floor records indicates that the youngest Verde sediments exposed in the mapped area, the upper unit, are approximately 6 m.y. old. Thus, the Verde Formation exposed in the Hackberry Mountain area is restricted to the Miocene.

SURFICIAL DEPOSITS

The surficial deposits consist of alluvial, landslide, colluvial, and travertine deposits that unconformably overlie the Tertiary and pre-Tertiary units. These deposits, particularly landslides, cover a major portion of the Hackberry Mountain area. They have all been assigned a Quaternary age except for the older gravel unit which could possibly be Pliocene.

Older Gravels

Terrace deposits of older gravels occur in the north-central and central parts of the Hackberry Mountain area at elevations greater than 1220 meters above sea level. Most of these deposits cap ridges between Fossil Creek Road and Sycamore Canyon. Two other deposits of older gravel occur three kilometers north and two kilometers northwest of Hackberry Mountain. Excellent sections of the gravels are exposed in road cuts along Forest Highway 9 (figure 19). The gravels generally occur 170 meters above the present stream floors. The deposits average 25 meters thick and reach a maximum of 45 meters; the thickest deposits occur along Sycamore Canyon. The gravel deposits contain about equal amounts of coarse clasts and sand matrix. Coarse clasts are subrounded to rounded and range from granule to boulder size.

The gravels are derived from local sources. Most clasts are basaltic, but some are andesite. North and northwest of Hackberry Mountain the older gravels contain some dacite clasts that were probably derived from the Hackberry Mountain Dacite. Minor rhyolite clasts derived from the rhyolite flow are also found in the gravels northwest of Hackberry Mountain. The other deposits contain sparse silicic tuffaceous clasts that were

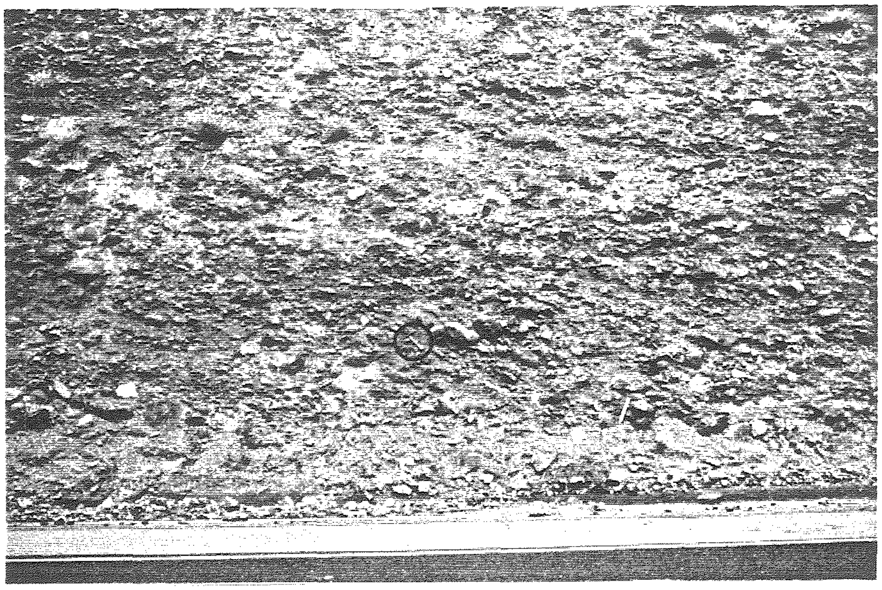


Figure 19.--Older gravel exposed in roadcut along Forest Highway 9. Hammer is circled for scale. View north.

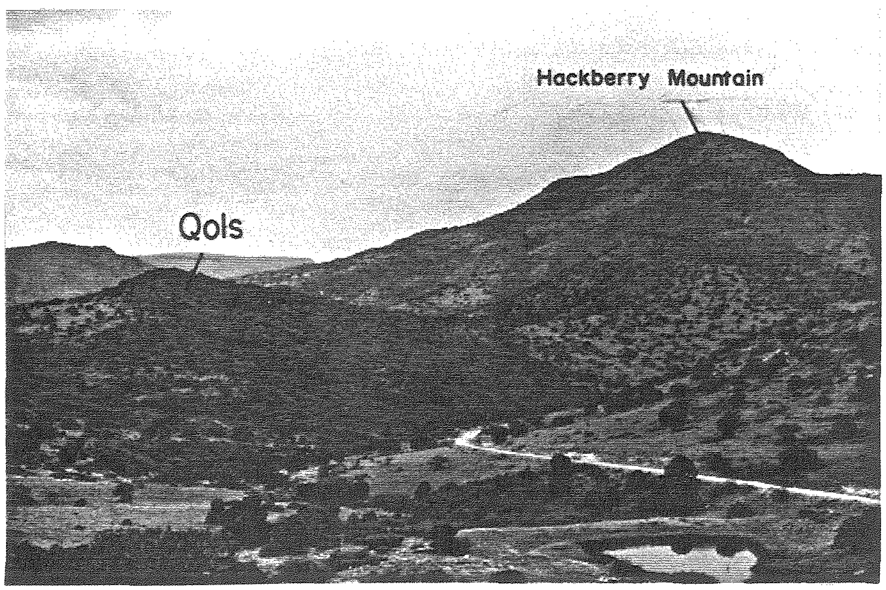


Figure 20.--Hills capped by deposits of older landslides (Qols) that form southern boundary of Hackberry Basin. Cimarron Tank and Fossil Creek Road are in the foreground. View west.

probably derived from Member 7 of the Towel Creek Tuff. The gravels are indurated by calcite. The direction of transport of clasts indicates that the gravels were deposited by streams following a drainage pattern similar to that of the present.

The older gravels accumulated after eruption of the youngest volcanic rocks prior to a major episode of denudation that occurred after the cessation of volcanic activity. They typically contain much more caliche than all other surficial deposits. Here they are tenatively assigned to Pliocene or Pleistocene.

Terrace Gravels of the Verde River

Terrace gravels along the Verde River and most of its tributaries occur at four discrete ranges of height above stream level (table 18). Their relative heights do not change systematically along the course of the Verde River. Level 3 terrace gravels cap Wingfield Mesa and are scattered as far south as the Childs powerplant. Level 2 terraces occur only near the Verde Hot Springs and Childs powerlant. Level 1 terraces are continuous along the Verde River in the study area mapped and also occur along the principal tributaries to the Verde River, including those that drain Gospel Hollow and Cottonwood Basin. Level 0 terraces occur along the west side of the Verde River about 1.5 kilometers southeast of Brown Springs and occur along the east side of the Verde River 1.9 to 3.3 kilometers northwest above the Verde Hot Springs.

The deposits at all levels rest on Miocene or Devonian rocks and are overlain by landslide and colluvial deposits. Gravel deposits from all levels range from about three to 10 meters thick.

All these gravels contain rounded to subrounded clasts in a sand to

Table 18.--Height of the Terrace Gravels of the Verde River

Terrace Level	Height of base of deposit above Verde River floodplain (in meters)
0	3 to 10
1	15 to 22
2	30 to 45
3	60 and greater

silt size matrix. The matrix is typically unconsolidated except where caliche has been deposited. Caliche is rare and best developed in a Level 3 gravel located northwest of Gospel Hollow. There are no consistent lithologic differences between gravel deposits from different levels. The clasts in the gravels exposed along the Verde River are primarily of volcanic origin. A subordinate number of clasts (less than one-third) is derived from crystalline rocks of Precambrian age, primarily a quartz diorite exposed beneath Squaw Peak. A few clasts of Paleozoic sedimentary rocks, primarily chert, are also present. The upper levels of the gravel deposits are generally slightly richer in clasts of non-volcanic origin. The abundance of non-volcanic rock clasts in the gravel deposits of all levels decreases progressively downstream. Gravels exposed along tributaries to the Verde River contain only volcanic rock clasts.

Terrace gravels of all levels along the Verde River are younger than all faults and older than recent landslide, alluvial, and colluvial deposits. Twenter and Metgzer (1963) assigned a Pleistocene age to the gravel exposed atop Wingfield Mesa (Level 3 of this report). Bones of a late Pleistocene mammoth were found by Lance (oral commun. to Peirce and Roseveare, 1962, p. 42) in a terrace deposit along the Verde River within the Verde Valley, but the level at which these bones were found is not known. All levels of these gravels are here tenatively assigned a Pleistocene age.

Barsch and Royse (1972, p. 69) in a study of the terrace deposits within the Tonto Basin to the southeast suggest that a similar sequence of terrace gravels occurs throughout the Southwestern United States; their occurrence is independent of the tectonic regime in which the terraces formed. Therefore, the different levels are the result of climactic changes which are probably related to glacial and interglacial periods. The gravels were deposited during glacial periods and were dissected during interglacial periods.

Terrace Gravels of Fossil Creek

Terrace gravels along Fossil Creek and its tributary, Boulder Canyon, have been informally divided into two map units according to their height above the stream level. The base of the Level 1 deposits are three to 10 meters above stream level, and the base of the Level 2 deposits are 10 meters or more above stream level. The Level 1 deposits are much more extensive than those of Level 2. Those assigned to Level 2 occur only along the northern side of Fossil Creek near its intersection with Boulder Canyon. Other than height above stream level, there are no apparent differences between the deposits of the two levels. Deposits of both levels are overlain by recent landslide deposits, and Level 1 gravel is locally overlain by an older landslide deposit. Both levels of the gravel deposits are assigned a tentative Pleistocene age. The terrace gravels of Level 1 on Fossil Creek may be correlative with Level 1 of the terrace gravels of the Verde River.

Terrace Gravels of Hackberry Basin

Several large deposits of terrace gravels occur in Hackberry Basin. These deposits are three to 10 meters thick and occur about 10 meters above the drainage floors of Hackberry Basin. These gravels contain subrounded to rounded pebbles or cobbles of locally derived volcanic rocks in an unconsolidated matrix of silt and sand. They have been tentatively assigned to the Pleistocene. The gravel deposits of Hackberry

Basin are possibly correlative with Level 1 of the terrace gravels of the Verde River.

Older landslide deposits

Extensive old landslides overlie parts of the altered Sally May Dacite. They cap a chain of hills that link Hackberry Mountain with the Cimarron Hills (figure 20). Another old slide occurs along the west side of Boulder Canyon just north of Fossil Creek. Preserved remnants of these slides are up to 30 meters thick. They rest chiefly on the Sally May Dacite and the Hackberry Basin Member of the Towel Creek Tuff. The slide in Boulder Canyon also rests on Level 1 of the Terrace Gravels of Fossil Creek. The older landslide deposits are overlain by a recent landslide deposit near Cimarron Saddle.

The older landslide deposits are composed primarily of dacitic clasts, both fresh and altered, with minor amounts of mafic volcanic clasts and sparse yellow clasts of opal. The altered dacitic clasts are derived chiefly from the Sally May Dacite, and unaltered dacitic clasts are probably derived chiefly from the Sally May Dacite and secondarily from the Hackberry Mountain Dacite. The mafic volcanic clasts are primarily basalt and most are derived from Member 4 of the Thirteenmile Rock Basalt. Some clasts of andesite were derived from Member 2 and/or Member 3 of the Cimarron Hills Andesite. The presence of these mafic clasts indicates that basalt and andesite flows once overlapped the Sally May Dacite stock. All the clasts are subrounded and range from granule to boulder size. The average dacite clast is cobble size, and the average mafic clast is pebble size. About one-quarter to one-half of these deposits consists of a buff to brown, well-indurated massive matrix composed of silt to medium sand.

Older landslide deposits have been tenatively assigned to the Pleistocene because of the erosion of their source area. At least 240 meters of Sally May Dacite has been eroded since the accumulation of these slides.

The topographic expression and composition of these deposits indicate that they slid down from an area of high relief that was underlain primarily by dacitic rocks and lesser amounts of mafic volcanic rocks. This area was located over the central part of the altered Sally May Dacite. The relief has now been inverted and the remaining topographic highs are mantled by the older landslide deposits, which are more resistant to erosion than the altered dacite.

Older alluvium

The older alluvium consists of one small exposure at the eastern end of Towel Creek that rests upon the altered Sally May Dacite and is overlain by recent landslide deposits. The upstream boundary of this exposure is a steep slope that descends to Sally May Wash which indicates that the source for this older alluvium, the altered Sally May Dacite, was removed by erosion, and the upper drainage of Towel Creek was captured by the Sally May Wash. The older alluvium is composed of poorly indurated, buff to brown, silt and sand size particles. This unit has been assigned the same age as the older landslide deposit, Pleistocene, because of similar stratigraphic and physiographic relationships.

Younger landslide deposits

Relatively young landslide deposits cover a major part of the Hackberry Mountain area. Large slides occur on the southern flank of Hackberry Mountain, on the northern and southern slopes of the Towel Peaks, on the western and eastern slopes of the Buzzard Peaks and Ike's Backbone, along the western slopes of Deadman Mesa, and on the slopes south and west of Ed's Point. A few smaller slides occur along Sycamore Canyon and its tributaries.

These deposits are characterized by hummocky, irregular topography. Smooth slope-covering surficial deposits were mapped as colluvium. However, colluvial deposits contiguous to landslide deposits were not broken out and mapped separately.

Most of the landslides are of the slump or Toreva block type. A notable example occurs on the southwestern slope of the Towel Peaks about 5 kilometers northwest of the Verde Hot Springs. Above this slide is an arcuate slip face about 110 meters high beneath which there is a relatively flat, boulderstrewn surface. The surface of this slide has many small closed depressions separated by thin, linear ridges arranged parallel to the scarp. The surface immediately below the slip face is rotated so that it dips slightly towards the scarp. Lower on the slide there are numerous irregularly shaped hills.

A notable example of a rock slide occurs on the southern side of Hackberry Mountain (figure 21). The deposit consists of numerous coherent blocks of dacite at least as large as 100 meters high and 200 meters across. Between these blocks is a boulder-strewn hummocky to smooth slope.

The landslide deposits commonly have a complex history; there is evidence in many slides of several generations of displacement. Sliding has evidently occurred intermittently during the Pleistocene and has

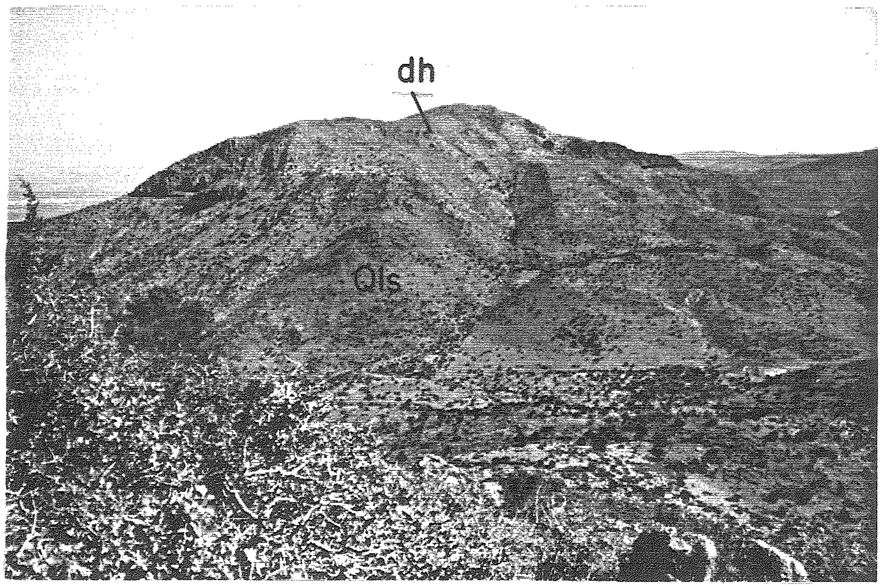


Figure 21.--View of southern side of Hackberry Mountain. Slopes beneath mountain are composed of younger landslide deposits (Qls) of rock slide type. dh - Hackberry Mountain Dacite

extended, locally, into the Holocene. Many slides extend to the present stream levels. Small scattered landslides in the northeastern part of the area mapped occur along steep canyons where basalt and andesite flows are underlain by less resistant mafic pyroclastic rocks.

Travertine

Small deposits of travertine are common along the banks of the Verde River. Only the larger deposits are shown on the geologic map. One is located 2.5 kilometers northwest and the other 450 meters east of the Verde Hot Springs on the eastern bank of the Verde River. Both deposits are one to three meters thick and overlie Level 1 of the terrace gravels of the Verde River. The deposit east of the Verde Hot Springs also overlaps a basalt flow assigned to Member 4 of the Hickey Formation. A small travertine deposit described by Feth and Hem (1963, p. H15) occurs on the western bank of the Verde River at the Verde Hot Springs. This deposit also rests on Member 4 of the Hickey Formation and may be related to the larger deposit on the eastern bank. As the travertine deposits overlie Level 1 terrace gravels of the Verde River, they are either very late Pleistocene or probably Holocene in age.

The travertine deposits consist of resistant, cream-colored, extremely porous limestone. These deposits are properly classified as calcareous tufa and not travertine because they are so porous and form at the surface (Pettijohn, 1975, p. 357-358). However, the term travertine will be retained because it was used by other authors who have studied these deposits (Feth and Hem, 1963, p. H15-H17, H44-H45; Scott, 1974).

Travertine deposits are common in central Arizona. Active travertine deposition is occurring at Fossil Springs, 15 kilometers northeast of the

Verde Hot Springs (Feth and Hem, 1963, p. H15). It is also occurring along the west bank of the Verde River just north of its confluence with Gap Creek (Scott, oral commun., 1982).

Colluvium

Colluvial deposits occur throughout the Hackberry Mountain area. Only those deposits that are large and cover areas of unknown bedrock geology were mapped. Those mapped occur along the Verde River near Gospel Hollow, within Gospel Hollow, within Brushy Prong, west of Hackberry Mountain, and along the northern boundary of Hackberry Basin. Most colluvial deposits form boulder strewn, slightly dissected slopes. Deposits mapped are at least three meters thick and some are much thicker. Some colluvial deposits overlie Level 1 of the Verde River terrace gravels. They probably range from late Pleistocene to Holocene in age.

Alluvium

Alluvial deposits occur within most stream channels in the Hackberry Mountain area. All deposits that occur along the the Verde River and Fossil Creek were mapped. Those deposits within the other drainages wider than 40 meters were also mapped.

INTRUSIVE ROCKS

The Hackberry Mountain area contains many intrusive volcanic rocks, primarily small dikes and plugs that were conduits for the numerous flows in the region. In this section of the report, intrusive rocks not directly associated with extrusive deposits are described. These intrusive rocks include the Sally May Dacite stock, dacitic plugs and dikes of unknown age, a rhyolite diatreme, and a rhyolite plug. This section of the report also contains a petrographic description of the dacitic rocks and the basic xenoliths that occur within them.

Sally May Dacite

Distribution and topographic expression

The drainage basin of Sally May Wash is underlain almost entirely by an altered stock of dacite, here named the Sally May Dacite. This stock is exposed over an area of about 20 square kilometers bounded on the east by landslide deposits below Ed's Point and Deadman Mesa, on the south by landslide deposits below the Buzzard and Towel Peaks, on the west by landslide deposits below Hackberry Mountain and the Towel Peaks, and on the northeast by Doren's Defeat Canyon. A few smaller exposures of the dacite are surrounded by landslide deposits south of the Towel Peaks and Hackberry Mountain. Several dacite plugs exposed within Hackberry Basin are also assigned to this unit.

The Sally May Dacite is very resistant and forms spires and peaks within Hackberry Basin and in the northern Cimarron Hills. In Hackberry Basin the dacite occurs as plugs intruded into the less-resistant pyroclastic rocks of the Towel Creek Tuff (see figure 22). The large exposure of altered dacite located in the drainage basin of the Sally May Wash,

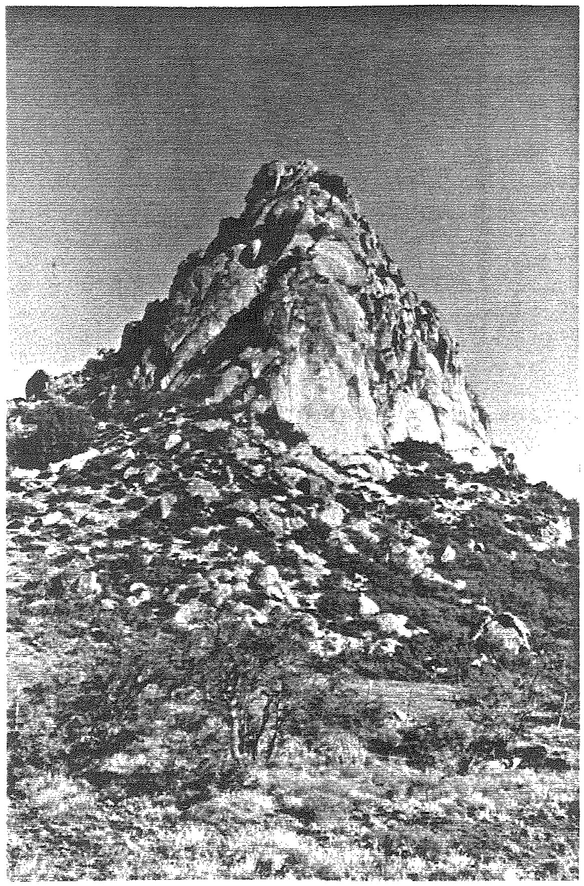


Figure 22.--Needle Rock, a dacitic plug assigned to the Sally May Dacite. This unaltered plug intrudes the Hackberry Basin Member of the Towel Creek Tuff just north of Hackberry Springs. View northwest.

on the other hand, is a topographically low area dissected by many canyons (figure 23).

Size and relation to other rocks

The Sally May Dacite consists primarily of one large intrusive body or stock. Most of the contact of the stock is covered by landslide deposits and its exact size and shape can only be estimated. The position of the concealed boundary of the Sally May Dacite, shown in plate 1, is based upon the location of the exposed contacts, the distribution of altered dacite clasts within the landslide deposits, and the location of apophyses of the intrusive body. At the surface the stock is roughly circular and seven to 8.5 kilometers across. Exposures of the stock are distributed over at least 600 meters of relief.

The Sally May Dacite stock is in intrusive contact with the Hackberry Basin Member of the Towel Creek Tuff and Member 1 of the Cimarron Hills Andesite. These rocks were deformed by intrusion of the dacite. Bedded units next to the stock dip away from it at angles of 25 to 70°. Commonly the intrusive dacite is brecciated near the contact. This brecciation is particularly noticeable at outcrops along Fossil Creek Road north of its junction with the road to the Verde Hot Springs where the stock consists of many subangular blocks (35 modal percent) within a groundmass of comminuted dacite.

The Sally May Dacite is overlain by the rubble unit, the Hackberry Mountain Dacite, and a dacitic air-fall tuff (at Chalk Springs). The stock was intruded by a dacite plug assigned to the Hackberry Mountain Dacite, a rhyolitic diatreme, and a rhyolitic plug. The Sally May Dacite occurs at higher elevations (1620 meters above sea level at High Saddle) than any of the adjacent country rock suggesting that it breached the

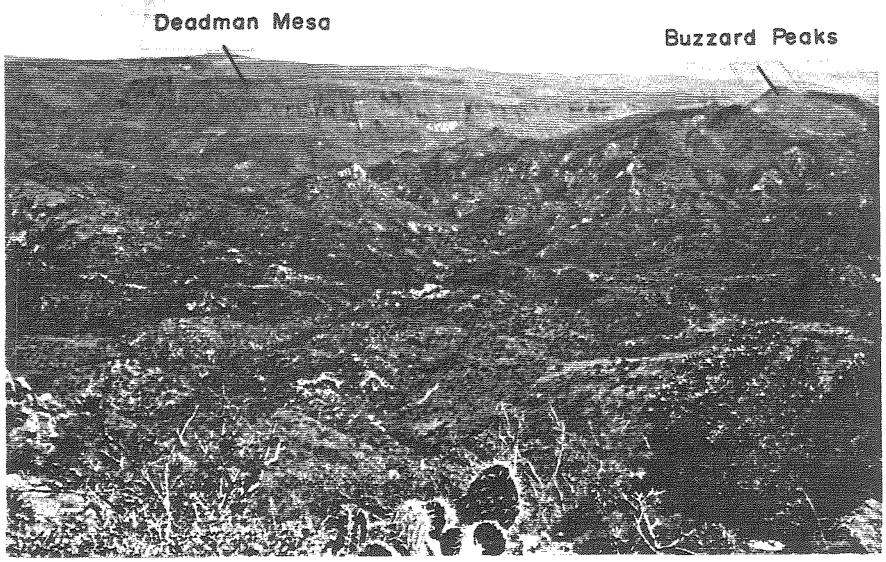


Figure 23.--Drainage basin of Sally May Wash which is composed almost exclusively of the altered Sally May Dacite stock. View southeast.

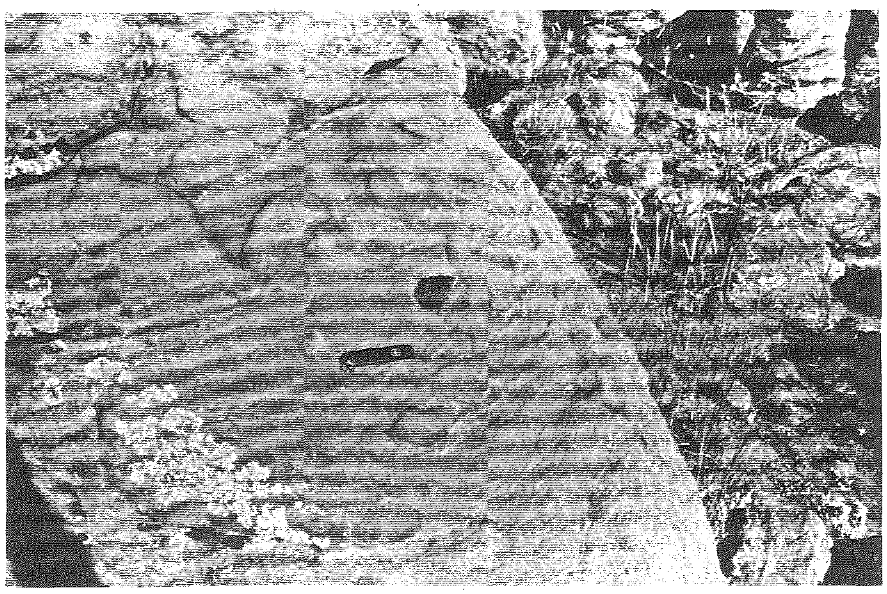


Figure 24.--Basic xenolith within unaltered part of the Sally May Dacite stock. Xenolith is above and to the right of the pocket knife.

surface when intruded.

The relationship between the Sally May Dacite and rocks younger than Member 1 of the Cimarron Hills Andesite and older than the rubble unit is not as well defined. At the northeasternmost exposure of the Sally May Dacite, just east of Cedar Flat Tank in the northern Cimarron Hills, there is either a sill or flow of dacite that protrudes from the stock and is bounded between the Hackberry Basin Member of the Towel Creek and the overlying Member 2 of the Cimarron Hills Andesite (see section B-B' of plate 3). The unit is believed to be a sill because rocks older than Member 2 of the Cimarron Hills Andesite were apparently deformed by the intrusion of the stock. The section of volcanic rocks on the northern flank of Hackberry Mountain dip north, away from the stock, at angles as great as 30°. This section includes all the rocks up through Member 3 of the Thirteenmile Rock Basalt. The contact between the stock and this section, unfortunately, is covered by the Hackberry Mountain Dacite (see section A-A' of plate 3). If the unit in question was indeed a flow, there should be deposits of detritus occurring at that stratigraphic level which would have been shed from the stock shortly after its emplacement. No such deposits occur at this level. The rubble unit consists of detritus shed from the Sally May Dacite, and it was probably deposited shortly after emplacement of the stock.

Lithology and internal structure

The Sally May Dacite stock is composed of massive dacite, most of which has been hydrothermally altered. Where unaltered, the dacite resembles the dacite found in lithic clasts and flows in the Towel Creek Tuff, Hackberry Moutain Dacite, and in various dacite dikes in the region (see petrographic descriptions in following section). Rare basic xenoliths are scattered throughout the stock. The internal structure of this stock cannot be readily deciphered owing to homogeneity of its lithologic characteristics and to subsequent alteration. As a result of the alteration, most of the dacite is soft and easily eroded; a regolith that supports a thick vegetative cover has developed on most slopes. Moreover, there are large differences in the degree of alteration of the dacite which tend to obscure any primary lithologic differences that may be present within the stock.

The stock appears to be composed primarily of one or possibly several large intrusive units cut by a subordinate number of dacitic dikes. Many dacitic dikes, which strike chiefly east and northeast, have been recognized within the eastern part of the stock. No dikes were recognized in most parts of the stock, however.

There are six plugs and several small dikes of dacite within Hackberry Basin. Although they are not contiguous with the Sally May Dacite stock they are closely spaced and can be traced to near its boundary. At the surface the plugs are either circular or elongate to the northwest. The plugs and dikes in the northeastern part of Hackberry Basin are aligned in a northwest direction. The plugs have an average diameter of 200 meters and rise above the basin floor by as much as 180 meters. They have nearly vertical contacts which commonly are brecciated. The brecciated boundary is generally less than 10 meters thick. The adjacent country rock is typically deformed and dips away from the plugs at angles up to 50°. The plug at the southeastern boundary of Hackberry Basin was intruded and deformed by a rhyolitic plug. The plugs commonly have well developed vertical and horizontal joints. Their interiors are typically massive; the plug, through which Doren's Defeat Canyon passes, does contain a circular brecciated zone 160 meters in diameter.

Chemistry and age

Chemical analyses of unaltered dacite from two plugs in Hackberry Basin are given in table 19. The normative mineralogy calculated from these analyses lies within the dacitic field of Streckeisen (1979, p. 332).

The Sally May Dacite intrudes Member 2 of the Cimarron Hills Andesite which is younger than Member 6 of the Towel Creek Tuff, and the stock is overlain by the Hackberry Mountain Dacite. These relationships indicate that the stock was intruded between 7.8 and 8.4 m.y. age (table 6). No other silicic intrusive bodies of similar age are described elsewhere in central or northern Arizona.

Dacite plugs and dikes of unknown age

This unit consists of dacitic plugs and dikes of unknown age, they probably are related either to the Towel Creek Tuff, the Sally May Dacite, or the Hackberry Mountain Dacite. They are lithologically similar to the dacites found in the three dacitic formations, they only intrude units lower than these formations, and they do not occur near any of these dacitic formations. The dacite of the plugs and dikes is typically white and more resistant than the units intruded, has moderately developed horizontal and vertical joints, and has nearly vertical contacts. One dacite plug, 300 meters across, is located in Gospel Hollow, and another, 400 meters across, lies south of the Towel Peaks. Intrusion of this latter body deformed the surrounding units, which dip away from the plug at angles up to 30°.

The dikes range in width from five to 80 meters and are found in

Table 19.--Major-element and normative compositions, in percent, of the Sally May Dacite

[Chemical analyses by x-ray fluorescence methods. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg]

Sample No.	RL-79-69	RL-79-71
Major oxides (weight percent)		
SiO_2	66.0	67.4
Al_2O_3	15.4	15.4
[1] Fe_2O_3	2.98	2.88
MgO	0.5	0.83
CaO	2.92	2.70
Na_2O	3.6	3.2
K_2O	2.7	2.55
TiO_2	0.39	0.31
MnO	<0.02	<0.02
P_2O_5	0.2	0.1
[2] Loss	2.19	3.30
Total	96.9	98.7
CIPW Norms[3]		
q	28.6	32.6
or	16.9	15.8
ab	32.2	28.4
an	13.9	13.4
c	1.8	2.8
hy	4.3	5.1
mt	0.9	0.9
il	0.8	0.6
ap	0.5	0.3

[1] All iron as Fe_2O_3.
[2] Loss on Ignition.
[3] Norms calculated with $FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).

See plate 7 for sample localities.

Gospel Hollow and near the Verde Hot Springs. The former set of dikes strike west or west-northwest and are subparallel to the faults in this area. Several of these dikes are offset by the faults.

The plug and dikes in the Gospel Hollow area may be related to the Hackberry Mountain Dacite, as discussed above. The dikes exposed farther south along the Verde River may be related to the Sally May Dacite. Several of the dikes exposed near the Childs powerplant are hydrothermally altered as is most of the Sally May Dacite, and the dikes strike radially away from the dacite stock.

A chemical analysis for a dacite dike from Gospel Hollow is in table 20. The rock is more silicic than any other reported dacite in the Hackberry Mountain area.

Petrography of the Dacitic rocks

All non-pyroclastic and non-brecciated dacitic rocks as well as the dacitic lithic clasts of the pyroclastic and brecciated units, regardless of formation or member, are so similar lithologically that they cannot be differentiated in hand specimen or microscope. Because of this high degree of similarity, the following lithologic description should suffice for all the above mentioned lithologies.

All dacitic rocks or clasts contain phenocrysts of euhedral to subhedral plagioclase (10 to 40 modal percent), euhedral hornblende (four to eight modal percent), euhedral biotite (two to three modal percent), and subhedral to euhedral opaque mineral phenocrysts. These phenocrysts occur within a white, red, or blue glassy groundmass.

The plagioclase phenocrysts are lath-shaped and typically broken. They commonly occur in glomerophyres in which the crystals have interlocking

Table 20.--Major-element and normative composition, in percent, of a dacite dike

[Chemical analysis by x-ray fluorescence methods. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg]

Sample No.	RL-79-26
Major oxides (weight percent)	
SiO_2	69.5
Al_2O_3	14.6
[1] Fe_2O_3	2.72
MgO	1.1
CaO	2.74
Na_2O	3.6
K_2O	3.28
TiO_2	0.32
MnO	0.04
P_2O_5	0.2
[2] Loss	0.720
Total	98.8
CIPW Norms[3]	
q	28.5
or	19.8
ab	31.1
an	12.6
c	0.6
hy	5.4
mt	0.9
il	0.6
ap	0.5

[1] All iron as Fe_2O_3.
[2] Loss on Ignition.
[3] Norm calculated with $FeO/Fe_2O_3 = 9.627 - 0.921 \cdot SiO_2$ (Wolfe and others, in preparation).

See plate 7 for sample locality.

boundaries. They are from less than 0.2 to greater than six millimeters in length and average 0.4 millimeter. The phenocrysts are andesine ($An_{35 - 45}$) and are usually zoned. Oscillatory zoning is common; reverse zoning less so. The plagioclase crystals commonly have inclusions of apatite + opaques ± biotite ± glass. Chemical analyses of plagioclase phenocrysts are in table 21.

The hornblende phenocrysts are green, where fresh, but are typically altered and rimmed by magnetite. In some instances, hornblende has been entirely altered to magnetite plus goethite (?). In these cases the outer rim is still outlined with magnetite. The average hornblende phenocryst is 0.3 millimeter in diameter. Magnetite inclusions are common, even in fresh crystals. Chemical analyses of several hornblende phenocrysts are given in table 13.

Brown biotite phenocrysts are commonly broken and are 0.5 to one millimeter across. They usually have plagioclase and magnetite inclusions. As with the hornblende phenocrysts, the biotite phenocrysts are typically altered, and their edges are outlined with magnetite. Where the alteration is intense, biotite grains are replaced entirely by magnetite and goethite (?). In general, these mafic phenocrysts have undergone a higher degree of alteration in the samples of the Sally May Dacite, even where apparently unaltered, than in samples of any other dacitic unit.

Phenocrysts of opaque minerals also occur in the dacitic rocks. They average 0.1 millimeter in diameter. Chemical analyses indicate that the opaque minerals are primarily magnetite (table 22). However, some of the larger grains have exsolved ulvöspinel.

Quartz and sanidine phenocrysts are present in trace amounts in most dacites. The quartz phenocrysts are anhedral and heavily resorbed,

Table 21.--Chemical analyses of plagioclase phenocrysts in dacitic rocks

[Analyses performed with MAC-5-SA3 electron microprobe using energy-dispersive method described by Albee and others (1980)]

Sample No.	RL-79-28	RL-79-71	RL-79-74a	RL-79-74b
Major oxides (weight percent)				
Na_2O	6.90	7.51	7.74	8.15
Al_2O_3	26.83	25.21	24.81	24.19
SiO_2	59.57	60.45	61.56	62.28
K_2O	0.58	0.48	0.55	0.79
CaO	8.26	6.68	6.24	5.74
FeO	0.28	0.19	0.16	0.45
Total	102.42	100.53	101.06	101.60

SAMPLE DESCRIPTIONS

RL-79-28	Dacitic dike of unknown age.
RL-79-71	Unaltered flow assigned to Sally May Dacite.
RL-79-74a	Core of plagioclase phenocryst, from flow of Hackberry Mountain Dacite.
RL-79-74b	Rim of same phenocryst as sample RL-79-74a.

Location of samples shown in plate 7.

Table 22.--Chemical analyses of opaque minerals in dacitic rocks

[Analyses performed with MAC-5-SA3 electron microprobe using energy-dispersive method described by Albee and others (1980)]

Sample No.	RL-79-28	RL-79-50a	RL-79-80b	RL-79-69
Major oxides (weight percent)				
MgO	0.75	2.19	1.76	0.30
Al_2O_3	1.01	0.45	0.41	0.62
SiO_2	2.71	0.84	0.37	1.48
CaO	0.65	0.02	0.00	0.33
TiO_2	1.43	4.53	23.48	10.26
Cr_2O_3	0.00	0.14	0.11	0.25
MnO	0.24	0.67	0.52	0.09
FeO	82.74	81.39	63.74	75.64
Total	89.52	90.23	90.39	88.97

SAMPLE DESCRIPTIONS

RL-79-28	Dacitic dike of unknown affinity
RL-79-50a	Dacite flow assigned to Hackberry Mountain Dacite
RL-79-50b	Same crystal as sample RL-79-50a. Analysis of an exsolution lamella
RL-79-69	Unaltered plug assigned to the Sally May Dacite

Location of samples shown in plate 7.

whereas the sanidine phenocrysts are typically subhedral. Both average about one millimeter in diameter. Hypersthene and clinopyroxene phenocrysts occur in trace amounts in only a few dacites. Both are subhedral to euhedral and average 0.2 millimeter across. The clinopyroxene phenocrysts typically occur in glomerophyres.

The groundmass of the dacitic rocks consists primarily of devitrified glass with a lesser amount of stumpy feldspar microlites. The glass is generally devitrified into a cryptofelsitic base; fresh glassy groundmass is very rare. Chemical analyses of the glass from several dacitic units are in table 23. The feldspar microlites typically constitute about one-fifth of the groundmass and are commonly aligned. Microlites of mafic minerals are also common.

Basic Xenoliths

Distinctive basic xenoliths occur in trace amounts in all dacitic units. Similar rocks occur as separate clasts within the brecciated and pyroclastic units. The xenoliths are globular, are one to 10 centimeters in diameter, and generally have sharp contacts with the enclosing dacitic rocks (figure 24).

The basic xenoliths consist of plagioclase (one modal percent) phenocrysts set within a matrix of hornblende (20 modal percent), plagioclase (20 modal percent), biotite (five modal percent), and opaque minerals (trace), and glass.

The plagioclase phenocrysts are ragged, commonly sieved, and subhedral. Inclusions of glass, biotite, and apatite are abundant. The phenocrysts are zoned and have a labradorite core (An_{58}) and an andesine rim (An_{45}). Plagioclase crystals within the groundmass are different from the pheno-

Table 23.--Chemical analyses of glass from dacitic rocks

[Analyses performed with MAC-5-SA3 electron microprobe using energy-dispersive method described by Albee and others (1980)]

Sample No.	RL-79-26	RL-79-50	RL-79-64	RL-79-69	RL-79-77	RL-79-80	Rl-79-83	RL-79-84
Major oxides (weight percent)								
Na_2O	4.84	4.00	2.61	3.01	2.20	2.27	5.80	2.38
MgO	0.00	0.00	1.34	0.00	0.00	0.00	0.00	0.00
Al_2O_3	12.82	12.69	11.61	11.61	12.46	12.57	18.43	12.55
SiO_2	80.66	76.61	75.83	81.71	73.12	76.10	71.39	75.49
P_2O_5	0.00	0.00	0.14	0.00	0.13	0.19	0.00	0.00
SO_3	0.02	0.06	0.10	0.00	0.02	0.00	0.15	0.00
Cl	0.04	0.05	0.00	0.03	0.10	0.07	0.00	0.06
K_2O	3.55	2.93	4.02	5.17	4.55	4.49	2.08	3.86
CaO	0.86	1.29	1.11	0.43	0.93	0.72	3.41	0.90
TiO_2	0.20	0.17	0.42	0.26	0.18	0.20	0.20	0.22
Cr_2O_3	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.10
MnO	0.06	0.09	0.00	0.04	0.00	0.06	0.00	0.00
FeO	0.20	1.18	2.31	0.52	0.47	0.97	0.96	0.95
NiO	0.07	0.01	0.19	0.02	0.00	0.16	0.02	0.00
Total	103.31	99.18	99.67	102.80	94.14	97.78	102.52	96.49

SAMPLE DESCRIPTIONS

RL-79-26	Dacitic dike of unknown age
RL-79-50	Flow of the Hackberry Mountain Dacite
RL-79-64	Member 5 of the Towel Creek Tuff
RL-79-69	Unaltered plug assigned to the Sally May Dacite
RL-79-77	Groundmass of Member 1 of the Towel Creek Tuff
RL-79-80	Groundmass of Member 2 of the Towel Creek Tuff
RL-79-83	Clast from Member 3 of the Towel Creek Tuff
RL-79-84	Clast from Member 4 of the Towel Creek Tuff

Location of samples shown in plate 7.

crysts. They are fresher, have fewer inclusions, and are more sodic (An_{36}). The anorthite content of the groundmass plagioclase is the same as the typical value for plagioclase phenocrysts in the dacitic rocks. They are randomly oriented, stumpy laths that range in length from 0.05 to 0.3 millimeter. Apatite inclusions are common.

Hornblende crystals are the principal component of the xenoliths and range in size from 0.1 to 1.5 millimeters. The hornblende crystals are subhedral and lath-shaped. Plagioclase inclusions are common.

Green and brown biotite grains occur within the groundmass. They are euhedral and average 0.3 millimeter in diameter. The biotite grains are commonly altered to goethite (?). The biotite and hornblende crystals are commonly in intimate contact. Hornblende crystals generally enclose biotite crystals, but the biotite, in places, encloses hornblende. Subhedral opaque grains, probably magnetite, occur within the groundmass. They average 0.1 millimeter across.

The majority of the groundmass is composed of glass (45 modal percent). The glass is clear and remarkably fresh. Spherical vesicles commonly occur within the glass; they average 0.1 millimeter in diameter.

A chemical analysis of a basic xenolith is given in table 24; it has the composition of a basalt according to Streckeisen's classification scheme (1979, p. 332). The composition plots on the boundary between the alkalic and tholeiitic basalt fields of MacDonald and Katsura (1969, p. 87) (figure 8).

Rhyolite diatreme

Location, topographic expression, and relations

A diatreme occurs in the northern part of the drainage basin of

Table 24. Major-element and normative composition, in percent, of a basic xenolith

[Chemical analysis by x-ray fluorescence methods. Analysts: J. Baker, J. Taggart, and J.S. Wahlberg]

Major oxides (weight percent)	
SiO_2	50.4
Al_2O_3	17.6
[1] Fe_2O_3	8.24
MgO	4.9
CaO	8.95
Na_2O	2.5
K_2O	1.67
TiO_2	1.14
MnO	0.12
P_2O_5	0.99
[2] Loss	1.50
Total	98.0
CIPW Norms[3]	
q	3.2
or	10.3
ab	22.1
an	33.2
di	5.2
hy	19.4
mt	1.9
il	2.3
ap	2.5

[1] All iron as Fe_2O_3.
[2] Loss on Ignition.
[3] Norm calculated with $FeO/Fe_2O_3 = 9.627 \cdot SiO_2$ (Wolfe and others, in preparation).

See plate 7 for sample locality.

Sample obtained from brecciated base of the Hackberry Mountain Dacite at The Rocks.

Sally May Wash. The diatreme consists of a dacite tuff-breccia and elongate bodies of rhyolite (referred to as dike-shaped bodies in explanation to geologic map, plate 2). The breccia is fairly non-resistant and forms a depression surrounded by the more resistant elongate bodies.

The diatreme cuts the Sally May Dacite, the Hackberry Basin Member of the Towel Creek Tuff, and basaltic dikes assigned to the Thirteenmile Rock Basalt. It is circular, has a diameter of about 500 meters, and is well exposed.

Lithology

The diatreme is filled by a moderately resistant white tuff-breccia of rhyolite and subordinate altered lithic dacite fragments. Several large, resistant, elongate bodies of rhyolite occur within the tuff-breccia. These bodies are composed of rhyolite similar to that of the rhyolite flow. They have well developed vertical flow-bands that are parallel to their long axes. The rhyolite is jointed parallel to the flow-bands. These bodies comprise about one-tenth of the diatreme and are concentrated along its boundary. The following structural relationships within the diatreme indicate that the elongate bodies of rhyolite existed prior to the intrusion of the tuff-breccia: (1) joints within the outermost portions of these bodies are split apart and filled with the tuff-breccia; (2) thin dikes of tuff-breccia intrude these bodies; (3) the outer boundaries of the elongate bodies are never brecciated as would be expected if they had intruded the tuff-breccia.

The tuff-breccia is massive and is composed of subangular blocks and fragments (45 modal percent) within a fine-grained groundmass. Rhyolitic fragments are the most conspicuous clasts (six modal percent); they average 1.5 centimeters across, but some are as large as one meter.

Coarse, altered dacite clasts are also common (four modal percent). They are either white or blue and are lithologically similar to the typical dacite (pages 159-164). The dacite clasts also average 1.5 centimeters across; they are as large as 30 centimeters across. Thin halos of altered yellow matrix, three to four millimeters thick, commonly surround the clasts. Silicic lithic clasts smaller than five millimeters across (30 modal percent) cannot be differentiated in hand specimen because flow-bands, which are unique to the rhyolite clasts, cannot be recognized in these smaller fragments. Examination of thin sections suggests that the majority of these smaller fragments are rhyolite. White, unaltered silicic pumiceous lapilli are common (five modal percent), and they range in size from three millimeters to four centimeters across. The tuff-breccia also contains a trace amount of blocks and smaller fragments of mafic volcanic rocks that average one centimeter across. They are typically purple, vesicular, aphyric, and altered. The relative abundance of the various lithic clasts are essentially constant throughout the tuff-breccia.

The groundmass of the tuff-breccia (55 modal percent) is composed of ash-sized particles. Approximately one-half of the groundmass consists of subrounded lithic grains of rhyolite. Minor dacite and sparse basalt grains are also present. The remainder of the groundmass consists of particles less than 0.1 millimeter across. About one-half are subangular, broken plagioclase grains. Biotite grains constitute a trace amount. The remainder of the groundmass is composed of goethite (?).

Enclosed within the tuff-breccia are several thin, discontinuous septae of unaltered dacitic air-fall tuff, each about one meter thick. The septae are vertical, and the tuff within them has near-horizontal beds. The tuff is similar to that exposed in a large block of Towel Creek Tuff suspended in the Sally May Dacite and adjacent to the diatreme. These septae are probably slivers of the Towel Creek Tuff that have dropped into the diatreme.

Alteration

The diatreme intrudes the hydrothermally altered part of the Sally May Dacite stock. The tuff-breccia is white in most outcrops except along the western boundary of the diatreme where it is yellow. The yellow color extends over a zone about 40 meters wide and becomes more intense towards the contact with the altered Sally May Dacite. Also, there are irregular yellow streaks within the tuff-breccia. The yellow zones contain a higher concentration of goethite (10%) than the remainder of the tuff-breccia.

Most of the dacite fragments within the tuff-breccia have been hydrothermally altered. They generally have a devitrified groundmass which is typical of the altered dacite. The elongate bodies of rhyolite are not visibly altered, even those that are in contact with the altered Sally May Dacite.

Chemistry

A chemical analysis of the tuff-breccia of the diatreme is given in table 15. The rock plots in the dacitic field of Streckeisen (1979), and the analysis is similar to those of the other dacitic rocks in this area.

Age

Because the diatreme cuts the Sally May Dacite, it is not older than 8.4 m.y. It is proposed that the diatreme was the conduit for the rhyolite flow because the rhyolite in both are petrographically indistinguishable, and remnants of the flow occur in line with the diatreme. If true, the diatreme was emplaced between 7.8 and 8.4 m.y. ago.

Origin

Most diatremes form when a volatile-rich magma rises to a level where the vapor pressure of the volatiles exceeds the lithostatic pressure. Once this occurs, there is rapid and violent unmixing or boiling of the volatiles causing disruption of the magma and an eruption. Shoemaker and others (1962, p. 341-347) provide a detailed qualitative description of this process.

Geologic relations within the rhyolite diatreme indicate that its formation was unlike that described above. The rhyolite provides no evidence of ever being volatile-rich; all fragments and bodies of rhyolite are dense, never frothy. The sharp contact between the bodies of dense rhyolite and the tuff-breccia suggests that the rhyolite was hard and brittle when the diatreme formed.

A phreatic eruption is the most plausible mechanism for the formation of the diatreme, and a proposed model follows. The rhyolite of the diatreme had been a massive pipe that may have been the source for the rhyolite flow. This pipe intruded the Sally May Dacite stock after it had been altered. The stock was water-rich at this time, and it is assumed that its permeability had been reduced considerably since the onset of alteration because of the precipitation of alteration minerals in its fractures. The magma within the pipe would have heated the water in the adjoining dacite, and this heated water would have attempted to migrate from the magma (e.g. Delaney, 1982), but could not because of the low permeability of the dacite. Consequently, a jacket of pressurized water surrounded the pipe.

When the rhyolite in the pipe solidified, it fractured and its permeability increased significantly (e.g. Norton and Knapp, 1977). A thin layer of pressurized water entered the fractures where it was able to expand and flash to steam. The expansion of the steam created more fractures in both the rhyolite and the dacite which permitted even more pressurized water to flash. The result was the rapid disruption of the rocks at the boundary of the pipe. The steam plus fragments of rhyolite and dacite produced a fluidized mixture that migrated up through the pipe, effectively reaming it out, until it reached the surface where the mixture was erupted. Because the dacite at the boundary of the diatreme is not disrupted, the initial disruption of the rhyolite must have occurred at a level lower than that exposed today. The tuff-breccia of the diatreme was the fluidized mixture that rose from depth, the enclosed dacite lithic clasts were wall rocks incorporated from lower levels of the stock, and the elongate bodies of rhyolite are the remains of the pipe.

Rhyolite plug

A very resistant rhyolite plug forms a prominent spire (hill 5619) at the southeastern boundary of Hackberry Basin. It is elliptical in plan and has a northeast trending major axis 300 meters long. This plug has nearly vertical contacts and intrudes the Hackberry Basin Member of the Towel Creek Tuff, Member 1 of the Cimarron Hills Andesite, the undifferentiated Thirteenmile Rock Basalt, Member 7 of the Towel Creek Tuff, and the Sally May Dacite. The plug intruded an apophysis of the Sally May Dacite.

This plug is composed of massive bluish-gray flow-banded rhyolite that is petrographically indistinguishable from the blocks and fragments within the rhyolite flow. A chemical analysis for a sample from the rhyolite plug is given in table 15. This rock is the most silica-rich of any analyzed in this report. An analysis of the glass from the plug is given in table 14.

The rhyolite plug is younger than the Sally May Dacite, so it is no older than 8.4 m.y. (table 6). An upper age limit is not well constrained because no unit is demonstrably younger than it. Because rhyolitic rocks are rare in the Hackberry Mountain area, it is possible that this plug is correlative with the rhyolite flow. If so, the plug is 7.8 to 8.4 m.y. old.

HYDROTHERMAL ALTERATION

Alteration associated with the Sally May Dacite stock

A large part of the Sally May Dacite stock has been hydrothermally altered. The altered rocks underlie about 15 square kilometers, as shown in plate 1. Some of the wall rocks of the stock, including the Towel Creek Tuff, Hickey Formation, and Cimarron Hills Andesite, are also altered.

Nature of alteration

The altered dacite appears fresher under the microscope than it does in hand specimen. The groundmass of the unaltered dacite is either glass plus plagioclase microlites or has been devitrified into a cryptofelsitic base. As the degree of alteration increases, the cryptofelsitic base becomes coarser-grained. The most altered rocks are silicified; in these the groundmass consists chiefly of quartz with minor amounts of sericite, chlorite, and iron oxides, all of which are anhedral. The quartz and chlorite grains average 20 microns across and the opaque minerals average three microns across. The sericite is in the form of laths that average 50 microns in length. The laths are probably the remnants of pre-existing plagioclase crystals. Quartz phenocrysts are not affected by the alteration process.

The condition of the plagioclase phenocrysts can be used as an indicator of degree of alteration. As the rock was altered the plagioclase phenocrysts were replaced by sericite. Smaller phenocrysts altered more readily than larger ones. Only in the most altered samples are the larger phenocrysts of plagioclase totally replaced by sericite. The sericite first occurs within the core of the phenocrysts.

All hornblende phenocrysts are altered. The rim is usually replaced with fine particles of iron oxide, primarily hematite. In more altered phenocrysts the hematite rims are thicker and their cores are replaced by sericite + chlorite + calcite. Biotite phenocrysts have not been altered as extensively as hornblende. Magnetite grains first occur around the rim of weakly altered biotite crystals and along the cleavage traces of more strongly altered crystals. At higher degrees of alteration, the core is replaced by sericite.

Silicified rocks are very rare and were only recognized in the central part of the stock. In the majority of outcrops, the dacite has undergone only a minor amount of alteration. Generally, only the cores of the plagioclase phenocrysts have been altered to sericite. In most samples, the primary textures are preserved and the mineralogy is relatively unchanged.

Altered dacite tuff and breccia of the Towel Creek Tuff are similar to the altered dacite of the Sally May. They can be differentiated by texture if not too altered.

Mafic volcanic rocks in and adjacent to the stock have in general undergone only minor degrees of alteration. In hand specimen they are usually green instead of gray. The phenocrysts are unchanged. Altered specimens contain numerous intergranular hydrated iron oxides and rare intersertal chlorite.

Boundary of alteration zone

The transition generally occurs over a distance of less than 50 meters, and it typically coincides with the boundary of the stock. Where the rocks adjoining the stock are relatively impervious (mafic flows or dikes) they are generally not altered; where the rocks are permeable (dacitic pyroclastic rocks or andesitic cinder) they are commonly altered.

The boundary of alteration zone occurs in the Sally May Dacite in the area of the Cimarron Hills and along Boulder Canyon. Here the transition takes place in distances of less than 10 meters thick. A more diffuse boundary within the stock occurs southeast of Hackberry Mountain. Here the altered Sally May Dacite grades upwards into unaltered dacite about 100 meters below the upper contact of the stock.

Timing of alteration

The Sally May Dacite contains many altered mafic dikes that must have been intruded either prior to or during the alteration event. The majority of the mafic dikes that intrude the altered dacite are not altered and probably postdate the alteration process. The Hackberry Mountain Dacite is in intimate contact with the altered dacite and is not visibly altered. Therefore, the alteration occurred after the intrusion of the Sally May Dacite and before the extrusion of the Hackberry Mountain Dacite, between 7.8 and 8.4 m.y. ago (table 6).

Nature of the alteration process

Geologic relationships previously reported indicate that the Sally May Dacite was emplaced at a very shallow level at a fairly high temperature. The rocks surrounding the stock and their enclosed pore fluids must have been heated significantly. As the stock cooled it probably would have contracted and formed numerous fractures, thus increasing its permeability (see Norton and Knapp, 1977, p. 920-921). Groundwater in the area would have migrated toward and into the fractured intrusive body, driven by the density decrease attendant on heating. Such fluid would have subsequently risen to the surface pushed by cooler, denser, inward migrating waters in the surrounding pyroclastic deposits. A shallow torroidal convection cell would thus have formed. This type of system has been described and quantified by numerous authors including Norton and Knight (1977).

The rising heated water produced the sericitic alteration of the Sally May Dacite. This type of alteration has been described by Hemley and Jones (1964, p. 543), and the chemical reaction for this process is:

$$0.75\ \underset{\text{Andesine}}{Na_2CaAl_4Si_8O_{24}} + 2H^+ + K^+ = \underset{\text{Sericite}}{KAl_3Si_3O_{10}(OH)_2} + 1.5\ Na + 0.75\ Ca^{++} + \underset{\text{Quartz}}{3SiO_2}$$

A high activity of potassium with respect to that of sodium and calcium is required. Glass from in tuffs surrounding the stock is the probable source of the potassium. The glass is abundant and has a potassium content commonly greater than five percent (table 23). Altered hornblende phenocrysts in the surrounding dacites may have been a minor source of potassium.

The duration of the alteration process was probably relatively short. Cathles (1977) modeled the convective cooling of small cylindrical intrusions (<3.4 kilometers in diameter) emplaced at shallow depths (within 1.4 kilometers of the surface) and determined that they would have cooled to within 50°C of the ambient geothermal gradient within 100,000 years. The Sally May Dacite stock differs from his model, it is larger and was emplaced to a shallower depth. According to Cathles (1977, p. 817) a larger intrusion would not take substantially longer to cool because the high surface heat flow would occur over a larger surface. A shallow intrusion would be emplaced into a lower temperature environment and, as a result, would cool faster.

An interesting feature of the boundary of the alteration zone is its approximate coincidence with the wall of the stock. This indicates that the wall rock never attained high temperatures. It could not have been heated up to greater than one-half the temperature of the intrusion (Jaeger, 1964). If the stock had vertical walls or ones that dipped away from the country rock, it is doubtful that the wall rock would have been heated appreciably. Also, in a convective cooling process the water migrates from the cooler country rocks into the hotter intrusive body, not the opposite way. The hottest and most reactive water was in the stock and did not enter the surrounding country rock in appreciable quantities until it had migrated near the surface where it could cool relatively rapidly.

The sharp boundary between altered and unaltered Sally May Dacite in the Cimarron Hills occurs near the outer boundary of the stock where it contains numerous dacitic dikes and sills. These structures probably cooled much more rapidly than the adjoining stock because of their greater surface area per volume. The uppermost exposures of the Sally May Dacite are not altered (southeast of Hackberry Mountain and in the Cimarron Hills) or are only slightly altered (High Saddle). This probably resulted from more rapid cooling of the stock because of its proximity to the surface.

The outcrops of older landslide deposits situated along the northern boundary of the Sally May Dacite contain clasts of opal. These deposits (and the enclosed clasts) were derived from the region where the altered stock is now exposed. No outcrops of opal are now present within the altered Sally May Dacite suggesting that the opal formed in a part of the intrusive body removed by erosion. These clasts are typically less than one meter across and contain fine laminae that are typical of those formed in vein deposits.

The opal probably precipitated in hot springs within the Sally May Dacite. Modern opals form in hot spring environments at depths of less than 25 meters below the surface (White and others, 1956, p. 53-54). The shallow formation depth of opal would explain the lack of such deposits within the present outcrop of the Sally May Dacite--subsequent erosion has removed them and only relict clasts are left in the older landslide deposits.

Robert E. Criss of the U.S. Geological Survey determined a $\delta^{18}O$ value of 9.5 per mil for a very highly altered and completely silicified sample of the Sally May Dacite collected from the center of the stock. He considered this value indicative of silification at a low temperature, probably less than 100°C.

In conclusion, the alteration of the Sally May Dacite stock was caused by heated (mostly $<100°C$) meteoric water convecting through the body as it cooled. Parts of the upper surface of the intrusive body may have remained unaltered, but hot springs and their deposits were probably common over the center of the stock.

Brushy Prong

Two small patches of hydrothermally altered dacitic tuff are exposed near Brushy Prong (plate 1). At both exposures the altered rock is ignimbrite assigned to Member 3 of the Towel Creek Tuff. The alteration in both places is similar to that described for the Sally May Dacite stock. These two outcrops occur within the cores of two different anticlines.

The occurrence of the altered rocks within the anticlines suggests that the alteration and folding are related.

Cottonwood Basin

A small portion of Member 6 of the Towel Creek Tuff has undergone low grade alteration. The altered rocks occur along the eastern margin of Cottonwood Basin in the southeastern corner of Section 9, T. 13 N., R. 6 E. Here Member 6 consists of a dacitic ignimbrite that is both underlain and overlain by sandstone of the Verde Formation.

Unusual structures occur within the ignimbrite at this outcrop. These structures are more resistant than the rest of the tuff, are slightly darker in color, and have three different forms of which the first predominates: 1) vertical cylindrical pipes that average 30 centimeters in diameter and protrude up to one meter above the adjacent tuff (figure 25), 2) horizontally elongate, ellipsoidal bodies up to one meter in length that are apparently rootless, and 3) rootless sub-horizontal pancake-shaped bodies that are 30 to 60 centimeters thick and up to one meter across. All of these bodies occur within the interior of the ignimbrite about 10 meters below its top. These structures contain abundant calcite, in contrast to the surrounding ignimbrite. The calcite has replaced most of the glass dust that occurs within the matrix of this ignimbrite. Calcite also fills some of the vesicles in the pumiceous lapilli. The calcite has hardened the ignimbrite, which is why these structures are more resistant to erosion.

Wadell (1972, p. 57-60) recognized these structures and suggested that their increased lithification and subsequent greater resistance to erosion was due to compaction by the weight of elephants. Their occurrence

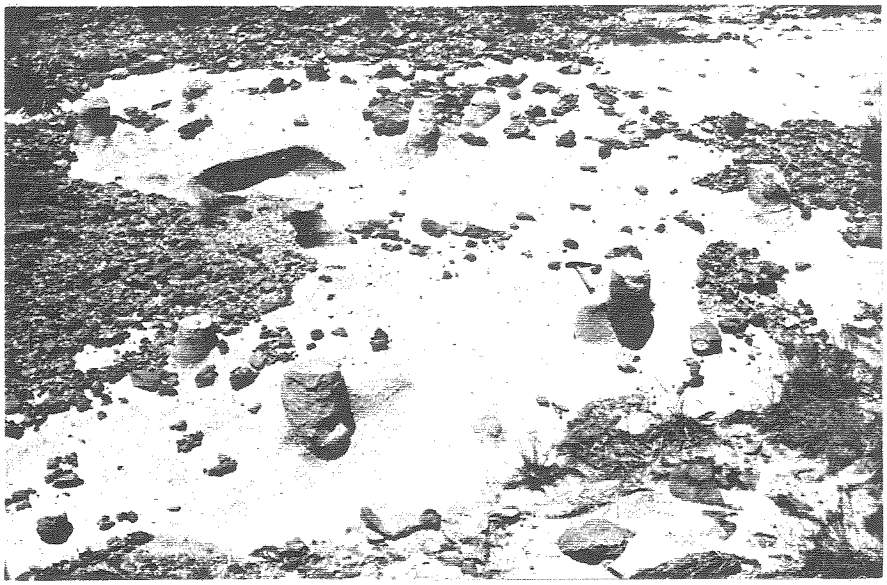


Figure 25.--Fossil fumaroles in Member 6 of the Towel Creek Tuff in Cottonwood Basin. Hammer for scale is left of fossil fumarole in right foreground.

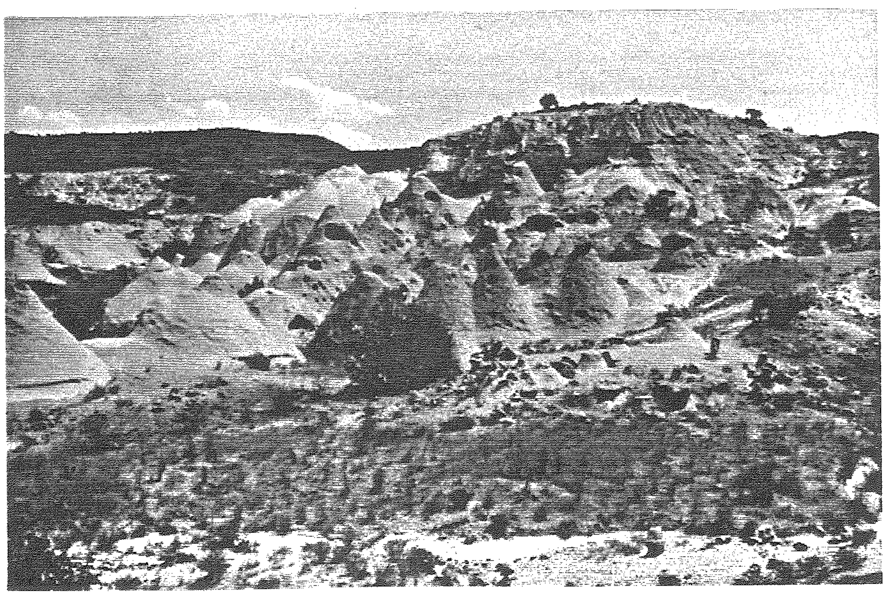


Figure 26.--"Tepees" in Member 6 of the Towel Creek Tuff in Cottonwood Basin. Numerous fossil fumaroles are in right foreground.

deep within the ignimbrite precludes this novel explanation.

The cylindrical structures are similar in form to "fossil fumaroles" described by MacDonald (1972, p. 163) and "steam tubes" described by Sheridan (1970, p. 852-853). If they are fossil fumaroles the cylinders would have been conduits through which steam escaped to the paleosurface soon after the ignimbrite was deposited. Several authors have suggested that the fumarolic vapors were derived from the ignimbrites during the processes of welding and subsequent devitrification (Smith, 1960b, p. 157; Ross and Smith, 1961, p. 31; Sheridan, 1970, p. 865). However, the ignimbrite that contains these cylindrical structures is not welded and has not been appreciably devitrified. This ignimbrite was erupted while the sandstone of the Verde Formation was accumulating, and it is possible that the water table occurred at a shallow depth within the underlying sandstone. It is proposed the water was driven by lithostatic pressure into the ignimbrite where it was heated. This heated water continued to migrate upwards until it reached a level where it flashed to steam. When the water boiled, calcium carbonate within it would have precipitated. If this proposed mechanism is valid, the rootless structures formed when discrete batches of water flashed within the ignimbrite. The vertical cylindrical structures which are more common formed where repeated batches of water rose up through a pre-heated conduit and flashed at different levels.

The ignimbrite in this "fumarolic" area is commonly pink instead of the more typical white. Other than color there are no apparent differences between the pink and white ignimbrite. The pink color indicates that the tuff was oxidized by the heated water and steam; similar coloration of tuffs above fumaroles have been described by Williams (1942, p. 86-87).

The ignimbrite in this pink zone forms resistant cones or "tepees" which commonly occur around the cylinders of cemented tuff (figure 26). Where the tuff is white there are no resistant cones, just bare cylinders.

STRUCTURE

The rocks of the Hackberry Mountain area were deformed during the late Miocene and possibly during Pliocene and early Pleistocene times. This deformation consists primarily of faults with subordinate folds. All faults are normal and trend northwest. Most dip southwest and have an average vertical separation of 25 meters. They are parallel to the major fault in this region, the Verde fault which is nine kilometers southwest of Hackberry Mountain (plate 6). The Verde fault dips northeast, has a vertical offset as great as 900 meters (Twenter and Metzger, 1963, p. 63), and is the northeastern boundary fault of the Black Hills.

The Hackberry Mountain area is a poorly defined northwest trending structural trough. The axis of this trough roughly bisects the area. Rocks along its southwestern limb dip 15° northeast, and those along its northeastern limb dip gently southwest, less than 1°. Rocks that adjoin the Sally May Dacite stock are generally steeply upwarped.

The Hackberry Mountain area forms the southeastern boundary of the Verde Valley. This valley was developed chiefly by normal faulting.

Faults

The rocks of the Hackberry Mountain area are offset by many, generally parallel, normal faults that trend northwest with a mean strike of N 38° W, a trend similar to that of the axis of the Verde Valley. Normal faults with similar trends occur throughout this region and have been mapped in the Verde Valley area by Lindgren (1926), Anderson and Creasey (1958), Lehner (1958), Twenter and Metzger (1963), Ulrich and Bielski (in preparation), and Wolfe (in preparation). Normal faults with similar strikes have been mapped along the Mogollon Rim north of the

Verde Valley by Huff and others (1966). They have been described in the Flagstaff area (Wolfe, personal commun., 1980; U.S. Geological Survey, 1980) and in Tonto Basin (Barsch and Royse, 1972, p. 61). Some of the faults in the Hackberry Mountain area were mapped previously by Twenter and Metzger (1963), Elston and Scott (1973b), and Scott (1974).

All faults in the Hackberry Mountain area are normal. Their dip ranges from 45 degrees to vertical and the majority dip between 55 and 70 degrees; most dip southwest. No evidence for strike slip was recognized on any fault. The faults are generally parallel. However, they are commonly interconnected especially where closely spaced.

All units older than surficial deposits are offset by these faults. The amount of offset on any fault varies along strike and may change considerably over a short distance. The average offset is about 25 meters. The amount of offset decreases to the southeast along most faults. Along some faults the stratigraphically lower units are offset more than higher ones, which indicates that these faults were active while the Miocene rocks accumulated.

The faults of the Hackberry Mountain area occur in two general groups. These groups are separated by a fairly wide region of undisturbed rocks which occurs within the western portion of Cottonwood Basin and continues southeast through Hackberry Mountain. The group that occurs to the southwest of this region is the Verde River fault zone, and all faults within this zone cross the Verde River. The group northeast of this region is the Sycamore Canyon fault zone. The combined stratigraphic throw for both fault zones is about 400 meters with the southwest side downdropped.

Most of the faults occur in the northwestern half of the Hackberry

Mountain area; the majority of these cannot be traced southeast past a line that trends northeast from Hackberry Mountain primarily because the faults die out at about this line, and secondarily because the faults are buried by surficial deposits or enter regions of monotonous lithology (e.g. Sally May Dacite) and cannot be discerned.

Sycamore Canyon fault zone

The Sycamore Canyon fault zone contains fewer than 10 faults. Most dip southwest and can be traced for fairly long distances, up to 10 kilometers. Typically, those that cannot be traced far dip northeast. These faults are widely spaced and are rarely interconnected. The maximum vertical throw across this zone, measured for Member 1 of the Cimarron Hills Andesite, is 315 meters downdropped to the southwest. The individual faults have an average throw of 50 meters. Three faults of interest are described below.

Cottonwood Spring fault--This fault is the southwesternmost of those in the Sycamore Canyon fault zone and was mapped previously by Twenter and Metzger (1963) and Scott (1974). It cuts across the central portion of Cottonwood Basin and dies out south of Sycamore Canyon. The fault is a single strand except at its southeastern end where it splits into two branches which rejoin. The fault dips 75 to 80° southwest.

The Cottonwood Spring fault offsets the Verde Formation and several Miocene volcanic units, and it is covered by deposits of alluvium and terrace gravel. In Sycamore Canyon the fault has a stratigraphic throw of 10 meters. It was difficult to determine the amount of offset within Cottonwood Basin because of the flat terrain. However, the contact between the Verde Formation and the underlying Thirteenmile Rock Basalt has an estimated offset of 35 meters. Offset within the the Verde Formation could not be determined because of a lack of marker beds.

An apparent fault scarp of up to 80 meters in height occurs along this fault in the southern part of Cottonwood Basin. The scarp is on the northeastern side of the fault and is underlain by basalt flows and cinder assigned to Member 14 of the Hickey Formation. A low, featureless area underlain by the Verde Formation and Member 6 of the Towel Creek Tuff is southwest of the fault. No outcrops of the Verde Formation occur northeast of the fault; its absence might be due to 1) removal of the Verde Formation on the northeastern side of the fault by erosion after cessation of fault activity, 2) the sediments butting up against a pre-existing hill along which a fault later developed, or 3) displacement on the fault prior to or during deposition of the Verde Formation that formed a scarp against which the sediments accumulated. The first explanation is unlikely because there is no evidence for 80 meters of post-Verde offset on this fault. The second explanation also is unlikely because it requires a remarkable coincidence. Local relief on the unconformity between the Verde Formation and the older basaltic rocks is common in this region but nowhere else is it greater than five meters. Development of a fault scarp prior to or during deposition of the Verde Formation is the most probable explanation.

Fossil Creek Road fault--This fault lies northeast of the Cottonwood Spring fault and can be traced from the eastern end of Wingfield Mesa southeast to Hackberry Basin. Fossil Creek Road commonly crosses or follows near the fault. The fault could not be traced farther south than Hackberry Basin where it passes into the lithologically monotonous Towel Creek Tuff. Nevertheless, it has the longest trace of any fault in the Hackberry Mountain area. The fault is a single strand 10.5 kilometers long that dips southwest at angles ranging from 60° to vertical.

The Fossil Creek Road fault, like the Cottonwood Spring fault, offsets the Verde Formation and older volcanic units and is buried by surficial deposits. Because it occurs chiefly within terrain of low relief or within lithologically homogeneous units, it is difficult to measure the displacement of this fault. The displacement is between 25 and 100 meters in Hackberry Canyon; this measurement is poorly constrained because stratigraphically equivalent units on opposite sides of the fault are separated by substantial distances.

Geologic relationships along the northern part of this fault are similar to those of the Cottonwood Spring fault. Along both faults the topographically low Verde Formation and Member 6 of the Towel Creek Tuff butt up against a scarp composed of mafic volcanic rocks. There are no exposures of Verde Formation and only a few of Member 6 of the Towel Creek Tuff east of the Fossil Creek Road fault. Probably, the Verde Formation and the tuff butted up against an active fault scarp when they accumulated.

Tenmile Tank fault--This fault occurs northeast of the Fossil Creek Road fault and can be traced from the northern boundary of the mapped area southeast to Hackberry Basin. The fault is a single strand as far southeast as Sycamore Canyon beyond which it splits into two branches. The southwestern branch connects with another fault. Where this fault is a single strand, it is parallel to and southwest of Forest Highway 9. The Tenmile Tank fault dips steeply southwest, has a maximum displacement of 85 meters, and offsets Miocene volcanic rocks.

Northwest of Sycamore Canyon the Tenmile Tank fault is covered by an apparently undisturbed older gravel. Buried beneath the gravel at this outcrop is a scarp 35 meters high that dips southwest at an angle greater than 45°. This is the steepest fault scarp in this area, probably because it was protected from erosion by the gravel. It is unlikely that the buried scarp resulted from differential erosion because massive, resistant basalt occurs on both sides.

Verde River fault zone

The Verde River fault zone is about six kilometers wide and contains as many as 30 closely spaced normal faults that are commonly interconnected and can be traced for up to six kilometers. The individual faults in this zone have an average vertical separation of about 25 meters. Most dip southeast but many also dip northeast. The net stratigraphic throw across the Verde River fault zone is about 90 meters, down to the southwest. The Verde River from Brown Springs south to the Childs powerplant is parallel to this fault zone, and its course was probably determined by it (see figure 27).

Age of faulting

Geologic relationships along both the Cottonwood Spring and Fossil Creek Road faults in Cottonwood Basin suggest that both were active prior to or during deposition of the Verde Formation. As this part of the Verde Formation is 7.8 to 8.4 m.y. old (the age of the interbedded Member 6 of the Towel Creek Tuff, table 6) both faults probably were active by this time.

Other faults in the Hackberry Mountain area may also have been active at about the same time. If so, the stratigraphic throw on other faults might decrease at successively higher stratigraphic levels.

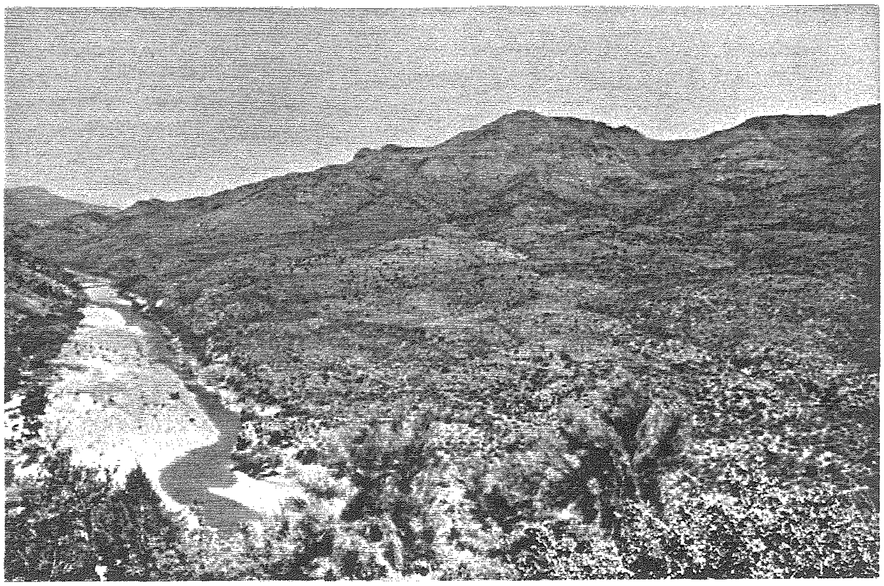


Figure 27.--Straight section of the Verde River where course is determined by faults within the Verde River fault zone. Towel Peaks are in right background. View northwest.

Although the field evidence is ambiguous, the vertical throw appears to be constant for strata that underly the Thirteenmile Rock Basalt; it may decrease in younger units.

The scarp of the Tenmile Tank fault that is covered by the older gravel is very steep. Regardless of lithology, very steep scarps (>45°) are usually no older than 10,000 years (Wallace, 1977, p. 1274). If this scarp was produced by fault displacement, it probably was buried soon after the Tenmile Tank fault ceased activity. As the older gravels were tentatively assigned a Pliocene or Pleistocene age, the Tenmile Tank fault may have been active during the Pliocene or possibly the early Pleistocene. Morrison and others (1981, p. 182) arrived at a similar conclusion for the activity on the Verde fault.

In summary, faults in the Hackberry Mountain area probably were active in the Miocene (7.8 to 8.4 m.y.), and offset along them may have continued into the Pliocene and possibly into the early Pleistocene.

Relation to regional tectonics

A plot of the trend of all dikes in the Hackberry Mountain area indicates that the many are parallel to the mean trend of the faults (figure 28). Scott (1974, p. 28-29) had earlier reported similar trends for the faults and dikes within his Thirteenmile Rock Volcanics (all units above the basal contact of Member 1 of the Towel Creek Tuff). Basaltic dikes of the Hickey Formation in the northern Black Hills have a similar strike (Lehner, 1958).

Normal faults and dikes occur perpendicular to the direction of least principal horizontal stress. Because the average strike for both in the Hackberry Mountain area is the same, they both probably formed under a similar stress field in which the least principal horizontal

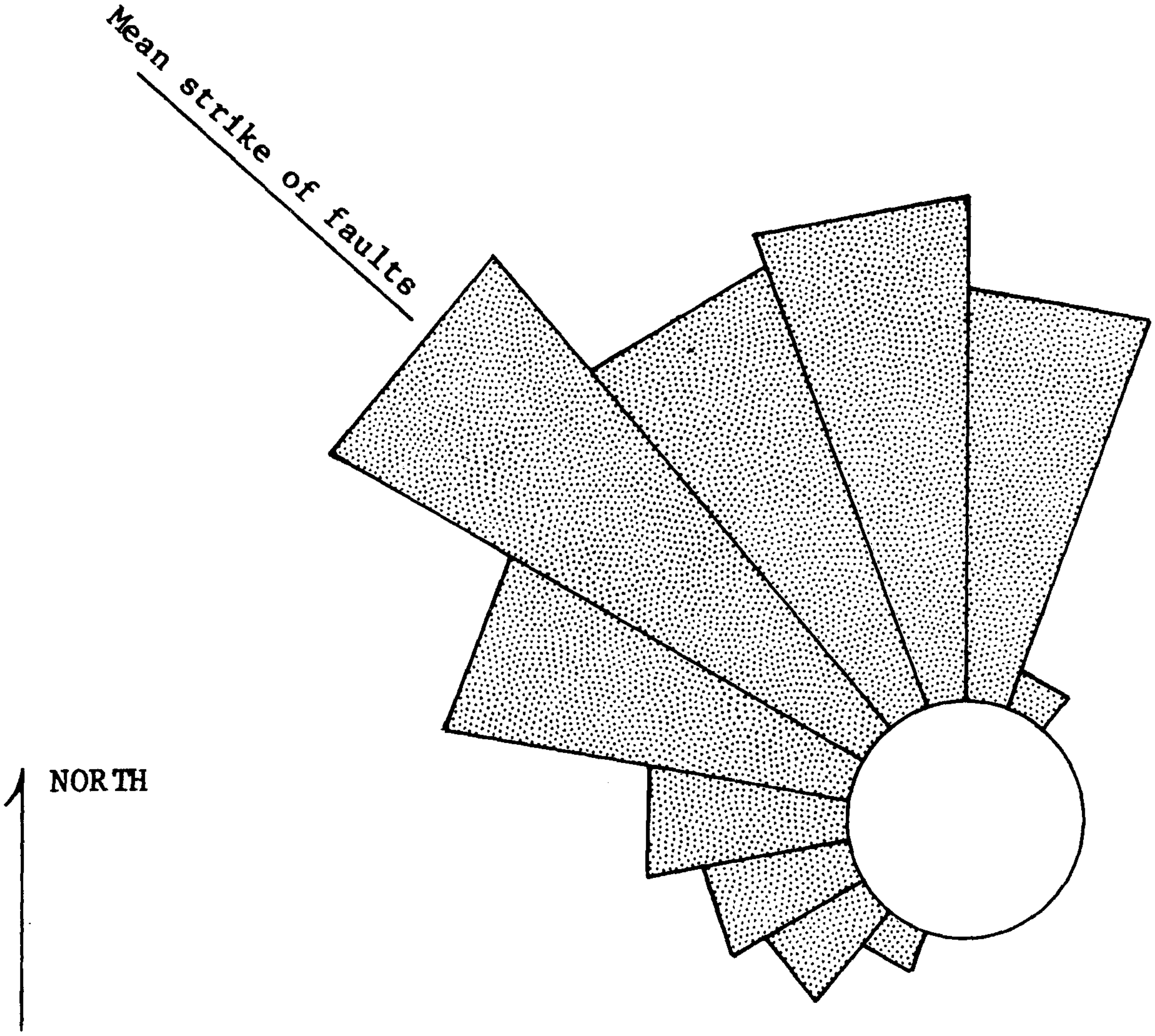


Figure 28.--Frequency versus strike of all dikes in the Hackberry Mountain area (modified from Scott, 1974, p. 28). Strike of 147 dikes measured. Single radial line represents mean strike of faults in the Hackberry Mountain area, 312°.

stress trended towards the northeast.

Folds

The rocks of the Hackberry Mountain area have been deformed into a broad northwest-trending assymetric syncline. The poorly defined axis for this fold is parallel to the normal faults and probably occurs between the Verde River and Sycamore Canyon fault zones. The southwestern limb of the syncline has a steeper dip that the northeastern (see cross section D-D' of plate 3). This fold is the continuation of a large syncline that is coincident with the axis of the Verde Valley (Twenter and Metzger, 1963, p. 63).

The strata within the southwestern limb of this syncline generally dip northeast. However, the younger beds within this limb (they occur primarily in the northwestern part of the limb) have diverse dip directions because they are affected by the quaquaversal initial dip of the Hackberry volcano. The angle of dip for all beds within this limb ranges from five to 25° and generally is between 10 and 15°. Much of the regional dip of this limb is compensated by displacement on the numerous normal faults of the Verde River fault zone.

The rocks within the northeastern limb of this syncline dip gently west with an average dip, determined for Member 1 of the Cimarron Hills Andesite, of 0.9°. A maximum of 1.5° occurs near the Tenmile Tank fault. This westward dip is so gentle that it may be entirely initial dip. The strata in this limb dip the same direction as most of the normal faults within the Sycamore Canyon fault zone.

The age of this syncline is poorly constrained. All rocks that underlie the rubble unit are folded; it could not be determined if the rubble and overlying units were deformed because they occur within the flat-lying axial region and are affected by the quaquaversal initial dip of the Hackberry volcano. No surficial deposits appear to be deformed by this syncline. It could be argued that because this fold and the normal faults have similar orientations, they are related and may be coeval.

Several small folds occur within Brushy Prong and the region to its west. These folds occur within 2.5 kilometers of surface exposures of the Sally May Dacite. They include two pairs containing an anticline and a syncline each and also a lone anticline. All the folds are short; the longest axis can be traced for less than one kiliometer. One anticline-syncline pair occurs in Brushy Prong, it plunges to the west; the other pair is in the next valley west, it plunges southwest. In both pairs the anticline is more tightly folded than the syncline and occurs south of the syncline. The anticline within Brushy Prong is the most tightly folded; both limbs dip as steeply as 55 to 70° (figure 29). The northern limbs of both synclines dip about 10° south. Small patches of altered ignimbrite of Member 3 of the Towel Creek occur in the cores of both anticlines. The lone anticline occurs north of Towel Creek and south of The Rocks. It plunges northeast. This fold is gentle; both limbs are generally no steeper than 15°. The axial trace of this anticline is offset slightly by a normal fault and appears to line up with that of the anticline in the valley west of Brushy Prong. The bedrock between these two folds is covered by extensive colluvium.

The units folded include Members 2, 3, and 4 of the Towel Creek Tuff and Members 11 and 13 of the Hickey Formation. The flat-lying flow of Hackberry Mountain Dacite unconformably overlies these folded

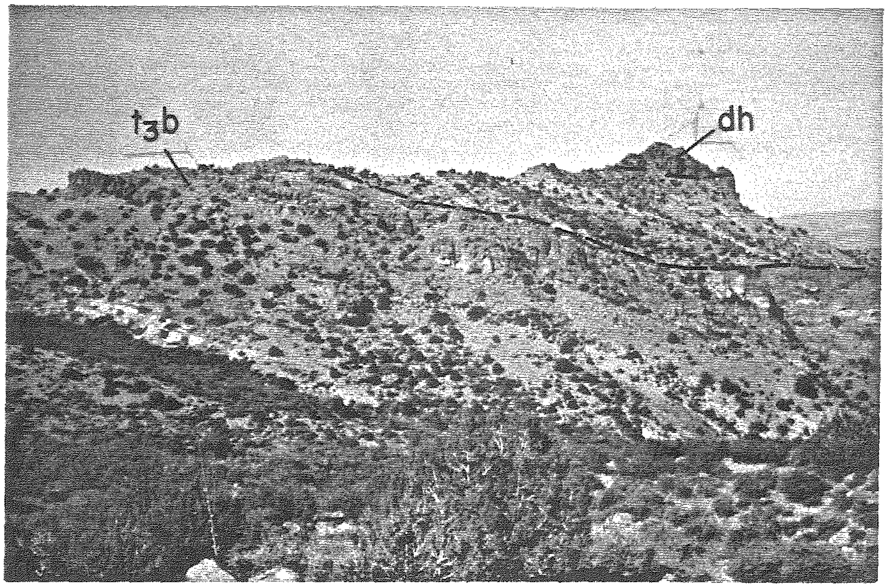


Figure 28.--Folded dacitic pyroclastic breccias of Member 3 (t_3b) of the Towel Creek Tuff on west side of Brushy Prong.
dh - Hackberry Mountain Dacite

members. Therefore, the folding occurred after accumulation of Member 4 of the Towel Creek Tuff and before extrusion of the Hackberry Mountain Dacite, from 7.8 to 9.6 m.y. ago (table 6).

The only other steeply inclined beds in the Hackberry Mountain area occur adjacent to the Sally May Dacite stock and its apophyses in Hackberry Basin. The small folds in the Brushy Prong area probably were formed over apophyses or dikes of the Sally May Dacite stock that have yet to be uncovered by erosion. This cause of the folding is consistent with the facts that the synclines are much more open than the anticlines and that altered dacitic tuff occurs within the cores of two of the anticlines. Similarily altered tuff is found elsewhere only close to the contact of Sally May Dacite stock. The folding occurred at about the same time as the emplacement of the Sally May Dacite stock, and the folds are also in fairly close proximity to the stock. If the anticlines are located over apophyses or dikes of Sally May Dacite, the synclines evidently are the result of horizontal compression accompanying the injection of these subjacent bodies.

DEVELOPMENT OF THE VERDE VALLEY

The Verde Valley is one of several late Cenozoic sedimentary basins that occur in the central Arizona mountain belt. The Hackberry Mountain area forms the southeastern boundary of this valley, and the investigation of this area has provided insight into the development of the sedimentary basin. Earlier workers suggested that the valley was formed when a lava dam blocked the ancestral Verde River (Jenkins, 1923, p. 69; Mahard, 1949, p. 104; Lehner, 1958, p. 586; Wadell, 1972, p. 18; Elston and Scott, 1973; Elston, McKee, Scott, and Gray, 1974, p. 610). The results of this study, however, indicate that the southeastern boundary of the Verde Valley was formed both by volcanic activity and structural deformation.

Starting about 14.6 m.y. ago (Krieger and others, 1971) the Hickey formation began to accumulate in the region of the Verde Valley. The basalt flows of the Hickey were extruded from cinder cones in the southern part of the region, and those in the northern part were possibly extruded from fissures (Lehner, 1958, p. 585; 1962, p. 96). While the Hickey was accumulating, the Verde fault zone, an ancient Precambrian structure, was reactivated. The area northeast of the fault was downdropped. The Black Hills are the upthrown block to the southwest. Faulting is believed to have begun at this time because there are no volcanic rocks in the Black Hills, just west of the Hackberry Mountain area, that are correlative with the Thirteenmile Rock Basalt (Scott, 1974, p. 26). The youngest dated rock in the Black Hills is a basalt flow 10.7 ± 0.4 m.y. old (Anderson and McKee, 1971, p. 2772). Absence of younger lavas suggests that there already was a fault scarp present when lavas of the younger Thirteenmile Rock Basalt were extruded from sources to the east. The Verde fault scarp may have formed a barrier to these flows. If so, uplift along the Verde fault began before 7.8 to 8.5 m.y. ago, the age of the oldest Thirteenmile Rock Basalt (table 6).

Northwest striking normal faults in the Hackberry Mountain area were active by 7.8 to 8.4 m.y. ago (age of the faulted Verde Formation) and probably continued until at least 6 m.y. ago (age of the youngest Verde in this area). During this same period, the rocks of the Hackberry Mountain area were probably deformed into a broad, gentle syncline. The faulting and folding probably occurred in response to the uplift on the Verde fault zone, which passes southwest of this area (see plate 6 for location of Verde fault).

The northeastern margin of the Verde Valley has been an enigma for some time. Early workers considered it erosional because no faults were identified (Mahard, 1949, p. 113; Feth and Hem, 1963, p. H22). Investigations by Akers (1962, p. B98) and Twenter and Metzger (1963, p. 61-63) indicated that this margin is the western limb of the Mormon Mountain anticline, a very broad northwest trending anticline whose dips do not exceed 4° on either limb. The crest of the anticline is nine to 15 kilometers east of the Verde Valley (plate 6). They considered the Verde Valley to be a syncline on the flank of this anticline. Elston, McKee, Scott, and Gray (1974, p. 607) and Elston, Nations, and Gray (1974, p. 639) recognized that rocks in northeastern part of the Hackberry Mountain area dip gently towards the Verde Valley.

Recent work by Wadell (1972, p. 63), Ulrich and Bielski, (in preparation) and the present study indicate that the northeastern margin of the Verde Valley owes its presence, in part, to northwest-trending normal faults. Displacement on these faults has contributed to the subsidence of the floor of the valley. Ulrich (personal commun., 1981) reported that about one-half of the total downdrop of strata toward the valley in the West Clear Creek area is from tilting and one-half is from fault offset. In the Hackberry Mountain area, about 60 percent is from fault offset and the remainder is from the westward tilt.

Fault displacement is considered by most to be the only means of downdrop on the southwestern boundary of the Verde Valley. However, the volcanic strata that occur within the strands of the Verde fault zone commonly dip towards the valley (Elston, McKee, Scott, and Gray, 1979, p. 607; Elston, Nations, and Gray, 1979, p. 639), and locally they dip as steeply as 25° (Wolfe, personal commun., 1980). Beds of the Verde Formation on the western side of the valley also commonly have appreciable eastward dips (Elston, Nations, and Gray, 1974, p. 639).

The southeastern boundary of the Verde Valley occurs within the Hackberry Mountain area because of structural features and volcanic activity. Most of the normal faults that contribute to the subsidence of the basin die out to the southeast of the area studied. Also, the Verde fault splays into several branches west of this area, and their total offset is less than that of the single branch (Twenter and Metzger, 1963; Wolfe, personal commun., 1980; U.S. Geological Survey, 1982b). The Mormon Mountain anticline dies out at a point about parallel with the southern boundary of the valley (Twenter and Metzger, 1963, p. 62); consequently, the westward-tilting of beds on the eastern flank of the Verde Valley also dies out in the same area.

The Hackberry volcano lies squarely to the southeast of the Verde Valley along its structural axis, and it must have contributed to the southern closure of this basin. The oldest tongue of Verde Formation overlies Member 4 of the Towel Creek Tuff. The Hackberry volcano was a major edifice, with greater than 500 meters of relief, when this tuff was erupted. Therefore, this dacite volcano probably impeded the southeastern drainage of this valley thus permitting deposition of the Verde Sandstone. The northwestern dips of the Verde Formation within Cottonwood Basin are probably initial dips off the flank of the volcano, and they provide further evidence that the Hackberry volcano was a major factor in the development of this basin. Remnants of the Hackberry volcano are prominent today and form a barrier which the Verde River must still detour around.

The northwestern boundary of the Verde Valley was determined primarily by erosion that dates back to the excavation of the ancestral Verde Valley. However, structural features at the northern boundary of the valley are similar to those at the southeastern, and they undoubtedly were important in the development of this margin. Fault offset along the Verde fault rapidly diminishes near the northwestern margin of the valley. The offset is about 600 meters south of Jerome (Anderson and Creasey, 1958, p. 80), and it reverses a few kilometers to the northwest (Lehner, 1958, p. 572).

Nations and others (1981, p. 143) suggested that the Verde formation could be separated into two portions whose boundary coincides with the Miocene-Pliocene boundary. The Miocene rocks consist of clastics overlain by evaporites in the southern part of the valley and overlain by limestones and dolomitic limestones in the northern part. The distribution of Miocene rocks within the Verde Formation documents a drainage pattern that flowed from the north and east into a closed basin with interior drainage. The Pliocene rocks are predominantly fossilferous lacustrine limestone with fine- to medium-grained interbedded clastic sediments; an environment of circulating fresh water and an external drainage is indicated by these sediments. On the basis of their sedimentological and paleontological data, Nations and others (1981, p. 146) suggested that, as the valley floor of the initially closed basin was aggraded by sedimentation, the ponded water overflowed to the south. This established a through-flowing drainage system that prevented the accumulation of evaporites. They further state that continued displacement along the Verde fault caused subsidence of the aggrading basin floor at or slightly below the drainage threshold.

Although an external drainage apparently had developed by the Pliocene, lacustrine sedimentation was still an important factor in the later history of the Verde formation. Most of the Pliocene lacustrine deposits are fresh-water, algal limestones which contain fossils of plants and animals that required water less than three meters deep (Twenter and Metzger, 1963, p. 48; Nations and others, 1981, p. 146). Mahard (1949, p. 119) cited the absence of shoreline features in the rocks surrounding the basin as evidence that the lake was shallow. The presence of the clastic rocks interbedded with the limestones indicates that the basin was periodically drained throughout the Pliocene (Nations and others, 1981, p. 146). Therefore, the Verde Valley required a balance between aggradation, subsidence, and erosion at its southern boundary to maintain a shallow water level throughout most of its history.

The age of the Verde Formation indicates subsidence of the basin from about 2.5 to 9.6 m.y. ago. There is ample evidence that the Verde fault zone was active while the Verde formation was accumulating. Anderson and Creasey (1958, p. 82) reported a zone up to 30 centimeters thick of crushed Verde Formation in outcrops adjoining the Verde fault. Wolfe (personal commun., 1980; U.S. Geological Survey, 1982b) discovered fan deposits within the Verde Formation near Squaw Peak that were derived from the erosion of the scarp along the Verde fault. Clasts of the Precambrian rock which presently constitute the lower 400 to 500 meters of the scarp are not contained within these deposits. This indicates more than 400 meters of displacement on the Verde fault since deposition of these alluvial fans of the Verde Foramtion.

Although the Verde formation intertongues with the Hickey formation and Thirteenmile Rock Basalt at the southeastern end of the valley, it is in unconformable contact with the Hickey formation at the northern end of the valley (Anderson and Creasey, 1958, p. 59; Lehner, 1958, p. 558; Twenter and Metzger, 1963, p. 45). This apparent discrepancy is the result of the long period of depostion of the Verde Formation. The Verde at the southern end of the valley is about 6 to 9.6 m.y. old and that at the northern end is less than 4.5 m.y. old (Bressler and Butler, 1978, p. 326). During this period of time the Hickey formation ceased accumulating, and it was uplifted considerably by the boundary faults of the Verde basin. The much younger Verde formation rests with angular unconformity on the older Hickey formation.

Deposition of the Verde formation ended when the rate of subsidence of the basin decreased relative to the rate of downcutting of the river at the southeastern boundary of the basin. Once this happened, the Verde river began to be incised into the sedimentary deposits of the basin. The Verde fault zone may have become inactive by about the end of deposition of the Verde Formation.

Summary

The sequence of events responsible for the development of the Verde Valley can be summarized as follows:

(1) Extrusion of the basalts of Hickey formation by at least 11.5 to 11.7 m.y. b.p. (before present).

(2) Reactivation of Verde fault during final stages of accumulation of the Hickey.

(3) Development of sedimentary basin with interior drainage caused by construction of the Hackberry volcano and subsidence of the basin.

(4) Deposition of basal unit of the Verde Formation beginning around 9.6 m.y. b.p. and concomitant extrusion of upper Hickey formation and Thirteenmile Rock basalt.

(5) Deposition of evaporitic sediments at southeastern end of basin starting about 8 m.y. b.p.

(6) Aggradation of sediments allows water level of lake to overtop southeastern boundary of basin and external drainage develops; occurs about 5 m.y. b.p.

(7) Deposition of freshwater limestones and clastics till around 2.5 m.y. b.p.

(8) Incision of the Verde River at the southeastern boundary of basin which terminated deposition of Verde formation.

(9) Erosional excavation of part of Verde formation.

EVOLUTION OF THE HACKBERRY VOLCANO

Hackberry volcano today

Today the Sally May Dacite stock occurs within the central part of the Hackberry volcano. The stock is hydrothermally altered and has been heavily eroded to form a large (about 4.5 kilometers across) heavily vegetated, bowl-shaped depression of considerable relief. The rhyolite diatreme occurs within the stock and is distinctive because of the resistant elongate bodies of rhyolite along its boundary which rise above the tuff-breccia and altered dacite.

The boundary of the stock is only exposed at the Cimarron Hills. Here many dikes and plugs of massive dacite protrude from the stock into the adjoining pyroclastic rocks of the Towel Creek Tuff and Cimarron Hills Andesite. The plugs can be traced north from the stock into Hackberry Basin where several resistant ones pierce through the dacitic pyroclastic deposits.

Thick sequences of the Towel Creek Tuff surround the Sally May Dacite stock. These sequences are typically resistant and consist of white dacitic pyroclastic rocks with subordinate buff sedimentary rocks. They form the flanks of the Hackberry volcano and locally can be traced into the surrounding mafic volcanic rocks with which they interfinger. Especially thick sequences (up to 250 meters thick) occur within Hackberry Basin, Boulder Canyon, and atop Ike's Backbone.

The most complete section of Towel Creek Tuff occurs within the eastern part of Towel Creek and in Brushy Prong. Here there is a thick sequence of dacitic pyroclastic breccia with subordinate ignimbrites and flows separated from the stock by younger landslides. As this section is traced west, its character rapidly changes; the dacitic pyroclastic breccias pinch out, the ignimbrites become the dominant lithology, and thick sequences of reworked tuffs appear. Farther west the ignimbrites and sediments thin and tongues of basalt appear. As the Towel Creek Tuff is traced beyond this point, it separates into several thin members that can be followed through Bull Run Creek to the Verde River where most pinch out.

The peaks west and south of the Hackberry volcano are capped by a thick, resistant flow of dacite, the Hackbery Mountain Dacite. Outcrops of this flow unconformably overlie the Towel Creek Tuff and mafic flows beneath it. The flow locally overlies, apparently with structural concordance, a sequence of thick-bedded rubble. The rubble is especially thick at Chalk Springs and is visible at a considerable distance.

General history of the Hackberry volcano

The Hackberry volcano was active from 10.6-11.7 to 7.8-8.4 m.y. ago (table 6). Its history can be divided into four phases: 1) pyroclastic; 2) intrusion of the Sally May Dacite stock; 3) rhyolitic activity; 4) extrusion of the Hackberry Mountain Dacite.

The members of the Towel Creek Tuff accumulated during the pyroclastic phase of the Hackberry volcano. These members consist primarily of numerous dacitic ignimbrites, subordinate breccias and reworked tuffs, and minor dacite flows, air-fall tuffs, base-surge tuffs, and lacustrine, fine-grained sediments. All or most of these units occur within the volcano; only the ignimbrites and air-fall tuffs occur in the most distal deposits. The basal members of the Towel Creek are more voluminous and better exposed than the upper three. Each successive basal member is more voluminous and its outcrop more extensive. These basal members were erupted between 10.6-11.7 and 8.9-9.6 m.y. ago. The upper three members were erupted from 7.8 to 8.5 m.y. ago and form small, discontinuous outcrops. They generally contain only ignimbrites, although Member 7 does include a dacite flow. Several rhyolitic ignimbrites within Member 7 were erupted from a vent outside the mapped area, possibly in the basin east of the Sycamore Buttes. Mafic volcanism occurred before, during, and continued after eruption of the Towel Creek Tuff. The distal deposits of the tuff are interstratified with basalt and andesite flows. During the waning stages of activity of Member 4 of the Towel Creek Tuff, several andesite flows were erupted from parasitic cinder cones that occurred within the Hackberry volcano.

The Hackberry volcano was forcibly intruded by a large dacite stock, the Sally May Dacite, after cessation of the pyroclastic phase and diminution in the volume of mafic volcanism. The stock is about eight kilometers in diameter and has a minimum volume of 30 cubic kilometers. This event and all succeeding volcanic events in the area occurred between 7.8 and 8.4 m.y. ago. Rocks adjoining the stock were upwarped considerably and some dip away from it at angles as great as 80°. The present high elevation of parts of the stock suggests that these parts, at least, breached the surface when emplaced. Shortly after its intrusion, the stock was hydrothermally altered. The alteration was followed by a major period of denudation during which thick, local deposits of flat-lying rubble accumulated around the periphery of the volcano. These rubble deposits unconformably overlie the Towel Creek Tuff.

The stock was later intruded by two rhyolite plugs. One plug occurs at the southwestern margin of Hackberry Basin and was emplaced along the boundary of the stock. The other intruded the central portion of the stock, and it possibly was the source for the rhyolite flow exposed near Hackberry Mountain. This plug was transfomed into a diatreme, possibly by a phreatic eruption, after extrusion of the flow.

The history of this volcano culminated with the extrusion of the Hackberry Mountain Dacite. This formation consists of a thick flow (up to 320 meters thick) erupted from vents that probably occurred within and outside of the Hackberry volcano. The outcrops atop Hackberry Mountain and Buckskin are believed to be remnants of a flow extruded from a vent now buried by landslides and located southeast of Hackberry Mountain. The source for the outcrops atop the Towel and Buzzard Peaks is unknown; all may have been derived from the same vent. The flow at The Rocks sits upon its vent. If the outcrops of this formation are considered to be the remnants of three flows, then greater than two cubic kilometers of dacite was erupted during this final phase of activity for the Hackberry volcano.

Pyroclastic phase

This section deals with the history of the Hackberry volcano during the early part of the pyroclastic phase, when Members 1 through 4 of the Towel Creek Tuff and the Hackberry Basin Member were erupted. The conditions under which the upper three members of this formation were erupted is not addressed because of lack of evidence.

The major lithology, by far, erupted from the Hackberry volcano during the pyroclastic phase was dacitic ignimbrites. They constitute a greater volume, there are more of them, and they are better exposed than any other rocks erupted during this period.

Rough bounds on the temperatures of the ignimbrites when they were emplaced can be set from paleomagnetic data of Scott (1974, p. 32-34) and from the lack of compaction and welding of the ignimbrites. Scott sampled the basal portion of a 12 meter thick ignimbrite from the Towel Creek Tuff, and obtained the same paleomagnetic directions for both a lithic fragment and the matrix. Therefore, the temperature of this tuff was above the minimum blocking temperature (425°C), as determined by a Curie balance, when emplaced.

Neither appreciable compaction nor welding was recognized in any ignimbrite in the Hackberry Mountain area. Riehle (1973, p. 2205) calculated that significant compaction of a rhyolitic ignimbrite would occur at a minimum temperature of 625°C for a 10 meter thick flow. A dacitic ignimbrite might be slightly less viscous than a rhyolitic one and, therefore, should show significant compaction at a lower temperature. Assuming that most ignimbrites of the Towel Creek Tuff are similar to the one sample by Scott, they probably were emplaced at temperatures between 425 and 625°C.

The ignimbrites probably cooled by mixing with air in a vertical eruption column. Smith (1960a, p. 805) suggests that ignimbrites with abundant glass escape welding only if they are cooled appreciably between the time they are erupted and the time they began their journey as pyroclastic flows. Ignimbrites preceded by air-fall of ash are rarely welded, apparently because their eruptive columns have a longer life span prior to collapse than the columns of the welded tuffs which do not have associated air-fall tuffs (Sparks and Wilson, 1976, p. 449). The longer life span of the eruptive columns allows the ash column to cool below the minimum temperature for incipient welding. Long lived eruptive columns are chiefly a consequence of high gas content of their magma (Sparks and Wilson, 1976, p. 449). Sparks and others (1978, p. 1731-1732) estimated that the water content must be greater than two percent to produce non-welded rhyolite ignimbrite. This estimate may also apply to dacitic ignimbrites although slightly higher water content of the magma may be required because the dacites are commonly less viscous and are erupted at higher temperatures than rhyolites. As many of the ignimbrites of the Towel Creek Tuff are underlain by air-fall tuffs, the model of Sparks and others (1978) suggests that the dacite magma had greater than two percent water content when erupted.

The presence of dacitic pyroclastic breccias within Members 2, 3, and 4 of the Towel Creek Tuff indicate that dacite dome(s) developed on the summit of the Hackberry volcano at several different times. It cannot be determined if there was a dacite dome when Member 1 accumulated because this member is not exposed sufficiently near the ancient volcano. The lack of pyroclastic breccias in the Hackberry Basin Member is puzzling because this member is believed to be correlative with Member 4. The Hackberry Basin Member may be younger than Member 4 and, when it accumulated, the dacitic dome(s) were no longer extant. Alternatively, the Hackberry Basin Member was deposited farther from the dome(s) and when the dome(s) collapsed, the ancient topography directed the resulting pyroclastic flows to the west rather than to the east and south where the present outcrops of the Hackberry Basin Member are located.

The presence of the lacustrine sediments within the Hackberry Basin member indicate that there was once a lake within the Hackberry volcano. Subsidence of part of the Hackberry volcano probably took place to form this lake. Very likely a shallow caldera developed during deposition of the

Hackberry Basin Member as a consequence of eruption of a relatively voluminous ignimbrite.

The only identified ignimbrite voluminous enough to have caused the formation of a caldera occurs within Member 4 of the Towel Creek Tuff. If Member 4 of the Towel Creek Tuff has been correctly correlated with the Hackberry Basin Member, this ignimbrite may occur at a proper stratigraphic position to account for subsidence and formation of the lake basin. The estimated volume for this ignimbrite is just great enough to be associated with formation of a shallow caldera (Smith, 1960a, p. 819; 1979, p. 6).

No independent structural evidence in the form of arcuate faults or ring dikes has been found for the presence of a caldera in the Hackberry volcano. However, the southern boundary of the fine-grained sediments, which may delineate the caldera, is not exposed, and the northern boundary is very poorly exposed.

Practically every outcrop of the fine-grained sediments, especially the laminated siltsones, is disrupted by small intraformational faults and slumps. These structures reflect deformation of the deposits before they had lithified. The slumping may have been caused by continued subsidence of the caldera, or by local seismicity. The presence of base-surge deposits higher in the section suggests that either another lake may have formed to the south or the same lake persisted but its northern boundary shifted to the south. The extent of the lake and suggested caldera will never be known because of the subsequent intrusion of the Sally May Dacite.

Pattern of eruptions during the early history of the Hackberry volcano

In general, each of the four basal members of the Towel Creek Tuff contains the same sequence of lithologies. From the base up this sequence is: (1) minor air-fall tuffs interbedded with many (commonly 5 to 15) non-welded ignimbrites; (2) pyroclastic breccias and rare dacite flows interbedded with thinner ignimbrites; (3) a thick unit of reworked tuffs. This generalized sequence shows that the eruptive activity began with the emplacement of numerous, small pyroclastic flows which were most voluminous in the beginning stages of activity but were emplaced throughout the eruptive period. As the quantity of ignimbrites emplaced began to wane, large dacite domes grew within the volcano, which collapsed intermittently with the subsequent accumulation of the pyroclastic breccias. The extrusion of stubby dacite flows may have occurred concomitantly with the growth of the dome. After dome development ceased, extensive erosion of the volcano resulted in depositon of the reworked tuffs.

This early history, in which the eruptive cycle was repeated at least four separate times, is an example of the Peléan style of eruption as originally defined by Lacroix (1904). According to Williams and McBirney (1979, p. 240) in a Peléan eruption:

> ... The most violent and destructive activity normally takes place during the opening stages where glowing avalanches of fresh, effervescing magma are produced. Airfall ejecta are generally much less widespread than those of most Vulcanian and Plinian explosions. Viscous magma follows to form steep-sided domes and spines or short, thick flows, the flanks of which may collapse by gravity or internal explosions to produce hot block-and-ash flows. The eruptive cycle generally lasts only a few years ...

The history for each eruptive period of the Hackberry volcano is similar to the 1902 and 1929-1932 eruptions of Mount Pelée (Bullard, 1976, p. 119-139; Perret, 1935) and the 1951 eruption of Mount Lamington (Taylor, 1958).

Although the Hackberry Basin Member probably is correlative in part with Member 4 and also possibly the lower members of the Towel Creek tuff, there are several major lithologic differences between the Hackberry member and these other members. The Hackberry Basin Member includes many more pyroclastic deposits than the other members, and thus it exhibits a more complete record of certain types of eruptive activity. However, there are no pyroclastic breccias within the Hackberry Basin Member. Either most exposed units of this member are younger than the breccias within Member 4 of the Towel Creek Tuff, or the breccias did not flow into this region because of a topographic barrier. If the presence of lacustrine deposits within the Hackberry Basin Member is the consequence of development of a caldera due to the eruption of the voluminous ignimbrite within Member 4, then the section of the Hackberry Basin Member exposed in Hackberry Basin is, for the most part, younger than the voluminous ignimbrite. If this is true, a significant time interval is represented by the lacustrine sediments.

The postulated development of a caldera within the Hackberry volcano may have led to a change in eruptive style from Peléan to Plinian. The presence of an increased number of air-fall tuffs in the Hackberry Basin Member in contrast to Members 3 and 4 (compare sections in appendix) also provide evidence, albeit weak, for a change in eruptive style. Plinian eruptions typically produce greater quantities of air-fall ejecta than Peléan (Williams and McBirney, 1979, p. 240, 245; MacDonald, 1972, p. 236). According to Williams and McBirney (1979, p. 244-245) in a Plinian eruption there are:

> ...voluminous explosions of pumice, first forming airfall showers and then glowing avalanches (ash-and-pumice-flows). So much magma is thereby drained from the feeding chamber that the top of the volcano may collapse to produce a caldera ...

Reworked tuffs greater than 75 meters thick occur in Member 4 of the Towel Creek Tuff west of The Rocks on the west flank of the volcano. These deposits record an episode of erosion that concluded the early pyroclastic history of the Hackberry volcano.

Sally May Dacite

Based upon its location, lithology, and size, I propose that the Sally May Dacite represents the material of the magma chamber of the Hackberry volcano after the chamber had migrated to the surface. The Sally May Dacite intruded and engulfed the central edifice of this volcano during its penultimate period of activity; little or no dacitic pyroclastic material was erupted subsequent to this event. The dacite of the intrusive and the dacites of the Towel Creek Tuff are similar in major-element chemistry and are lithologically indistinguishable. The lateral extent and shape of the Sally May Dacite, roughly circular with a diameter between seven and 8.5 kilometers, is analogous to those of known magma chambers (e.g. Kerr, 1982, p. 1302) and to many calderas (Williams, 1941; Christensen, 1979, p. 31) which are assumed to be equivalent in ground plan to their underlying magma chambers (Smith, 1979, p. 8).

Silicic magma chambers are believed to occur between two (Lipman and others, 1966, p. F45; Bailey and others, 1976, p. 742) and 7.5 kilometers beneath the surface (Smith and Shaw, 1975, p. 73; Heiken, 1979, p. 565). Therefore, the Sally May Dacite probably resided at these depths while the members of the Towel Creek were erupted.

Large intrusive silicic bodies rarely reach the surface. Generally they either solidify before reaching the surface or their upper portions are erupted violently with the attendant development of a caldera, for example Crater Lake (Williams, 1942). In the latter case, unmixing of the volatiles within the silicic magma chamber leads to evisceration of the chamber and collapse of the roof. As the Sally May Dacite magma never gave rise to a paroxysmal eruption it must have lacked the volatiles required for this type of eruption.

Method of intrusion

The Sally May Dacite stock probably was emplaced by a combination of stoping of the roof rocks and forceful injection. Stoping of the roof depends on sufficiently high density of the country rock that the stoped blocks will descend through the rising intrusive body. As it rose, the dacitic magma intruded Precambrian crystalline rocks, included mafic volcanic rocks, lower Paleozoic sandstone and carbonate rock, and Tertiary basalt almost all of which are denser than the dacitic magma (Daly and others, 1966). As it approached the surface, the dacite intruded and engulfed the stack of primarily clastic dacitic rocks of the Hackberry volcano. Because it is at a temperature greater than its solidus, the magma would have had a specific gravity seven to 10 percent less than the intruded solid dacite (Billings, 1972, p. 382). Whether these clastic blocks rose or sank must have depended on their porosity. Dense breccias probably were able to sink, whereas ignimbrites, air-fall tuffs, and sedimentary units may have floated.

Two blocks of dacitic air-fall tuff, up to 500 meters across, assigned to the Towel Creek Tuff are suspended in the Sally May Dacite stock. They occur west of the rhyolitic diatreme, and they lie at least 200 meters beneath the initial upper surface of the intrusive. These blocks may have been settling slowly through the dacite magma and probably were close to buoyant equilibrium with the molten dacite. Both blocks are somewhat altered and would have been much more difficult to distinguish if they had lacked well-developed beds. Smaller stoped blocks were not recognized, but this could be the result of lithologic and chemical similarity of wall roof blocks with the intrusive dacite, poor exposure because of alteration, and lack of recognizable structures in small blocks. Dense dacite blocks probably settled to a level in the intrusion beneath that exposed at present.

The upwarped country rock which surrounds the Sally May Dacite provides ample evidence for forceful injection of the stock. Stratified units adjoining the intrusive body dip away from it an angles as great as 70°. The entire section of rocks north of Hackberry Mountain up to Member 3 of the Thirteenmile Rock Basalt has been tilted north, away from the stock, at angles as great as 30°.

The best exposure of the contact between the Sally May Dacite and the intruded country rock is in the Cimarron Hills, and the contact relationships suggest that both forceful injection and magmatic stoping took place. Several dacitic dikes extend into the country rock from the Sally May Dacite in this area, and many more dacitic dikes occur within the country rock that cannot be traced back to the adjacent dacitic body. Several dacitic plugs occur along strike with the dikes. These dikes and plugs effectively divide the country rock into many relatively small blocks. The observed relationships suggest invasion of the country rock began with the emplacement of numerous dikes along zones of weakness. Many dikes strike northwest parallel to the normal faults of the area. Flow of magma in the dikes probably was soon concentrated in small plugs as indicated by the theory of Delaney and Pollard (1981). Blocks divided by these small intrusions then were engulfed by the underlying magma, if they had sufficient density.

Application of Stokes Law to a spherical body the size of the Sally May Dacite stock indicates that for typical values of crustal viscosity (10^{20} poises) and density contrast (0.3 gram/cubic centimeter) the stock can not rise by buoyant forces alone. Intrusion of the Sally May Dacite stock probably was facilitated by the crustal extension and normal faulting of the area. The initiation of faulting in the Hackberry Mountain area (7.8 to 8.4 m.y. ago) occurred at about the same time as the intrusion for the Sally May Dacite. When normal faulting was initiated, the dacitic magma probably was injected as dikes normal to the direction of regional extension. This may have initiated upward migration of the magma chamber. Continued tectonic extension probably facilitated continued ascent of the Sally May Dacite. The northwestern alignment of the dacitic plugs within Hackberry Basin and the similar direction of elongation for dacitic dikes assigned to the Sally May Dacite is consistent with this general interpretation.

Duration of silicic activity

Dacitic and, to a lesser extent, rhyolitic rocks were extruded from the vents within the Hackberry volcano for a considerable period of time, 2.2 to 3.9 m.y. (table 6). It is unlikely that a silicic magma chamber could remain molten that long without an external source of heat. One million years is considered sufficient to allow complete crystallization and solidification of silicic magma in even the largest chambers (Christiansen, 1979, p. 39).

A likely external heat source would be the intrusion of hot basaltic magma, a process proposed by many authors. This magma could either heat the rocks surrounding a silicic magma chamber (e.g. Lachenbruch and others, 1976, p. 781-782; Duffield and others, 1980, p. 2400-2402), or it could be injected directly into the silicic magma chamber (Eichelberger and Gooley, 1977, p. 59). The many basalt flows of the Hickey Formation and the Thirteenmile Rock Basalt that were extruded continuously during the life of the dacitic magma chamber in this area provide evidence that basaltic magma was present at depth.

The presence of numerous globular basic xenoliths within all the dacitic units of the Hackberry Mountain area suggests that the long life span of this magma chamber was a consequence of the injection of basaltic magma. These xenoliths are composed primarily of hornblende + plagioclase + vesiculated glass. Lithologically identical and chemically similar xenoliths (or inclusions) have been reported in many silicic and intermediate volcanic rocks (Eichelberger, 1975, p. 1334-1340; 1978, p. 23-24; 1980, p. 446; Eichelberger and Gooley, 1977, p. 59-65; Sparks and others, 1977, p. 316). These authors all considered the xenoliths to be the quenched remnants of basaltic magma that had been injected into cooler, more silicic magma chambers.

According to Eichelberger (1980), the basic xenoliths formed when wet but unsaturated basaltic magma was injected into the silicic magma chamber. The basalt was rapidly cooled and the enclosed water was concentrated in the glassy portion of the inclusion from which it eventually exsolved. As a result, vesicles were formed and the basaltic inclusions became less dense than silicic magma they intruded. The inclusions then rose upward through the magma chamber.

The basic xenoliths in the deposits erupted from the Hackberry volcano are chemically similar to all the basaltic rocks in the region However, these inclusions are quite different mineralogically. They contain crystals of hornblende and biotite and do not contain those of clinopyroxene and olivine which are typical of the basaltic rocks. Eichelberger (1978, p. 23) recognized this inconsistency and documented that the composition of the hornblende of the basic inclusions closely coincides with the composition of hornblende co-existing with melt in basaltic systems from 1000°C to 700°C. These xenoliths evidently contain hydrous phases not present in the basalt flows because they crystallized at a higher pressure where the dissolved water was in equilibrium with the melt.

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APPENDIX

STRATIGRAPHIC SECTIONS

The thickness of stratigraphic units was measured with a Jacob's staff. The measurements of thickness are recorded in the stratigraphic sections to the nearest 1/2 meter when the individual unit is greater than 10 meters thick; when the individual unit is less than 10 meters thick, the thickness is recorded to the nearest 1/10 meter. In many places repeat measurements could be as much as 10 percent above or below the recorded measurement. A plus or minus (±) is used for thicknesses that seem significantly less accurate than average because of poor exposure or structural complexity; a query (?) is used for values that are probably even less accurate.

The rock names for volcanic flows follow the guidelines proposed by Streckeisen (1979); the rock names for pyroclastic rocks follow the guidelines proposed by Schmid (1981); the rock names for gravels follow the guidelines proposed by Willman (1942). An olivine basalt is a basalt that has greater than 20 percent modal olivine phenocrysts or microphenocrysts. The terminology for textures and structures of volcanic rocks follows that of Williams and others (1954). In this report, microvesicles are those vesicles with an average diameter of less than one millimeter; microphenocrysts are those phenocrysts with an average diameter of less than one millimeter. The terminology for stratification of sedimentary and pyroclastic rocks follows that of McKee and Weir (1953). All percentages were determined by comparison with the charts prepared by Terry and Chilingar (1955). For each unit in the stratigraphic section, the resistance and quality of exposure are only applicable to the area where they were measured.

The locations of the stratigraphic sections are shown in plate 8.

1. COTTONWOOD WELL

[Measured November 1980 along the northern side of the canyon 1000 m east of Cottonwood Well]

Top of section; not top of exposure, overlain by older gravel of Quaternary and/or Tertiary age.

Towel Creek Tuff:

Member 7 (incomplete):

Tuff: Meters

12. Dacitic air-fall tuff, light bluish-gray; weathers same color. Upper portion of unit is structureless; lower portion has well developed very thin beds, 1.5 to 2 cm thick. Well sorted, fine to coarse sand size, subrounded grains. Contains white plagioclase crystals (70%); white dacitic pumiceous grains (25%); blue dacitic lithic grains (5%), usually the largest of the different types; red to brown mafic mineral grains (trace). Poorly indurated; highly porous, at least 25% of volume; very poorly exposed; non-resistant; basal contact not exposed---------- 6.5+

Thirteenmile Rock Basalt:

Undivided:

Flow:

11. Basalt, purplish-brown; weathers same color; upper 3 m is brecciated, rest of flow is massive. Porphyritic: contains subhedral olivine microphenocrysts (5 to 10%), altered to iddingsite; euhedral to subhedral green pyroxene phenocrysts (trace), average 1 mm across; very dark gray aphanitic groundmass. Vesicular (0 to 20%); filled with calcite; subrounded to rounded; average 3 to 4 mm across; basal portion of flow is most vesicular. Horizontal to sub-horizontal joints, 1 to 2 cm apart. Well exposed; very resistant; sharp basal contact----------- 14.0

Offset in section so that units 11 and 12 were measured 140 m west of underlying units.

10. Basaltic ash, pale red; weathers pale yellowish-brown; structureless. Contains orange anhedral olivine microphenocrysts (30%), altered to iddingsite; subhedral green pyroxene microphenocrysts (5%), as large as 1 mm; subhedral white plagioclase microphenocrysts (trace); calcite (65%), coats all grains, fills all pore spaces. Well indurated; poorly exposed; moderately resistant; sharp basal contact-- 1.3

9. Basalt, dark bluish-gray; weathers rust and metallic blue; upper 1/3 of flow is brecciated, rest is massive. Microporphyritic: contains euhedral green pyroxene microphenocrysts (20%), as large as 2 mm; subhedral olivine microphenocrysts (10%), as large as 1.5 mm; dark bluish-gray aphanitic groundmass. Poorly developed columnar joints in basal portion of flow; very well developed horizontal

1. COTTONWOOD WELL--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Flow--Continued | Meters

joints. Very well exposed; lower 2/3 of flow is extremely resistant, upper 1/3 is moderately resistant; sharp basal contact-- 10.5

Towel Creek Tuff:
Member 6:

8. Dacitic ignimbrite, grayish-orange-pink; weathers same color; structureless. Contains white subhedral plagioclase microphenocrysts (15%), as large as 1 mm; white rounded dacitic pumiceous lapilli (7%), average 5 mm across, as large as 3 cm; subhedral hornblende microphenocrysts (2%); subrounded red dacitic lithic fragments (1%), average 1.5 mm across; euhedral golden biotite microphenocrysts (trace), slightly altered; rounded basaltic lapilli and bombs (trace), green pyroxene rich, as large as 10 cm; glass dust matrix. Well indurated; very poorly exposed; non-resistant; basal contact not exposed------------------- 1 ?

Cimarron Hills Andesite:
Member 1:
Flow:

7. Andesite, gray to brownish-gray, base is red; weathers same colors; basal 24 m is brecciated, rest of flow is massive. Porphyritic: contains milky-white euhedral to subhedral plagioclase phenocrysts (5%), lath-shaped, average 2 mm across, as large as 6 mm; subhedral olivine microphenocrysts (trace), altered to iddingsite; euhedral green pyroxene microphenocrysts (trace); gray very fine-grained groundmass. Very well exposed; very resistant; sharp basal contact--------------------------------------- 34.5

Hickey Formation:
Member 14:
Cinder:

6. Basaltic ash, grayish-orange; weathers grayish-orange-pink; structureless. Contains subangular to subrounded brownish-red basaltic lapilli and bombs (10%), 5 mm to 2 m across, average 8 mm across; subhedral green pyroxene microphenocrysts (5%), as large as 3 mm; orange anhedral olivine microphenocrysts (4%), altered to iddingsite; white subhedral plagioclase microphenocrysts (1%), as large as 2 mm; dust size matrix (25%); calcite (55%), fills all pore spaces. Very well indurated, calcareous cement; poorly exposed; moderately resistant; basal contact not exposed-- 6.6
5. Basaltic breccia, medium red; weathers same color; brecciated, clasts average 2 cm across, as large as 80 cm. Porphyritic: contains euhedral green pyroxene pheno-

1. COTTONWOOD WELL--Continued

Hickey Formation--Continued
Member 14--Continued
Cinder--Continued — Meters

crysts (15%), average 2.5 mm across; orange equant subhedral olivine phenocrysts (10%), altered to iddingsite, average 2 mm across; gray aphanitic groundmass. Very well exposed; very resistant; sharp basal contact---------- 2.5

4. Basaltic ash, grayish-orange-pink; weathers same color. Well developed laminae, average 3 mm thick; shown by differences in grain size, finer- and coarser-grained laminae. Finer-grained laminae are moderately sorted, coarse to fine sand size, subangular; coarser-grained laminae are poorly sorted, granule to fine sand size, subangular. Unit contains brown basaltic lithic grains (30%); orange microvesicular basaltic vitric grains (15%); orange olivine crystals (5%), altered to iddingsite; green pyroxene crystals (2% in finer-grained laminae, 5% is coarser-grained laminae); calcite (45%+), fills all pore spaces. Poorly indurated, calcareous cement; very poorly exposed; non-resistant; basal contact not exposed--- 17 ±

Offset in section so that overlying units measured 120 m east of underlying beds.

Cimarron Hills Andesite:
Member 1:
Flow:

3. Andesite, base and top of flow are rusty brown, main body of flow is dark olive; weathers same colors; may be two separate flows. Porphyritic: contains white euhedral plagioclase phenocrysts (15%), lath-shaped, commonly sieved, always have orange rims, bimodal size distribution, 2.5% are 3 to 5 mm long and 1.5 mm wide, 12.5% are 1 mm long; subhedral olivine phenocrysts (1%), altered to iddingsite, average 1 mm across; equant subhedral green pyroxene phenocrysts (trace), average 1 mm across; blue aphanitic groundmass. Smaller size plagioclase is commonly glomerophyric or cumulophyric with pyroxene; olivine occurs in rare cumulophyres with pyroxene. Vesicular (1 to 20%); all are lined with silica; spheriodal; average 3 mm across, as large as 15 mm; comprise 20% of upper and lower portions of flow, 1% of central portion of flow. Vesicular portion of flow has poorly developed horizontal and vertical joints; central portion of flow has well developed horizontal to sub-horizontal joints, 3 to 10 cm thick, and poorly developed vertical joints. Very well exposed; vesicular portion of flow is extremely resistant, rest of flow is moderately resistant; sharp basal contact-- 25.0

1. COTTONWOOD WELL--Continued

Hickey Formation:
Member 14:
Flow: Meters
2. Basalt, very dark gray; weathers olive green; base of unit is brecciated, average 80 cm thick. Porphyritic: contains subhedral to euhedral olivine phenocrysts (10%), altered to iddingsite, average 1 mm across, as large as 2 mm; euhedral green pyroxene phenocrysts (trace), lath-shaped, average 1 mm across; very dark gray aphanitic groundmass. Rare cumulophyres of olivine + pyroxene, average 1.5 mm across. Irregular arcuate vertical joints; regular horizontal joints. Very well exposed; lower 2/3 of unit is extremely resistant, upper 1/3 is very resistant; sharp basal contact---------------------------------- 19.0

Cinder (incomplete):
1. Basaltic ash, grayish-orange-pink; weathers same color. Well developed laminae; average 3 mm thick, as thick as 1.5 cm; expressed by differences in concentration of basaltic lithic and basaltic vitric grains; thicker beds are composed primarily of basaltic lithic grains. Moderately sorted; coarse to fine sand size; subrounded. Contains purplish-brown basaltic lithic grains (30%); orange microvesicular basaltic vitric grains (15%); orange olivine crystals (5%), altered to iddingsite; green pyroxene crystals (trace); calcite (50%), fills all pore pore spaces. Poorly indurated, calcareous cement; very well exposed; moderately resistant------------------------ 15.0+

Base of secton; base of exposure.

2. SYCAMORE CANYON

[Measured November 1980 along the northern side of Sycamore Canyon about 1.6 km southwest of Thirteenmile Rock Butte]

Top of section; top of exposure.
Thirteenmile Rock Basalt:
Undivided:
Flow (incomplete):
14. Basalt, dark gray; weathers bluish-gray and rust. Porphyritic: contains subhedral olivine phenocrysts (0.5%), altered to iddingsite, average 1 mm across; subhedral to euhedral green pyroxene phenocrysts (trace), average 1 mm across; dark gray aphanitic groundmass. Rare cumulophyres of olivine microphenocrysts surrounded by pyroxene microphenocrysts, average 5 mm across. Slightly vesicular (7%); all are filled with calcite; most are stretched, up to 4 mm long. Well developed horizontal joints, aver-

2. SYCAMORE CANYON--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Flow (incomplete)--Continued — Meters

age 1 cm apart. Well exposed; moderately resistant; sharp basal contact-- 3.0+

Cimarron Hills Andesite:
Member 2:
Flow:

13. Andesite, medium reddish-brown; weathers same color. Porphyritic: contains milky-white subhedral to euhedral plagioclase phenocrysts (10%), lath-shaped, average 1 mm long; subhedral olivine phenocrysts (5%), altered to iddingsite, average 1.5 mm across; subhedral green pyroxene phenocrysts (2%), average 1 mm across; dark gray aphanitic groundmass. Extremely vesicular; commonly lined with calcite; usually stretched out, quite irregular in shape. Poorly developed columnar joints, average 1 m across; poorly developed horizontal joints, 20 to 50 cm apart. Well exposed; very resistant; sharp basal contact-- 7.5

Offset is section so that overlying units measured 300 m northeast of underlying units.

Thirteenmile Rock Basalt:
Undivided:
Flow:

12. Basalt, very dark gray; weathers brownish-gray. Porphyritic: contains subhedral orange olivine phenocrysts (12%), altered to iddingsite, average 1.5 mm across, as large as 3 mm; subhedral green pyroxene phenocrysts (trace), average 1 mm across, most occur as glomerophyres 1.5 mm across; very dark gray aphanitic groundmass. Well developed sub-horizontal joints, average 20 cm apart, best developed in the base of flow; well developed sub-vertical joints, 10 cm to 1 m apart. Main body of flow is well exposed and very resistant, upper 9 m is very poorly exposed and non-resistant; sharp basal contact------ 20 ±
11. Basalt, dark gray; weathers same color or dark yellowish-orange; compound flow, boundary 13.5 m above base. Porphyritic: contains subhedral green pyroxene phenocrysts (25%), average 2 mm across, as large as 6 mm; subhedral olivine phenocrysts (2%), altered to iddingsite, average 1 mm across, as large as 7 mm; dark gray aphanitic groundmass. Rare cumulophyres; large olivine phenocrysts surrounded by small (0.5 mm across) pyroxene microphenocrysts; 1/4 of all olivine occurs in cumulophyres. Extremely well developed joints; pervasive horizontal set, average 10 cm apart; vertical to sub-vertical set, average 30 cm apart. Very well exposed; very resistant; sharp basal contact-- 25.5

2. SYCAMORE CANYON--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Flow--Continued — Meters

10. Basaltic ash, grayish-pink; weathers pale red; structureless. Contains subrounded orange basaltic vitric grains (50%), as large as 1 mm; subrounded brown basaltic lithic grains (7%), average 1 mm across, as large as 5 mm; subhedral green pyroxene microphenocrysts (3%), as large as 1 mm across; randomly scattered red vesicular basaltic bombs (trace), green pyroxene rich; calcite (40%), fills all pore spaces. Well indurated, calcareous cement; extremely poorly exposed; non-resistant; basal contact not exposed-- 16.0
9. Basalt, dark gray, weathers medium gray. Porphyritic: contains subhedral olivine microphenocrysts (9%) and phenocrysts (1%), altered to iddingsite, phenocrysts average 1.5 mm across; subhedral green pyroxene phenocrysts (1%), average 1.5 mm across; dark gray aphanitic groundmass. 1/2 of pyroxene occurs in glomerophyres, average 1 cm across, as large as 3 cm. Basal portion of flow contains trace amount of round xenoliths, composed of plagioclase + quartz, average 6 cm across. Slightly vesicular (3%); filled with calcite; average 1.5 mm across, as large as 1 cm. Well developed joints; horizontal set is 10 to 20 cm apart; vertical set is 20 to 50 cm apart. Very well exposed; extremely resistant; basal contact not exposed---------------------------------- 33 ±
8. Basaltic ash, moderate red; weathers pale red. Well developed very thin to thin beds, 2.5 to 20 cm thick. Contains subrounded orange basaltic lithic grains (85%), aphyric, average 0.5 mm across, microvesicular; calcite (15%), fills pores and vesicles. Well indurated, calcareous cement; very poorly exposed; non-resistant; basal contact not exposed-- 3.5
7. Basalt, dark brown; weathers dark olive and bluish-brown; lowermost and uppermost 1 m of flow are brecciated, rest of flow is massive. Porphyritic: contains subhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across; subhedral to euhedral green pyroxene phenocrysts (2%), average 1 mm across; dark brown aphanitic groundmass. Cumulophyres of green pyroxene surrounded by olivine crystals are quite common, average 2 mm across. Slightly vesicular (3%); filled with calcite; irregular in shape and stretched; average 1.5 by 5 mm. Well exposed; very resistant; sharp basal contact-------------- 4.5
6. Basaltic ash, dark yellowish-orange; weathers same color; structureless. Contains subrounded orange basaltic vitric lapilli (60%), average 3 mm across, microvesicular; subrounded brown basaltic lithic lapilli (4%), average 3 mm across, as large as 1 cm; subhedral green pyroxene microphenocrysts (1%); calcite (35%), fills all pore

2. SYCAMORE CANYON--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Flow--Continued Meters
spaces and 1/2 of microvesicles. Moderately well indurated, calcareous cement; poorly exposed; non-resistant; basal contact not exposed---------------------------------- 4.3

Cimarron Hills Andesite:
Member 1:
Flow:
5. Andesite, medium dark gray; weathers medium blue and rusty-brown where vesicular. Lowermost 2 m and uppermost 6 m of flow is brecciated and vesicular, rest of flow is massive. Porphyritic: contains euhedral milky-white plagioclase phenocrysts (10%), usually lath-shaped, commonly have thin (<1/2 mm) orange rims, average 1.5 mm long, as long as 6 mm; subhedral olivine microphenocrysts (2%), altered to iddingsite, as large as 1 mm across; euhedral green pyroxene phenocrysts (2%), average 1 mm across; medium dark gray aphanitic groundmass. Cumulophyres (1% of rock); pyroxene + plagioclase or pyroxene + olivine; round; average 2 mm across. Vesicular portion of flow (20% vesicles); filled with calcite; either spheroidal or stretched, spheroidal average 3 mm across, stretched are 2 to 3 mm wide and up to 4 cm long. Vesicular portion of flow has poorly developed joints, horizontal set averages 1 to 1.5 m apart, sub-vertical set averages 1 m apart; massive portion of flow has very well developed joints, arcuate sub-horizontal set averages 10 to 15 cm apart, sub-vertical set averages 30 to 40 cm apart. Moderately well exposed; vesicular portions of flow are very resistant, massive portion of flow is extremely resistant; sharp basal contact---------------------------- 21 ±

Hickey Formation:
Member 15:
4. Basalt, medium gray; weathers light gray; basal 30 cm is brecciated. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across; euhedral green pyroxene phenocrysts (2%), average 1 mm across, as large as 6 mm, also occur in rare glomerophyres that average 1.2 cm across; medium gray aphanitic groundmass. Well developed arcuate vertical joints, average 1 to 2 m apart; poorly developed horizontal joints, average 1 m apart. Very well exposed; extremely resistant; sharp basal contact---------------------------- 23.5
3. Basaltic ash, pale red; weathers same color. Well developed thin beds; average 15 cm thick, as thick as 40 cm; shown by differences in grain size. Unit contains rounded basaltic lithic lapilli (45%), microvesicular (filled with calcite), average 2 mm across, as large as 5 mm; subhedral

2. SYCAMORE CANYON--Continued

Hickey Formation--Continued
Member 15--Continued Meters

red olivine phenocrysts (10%?), altered to iddingsite, average 1 mm across; subhedral green pyroxene phenocrysts (2%), average 1 mm across, as large as 2 mm; basaltic bombs (trace), green pyroxene rich, average 7 cm across, as large as 20 cm; anhedral clear plagioclase phenocrysts (trace), average 2 mm across; calcite (43%), fills all pore spaces. The source vent for this unit is 700 m to the southwest. Very well indurated, calcareous cement; very well exposed; extremely resistant; sharp basal contact--- 9.4

2. Basalt, very dark bluish-gray; weathers medium bluish-gray. Porphyritic: contains subhedral olivine microphenocrysts (2%), altered to iddingsite, as large as 1.5 mm across; euhedral green pyroxene phenocrysts (1%), average 1.5 mm across, as large as 1 cm; aphanitic groundmass. Moderately developed vertical joints, 15 cm to 1 m apart; poorly developed arcuate horizontal joints, average 1 m apart. Very well exposed; extremely resistant; very sharp basal contact-- 11.0

1. Basalt (incomplete), brownish-gray; weathers medium gray to medium bluish-gray; aphyric, aphanitic groundmass. Slightly vesicular (2 to 5%); filled with concentrically banded silica; usually stretched, direction parallel to joints; 2 to 3 mm thick and as long as 3 cm. Very well developed vertical joints, averages 80 cm apart; well developed horizontal joints, averages 5 cm apart. Very well exposed; extremely resistant-------------------------- 9.0+

Base of section; base of exposure.

3. THIRTEENMILE ROCK

[Measured December 1980 and April 1981 700 m east of Thirteenmile Rock Butte]

Top of section; top of exposure.
Thirteenmile Rock Basalt:
Undivided:
Flow (incomplete):

15. Olivine basalt, grayish-black; weathers medium gray. Porphyritic: contains anhedral olivine phenocrysts (20%), altered to iddingsite, average 1 mm across, as large as 3 mm; subhedral green pyroxene microphenocrysts (25%); subhedral white plagioclase phenocrysts (trace), average 2 mm across; aphanitic groundmass. Well developed horizontal joints, average 20 cm apart; moderately developed vertical joints, 0.5 to 1 m apart. Well exposed; extremely resistant; sharp basal contact------------------- 10.0+

3. THIRTEENMILE ROCK--Continued

Cimarron Hills Andesite:
Member 3:
Flow: Meters

14. Andesite, moderate reddish-brown; weathers same color; basal 2.7 m is brecciated. Porphyritic: contains subhedral white plagioclase phenocrysts (12%), lath-shaped, commonly have orange rim, average 1.5 mm long, as long as 4 mm; anhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across; subhedral green pyroxene phenocrysts (1%), average 1.5 mm across; aphanitic groundmass. Moderately vesicular (20%); some are filled or lined with silica; usually stretched; 1 to 2 mm across. Poorly developed vertical and horizontal joints, average 1 m apart. Well exposed; very resistant; sharp basal contact---------------------------------- 17.0

Thirteenmile Rock Basalt:
Undivided:
Flow:

13. Basalt, medium dark gray; weathers medium gray and brownish-gray. Porphyritic: contains subhedral olivine phenocrysts (10%), average 1 mm across, as large as 3 mm; subhedral plagioclase microphenocrysts (4%); subhedral to euhedral green pyroxene phenocrysts (2%), average 1 mm across; aphanitic groundmass. Moderately developed horizontal joints, 10 to 50 cm apart; poorly developed vertical joints, average 1 m apart. Well exposed; very resistant; basal contact not exposed---------------------- 11.0

Towel Creek Tuff:
Member 7:
Tuff:

12. Siltstone, pale yellowish-brown; weathers dark yellowish-brown; structureless. Poorly sorted; contains medium to very coarse sand size mineral grains [subrounded plagioclase (40%) and biotite + hornblende (5%)] in a clay to silt size matrix (55%). Very poorly exposed; non-resistant; basal contact not exposed-------------------------- 14 ?

11. Dacitic ignimbrite, light brown; weathers same color; structureless. Contains subrounded bluish-gray dacitic lithic lapilli (30%), as large as 1 cm across; anhedral white plagioclase phenocrysts (20%), as large as 5 mm across; subhedral hornblende and biotite phenocrysts (2%); glass dust matrix. Lack of pumice is very unusual. Very poorly exposed; non-resistant, basal contact not exposed--- 4 ?

3. THIRTEENMILE ROCK--Continued

Thirteenmile Rock Basalt:
Undivided:
Flow: Meters

10. Basaltic tuff, grayish-orange; weathers same color; structureless. Contains subrounded orange basaltic vitric lapilli (40%), microvesicular, average 2 mm across, as large as 1 cm; subrounded reddish-brown basaltic lithic lapilli (2%), average 3 mm across, as large as 1 cm; subhedral green pyroxene phenocrysts (trace), average 1 mm across, as large as 1 cm; calcite (58%), fills all pore spaces and microvesicles. Moderately indurated, calcareous cement; non-resistant; basal contact not exposed------ 9.0

9. Basalt, medium dark gray; weathers medium gray. Porphyritic: contains subhedral olivine phenocrysts (2%), altered to iddingsite, average 1 mm across; very fine-grained groundmass. Moderately developed horizontal joints, average 10 cm apart; poorly developed vertical joints, average 50 cm apart. Moderately exposed; moderately resistant; sharp basal contact-------------------- 2.0

8. Basalt, grayish-black; weathers medium gray; basal 1.5 m is a red breccia. Porphyritic: contains subhedral to euhedral green pyroxene phenocrysts (20%), average 1 mm across, as large as 5 mm; subhedral to anhedral olivine phenocrysts (2%), altered to iddingsite, average 1 mm across; aphanitic groundmass. Very well developed horizontal joints, 20 to 50 cm apart. Well exposed; extremely resistant; sharp basal contact------------------ 13.0

7. Basalt, medium to very dark gray; weathers dark gray; uppermost 1 m is brecciated. Porphyritic: contains subhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across, as large as 2 mm; aphanitic groundmass. Slightly vesicular (1%), filled with calcite. Moderately developed horizontal joints, 10 to 15 cm apart; poorly developed vertical joints, average 1 m apart. Well exposed; extremely resistant; basal contact not exposed--- 6.0

6. Basaltic tuff, grayish-orange; weathers same color; structureless. Contains subrounded purplish-brown basaltic lithic fragments (30%), average 1 mm across, as large as 2 mm; subrounded orange basaltic vitric lapilli (20%), microvesicular, 1 to 5 mm across; subhedral black pyroxene phenocrysts (1%), average 1 mm across; calcite (49%), fills all pore spaces and vesicles. Poorly indurated, calcareous cement; poorly exposed; moderately resistant; basal contact not exposed---------------------------------- 11.5

Offset in section so that overlying units measured 500 m south of underlying units.

3. THIRTEENMILE ROCK--Continued

Towel Creek Tuff:
Member 7:
Tuff: Meters

5. Dacitic ignimbrite, grayish-pink; weathers moderate orange-pink; lowermost 40 cm is air-fall tuff; unit contains two flow units, boundary 6.9 m above base; structureless. Contains subhedral white plagioclase phenocrysts (20%), average 1.5 mm across; subangular white to pale blue dacitic lithic lapilli (15%), average 2 cm across, as large as 1 cm; subangular grayish-purple basaltic lithic lapilli (7%), average 5 mm across, as large as 2 cm; rounded white dacitic pumiceous lapilli (3%), average 3 mm across; subhedral biotite and hornblende phenocrysts (1%), average 1 mm across; glass dust groundmass. Well indurated; poorly exposed; basal portion of unit is moderately resistant, upper portion is non-resistant; sharp basal contact-- 33.5

Thirteenmile Rock Basalt:
Undivided:
Cinder:

4. Basaltic tuff, similar to unit 2--------------------------- 7.8

Towel Creek Tuff:
Member 7:
Tuff:

3. Rhyolitic(?) ignimbrite, pale red; weathers same color; structureless. Contains rounded white silicic pumiceous grains (20%), average 1 mm across, as large as 1.5 cm; angular blue rhyolitic lithic grains (5%), average 1 mm across, as large as 5 mm; subangular basaltic lithic grains (1%), average 1 mm across, as large as 5 mm; subhedral biotite and hornblende microphenocrysts (trace); glass dust matrix. Well indurated; moderately exposed; moderately resistant; sharp basal contact----------------- 1.5

Thirteenmile Rock Basalt:
Undivided:
Cinder:

2. Basaltic tuff, light gray and yellowish-gray; weathers same colors. Well developed and very continuous thin beds; shown by differences in color related to grain size, the richer a bed is in the coarser basaltic lapilli the more orange it is; some well developed laminae within the beds, shown by concentrations of finer-grained basaltic lithic lapilli, average 5 mm across. Unit contains subrounded orange basaltic vitric grains (40%), average 1 mm across, as large as 2 mm; euhedral green pyroxene phenocrysts (5%), average 1 mm across; subrounded basaltic lithic lapilli (1%), average 1 cm across; silica (54%), fills all pore spaces. Moderately indurated,

3. THIRTEENMILE ROCK--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Cinder--Continued — Meters

siliceous cement; well exposed; moderately resistant. Gradational basal contact; uppermost portion of unit below is brecciated and the area between the blocks is filled in with a bedded basaltic tuff; the bedding of this basaltic tuff is unconformably overlain by the horizontal bedding of the basaltic tuff already described----- 28.0

Cimarron Hills Andesite:
Member 2:
Flow:
1. Andesite(not described).

Base of section; not base of exposure.

4. THE GROTTO

[Measured December 1980 along the northern side of the Verde River 1.8 km east of the intersection of Chasm Creek and the Verde River]

Top of section; top of exposure.
Thirteenmile Rock Basalt:
Member 1:
Flow (incomplete):

22. Basalt, dark gray; weathers moderate brown. Compound flow; four flows with boundaries at 9, 18, and 33 m above base of unit. Microporphyritic: contains subhedral olivine microphenocrysts (15%), altered to iddingsite; subhedral black to green pyroxene phenocrysts (7%), average 1 mm across, as large as 3 mm; aphanitic groundmass. Some portions of unit are slightly vesicular, all vesicles are filled with calcite. Poorly developed columnar joints, average 1 m apart. Moderately exposed; basal portion of unit is moderately resistant, upper portion is non-resistant; basal contact not exposed---------------------------- 34.5
21. Covered, probably Member 5 of the Towel Creek Tuff because of scattered blocks of dacite------------------------------ 11.5

Hickey Formation:
Member 15:

20. Basalt, dark gray; weathers same color. Microporphyritic: contains subhedral olivine microphenocrysts (5%), altered to iddingsite; subhedral black pyroxene phenocrysts (3%), average 1 mm across; very dark gray aphanitic groundmass. Slightly vesicular; filled with silica; stretched; average 0.5 by 2 mm. Poorly exposed; moderately resistant; basal contact not exposed--------------------------------------- 1.3

4. THE GROTTO--Continued

Verde Formation: Meters

19. Sandstone, pale pink and pinkish-gray; weathers same colors. Moderately developed very thin to thin beds shown by differences in concentration of lithic fragments; beds are quite variable in thickness, as thin as 1 cm where expressed by granule concentrations, as thick as 20 cm where bedding is shown by differences in concentration of dacitic pumiceous fragments; long axes of clasts are commonly parallel to beds. Unit contains lithic fragments (15%), [dacitic (1%) and mafic (14%)], granule to boulder size, average is pebble size, mafic rocks are subangular to angular; rounded white dacitic pumiceous fragments (1 to 10% depending upon bed), coarse sand to pebble size, average granule size; matrix (85%+), subangular to subrounded silt to medium sand size grains of plagioclase (98%), olivine (1%), green pyroxene (1%), biotite (trace), and hornblende (trace). Well indurated, calcareous cement; poorly exposed; non-resistant; basal contact not exposed-- 10 ±

Hickey Formation:

Member 15:

18. Basalt, grayish-black; weathers medium gray and dark olive. Microporphyritic: contains subhedral green pyroxene microphenocrysts (5%); anhedral to subhedral plagioclase phenocrysts (1%), commonly have orange rim, average 1 mm across, as large as 2 mm; aphanitic groundmass. Poorly developed columnar joints, average 1 m apart. Very well exposed; extremely resistant; sharp basal contact-- 5.7

17. Basalt, medium gray; weathers yellowish-gray. Microporphyritic: contains subhedral to euhedral green pyroxene microphenocrysts (1%); subhedral olivine microphenocrysts (trace), altered to iddingsite; aphanitic groundmass. Slightly vesicular (2%); filled with calcite; irregular shapes; average 2 mm across, as large as 1.5 cm. Well developed sub-horizontal joints, average 1 cm apart; moderately developed vertical joints, 30 cm to 1 m apart. Well exposed; extremely resistant; sharp basal contact-- 7.0

16. Basalt, medium gray; weathers dark olive and dusky gray; compound flow, contains 6 flows each 3 m thick. Microporphyritic: contains euhedral olivine microphenocrysts (5%), altered to iddingsite; subhedral green pyroxene microphenocrysts (trace); aphanitic groundmass. Slightly vesicular (5%); filled with calcite; spheroidal; average 2 mm across. Well developed sub-vertical joints, average 30 cm apart. Well exposed; very resistant; sharp basal contact-- 18 ±

4. THE GROTTO--Continued

Towel Creek Tuff:

Member 4: Meters

15. Pebbly sandstone, grayish-orange-pink; weathers same color. Moderately developed thin beds; 1 to 30 cm thick; shown by difference in size and amount of dacitic lithic fragments. Poorly sorted; very fine sand to boulder size. Contains subrounded plagioclase grains (35%), fine to very coarse sand size, average medium sand size; subrounded dacitic lithic fragments (15%), granule to boulder size, average pebble size; rounded white dacitic pumiceous fragments (5%), very coarse sand to granule size; subangular biotite and hornblende grains (2%), fine to very coarse sand size, average medium sand size; matrix (43%), very fine to fine sand size. Moderately indurated; moderately exposed; moderately resistant; sharp basal contact-- 15.5

14. Dacitic pyroclastic breccia, similar to unit 13------------- 9.0

13. Dacitic pyroclastic breccia, pinkish-gray, weathers same color; structureless. Contains white dacitic lithic lapilli and blocks (50%), average 4 cm across, as large as 50 cm; subhedral plagioclase phenocrysts (10%), average 1 mm across; euhedral biotite microphenocrysts (1%), as large as 2 mm across; glassy groundmass. Well exposed; very resistant; sharp basal contact------------------------ 4.0

12. Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded white dacitic pumiceous lapilli (30%), average 1.5 cm across, as large as 1 m across; subhedral plagioclase phenocrysts (25%), average 1 mm across, as large as 2 mm; subangular blue dacitic lithic lapilli (10%), 1 mm to 8 cm across, average 1 cm across; euhedral biotite phenocrysts (2%), 1 to 2 mm across; glass dust matrix. Well exposed; moderately resistant; sharp basal contact----------------------------- 2.5

11. Pebbly sandstone, grayish-orange-pink; weathers same color. Poorly developed thin beds; average 6 cm thick; shown by differences in concentration of dacitic lithic fragments. Poorly sorted; very fine sand to cobble size. Contains subangular to subrounded plagioclase grains (45%), medium to very coarse sand size; subrounded to subangular dacitic lithic fragments (10%), very coarse sand to cobble size, average pebble size; rounded dacitic pumiceous fragments (3%), coarse sand to pebble size, average granule size; subangular biotite and hornblende grains (2%), medium to coarse sand size; matrix (40%), very fine to fine sand size. Poorly exposed; moderately resistant; sharp basal contact----------------------------- 1.3

10. Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded white dacitic pumiceous lapilli (30%), average 3 mm across, as large as 4 cm; subhedral plagioclase phenocrysts (20%), average 1 mm across; subangular blue and pink dacitic lithic lapilli

4. THE GROTTO--Continued

Towel Creek Tuff--Continued
Member 4--Continued — Meters

(7%), average 1 cm across, as large as 10 cm; subhedral biotite and hornblende microphenocrysts (2%); subrounded hornblende-rich micro-diorite lapilli (trace); glass dust matrix. Well exposed; very resistant; sharp basal contact-- 8.5

9. Dacitic air-fall tuff, white; weathers same color; well developed laminae. Contains rounded white dacitic pumiceous grains (85%), average 1 mm across; subhedral plagioclase microphenocrysts (13%), as large as 1.5 mm across; euhedral biotite and hornblende microphenocrysts (2%). Poorly exposed; non-resistant; sharp basal contact--------- 0.5

Hickey Formation:
Member 13:
Flow:

8. Olivine basalt, medium bluish-gray; weathers dark olive; compound flow, consists of up to 7 separate flows. Porphyritic: contains euhedral olivine phenocrysts (20%), altered to iddingsite, average 1 mm across, as large as 2 mm; subhedral green pyroxene phenocrysts (5%), average 1 mm across; aphanitic groundmass. Cumulophyres with olivine phenocryst surrounded by pyroxene microphenocrysts are common, sometimes pyroxene is in the center surrounded by olivine; average 4 mm across. Slightly vesicular (7%); filled with calcite; usually have a stretched shape; average 1 to 3 mm across, as large as 1 cm. Well exposed; very resistant; basal contact not exposed-- 21.5

7. Basalt, dark gray; weathers medium gray. Porphyritic: contains subhedral olivine phenocrysts (2%), rims altered to iddingsite, average 1 mm across; subhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Somewhat vesicular (5%); filled with calcite; spheroidal; average 1.5 mm across, as large as 3 mm. Very well developed horizontal joints, average 1 cm apart; well developed sub-vertical joints, average 3 cm apart. Well exposed; extremely resistant; sharp basal contact----- 4.5

6. Basaltic ash, pale pink; weathers same color. Moderately developed laminae; expressed by differences in amounts of pore space; average 5 mm thick. Moderately sorted; fine to very coarse sand size; subrounded. Contains orange olivine crystals (50%), altered to iddingsite; orange basaltic vitric lapilli (10%), microvesicular; green pyroxene crystals (trace); calcite (40%), fills all pore spaces and microvesicles. Well indurated, calcareous cement; poorly exposed; non-resistant; basal contact not exposed-- 2.7

5. Basalt, grayish-black; weathers medium gray and grayish-orange; basal 60 cm of flow is brecciated, rest of flow

4. THE GROTTO--Continued

Hickey Formation--Continued
Member 13-Continued
Flow--Continued | Meters

is massive. Porphyritic: contains euhedral olivine phenocrysts (7%), altered to iddingsite, average 1 mm across; subhedral green pyroxene phenocrysts (1%), average 1 mm across; aphanitic groundmass. Well developed vertical joints, average 30 cm apart; moderately developed horizontal joints, average 2 cm apart. Very well exposed; extremely resistant; sharp basal contact---------- 21.5

4. Basalt, grayish-red; weathers brownish-gray; basal 1 m is brecciated, rest of flow is massive. Microporphyritic: contains subhedral green pyroxene microphenocrysts (1%); subhedral olivine microphenocrysts (trace), altered to iddingsite; aphanitic groundmass. Slightly vesicular (2%); filled with calcite; usually elongate; average 0.5 by 3 mm. Poorly developed horizontal and vertical joints; both average 40 cm apart. Well exposed; extremely resistant; sharp basal contact---------------------------------- 3.0

Towel Creek Tuff:
Member 3:
Tuff:

3. Dacitic ignimbrite, grayish-orange pink; weathers same color; structureless. Contains subrounded white to blue dacitic lithic lapilli (20%), average 1 cm across, as large as 10 cm; euhedral white plagioclase phenocrysts (20%); rounded white dacitic pumiceous lapilli (10%), average 5 mm across, as large as 10 cm, large lapilli are concentrated in the base of the flow; euhedral hornblende and biotite phenocrysts (3%); glass dust matrix. Well exposed; moderately resistant; sharp basal contact--------- 2.8

Hickey Formation:
Member 11:

2. Basalt, purple; weathers medium bluish-gray. Porphyritic: contains subhedral olivine phenocrysts (10%), rims altered to iddingsite, average 1 mm across; subhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Moderately vesicular (15%); all filled with calcite; spheroidal; average 2 mm across, as large as 2 cm. Well developed vertical joints; 1 to 4 cm apart. Well exposed; very resistant; sharp basal contact---------- 3.4

1. Basaltic agglomerate (incomplete), moderate red; weathers same color, grayish-purple, and light brownish-gray; structureless. Contains fusiform basaltic lapilli and bombs (40%), 1 mm to 20 cm across, average 5 mm across; finely comminuted basaltic groundmass (60%). Porphyritic: contains subhedral green pyroxene phenocrysts (5%), average 1.5 mm across; subhedral olivine phenocrysts (2%), altered to iddingsite, average 1.5 mm across, as

4. THE GROTTO--Continued

Hickey Formation--Continued
Member 11--Continued Meters
large as 3 mm; aphanitic groundmass. Slightly vesicular (10%), filled with calcite. Well exposed; moderately resistant--- 5.1+

Base of section; base of exposure.

5. DOE TANK

[Measured May 1981 along the southern side of Sycamore canyon about 2 km west of the intersection of Hackberry and Sycamore Canyons]

Top of section; top of exposure.
Thirteenmile Rock Basalt:
Member 1:
10. Basalt (incomplete), light olive gray; weathers dark olive and medium bluish-gray; compound flow, composed of many flows, average 5 to 10 m thick. Porphyritic: contains subhedral olivine phenocrysts (18%), altered to iddingsite, average 1 mm across, many are smaller than 1 mm, as large as 1 cm; subhedral green pyroxene (trace), average 1 mm across; aphanitic groundmass. Slightly vesicular (5%); filled with calcite; spheroidal; average 1.5 mm across, as large as 2 cm. Poorly developed vertical joints, average 10 cm apart. Poorly exposed; moderately resistant; sharp basal contact------------------------------ 90+
9. Basalt, medium brownish-red; weathers medium reddish-brown. Microporphyritic: contains subhedral to euhedral green pyroxene microphenocrysts (2%); subhedral olivine microphenocrysts (trace), altered to iddingsite; aphanitic groundmass. Moderately vesicular (10%); filled with calcite; average 1 mm across. Well developed vertical joints, average 50 cm apart. Moderately exposed; moderately resistant; basal contact not exposed----------------- 6.0
8. Basalt, dark brownish-gray; weathers dark olive. Microporphyritic: contains subhedral olivine microphenocrysts (5%), altered to iddingsite, as large as 1 mm across; aphanitic groundmass. Moderately vesicular (10 to 15%); filled with calcite; usually stretched; average 2 mm across, as large as 6 cm. Moderately developed vertical joints, average 0.5 to 1 m apart; poorly developed horizontal joints, average 1 cm apart. Poorly exposed; nonresistant; sharp basal contact------------------------------ 3.0
7. Basalt, medium gray and medium red (where brecciated); weathers medium bluish-gray and pale olive and same color (where brecciated). Compound flow; lower flow is 27 m thick, basal 6.7 m of upper flow is brecciated. Porphyritic: contains anhedral quartz phenocrysts (2%), average 2 mm across, as large as 5 mm; subhedral green pyroxene microphenocrysts (1%); olivine microphenocrysts (trace),

5. DOE TANK--Continued

Cimarron Hills Andesite--Continued
Member 1--Continued
Flow--Continued — Meters

crysts (7%), lath-shaped, commonly sieved, have orange rims, average 3 to 4 mm long, as long as 1 cm; subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 5 mm; aphanitic groundmass. Well developed horizontal joints in massive portion of unit, average 2 cm apart. Well exposed; moderately to very resistant; sharp basal contact---------------------- 35.5

2. Andesite, moderate red and pale blue; weathers same colors and moderate reddish-brown; moderate red where brecciated; basal 1.2 m is brecciated. Porphyritic: contains plagioclase phenocrysts (7%), identical to unit 3; subhedral olivine phenocrysts (2%), average 1 mm across, as large as 4 mm; aphanitic groundmass. Slightly vesicular (5%); spheroidal; average 1.5 mm across. Poorly developed vertical jointing, average 1 m apart. Well exposed; moderately to extremely resistant; sharp basal contact---------------- 3.0

Hickey Formation:
Member 15 (incomplete):

1. Basalt, medium gray and red where brecciated; weathers medium bluish-gray and dusky yellow; upper 2 m of unit is brecciated; aphyric; aphanitic groundmass. Well developed irregular vertical joints, average 35 cm apart. Slightly vesicular (5%); spheroidal; average 1 mm across. Well exposed; extremely resistant------------------------------ 7.0+

6. BUCKSKIN

[Measured November 1980 600 m due east of Dollar More Tank]

Top of section; top of good exposure. Overlying rocks are colluvium shed from the Hackberry Mountain Dacite which caps Buckskin.

Towel Creek Tuff:
Member 7:
Tuff:

20. Dacitic ignimbrite (incomplete), pale pink; weathers same color; structureless. Contains euhedral hornblende and biotite microphenocrysts (5%); rounded white dacitic pumiceous grains (2%), average 1 mm across, as large as 2 mm; subhedral plagioclase microphenocrysts (1%); glass dust matrix. Well developed horizontal and vertical joints, average 2.5 cm apart. Well exposed; moderately resistant; sharp basal contact----------------------------- 1.6

19. Sandstone, grayish-orange-pink; weathers same color; structureless. Poorly sorted; very fine sand through pebble size grains, average coarse sand size; subrounded. Contains white dacitic pumiceous grains (25%), make up coarse size fraction of rock, average granule size; plagioclase

6. BUCKSKIN--Continued

Towel Creek Tuff--Continued
Member 7--Continued
Tuff--Continued — Meters

grains (17%); dacitic lithic grains (15%); mafic lithic grains (10%); mafic mineral grains (3%); matrix (40%), fine sand size and smaller. Well exposed; very resistant; sharp basal contact-- 2.7

Thirteenmile Rock Basalt:
Undivided:
Flow:

18. Amygdaloidal basalt, very dark gray; weathers medium bluish-gray; upper 1.5 m is highly brecciated. Porphyritic: contains euhedral to subhedral olivine phenocrysts (7%), altered to iddingsite, average 1 mm across, as large as 2.5 mm; euhedral green pyroxene phenocrysts (1%), average 2 mm across; very fine-grained groundmass. Moderately vesicular (20%); filled with silica; spheroidal or elongate; average 2 mm across. Basal portion of flow has well developed horizontal joints, average 4 cm across. Very well exposed; extremely resistant; sharp basal contact----- 6.0

Cimarron Hills Andesite:
Member 3:
Flow:

17. Andesite, very dark gray; weathers medium bluish-gray; upper 3 m is highly brecciated. Porphyritic: contains subhedral to euhedral white plagioclase phenocrysts (7%), commonly have orange rims, average 2 mm across, as large as 5 mm; subhedral to euhedral olivine microphenocrysts (7%), altered to iddingsite; euhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Uppermost 10.5 m of flow is slightly vesicular (10%); filled with calcite; very irregular shapes; average 3 mm wide. Basal 7.5 m of flow has well developed horizontal joints, average 20 cm apart, and poorly developed vertical joints. Well exposed; extremely resistant; sharp basal contact-- 18.0

Thirteenmile Rock Basalt:
Undivided:
Flow:

16. Basalt, medium bluish-gray; weathers dark bluish-gray. Porphyritic: contains euhedral olivine phenocrysts (10%), altered to iddingsite, average 1.5 mm across, as large as 4 mm; subhedral to anhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Slightly vesicular; fulled with silica (?); spheroidal or stretched; average 2 mm across, stretched are as long as 5 cm. Well exposed; extremely resistant; sharp basal contact-- 9.0

6. BUCKSKIN--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Flow--Continued Meters

15. Basalt, dark bluish-gray; weathers dark olive; upper portion of flow is brecciated. Porphyritic: contains euhedral olivine phenocrysts (15%), altered to iddingsite, average 1.5 mm across; euhedral black pyroxene phenocrysts (5%), average 1 mm across; aphanitic groundmass. Slightly vesicular (2%); filled with silica. Well developed horizontal joints, average 10 cm apart; moderately developed vertical joints. Well exposed; moderately resistant; sharp basal contact-- 7.5

Cimarron Hills Andesite:
Member 3:
Flow:

14. Andesite, medium bluish-gray; weathers same color; lowermost 1.4 m and uppermost 8.5 m are brecciated. Porphyritic: contains euhedral plagioclase phenocrysts (8.5%), average 1 mm across; euhedral olivine phenocrysts (1%), rim or totally altered to iddingsite, average 1 mm across; aphanitic groundmass. Slightly vesicular (5%); filled with silica (?); spheroidal; average 1 mm across. Well exposed; extremely resistant; sharp basal contact---------- 17.5

Towel Creek Tuff:
Member 7:
Tuff:

13. Dacitic ignimbrite, pale red; weathers grayish-orange-pink; structureless. Contains subhedral plagioclase phenocrysts (25%), average 1 mm across; subrounded basaltic lithic lapilli (10%), average 7 mm across, as large as 2 cm, commonly vesicular; rounded white dacitic pumiceous lapilli (5%), average 2 mm across, as large as 2 cm; biotite and hornblende microphenocrysts (1%); glass dust matrix. Well exposed; extremely resistant; sharp basal contact---------- 1.4

12. Dacitic air-fall tuff, grayish-orange-pink; weathers same color. Well developed very thin beds; average 2 cm thick, as thick as 5 cm; shown by concentrations of white dacitic pumiceous lapilli. Contains white dacitic pumiceous lapilli (50%), average 5 mm across in pumice-rich beds and 2 mm across in pumice poor beds, as large as 2 cm in pumice-rich zones; subhedral plagioclase microphenocrysts (30%); subrounded dacitic lithic grains (10%), average 1 mm across; subrounded basaltic lithic lapilli (5%), average 2 mm across, as large as 1.5 cm; biotite and hornblende microphenocrysts (5%). Well exposed; extremely resistant; sharp basal contact------------------- 0.4

6. BUCKSKIN--Continued

Thirteenmile Rock Basalt:
Undivided:
Flow: Meters

11. Olivine basaltic breccia, pale reddish-gray; weathers very light gray; brecciated, consists of blocks averaging 15 cm across. Porphyritic: contains euhedral to subhedral olivine phenocrysts (30%), altered to iddingsite, average 3 mm across, as large as 7 mm; subhedral green pyroxene phenocrysts (5%), average 1.5 mm across, as large as 4 mm; aphanitic groundmass. Slightly vesicular (10%), filled with silica; spheroidal; average 2 mm across. Moderately exposed; moderately resistant; basal contact not exposed-- 18.5

10. Basaltic tuff, pale red; weathers same color. Poorly developed very thin beds, 2 to 6 cm thick; shown by concentrations of basaltic lithic lapilli of similar size; uppermost 40 cm of unit has well developed laminae. Contains subrounded vesicular basaltic lithic lapilli (50%), average 4 mm across, as large as 5 cm, vesicles are filled with calcite; olivine microphenocrysts (7%), altered to iddingsite; dacitic lithic lapilli (5%); green pyroxene phenocrysts (3%), average 1 mm across; aphanitic groundmass. Poorly exposed; nonresistant; sharp basal contact----------------------------- 7.5

Cimarron Hills Andesite:
Member 1:
Flow:

9. Andesite, pale blue; weathers same color and medium bluish-gray; lowermost 1.6 m and uppermost 2 m are brecciated. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1.5 mm across; euhedral plagioclase phenocrysts (2.5%), average 4 mm across, as large as 6 mm; aphanitic groundmass. Moderately vesicular (15%); some are filled with zeolites (?); spheroidal; 1 to 3 mm across. Poorly developed horizontal joints, average 1 m apart. Well exposed; extremely resistant; sharp basal contact----------------------------- 16.5

Hickey Formation:
Member 15:

8. Basalt, light olive gray; weathers light gray. Porphyritic: contains subhedral olivine phenocrysts (0.5%), altered to iddingsite, average 1 mm across; subhedral to euhedral green pyroxene phenocrysts (trace), average 1.5 mm across; very fine-grained groundmass. Somewhat vesicular; filled with zeolites (?); usually stretched; average 2 mm by 2 cm. Well exposed; extremely resistant; sharp basal contact-- 3.4

7. Basaltic breccia, moderate red and grayish-purple; weathers same colors. Highly brecciated; 50% of unit is sub-

6. BUCKSKIN--Continued

Hickey Formation--Continued
Member 15--Continued — Meters

rounded blocks and lapilli; 5 mm to 30 cm across, average 3.5 cm across; all are extremely vesicular. Blocks contain subhedral green pyroxene phenocrysts (5%), average 1 mm across, commonly occur as glomerophyres; euhedral to subhedral olivine microphenocrysts (3%), altered to iddingsite; aphanitic groundmass. Rest of rock (50%) is aphanitic groundmass. Well exposed; moderately resistant; sharp basal contact-- 17.5

Towel Creek Tuff:
Hackberry Basin Member (?):

6. Dacitic ignimbrite, light brownish-gray; weathers same color; structureless. Contains subhedral plagioclase phenocrysts (25%), average 1 mm across; subrounded red basaltic lithic lapilli (10%), average 1 cm across, as large as 5 cm across; subhedral biotite and hornblende microphenocrysts (2%); euhedral green pyroxene xenocrysts (trace), average 1 mm across; glass dust matrix. Poorly exposed; non-resistant; sharp basal contact---------------- 2.0
5. Dacitic ignimbrite, light brownish-gray; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli (10%), average 3 mm across, as large as 4 cm; subhedral plagioclase phenocrysts (5%), average 1 mm across; subhedral biotite phenocrysts (1%), altered, average 1.5 mm across; glass dust matrix. Poorly exposed; non-resistant; basal contact not exposed------------------ 3.5

Hickey Formation:
Member 15:

4. Basalt, medium bluish-gray; weathers medium gray; basal 1.5 m is brecciated. Porphyritic: contains subhedral olivine microphenocrysts (15%), altered to iddingsite; subhedral to euhedral green pyroxene phenocrysts (7%), average 1 mm across, commonly in star-shaped glomerophyres up to 4 mm across; very fine-grained groundmass. Slightly vesicular (5%); lined with calcite; spheroidal; average 2 mm across, as large as 4 cm. Poorly developed vertical joints, average 30 cm apart. Well exposed; extremely resistant; sharp basal contact-- 10.0
3. Basalt, medium bluish-gray; weathers same color;. Porphyritic: contains euhedral olivine phenocrysts (trace), altered to iddingsite, average 2 mm across; euhedral to subhedral green pyroxene microphenocrysts (trace); very fine-grained groundmass. Uppermost 1.7 m of unit is extremely vesicular (35%); filled with zeolites (?); commonly have elongate shape; 1.5 by 4 mm. Basal 6.8 m of unit has extremely well developed horizontal joints, average 5 m apart; poorly developed sub-vertical joints, average 10 cm across. Well exposed; jointed portion of

6. BUCKSKIN--Continued

Hickey Formation--Continued
Member 15--Continued Meters

flow is very resistant, vesicular portion is extremely resistant; sharp basal contact------------------------------ 8.5

Cimarron Hills Andesite:
Member 1:
Flow:

2. Andesite, moderate red where brecciated and bluish-gray where massive; weathers same colors; lowermost 2 m and uppermost 1.5 m of flow are brecciated, rest of unit is massive. Porphyritic: contains subhedral to euhedral olivine phenocrysts (7%), rims altered to iddingsite; subhedral plagioclase phenocrysts (1%), lath-shaped, average 2 by 5 mm; subhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Slightly vesicular (3%); filled or lined with zeolites (?); usually stretched with long axis parallel to base of flow; average 1 mm across, as large as 2 cm. Poorly developed vertical joints in massive portion of flow, average 15 cm apart. Moderately exposed; moderately resistant; sharp basal contact-- 6.5

Hickey Formation:
Member 14 (incomplete):
Flow:

1. Olivine Basalt, medium bluish-gray; weathers grayish-black. Compound flow; two separate flow units divided by a 2 to 3 m thick brecciated zone 23 m above lowest exposure; uppermost 1 to 2 m of outcrop are brecciated. Porphyritic: contains euhedral olivine phenocrysts (20%), altered to iddingsite, average 2.5 mm across, as large as 1 cm; euhedral to subhedral green pyroxene phenocrysts (7%), average 3 mm across, as large as 1 cm; aphanitic groundmass. Upper portion of unit is slightly vesicular; filled with calcite. Lower portion of unit has well developed horizontal and vertical joints; where vesicular the joints are very poorly developed. Moderately exposed; moderately resistant------------------------------- 40+

Base of section; base of exposure.

7. NORTHERN HACKBERRY BASIN

[Measured May 1981 along the northern side of Hackberry Basin 2.6 km due east of Buckskin (Hill 5296)]

Top of section; top of exposure.
Thirteenmile Rock Basalt:
Undivided:
Flow: Meters

15. Basalt (incomplete), dark gray; weathers medium gray. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 4 mm; subhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Well developed vertical joints, 20 to 50 cm apart; moderately developed horizontal joints, average 3 to 5 mm apart. Well exposed; very resistant; basal contact not exposed------------------ 10.0+
14. Basaltic ash, light brown; weathers same color; structureless. Contains grayish-brown subrounded basaltic lithic lapilli and blocks (15%), average 5 mm across, as large as 8 cm, microvesicular; orange subhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across; euhedral black pyroxene phenocrysts (5%), average 1 mm across; groundmass of indecipherable dust sized material. Poorly exposed; non-resistant; basal contact not exposed--- 23 ±
13. Basalt, dark gray; weathers dark bluish-gray. Porphyritic: contains subhedral green pyroxene phenocrysts (7%), average 1 mm across, as large as 3 mm; subhedral olivine microphenocrysts (4%) and phenocrysts (1%), altered to iddingsite, phenocrysts average 2 mm across; aphanitic groundmass. Moderately developed horizontal joints, average 1 cm apart; poorly developed vertical joints, average 50 cm apart. Poorly exposed; moderately resistant; basal contact not exposed--------------------------- 5.5
12. Covered-- 5.0
11. Amygdaloidal basalt, medium to dark gray; weathers dark olive and moderate brown. Porphyritic: contains anhedral olivine phenocrysts (1%), altered to iddingsite, average 1 mm across, as large as 3 mm; aphanitic groundmass. Extremely vesicular (25%); all filled with calcite; spheroidal; 1 to 2 mm across. Poorly developed vertical joints, 20 to 50 cm apart; very poorly developed horizontal joints, 30 cm to 1 m apart. Well exposed; very resistant; sharp basal contact-------------- 4.5

Cimarron Hills Andesite:
Member 3:
Flow:

10. Andesite, medium gray; weathers medium light gray. Porphyritic: contains subhedral plagioclase phenocrysts (2%), average 1 mm across; subhedral olivine phenocrysts (1%), altered to iddingsite, average 1 mm across, as

7. NORTHERN HACKBERRY BASIN--Continued

Cimarron Hills Andesite--Continued

Member 3--Continued

Flow--Continued — Meters

large as 4 mm; anhedral green pyroxene phenocrysts (1%), average 1.5 mm across; aphanitic groundmass. Slightly vesicular (5%); filled with calcite; spheroidal; average 2 mm across, as large as 1 cm. Moderately developed columnar joints, 50 cm to 2 m apart; moderately developed horizontal joints, 2 cm to 2 m apart. Well exposed; extremely resistant; sharp basal contact------------------- 17.5

9. Vesicular andesite, medium dark gray; weathers brownish-gray. Porphyritic: contains subhedral to euhedral plagioclase phenocrysts (1%), usually have thin orange rim, average 2 mm across; subhedral olivine microphenocrysts (2%), altered to iddingsite; aphanitic groundmass. Extremely vesicular (25%); a few are lined or filled with calcite; spheroidal; average 4 mm across, as large as 2 cm. Poorly developed columnar joints, 50 cm to 1.5 m apart. Well exposed; very resistant; sharp basal contact-- 11.5

Thirteenmile Rock Basalt:

Undivided:

Flow:

8. Basalt, dark gray; weathers medium gray. Porphyritic: contains anhedral olivine phenodrysts (2%), altered to iddingsite, average 1 mm across, as large as 2 mm; subhedral plagioclase phenocrysts (1%), average 4 mm across; aphanitic groundmass. Well developed horizontal joints, average 1 cm apart; poorly developed vertical joints, 15 to 30 cm apart. Well exposed; very resistant; sharp basal contact--- 5 ±

Cimarron Hills Andesite:

Member 3:

Flow:

7. Andesite, dark gray; weathers grayish-brown. Porphyritic: contains anhedral to euhedral plagioclase phenocrysts (7%), average 2 mm across, as large as 1 cm; anhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 5 mm; aphanitic groundmass. Slightly vesicular (5 to 10%); spheroidal to elongate; average 3 mm across. Well developed vertical joints, 50 cm to 1.5 m apart; poorly developed horizontal joints, 1 to 3 m apart. Well exposed; extremely resistant; basal contact not exposed-- 11.0

6. Andesite, medium gray; weathers same color and pale blue. Porphyritic: contains subhedral plagioclase phenocrysts (7%), lath-shaped, average 3 mm across, as large as 5 mm; subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 4 mm; aphanitic groundmass. Moderately developed vertical joints, 5 to 20 cm

Cimarron Hills Andesite--Continued
Member 3--Continued
Flow--Continued — Meters

apart; poorly developed horizontal joints, average 1 cm apart. Moderately exposed; lower half of unit is moderately resistant, upper half is extremely resistant; basal contact not exposed---------------------------------- 31.0

5. Andesite, medium gray; weathers dark olive. Microporphyritic: contains euhedral plagioclase microphenocrysts (5%); subhedral olivine microphenocrysts (1%), altered to iddingsite; aphanitic groundmass. Uppermost portion of flow is extremely vesicular (20%); some are lined with calcite; elongate; average 2 mm across, as large as 5 mm. Well exposed; extremely resistant; sharp basal contact----- 6.4

Thirteenmile Rock Basalt:
Undivided:
Flow:

4. Basalt, dark gray; weathers medium dark gray and dark olive. Porphyritic: contains subhedral green pyroxene phenocrysts (7%), average 1 mm across, as large as 5 mm; anhedral olivine phenocrysts (2%), altered to iddingsite, same size as the pyroxene; aphanitic groundmass. Somewhat vesicular (2%); all filled with calcite; spheroidal; 1 to 3 mm across. Well developed vertical joints, 15 cm to 1 m apart; well developed horizontal joints 3 to 10 cm apart. Very well exposed; extremely resistant; basal contact not exposed---------------------- 6.6

Towel Creek Tuff:
Member 7:
Tuff:

3. Dacitic ignimbrite, grayish-orange-pink; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli (30%), average 4 mm across; subhedral plagioclase phenocrysts (15%), average 1 mm across; euhedral hornblende and biotite phenocrysts (1%), average 1 mm across; subrounded brown basaltic lithic lapilli (trace), microvesicular, average 5 mm across, as large as 2 cm; glass dust matrix. Very poorly exposed; non-resistant; basal contact not exposed--------------------------- 10.0

Thirteenmile Rock Basalt:
Undivided:
Flow:

2. Basalt, grayish-black; weathers pale blue, yellowish-gray, and light olive gray; compound flow, boundary 19.5 m above the base. Microporphyritic: contains subhedral olivine microphenocrysts (1%), altered to iddingsite; subhedral green pyroxene microphenocrysts (trace); aphanitic groundmass. Very well developed horizontal joints, 5 mm

7. NORTHERN HACKBERRY BASIN--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Flow--Continued Meters

to 5 cm apart; well developed vertical jointing, 10 to 40 cm apart. Moderately exposed; moderately resistant; gradational basal contact---------------------------------- 33 ±

Offset in section so that overlying units measured 160 m west of underlying units.

1. Basaltic ash (incomplete), pale pink and moderate red; weathers same colors. Poorly developed very thin beds; 1 to 5 cm thick; shown by differences in grain size, lapilli-rich versus ash-rich. Contains subrounded red basaltic lithic lapilli and bombs (50%), 2 mm to 10 cm across, average 1 cm across; rounded orange basaltic glass lapilli (5%), average 2 mm across, as large as 1 cm, microvesicular; rounded white dacitic pumiceous lapilli (5%), average 1 mm across, as large as 3 cm; subhedral plagioclase phenocrysts (5%); aphanitic groundmass. Lowest exposure of unit is rich in basaltic bombs and lapilli (15%), average 5 cm across, as large as 25 cm; bombs contain olivine phenocrysts (5%) and green pyroxene phenocrysts (trace) in an aphanitic groundmass. Poorly exposed; moderately resistant---------------------- 10.0+

Base of section; base of good exposure.

8. HACKBERRY SPRINGS

[Measured September 1981 from Hackberry Springs to hill 4814 towards the southeast]

Top of section; not top of exposure.
Towel Creek Tuff:
Hackberry Basin Member:
Sediments:

3. Sandstone, very light gray; weathers same color. Fairly massive; commonly have small lenses of concentrated subangular pumice-rich pebbles and granules, average 1 cm thick. Moderately sorted; fine sand to cobble size. Contains subangular blue dacitic lithic fragments (50%), medium sand to pebble size, average granule size; subangular plagioclase grains (35%), fine to coarse sand size, average medium sand size; rounded white dacitic pumiceous fragments (13%), very coarse sand to pebble size, average granule size; subangular biotite grains (2%), same size as plagioclase grains. Moderately indurated; moderately exposed; non-resistant; gradational basal contact, a zone of interbedded sandstone and siltstone-------------------- 13 ±

8. HACKBERRY SPRINGS--Continued

Towel Creek Tuff--Continued
Hackberry Basin Member--Continued — Meters
Sediments--Continued

2. Siltstone, very pale orange; weathers grayish-orange. Very well developed laminae; 1 mm to 1 cm thick; shown by differences in color; structures due to soft-sediment deformation are very common. Well sorted; silt to very fine sand size. There are a few thick sandy beds; up to 5 cm thick; well sorted, average medium sand size, subrounded grains. Unit is poorly indurated; poorly exposed; non-resistant; gradational basal contact, zone of interbedded sandstone and siltstone with the amount of siltstone decreasing as go down section------------------------ 11 ±
1. Sandstone (95%) and siltstone (5%) (incomplete); sandstone similar to unit 3; siltstone similar to unit 2. Thick sandstone beds, average 20 cm thick; thin siltstone interbeds, 1 to 2 cm thick. Poorly exposed; non-resistant--- 9.0+

9. WILLOW SPRING

[Measured September 1981 near Willow Spring in Hackberry Basin]

Top of section; top of good exposure.
Towel Creek Tuff:
Hackberry Basin Member:
Tuff:

10. Dacitic ignimbrite (incomplete), grayish-orange-pink; weathers same color. Contains multiple flows, each 20 to 50 cm thick; commonly separated by dacitic air-fall tuffs, average 3 cm thick. Ignimbrites contain subrounded white dacitic pumiceous grains (25%), average 1.5 mm across, as large as 5 mm; subhedral plagioclase phenocrysts (20%), average 1 mm across; subrounded blue dacitic lithic lapilli (2%), average 1.5 cm across; subhedral biotite phenocrysts (1%), average 1 mm across; glass dust matrix. Within the upper 11.5 cm of outcrop many of the ignimbrite flows contain basaltic blocks and lapilli (35%); average 5 cm across, as large as 25 cm; contain subhedral green pyroxene microphenocrysts (10%), olivine (altered to iddingsite) microphenocrysts (3%) in a dark gray aphanitic groundmass. Well exposed; moderately resistant; sharp basal contact--- 31.5+
9. Dacitic ignimbrite, white; weathers very light gray; structureless. Contains subrounded to subangular white dacitic pumiceous lapilli (25%), 1 mm to 5 cm across, average 4 mm; subangular blue dacitic lithic lapilli and blocks (20%), 1 mm to 1 m across, average 1 cm across; subhedral plagioclase phenocrysts (15%), average 1 mm across; euhedral biotite phenocrysts (1%), average 1 mm across; glass dust martix. Well exposed; very resistant;

9. WILLOW SPRING--Continued

Towel Creek Tuff--Continued
Hackberry Basin Member--Continued
Tuff--Continued Meters

sharp basal contact-- 14.5

8. Dacitic base-surge tuff, grayish-pink; weathers same color. Very well developed laminae; average 2 to 3 mm thick; very undulatory with well developed cross-beds; bomb sags are common. Contains anhedral plagioclase microphenocrysts (25%); subrounded red and blue dacitic lithic lapilli and blocks (20%), average 2 mm across, as large as 10 cm; subrounded white dacitic pumiceous grains (15%), average 1 mm across; subhedral biotite and hornblende microphenocrysts (1%); glass dust matrix. Very well exposed; moderately resistant; sharp basal contact---------------------- 8.2
7. Dacitic ignimbrite and base-surge tuff, interbedded; ignimbrite similar to unit 5; base-surge tuff similar to unit 3. Base-surge tuffs are 10 to 30 cm thick; ignimbrites are 20 to 50 cm thick. Well exposed; very resistant; sharp basal contact----------------------------------- 1.9
6. Dacitic ignimbrite, similar to unit 5---------------------- 3.8
5. Dacitic ignimbrite, white; weathers grayish-white; structureless. Contains rounded white dacitic pumceous lapilli (20%), average 5 mm across, as large as 6 cm; subhedral plagioclase phenocrysts (12%), average 1 mm, as large as 5 mm; subangular red and white dacitic lithic lapilli and bombs (7%), average 6 mm across, as large as 50 cm; subangular blue and gray mafic lithic lapilli and blocks (3%), commonly altered, average 8 mm across, as large as 10 cm; subhedral hornblende and biotite phenocrysts (1%), average 1 mm across, as large as 3 mm; glass dust matrix. Well exposed; very resistant; sharp basal contact-- 12.5
4. Dacitic base-surge tuff and dacitic air-fall tuff, interbedded; base-surge tuff similar to unit 3 except it lacks the larger bombs, beds are 10 to 20 cm thick; air-fall tuff beds are 20 to 30 cm thick. Air-fall tuff, white; weathers same color. Contains rounded white dacitic pumiceous lapilli (70%), 1 mm to 50 cm across, average 5 mm across; subangular basaltic lithic lapilli (15%), altered, average 5 mm across, as large as 5 cm; subangular blue dacitic lithic lapilli (10%), average 5 mm across, as large as 2 cm; glass dust matrix. Unit is well exposed; moderately resistant; sharp basal contact----------------- 2.6
3. Dacitic base-surge tuff, light gray; weathers same color. Very well developed laminae; 2 to 3 mm thick; shown by slight differences in average grain size; beds are commonly undulatory, 1 m wavelength with a maximum amplitude of 20 cm; some cross-beds; bomb sags are common. Contains anhedral plagioclase microphenocrysts (50%), as large as 1.5 mm; subrounded blue and red dacitic lithic grains (15%), average 1 mm across; rounded white dacitic

9. WILLOW SPRING--Continued

Towel Creek Tuff--Continued
Hackberry Basin Member--Continued
Tuff--Continued — Meters

pumiceous lapilli (5%), average 2 mm across; subangular to subrounded blue dacitic lithic blocks (1%), average 6 cm across, as large as 30 cm; subhedral biotite microphenocrysts (trace), as large as 2 mm across; mafic lithic blocks (trace), same size and shape as dacitic lithic blocks; glass dust matrix. Moderately exposed; non-resistant; basal contact not exposed------------------ 10.5

2. Dacitic ignimbrite, grayish-orange-pink; weathers very light gray; structureless. Contains rounded white dacitic pumiceous lapilli (20%), average 3 mm across, as large as 2 cm; subhedral plagioclase phenocrysts (15%), average 1 mm across, as large as 3 mm; subangular red and purple dacitic lithic lapilli (5%), same size as dacitic pumiceous lapilli; biotite phenocrysts (1%); glass dust matrix. Poorly exposed; non-resistant; sharp basal contact--- 4 ±

1. Pebbly sandstone (incomplete), grayish-orange-pink; weathers same color or very light gray. Well developed thick beds; 30 cm to 1 m thick; some rare laminae, 2 mm thick, commonly cross-bedded. Poorly sorted; fine sand to boulder size; most grains and fragments are subangular. Contains plagioclase grains (55%), average coarse sand size; dacitic lithic fragments (20%), granule to boulder size, average pebble size; rounded dacitic pumiceous fragments (2%), average granule size; subrounded to rounded mafic lithic fragments (2%), granule to boulder size; biotite (1%) and quartz (1%) grains, average coarse sand size; fine sand size matrix. Commonly have lense-shaped beds rich in dacitic pumice; unit as a whole becomes coarser as go up section; there are a few interbedded dacitic ignimbrites within this unit. Unit is well exposed; moderately resistant------------------------ 31.5+

10. BOULDER CANYON

[Measured May 1981 on the eastern side of Boulder Canyon 1.4 km due east of Cedar Flat Tank]

Top of section; top of exposure.
Cimarron Hills Andesite:
Member 3:
Flow:

37. Andesite, brownish-gray; weathers light brownish-gray. Compound flow; contains 3 flows; 7.5, 10, and 10 m thick from the base of the unit up. Porphyritic: contains subhedral olivine phenocrysts (3%), altered to iddingsite, average 1 mm across; anhedral to subhedral plagioclase phenocrysts (2%), average 3 mm across; euhe-

Cimarron Hills Andesite--Continued
Member 3--Continued
Flow--Continued — Meters

dral green pyroxene phenocrysts (1%), average 1 mm across; aphanitic groundmass. Poorly developed sub-vertical joints, average 1 m apart. Well exposed; very resistant; sharp basal contact-- 28.5+

Thirteenmile Rock Basalt:
Undivided:
Flow:

36. Basalt, medium gray; weathers same color. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 4 mm; subhedral green pyroxene phenocrysts (1%), average 2 mm across, as large as 5 mm; anhedral plagioclase phenocrysts (trace), commonly have orange rims, average 3 mm across; aphanitic groundmass. Contains a few cumulophyres of olivine surrounded by green pyroxene, average 2 mm across. Basal 10.5 m of flow has very well developed horizontal joints, average 1 cm apart. Well exposed, extremely resistant; sharp basal contact------------------ 31.0

Cimarron Hills Andesite:
Member 2:
Flow:

35. Andesite, medium gray; weathers same color and medium dark gray. Compound flow; contains 5 separate flows; 10.5 3, 8.5, 5, and 3 m thick. Porphyritic: contains euhedral olivine phenocrysts (7%), altered to iddingsite, average 1.5 mm across, as large as 5 mm; anhedral to subhedral plagioclase phenocrysts (3%), average 2 mm across, as large as 4 mm; fine-grained groundmass. Very well developed vertical joints, 1 to 2 m apart. Very well exposed; extremely resistant; sharp basal contact---------- 30 ±

Offset in section so that overlying units measured 120 m southeast of underlying units.

Thirteenmile Rock Basalt:
Undivided:
Flow:

34. Basalt, dark gray; weathers medium gray. Compound flow; flows are 7, 7.5, 10.5, and 5.6 m thick. Porphyritic: contains subhedral olivine phenocrysts (3%), altered to iddingsite; subhedral green pyroxene phenocrysts (3%), average 1 mm across; anhedral plagioclase phenocrysts (1%), average 1 mm across; aphanitic groundmass. Portions of unit have well developed vertical joints, 1 to 10 cm apart. Moderately exposed; moderately to very resistant; basal contact not exposed---------------------- 30.5

10. BOULDER CANYON--Continued

Thirteenmile Rock Basalt--Continued
Undivided--Continued
Flow--Continued Meters

33. Basalt, medium gray; weathers same color and pale red. Porphyritic: contains subhedral olivine phenocrysts (2%), altered to iddingsite, average 1 mm across, as large as 3 mm; subhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Well developed horizontal joints, average 1 cm apart; moderately developed columnar joints, 50 to 70 cm apart. Well exposed; very resistant; sharp basal contact--------------- 27.0

Towel Creek Tuff:
Hackberry Basin Member:
Tuff:

32. Pebbly sandstone, moderate orange-pink; weathers moderate reddish-orange. Poorly developed horizontal beds shown by alignment of white dacitic pumiceous fragments. Very poorly sorted; silt to pebble size, average is medium sand size; granule and smaller size grains are subangular, pebble size fragments are subrounded. Contains dacitic pumiceous fragments (20%), granule to pebble size; dacitic lithic fragments (10%), granule to pebble size; plagioclase grains (25%), mafic mineral grains (3%), and basaltic lithic grains (1%); very fine-grained groundmass. Well indurated; moderately exposed; moderately resistant; sharp basal contact-- 17 ±
31. Basaltic tuff, light yellowish-orange; weathers medium orange; structureless. Contains subhedral green pyroxene phenocrysts (15%), average 1 mm across, as large as 2 mm; brown subhedral olivine phenocrysts (1%), altered to iddingsite; subrounded purple basaltic lithic lapilli (trace), average 5 mm across; glass dust matrix (84%). Well exposed; moderately resistant; sharp basal contact---- 0.5
30. Pebbly sandstone, similar to unit 32----------------------- 9 ±
29. Covered (unmeasured).
28. Dacitic ignimbrite, grayish-orange-pink, weathers same color; structureless. Contains subangular blue dacitic lithic lapilli and blocks (20%), average 5 mm across, as large as 10 cm; subhedral to euhedral plagioclase phenocrysts (15%), average 1 mm across, as large as 3 mm; subrounded white dacitic pumiceous lapilli (10%), average 3 mm across; subangular basaltic lithic lapilli (trace), average 4 mm across, as large as 3 cm; euhedral biotite and hornblende phenocrysts (trace), average 1 mm across; glass dust matrix. Well exposed; very resistant; sharp basal contact-- 10 ±
27. Dacitic air-fall tuff, similar to unit 21------------------ 1.0
26. Dacitic ignimbrite, similar to unit 28-------------------- 1.6

10. BOULDER CANYON--Continued

Towel Creek Tuff--Continued
Hackberry Basin Member--Continued
Tuff--Continued | Meters

25. Basaltic tuff, medium bluish-gray; weathers moderate orange-pink. Well developed very thin beds; shown by differences in color of lapilli. Contains subrounded blue basaltic lithic lapilli (65%), average 3 mm across, microvesicular; calcite (35%), fills most pore spaces. Well indurated, calcareous cement; moderately exposed; moderately resistant; sharp basal contact------------------ 1.3
24. Dacitic ignimbrite, grayish-orange-pink; weathers dark grayish-orange-pink; structureless. Contains euhedral plagioclase phenocrysts (20%), average 1 mm across; subrounded white to blue dacitic lithic grains (20%), average 1.5 mm across, as large as 4 mm; subrounded white dacitic pumiceous lapilli (7%), average 1 mm across, as large as 5 mm; euhedral biotite phenocrysts (1%), average 1 mm across; glass dust matrix. Poorly exposed; moderately resistant; sharp basal contact---------------------- 2.5

Cimarron Hills Andesite:
Member 1:
Flow:

23. Andesite, medium dark gray; weathers grayish-blue. Compound flow; two flows with boundary 4.5 m above the base of the unit. Porphyritic: contains subhedral plagioclase phenocrysts (2%), average 1.5 mm across, as large as 4 mm; euhedral olivine microphenocrysts (trace), altered to iddingsite; aphanitic groundmass. Slightly vesicular (10%); usually stretched; average 2 mm across. Well developed horizontal joints, average 50 cm apart; moderately developed vertical joints, 50 cm to 1 m apart. Well exposed; extremely resistant; sharp basal contact-- 6.5

Towel Creek Tuff:
Hackberry Basin Member:
Tuff:

22. Dacitic ignimbrite, grayish-orange-pink; weathers same color; structureless. Contains subhedral plagioclase phenocrysts (30%), average 1 mm across; white to blue subrounded dacitic lithic lapilli (25%), average 3 mm across, as large as 2 cm; white rounded dacitic pumiceous lapilli (20%), average 5 mm across, as large as 4 cm; euhedral biotite and hornblende phenocrysts (trace), average 1 mm across; glass dust matrix. Well exposed; extremely resistant; sharp basal contact------------------- 3.0
21. Dacitic air-fall tuff, white; weathers same color. Very well developed laminae, 5 mm to 1 cm thick; shown by contrasts in concentration of pumiceous lapilli. Contains rounded white dacitic pumiceous lapilli (50%), average 5

10. BOULDER CANYON--Continued

Towel Creek Tuff--Continued
Hackberry Basin Member--Continued
Tuff--Continued — Meters

mm across; subrounded blue dacitic lithic lapilli (40%), average 3 mm across; subhedral plagioclase phenocrysts (10%), average 1.5 mm across. Well exposed; extremely resistant; sharp basal contact---------------------------- 2.0

20. Sandstone, grayish-orange-pink; weathers same color; strutureless. Poorly sorted; fine sand to granule size, average medium sand size; subrounded. Contains plagioclase grains (70%); white dacitic lithic grains (10%), coarse sand size; basaltic lithic grains (5%), microvesicular; biotite and hornblende crystals (1%); matrix. Well indurated; moderately exposed; moderately resistant; sharp basal contact-- 8.6

19. Dacitic air-fall tuff, similar to unit 17 except less resistant--- 2.8

18. Dacitic ignimbrite, grayish-orange-pink; weathers same color; structureless. Contains subhedral plagioclase phenocrysts (25%), average 1 mm across; subrounded white dacitic pumiceous lapilli (10%), average 5 mm across, as large as 2 cm; subrounded blue dacitic lithic lapilli (5%), average 5 cm across; subhedral biotite and hornblende microphenocrysts (trace); subrounded basaltic lithic lapilli (trace), average 5 cm across; glass dust matrix. Well exposed; very resistant; irregular but sharp basal contact-- 2.1

17. Dacitic air-fall tuff, white; weathers same color. Very well developed thin beds, 10 to 20 cm thick; shown by differences in size of pumiceous lapilli. Contains subrounded to subangular white to blue dacitic lithic lapilli (55%), subhedral plagioclase phenocrysts (25%), average 1.5 mm across; subrounded white dacitic pumiceous lapilli (5%), average 3 mm across, as large as 5 mm; subhedral biotite and hornblende (trace), average 1 mm across; glass dust matrix. Well exposed; very resistant; basal contact not exposed-- 7.9

16. Dacitic ignimbrite, white; weathers very light gray; structureless. Compound flow; contains many flow units from 3 to 30 cm thick, average thickness of 10 cm. Contains rounded white dacitic pumiceous lapilli (30%), average 5 mm across, as large as 15 mm; subhedral plagioclase phenocrysts (25%); subrounded red or blue dacitic lithic lapilli and blocks (10%), average 3 mm across, as large as 20 cm; euhedral biotite and hornblende phenocrysts (2%), average 1.5 mm across; glass dust matrix. Well exposed; very resistant; sharp basal contact---------- 20 ±

15. Basaltic tuff, pale reddish-brown; weathers same color; structureless. Contains subangular aphyric basaltic lapilli (35%), average 3 mm across; very fine-grained matrix (65%). Poorly exposed; non-resistant; sharp basal

10. BOULDER CANYON--Continued

Towel Creek Tuff--Continued
Hackberry Basin Member--Continued
Tuff--Continued

		Meters
	contact	1.4
14.	Dacitic air-fall tuff, white; weathers same color. Well developed thin beds; shown by concentration of ash-rich laminae in zones 2.5 cm thick occuring about every 30 cm. Unit contains rounded white dacitic pumiceous lapilli (65%), average 5 mm across, as large as 1 cm; rounded blue dacitic lithic lapilli (30%), same size as pumice; subhedral to euhedral plagioclase phenocrysts (5%), 1 to 2 mm across. Poorly exposed; non-resistant; basal contact not exposed	3.8
13.	Dacitic ignimbrite, similar to unit 9 except slightly darker color	2.7
12.	Dacitic air-fall tuff, similar to unit 2	3.7
11.	Dacitic ignimbrite, similar to unit 9. Compound unit; contains numerous flows that average 30 cm thick	18.0
10.	Dacitic air-fall tuff, similar to unit 2	1.2
9.	Dacitic ignimbrite, grayish-orange-pink; weathers same color; structureless. Contains anhedral plagioclase phenocrysts (30%), average 1 mm across; as large as 2 mm; subrounded blue dacitic lithic lapilli and blocks (10%), average 5 mm across, as large as 50 cm; subrounded white dacitic pumiceous lapilli and blocks (7%), average 2 mm across, as large as 50 cm; subhedral biotite microphenocrysts (1%); glass dust matrix. Well exposed; extremely resistant; sharp basal contact	6.2
8.	Dacitic air-fall tuff, similar to unit 2. Well developed thin beds, average 5 cm thick. Lower half of unit is well exposed, upper half is poorly exposed	9.0
7.	Dacitic ignimbrite, white; weathers same color; slightly altered. Compound flow; two separate flows 2.3 and 3.0 m thick; separated by a very thin (15 cm) dacitic air-fall tuff. Contains rounded white dacitic pumiceous lapilli (40%), average 2 mm across, as large as 1.5 cm; subhedral plagioclase phenocrysts (20%), average 1 mm across; subangular blue dacitic lithic lapilli and blocks (7%), average 5 mm across, as large as 30 cm; euhedral to subhedral biotite phenocrysts (1%), average 1 mm across; glass dust matrix. Well exposed; extremely resistant; sharp basal contact	5.3
6.	Dacitic air-fall tuff, similar to unit 2	0.2
5.	Dacitic ignimbrite, light bluish-gray; weathers same color; structureless. Contains subhedral plagioclase microphenocrysts (45%), as large as 3 mm; subangular bluish-gray dacitic lithic grains (30%), average 1 mm across, as large as 5 mm; rounded white dacitic pumiceous grains (5%), same size as lithic grains; subhedral biotite and hornblende microphenocrysts (trace); glass dust matrix. Well exposed; extremely resistant	1.0

10. BOULDER CANYON--Continued

Towel Creek Tuff--Continued
Hackberry Basin Member--Continued
Tuff--Continued — Meters

4. Dacitic air-fall tuff, similar to unit 2------------------- 0.1
3. Dacitic ignimbrite, similar to unit 5---------------------- 0.2
2. Dacitic air-fall tuff, grayish-orange-pink; weathers same color. Very well developed very thin to thin beds; 2 to 10 cm thick, average 5 cm thick; shown by differences in grain size. Contains subhedral plagioclase phenocrysts (50%), average 1 mm across; rounded white dacitic pumiceous grains (25%), average 1 mm across; subrounded dacitic lithic lapilli (25%), average 2 mm across, as large as 1 cm. Moderately indurated; well exposed; very resistant; gradational basal contact---------------------- 3.2
1. Dacitic ignimbrite (incomplete), grayish-orange-pink; weathers same color. Compound flow; average flow unit is 20 cm thick. Contains rounded to subrounded white dacitic pumiceous lapilli (30%), average 3 mm across, as large as 2 cm; subrounded blue dacitic lithic lapilli (12%), average 2 mm across; anhedral plagioclase phenocrysts (10%), average 1 mm across; biotite phenocrysts (1%), average 1 mm across, as large as 2 mm; glass dust matrix. Well exposed; extremely resistant---------------- 9.0+

Base of section; base of exposure.

11. VERDE RIVER NORTH OF BROWN SPRINGS

[Measured May 1981 along southwestern side of the Verde River 1 km north of Brown Springs Ranch]

Top of section; not top of exposure
Hickey Formation:
Member 8 (incomplete):
Flow:

8. Basaltic breccia and basalt, basaltic breccia is moderate red and weathers the same color, basalt flows are dark gray and weather dark olive. Unit is composed of interbedded lava and breccia flows; breccia flows are thicker and compose the majority of the unit. The breccias contain subrounded basaltic lithic lapilli and blocks (80%), 1 mm to 1 m across, average 3 cm across, moderately vesicular vesicular (15%); calcite (20%), fills all vesicles and pores. Both lava and breccia are porphyritic: contain subhedral olivine phenocrysts (15%), average 1 mm across, as large as 6 mm; subhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Slightly microvesicular (10%), filled with calcite. Breccia flows are massive; lava flows have well developed vertical and horizontal joints, 20 to 50 cm apart. Well exposed; extremely resistant; sharp basal

11. VERDE RIVER NORTH OF BROWN SPRINGS--Continued

Hickey Formation--Continued
Member 8 (incomplete)--Continued
Flow--Continued Meters
contact-- 20.0+
Member 7:
7. Basalt, grayish-black; weathers medium bluish-gray and dark yellowish-orange. Porphyritic: contains subhedral olivine phenocrysts (20%), altered to iddingsite, average 1.5 mm across; aphanitic groundmass. Extremely well developed columnar joints, average 50 cm apart. Well exposed; extremely resistant; sharp basal contact---------- 19.0
6. Basalt, grayish-red-purple; weathers medium gray; basal 50 cm brecciated. Porphyritic: contains subhedral to euhedral olivine phenocrysts (20%), altered to iddingsite, average 1.5 mm across, as large as 3 mm; aphanitic groundmass. Slightly vesicular (10%); filled with calcite; usually spheroidal; average 1 mm across, as large as 1 cm. Well developed vertical joints, average 20 cm apart; moderately developed horizontal joints, 1 to 5 cm apart. Well exposed; very resistant; sharp basal contact-- 6.8
5. Basaltic tuff, moderate pink; weathers same color. Well developed very thin beds; average 2.5 mm thick; shown by differences in grain size, lapilli-rich beds and ash-rich beds. Lapilli-rich beds consist of subrounded basaltic lithic lapilli (60%), average 3 mm across, as large as 2 cm across, moderately vesicular (20%); calcite (40%), fills all vesicles and pore spaces. Lapilli is microporphyritic: contains subhedral olivine microphenocrysts (15%), altered to iddingsite; subhedral green pyroxene phenocrysts (trace), average 1 mm across, commonly in glomerophyres 1.5 cm across; aphanitic groundmass. Smaller size lapilli (1 to 2 mm across) are crystals of olivine and pyroxene. Well exposed; moderately resistant; basal contact not exposed---------------------- 14.0
4. Basaltic breccia, medium purple; weathers medium gray and light brown. Consists of subrounded basaltic lithic lapilli and blocks; 2 cm to 2 m across, average 10 cm across. Lapilli and blocks are porphyritic: contain subhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across, as large as 2.5 mm; subhedral green pyroxene microphenocrysts (trace); aphanitic groundmass. 75% of unit is lapilli and blocks and 25% is pore space filled with calcite. Moderately vesicular (20%); filled with calcite; spheroidal; average 1 mm across. Well exposed; very resistant; sharp basal contact---------- 20.5
Member 6:
3. Basalt, grayish-black; weathers medium gray and grayish-orange-pink. Porphyritic: contains subhedral green pyroxene phenocrysts (1%), average 1 mm across; aphanitic groundmass. Very well developed columnar joints, 5 to

11. *VERDE RIVER NORTH OF BROWN SPRINGS--Continued*

Hickey Formation--Continued
Member 6--Continued — Meters

20 cm apart; very well developed horizontal joints, 5 to 30 cm apart. Well exposed; extremely resistant; sharp basal contact-- 15.0

Member 5:
Flow:
2. Basaltic ash, moderate pink; weathers same color. Well developed very thin beds; shown by slight differences in average grain size and sorting; beds are 1 to 5 cm thick. Unit consists of aphyric subrounded basaltic lithic lapilli (65%), average 2 to 4 mm across (depending upon bed); calcite (35%), fills all vesicles and pore spaces. Poorly exposed; non-resistant; basal contact not exposed-- 11.5
1. Olivine basalt (incomplete), grayish-black; weathers light to medium gray and moderate pink; upper 3 m is brecciated. Porphyritic: contains subhedral olivine phenocrysts (20%), rims altered to iddingsite, average 1 mm across, as large as 4 mm; euhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Moderately developed columnar joints, 1.5 to 2 m thick; poorly developed sub-horizontal joints, average 2 cm apart. Well exposed; very resistant---------------------- 13.5+

12. TOWEL CREEK

[Measured October 1980 along the northern side of Towel Creek]

Top of section; not top of exposure.
Hickey Formation:
Member 13 (unmeasured):
Flow:
22. Basalt, very dark gray, weathers same color. Contains alternating beds of brecciated and massive basalt; massive basalt is 2 to 4 m thick, brecciated basalt averages 1 m thick. Porphyritic: contains subhedral to euhedral olivine phenocrysts (10 to 15%), rims or entire mineral altered to iddingsite, average 1 mm across; very fine-grained groundmass. Moderately vesicular (20%), filled with calcite. Well exposed; very resistant; sharp basal contact.

Towel Creek Tuff;
Member 3:
Flow:
21. Pebbly sandstone, similar to unit 18------------------------ 14.5
20. Dacitic ignimbrite, white; weathers same color. Compound flow; boundary 5.4 m above the base. Contains subrounded white dacitic pumiceous lapilli and bombs (40%), average 2 cm across, as large as 10 cm; subhedral to euhedral

12. TOWEL CREEK--Continued

Towel Creek Tuff--Continued
Member 3--Continued
Flow--Continued — Meters

plagioclase phenocrysts (20%), average 2.5 mm across; subangular pink dacitic lithic lapilli and blocks (5%), average 1.5 mm across, as large as 25 cm; euhedral biotite and hornblende phenocrysts (1%), average 1 mm across; glass dust matrix. Well exposed; moderately resistant; sharp basal contact-- 27.0

19. Dacitic air-fall tuff, white; weathers same color. Compound unit; consists of three separate tuffs each of equal thickness; structureless within each unit. Contains rounded white dacitic pumiceous lapilli (60%), average 2 mm across, as large as 2 cm; subhedral plagioclase phenocrysts (30%), average 1 mm across; subrounded purple dacitic lithic grains (10%), average 1.5 mm across. Poorly exposed; non-resistant; sharp basal contact-- 0.5

18. Pebbly sandstone, grayish-orange-pink; weathers same color. Moderately developed thin horizontal beds; average 30 cm thick; shown by differences in grain size and concentration of dacitic lithic clasts. Coarser beds contain lithic fragments ranging in size from granule to boulder; average size is cobble; finer beds contain lithic fragments ranging in size from granule to small pebble. Finer-grained beds commonly have poorly developed laminae shown by alignment of mafic mineral grains. Unit is very poorly sorted; grains and clasts are subangular. Contains plagioclase grains (40%), average very coarse sand size; pink dacitic lithic fragments (30%); rounded white dacitic pumiceous grains (10%), coarse to very coarse sand size; biotite and hornblende grains (4%), coarse sand size; basaltic lithic clasts (1%), same size as dacitic lithic clasts; very fine-grained groundmass. Well exposed; extremely resistant; basal contact not exposed---------------------------------- 24.0

17. Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded white dacitic pumiceous lapilli (35%), average 3 mm across, as large as 1 cm; subrounded pink and blue dacitic lithic lapilli and blocks (15%), average 2 cm across, as large as 25 cm; subhedral to euhedral plagioclase phenocrysts (15%), average 1 mm across; euhedral biotite and hornblende microphenocrysts (trace); glass dust matrix. Well exposed; moderately resistant; sharp basal contact---------------------------- 22.0

Offset in section so that overlying units measured 740 m southeast of underlying units.

12. TOWEL CREEK--Continued

Hickey Formation:

Member 11: Meters

16. Andesite, moderate red; weathers same color and medium bluish-gray. Lowermost 3 m and uppermost 1 m are brecciated. Porphyritic: contains subhedral to euhedral olivine phenocrysts (10%), rims altered to iddingsite, average 1 mm across; euhedral plagioclase phenocrysts (2%), lath-shaped, average 5 mm long; aphanitic groundmass. Moderately vesicular (20%); filled with calcite; spheroidal; average 5 mm across. Moderately exposed; non-resistant; sharp basal contact------------------------ 6.0

Towel Creek Tuff:

Member 2:

15. Dacitic pyroclastic breccia, white; weathers grayish-orange-pink; structureless. Contains bluish-gray subangular to subrounded dacitic blocks and lapilli (45%), 1 mm to 4 m across, average 8 cm across; subhedral plagioclase phenocrysts (20%), average 1 mm across; euhedral biotite phenocrysts (2%), average 2 mm across; basic xenoliths (trace); glassy groundmass. Well exposed; extremely resistant; sharp basal contact------------------- 25.5

14. Dacitic ignimbrite, white; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli and blocks (40%), average 1 cm across, as large as 10 cm; subhedral to euhedral plagioclase phenocrysts (20%), average 1 mm across; subangular dacitic lithic lapilli (4%), average 1.2 cm across, as large as 5 cm; euhedral biotite and hornblende phenocrysts (3%), average 1 mm across; subangular basaltic lithic lapilli (1%), commonly altered, same size as dacitic lithic lapilli; glass dust matrix. Well exposed; very to extremely resistant; sharp basal contact-- 28.5

13. Dacitic air-fall tuff, similar to unit 7 except average pumiceous lapilli is larger, average 1 cm across----------- 0.2

12. Dacitic ignimbrite, similar to unit 8----------------------- 2.5

11. Dacitic air-fall tuff, similar to unit 7 except it has no lithic fragments-- 0.2

10. Dacitic ignimbrite, similar to unit 8 except slightly more resistant--- 4.7

9. Dacitic air-fall tuff, similar to unit 7. This unit has 14 or 15 separate beds, each around 4 cm thick. Contains dacitic lithic lapilli; average 5 mm across, as large as 2 cm; most common in lowermost 2/3 of unit--------------- 0.5

8. Dacitic ignimbrite, white; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli (35%), average 1.5 cm across, as large as 4 cm; subhedral plagioclase phenocrysts (15%), average 1 mm across; subangular pink dacitic lithic lapilli (10%), average 1 cm across, as large as 5 cm; euhedral to subhedral biotite and hornblende microphenocrysts (2%); basaltic lithic

12. TOWEL CREEK--Continued

Towel Creek Tuff--Continued
Member 2--Continued Meters

lapilli (trace), usually altered; glass dust matrix. Well exposed; moderately resistant; sharp basal contact---- 7.2

7. Dacitic air-fall tuff, white; weathers same color. Well developed very thin beds; average 3 cm thick; shown by differences in grain size of the pumiceous lapilli; reversely graded beds are common. Contains rounded white dacitic pumiceous lapilli (70%), average 5 mm across, as large as 2.5 cm; subhedral plagioclase phenocrysts (15%), average 1 mm across; dacitic lithic lapilli (10%), average 2 mm across, as large as 1 cm; euhedral biotite and hornblende phenocrysts (5%), average 1 mm across; subangular basaltic lithic lapilli (trace), average 2.5 mm across. Well exposed; very resistant; sharp basal contact---------- 0.3

6. Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded white dacitic pumiceous lapilli and blocks (35%), average 1.5 cm across, as large as 10 cm; subhedral plagioclase phenocrysts (20%), average 1.5 mm across; euhedral biotite and hornblende microphenocrysts (5%), subangular dacitic lithic lapilli (2%), average 1 cm across, as large as 5 cm; subangular basaltic lithic lapilli (trace), same size as dacitic lithic lapilli, concentrated in basal portion of unit; glass dust matrix. Very well exposed; non-resistant; sharp basal contact-- 15.0

Offset in section so that overlying units measured 280 m south of underlying units.

Hickey Formation:
Member 10:
Flow:

5. Basalt, pale bluish-gray; weathers same color; uppermost 2 m is brecciated. Microporphyritic: contains subhedral olivine microphenocrysts (2%), altered to iddingsite; aphanitic groundmass. Slightly vesicular (5-10%); filled with silica; spheroidal; less that 1 mm across. Well developed vertical joints. Well exposed; very resistant; sharp basal contact-------------------------------------- 32.5

Towel Creek Tuff:
Member 1:

4. Dacitic pyroclastic breccia, white; weathers same color and grayish-orange-pink; structureless. Contains subangular red and gray dacitic lithic blocks and lapilli (50%), 3 mm to 20 cm across, average 4.5 cm across; subhedral to euhedral plagioclase phenocrysts (5%), average 1.5 mm across; euhedral biotite and hornblende phenocrysts (1%), average 1 mm across; rounded basic xenoliths (trace); glassy matrix. Well exposed; extremely resistant; sharp

12. TOWEL CREEK--Continued

Towel Creek Tuff--Continued

Member 1--Continued — Meters

basal contact-- 2.8

3. Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded white dacitic pumiceous lapilli (35%), 2 mm to 4.5 cm across, average 1 cm across; subhedral to euhedral plagioclase phenocrysts (8%), average 1 mm across; subangular to subrounded dacitic lithic lapilli (4%), 2 mm to 6 cm across, average 1.5 cm across; euhedral hornblende and biotite phenocrysts (2%), average 1 mm across; basaltic lithic lapilli (trace); glass dust matrix. Well exposed; extremely resistant; sharp basal contact---------------------------- 13.2

2. Dacitic ignimbrite, medium brown; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli (25%), 2 mm to 6 cm across, average 8 mm across; subhedral plagioclase phenocrysts (15%), average 1.5 mm across; euhedral biotite and hornblende phenocrysts (2.5%), average 1.5 mm across; dacitic lithic lapilli (trace); glass dust matrix. Poorly exposed; moderately resistant; basal contact not exposed---------------------- 0.5

Hickey Formation:

Member 9 (unmeasured):

Flow:

1. Amygdaloidal basalt, moderate red and medium bluish-gray; weathers same colors; portions of flow are brecciated. Microporphyritic: contains olivine microphenocrysts (15%), altered to iddingsite; aphanitic groundmass. Extremely vesicular (30%); lined with silica; less than 1 mm across. Moderately exposed; moderately resistant.

Base of section; not base of exposure.

13. BRUSHY PRONG

[Measured October 1980 southeast of intersection of Towel Creek and Brushy Prong]

Top of section; not top of exposure.

Hackberry Mountain Dacite (not measured):

Flow:

14. Dacitic breccia, white and bluish-gray; weathers same colors; structureless. Lowermost 10 m of unit is highly brecciated and it grades upward into a massive dacitc flow. Breccia contains subangular bluish-gray dacitic lithic blocks and lapilli (40%), 5 mm to 10 m across, average 1 mm across; subhedral to euhedral biotite and hornblende phenocrysts (5%), average 1 mm across; subrounded dacitic pumiceous lapilli (5%), average 3 mm across; glassy groundmass. Well exposed; extremely

Hackberry Mountain Dacite (not measured)--Continued
Flow--Continued — Meters

resistant; sharp basal contact.

Rubble:

13. Sandstone, moderate pink and white; weathers same color. Moderately developed thin beds in basal 1 m of unit; shown by differences in concentration of granule size grains. Poorly sorted; fine sand to boulder size; mineral grains are fine sand to coarse sand size, average medium sand size; dacitic lithic clasts are medium sand to boulder size; all grains and fragments are subangular. Contains plagioclase grains (50%); dacitic lithic grains (25%), average coarse sand size; biotite grains (5%); dacitic lithic fragments (5%), very coarse to boulder size, average granule size; very fine-grained matrix (15%). Well indurated; well exposed; extremely resistant; sharp basal contact-- 2.5
12. Sandy conglomerate, white; weathers same color. Moderately well developed thin beds; average 50 cm thick; shown by differences in concentration of the larger dacitic lithic fragments, pebble to boulder size. Poorly sorted; fine sand to boulder size; matrix of mineral grains is fine sand to granule size; grains and fragments are subangular to subrounded. Contains white dacitic lithic fragments (40%), average pebble size; plagioclase grains (30%); biotite and hornblende grains (5%); dacitic pumiceous fragments (trace); very fine-grained matrix (25%). Well indurated; well exposed; very to extremely resistant; sharp basal contact---------------------------- 33 ±

Angular unconformity.

Towel Creek Tuff:
Member 4:

11. Dacitic ignimbrite, white; weathers same color; structureless. Contains euhedral plagioclase phenocrysts (25%), 1 to 2 mm across; subrounded dacitic pumiceous lapilli (20%), average 1 cm across; subangular bluish-gray lithic lapilli (15%), average 5 mm across, as large as 4 cm; euhedral biotite and hornblende phenocrysts (5%), average 1 mm across; glass dust matrix. Well exposed; extremely resistant; sharp basal contact---------------------------- 2.9
10. Sandstone, grayish-orange; weathers same color. Moderately developed thin beds; average 40 cm thick; shown by differences in size of dacitic lithic fragments, cobble versus pebble and granule size; finer-grained beds are less resistant. Poorly sorted; fine sand to boulder size; mineral grains are fine to coarse sand size; lithic fragments are granule to boulder size. Contains rounded white dacitic pumiceous fragments (25%); subrounded to

13. BRUSHY PRONG--Continued

Towel Creek Tuff--Continued
Member 4--Continued — Meters

rounded dacitic lithic fragments (20%), average pebble size; subrounded plagioclase grains (10%); subrounded biotite grains (trace); subangular green pyroxene grains (trace); fragments of basalts and basic xenoliths (trace). Well indurated; moderately exposed; very resistant; sharp basal contact-- 23.5

9. Dacitic ignimbrite, white; weathers same color; structureless, basal 50 cm is a dacitic air-fall tuff. Contains subrounded white dacitic pumiceous lapilli and blocks (55%), 2 mm to 8 cm across, average 2 cm across; subhedral to euhedral plagioclase phenocrysts (15%), 1 to 2 mm across; subrounded pink and blue dacitic lithic lapilli (5%), average 3 cm across; biotite phenocrysts (trace); glass dust matrix. Well exposed; very resistant; sharp basal contact-- 4.5

Hickey Formation:
Member 13:
Flow:

8. Basaltic ash, moderate red; weathers same color. Well developed laminae; shown by differences in grain size of lapilli and differences in color. Contains subangular basaltic lithic lapilli (99%), average 2 mm across, as large as 1 cm, microvesicular; green pyroxene phenocrysts (1%), average 1 mm across. Poorly indurated; well exposed; non-resistant; sharp basal contact----------- 4.8

Offset in section so that overlying units measured 160 m southeast of underlying units.

Towel Creek Tuff:
Member 3:
Tuff:

7. Dacitic ignimbrite, white; weathers same color; compound unit, contains 10 to 15 separate flows, average 2 m thick. Average flow contains rounded dacitic pumiceous lapilli (45%), 2 mm to 2.5 cm across, average 4 mm across; subhedral plagioclase phenocrysts (20%), average 1.5 mm across, as large as 5 mm; dacitic lithic lapilli (2%), 2 to 25 mm across, average 4 mm across; euhedral biotite microphenocrysts (2%); glass dust matrix. Well exposed; moderately resistant; sharp basal contact--------- 33.5
6. Dacitic pyroclastic breccia, similar to unit 4------------- 2.0
5. Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded to rounded white dacitic pumiceous lapilli (30%), 2 to 25 mm across, average 1 cm across; euhedral plagioclase phenocrysts (10%), average 1 mm across, as large as 2 mm; dacitic lithic lapilli (10 to 30%), average 2 cm across, as large as 5 cm; euhe-

13. BRUSHY PRONG--Continued

Towel Creek Tuff--Continued
Member 3--Continued
Tuff--Continued — Meters

dral biotite phenocrysts (2%); glass dust matrix. Well exposed; moderately resistant; sharp basal contact-------- 17.5

4. Dacitic pyroclastic breccia, grayish-pink; weathers same color; compound unit, contains 3 flows 5.9, 5.4, and 10.2 m thick. Contains subangular pink dacitic lithic blocks and lapilli (40%), average 10 cm across, as large as 50 cm; subhedral plagioclase phenocrysts (25%), average 1 mm across; euhedral biotite and hornblende phenocrysts (5%), average 1 mm across; rounded dacitic pumiceous lapilli (5%); subrounded lapilli of basic xenoliths (trace); glassy martix. Well exposed; very resistant; sharp basal contact-- 21.5

3. Dacitic ignimbrite, white; weathers same color; structureless. Contains euhedral plagioclase phenocrysts (25%), average 1 mm across, as large as 2 mm; subrounded to rounded white dacitic pumiceous lapilli, 2 to 25 mm across, average 1 cm across; pink and gray dacitic lithic lapilli and blocks (10 to 20%), average 5 mm across, as large as 20 cm; euhedral biotite and hornblende phenocrysts (2%); glass dust matrix. Well exposed; non-resistant; sharp basal contact---------------------------------- 13.5

Breccia:

2. Dacitic pyroclastic breccia, grayish-pink; weathers same color; structureless. Contains subangular pink dacitic lithic blocks (45%), 5 mm to 4 m across, average 15 cm across, larger blocks have basic xenoliths; subhedral plagioclase phenocrysts (35%), average 1 mm across; euhedral biotite and hornblende phenocrysts (5%), average 1 mm across; rounded lapilli of basic xenoliths (trace), 2 mm to 1.5 cm across; glassy groundmass. Very well exposed; extremely resistant; sharp basal contact---------- 69.0

Tuff (incomplete):

1. Dacitic ignimbrite, white; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli (30%), average 5 mm across; euhedral plagioclase phenocrysts (20%), average 1.5 mm across, as large as 5 mm; pink dacitic lithic lapilli and blocks (12%), 0.5 mm to 50 cm across, average size is 2 mm across; euhedral biotite and hornblende phenocrysts (5%), average 1 mm across; glass dust matrix. Well exposed; very resistant---------- 15.0+

Base of section; base of exposure.

14. CATHEDRAL BUTTE

[Measured May 1981 600 m southeast of Brown Springs Ranch on the eastern side of the Verde River]

Top of section; not top of exposure.
Hickey Formation:
Member 5:
Flow:

16. Basalt (incomplete), very dark gray; weathers medium to medium dark gray. Porphyritic: contains subhedral green pyroxene phenocrysts (5%), average 2 mm across, as large as 5 mm; subhedral olivine microphenocrysts (trace), altered to iddingsite; aphanitic groundmass. Well developed horizontal joints, average 15 cm apart; moderately developed vertical joints, 20 to 50 cm apart. Moderately exposed; moderately resistant; basal contact not exposed-- 2.0+
15. Covered--- 13.0
14. Basalt, grayish-red-purple; weathers pale reddish-purple. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across; subhedral green pyroxene phenocrysts (trace), average 1.5 mm across, as large as 1 cm; aphanitic groundmass. Very well developed vertical joints, 10 to 50 cm apart; well developed horizontal joints, 1 to 5 cm apart. Very well exposed; extremely resistant; sharp basal contact---- 42.0
13. Andesitic breccia and air-fall tuff, moderate red and moderate reddish-brown; weathers same colors. Uppermost 1.7 and lowermost 3 m of unit is a breccia, rest is a well-bedded lapilli air-fall tuff. Breccia consists of subrounded to subangular lapilli and blocks (70%), 1 cm to 1 1 m across, average 3 cm across; calcite (30%), fills all pore spaces and vesicles. All lapilli and blocks are porphyritic: contain subhedral white plagioclase phenocrysts (1%), lath-shaped, average 1 by 2 mm, commonly have orange rim; subhedral to euhedral green pyroxene phenocrysts (trace), average 1 mm across; anhedral to subhedral olivine phenocrysts (trace), altered to iddingsite, average 1 mm across; aphanitic groundmass. Very well exposed; extremely resistant; sharp basal and internal contacts-- 11.5

Member 4:
Flow:

12. Basalt, very dark gray; weathers dark olive and yellowish-gray. Porphyritic: contains subhedral olivine phenocrysts (7%), altered to iddingsite, average 1 mm across, as large as 3 mm; subhedral green pyroxene phenocrysts (1%), average 1.5 mm across, as large as 5 mm; aphanitic groundmass. Well developed vertical joints, 5 to 30 cm apart. Well exposed; extremely resistant; sharp basal contact-- 21.0

14. CATHEDRAL BUTTE--Continued

Hickey Formation--Continued

Member 3: Meters

11. Basalt, moderate red; weathers same color. Microporphyritic: contains subhedral olivine microphenocrysts (5%), altered to iddingsite; aphanitic groundmass. Extremely vesicular; filled with calcite; spheroidal or stretched; average 1.5 mm across. Poorly exposed; very resistant; basal contact not exposed---------------------------------- 3.0

10. Basalt, very dark gray; weathers medium gray and moderate brown. Porphyritic: contains subhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across, as large as 4 mm; anhedral green pyroxene phenocrysts (trace), average 1.5 mm across; aphanitic groundmass. Slightly vesicular (1%); filled with calcite; spheroidal; average 5 mm across. Very well developed vertical joints, 5 to 15 cm apart. Moderately exposed; very resistant; basal contact not exposed---------------------------------- 12.0

9. Basalt, grayish-black; weathers light brownish-gray. Microporphyritic: contains subhedral to euhedral olivine microphenocrysts (1%); green pyroxene microphenocrysts (trace); aphanitic groundmass. Very well developed vertical joints, average 10 cm apart; well developed horizontal joints, 2 to 15 cm apart. Moderately exposed; very resistant; sharp basal contact------------------------ 7.0

8. Basalt, medium gray; weathers medium light gray, dark olive, and pale purple. Porphyritic: contains subhedral olivine phenocrysts (10%), altered to iddingsite, average 1.5 mm across, as large as 6 mm; subhedral green pyroxene phenocrysts (1%), average 1 mm across; aphanitic groundmass. Very well developed vertical joints, average 10 cm apart; moderately developed sub-horizontal joints, average 5 cm apart. Well exposed; extremely resistant; sharp basal contact-- 37.5

7. Olivine Basalt, dark reddish-brown; weathers medium gray. Porphyritic: contains subhedral olivine phenocrysts (25%), rims altered to iddingsite, average 1 mm across, as large as 5 mm; subhedral green pyroxene (1%), average 1 mm across; aphanitic groundmass. Cumulophyres are common with pyroxene microphenocrysts surrounding olivine microphenocrysts; average 5 mm across. Both lowermost and uppermost portions of flow are extremely vesicular (25 to 30%); filled with calcite; spheroidal; average 5 mm across. Non-vesicular portion of flow has very well developed vertical joints, 10 to 40 cm apart; moderately developed horizontal joints, 20 cm to 2 m apart. Well exposed; extremely resistant; sharp basal contact----- 7.5

6. Basaltic ash, light red; weathers same color; extremely poor exposure--- 15.0

5. Basalt, medium gray; weathers moderate reddish-brown and grayish-olive. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm

14. CATHEDRAL BUTTE--Continued

Hickey Formation--Continued

Member 3--Continued — Meters

across, as large as 3 mm; subhedral green pyroxene phenocrysts (trace), average 2 mm across; aphanitic groundmass. Slightly vesicular (5%); filled with calcite; spheroidal; average 1 mm across. Very well developed vertical joints, average 10 cm apart. Well exposed; extremely resistant; sharp basal contact------------------ 10.5

Member 2:

Cinder:

4. Basaltic breccia, moderate red; weathers same color. Subrounded breccia lapilli and blocks (80%) [have bimodal size distribution: large size (50%), 1 to 20 cm across, average 2 cm across; smaller size (30%), average 1.5 mm across, as large as 5 mm]; calcite (20%); fills all pore spaces and vesicles. Lapilli and blocks porphyritic: contains subhedral to euhedral olivine phenocrysts (2%), altered to iddingsite, average 1 mm across; aphanitic groundmass. Poorly developed vertical joints, average 40 cm apart. Well exposed; very resistant; sharp basal contact--- 7.2

Flow:

3. Basalt, grayish-black; weathers medium light gray. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 3 mm; subhedral green pyroxene phenocrysts (1%), average 1 mm across, as large as 2 mm; aphanitic groundmass. Well developed vertical and horizontal joints, average 30 cm apart. Well exposed; very resistant; sharp basal contact-- 11.5

2. Basaltic ash, light red; weathers same color; structureless. Contains rounded basaltic lithic ash and lapilli (70%), aphyric, 0.5 to 5 mm across; microvesicular; calcite (30%), fills all pore spaces and microvesicles. poorly exposed; non-resistant; basal contact not exposed--- 6.0

1. Basalt (incomplete), medium dark gray; weathers same color, medium reddish-brown, and greenish-black. Porphyritic: contains subhedral olvine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 3 mm; subhedral black pyroxene phenocrysts (1%), average 1 mm across, as large as 5 mm; anhedral quartz (?) phenocrysts (trace), average 2 mm across; aphanitic groundmass. Cumulophyres of olivine microphenocrysts surrounded by pyroxene microphenocrysts are common; average 2 cm across. Pyroxene gradually disappears as go up from base of exposure; only trace amount at top of unit. Slightly vesicular (5%); filled with silica; usually stretched parallel to base of flow; average 1 by 2 mm. Well developed columnar joints, 5 to 15 cm apart; well developed horizontal joints, average 1 cm apart. Very well exposed; extremely resistant---- 25.0+

Base of section; base of exposure.

15. GOSPEL HOLLOW

[Measured May 1981 along the Verde River at Gospel Hollow]

Top of section; top of exposure, overlain by gravel of Quaternary age.

Martin Formation:

Jerome Member:

Aphanitic Dolomite Unit:

6. Dolomite, pinkish-gray; weathers very light gray. Very well developed thick horizontal beds; 20 cm to 1.5 m thick. Aphanitic; contains dolomite (99%); subrounded to rounded quartz grains (trace), average fine sand size; pale green claystone, very thin beds (2 to 4 cm thick) occur between some dolomite beds. Well developed conchoidal fracture; very resistant; sharp but irregular basal contact-- 30.0+

Fetid Dolomite Unit:

5. Dolomitic breccia, pale yellowish-brown; weathers same color; structureless. Contains angular to subangular breccia fragments (55%), granule to boulder size, average pebble size, primarily laminated dolomite (50%), some chert (5%); matrix of finely crystalline calcite (45%). Well exposed; very resistant; sharp but irregular basal contact-- 1.1
4. Dolomite, grayish-orange-pink; weathers same color; aphanitic. Well developed very thin beds; 1 to 6 cm thick; upper portion has thicker beds, up to 50 cm thick. Well developed wavy horizontal laminae within beds; average 1 mm thick; shown by color contrast of white versus grayish-orange-pink. Well exposed; extremely resistant; sharp basal contact-- 2.5

Unconformity.

Chino Valley Formation:

3. Dolomite, pale reddish-purple and grayish-orange-pink, becomes grayish-orange-pink as go up section; weathers same colors. Moderately developed laminae; 1 to 5 mm thick; shown by sharp breaks in otherwise massive rock. Very finely crystalline. Poorly exposed; moderately resistant; sharp basal contact---------------------------- 7.9

Unconformity.

Tapeats Sandstone:

2. Sandstone, moderate orange-pink to pale yellowish-orange; weathers same colors; poorly sorted. Well developed thick beds; average 1 cm thick; shown by granule-rich beds; well developed low-angle tabular cross-stratification. Contains subangular quartz (85%) and feldspar (15%) grains; medium sand to pebble size, average coarse sand size. Very well indurated; very well exposed; very resistant; sharp but irregular basal contact--------------- 13.0

15. GOSPEL HOLLOW--Continued

Unconformity.

Precambrian Basalt (incomplete)

1. Basalt, medium dark gray; weathers bluish-green and pale red. Uppermost portion of unit, 0 to 15 m thick, is hematized and pale red; not as well exposed, as resistant, or as coherent as the remainder of the flow; aphyric. Main body of flow is porphyritic: contains subhedral white plagioclase phenocrysts (35%), sericitized, average 1.5 mm across, as large as 5 mm; aphanitic groundmass. Very well developed sub-horizontal joints, dip 45° to the north, 10 cm to 2 m apart; very well developed sub-vertical joints, perpindicular to sub-horizontal joints, 20 to 50 cm apart. Well exposed; very to extremely resistant-------------------------------- 20.0+

Base of section; base of exposure.

16. SOUTHEASTERN BOUNDARY OF GOSPEL HOLLOW

[Measured May 1981 on the southeastern boundary of Gospel Hollow 3.8 km southeast of Brown Springs Ranch]

Top of section; top of exposure, overlain by a landslide deposit.

Hickey Formation:

Member 12 (unmeasured)

20. Basalt, medium gray; weathers medium dark gray. Porphyritic: contains anhedral to subhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across, as large as 3 mm; aphanitic groundmass. Well developed horizontal and vertical joints, average 5 cm apart. Poorly exposed; non-resistant; basal contact not exposed.

Towel Creek Tuff:

Member 3:

Tuff:

19. Dacitic ignimbrite, grayish-pink; weathers same color; structureless. Contains anhedral plagioclase phenocrysts (25%), average 1 mm across, as large as 2 mm; rounded white dacitic pumiceous lapilli (10%), average 2 mm across, as large as 2 cm; subrounded blue and red dacitic lithic grains (5%), average 1 mm across, as large as 4 mm; subhedral biotite and hornblende phenocrysts (1%), average 1 mm across, as large as 4 mm; glass dust matrix. Well exposed; moderately resistant; sharp basal contact---- 19.5

18. Basaltic tuff, moderate pink; weathers same color; structureless. Contains subrounded basaltic lithic lapilli (65%), average 2 mm across, as large as 1 cm; subhedral black pyroxene phenocrysts (trace), average 2 mm aross; calcite (35%), fills all pore spaces. Moderately exposed; moderately resistant; sharp basal contact--------- 1.3

16. SOUTHEASTERN BOUNDARY OF GOSPEL HOLLOW--Continued

Towel Creek Tuff--Continued
Member 3--Continued
Tuff--Continued — Meters

17. Dacitic ignimbrite, moderate pink; weathers pale red; structureless. Contains subhedral plagioclase phenocrysts (20%), average 1 mm across; subrounded to subangular basaltic lithic lapilli (10%), average 1 cm across, as large as 3 cm; subrounded red dacitic lithic lapilli (5%), average 2 mm across, as large as 1 cm; subhedral biotite phenocrysts (4%), altered, average 1 mm, as large as 3 mm; subhedral hornblende phenocrysts (3%), average 1 mm across; rounded white dacitic pumiceous lapilli (5%), average 2 mm across; glass dust matrix. Well exposed; moderately resistant; sharp basal contact------------------ 10.5

Hickey Formation:
Member 11:

16. Basalt, dark gray; weathers light bluish-gray; uppermost 7 m is brecciated, rest is massive. Porphyritic: contains green pyroxene phenocrysts (12%), average 1 mm across, as large as 2 mm; subhedral olivine phenocrysts (1%) and microphenocrysts (5%), altered to iddingsite, phenocrysts average 1 mm across; aphanitic groundmass. Very well developed horizontal joints, average 10 cm apart; well developed vertical joints, 10 to 30 cm apart. Well exposed; extremely resistant------------------------------ 60.0
15. Andesitic tuff, pale red; weathers same color; structureless. Contains subrounded red basaltic lithic lapilli (15%), average 2 mm across, as large as 1.5 cm; subhedral plagioclase phenocrysts (5%), average 1 mm across; subhedral olivine microphenocrysts (2%), as large as 2 mm; euhedral biotite phenocrysts (1%), average 1 mm across; subhedral green pyroxene microphenocrysts (trace); aphanitic groundmass. Slightly vesicular (5%); filled with silica; spheroidal, 1 to 3 mm across; elongate, average 2 mm by 1 cm. Moderately exposed; moderately resistant; basal contact not exposed---------------------------------- 9.2
14. Basalt, grayish-black; weathers same color and dark olive; possibly a compound flow with boundary 10.5 m above the base of the unit. Porphyritic: contains subhedral olivine phenocrysts (2%), altered to iddingsite, average 1.5 mm across; subhedral green pyroxene phenocrysts (2%), average 1 mm across; aphanitic groundmass. Rare cumulophyres of pyroxene surrounded by olivine crystals, average 3 mm across. Well developed horizontal joints, 5 mm to 1 cm apart; well developed irregular vertical joints, average 5 cm apart. Well exposed; very resistant; basal contact not exposed-- 22.5
13. Basalt, grayish-black; weathers light to medium gray and dark olive; probably a compound flow with boundary 30 m above the base of the unit. Microporphyritic: contains

16. SOUTHEASTERN BOUNDARY OF GOSPEL HOLLOW--Continued

Hickey Formation--Continued
Member 11--Continued | Meters

tains subhedral olivine microphenocrysts (5%), altered to iddingsite; subhedral green pyroxene phenocrysts (1%), average 1 mm across; aphanitic groundmass. Well developed horizontal joints, 1 to 10 cm apart; moderately developed vertical joints, 5 to 15 cm apart. Well exposed; extremely resistant; basal contact not exposed, probably a basaltic tuff 3 m thick at base of unit---------- 58.5

12. Basalt, light bluish-gray; weathers medium bluish-gray; basal 0.5 m is brecciated. Porphyritic: contains anhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across, as large as 3 mm; subhedral green pyroxene phenocrysts (1%), average 1 mm across; aphanitic groundmass. Slightly vesicular (10%); filled with calcite; spheroidal; average 5 mm across, as large as 3 cm. Poorly developed vertical joints, 5 to 30 cm apart; poorly developed horizontal joints, average 20 cm apart. Moderately exposed; very resistant; sharp basal contact---- 34.5

11. Basaltic tuff, moderate red; weathers same color; moderately developed very thin beds, shown by differences in grain size. Contains red aphyric basaltic lithic ash (70%), average 1 mm across, as large as 4 mm; subhedral to euhedral olivine phenocrysts (5%), altered to iddingsite; calcite (25%), fills all pore spaces. Well exposed; moderately resistant; sharp basal contact------------------ 3.3

10. Basalt, same as unit 12. Part of the same compound flow. Sharp basal contact-- 1.8

9. Basaltic tuff, very poorly exposed but probably similar to unit 11. Sharp basal contact------------------------------ 1.0

8. Basalt, same as unit 12. Part of the same compound flow. Sharp basal contact-- 51.0

7. Andesitic breccia, medum dark gray; weathers dark bluish-gray. Breccia composed of angular lapilli and blocks; average 30 cm across, as large as 1.0 m . Porphyritic: contains anhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across; subhedral plagioclase phenocrysts (3%), average 3 mm across, commonly have orange rims. Extremely vesicular (20%); all filled with calcite; stretched; average 1 mm across, as large as 5 mm. Well exposed; very resistant; sharp basal contact---------- 1.0

6. Basaltic tuff, moderate red; weathers same color; structureless. Contains subrounded basaltic lithic lapilli (70%), average 3 mm across, as large as 1 cm, microvesicular; calcite (30%), fills all pore spaces. Poorly exposed, non-resistant; sharp basal contact---------------- 9.0

5. Basalt, same as unit 12. Part of same compound flow. This portion of flow is non-vesicular and has better developed joints. Well developed columnar joints, 20 to 30 cm apart; well developed horizontal joints, 5 mm to 10 cm apart. Sharp basal contact----------------------------------- 39.0

16. SOUTHEASTERN BOUNDARY OF GOSPEL HOLLOW--Continued

Towel Creek Tuff:

Member 2: Meters

4. Dacitic ignimbrite, grayish-pink; weathers same color; structureless. Contains white rounded dacitic pumiceous grains (15%), average 1 mm across, as large as 5 mm; euhedral plagioclase phenocrysts (5%), average 1 mm across; subrounded basaltic lithic lapilli (2%), average 2 mm across, as large as 4 mm; subhedral biotite and hornblende microphenocrysts (1%); glass dust matrix. Moderately exposed; very resistant; sharp basal contact---- 8.2

Hickey Formation:

Member 10 (not measured):

Flow:

3. Basalt, medium dark gray; weathers medium gray. Porphyritic: contains subhedral olivine phenocrysts (2%), altered to iddingsite, average 1 mm across, as large as 2 mm; subhedral green pyroxene phenocrysts (trace), average 1 mm across. Moderately developed vertical joints, 1 to 20 cm apart; poorly developed horizontal joints, average 5 cm apart. Moderately exposed; moderately resistant; sharp basal contact.

Towel Creek Tuff:

Member 1 (unmeasured):

2. Dacitic ignimbrite, grayish-pink; weathers pale red; structureless. Contains rounded white dacitic pumiceous grains (20%), average 1 mm across, as large as 5 mm; subangular basaltic lithic lapilli (4%), average 1.5 mm across, as large as 1 cm; euhedral plagioclase phenocrysts (2%), average 1 mm across; subrounded gray dacitic lithic lapilli (1%), average 2 mm across; euhedral biotite and hornblende phenocrysts (1%), average 1 mm across; glass dust matrix. Well exposed; very resistant; sharp basal contact.

Hickey Formation:

Member 9 (not measured):

Cinder:

1. Basalt, grayish-purple; weathers same color. Porphyritic: contains subhedral green pyroxene phenocrysts (2%), average 1 mm across, as large as 5 mm; aphanitic groundmass. Well exposed; moderately to non-resistant.

Base of section; not base of exposure.

17. CHALK SPRING

[Measured November 1980 at Chalk Spring which is 4.4 km north of the Childs powerplant]

Top of section; not top to exposure.

Rubble (not measured): Meters

6. Sandy conglomerate, grayish-orange-pink; weathers same color. Well developed thick beds; 50 cm to 4 m thick, the coarser the material in the bed the thicker it is; thicker beds are graded, amount of coarse dacitic fragments is reduced about 30% between the top and bottom of a bed. Poorly sorted; silt to boulder size. Contains subangular white and blue dacitic lithic fragments (40%), granule to boulder size, average cobble size; subrounded plagioclase grains (20%), very fine to coarse sand size, average medium sand size; subrounded biotite grains (2%), medium sand size; very fine sand to silt size matrix. Well indurated; very well exposed; extremely resistant.
5. Dacitic ignimbrite, white; weathers same color; structureless. Contains subhedral plagioclase phenocrysts (10%), average 1 mm across; subrounded blue dacitic lithic lapilli (3%), average 2 mm across; euhedral biotite microphenocrysts (1%); glass dust matrix. Well exposed; non-resistant; sharp basal contact.
4. Sandy conglomerate, same as unit 6.

Angular uncomformity, overlying units are horizontal and underlying units dip 30° towards the north.

Towel Creek Tuff:

3. Pebbly sandstone, very light gray; weathers same color. Poorly developed beds; shown by concentrations of dacitic lithic pebbles; long axes of pebbles are parallel to beds. Poorly sorted, very fine sand to boulder size; all grains and fragments are subrounded. Contains plagioclase grains (80%), very fine to coarse sand size, average medium sand size; pink and blue dacitic lithic fragments (15%), coarse sand to boulder size, average granule size; dacitic pumiceous fragments (3%), granule to pebble size, average pebble size; biotite grains (2%), same size as plagioclase grains. Moderately indurated; well exposed; moderately resistant; sharp basal contact---- 32.5
2. Dacitic air-fall tuff, white; weathers same color. Well developed thin beds; 1 to 10 cm thick; shown by concentrations of dacitic lithic fragments. Contains subrounded to subangular dacitic lithic lapilli and blocks (35%), 1 mm to 10 cm across, average 3 mm across; subhedral to euhedral plagioclase phenocrysts (30%), average 1 mm across; rounded white dacitic pumiceous lapilli (30%), average 3 mm across; euhedral biotite phenocrysts (5%),

17. CHALK SPRING--Continued

Towel Creek Tuff--Continued — Meters

average 1.5 mm across. Majority of dacitic lithic lapilli are altered in basal portion of unit; amount of altered lapilli decrease as go up section. Well indurated; well exposed; moderately resistant; sharp basal contact--------- 40.5

Unconformity.

Sally May Dacite (not measured):

1. Dacite, pale purple; weathers same color; structureless; highly altered. Contains subhedral white plagioclase phenocrysts (35%), average 2 mm across, as large as 1 cm; altered euhedral hornblende phenocrysts (3%), average 1 mm across; altered euhedral biotite phenocrysts (1%), average 2.5 mm across. Well exposed; very resistant.

Base of section; base of exposure.

18. NORTH OF THE VERDE HOT SPRINGS

[Measured May 1981 2.0 km northwest of the Verde Hot Springs on the northeastern side of the Verde River]

Top of section; top of exposure, overlain by landslide deposit.

Hickey Formation:

Member 11:

14. Basalt (incomplete), medium gray; weathers same color. Microporphyritic: contains subhedral green pyroxene microphenocrysts (1%), also occur as glomerophyres that average 1 cm across; subhedral olivine microphenocrysts (trace), altered to iddingsite; aphanitic groundmass. Very well developed vertical and horizontal joints, 2 to 5 cm apart. Moderate exposure due to extreme joints; moderately to very resistant; basal contact not exposed---- 36.0+
13. Basaltic ash, medium red; weathers pale red; structureless; baked by basalt flow above. Contains subrounded orange to medium red basaltic vitric ash, average 1 mm across, microvesicular; euhedral white plagioclase phenocrysts (1%), average 1 mm across; anhedral black pyroxene microphenocrysts (trace); aphanitic groundmass. Very poorly exposed, only uppermost cooked portion is exposed; non-resistant; basal contact not exposed------------------ 11.0
12. Basalt, very dark gray; weathers dark olive and dark yellowish-orange. Porphyritic: contains anhedral olivine phenocrysts (15%), rims altered to iddingsite, average 1 mm across, as large as 2 mm; subhedral green pyroxene microphenocrysts (5%), as large as 1 mm across; aphanitic groundmass. Cumulophyres of pyroxene microphenocrysts

18. NORTH OF THE VERDE HOT SPRINGS--Continued

Hickey Formation--Continued

Member 11--Continued | Meters

surrounding olivine microphenocrysts are common; at least 1/2 of all pyroxene occurs in cumulophyres; up to 2.5 mm across. Poorly developed horizontal and vertical joints, average 20 cm apart. Moderately exposed; moderately to very resistant; sharp basal contact-------------------- 30 ±

11. Basaltic ash; same as unit 13------------------------------- 6.9

10. Basalt, very dark gray; weathers dark olive; aphyric; aphanitic goundmass. Extremely well developed joints; horizontal set averages 5 mm apart, columnar set is 3 cm to 1 m apart. Well exposed; extremely resistant; sharp basal contact--- 18.5

Member 9:

Pyroclastics:

9. Basaltic ash, light red; weathers same color. Well developed thin laminae, less than 1 mm thick; shown by concentrations of pore spaces. Unit contains subrounded red basaltic vitric lapilli (89%); anhedral green pyroxene microphenocrysts (1%); calcite (10%), fills all pore spaces. Poorly indurated, calcareous cement; very poorly exposed; non-resistant; sharp basal contact--------- 18.5

Offset in section so that overlying units measured 300 m northeast of underlying units.

Member 6:

8. Basalt, very dark gray; weathers light brown and light gray; aphyric; aphanitic groundmass. Very well developed vertical joints, 5 to 30 cm apart; moderately developed horizontal joints, average 5 cm apart. Very well exposed; extremely resistant; sharp basal contact---------- 50 ?

Member 5:

Flow:

7. Basaltic ash, medium red; weathers same color; structureless. Contains subrounded red basaltic vitric lapilli (90%), microvesicular; calcite (10%), fills all vesicles and pore spaces. Very poorly exposed; non-resistant; basal contact not exposed-------------------------------- 15 ±

6. Basalt, very dark gray; weathers light gray; basal 1.2 m is brecciated. Porphyritic: contains subhedral olivine phenocrysts (18%), altered to iddingsite, average 1 mm across, as large as 5 mm; aphanitic groundmass. Well developed vertical joints, 1 to 20 cm thick. Moderately exposed; moderately resistant; basal contact not exposed-- 30.0

5. Andesite, grayish-purple; weathers medium gray or pale red; compound flow, two units with the lower one 9 m thick. Porphyritic: contains subhedral olivine phenocrysts (7%), altered to iddingsite, average 1 mm across, as large as 4 mm; subhedral plagioclase phenocrysts (2%),

18. NORTH OF THE VERDE HOT SPRINGS--Continued

Hickey Formation--Continued
Member 5--Continued
Flow--Continued | Meters

lath-shaped, average 2 mm across, as large as 5 mm; anhedral green pyroxene microphenocrysts (trace), occur in glomerophyres that average 2 mm across, as large as 5 mm; aphanitic groundmass. Upper portion of flow is extremely vesicular (35%); all filled with calcite. Well developed columnar joints, average 20 cm apart; well developed sub-horizontal joints, average 10 cm apart. Well exposed; lower flow and vesicular portion of upper flow are moderately resistant, rest of unit is very resistant; sharp basal contact---------------------------- 34.5

4. Basalt, pale purple; weathers medium red or medium grayish-blue. Compound flow; contains 5 flows: lowest flow is 11.4 m thick; second flow is 21.8 m thick, basal 1.5 m is brecciated; third flow is 4.2 m thick, basal 1.5 m is brecciated; fourth flow is 7.2 m thick, basal 6.0 m is brecciated; highest flow is 7.0 m thick, basal 6.0 m is brecciated. Porphyritic: contains subhedral olivine phenocrysts (7%), altered to iddingsite, average 1 mm across, as large as 3 mm; anhedral to subhedral plagioclase phenocrysts (trace), average 1 mm across, as large as 2 mm; anhedral green pyroxene phenocrysts (trace), average 1 mm across; aphanitic groundmass. Rare cumulophyres of olivine + pyroxene; average 5 mm across. Lowest flow unit is slightly vesicular (10%); filled with calcite; as large as 3 mm across. Non-brecciated portions of flow have well developed columnar joints, average 1 m apart; well developed horizontal joints at the base of the flow units, 2 to 5 cm apart. Well exposed; brecciated portions of flow units are moderately resistant, rest of flow units are very resistant; sharp basal contact-- 51.5

3. Basalt, pale blue; weathers pale purple or medium red; aphyric; aphanitic groundmass. Pervasively jointed in all directions, average 5 mm apart. Very well exposed; basal 7 m is moderately resistant, rest of flow is very resistant; sharp basal contact---------------------------- 22.0

Member 4:
Flow:

2. Basalt, grayish-black; weathers medium gray or dark yellowish-orange. Porphyritic: contains anhedral olivine microphenocrysts (7%), altered to iddingsite, anhedral black pyroxene phenocrysts (2%), average 2 mm across, as large as 5 mm; anhedral plagioclase phenocrysts (trace); aphanitic groundmass. Altered zones within flow; zones are less resistant and medium red; commonly have pedestals of fresh rock within altered zones. Well developed sub-horizontal joints, 1 to 2 cm thick; well developed columnar joints, 5 to 10 cm apart. Very well exposed;

18. NORTH OF THE VERDE HOT SPRINGS--Continued

Hickey Formation--Continued
Member 4--Continued
Flow--Continued

	Meters
very resistant; sharp basal contact----------------------	55.5

Cinder (incomplete):

1. Basaltic tuff, grayish-purple; weathers grayish-orange or moderate brown; majority of unit is highly altered. Well developed very thin beds, average 3 cm thick. Moderately exposed; non-resistant----------------------------------- 54.0+

Base of section; base of exposure.

19. IKE'S BACKBONE

[Measured November 1980, April 1981, and May 1981 along the road from Ike's Backbone to Childs powerplant]

Top of section; top of exposure.
Cimarron Hills Andesite:
Member 2 (incomplete):
Flow:

44. Andesite, medium dark gray; weathers dark olive; compound flow, two flows 5.0 and 4.5 m thick. Porphyritic: contains subhedral olivine phenocrysts (15%), altered to iddingsite, average 1.2 mm across; subhedral plagioclase microphenocrysts (10%), commonly sieved, as large as 1 cm; aphanitic groundmass. Somewhat vesicular (2 to 5%); average 5 mm across. Well developed horizontal joints, average 30 cm apart; moderately developed sub-vertical arcuate joints, average 50 cm apart. Well exposed; extremely resistant; sharp basal contact----------------- 9.5+

Towel Creek Tuff:
Hackberry Basin Member:
Tuff:

43. Pebbly sandstone, grayish-orange-pink; weathers same color. Moderately developed very thin beds; average 2 cm thick; shown by alignment of uniformly sized grains. Poorly sorted; very fine sand to cobble size; matrix is very fine to fine sand size; mineral grains are medium to coarse sand size; lithic fragments are coarse sand to cobble size. Contains subangular plagioclase grains (30%); subrounded dacitic lithic grains (15%); angular mafic mineral grains (2%); subrounded quartz grains (trace); rounded dacitic pumiceous grains (trace); matrix. Moderately indurated; poorly exposed; moderately resistant; basal contact not exposed--------------------- 48.0

19. IKE'S BACKBONE--Continued

Cimarron Hills Andesite:
  Member 1:
    Flow: Meters

42. Andesite, grayish-black; weathers dark bluish-gray. Porphyritic: contains euhedral to subhedral green pyroxene phenocrysts (12%), average 1 mm across, as large as 6 mm; subhedral olivine phenocrysts (2%), altered to iddingsite, average 1 mm across, as large as 3 mm; anhedral plagioclase phenocrysts (1%), average 3 mm across, as large as 6 mm; aphanitic groundmass. Slightly vesicular (2%); lined with silica; usually stretched; as large as 2 cm. Poorly developed horizontal joints, average 25 cm apart; poorly developed vertical joints, average 50 cm apart. Well exposed; extremely resistant; sharp basal contact-- 10.0

Towel Creek Tuff:
  Hackberry Basin Member:
    Tuff:

41. Dacitic ignimbrite, white; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli and blocks (45%), average 15 mm across, as large as 10 cm; plagioclase phenocrysts (30%), biotite phenocrysts (5%); subangular dacitic lithic lapilli (4%), average 8 mm across, as large as 4 cm; glass dust matrix. Moderately exposed; moderately resistant; basal contact not exposed-- 10.0

40. Pebbly sandstone, similar to unit 43. Portions of unit has well developed very thin to thin beds; 2 to 20 cm thick; shown by differences in average grain size of the beds--- 20.5

39. Dacitic ignimbrite, similar to unit 41--------------------- 5.1

38. Dacitic air-fall tuff, similar to unit 36------------------ 0.1

37. Dacitic ignimbrite, similar to unit 41--------------------- 9.0

36. Dacitic air-fall tuff, white; weathers same color. Well developed very thin beds; 1.5 to 4 cm thick; shown by alternation of pumice rich beds Well exposed; moderately resistant; sharp basal contact---------------------------- 1.4

35. Sandy conglomerate, pale pink; weathers same color; structureless. Poorly sorted; medium sand to pebble size, mineral grains are medium to very coarse sand size, pumice and lithic fragments are granule to pebble size. Contains subangular plagioclase grains (50%); rounded dacitic pumiceous fragments (25%); subrounded dacitic lithic fragments (20%); angular hornblende grains (3%); angular biotite grains (2%). Moderately indurated; poorly exposed; moderately resistant; sharp basal contact-- 9.0

34. Dacitic ignimbrite, white; weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli and blocks (30%), average 1 cm across, as large as 10 cm; subhedral plagioclase phenocrysts (20%); subrounded

19. IKE'S BACKBONE--Continued

Towel Creek Tuff--Continued

Hackberry Basin Member--Continued

Tuff--Continued — Meters

dacitic lithic lapilli and blocks (10%), average 2 cm across, as large as 15 cm; euhedral biotite and hornblende phenocrysts (5%); glass dust martix. Poorly exposed; non-resistant; sharp basal contact---------------- 13.5

33. Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded pink and white dacitic lithic blocks and lapilli (40%), 20 cm to 2 m across, average 70 cm across, rest of rock is similar to unit 32. Well exposed; very resistant; gradational basal contact--------- 1.8

32. Dacitic ignimbrite, white; weathers same color; structureless. Contains subhedral plagioclase phenocrysts (35%), average 1 mm across; rounded white dacitic pumiceous lapilli (25%), 5 mm to 4 cm across, average 1 cm across; dacitic lithic lapilli (10%), 3 mm to 6 cm across, average 1 cm across; glass dust matrix. Poorly exposed; moderately resistant; basal contact not exposed--------------- 3.0

31. Dacitic air-fall tuff, white, weathers same color; structureless. Contains rounded white dacitic pumiceous lapilli (65%), long axes of lapilli are parallel to base of flow; euhedral plagioclase phenocrysts (25%), average 1 mm across; euhedral biotite microphenocrysts (5%); pink dacitic lithic lapilli (5%), 2 mm to 4 cm across, average 5 mm across. Poorly exposed; moderately resistant; sharp basal contact--- 1.0

30. Pebbly sandstone, grayish-orange-pink; weathers same color. Well developed very thin beds; average 3 cm thick; shown by differences in size of coarser fraction of beds, granule versus pebble size. Poorly sorted; very fine sand to pebble size; mineral grains are subangular, lithic and vitric fragments are subrounded. Contains plagioclase grains (35%), medium to coarse sand size; dacitic lithic fragments (20%), coarse sand to cobble size; dacitic pumiceous fragments (5%), medium sand to granule size; biotite and hornblende grains (5%), very fine to coarse sand size; matrix (35%), very fine to medium sand size. Well indurated; very poorly exposed; moderately resistant; sharp basal contact-- 8 ±

Cimarron Hills Andesite:

Member 1:

Flow:

29. Andesite, medium gray; weathers same color. Porphyritic: contains subhedral olivine phenocrysts (7%), rim or totally altered to iddingsite, average 2 mm across, as large as 5 mm; euhedral plagioclase phenocrysts (5%), average 1 mm across, lath-shaped, commonly in star shaped clusters; subhedral to euhedral green pyroxene phenocrysts (3%), average 1 mm across, as large as 2 mm, all

19. IKE'S BACKBONE--Continued

Cimarron Hills Andesite--Continued
Member 1--Continued
Flow--Continued

Meters

occur in cumulophyres with pyroxene in center surrounded by olivine; very fine-grained groundmass. Slightly vesicular (10%); filled or lined with calcite; spheroidal; average 4 mm across. Well exposed; moderately resistant; sharp basal contact-- 13.5

Towel Creek Tuff:
Hackberry Basin Member:
Tuff:

28. Sandstone, grayish-orange-pink, weathers same color. Poorly developed very thin beds; shown by alignment of pumice grains. Poorly sorted; grain size ranges from fine sand to cobble; mineral grains are fine to coarse sand size, pumiceous and lithic fragments are granule to cobble size. Contains subangular to subrounded plagioclase grains (63%); rounded dacitic pumiceous fragments (15%); dacitic lithic fragments (10%); subrounded basaltic lithic clasts (5%); subangular biotite grains (5%); subangular green pyroxene grains (2%); olivine grains (trace). Well indurated; well exposed; extremely to moderately resistant; sharp basal contact----------------- 10.0

27. Dacitic air-fall tuff, white; weathers same color. Uppermost portion of unit has very well developed very thin beds, average 1 cm thick. Contains rounded dacitic pumiceous lapilli, average 5 mm across. Well exposed; extremely to moderately resistant; sharp but irregular basal contact--- 1.0

Offset in section so that overlying units measured 180 m south of underlying unit.

Hickey Formation:
Member 13:
Flow:

26. Basalt, grayish-black; weathers medium bluish-gray; compound flow, boundaries 17.5 and 31.5 m above base of unit. Porphyritic: contains euhedral to subhedral green pyroxene phenocrysts (10%), average 1 mm across, as large as 3 mm; subhedral olivine microphenocrysts (10%), altered to iddingsite; aphanitic groundmass. Some cumulophyres with olivine in the center surrounded by pyroxene. Well developed horizontal joints, average 15 cm apart; moderately developed sub-vertical joints, average 40 cm apart. Well exposed; very resistant; sharp basal contact-- 51.0

Offset in section so that overlying unit measured 80 m northwest of underlying units.

19. IKE'S BACKBONE--Continued

Towel Creek Tuff:
Member 3:
Tuff:

		Meters
25.	Dacitic ignimbrite, similar to unit 19; extremely resistant	4.5
24.	Dacitic ignimbrite, similar to unit 20	5.5
23.	Dacitic ignimbrite, similar to unit 19	3.0
22.	Dacitic ignimbrite, similar to unit 20	12.0
21.	Dacitic ignimbrite, similar to unit 20. Contains more dacitic lithic lapilli and blocks (15%), average 6 cm across; very resistant	4.3
20.	Dacitic ignimbrite, white; weathers same color; structureless. Contains subhedral plagioclase phenocrysts (35%), average 1.5 mm across; rounded white dacitic pumiceous lapilli (30%), average 1 cm across, as large as 3 cm; euhedral biotite phenocrysts (5%), average 1.5 mm across; subrounded to subangular dacitic lithic lapilli (2%), 3 mm to 4 cm across, average 1.5 cm across; glass dust matrix. Well exposed; moderately resistant; sharp basal contact	7.0
19.	Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded dacitic lithic blocks and lapilli (30%), 2 mm to 75 cm across, average 10 cm across, concentrated in basal portion of unit; rounded white dacitic pumiceous lapilli (25%), average 3 mm across; subhedral plagioclase phenocrysts (25%), average 1 mm across; biotite phenocrysts (2%), 1 to 1.5 mm across; glass dust matrix. Well exposed; very resistant; sharp basal contact	4.5
18.	Dacitic ignimbrite, similar to unit 16	6.0
17.	Dacitic ignimbrite, similar to unit 16. Contains more subangular dacitic lithic lapilli (20%), average 1 cm across, as large as 5 cm	1.0
16.	Dacitic ignimbrite, white; weathers same color; structureless. Contains subrounded white dacitic pumiceous lapilli (30%), average 5 mm across; euhedral plagioclase phenocrysts (15%), average 1.5 mm across; subangular pink dacitic lithic lapilli (2.5%), average 2.5 mm across, as large as 1 cm; euhedral biotite microphenocrysts (2%); glass dust matrix. Poorly exposed; nonresistant; basal contact not exposed	5.0
15.	Lahar, pinkish-gray; weathers same color; structureless. Contains pink dacitic lithic lapilli and blocks (45%), 2 mm to 2 m across, average 4 cm across; subrounded to subangular plagioclase grains (20%), medium sand to granule size, average very coarse sand size; subrounded dacitic pumiceous lapilli (3%), average 1 mm across; rounded lapilli of basic xenoliths (2%), average 2 cm across, as large as 5 cm; subangular biotite grains (1%), very coarse sand size; silt size matrix. Well exposed; extremely resistant; basal contact not exposed	7.5

19. IKE'S BACKBONE--Continued

Offset in section so that overlying units measured 160 m south of underlying units.

Hickey Formation:
Member 5:
Cinder: Meters

14. Basalt, medium dark gray; weathers medium bluish-gray. Porphyritic: contains subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 2.5 mm; subhedral green pyroxene phenocrysts (3%), average 1.5 mm across, as large as 3 mm; aphanitic groundmass. Comulophyres of olivine + pyroxene are common (1%), average 2.5 mm across. Poorly developed sub-horizontal and sub-vertical joints. Moderately to poorly exposed; moderately resistant; basal contact not exposed-- 43.5
13. Basalt (unmeasured), moderate red; weathers same color. Porphyritic: contains euhedral to subhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across; aphanitic groundmass. Moderately vesicular (15%); filled with silica; spheroidal; average 2 mm across. Poorly exposed; non-resistant; sharp basal contact.

Offset in section so that overlying units measured 500 m southeast of underlying units.

Member 4:
Flow:

12. Basalt, medium gray; weathers same color and dark olive; compound flow, boundary 12 m above base of unit. Porphyritic: contains subhedral olivine phenocrysts (12.5%), rim or totally altered to iddingsite, average 1 mm across, as large as 3 mm; subhedral green pyroxene phenocrysts (1%), average 1 mm across, as large as 3 mm; aphanitic groundmass. Lower flow has well developed horizontal joints, 5 to 10 cm apart. Moderately exposed; moderately resistant; sharp basal contact---------------------- 24.5
11. Basaltic ash, pale blue; weathers grayish-blue; structureless. Contains rounded aphyric basaltic lapilli (50%), average 7 mm across; olivine microphenocrysts (5%), altered to iddingsite; ash size groundmass. Extremely microvesicular (25%); filled with calcite. Moderately exposed; non-resistant; thickness is approximate because basal contact not exposed due to intrusion of a dacitic dike-- 25 ±
10. Basalt, grayish-black; weathers grayish-blue and grayish-orange. Microporphyritic: contains anhedral olivine microphenocrysts (1%), altered to iddingsite; subhedral green pyroxene microphenocrysts (1%), as large as 5 mm; aphanitic groundmass. Well developed vertical joints,

19. IKE'S BACKBONE--Continued

Hickey Formation--Continued
Member 4--Continued
Flow--Continued

		Meters
	average 5 cm apart; moderately developed horizontal joints, average 10 cm apart. Well exposed; very resistant; sharp basal contact. Thickness is approximate because upper contact is not exposed due to intrusion of a dacitic dike	16 ±
9.	Basaltic ash, similar to unit 11 except it is moderate red	9.9
8.	Basalt, same as unit 10	4.5
7.	Basaltic ash, similar to unit 11	12.0
6.	Basalt, same as unit 10	9.0

Offset in section so that overlying units measured 200 m south of underlying units.

Member 2:
Flow:

5.	Basalt, medium to light gray; weathers moderate reddish-brown to pale brown and dark olive; uppermost unit in a compound flow. Porphyritic: contains euhedral olivine phenocrysts (5%), altered to iddingsite, average 1 mm across, as large as 2 mm; anhedral to subhedral green pyroxene phenocrysts (trace), average 3 mm across; aphanitic groundmass. Well developed columnar joints, 60 cm to 1 m thick; moderately developed horizontal joints; average 15 cm apart. Moderately exposed; moderately resistant; sharp basal contact	13.0
4.	Basaltic ash, pale pink; weathers white to yellowish-gray; highly altered. Well developed thin beds; average 5 cm thick, as thick as 50 cm. Contains rounded aphyric basaltic lithic grains and lapilli (20%), average 1 mm across, as large as 5 mm; aphanitic groundmass (50%); calcite (30%), fills all pore spaces. Very poorly exposed; non-resistant; basal contact not exposed	12.0
3.	Basalt, same as unit 5. Compound flow; contains three separate flows 16.5, 31.5, and 10.5 m thick from the base of the unit up	58.5
2.	Basaltic ash, same as unit 4	14.5

Member 1 (incomplete)
Flow:

1.	Basalt, dark olive; weathers medium bluish-gray and brownish-gray. Porphyritic: contains subhedral to anhedral olivine phenocrysts (15%), altered to iddingsite, average 1 mm across, as large as 5 mm; euhedral green pyroxene phenocrysts (5%), average 1.5 mm across, commonly in cross-shaped glomerophyres; aphanitic groundmass. Well developed horizontal joints, 5 to 10 cm apart; moderately developed vertical joints, 10 to 20 cm apart. Well exposed; very resistant	15.0+

Base of section; base of exposure.