Bases: Shaded relief and contours from National Atlas.

Universal Transverse Mercator projection, Zone 12N,

U.S. Department of the Interio Open-File Report 2022-1016 U.S. Geological Survey **DESCRIPTION OF MAP UNITS** CORRELATION OF MAP UNITS [Second eruptive cycle (Tf2). Rhyodacite in composition, see Fuis, 1973, 1996, and Fuis and others, 2019] The first author, Gary S. Fuis, conducted this mapping in the summer of 1967 in partial **Red lithic breccia**—These breccias, in as many as two horizons, are interpreted as lahar fulfillment of the entry requirements into the Ph.D program of the Division of Geological deposits. Ledge formers. Numbers 1 and 2 in the unit labels refer to a local sequence, with 1 PEACH SPRING TUFF (MIOCENE) being the oldest. Correlation where outcrops are separated by more than ~0.5 km is and Planetary Sciences of the California Institute of Technology, Pasadena, Calif. The area unconformity mapped lies wholly within the Fort Rock Ranch, a private ranch spanning ~50 square miles uncertain. Tf2rl with no number indicates uncertain correlation or areally minor outcrop. Peach Springs Tuff of Young (1966)—Known formally now as Peach Spring Tuff (Billingsley These units resemble Tf3rl1,2,3 and are described in detail in Fuis (1973, 1996). At the type in Mohave and Yavapai Counties, Arizona. Access to the ranch is limited, and it is uncertain PEACH SPRING TUFF and others, 1999). Cliff former. At Penitentiary Butte, thickness 14.8 m. Upper 12.2 m welded, section for the Fort Rock Creek Rhyodacite (Three Sisters Buttes), Tf2rl2 is ledge former of whether a detailed geologic map of the Aquarius Mountains can be recreated today. crytallized (lithic groundmass). Lower 2.5 m non-welded to partially welded (vitric). Basal unsorted red accessory clasts, 1–3 cm in diameter, that is only about 0.15 m thick. At the Therefore, we are making this map available to the public in this Open-File Report. 0.1 m well sorted, well bedded tuff. See Fuis (1973, 1996) for more detailed description. reference section for the Fort Rock Creek Rhyodacite, Tf2rl2 is a ledge former of unsorted The original mapping was compiled on an enlarged single aerial photograph at an Compare to Valentine and others (1989). Radiometrically dated at 18.78±0.02 Ma by approximate scale of 1:15,600. The second author, J. Luke Blair, photogrammetrically red accessory clasts, 0.5–10 cm in diameter, that is about 1 m thick. This unit is included as unconformity Ferguson and others (2013) in the Black Mountains, 100 km west of the map area. rectified the original map and added modern topography, which was not available at the a basal unit of the Three Sisters Butte Member of the Fort Rock Creek Rhyodacite of Fuis FORT ROCK CREEK RHYODACITE time the original map was completed. Modern roads and drainages were also added, FORT ROCK CREEK RHYODACITE (LOWER MIOCENE) including I–40, built after the original map was completed. Both authors reformatted the Red glassy flow—Characterized by contorted or wavy banding. Cliff former. FELSIC INTRUSIVE ROCKS FELSIC INTRUSIVE ROCKS original map using current USGS geologic map standards. Welded breccia—Gray glassy clasts in as many as 3 horizons; some upper layers within some **Dike**—Foliated by partial phenocryst alignment. Rock color (groundmass color), shown in GEOLOGY OF AQUARIUS MOUNTAINS AND VICINITY units are gray glassy flows. Cliff formers. Numbers 1, 2, and 3 in unit labels refer to a local schematic foliation symbols, varies from gray (blue foliation symbols) to red (red foliation sequence, with 1 being the oldest. Correlation where outcrops are separated by more than The rocks depicted on this map include Precambrian layered metamorphic and symbols). Contains 5 percent plagioclase phenocrysts; 5 percent plagioclase and potassium intrusive igneous rocks, all cataclastically deformed, mapped as "Undivided Precambrian ~0.5 km is uncertain. Tf2wb with no number indicates uncertain correlation. Formed feldspar microphenocrysts; 3 percent hornblende and 4 percent biotite as both phenocrysts around the rim of eruptive center 2. Estimated thickness is as much as 25 m. This unit may rocks," and Miocene volcanic and intrusive rocks that comprise two formations that were and microphenocrysts; groundmass glassy to aphanitic. A sample of Td labeled RDD in have different origins as described for Tf3wb. Petrography and chemical analysis are defined after this map was made. These two formations are the Crater Pasture Formation figures 1 and 3 and on the map is described petrographically and chemically in Fuis and described in Fuis (1973, 1996) and Fuis and others (2019); petrography is similar to Td but and the Fort Rock Creek Rhyodacite (Fuis, 1973, 1996). The Crater Pasture Formation was others (2019), and was radiometrically dated at 21.7±0.03 Ma. nonconformity contains 1.5 percent quartz phenocrysts and microphenocrysts. A sample of Tf2wb2, defined on the Fort Rock dome, east of the map area (figs. 1, 2, 3), and consists of Intrusive rock—Foliated by partial phenocryst alignment. Rock color (groundmass color), FELSIC EXTRUSIVE ROCKS labeled RWD in figures 1 and 3 and on the map, was radiometrically dated at 21.7±0.03 Ma ultramafic to intermediate volcanic and intrusive rocks emplaced from several scattered shown in schematic foliation symbols, varies from gray (blue foliation symbols) to red (red vents. On this map, these and related rocks are mapped as "Undivided Crater Pasture" (Fuis and others, 2019), and is the same age as Td. foliation symbols). Petrography appears similar to Td. Formation." The Fort Rock Creek Rhyodacite was defined at Three Sisters Buttes and at Tf2 White non-welded ashflow tuffs and thin intercalated volcanic sedimentary rocks—The FELSIC EXTRUSIVE ROCKS Penitentiary Butte (figs. 1–4). It consists of early Miocene felsic volcanic and intrusive ashflow tuffs are commonly bluff formers. These rocks are consistent with those described rocks emplaced from centers 1–3 (fig. 3 and map). [Fourth eruptive cyle (partial cycle). Rhyodacite composition, see Fuis, 1973, 1996, and Fuis and others, 2019]. in the Old Stage Road Member at the type and reference sections for the Fort Rock Creek cycle (partial) The Fort Rock dome is a roughly circular geologic structure in plan view, 2.5 Rhyodacite of Fuis (1973, 1996). At the type section, the easternmost of the Three Sisters Tt4b Tuff breccia—White; unsorted; slope former. Clasts greater than 2 mm in diameter make up over kilometers (km) in diameter, that is similar in many ways to an impact crater; however, it is Buttes, Tf2 consists of 3 ashflow tuffs, all bluff formers. The thickest is 5 m and the total half the rock: in this size range 35–45 percent of the rock is white pumice, 15–35 percent is a structural dome caused by a potassic mafic intrusion at depth in the earliest Miocene, and for this member is 17 m, including intercalated volcanic sedimentary beds. At the reference accessory gray rhyodacite casts, and a trace is accidental clasts of Precambrian rocks and the craterlike depression in its center is erosional in origin. Two samples from the dome section, Penitentiary Butte, there are 12 ashflow tuffs, with about half being bluff formers. dark brown to gray rocks of the Crater Pasture Formation. Modal diameter ill-defined; were radiometrically dated, a hornblende-pyroxene trachyandesite and an olivine The thickest ashflow tuff is 15 m, and the total for the Old Stage Road Member is 113 m, maximum clast size about 30 cm. The total thickness of the fourth eruptive cycle at the type trachybasalt (HPTA, OTB, respectively, figs. 1, 3 and map; see "Radiometric dating" although this unit may be as thick as 150 m elsewhere in the map area. The ashflow tuffs section is ~5 m (atop the easternmost butte), but in the map area reaches more than 60 m. section below). The 22.3 mega-annum (Ma) trachyandesite was erupted prior to doming are unsorted and massive but show faint grading, with larger and more pumice fragments from a small center near the current rim of the crater, and the 22.1 Ma trachybasalt was near their tops. Clasts greater than 2 mm in diameter make up a little more than half of the

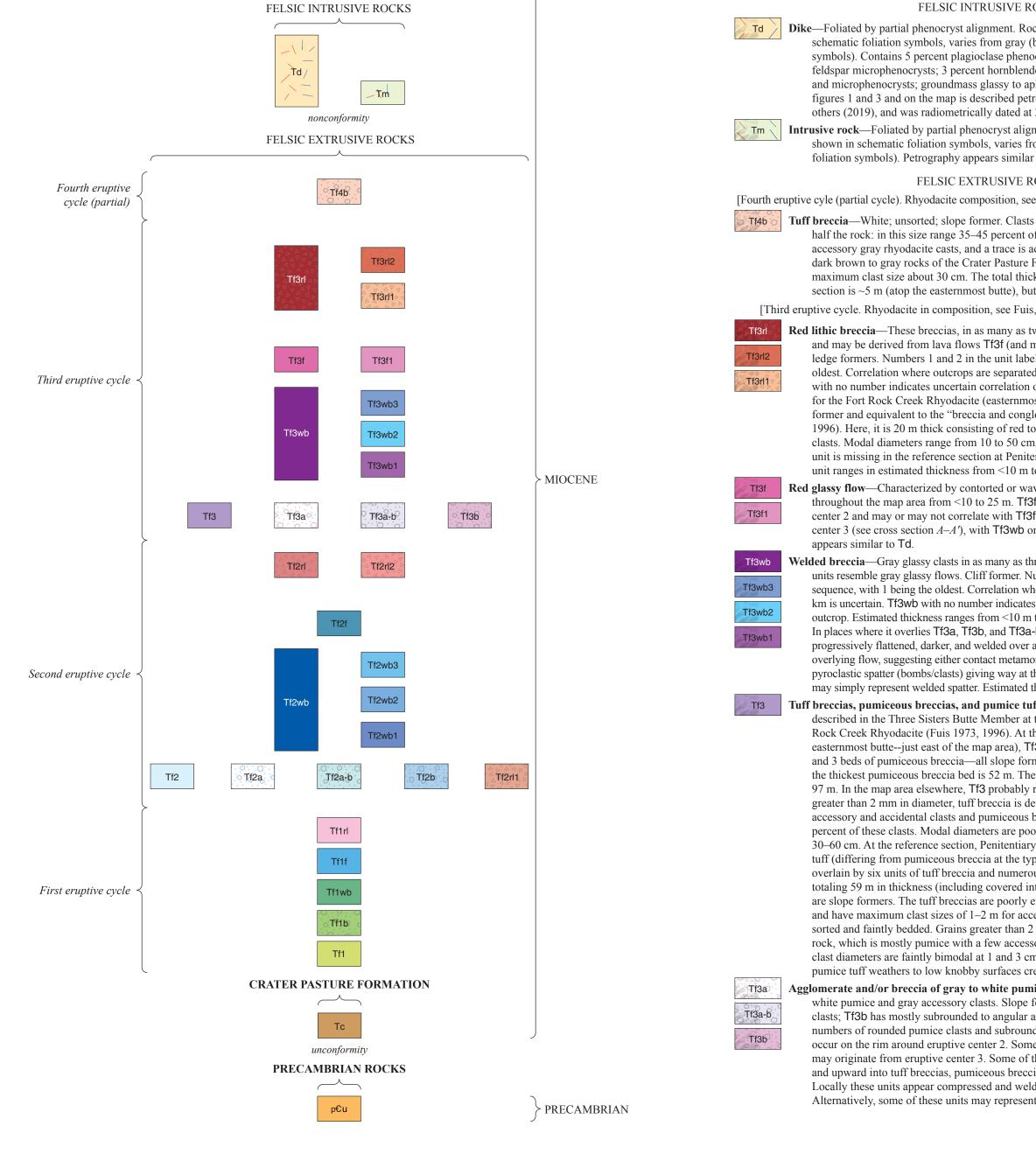


Figure 1. Map showing topography of the Aquarius Mountains and vicinity. Black filled circles are samples of

volcanic rocks that were radiometrically dated (see text). Irregular black line outlines the geologic map.



Figure 2. Satellite image of the Aquarius Mountains and vicinity. Irregular black dashed line outlines the

EXPLANATION

perpendicular to view plane

Foliation approximately parallel to

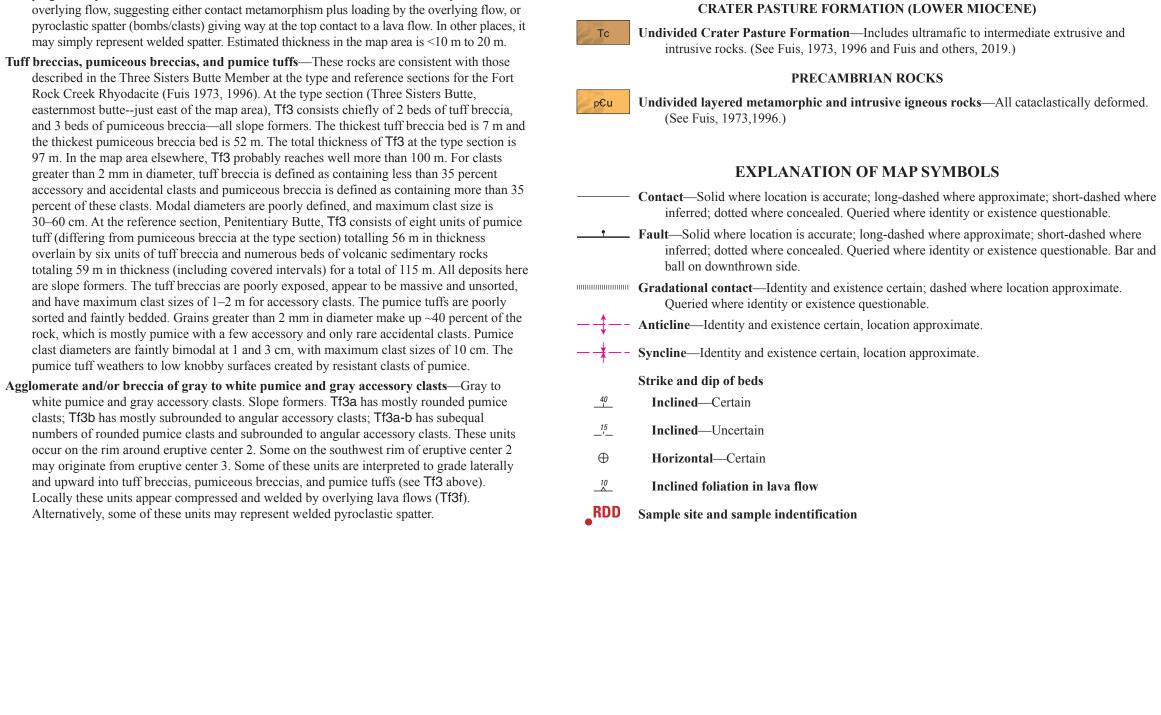
Schematic foliation (phenocryst

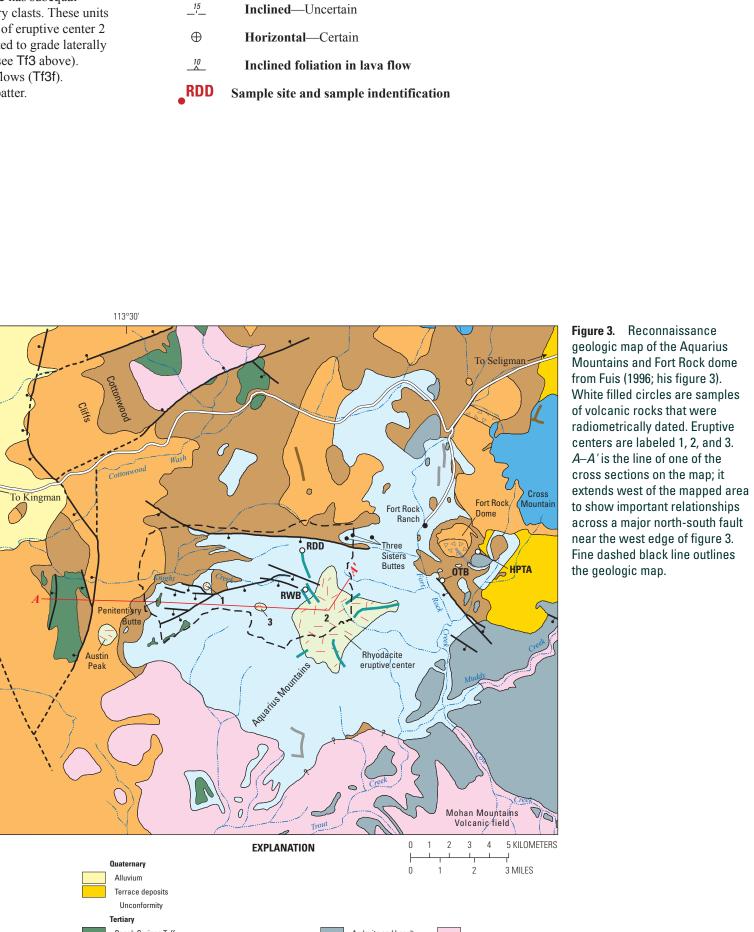
alignment). Color denotes

ground-mass color

Foliation approximately

geologic map. Image base from USDA NAIP, 2019 (U.S. Geological Survey, 2019).





rock. Among these clasts, 20–30 percent is white pumice, 20–30 percent is red to gray

accessory clasts, a few percent is accidental clasts of Precambrian rocks, and a trace to 1

percent is dark brown to gray accidental clasts of the Crater Pasture Formation. Modal

formers. Tf2a has mostly rounded pumice clasts; Tf2b has mostly subrounded to angular

angular accessory clasts. These units are interpreted to grade laterally and upward into

non-welded ashflow tuffs (see Tf2 above). Formed around the rim of eruptive center 2.

accessory clasts; Tf2a-b has subequal numbers of rounded pumice clasts and subrounded to

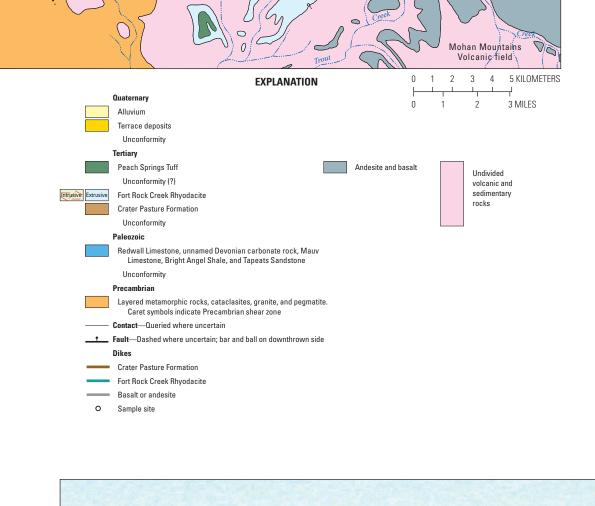
Agglomerate and (or) breccia—Gray to white pumice and gray accessory clasts. Slope

diameters are 0.5–1 cm, and maximum clast size is a few cm.

Ledge former but very thin (<1 m). Similar texture to Tf2rl.

estimated from cross section to be < 50 m.

section is probably <100 m.



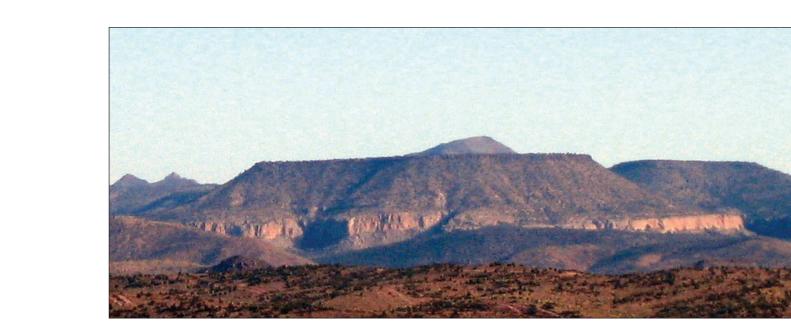
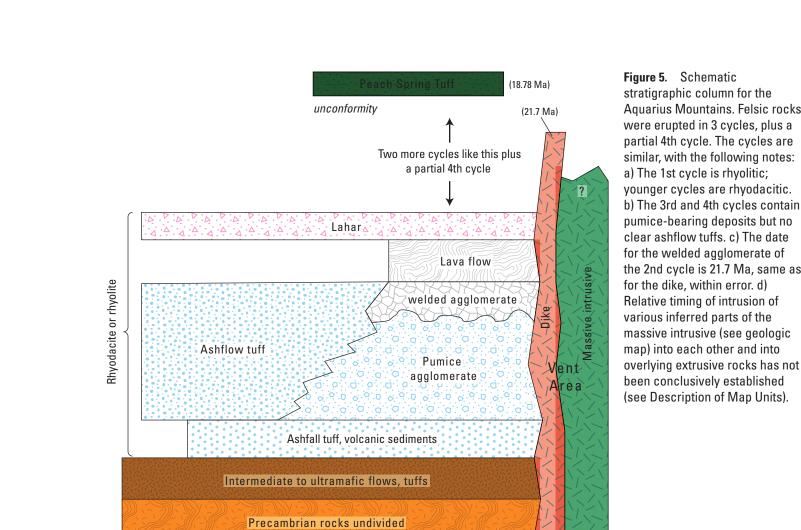
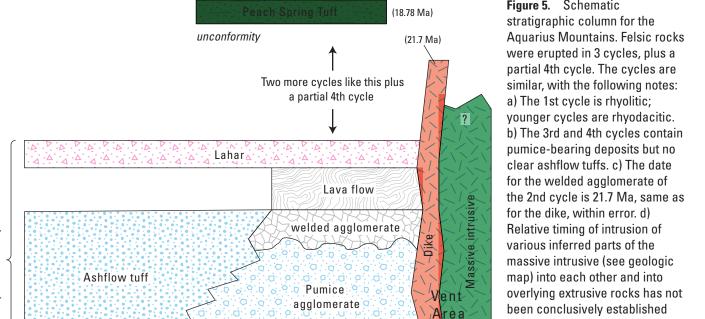


Figure 4. Photograph of Penitentiary Butte viewed from the west. A prominent bluff-forming white ashflow tuff (non-welded) is seen near the base of the butte. The butte is capped by the Peach Spring Tuff. U.S. Geological Survey photograph taken by Gary S. Fuis.





Arizona—geology, geochemistry, and petrogenesis: State University of New York at Buffalo, Ph.D. dissertation, 294 p. Simmons, A.M., and Ward, A.W., 1992, Preliminary geologic map of the Mohon Mountains

erupted from a magma chamber beneath the dome that is interpreted to have caused the

In the map area, the Fort Rock Creek Rhyodacite contains three eruptive cycles plus a

partial 4th cycle, labeled Tf1, Tf2, Tf3 and Tf4 (fig. 5; see also Correlation of Map Units).

Each cycle began with eruption of relatively thin ashfall tuffs followed by agglomerates,

non-welded ashflow tuffs, welded agglomerates and breccias, lava flows, and lahars. Here

we use "agglomerate" to refer to fragments of lava, including pumice, that are rounded to

subrounded; breccia refers to lava fragments that are subangular to angular. Ashflow tuffs

are missing in the 3rd and 4th cycles. The oldest cycle occurred at the westernmost center,

center 1; rock composition at this center is rhyolite, based on unpublished chemical and

petrographic analysis. The youngest three cycles erupted from centers 2 and 3 (fig. 3 and

proximal agglomerates and breccias around the eruptive centers appear to grade laterally

into non-welded ashflow tuffs or tuff breccias and upward into welded agglomerates and

breccias. Evidence for proximal deposits is missing for the 4th partial cycle. The ashflow

tuffs and tuff breccias of cycles 2 and 3 contain more accessory and accidental clasts than

the proximal agglomerates and breccias. Lava flows followed eruption of the agglomerates

and breccias, and the upper parts of the agglomerates and breccias were welded beneath the

lava flows. Lahars followed, apparently resulting from collapse of the lava flows. The most

distinctive lahar is a cliff-forming unit (labeled Tf2rl2) at the top of the second cycle. The

interpreted to be late intrusions into the throats and rims of centers 2 and 3. Note that some

respectively, some of the Tf3 rocks may have also been erupted from center 2, but evidence

Fuis (1973, 1996) subdivided the Fort Rock Creek Rhyodacite into 2 formal and 2

conglomerate of the Crossing. The sedimentary breccia of Noon Gorge occurs only on the

The Old Stage Road and Three Sisters Butte Members comprise the bulk of the Fort Rock

Creek Rhyodacite; however, formation components are grouped slightly differently on this

map from the later definitions of Fuis (1973, 1996). Eruptive cycles Tf1, Tf2, Tf3, and Tf4

were used for groupings on this map. Rocks of the Tf1 eruptive cycle were not addressed by

Fuis (1973, 1996). Tf2rl2 is the basal unit of the Three Sisters Butte Member but here is

included as the top unit of Tf2. Tf3rl2 is the youngest informal member defined by Fuis

(1973, 1996), namely the breccia and conglomerate of the Crossing, but here is included as

the top unit of Tf3. Otherwise, the Tf2 and Tf3 eruptive cycles correspond to the Old Stage

Road Member and the Three Sisters Butte Member, respectively. Tf4 was not addressed in

At the type section for the Fort Rock Creek Rhyodacite, the easternmost of the Three

formers. The thickest is 5 meters (m) thick. These deposits are unsorted and massive but show

millimeters (mm) in diameter make up a little more than half of the rock. Among these clasts,

overlying lava flows and lahars), a few percent is accidental clasts of Precambrian rocks, and a

1996). Between the ashflow tuffs are lapilli tuffs and volcanic sedimentary rocks. At the top of

Tf2 is the interpreted lahar, Tf2rl2, a ledge former of unsorted red accessory clasts, 1–3 cm in

diameter, that is only about 0.15 m thick here at the easternmost of Three Sisters Buttes. Total

"pumiceous breccia," all slope formers (see details in Description of Map Units). The thickest

At the reference section for the Fort Rock Creek Rhyodacite, Penitentiary Butte (figs. 1–4), Tf2 consists of 12 ashflow tuffs, about half of which are bluff formers. The thickest bed is a 15-m bluff former (fig. 4). These units have descriptions similar to those of Tf2 at Three Sisters Buttes. Volcanic sediments are intercalated between the ashflow tuffs. At the top of Tf2 is the interpreted lahar, Tf2rl2, a ledge former of unsorted red accessory clasts, 0.5–10 cm in diameter, that is 1 m thick here. Total thickness of the Tf2 eruptive cycle is 114 m. Tf3 consists of 8 units of pumice tuff totaling 56 m in thickness and 6 units of tuff breccia

and intercalated volcanic sedimentary beds totaling 59 m in thickness. Both types of deposits

are slope formers, but the pumice tuff weathers to a low knobby surface created by resistant

clasts of pumice. In the Tf3 eruptive cycle here, there is no capping breccia, as there is at the

capped by the Peach Spring Tuff (fig. 4), a regional welded ashflow tuff that erupted in the

Black Mountains, 100 km west of Penitentiary Butte (Ferguson and others, 2013), nearly 3

The Tf1 eruptive cycle has a similar sequence of rock types as Tf2 and Tf3, but is more

ocalized in outcrop area, as it is largely buried by rocks of Tf2 and Tf3 (see cross sections).

Thicknesses of rock units are constrained from cross sections only and may reach as much

GEOLOGIC STRUCTURE

west-southwest to east-southeast) and displacements (mostly less than 30 m) that are commonly down to the south. We have extended Cross Section A–A' west of the map area to show one north–south fault along the edge of the Colorado Plateau that has some interesting relations (fig. 3 and map). West of this fault, the Peach Spring Tuff rests directly on mafic rocks of Crater Pasture affinity. Four kilometers east, at Penitentiary Butte, the Peach Spring Tuff rests atop 300 m of felsic rocks of the Fort Rock Creek Rhyodacite. A preliminary interpretation of this relationship is that after the felsic rocks were erupted, the fault moved up on the west, allowing the felsic rocks to be eroded off that block. Then the Peach Spring Tuff was deposited, followed by down-to-the-west movement on that fault, which is the

most recent sense of motion on faults along this edge of the Colorado Plateau.

Mapped faults in the Aquarius Mountains have largely east—west strikes (ranging from

Radiometric ages of rocks in the Aquarius Mountains and on the Fort Rock dome are described in Fuis and others (2019) and summarized here. Two mafic samples from the Fort Rock dome, a hornblende-pyroxene trachyandesite and olivine trachybasalt (HPTA and OTB, respectively, in figs. 1, 3) were dated respectively at 22.3±0.03 Ma and 22.1±0.02 Ma. The two samples from the Aquarius Mountains eruptive center(s) are a rhyodacite welded

breccia (Tf2wb2) and a younger rhyodacite dike rock (Td) (RWB and RDD, respectively, in

figures 1, 3 and on the map). RWB is from Tf2 and RDD is from a dike intruding rocks of Tf2–Tf4. Both are dated at 21.7±0.03 Ma, indicating a short interval of time for the last three cycles and the final dike intrusion. The total duration of Tf2-Tf4 eruptions and the

final dike intrusion is constrained only by the error bar for the dates of RWB and RDD,

The Peach Spring Tuff, originally defined by Young (1966), has been dated by

Ferguson and others (2013) at 18.78±0.02 Ma, nearly 3 Ma after cessation of eruptions in

the Aquarius Mountains. The Peach Spring Tuff in turn underlies the bulk of the volcanic

rocks of the Mohon Mountains and Hope Mountain volcanic fields, to south and southeast of the Aquarius Mountains (figs. 1, 3). The rocks of the Mohon Mountains and Hope Mountain volcanic fields range in age from 22 to 5 Ma (Simmons, 1990; Simmons and

PHOTOGRAMMETRIC METHODS

Modern photogrammetry software was used to orthorectify the map. Overlapping or

available for download from USGS's EarthExplorer website (https://earthexplorer.usgs.gov/).

Nineteen adjacent and overlapping images were processed in Agisoft Photoscan software

stereo imagery was used to produce digital elevation data and orthomosaics. The mapped image is part of a set of aerial photographs taken at a scale of 1:54,000 on March 6, 1954 and are

(version 1.4.3, build 6529). The images were aligned by the software through identifying nearly 100,000 matched points, or tie points, which are pixel matches in the overlap of the images. After alignment, a bundle adjustment was performed to model the exterior orientation (pitch and roll of the aircraft) and model the lens distortion. Taking all parameters into account, a final model and orthomosaic was generated. The scanned image with mapped lines was then added to the model and aligned by Photoscan with the 19-image orthomosaic. Six ground control points were added to the model to georeference it. The ground control points were taken from modern orthorectified imagery where man-made structures that existed in both the modern imagery and the 1954 imagery were identified, and the XYZ position was recorded. The Z value was taken from USGS 10-m digital elevation map data. The ground control points were

ACKNOWLEDGMENTS

The authors thank reviewers John Tinsley and David Buesch for their reviews of this

professors Gene Shoemaker and Lee Silver, professors at Caltech in 1967, for their help and

section at Penitentiary Butte. This map could not have been completed without the support

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geologic map of the southwestern part of the Hualapai Indian Reservation and vicinity,

work, Mitchell Phillips and Katie Sullivan for their publishing assistance, and Caltech

encouragement. Larry Soderblom, former classmate at Caltech, was also very helpful in

completing this research. Bob Powell and Joel Everson helped to measure the geologic

type section (Tf3rl2, or breccia and conglomerate of the Crossing). Penitentiary Butte is

Ma after cessation of eruption of the Fort Rock Creek Rhyodacite.

as 370 m in total. See Description of Map Units.

namely 300 kilo-annum.

assigned ± 10 -m accuracy in Photoscan.

of Stacey Andrews, Gary's late wife.

https://doi.org/10.3133/ofr20191038.

scale 1:48,000, 50 p.

1:5000.

tuff breccia bed is 7 m thick, and the thickest pumiceous breccia bed is 52 m thick. For these deposits, for clasts greater than 2 mm in diameter, tuff breccia contains less than 35 percent accessory and accidental clasts, and pumiceous breccia contains more than 35 percent of these clasts. Modal diameters are poorly defined, and maximum clast size is 30–60 cm. The type section is capped by a cliff-forming breccia (Tf3rl2, or "breccia and conglomerate of the Crossing" of Fuis [1973, 1996]), that is 20 m thick consisting of red to gray accessory clasts and a few accidental clasts. Modal diameters range from 10–50 cm, and maximum clast sizes are 2–3 m. The total thickness of the Tf3 eruptive cycle here is 97 m. Only 5 m (maximum) of

thickness of Tf2 here is 17 m. Tf3 consists chiefly of 2 beds of tuff breccia, and 3 beds of

Tf4 is preserved on the top of Three Sisters Buttes.

Sisters Buttes (just east of the map area; figs. 1–3), Tf2 consists of 3 ashflow tuffs, all bluff

faint grading, with larger and more pumice fragments near their tops. Clasts greater than 2

20–30 percent is white pumice, 20–30 percent is red to gray accessory clasts (resembling

trace to 1 percent is dark brown to gray accidental clasts of the Crater Pasture Formation.

Modal diameters are 0.5–1 centimeters (cm), and maximum clast size is a few cm (Fuis,

flanks of the Fort Rock dome where it was locally deposited during erosion of the dome.

informal units. From oldest to youngest, they are the sedimentary breccia of Noon Gorge,

massive rhyodacite occupying centers 2 and 3 (Tm, Tf3) and radiating dikes (Td) are

of bombs and clasts. Although the cycles Tf1-3 appear to have erupted from centers 1-3

has been obscured by the massive rhyodacite now occupying the throat of center 2.

the Old Stage Road Member, the Three Sisters Butte Member, and the breccia and

map); rock composition at these centers is rhyodacite (Fuis, 1973, 1996). In cycles 2 and 3,

doming (Fuis, 1973, 1996; Fuis and others, 2019). Felsic volcanism from the Aquarius

Mountains eruptive centers began as the Fort Rock dome was eroding.

volcanic field, Mohave and Yavapai Counties, Arizona: U.S. Geological Survey Open-File Report 92–198, 2 plates, scale 1:50,000. U.S. Geological Survey, 2019, National Agriculture Imagery Program (NAIP) Aerial Imagery: U.S. Geological Survey Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, accessed March, 2020, at https://azgeo-open-dataagic.hub.arcgis.com/datasets/azgeo::arizona-2019-naip-imagery. Valentine, G.A., Buesch, D.C., and Fisher, R.V., 1989, Basal layered deposits of the Peach Springs Tuff, northwestern Arizona, USA: Bulletin of Volcanology, v. 51, p. 395–414. Young, R.A., 1966, Cenozoic geology along the edge of the Colorado Plateau in

northwestern Arizona: Washington University, Ph.D. dissertation, 167 p.

Preliminary Geologic Map of Early Miocene Felsic Eruptive Centers in the Aquarius Mountains, West-Central Arizona

Vertical Exaggeration: 2:1

Geology by Gary S. Fuis 1967; revisions 2018–2020.

CONTOUR INTERVAL 40 FEET

Photogrammetry, GIS database, and cartography by

Manuscript approved for publication February 10, 2022

Geology translated from enlargement of a single aerial photograph (approximate scale 1:15,000) with photogrammetric software.

Edited by Mitchell Phillips; digital cartographic production by Katie Sullivan

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