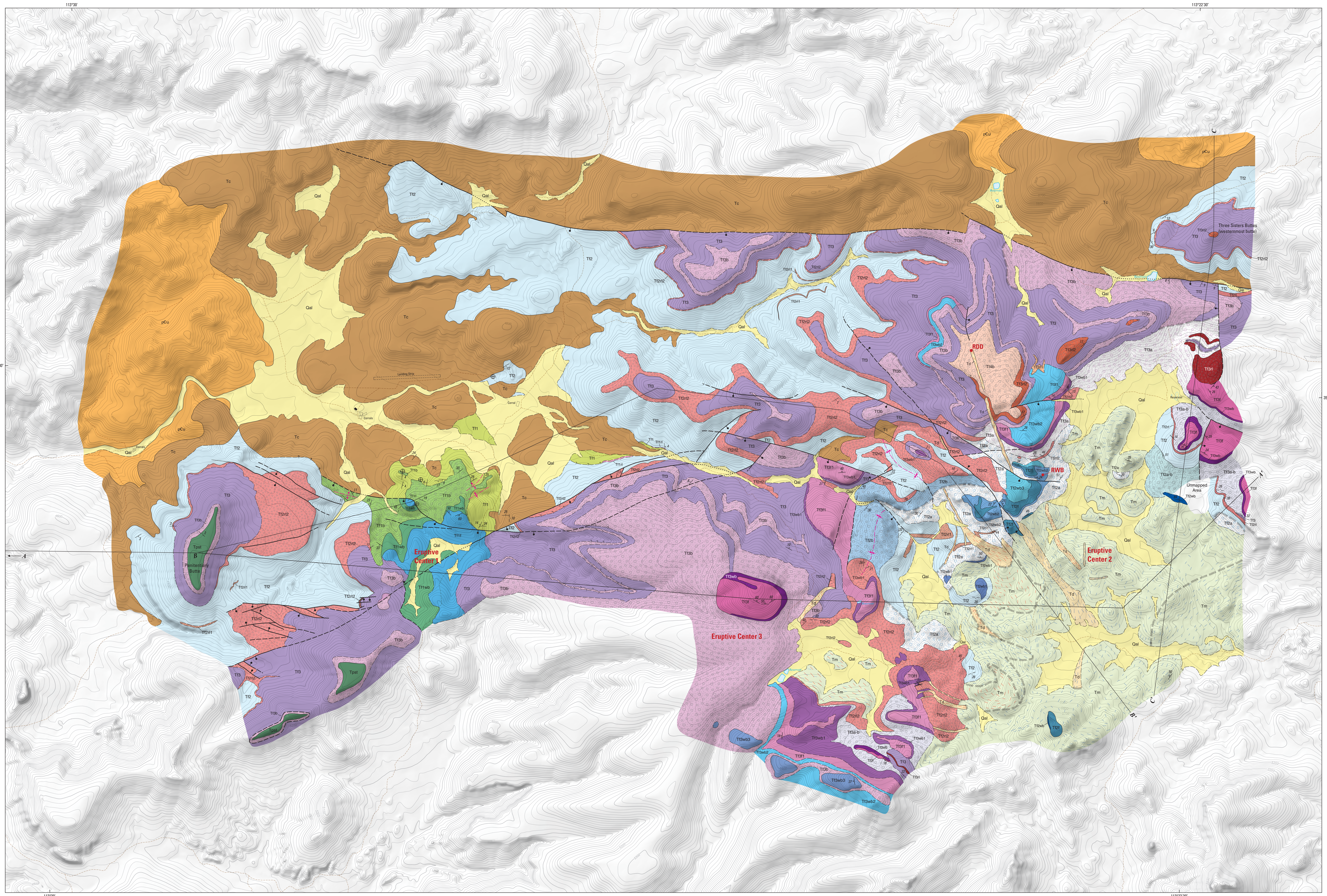

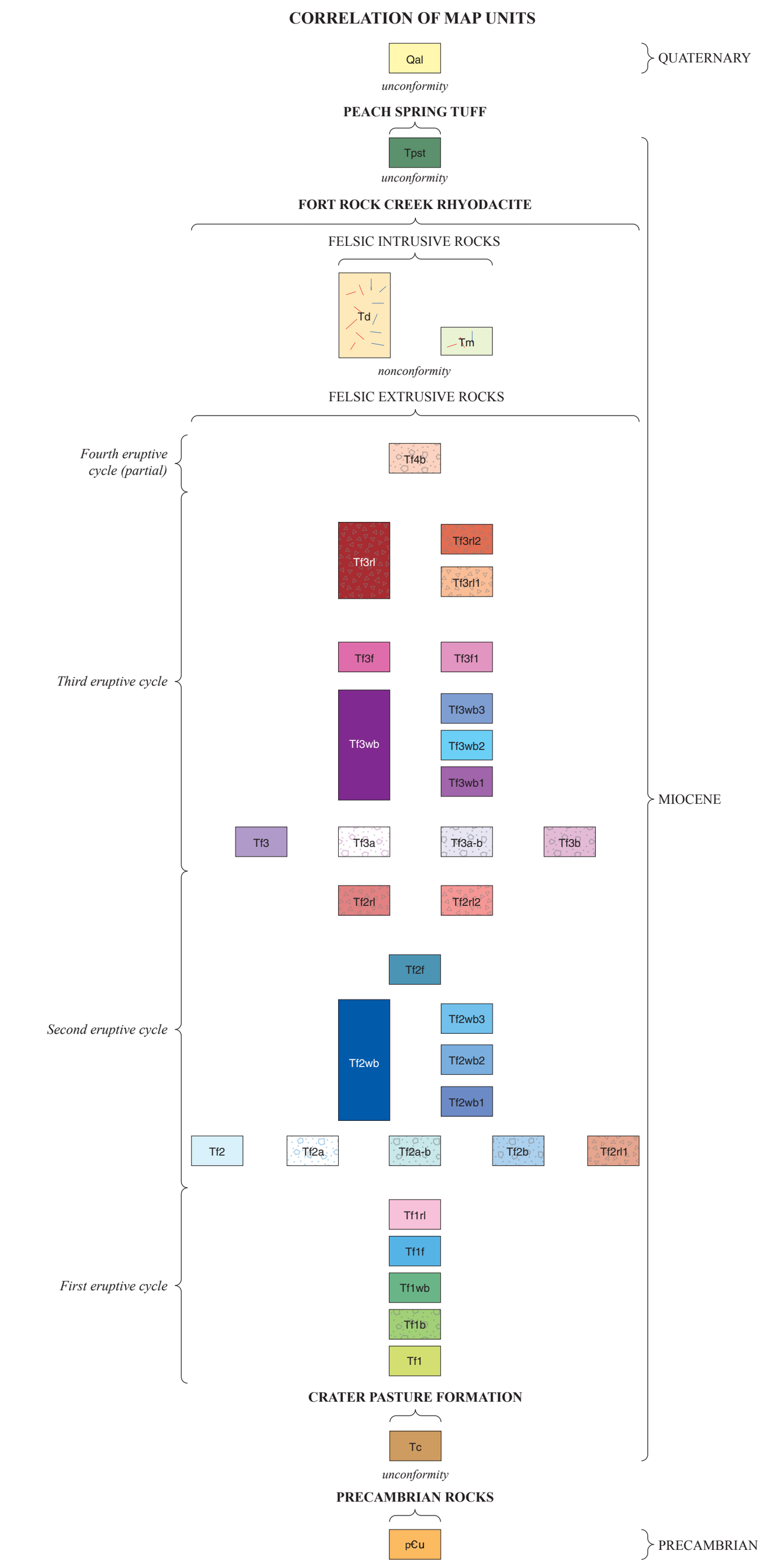

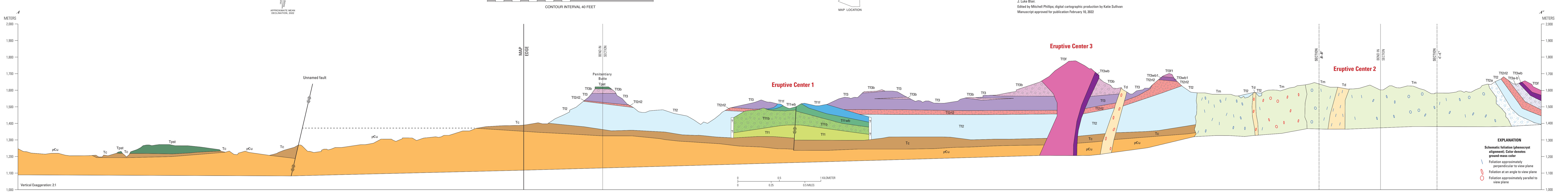

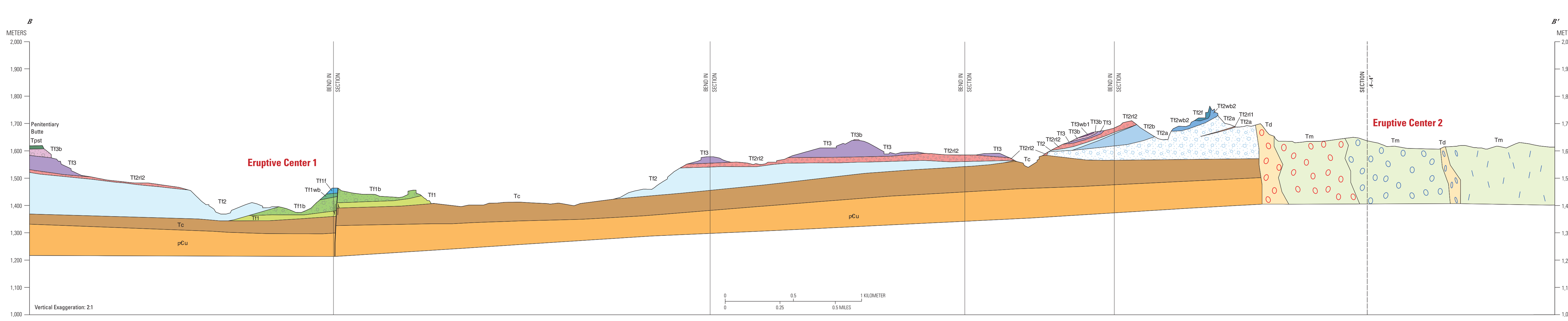

INTRODUCTION

The first author, Gary S. Fuis, conducted this mapping in the summer of 1967 in partial fulfillment of the entry requirements into the Ph.D program of the Division of Geological and Planetary Sciences of the California Institute of Technology, Pasadena, Calif. The area mapped lies wholly within the Fort Rock Ranch, a private ranch spanning ~50 square miles in Mohave and Yavapai Counties, Arizona. Access to the ranch is limited, and it is uncertain whether a detailed geologic map of the Aquarius Mountains can be recreated today. Therefore, we are making this map available to the public in this Open-File Report.

The original mapping was compiled on an enlarged single aerial photograph at an approximate scale of 1:15,600. The second author, J. Luke Blair, photogrammetrically rectified the original map and added modern topography, which was not available at the time the original map was completed. Modern roads and drainages were also added, including I–40, built after the original map was completed. Both authors reformatted the original map using current USGS geologic map standards.

GEOLOGY OF AQUARIUS MOUNTAINS AND VICINITY

The rocks depicted on this map include Precambrian layered metamorphic and intrusive igneous rocks, all cataclastically deformed, mapped as "Undivided Precambrian rocks," and Miocene volcanic and intrusive rocks that comprise two formations that were defined after this map was made. These two formations are the Crater Pasture Formation and the Fort Rock Creek Rhyodacite (Fuis, 1973, 1996). The Crater Pasture Formation was defined on the Fort Rock dome, east of the map area (figs. 1, 2, 3), and consists of ultramafic to intermediate volcanic and intrusive rocks emplaced from several scattered vents. On this map, these and related rocks are mapped as "Undivided Crater Pasture Formation." The Fort Rock Creek Rhyodacite was defined at Three Sisters Buttes and at Penitentiary Butte (figs. 1–4). It consists of early Miocene felsic volcanic and intrusive rocks emplaced from centers 1–3 (fig. 3 and map).

The Fort Rock dome is a roughly circular geologic structure in plan view, 2.5 kilometers (km) in diameter, that is similar in many ways to an impact crater; however, it is a structural dome caused by a potassic mafic intrusion at depth in the earliest Miocene, and the craterlike depression in its center is erosional in origin. Two samples from the dome were radiometrically dated, a hornblende-pyroxene trachyandesite and an olivine trachybasalt (HPTA, OTB, respectively, figs. 1, 3 and map; see "Radiometric dating" section below). The 22.3 mega-annum (Ma) trachyandesite was erupted prior to doming from a small center near the current rim of the crater, and the 22.1 Ma trachybasalt was erupted from a magma chamber beneath the dome that is interpreted to have caused the doming (Fuis, 1973, 1996; Fuis and others, 2019). Felsic volcanism from the Aquarius Mountains eruptive centers began as the Fort Rock dome was eroding.

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 map); rock composition at these centers is rhyodacite (Fuis , 1973, 1996). In cycles 2 and 3, 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 massive rhyodacite occupying centers 2 and 3 (Tm, Tf3) and radiating dikes (Td) are interpreted to be late intrusions into the throats and rims of centers 2 and 3. Note that some of the welded agglomerates (and even lava flows) may have originated as pyroclastic spatter of bombs and clasts. Although the cycles Tf1–3 appear to have erupted from centers 1–3, respectively, some of the Tf3 rocks may have also been erupted from center 2, but evidence has been obscured by the massive rhyodacite now occupying the throat of center 2.

Fuis (1973, 1996) subdivided the Fort Rock Creek Rhyodacite into 2 formal and 2 informal units. From oldest to youngest, they are the sedimentary breccia of Noon Gorge, the Old Stage Road Member, the Three Sisters Butte Member, and the breccia and conglomerate of the Crossing. The sedimentary breccia of Noon Gorge occurs only on the flanks of the Fort Rock dome where it was locally deposited during erosion of the dome. 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 Fuis (1973, 1996).

At the type section for the Fort Rock Creek Rhyodacite, the easternmost of the Three Sisters Buttes (just east of the map area; figs. 1–3), Tf2 consists of 3 ashflow tuffs, all bluff formers. The thickest is 5 meters (m) thick. These deposits are unsorted and massive but show faint grading, with larger and more pumice fragments near their tops. Clasts greater than 2 millimeters (mm) in diameter make up a little more than half of the rock. Among these clasts, 20–30 percent is white pumice, 20–30 percent is red to gray accessory clasts (resembling overlying lava flows and lahars), 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 diameters are 0.5–1 centimeters (cm), and maximum clast size is a few cm (Fuis, 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 thickness of Tf2 here is 17 m. Tf3 consists chiefly of 2 beds of tuff breccia, and 3 beds of "pumiceous breccia," all slope formers (see details in Description of Map Units). The thickest 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 Tf4 is preserved on the top of Three Sisters Buttes.

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 type section (Tf3rl2, or breccia and conglomerate of the Crossing). Penitentiary Butte is 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 Ma after cessation of eruption of the Fort Rock Creek Rhyodacite.

The Tf1 eruptive cycle has a similar sequence of rock types as Tf2 and Tf3, but is more localized 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 as 370 m in total. See Description of Map Units.

GEOLOGIC STRUCTURE

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

RADIOMETRIC DATING

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, namely 300 kilo-annum.

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 Ward, 1992).

PHOTOGRAMMETRIC METHODS

Modern photogrammetry software was used to orthorectify the map. Overlapping or 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 available for download from USGS's EarthExplorer website (https://earthexplorer.usgs.gov/). Nineteen adjacent and overlapping images were processed in Agisoft Photoscan software (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 assigned ±10-m accuracy in Photoscan.

ACKNOWLEDGMENTS

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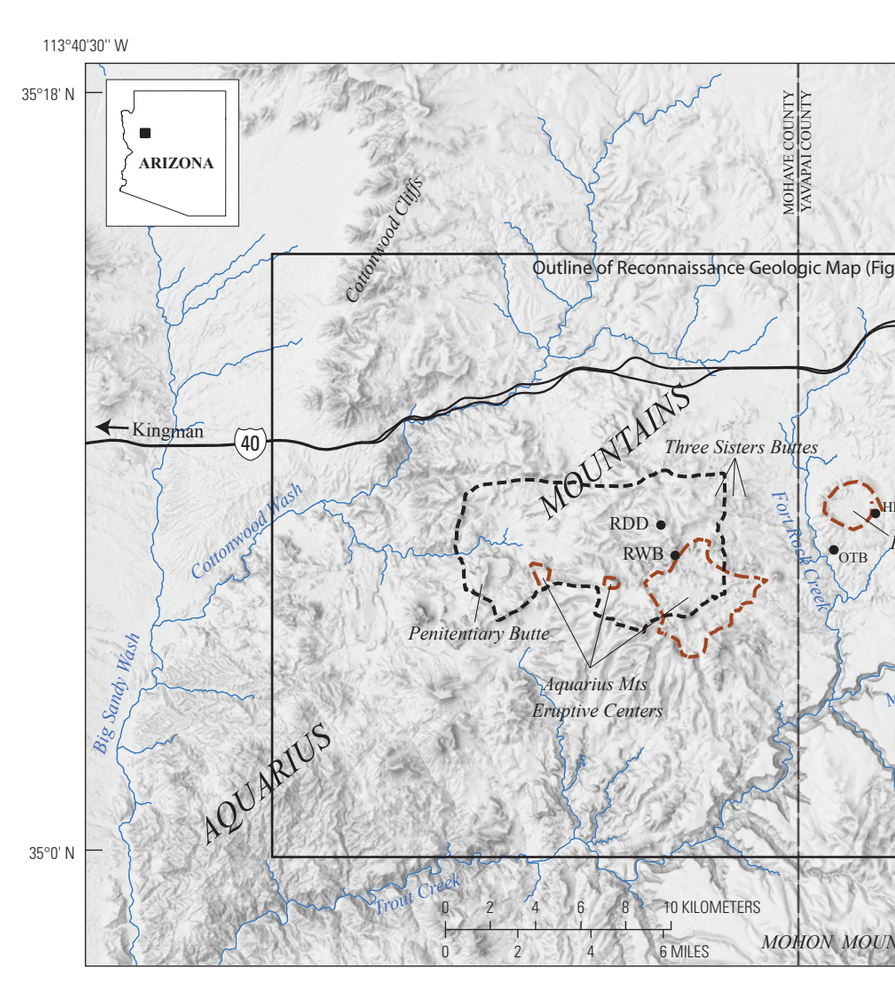


Figure 1. Map showing topography of the Aquarius Mountains and vicinity. Black filled circles are samples of volcanic rocks that were radiometrically dated (see text). Irregular black line outlines the geologic map.

Figure 2. Satellite image of the Aquarius Mountains and vicinity. Irregular black dashed line outlines the geologic map. Image base from USDA NAIP, 2019 (U.S. Geological Survey, 2019).

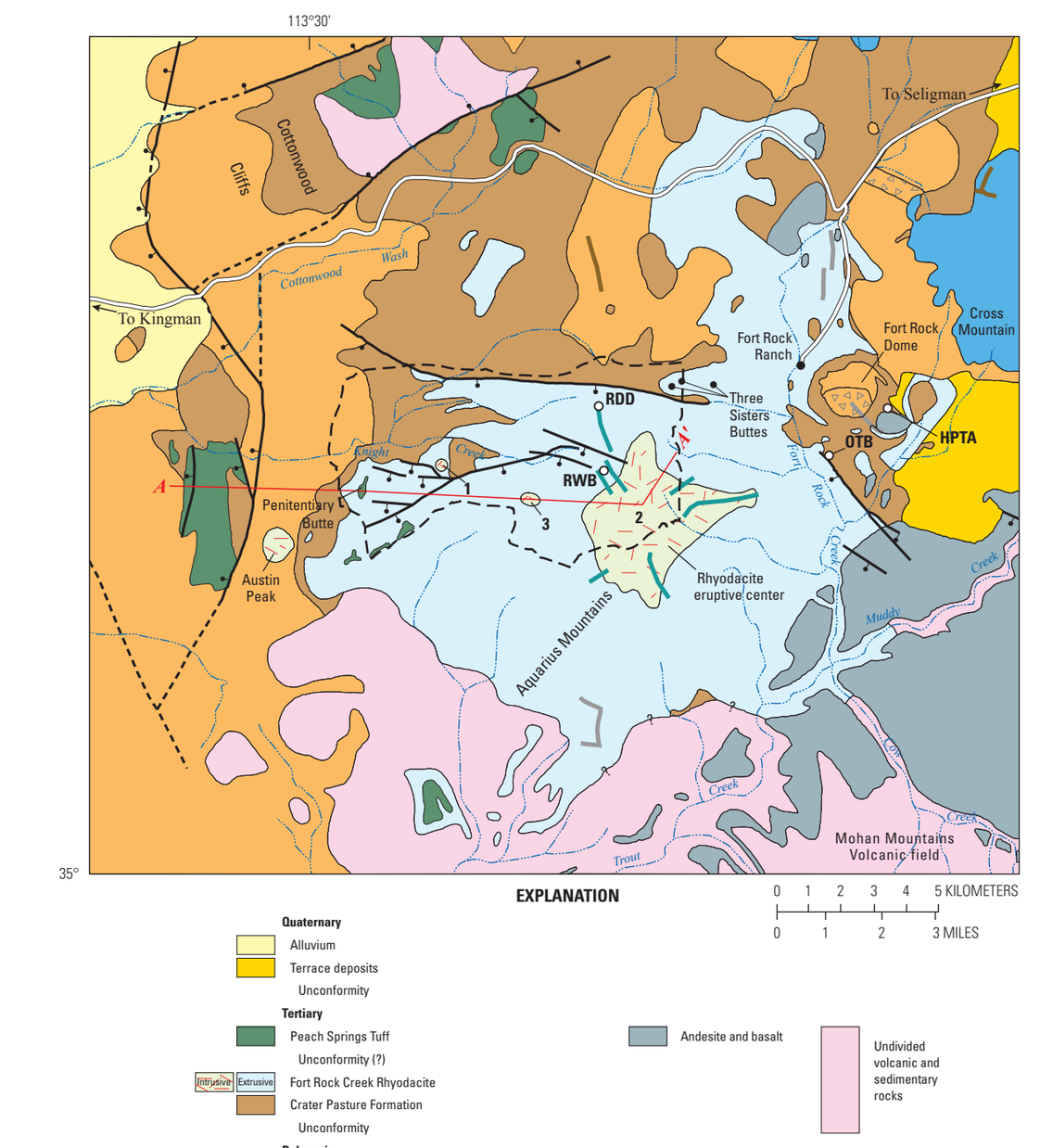


Figure 3. Reconnaissance geologic map of the Aquarius Mountains and Fort Rock dome from Fuis (1996; his figure 3). White filled circles are samples of volcanic rocks that were radiometrically dated. Eruptive centers are labeled 1, 2, and 3. *A–A′* is the line of one of the cross sections on the map; it extends west of the mapped area to show important relationships across a major north-south fault near the west edge of figure 3. Fine dashed black line outlines the geologic map.

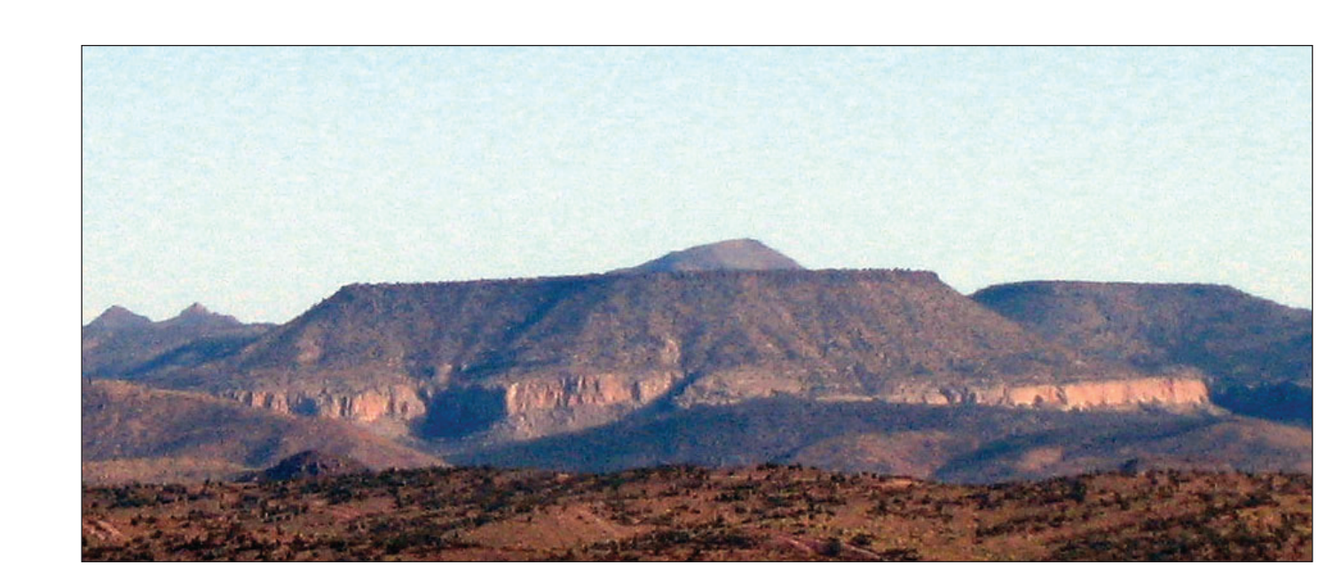


Figure 4. Photograph of Penitentiary Butte viewed from the west. A prominent bluff-forming white ashflow tuff (non-welded) is seen near the base of the butte. The butte is capped by the Peach Spring Tuff. U.S. Geological Survey photograph taken by Gary S. Fuis.

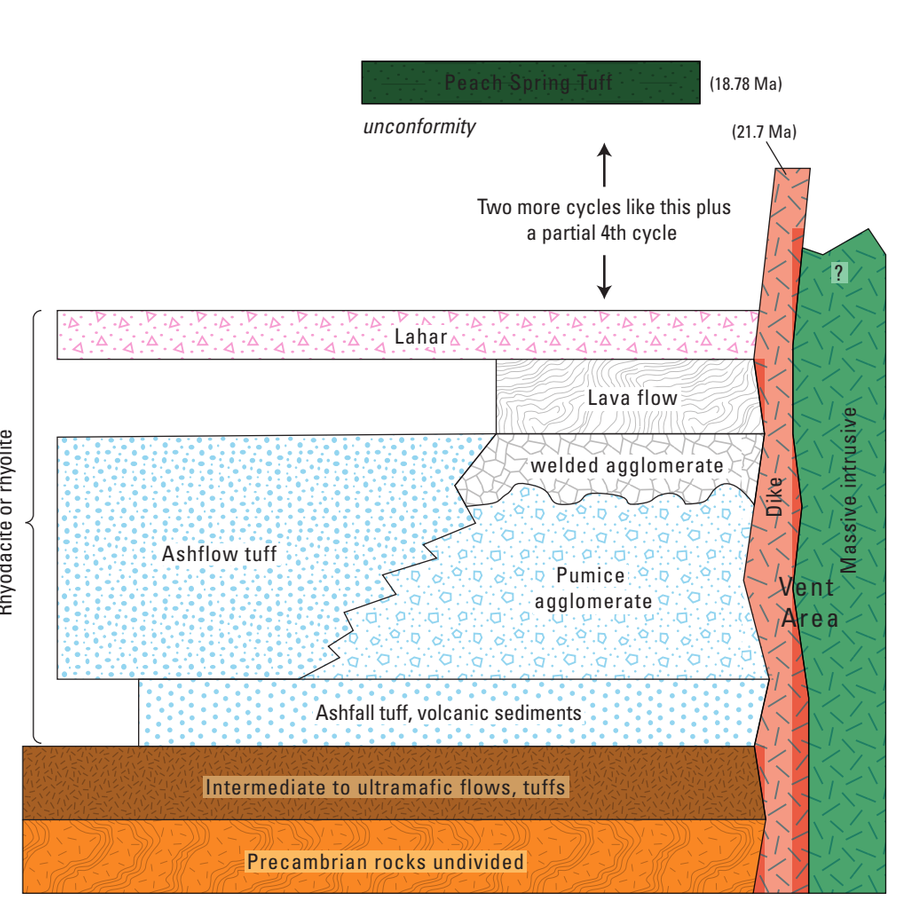
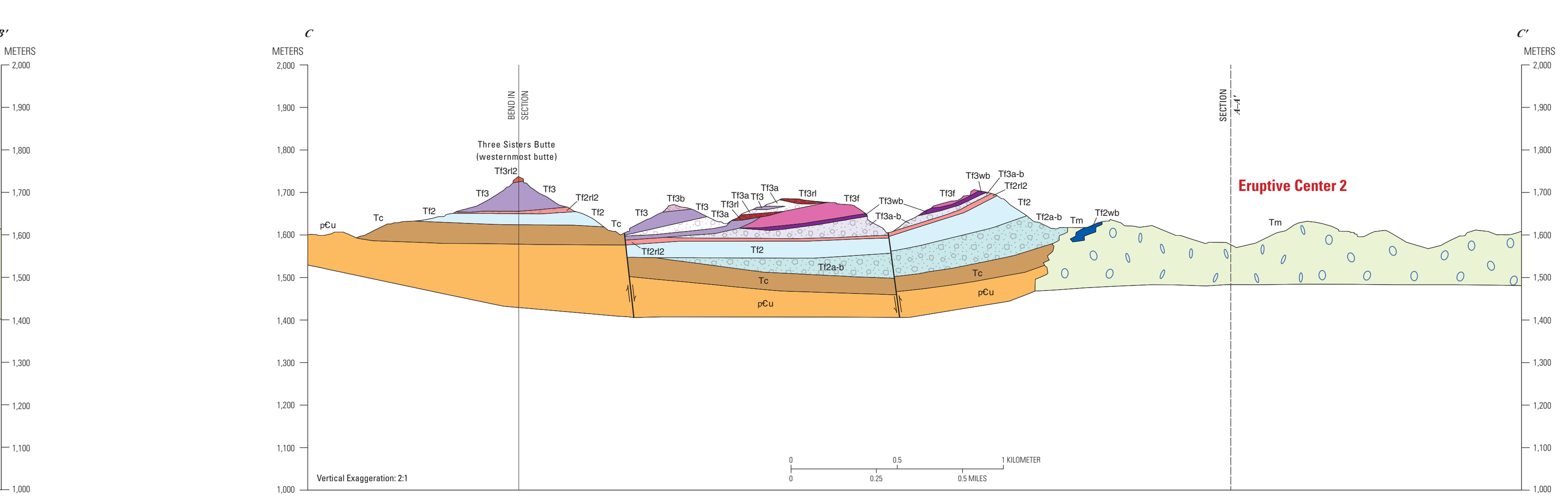


Figure 5. Schematic stratigraphic column for the Aquarius Mountains. Felsic rocks were erupted in 3 cycles, plus a partial 4th cycle. The cycles are similar, with the following notes: a) The 1st cycle is rhyolitic; younger cycles are rhyodacitic. b) The 3rd and 4th cycles contain pumice-bearing deposits but no clear ashflow tuffs. c) The date for the welded agglomerate of the 2nd cycle is 21.7 Ma, same as for the dike, within error. d) Relative timing of intrusion of various inferred parts of the massive intrusive (see geologic map) into each other and into overlying extrusive rocks has not been conclusively established (see Description of Map Units).



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

By

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