National Park Service
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Natural Resource Stewardship and Science

National Park Service Geologic Type Section Inventory

Southern Colorado Plateau Inventory & Monitoring Network

Natural Resource Report NPS/SCPN/NRR—2022/2367

ON THE COVER

Gunsight Butte on Lake Powell, the type section location of the Gunsight Butte Member of the Entrada Sandstone, Glen Canyon National Recreation Area, Utah (NPS).

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Contents

Page

Contents (continued)

Page

Figures

Figures (continued)

Page

Figures (continued)

Page

Figures (continued)

Page

Figures (continued)

Page

Figures (continued)

Page

Figures (continued)

Page

Figures (continued)

Page

Tables

Photographs

Executive Summary

A fundamental responsibility of the National Park Service (NPS) is to ensure that park resources are preserved, protected, and managed in consideration of the resources themselves and for the benefit and enjoyment by the public. Through the inventory, monitoring, and study of park resources, we gain a greater understanding of the scope, significance, distribution, and management issues associated with these resources and their use. This baseline of natural resource information is available to inform park managers, scientists, stakeholders, and the public about the conditions of these resources and the factors or activities which may threaten or influence their stability and preservation.

There are several different categories of geologic or stratigraphic units (supergroup, group, formation, member, bed) that form a hierarchical system of classification. The mapping of stratigraphic units involves the evaluation of lithologies (rock types), bedding properties, thickness, geographic distribution, and other factors. Mappable geologic units may be described and named through a rigorously defined process that is standardized and codified by the professional geologic community (North American Commission on Stratigraphic Nomenclature 2021). In most instances when a new geologic unit (such as a formation) is described and named in the scientific literature, a specific and well-exposed section or exposure area of the unit is designated as the stratotype (see "Definitions" below). The type section is an important reference exposure for a named geologic unit that presents a relatively complete and representative example for this unit. Geologic stratotypes are important both historically and scientifically, and should be available for other researchers to evaluate in the future.

The inventory of all geologic stratotypes throughout the 423 units of the NPS is an important effort in documenting these locations in order that NPS staff recognize and protect these areas for future studies. The focus adopted for completing the baseline inventories throughout the NPS was centered on the 32 inventory and monitoring networks (I&M) established during the late 1990s. The I&M networks are clusters of parks within a defined geographic area based on the ecoregions of North America (Fenneman 1946; Bailey 1976; Omernik 1987). These networks share similar physical resources (geology, hydrology, climate), biological resources (flora, fauna), and ecological characteristics. Specialists familiar with the resources and ecological parameters of the network and associated parks work with park staff to support network-level activities (inventory, monitoring, research, data management).

Adopting a network-based approach to inventories worked well when the NPS undertook paleontological resource inventories for the 32 I&M networks. The planning team from the NPS Geologic Resources Division who proposed and designed this inventory selected the Greater Yellowstone Inventory and Monitoring Network (GRYN) as the pilot network for initiating this project. Through the research undertaken to identify the geologic stratotypes within the parks of the GRYN methodologies for data mining and reporting on these resources were established. Methodologies and reporting adopted for the GRYN have been used in the development of this report for the Southern Colorado Plateau Inventory & Monitoring Network (SCPN).

The goal of this project is to consolidate information pertaining to geologic type sections that occur within NPS-administered areas, in order that this information is available throughout the NPS to inform park managers and to promote the preservation and protection of these important geologic landmarks and geologic heritage resources. The review of stratotype occurrences for the SCPN shows there are currently no designated stratotypes for Aztec Ruins National Monument (AZRU), Chaco Culture National Historical Park (CHCU), El Malpais National Monument (ELMA), El Morro National Monument (ELMO), Hubbell Trading Post National Historic Site (HUTR), Navajo National Monument (NAVA), Petroglyph National Monument (PETR), Rainbow Bridge National Monument (RABR), Sunset Crater Volcano National Monument (SUCR), Walnut Canyon National Monument (WACA), and Yucca House National Monument (YUHO).

Bandelier National Monument (BAND) has one type section, one type locality, and two type areas; Canyon De Chelly National Monument (CACH) has one type section and two type localities; Glen Canyon National Recreation Area (GLCA) has four type sections, two type localities and one reference section; Grand Canyon National Park (GRCA) has 24 type sections, 16 type localities, six type areas, and eight reference sections; Mesa Verde National Park (MEVE) has two type sections and three type localities; Petrified Forest National Park (PEFO) has 12 type sections and 27 reference sections; Salinas Pueblo Missions National Monument (SAPU) has two type sections; Valles Caldera National Preserve (VALL) has two type localities and ten type areas; and Wupatki National Monument (WUPA) has one type area (Table 1).

This report ends with a recommendation section that addresses outstanding issues and future steps regarding park unit stratotypes. These recommendations will hopefully guide decision-making and help ensure that these geoheritage resources are properly protected and that proposed park activities or development will not adversely impact the stability and condition of these geologic exposures.

Table 1. List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
BAND	Alamo Canyon Member, Cerro Toledo Formation	Jacobs and Kelley 2007; Gardner et al. 2010	Type section: in Alamo Canyon from the north side of the canyon at Alamo bend on the southeastern Pajarito Plateau, Sandoval Co., NM.	Pleistocene
BAND	Tshirege Member, Bandelier Tuff (Qbt)	Griggs and Hem 1964	Type area: Pajarito Plateau and adjacent lower slopes of the Sierra de los Valles, Los Alamos area, Sandoval Co., NM.	Pleistocene
BAND	Tsankawi Pumice Bed, Tshirege Member, Bandelier Tuff	Bailey et al. 1969	Type locality: in vicinity of Tsankawi ruin on Pajarito Plateau [Espanola 15′ Quadrangle], Santa Fe Co., NM. Type area: along south side of Tsankawi Mesa, in secs. 20 and 21, T. 19 N., R. 7 E., [White Rock 7.5′ Quadrangle]; along East Jemez Road in Sandia Canyon, in center of sec. 24, T. 19 N., R. 6 E., [Frijoles 7.5′ Quadrangle, 1984 ed.]; and in roadcuts along NM Route 4 where it crosses Potrillo and Ancho Canyons, [White Rock and Frijoles 7.5′ Quadrangles], Los Alamos and Santa Fe Cos., NM.	Pleistocene
CACH	Chinle Formation (TRc)	Gregory and Moore 1931	Type locality: Chinle Valley, Apache Co., AZ.	Late Triassic
CACH	De Chelly Sandstone, Cutler Group (Pdc)	Gregory 1917; Baars 1973	Type locality: Canyon de Chelly, Apache Co., AZ.	early Permian
CACH	White House Member, De Chelly Sandstone	Peirce 1962, 1964	Type section: White House Trail in Canyon de Chelly National Monument, Apache Co., AZ.	early Permian
GLCA	Romana Sandstone (Jr)	Peterson 1988	Type section: northeast side of Crosby Canyon, in SE/4 NE/4 SE/4 sec. 8, T. 43 S., R. 4 E., Kane Co., UT.	Late Jurassic
GLCA	Gunsight Butte Member, Entrada Sandstone	Thompson and Stokes 1970	Type section: Gunsight Butte on west side of Gunsight Canyon, in secs. 15, 16, 21, and 22, T. 43 S., R. 5 E., Kane Co., UT.	Middle Jurassic
GLCA	Carmel Formation (Jcw, Jcp)	Peterson and Pipiringos 1979	Reference section: in SW/4 SW/4 sec. 1, SE/4 SE/4 sec. 2, T. 41 N., R. 8 E., Coconino Co., AZ.	Middle Jurassic
GLCA	Page Sandstone (Jpj, Jpt)	Peterson and Pipiringos 1979	Type section: on the northwest side of Manson Mesa on which the town of Page is situated, about 1 km (0.6 mi) northeast of Glen Canyon Dam [SW/4 NW/4 sec. 19, T. 41 N., R. 9 E.], Coconino Co., AZ.	Middle Jurassic
GLCA	Glen Canyon Group (Jn, Jk, JTRw, JTRmd)	Reeside et al. 1927; Molenaar 1969	Type locality: Glen Canyon of the Colorado River, Kane Co., UT.	Triassic–Jurassic

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
GLCA	Moody Canyon Member, Moenkopi Formation	Blakey 1974	Type section: measured along an east–west line exactly 3.5 km (2.16 mi) due south of the 5728 BM on Horse Pasture Mesa, Circle Cliffs, Garfield Co., UT.	Early–Middle Triassic
GLCA	Cedar Mesa Sandstone (Pcm)	O'Sullivan 1965	Type locality: Cedar Point, west of Mexican Hat, in sec. 18, T. 41 S. R. 18 E., San Juan Co., UT.	early Permian
GRCA	Tuckup Canyon Basalt (Qtb, Qtp, Qtid)	Billingsley and Hampton 2000	Type area: Tuckup Canyon, central Grand Canyon, in sec. 11, T. 34 N., R. 6 W., northern Mohave Co., AZ.	Pleistocene
GRCA	Basalt of Hancock Knolls (Qhb, Qhp)	Billingsley and Hampton 2000	Type area: Hancock Knolls, Kanab Plateau, in sec. 20, T. 35 N., R. 6 W., northern Mojave Co., AZ.	Pleistocene
GRCA	Snap Point Basalt	Billingsley and Wellmeyer 2003	Type area: Snap Point, Shivwits Plateau, in sec. 16, T. 32 N., R. 14 W., Mohave Co., AZ.	Miocene
GRCA	Fossil Mountain Member, Kaibab Formation (Pkf)	McKee 1938; Sorauf and Billingsley 1991	Type locality: Bass Trail on Fossil Mountain, Coconino Co., northern AZ.	early Permian
GRCA	Toroweap Formation (Pt)	McKee 1938; Rawson and Turner 1974	Type section: in Brady Canyon, an eastern side canyon of Toroweap (Tuweep) Valley, about 14 km (9 mi) above the mouth and 13 km (8 mi) north of Colorado River, Mohave Co., AZ.	early Permian
GRCA	Brady Canyon Member, Toroweap Formation (Ptb)	Sorauf and Billingsley 1991	Type locality: in Brady Canyon, on the eastern side of Toroweap Valley about 20.6 km (12.8 mi) north of the Colorado River, Mohave Co., northern AZ.	early Permian
GRCA	Hermit Formation (Ph)	Noble 1922	Type locality: Hermit basin, Grand Canyon, Coconino Co., northern AZ.	early Permian
GRCA	Redwall Limestone (Mr)	Darton 1910	Type locality: Redwall Canyon, in the Shinumo drainage basin on the north side of Grand Canyon, Coconino Co., northern AZ.	Mississippian
GRCA	Horseshoe Mesa Member, Redwall Limestone	McKee 1963	Type section: Horseshoe Mesa, Coconino Co., AZ.	Mississippian
GRCA	Thunder Springs Member, Redwall Limestone	McKee 1963	Type section: in cliff west of springs at head of Thunder River about 3.2 km (2 mi) north of Colorado River, Coconino Co., AZ.	Mississippian
GRCA	Whitmore Wash Member, Redwall Limestone	McKee 1963	Type section: east side of Whitmore Wash Valley, on the upthrown side of the Hurricane Fault, about 0.4 km (0.25 mi) north of Colorado River, Mohave Co., AZ.	Mississippian
GRCA	Temple Butte Formation (Dtb)	Walcott 1883; McKee 1974	Type section: at Temple Butte on the west side of the Colorado River a few miles below its junction with the Little Colorado River, Coconino Co., AZ.	Middle–Late Devonian

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
GRCA	Tonto Group (Cm, Cba, Ct)	Noble 1922; Elston 1989a; Rose 2011	Type section (Noble): measured along the South Bass Trail, Coconino Co., AZ. Type section (Rose): measured in Blacktail Canyon, lat. 36°14′25″ N., long. 112°26′21″ W., Coconino Co., AZ.	early–middle Cambrian
GRCA	Muav Formation (Cm)	Noble 1914, 1922; McKee 1945	Type locality: Muav Canyon, Coconino Co., AZ.	middle Cambrian
GRCA	Havasu Member, Muav Formation	McKee 1945	Type locality: near the mouth of Havasu Canyon, on the south side of Kanab Plateau [Tuckup Canyon 15′ Quadrangle], Coconino Co., northwestern AZ.	middle Cambrian
GRCA	Kanab Canyon Member, Muav Formation	McKee 1945	Type locality: at the mouth of Kanab Canyon, where it is lowest massive cliff-forming unit, not far above the level of the Colorado River [Kanab Point 15′ Quadrangle], Mohave and Coconino Cos., northwestern AZ.	middle Cambrian
GRCA	Lava Falls Tongue, Muav Formation	McKee 1945	Type locality: about 1.6 km (1 mi) east of Lava Falls at the foot of Toroweap Canyon, Coconino Co., northwestern AZ.	middle Cambrian
GRCA	Bright Angel Formation (Cba)	McKee 1945	Type locality: exposures in the cliffs of Bright Angel Canyon, AZ.	middle Cambrian
GRCA	Tapeats Sandstone (Ct)	Noble 1914; Molenaar 1969	Type locality: Tapeats Creek, Coconino Co., AZ.	early(?)–middle Cambrian
GRCA	Grand Canyon Supergroup (Zk*, Zg*, Yd*, Ys, Yh, Tb)	Powell 1876; Molenaar 1969	Type locality: Grand Canyon, AZ.	Mesoproterozoic–Neoproterozoic
GRCA	Sixtymile Formation (Cs)	Ford and Breed 1973	Type section: cliffs on the north side of the upper part of Sixty Mile Canyon, Coconino Co., AZ. Reference section: top of Nankoweap Butte, Awatubi Canyon, Coconino Co., AZ.	early–middle Cambrian
GRCA	Chuar Group	Walcott 1883; Molenaar 1969	Type locality: Chuar Valley, Coconino Co., AZ.	Neoproterozoic
GRCA	Kwagunt Formation (Zkw, Zka, Zkcb)	Ford and Breed 1973	Type area: Kwagunt Canyon, in the northern slopes of which the formation is fully exposed, Coconino Co., AZ.	Neoproterozoic
GRCA	Walcott Member, Kwagunt Formation (Zkw)	Ford and Breed 1973	Type section: head of Walcott Glen and upper part of Nankoweap Butte, Coconino Co., AZ.	Neoproterozoic
GRCA	Awatubi Member, Kwagunt Formation (Zka)	Ford and Breed 1973	Type section: Awatubi Canyon, Coconino Co., AZ. Reference section: southeast slope of Nankoweap Butte, Coconino Co., AZ.	Neoproterozoic

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
GRCA	Carbon Butte Member, Kwagunt Formation (Zkcb)	Ford and Breed 1973	Type section: Carbon Butte, Coconino Co., AZ. Reference section: south fork of Nankoweap Canyon, Coconino Co., AZ	Neoproterozoic
GRCA	Galeros Formation (Zgd, Zgcc, Zgj, Zgt)	Ford and Breed 1973	Type area: Galeros Promontory, which overlooks the southern part of the Chuar outcrops in Chuar and Carbon Canyons, Coconino Co., AZ.	Neoproterozoic
GRCA	Duppa Member, Galeros Formation (Zgd)	Ford and Breed 1973	Type section: below Duppa Butte in Kwagunt Canyon, Coconino Co., AZ.	Neoproterozoic
GRCA	Carbon Canyon Member, Galeros Formation (Zgcc)	Ford and Breed 1973	Type section: Carbon Canyon west fork and mid-Chuar Canyon, Coconino Co., AZ.	Neoproterozoic
GRCA	Jupiter Member, Galeros Formation (Zgj)	Ford and Breed 1973	Type section: below Jupiter Temple in lower part of Chuar Canyon, Coconino Co., AZ.	Neoproterozoic
GRCA	Tanner Member, Galeros Formation (Zgt)	Ford and Breed 1973	Type section: overlooking Tanner Rapids in the cliffs of Basalt Canyon, Coconino Co., AZ. Reference section: lower end of Chuar Canyon, Coconino Co., AZ	Neoproterozoic
GRCA	Nankoweap Formation (Zn)	Van Gundy 1951	Type section: Basalt Canyon, on the north side of the Colorado River just south of its intersection with the Little Colorado River, Coconino Co., AZ.	Neoproterozoic
GRCA	Ferruginous Member, Nankoweap Formation	Elston and Scott 1976	Type section: in the graben at the Tanner Canyon rapids, Coconino Co., AZ.	Neoproterozoic
GRCA	Unkar Group (Yd*, Ys, Yh, Yb)	Walcott 1894; Molenaar 1969	Type locality: Unkar Valley, Coconino Co., AZ.	Mesoproterozoic
GRCA	Dox Formation (Yd, Ydo, Ydc, Yds, Yde)	Noble 1914; Beus et al. 1974	Type section: beneath Dox Castle in a tributary to Shinumo Creek, Coconino Co., AZ	Mesoproterozoic
GRCA	Ochoa Point Member, Dox Formation (Ydo)	Stevenson and Beus 1982	Type section: in an unnamed stream on the southwest side of Ochoa Point, a promontory west of Basalt Canyon, northwest side of the Colorado River [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic
GRCA	Comanche Point Member, Dox Formation (Ydc)	Stevenson and Beus 1982	Type section: exposures in the bed of unnamed creek tributary to Tanner Canyon, 1.6 km (1 mi) west of Comanche Point, southeast side of the Colorado River between Tanner Canyon and Comanche Creek [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic
GRCA	Solomon Temple Member, Dox Formation (Yds)	Stevenson and Beus 1982	Type section: 2.4 km (1.5 mi) northeast of Solomon Temple, south of Unkar Creek [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
GRCA	Escalante Creek Member, Dox Formation (Yde)	Stevenson and Beus 1982	Type section: Escalante Creek [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic
GRCA	Shinumo Sandstone (Ys)	Noble 1914; Molenaar 1969	Type locality: Shinumo Creek canyon, Coconino Co., AZ.	Mesoproterozoic
GRCA	Hakatai Shale (Yh)	Noble 1914; Beus et al. 1974	Type section: Hakatai Canyon, Coconino Co., AZ.	Mesoproterozoic
GRCA	Bass Formation (Yb)	Noble 1914; Beus et al. 1974	Type section: in Hotauta Canyon, on the north side of the Colorado River [Shinumo Quadrangle], Coconino Co., northern AZ.	Mesoproterozoic
GRCA	Hotauta Conglomerate Member, Bass Formation	Noble 1914; Molenaar 1969	Type locality: in Hotauta Canyon, on the north side of the Colorado River [Shinumo Quadrangle], Coconino Co., northern AZ.	Mesoproterozoic
GRCA	Zoroaster Granite	Campbell and Maxson 1938; Barnes 1989	Type area: exposures between Zoroaster and Cremation Canyons, Coconino Co., AZ.	Paleoproterozoic
GRCA	Vishnu Schist (Xv)	Campbell and Maxson 1938; Ilg et al. 1996	Type locality: in lower canyon of Vishnu Creek, Coconino Co., AZ. Reference section: Vishnu Canyon, Coconino Co., AZ.	Paleoproterozoic
GRCA	Rama Schist and Gneiss (Xr)	Ilg et al. 1996	Reference sections: 1) for higher-grade quartzofeldspathic gneisses, ~1 km (0.6 mi) downstream from Hance Canyon in the core of the Sockdolager antiform; 2), for the massive, metamorphosed lapilli-crystal tuffs, in Shinumo Creek ~6 km (3.7 km) from the Colorado River; and 3), for quartz-eye metarhyolite, near river mile 127 [measured downstream from Lee's Ferry]	Paleoproterozoic
MEVE	Mesaverde Group (Kch, Kme, Kpl)	Collier 1919; Dubiel 2013	Type locality: Mesaverde National Park in southwestern CO.	Late Cretaceous
MEVE	Cliff House Formation (Kch)	Collier 1919; Lochman-Balk 1967	Type locality: Echo Cliffs in MEVE, Montezuma Co., CO.	Late Cretaceous
MEVE	Point Lookout Sandstone (Kpl)	Collier 1919; Lochman-Balk 1967	Type locality: Cliffs at Point Lookout, about 12 km (7.5 mi.) SW of Mancos, Montezuma Co., CO.	Late Cretaceous

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
MEVE	Mancos Shale (Km, Kms, Kmj)	Leckie et al. 1997	Principal reference section (composite): transect extending from sec. 19 and 20, T. 36 N., R. 14 W., north of MEVE, to sec. 5, T. 35 N., R. 14 W. at the base of the sandstone cliffs of Point Lookout within the park, Montezuma Co., CO.	Late Cretaceous
MEVE	Cortez Member, Mancos Shale	Leckie et al. 1997	Type section: in the western half of sec. 5, T. 35 N., R. 14 W., Montezuma Co., CO.	Late Cretaceous
PEFO	Painted Desert Member, Petrified Forest Formation, Chinle Group (*now obsolete and considered the Petrified Forest Member of the Chinle Formation*)	Lucas 1993; Heckert and Lucas 2002	Type section (composite): 1) SE/4 NE/4 sec. 11, T. 19 N., R. 23 E.; 2) W/2 NW/4 SW/4 sec. 34, T. 20 N., R. 24 E.; and 3) NW/4 sec. 9 and SW/4 sec. 4, T. 20 N., R. 24 E., Apache Co., AZ.	Late Triassic
PEFO	Black Forest Bed, Petrified Forest Member, Chinle Formation (TRcpfbf)	Ash 1992	Type section: below Kachina Point and about 40 m (131 ft) west of the trail leading into the Painted Desert Section of PEFO, in SW/4 SW/4 SW/4, sec. 33, T. 20 N., R. 24 E., Apache Co., AZ.	Late Triassic
PEFO	Lithodendron Wash Bed, Petrified Forest Member, Chinle Formation (TRcpd3)	Heckert and Lucas 2002	Type section: Chinde Point II section, in NW/4 SE/4 NE/4, sec. 33, T. 20 N., R. 24 E., Apache Co., AZ.	Late Triassic
PEFO	Flattops Bed 4, Petrified Forest Member, Chinle Formation (TRcpff4)	Cooley 1957; Roadifer 1966; Murry and Long 1989; Heckert and Lucas 2002	Type section: Flattops west section, in SW/4 NE/4 NW/4 sec. 32, T. 17 N., R. 24 E., Apache Co., AZ. Reference sections: 1) S/2 SE & SW/4, sec. 32, T. 17 N., R. 24 E., Apache Co., AZ (Cooley 1957); 2) SE/4 SW/4 sec. 32, T. 17 N., R. 24. E., Apache Co., AZ (Roadifer 1966); and 3) sec. 32, T. 17 N., R. 24 E., at approx. lat. 34°49′50″ N, long. 109°48′48″ W., Apache Co., AZ (Murry and Long 1989).	Late Triassic

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
PEFO	Flattops Bed 3, Petrified Forest Member, Chinle Formation (TRcpff3)	Cooley 1957; Roadifer 1966; Murry and Long 1989; Heckert and Lucas 2002	Type section: Flattops west section, in SW/4 NW/4 sec. 32, T. 17 N., R. 24 E., Apache Co., AZ. Reference sections: 1) S/2 SE & SW/4, sec. 32, T. 17 N., R. 24 E., Apache Co., AZ (Cooley 1957); 2) SE/4 SW/4 sec. 32, T. 17 N., R. 24. E., Apache Co., AZ (Roadifer 1966); and 3) sec. 32, T. 17 N., R. 24 E., at approx. lat. 34°49′50″ N, long. 109°48′48″ W., Apache Co., AZ (Murry and Long 1989).	Late Triassic
PEFO	Flattops Bed 2, Petrified Forest Member, Chinle Formation (TRcpff2)	Cooley 1957; Roadifer 1966; Murry and Long 1989; Heckert and Lucas 2002	Type section: Flattops west section, in NE/4 NE/4 sec. 31, T. 17 N., R. 24 E., Apache Co., AZ. Reference sections: 1) S/2 SE & SW/4, sec. 32, T. 17 N., R. 24 E., Apache Co., AZ (Cooley 1957); 2) SE/4 SW/4 sec. 32, T. 17 N., R. 24. E., Apache Co., AZ (Roadifer 1966); and 3) sec. 32, T. 17 N., R. 24 E., at approx. lat. 34°49′50″ N, long. 109°48′48″ W., Apache Co., AZ (Murry and Long 1989).	Late Triassic
PEFO	Flattops Bed 1, Petrified Forest Member, Chinle Formation (TRcsmb)	Woody 2006	Type section: section Mountain Lion Mesa 1 – UTM Zone 12S, E608482, N3857866, NAD 27. Reference sections: 1) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27; 2) section Agate Mesa West 1 – UTM Zone 12S, E607822, N3860933, NAD 27; 3) section Old 180 4 – UTM Zone 12S, E608325, N3850628, NAD 27; 4) section Crystal Forest – UTM Zone 12S, E610591, N3859345, NAD 27; and 5) section Dry Wash N – UTM Zone 12S, E610014, N3856388, NAD 27.	Late Triassic
PEFO	Sonsela Member, Chinle Formation (TRcsrf, TRcsb, TRcsjc, TRcsmb, TRcspd1)	Woody 2006	Reference sections: 1) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27; and 2) section Mountain Lion Mesa 1 – UTM Zone 12S, E608482, N3857866, NAD 27.	Late Triassic

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
PEFO	Agate Bridge Bed, Sonsela Member, Chinle Formation	Heckert and Lucas 2002	Type section: just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge, northwest of Giant Logs in N/2 SW/4 SW/4 to NW/4 NW/4 SW/4 sec. 35, T. 17 N., R. 23 E., Navajo Co., AZ. Reference section: units 7–11 of Murry and Long's (1989) "Sonsela section", north of Agate Bridge, Apache Co., AZ.	Late Triassic
PEFO	Jim Camp Wash Beds, Sonsela Member, Chinle Formation (TRcsjc, TRcsb)	Heckert and Lucas 2002; Woody 2006	Type section: just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge, northwest of Giant Logs in N/2 SW/4 SW/4 to NW/4 NW/4 SW/4 sec. 35, T. 17 N., R. 23 E., Apache Co., AZ. Reference sections: 1) section Agate Mesa West 1 – UTM Zone 12S, E607822, N3860933, NAD 27; 2) section Mountain Lion Mesa 1 – UTM Zone 12S, E608482, N3857866, NAD 27; 3) section Dry Wash North – UTM Zone 12S, E610014, N3856388, NAD 27; and 4) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27.	Late Triassic
PEFO	Jasper Forest Bed, Sonsela Member, Chinle Formation (TRcsrf)	Martz and Parker 2010	Reference section: the capping sandstone at Agate Mesa, best exposed on the northern face, Apache Co., AZ.	Late Triassic
PEFO	Rainbow Forest Bed, Sonsela Member, Chinle Formation (TRcsrf)	Cooley 1957; Heckert and Lucas 2002; Woody 2006	Type section: just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge, northwest of Giant Logs in N/2 SW/4 SW/4 to NW/4 NW/4 SW/4 sec. 35, T. 17 N., R. 23 E., Apache County, AZ. Reference sections (Woody 2006): 1) section Lots Wife – UTM Zone 12S, E610276, N3862740, NAD 27; 2) section Old 180 W – UTM Zone 12S, E602742, N3853275, NAD 27; 3) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27; and 4) section Camp Butte – UTM Zone 12S, E612581, N3867223, NAD 27. Reference section (Heckert and Lucas 2002): 5) unit 3 of Cooley's (1957) Rainbow Forest Sandstone, in W/2 S/2 NW/2 to W/2 N/2 NW/2 sec. 1, T. 16 N., R. 23 E., Navajo Co., AZ.	Late Triassic

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
PEFO	Blue Mesa Member, Chinle Formation (TRcbm)	Heckert and Lucas 2002; Woody 2006	Type section (composite): from the Haystacks (units 1–8 in the SW/4 SW/4 SE/4 sec. 21) through the Teepees (units 9–11 in the SW/4 NW/4 SW/4 NE/4 sec. 22); and "Camp's Butte" (units 12–15, SE/4 NW/4 SW/4 sec. 23) to the Blue Mesa area proper (units 16–21 in the E/2 SE /4 SE/4 SW/4 sec. 23) in T. 18 N., R. 24 E., Apache Co., AZ.	Late Triassic
PEFO	Newspaper Rock Bed, Blue Mesa Member, Chinle Formation (TRcbnr)	Heckert and Lucas 2002	Type section: Newspaper Rock Section in the SE/4 SE/4 NW/4 sec. 16, T. 18 N., R. 24 E., Apache Co., AZ.	Late Triassic
SAPU	Abo Formation (Pa)	Lee 1909; Lucas et al. 2005	Type section: between Priest Canyon and the Abo Mission Ruins in Abo Canyon, southern Manzano Mountains. Bottom of section measured in sec. 3, T. 2 N., R. 5 E.; top measured in secs. 35–36, T. 3 N., R. 5 E., Torrance Co., NM.	early Permian
SAPU	Cañon de Espinoso Member, Abo Formation (Pa)	Lucas et al. 2005	Type section: measured near the top of the Abo type section (units 22–68 of the Abo type section) in secs. 35–36, T. 3 N., R. 5 E., Torrance Co., NM.	early Permian
VALL	Valles Rhyolite (Qv*)	Griggs and Hem 1964	Type locality: rhyolite domes in Valles Caldera in west-central part of Los Alamos area, Sandoval Co., NM.	Pleistocene
VALL	East Fork Member, Valles Rhyolite	Gardner et al. 2010	Type area: composite of type areas of constituent units (Banco Bonito, Battleship Rock, and El Cajete), centered at approx. lat. 35°50′ N., long. 106°35′ W. [in Jemez Springs, Redondo Peak, Valle San Antonio, and Seven Springs 7.5′ Quadrangles], Sandoval Co., NM.	Pleistocene
VALL	South Mountain Member, Valles Rhyolite (Qvsm1, Qvsm2, Qvsm3, Qvsm4)	Gardner et al. 2010	Type area: a northeast-trending rectangular area about 5 km (3 mi) long and 2 km (1.35 mi) wide, centered on UTM 13S, 361850E 3966750N, NAD 27, Sandoval Co., NM.	Pleistocene
VALL	San Antonio Mountain Member, Valles Rhyolite (Qvsa1, Qvsa2, Qvsa3)	Gardner et al. 2010	Type area: designated as the area defined by roughly a 3 km (1.86 mi) radius about UTM 13S, 354180E 3978100N, NAD 27, Sandoval Co., NM.	Pleistocene
VALL	Cerro Seco Member, Valles Rhyolite (Qvset, Qvse1, Qvse2)	Gardner et al. 2010	Type area: designated as the rectangular area defined with the northwest corner at UTM 13S, 356050E 3981750N, and the southeast corner at UTM 13S, 359600E 3977300N, NAD 27, Sandoval Co., NM.	Pleistocene
VALL	Cerro San Luis, Valles Rhyolite (Qvsl1, Qvsl2)	Gardner et al. 2010	Type area: the area of about 1.5 km (1 mi) radius around UTM 13S, 361400E 3979100N, NAD 27, Sandoval Co., NM.	Pleistocene

Table 1 (continued). List of SCPN stratotypes sorted by park unit and geologic age, with associated reference publications and locations.

Park	Unit Name (map symbol)	Reference	Stratotype Location	Age
VALL	Cerro Santa Rosa Member, Valles Rhyolite (Qvsr1, Qvsr2, Qvsrt)	Gardner et al. 2010	Type area: the north–northeast-trending chain of hills, about 3.5 km (2.2 mi) long and less than 2 km (1.25 mi) wide, centered at UTM 13S, 3664350E 3979000N, NAD 27, Sandoval Co., NM.	Pleistocene
VALL	Cerros del Abrigo Member, Valles Rhyolite (Qvda1, Qvda2, Qvda3, Qvda4)	Gardner et al. 2010	Type area: an area of about 1–2 km (~0.5–1 mi) radius centered about UTM 13S, 366475E 3977650N, NAD 27, Sandoval Co., NM.	Pleistocene
VALL	Cerro del Medio Member, Valles Rhyolite (Qvdm1, Qvdm2, Qvdm3, Qvdm4, Qvdm5, Qvdm6, Qvdmt)	Gardner et al. 2010	Type area: an area of 2–3 km (~1–2 mi) radius about UTM 13S, 368800E 3974250N, NAD 27, Sandoval Co., NM.	Pleistocene
VALL	Redondo Creek Member, Valles Rhyolite (Qrc)	Bailey et al. 1969	Type locality: in steep slopes on west side of Sulphur Creek, between Sulphur Springs and La Cueva [Jemez Springs 15′ Quadrangle], Sandoval Co., NM.	Pleistocene
VALL	Deer Canyon Member, Valles Rhyolite (Qdc, Qdct)	Bailey et al. 1969	Type area: Deer Canyon, southwest side of Redondo Border [Jemez Springs 15′ Quadrangle], Sandoval Co., NM.	Pleistocene
VALL	Valle Toledo Member, Cerro Toledo Formation (Qct)	Griggs 1964; Gardner et al. 2010	Type area: on the northeast side of Valles Caldera in steep forested northwest-trending ridge, the Sierra de Toledo, between Rito de los Indios and Valle de los Posos, Sandoval Co., NM. Type area expanded to include vicinity of Valle Toledo.	Pleistocene
WUPA	Wupatki Member, Moenkopi Formation (TRmw)	Akers et al. 1958	Type area: near Wupatki Pueblo, Coconino Co., AZ.	Early Triassic

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Many individuals were consulted in the preparation of this report on the geologic type sections for the national parks of the Southern Colorado Plateau Inventory and Monitoring Network. We first want to extend our sincere appreciation to Randy Orndorff, David Soller, and Nancy Stamm (U.S. Geological Survey) for their assistance with this geologic type section inventory and other important NPS projects. Randy, Dave, and Nancy manage the National Geologic Map Database for the United States (NGMDB, https://ngmdb.usgs.gov/ngm-bin/ngm_compsearch.pl?glx=1) and the U.S. Geologic Names Lexicon ("GEOLEX", https://ngmdb.usgs.gov/Geolex/search), the national compilation of names and descriptions of geologic units for the United States, two critical sources of geologic information for science, industry, and the American public.

We thank our colleagues and partners in the Geological Society of America (GSA) and Stewards Individual Placement Program for their continued support to the NPS with the placement of geologic interns and other ventures. A special thanks to Jeanette Hammann (GSA Director of Publications), Mike Conway (Arizona Geological Survey), Belinda Harris (New Mexico Bureau of Geology and Mineral Resources), David Lemke (New Mexico Geological Society), Spencer Lucas (New Mexico Museum of Natural History & Science), Paul Inkenbrandt (Utah Geological Association), and Jennifer Miller (Utah Geological Survey) for the permission to use figures in this publication. Additionally, we are grateful to Rory O'Connor-Walston and Alvin Sellmer from the NPS Technical Information Center in Denver for their assistance with locating hard-to-find publications.

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Dedication

This Southern Colorado Plateau Inventory and Monitoring Network Geologic Type Section Inventory is dedicated to two individuals who have invested their careers to advance our understanding of the geology of parks on the Colorado Plateau and especially at Grand Canyon: George Billingsley (USGS retired) and Karl Karlstrom (University of New Mexico). George has created numerous geologic maps and other significant publications for the parks in this region. Karl had a significant role in the development of "The Trail of Time" that showcases the geologic history of Grand Canyon along the rim trail. Dedicated in 2010, The Trail of Time provides a visceral appreciation for the rich geologic story of Grand Canyon National Park and is a testament today for all visitors.

George Billingsley, retired USGS geologist

Karl Karlstrom (University of New Mexico)

Introduction

The NPS Geologic Type Section Inventory Project ("Stratotype Inventory Project") is a continuation of, and complements the work performed by the Geologic Resources Inventory (GRI). The GRI is funded by the NPS Inventory & Monitoring Program and administered by the Geologic Resources Division (GRD). The GRI is designed to compile and present baseline geologic resource information available to park managers, and advance science-informed management of natural resources in the national parks. The goals of the GRI are to increase understanding and appreciation of the geologic features and processes in parks and provide robust geologic information for use in park planning, decision making, public education, and resource stewardship.

Documentation of stratotypes (i.e., type sections/type localities/type areas) that occur within national park boundaries represents a significant component of a geologic resource inventory, as these designations serve as the standard for defining and recognizing geologic units (North American Commission on Stratigraphic Nomenclature 2021). The importance of stratotypes lies in the fact that they represent important comparative sites where past investigations can be built upon or re-examined, and can serve as teaching sites for the next generation of students (Brocx et al. 2019). The geoheritage significance of stratotypes is analogous to libraries and museums in that they are natural repositories of Earth history and record the physical and biologic evolution of our planet.

The goals of this project are to (1) systematically report the assigned stratotypes that occur within national park boundaries, (2) provide detailed descriptions of the stratotype exposures and their locations, and (3) reference the stratotype assignments from published literature. It is important to note that this project cannot verify a stratotype for a geologic unit if one has not been formally assigned and/or published. Additionally, numerous stratotypes are located geographically outside of national park boundaries, but only those within 48 km (30 mi) of park boundaries are presented in this report.

This geologic type section inventory for the parks of the Southern Colorado Plateau Inventory & Monitoring Network (SCPN) follows standard practices, methodologies, and organization of information introduced in the Greater Yellowstone I&M Network type section inventory (Henderson et al. 2020). All network-specific reports are prepared, peer-reviewed, and submitted to the Natural Resources Stewardship and Science Publications Office for finalization. A small team of geologists and paleontologists from the NPS Geologic Resources Division and the NPS Paleontology Program has stepped up to undertake this important inventory for the NPS.

This inventory fills a void in basic geologic information compiled by the NPS at most parks. Instances where geologic stratotypes occurred within NPS areas were determined through research of published geologic literature and maps. Sometimes the lack of specific locality or other data limited determination of whether a particular stratotype was located within NPS administered boundaries. Below are the primary justifications that warrant this inventory of NPS geologic stratotypes.

- Geologic stratotypes are a part of our national geologic heritage and are a cornerstone of the scientific value used to define the societal significance of geoheritage sites (https://www.nps.gov/articles/scientific-value.htm);
- Geologic stratotypes are important geologic landmarks and reference locations that define important scientific information associated with geologic strata. Geologic formations are commonly named after topographic or geologic features and landmarks that are recognizable to park staff;
- Geologic stratotypes are both historically and scientifically important components of earth science investigations and mapping. Geologic stratotypes are similar in nature to type specimens in biology and paleontology, serving as the primary reference for defining distinctive characteristics and establishing accurate comparisons;
- Understanding and interpreting the geologic record depends on the stratigraphic occurrences of mappable lithologic units (formations, members). These geologic units are the foundational attributes of geologic maps;
- Geologic maps are important tools for science, resource management, land use planning, and other areas and disciplines;
- Geologic stratotypes within NPS areas have not been previously inventoried and there is a general absence of baseline information for this geologic resource category;
- NPS staff may not be aware of the concept of geologic stratotypes and therefore would not understand the significance or occurrence of these natural references in the parks;
- Given the importance of geologic stratotypes as geologic references and geologic heritage resources, these locations should be afforded some level of preservation or protection when they occur within NPS areas;
- If NPS staff are unaware of geologic stratotypes within parks, the NPS cannot proactively monitor the stability, condition, or potential impacts to these locations during normal park operations or planning. This lack of information also prevents the protection of these localities from activities that may involve ground disturbance or construction;
- This inventory can inform important conversations on whether geologic stratotypes rise to the level of national register documentation. The NPS should consider if any other legal authorities (e.g., National Historic Preservation Act), policy, or other safeguards currently in place can help protect geologic stratotypes that are established on NPS administered lands. Through this inventory, the associated report, and close communication with park and I&M Network staff, we hope there will be an increased awareness about these important geologic landmarks in parks. In turn, the awareness of these resources and their significance may be recognized in park planning and operations, to ensure that geologic stratotypes are preserved and available for future study.

Geology and Stratigraphy of the SCPN I&M Network Parks

The Southern Colorado Plateau Inventory and Monitoring Network (SCPN) is composed of 19 national park units in Arizona, Colorado, New Mexico, and Utah (Figure 1). Park units of the SCPN include Aztec Ruins National Monument (AZRU), Bandelier National Monument (BAND), Canyon De Chelly National Monument (CACH), Chaco Culture National Historical Park (CHCU), El Malpais National Monument (ELMA), El Morro National Monument (ELMO), Glen Canyon National Recreation Area (GLCA), Grand Canyon National Park (GRCA), Hubbell Trading Post National Historic Site (HUTR), Mesa Verde National Park (MEVE), Navajo National Monument (NAVA), Petrified Forest National Park (PEFO), Petroglyph National Monument (PETR), Rainbow Bridge National Monument (RABR), Salinas Pueblo Missions National Monument (SAPU), Sunset Crater Volcano National Monument (SUCR), Valles Caldera National Preserve (VALL), Walnut Canyon National Monument (WACA), Wupatki National Monument (WUPA), and Yucca House National Monument (YUHO). Parks that comprise the Southern Colorado Plateau Network protect a combined 1,269,514 hectares (3,137,038 acres) of land and vary in size from 13 hectares (34 acres) in YUHO, to 507,523 hectares (1,254,117 acres) in GLCA.

The Colorado Plateau is characterized as a high-standing crustal block of relatively undeformed strata that exhibit broad flexures, monoclines (step-like folds), normal faults, igneous laccoliths (dome-like intrusions), and volcanoes. The province is surrounded by the Rocky Mountains and Uinta Mountains to the north and northeast, the Rio Grande Rift Valley to the east, and the Mogollon Rim to the south. The western boundary of the Colorado Plateau represents a transition zone where geologic features are transitional between typical Colorado Plateau and the Basin and Range. Many of the parks in the SCPN represent iconic geologic landscapes consisting of sparely vegetated plateaus, mesas, deep canyons, and badlands that encompass the area drained by the Colorado River and its tributaries. Parks of the SCPN occupy four of the six sections of the Colorado Plateau as defined by Rigby (1977): 1) Grand Canyon section, the highest structural part of the Colorado Plateau—GRCA, SUCR, WACA, and WUPA; 2) Canyonlands section, a region of deeply incised canyons, large monoclines, and laccolithic mountains—GLCA, MEVE, RABR, and YUHO; 3) Navajo section, an area of scarped plateaus that is less dissected than the Canyonlands section—AZRU, CACH, CHCU, HUTR, NAVA, and PEFO; and the 4) Datil section, which is largely volcanic in origin—ELMA and ELMO (Figure 2). Only BAND, PETR, SAPU, and VALL are located outside the Colorado Plateau physiographic province in and near the Rio Grande Rift, an area characterized by east–west crustal extension. Dynamic crustal extensional processes associated with the Rio Grande Rift resulted in thick packages of sedimentary deposits (Santa Fe Group), but also thinned and weakened the crust, producing fault-bounded basins and numerous volcanic fields throughout New Mexico and Colorado (Keller and Baldridge 1999; KellerLynn 2017).

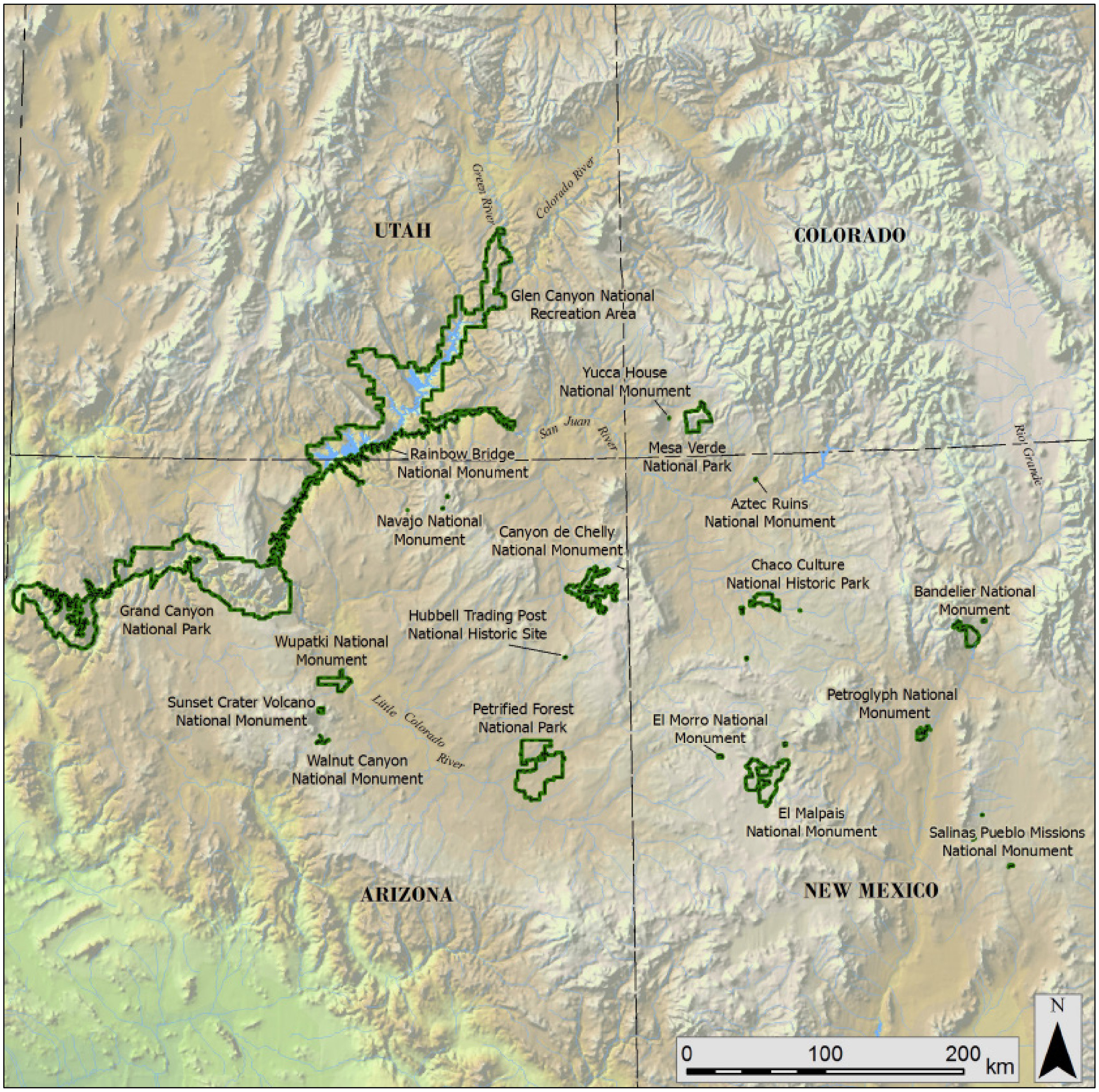


Figure 1. Map of Southern Colorado Plateau I&M Network parks, including: Aztec Ruins National Monument (AZRU), Bandelier National Monument (BAND), Canyon De Chelly National Monument (CACH), Chaco Culture National Historical Park (CHCU), El Malpais National Monument (ELMA), El Morro National Monument (ELMO), Glen Canyon National Recreation Area (GLCA), Grand Canyon National Park (GRCA), Hubbell Trading Post National Historic Site (HUTR), Mesa Verde National Park (MEVE), Navajo National Monument (NAVA), Petrified Forest National Park (PEFO), Petroglyph National Monument (PETR), Rainbow Bridge National Monument (RABR), Salinas Pueblo Missions National Monument (SAPU), Sunset Crater Volcano National Monument (SUCR), Walnut Canyon National Monument (WACA), Wupatki National Monument (WUPA), and Yucca House National Monument (YUHO) (NPS). Note that Valles Caldera National Preserve (VALL) is not shown in the figure but is adjacent to northwestern BAND.

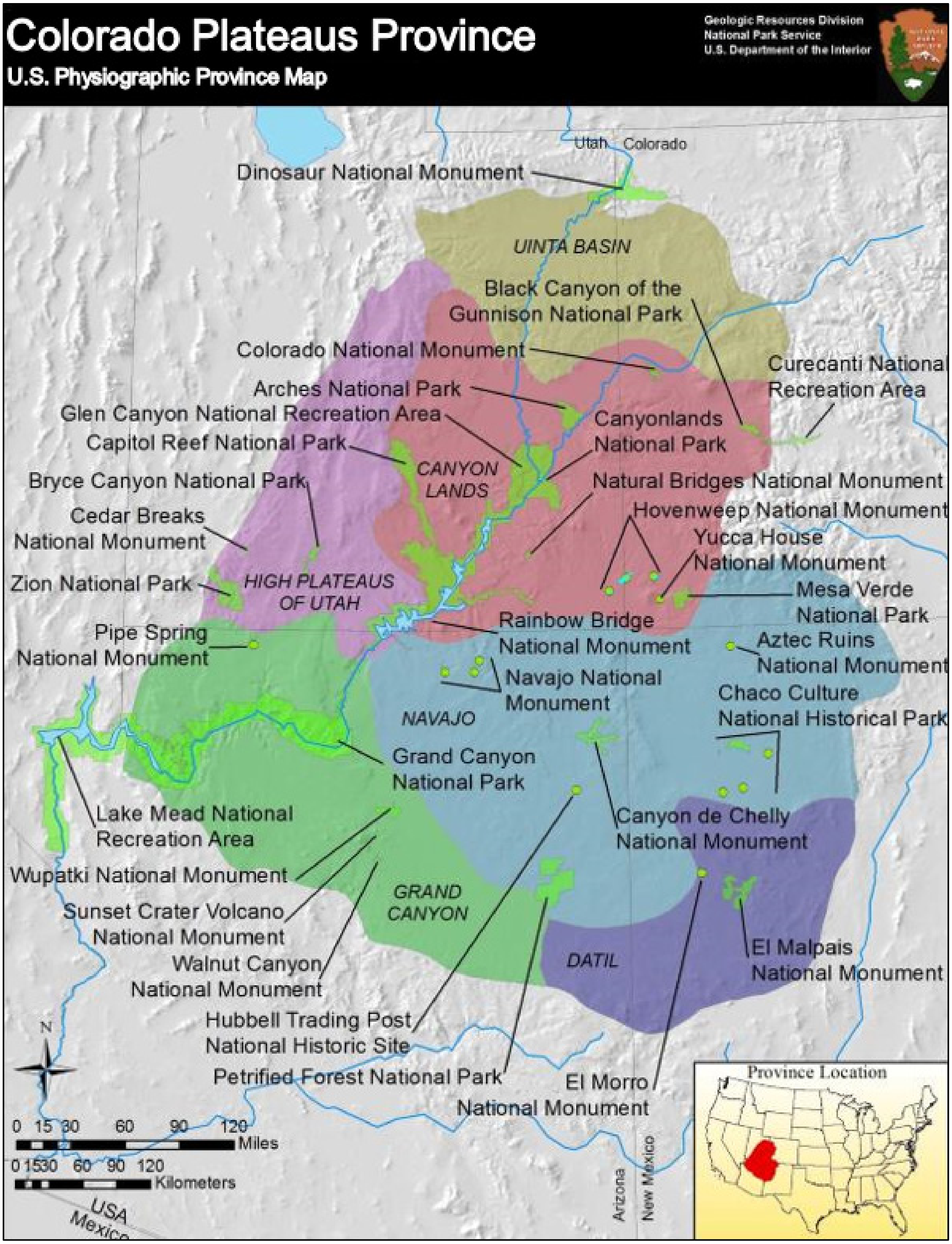


Figure 2. Map of the Colorado Plateau Physiographic Province, showing the six regional divisions of the Colorado Plateau and NPS park unit locations (NPS).

Precambrian

Precambrian-age rocks are mapped in the Upper, Middle, and Lower Granite Gorges of GRCA and include the oldest exposures in the Southern Colorado Plateau Network (Seaman et al. 2021; see Appendix B for a geologic time scale). These ancient exposures include the Paleoproterozoic Elves Chasm pluton (1.84 billion years old); Granite Gorge Metamorphic Suite (1.751–1.750 billion years old) that includes the Vishnu, Brama, and Rama schists; granodioritic intrusive rocks of the Zoroaster Plutonic Complex (1.740–1.713 billion years old); granitic intrusive rocks (Phantom granite) and pegmatite dikes (Cremation pegmatite) between 1.698–1.662 billion years old; and the Quartermaster granite in western GRCA (1.375 billion years old) (Karlstrom et al. 2021). The Grand Canyon Supergroup is localized to GRCA and includes the Mesoproterozoic Unkar Group (Bass Formation, Hakatai Shale, Shinumo Sandstone, Dox Formation, and Cardenas Basalt), and Neoproterozoic Chuar Group (Nankoweap Formation, Galeros Formation, and Kwagunt Formation).

Other Precambrian exposures are mapped in ELMA, consisting of Mesoproterozoic metamorphic and igneous rocks about 1.4 billion years old.

Paleozoic

Thick sequences of Paleozoic sedimentary rocks are mapped in several of the park units of the SCPN. The extensive and world-renowned Paleozoic strata exposed in GRCA include the Cambrian Tonto Group (Sixtymile Formation, Tapeats Sandstone, Bright Angel Formation, and Muav Formation), Mississippian Redwall Limestone, Surprise Canyon Formation, Pennsylvanian–Permian Supai Group and related units (Watahomigi Formation, Manakacha Formation, Wescogame Formation, Pakoon Limestone, and Esplanade Sandstone), and the Permian Hermit Formation. The Permian Coconino Sandstone is exposed in GRCA and WACA. The Permian Toroweap Formation is mapped in GRCA, WACA, and WUPA. The Permian Kaibab Formation is found in GLCA, GRCA, WACA, and WUPA.

Other Paleozoic-age units include the Pennsylvanian Hermosa Group (GLCA), Pennsylvanian–Permian Supai Formation (CACH), Permian San Andres Limestone (ELMA and SAPU), Abo Formation (ELMA and SAPU), Cutler Group (CACH and GLCA), Glorieta Sandstone (ELMA), Yeso Formation (ELMA), and Arroyo de Alamillo Formation (SAPU).

Mesozoic

Mesozoic rocks are mapped in 13 of the 19 park units of the SCPN. Exposure in GLCA may represent the best overall Mesozoic stratigraphic section in the National Park Service, providing exceptional documentation of ancient ecosystems and paleoclimates from about 252 million to 66 million years ago. Mapped units in GLCA include the Triassic Moenkopi Formation and Chinle Formation; Triassic–Jurassic Glen Canyon Group (Wingate Sandstone, Moenave Formation, Kayenta Formation and Navajo Sandstone); Jurassic San Rafael Group (Entrada Sandstone, Page Sandstone, Carmel Formation, Romana Sandstone, and Summerville Formation) and Morrison Formation; and Cretaceous Naturita Formation [formerly Dakota Formation], Tropic Shale, and Straight Cliffs Formation.

Several units are found is multiple parks, such as the Triassic Moenkopi Formation (GLCA, GRCA, and WUPA) and Chinle Formation (CACH, GLCA, GRCA, HUTR, and PEFO); Triassic–Jurassic Glen Canyon Group (GLCA, GRCA, NAVA, and RABR); Jurassic Zuni Sandstone (ELMA and ELMO); and Cretaceous Naturita Formation (ELMA, ELMO), Mesaverde Group (CHCU, MEVE), and Mancos Shale (ELMA, MEVE, YUHO). Other mapped Mesozoic rocks within the park units of SCPN include the Jurassic Wanakah Formation (ELMA) and Cretaceous Pictured Cliffs Sandstone and Lewis Shale (CHCU), Tres Hermanos Sandstone (ELMA), and Point Lookout Sandstone (MEVE).

Cenozoic

Cenozoic bedrock and surficial deposits are found in most parks of the SCPN and include igneous rocks associated with the Rio Grande Rift, Albuquerque volcanic field, San Francisco volcanic field, and Valles–Toledo caldera complex (a caldera is a basin formed when a magma chamber is emptied by eruption and the overlying rock collapses into it).

Mapped units in AZRU include the Paleocene Nacimiento Formation and Pleistocene Naha and Tsegi Alluviums. The Naha Alluvium is also mapped in CHCU. Several Cenozoic-age units are found in BAND and adjacent VALL, including the Eocene Galisteo Formation; Miocene Chamita, Tesuque, and Paliza Canyon Formations; Miocene–Pliocene Cochiti Formation; Pliocene Tschicoma Formation; and Pleistocene Tewa Group (Bandelier Tuff, Cerro Toledo Formation, Valles Rhyolite). Cenozoic volcanic rocks, basalt flows, and dikes are located in both ELMA, ELMO, SAPU, and WUPA. A number of volcanic units are distributed throughout GRCA and record Miocene, Pliocene, and Pleistocene-age volcanism. The Miocene Bidahochi Formation is found in PEFO. Several Cenozoic-age deposits are mapped in PETR and include the Pliocene–Pleistocene Ceja Formation and Pleistocene Lomatas Negras Formation, Los Duranes Formation, and volcanic rocks associated with the Albuquerque volcanic field. The volcanic landscape of SUCR consists entirely of Pleistocene-age volcanic rock lava flows, volcanic ash, and cinder deposits of the San Francisco volcanic field.

Geologically young surficial deposits of Pleistocene–Holocene-age are mapped in nearly every park of the SCPN, and predominantly consist of alluvium, colluvium, alluvial fan deposits, eolian sands, terrace gravels, landslide deposits, and slump deposits.

National Park Service Geologic Resource Inventory

The Geologic Resources Inventory (GRI) provides digital geologic map data and pertinent geologic information on park-specific features, issues, and processes to support resource management and science-informed decision-making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. The GRI team consists of a partnership between the GRD and the Colorado State University Department of Geosciences to produce GRI products.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for non-geoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Scoping sessions were held on the following dates for the SCPN parks: MEVE and YUHO on July 14–15, 1998; GLCA and RABR on September 23–25, 1999; NAVA on June 25, 2001; GRCA on June 26, 2001; PEFO on June 27–28, 2001; SUCR, WACA, and WUPA on June 28–29, 2001; PETR and SAPU on March 29, 2006; ELMA and ELMO on March 30, 2006; AZRU on February 13, 2007; CHCU on February 14, 2007; CACH on February 15–16, 2007; HUTR on February 16, 2007; and BAND on July 13–14, 2007. No scoping session has been held for VALL.

Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. As of 2021, GRI reports have been completed for AZRU, BAND, CHCU, ELMA, ELMO, GLCA, GRCA, MEVE, NAVA, PEFO, PETR, RABR, SAPU, SUCR, WACA, WUPA, and YUHO. The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). Additional information regarding the GRI, including contact information, is available at https://www.nps.gov/subjects/geology/gri.htm.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the SCPN parks follows the selected source maps and includes components such as: faults, mine area features, mine point features, geologic contacts, geologic units (bedrock, surficial, glacial), geologic line features, structure contours, and so forth. These are commonly acceptable geologic features to include in a geologic map.

Posters display the data over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at, or beneath the land surface (Evans 2016). Color and sometimes symbols on geologic maps are used to distinguish geologic map units. The unit labels consist of an uppercase letter (or symbol for some ages) indicating the geologic age and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website (https://www.americangeosciences.org/environment/publications/mapping) and work by Bernknopf et al. (1993) provide more information about geologic maps and their uses.

Geologic maps are typically one of three types: surficial, bedrock, or a combination of both. Surficial geologic maps typically encompass deposits that are unconsolidated and which formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated, sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type, geologic processes, and/or depositional environment. GRI has produced various maps for the SCPN parks.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are typically included in a master geology document (PDF) for a specific park. The GRI team uses a unique "GMAP ID" value for each geologic source map, and all sources to produce the GRI GIS data sets for the SCPN parks can be found in Appendix A.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The most recent GRI GIS data for NAVA, PEFO, and WACA was compiled using data model version 2.3, which is available at https://www.nps.gov/articles/gri-geodatabase-model.htm; the AZRU, BAND, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, HUTR, MEVE, PETR, RABR, SAPU, SUCR, WUPA, and YUHO data are based on older data models and need to be upgraded to the most recent version. Digital GRI mapping of VALL has not yet been completed. The data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI website (https://www.nps.gov/subjects/geology/gri.htm) provides more information about the program's products.

GRI GIS data are available on the GRI publications website (https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm) and through the NPS Integrated Resource Management Applications (IRMA) Data Store portal (https://irma.nps.gov/DataStore/Search/Quick). Enter "GRI" as the search text and select AZRU, BAND, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, HUTR, MEVE, NAVA, PEFO, PETR, RABR, SAPU, SUCR, VALL, WACA, WUPA, or YUHO from the unit list.

The following components are part of the data set:

- A GIS readme file that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology;
- Federal Geographic Data Committee (FGDC)-compliant metadata;
- An ancillary map information document that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- ESRI map documents that display the GRI GIS data; and
- A version of the data viewable in Google Earth (.kml / .kmz file).

GRI Map Posters

Posters of the GRI GIS draped over shaded relief images of the park and surrounding area are included in GRI reports. Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the posters. Based on the source map scales (1:100,000, 1:62,500, and 1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 51 m (167 ft), 32 m (104 ft), and 12 m (40 ft), respectively, of their true locations.

Methods

Described here are the methods employed and definitions adopted during this inventory of geologic type sections located within the administrative boundaries of the parks in the SCPN. This report is part of an inventory of geologic type sections throughout the National Park System. Therefore, the methods, definitions, and challenges identified here pertain not only to the parks of the SCPN, but also to other inventory and monitoring networks and parks.

There are several considerations for this inventory. The most up-to-date information available is necessary, either found online or in published articles and maps. Occasionally, there is a lack of specific information which limits the information contained within the final report. This inventory does not include any field work and is dependent on the existing information related to individual park geology and stratigraphy. Additionally, this inventory does not attempt to resolve any unresolved or controversial stratigraphic interpretations, which is beyond the scope of the project.

Stratigraphic nomenclature may change over time with refined stratigraphic field assessments and discovery of information through the expansion of stratigraphic mapping and measured sections. One important observation regarding stratigraphic nomenclature relates to differences in use of geologic names for units which transcend state boundaries. Geologic formations and other units which cross state boundaries may be referenced with different names in each of the states the units are mapped. An example would be the Triassic Chugwater Formation in Wyoming, which is equivalent to the Spearfish Formation in the Black Hills of South Dakota and Wyoming.

The lack of a designated and formal type section, or inadequate and vague geospatial information associated with a type section, limits the ability to capture precise information for this inventory. The available information related to the geologic type sections is included in this report.

Finally, this inventory report is intended for a wide audience, including NPS staff who may not have a background in geology. Therefore, this document is developed as a reference document that supports science, resource management, and a historic framework for geologic information associated with NPS areas.

Methodology

The process of determining whether a specific stratotype occurs in an NPS area involves multiple steps. The process begins with an evaluation of the existing park-specific GRI map to prepare a full list of recognized map units (Figure 3).

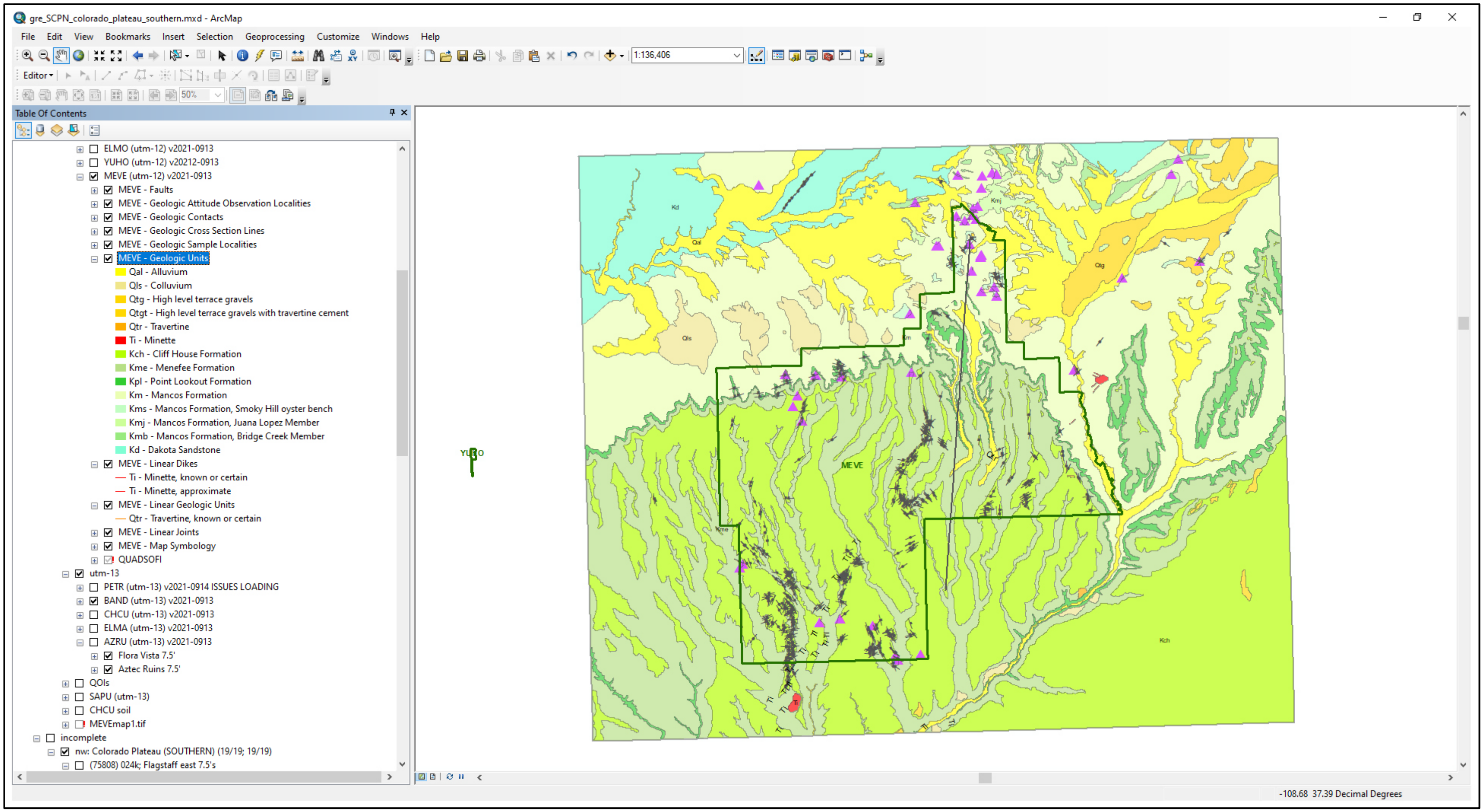


Figure 3. Screenshot of digital geologic map of Mesa Verde National Park showing mapped units.

Each map unit name is then queried in the USGS Geologic Names Lexicon online database ("GEOLEX", a national compilation of names and descriptions of geologic units) at https://ngmdb.usgs.gov/Geolex/search. Information provided by GEOLEX includes unit name, stratigraphic nomenclature usage, geologic age, and published stratotype location descriptions, and the database provides a link to significant publications as well as the USGS Geologic Names Committee Archives (Wilmarth 1938; Keroher et al. 1966). Figure 4 below is taken from a search on the Gunsight Butte Member of the Entrada Sandstone of the San Rafael Group.

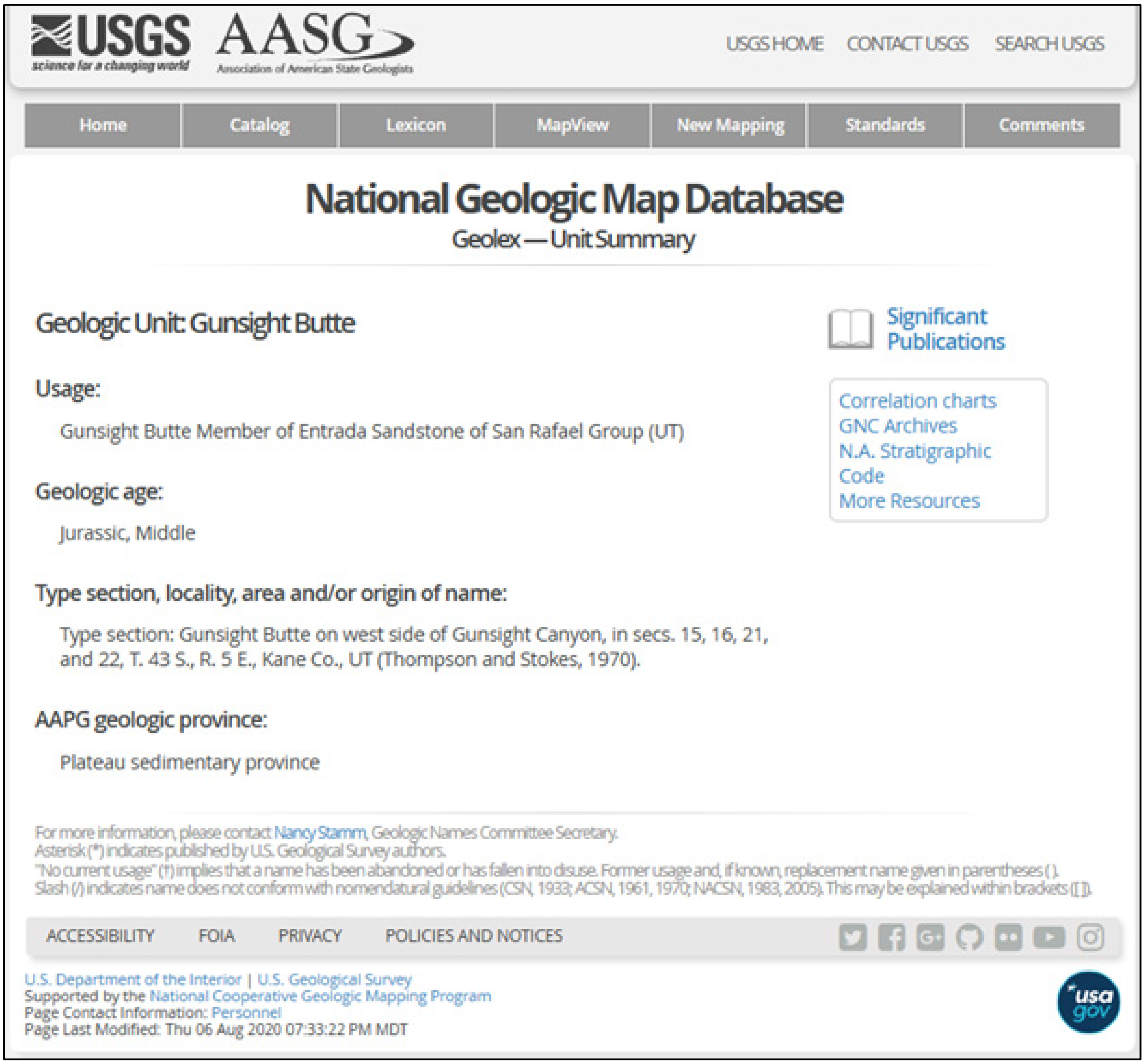
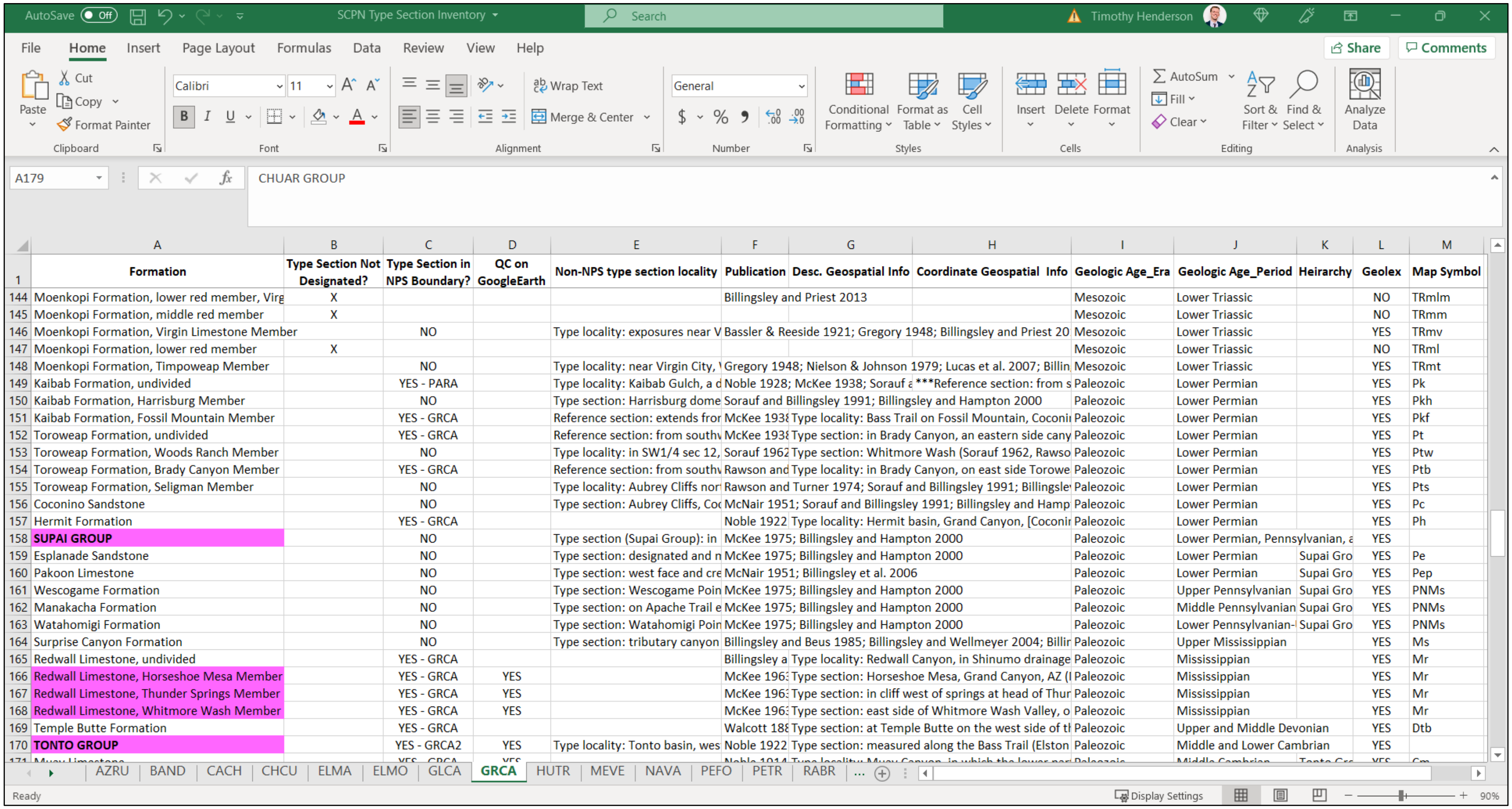


Figure 4. GEOLEX search result for the Gunsight Butte Member.

Published GEOLEX stratotype spatial information is provided in three formats: (1) descriptive, using distance from nearby points of interest; (2) latitude and longitude coordinates; or (3) Township/Range/Section (TRS) coordinates. TRS coordinates are based upon subdivisions of a single 93.2 km^2 (36 mi^2) township into 36 individual 2.59 km^2 (1 mi^2) sections, and were converted into Google Earth (.kmz file) locations using Earth Point (https://www.earthpoint.us/TownshipsSearchByDescription.aspx). They are typically presented in an abbreviated format such as "sec. [#], T. [#] [N. or S.], R. [#] [E. or W.]". The most accurate GEOLEX descriptions using TRS coordinates can help locate features within 0.1618 km^2 (0.0625 mi^2). Once stratotype locality information provided for a given unit is geolocated using Google Earth, a GRI digital geologic map of the national park is draped over it. This step serves two functions: to improve accuracy in locating the stratotype, and validating the geologic polygon for agreement with GEOLEX nomenclature. Geolocations in Google Earth are then converted into an ArcGIS format using a "KML to Layer" conversion tool in ArcMap.

Upon accurately identifying the stratotypes, a Microsoft Excel spreadsheet is populated with information pertinent to the geologic unit and its stratotype attributes. Attribute data recorded in this way include: (1) whether a stratotype is officially designated; (2) whether the stratotype is on NPS land; (3) whether the stratotype location has undergone a quality control check in Google Earth; (4) reference of the publication citing the stratotype; (5) description of geospatial information; (6) coordinates of geospatial information; (7) geologic age (era, period, epoch, etc.); (8) hierarchy of nomenclature (supergroup, group, formation, member, bed, etc.); (9) whether the geologic unit was listed in GEOLEX; and (10) a generic notes field (Figure 5).



	Formation	Type Section Not Designated?	Type Section in NPS Boundary?	QC on GoogleEarth	Non-NPS type section locality	Publication	Desc. Geospatial Info	Coordinate Geospatial Info	Geologic Age_Era	Geologic Age_Period	Heirarchy	Geolex	Map Symbol
144	Moenkopi Formation, lower red member, Virg	X				Billingsley and Priest 2013			Mesozoic	Lower Triassic		NO	TRmlm
145	Moenkopi Formation, middle red member	X							Mesozoic	Lower Triassic		NO	TRmm
146	Moenkopi Formation, Virgin Limestone Member		NO		Type locality: exposures near V	Bassler & Reeside 1921; Gregory 1948; Billingsley and Priest 20			Mesozoic	Lower Triassic		YES	TRmv
147	Moenkopi Formation, lower red member	X							Mesozoic	Lower Triassic		NO	TRml
148	Moenkopi Formation, Timpoweap Member		NO		Type locality: near Virgin City, \	Gregory 1948; Nielson & Johnson 1979; Lucas et al. 2007; Billin			Mesozoic	Lower Triassic		YES	TRmt
149	Kaibab Formation, undivided		YES - PARA		Type locality: Kaibab Gulch, a d	Noble 1928; McKee 1938; Sorauf a		***Reference section: from s	Paleozoic	Lower Permian		YES	Pk
150	Kaibab Formation, Harrisburg Member		NO		Type section: Harrisburg dome	Sorauf and Billingsley 1991; Billingsley and Hampton 2000			Paleozoic	Lower Permian		YES	Pkh
151	Kaibab Formation, Fossil Mountain Member		YES - GRCA		Reference section: extends fror	McKee 1938	Type locality: Bass Trail on Fossil Mountain, Coconi		Paleozoic	Lower Permian		YES	Pkf
152	Toroweap Formation, undivided		YES - GRCA		Reference section: from southv	McKee 1938	Type section: in Brady Canyon, an eastern side cany		Paleozoic	Lower Permian		YES	Pt
153	Toroweap Formation, Woods Ranch Member		NO		Type locality: in SW1/4 sec 12,	Sorauf 1962	Type section: Whitmore Wash (Sorauf 1962, Rawso		Paleozoic	Lower Permian		YES	Ptw
154	Toroweap Formation, Brady Canyon Member		YES - GRCA		Reference section: from southv	Rawson and	Type locality: in Brady Canyon, on east side Torowe		Paleozoic	Lower Permian		YES	Ptb
155	Toroweap Formation, Seligman Member		NO		Type locality: Aubrey Cliffs nor	Rawson and Turner 1974; Sorauf and Billingsley 1991; Billingsle			Paleozoic	Lower Permian		YES	Pts
156	Coconino Sandstone		NO		Type section: Aubrey Cliffs, Coc	McNair 1951; Sorauf and Billingsley 1991; Billingsley and Hamp			Paleozoic	Lower Permian		YES	Pc
157	Hermit Formation		YES - GRCA			Noble 1922	Type locality: Hermit basin, Grand Canyon, [Coconi		Paleozoic	Lower Permian		YES	Ph
158	**SUPAI GROUP**		NO		Type section (Supai Group): in	McKee 1975; Billingsley and Hampton 2000			Paleozoic	Lower Permian, Pennsylvanian, a		YES	
159	Esplanade Sandstone		NO		Type section: designated and n	McKee 1975; Billingsley and Hampton 2000			Paleozoic	Lower Permian	Supai Gro	YES	Pe
160	Pakoon Limestone		NO		Type section: west face and cre	McNair 1951; Billingsley et al. 2006			Paleozoic	Lower Permian	Supai Gro	YES	Pep
161	Wescogame Formation		NO		Type section: Wescogame Poin	McKee 1975; Billingsley and Hampton 2000			Paleozoic	Upper Pennsylvanian	Supai Gro	YES	PNMs
162	Manakacha Formation		NO		Type section: on Apache Trail e	McKee 1975; Billingsley and Hampton 2000			Paleozoic	Middle Pennsylvanian	Supai Gro	YES	PNMs
163	Watahomigi Formation		NO		Type section: Watahomigi Poin	McKee 1975; Billingsley and Hampton 2000			Paleozoic	Lower Pennsylvanian-	Supai Gro	YES	PNMs
164	Surprise Canyon Formation		NO		Type section: tributary canyon	Billingsley and Beus 1985; Billingsley and Wellmeyer 2004; Billir			Paleozoic	Upper Mississippian		YES	Ms
165	Redwall Limestone, undivided		YES - GRCA			Billingsley a	Type locality: Redwall Canyon, in Shinumo drainage		Paleozoic	Mississippian		YES	Mr
166	Redwall Limestone, Horseshoe Mesa Member		YES - GRCA	YES		McKee 1963	Type section: Horseshoe Mesa, Grand Canyon, AZ (I		Paleozoic	Mississippian		YES	Mr
167	Redwall Limestone, Thunder Springs Member		YES - GRCA	YES		McKee 1963	Type section: in cliff west of springs at head of Thur		Paleozoic	Mississippian		YES	Mr
168	Redwall Limestone, Whitmore Wash Member		YES - GRCA	YES		McKee 1963	Type section: east side of Whitmore Wash Valley, o		Paleozoic	Mississippian		YES	Mr
169	Temple Butte Formation		YES - GRCA			Walcott 188	Type section: at Temple Butte on the west side of tl		Paleozoic	Upper and Middle Devonian		YES	Dtb
170	**TONTO GROUP**		YES - GRCA2	YES	Type locality: Tonto basin, wes	Noble 1922	Type section: measured along the Bass Trail (Elston		Paleozoic	Middle and Lower Cambrian		YES	

Figure 5. Stratotype inventory spreadsheet of the SCPN displaying attributes appropriate for geolocation assessment. Purple highlighted cells represent geologic units supplemented to the GRI map unit listing.

Definitions

In order to clarify, standardize, and consistently reference stratigraphic concepts, principles, and definitions, the North American Stratigraphic Code is recognized and adopted for this inventory. This code seeks to describe explicit practices for classifying and naming all formally defined geologic units. An important designation for a geologic unit is known as a ***stratotype***–the standard exposure (original or subsequently designated) for a named geologic unit or boundary and constitutes the basis for definition or recognition of that unit or boundary (North American Commission on Stratigraphic Nomenclature 2021). There are several variations of stratotype referred to in the literature and this report, and they are defined as follows:

1) **Unit stratotype**: the **type section** for a stratified deposit or the **type area** for a non-stratified body that serves as the standard for recognition and definition of a geologic unit (North American Commission on Stratigraphic Nomenclature 2021). Once a unit stratotype is assigned, it is never changed (unless the unit is abandoned). The term "unit stratotype" is commonly referred to as "type section" and "type area" in this report.

2) **Type locality**: the specific geographic locality encompassing the unit stratotype of a formally recognized and defined unit. On a broader scale, a type area is the geographic territory encompassing the type locality. Before development of the stratotype concept, only type localities and type areas were designated for many geologic units that are now long- and well-established (North American Commission on Stratigraphic Nomenclature 2021).

3) **Reference sections**: for well-established geologic units for which a type section was never assigned, a reference section may serve as an invaluable standard in definitions or revisions. A principal reference section may also be designated for units whose stratotypes have been destroyed, covered, or are otherwise inaccessible (North American Commission on Stratigraphic Nomenclature 2021). Multiple reference sections can be designated for a single unit to help illustrate heterogeneity or some critical feature not found in the stratotype. Reference sections can help supplement unit stratotypes in the case where the stratotype proves inadequate (North American Commission on Stratigraphic Nomenclature 2021).

4) **Lithodeme**: the term "lithodeme" is defined as a mappable unit of plutonic (igneous rock that solidified at great depth) or highly metamorphosed and pervasively deformed rock and is a term equivalent in rank to "formation" among stratified rocks (North American Commission on Stratigraphic Nomenclature 2021). The formal name of a lithodeme consists of a geographic name followed by a descriptive term that denotes the average modal composition of the rock (example: Cathedral Peak Granodiorite). Lithodemes are commonly assigned type localities, type areas, and reference localities.

Aztec Ruins National Monument (AZRU)

Aztec Ruins National Monument (AZRU) is located along the banks of the Animas River in San Juan County, northwestern New Mexico (Figure 6). Established on January 24, 1923, AZRU encompasses approximately 129 hectares (318 acres) and protects some of the best-preserved monumental great house architecture in the Southwest (National Park Service 2016a). Architectural remains of a 1100–1300 CE Ancestral Puebloan community have been partially excavated and stabilized, providing opportunities for greater understanding of the evolution of Chacoan culture. The national monument has a symmetrical layout that protects the core of an expansive ceremonial center that contains remnant buildings, roads, earthworks, and kivas (circular rooms used by Puebloans for rites and political meetings) with original intact masonry, wooden roofs, and tri-wall structures. The largest structure in AZRU is the West Ruin, a three-story plaza consisting of at least 400 contiguous rooms and numerous kivas, including the Great Kiva. The pioneering excavation and reconstruction efforts of Earl Morris between 1916 and 1934 made the Great Kiva internationally famous. The number, variety, and scale of the structures concentrated in AZRU are internationally recognized, and the monument was designated a World Heritage Site on December 8, 1987.

The geology of Aztec Ruins National Monument consists of Cenozoic-age rocks that include the Paleocene Nacimiento Formation, Pleistocene terrace and pediment deposits, and Holocene Naha and Tsegi Alluviums (Figure 7). The Nacimiento Formation forms a major portion of the underlying bedrock of AZRU and consists of sandstone, siltstone, shale, and claystone that were deposited in ancient floodplains, river channels, swamps, and lakes (Williamson 1996). Sediments of the Nacimiento Formation were shed from the San Juan and Brazos–Sangre de Cristo uplifts to the north and east of AZRU during the Laramide Orogeny (KellerLynn 2016). Ancestral Puebloans utilized blocks of the Nacimiento Formation for building stone, but also used materials deposited by the Animas River that range in size from cobbles (used in structural foundations) to silt (used for mortar). Unconsolidated deposits of the Naha Alluvium and Tsegi Alluvium are mapped in the western portion of AZRU and consist of gravel, sand and silt that were sourced from the uplifted central core of the San Juan Mountains located 32–80 km (20–50 mi) north of the San Juan Basin (Scott and Moore 2007).

There are no designated stratotypes identified within the boundaries of AZRU. There is one identified stratotype located within 48 km (30 mi) of AZRU boundaries, for the Eocene Ditch Canyon Member of the San Jose Formation (type section).

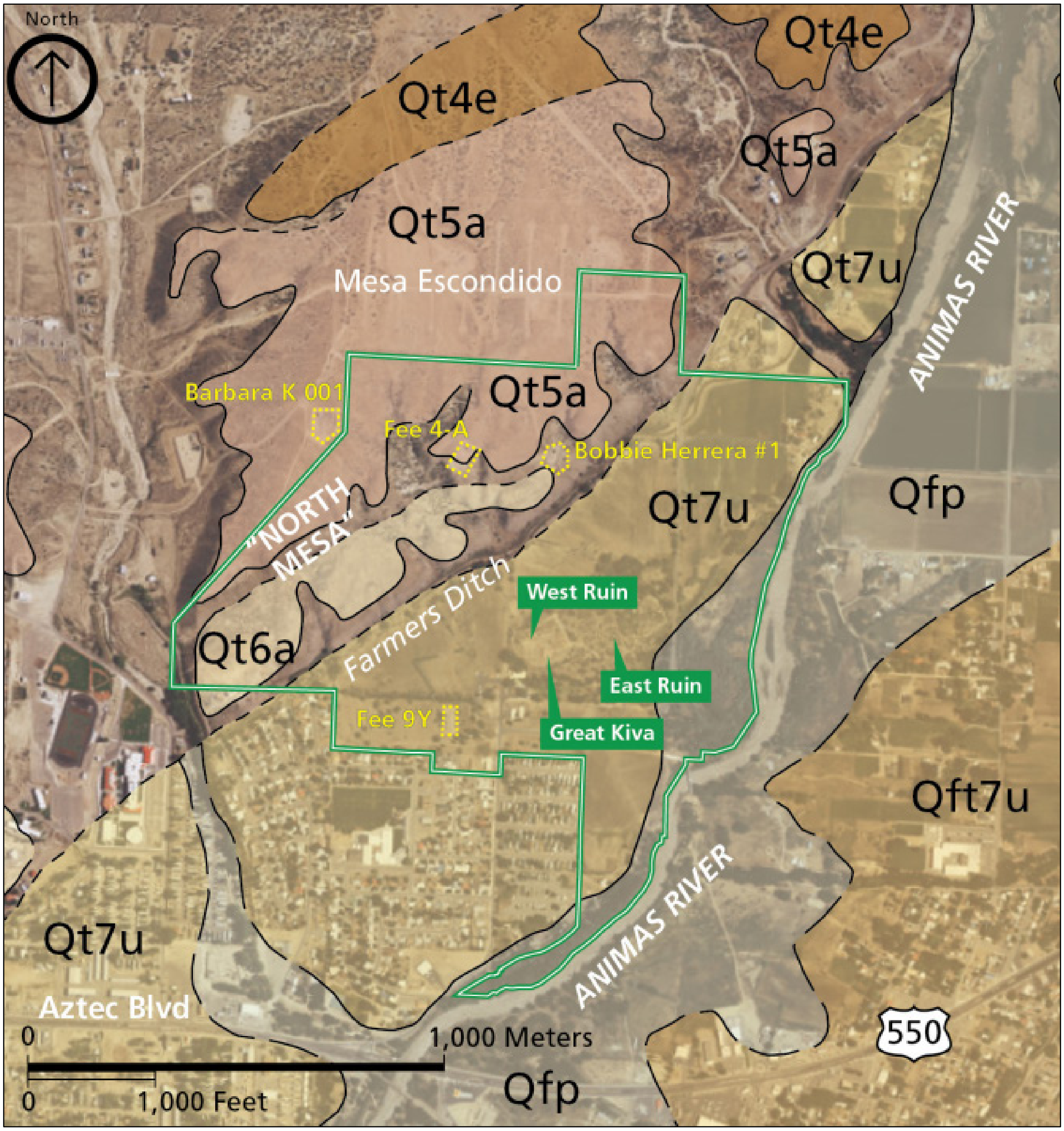


Figure 6. Satellite imagery park map of AZRU, New Mexico showing major geologic features and mapped units (NPS).

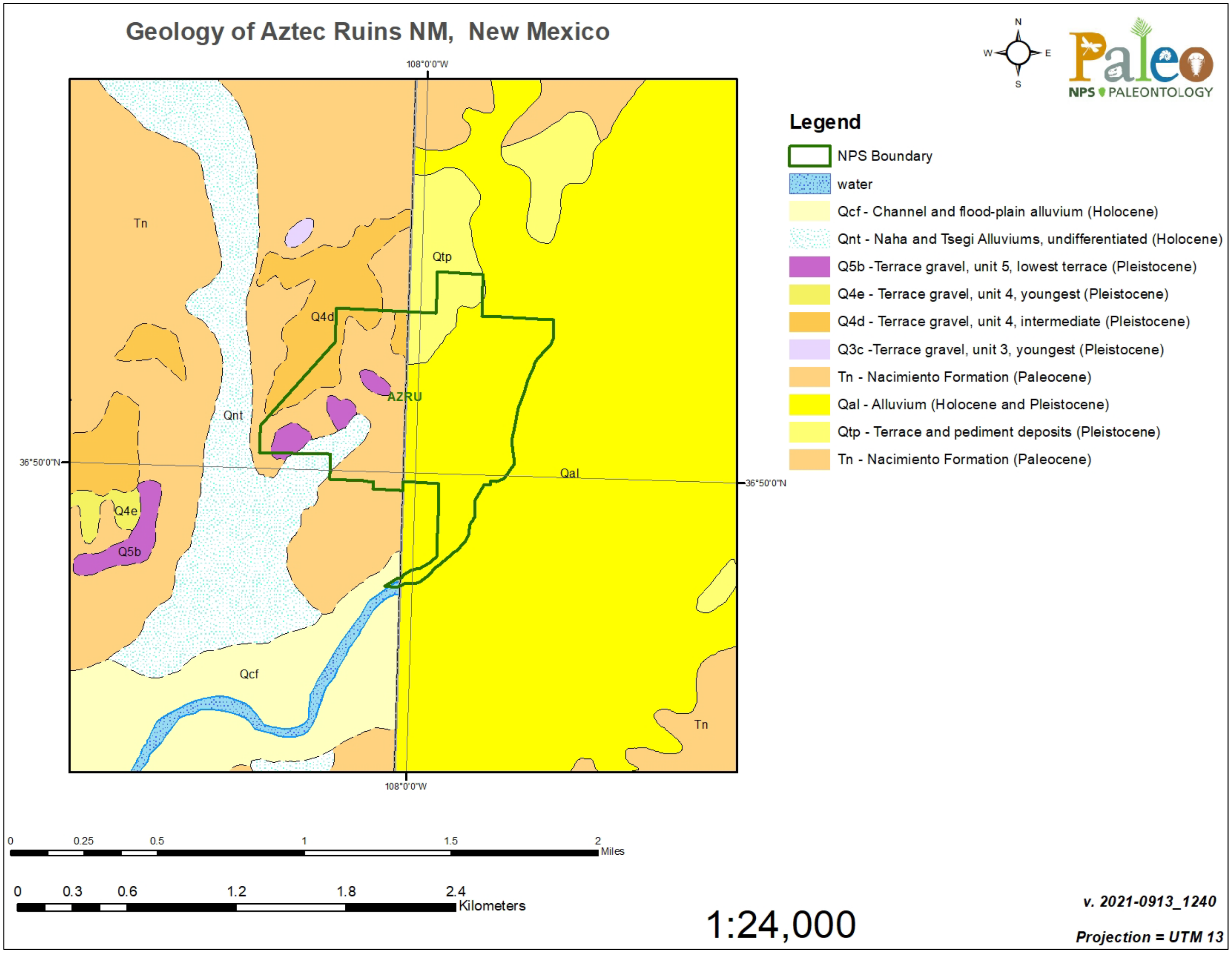


Figure 7. Geologic map of AZRU, New Mexico.

Bandelier National Monument (BAND)

Bandelier National Monument (BAND) is located on the southern Pajarito Plateau in Los Alamos, Sandoval, and Santa Fe Counties, New Mexico (Figure 8). Established on February 11, 1916, BAND encompasses about 13,665 hectares (33,677 acres) and protects one of the largest concentrations of Ancestral Pueblo archeological sites in the American Southwest (National Park Service 2016a). The mesa tops and canyon walls of the Pajarito Plateau contain more than 3,000 sites and include Pueblo cliff houses, villages, and small farming hamlets dating from 1100 to 1550 CE. The cliff houses represent a unique architectural form called "cavates", which have been carved out of the soft volcanic tuff bedrock. Major sites within BAND include Frijolito, Yapashi, Tyuonyi, Long House, San Miguel, Painted Cave, and Tsankawi. Bandelier National Monument is named after Adolph F. Bandelier, a pioneer in the study of Southwest history and ethnology who was the first person to record the existence of the major archeological sites in the BAND area (National Park Service 2015a).

Bandelier National Monument hosts an assemblage of volcanic rocks and features that have made the monument a popular destination for geologists and volcanologists. The bedrock geology of the monument is dominated by the extensive Pleistocene Bandelier Tuff, a premier example of an ash-flow tuff that represents caldera-forming eruptions on a scale that has never been witnessed by humans (Figures 9 and 10; Dunbar 2005). The Bandelier Tuff is subdivided into three members (La Cueva, Otowi, and Tshirege Members), of which the Tshirege Member forms a major portion of the monument landscape and makes up the mesas and canyon walls (KellerLynn 2015a). Preferential weathering and erosion of the Tshirege Member has produced holes in some of the cliffs, some of which were enlarged for living and storage by the Ancestral Puebloans. The presence of the notable cliff dwellings is intimately tied to the soft friable nature of the Bandelier Tuff. Mapped units throughout BAND can be broken down into three major groups of rocks: the Miocene–Pliocene Keres Group (Paliza Canyon and Tschicoma Formations), the Pleistocene Tewa Group (Valles Rhyolite, Cerro Toledo Formation, and Bandelier Tuff), and the Miocene–Pleistocene Santa Fe Group (Tesuque, Chamita, and Cochiti Formations). The Keres Group represents the older pre-caldera portion of the Jemez Mountains volcanic field and consists of domes, flows, and tuffs that started erupting about 14 million years ago (Gardner et al. 2010). The Tewa Group represents the Valles–Toledo caldera complex that produced the Bandelier Tuff, Cerro Toledo Formation, and Valles Rhyolite between ~1.85 million to 40,000 years ago, and also includes rhyolite domes, lava flows, pyroclastic flows, fallout tephras, and a variety of volcaniclastic deposits (Gardner et al. 2010).

Bandelier National Monument contains four identified stratotypes that represent the Pleistocene Tshirege Member of the Bandelier Tuff, Tsankawi Pumice Bed of the Tshirege Member, and Alamo Canyon Member of the Cerro Toledo Formation (Table 2; Figure 11).

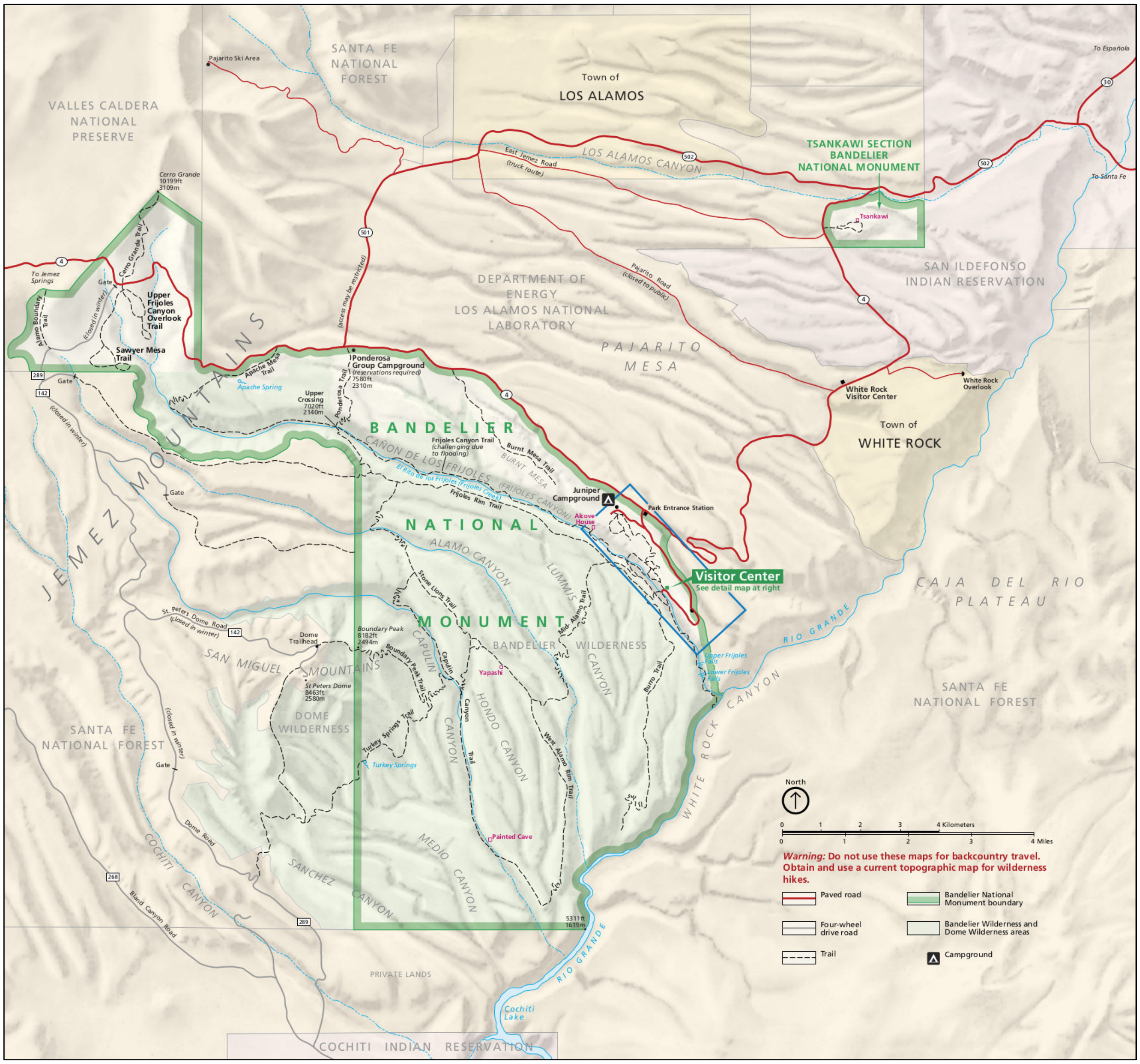


Figure 8. Park map of BAND, New Mexico (NPS).

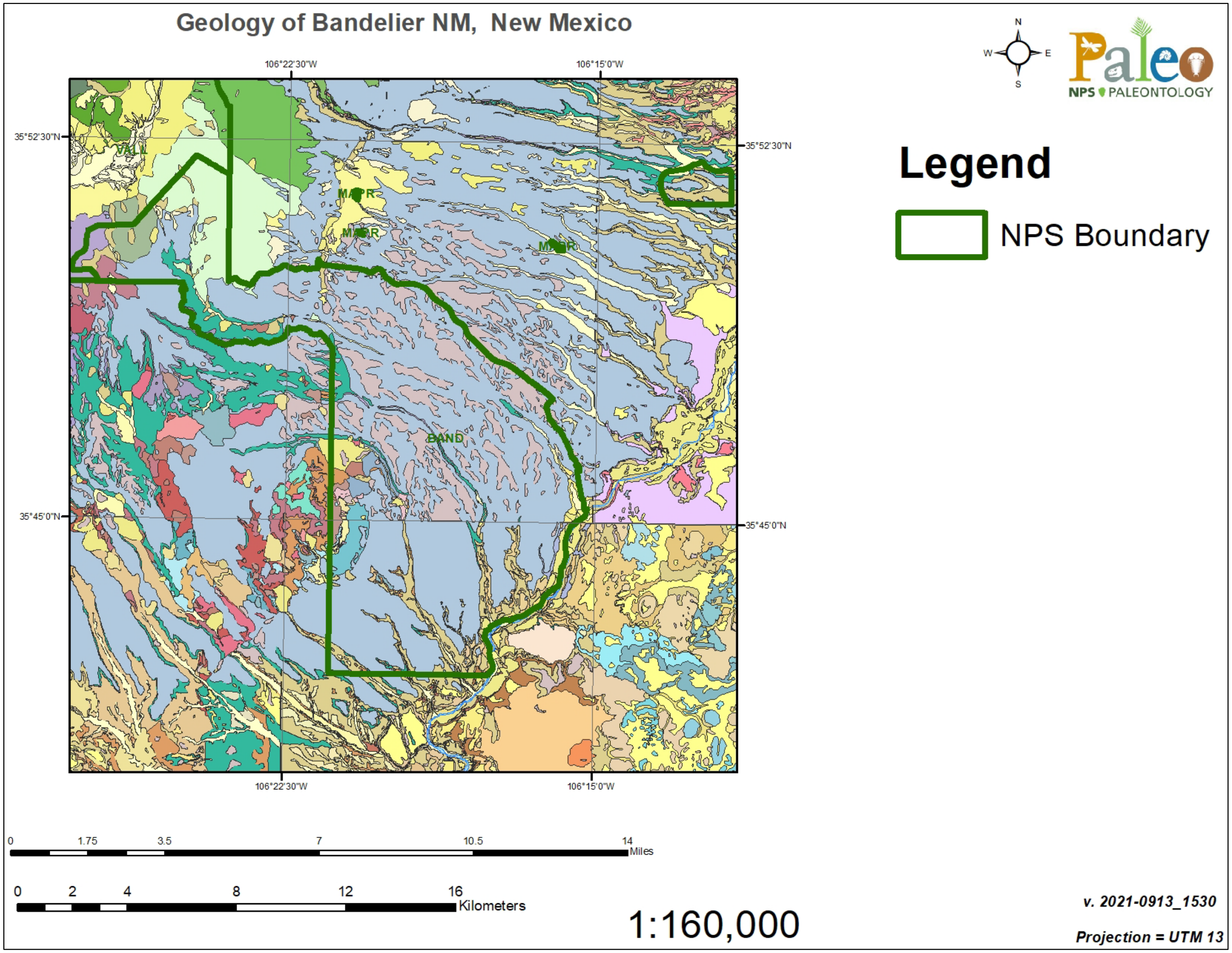


Figure 9. Geologic map of BAND, New Mexico; see Figure 10 for legend.

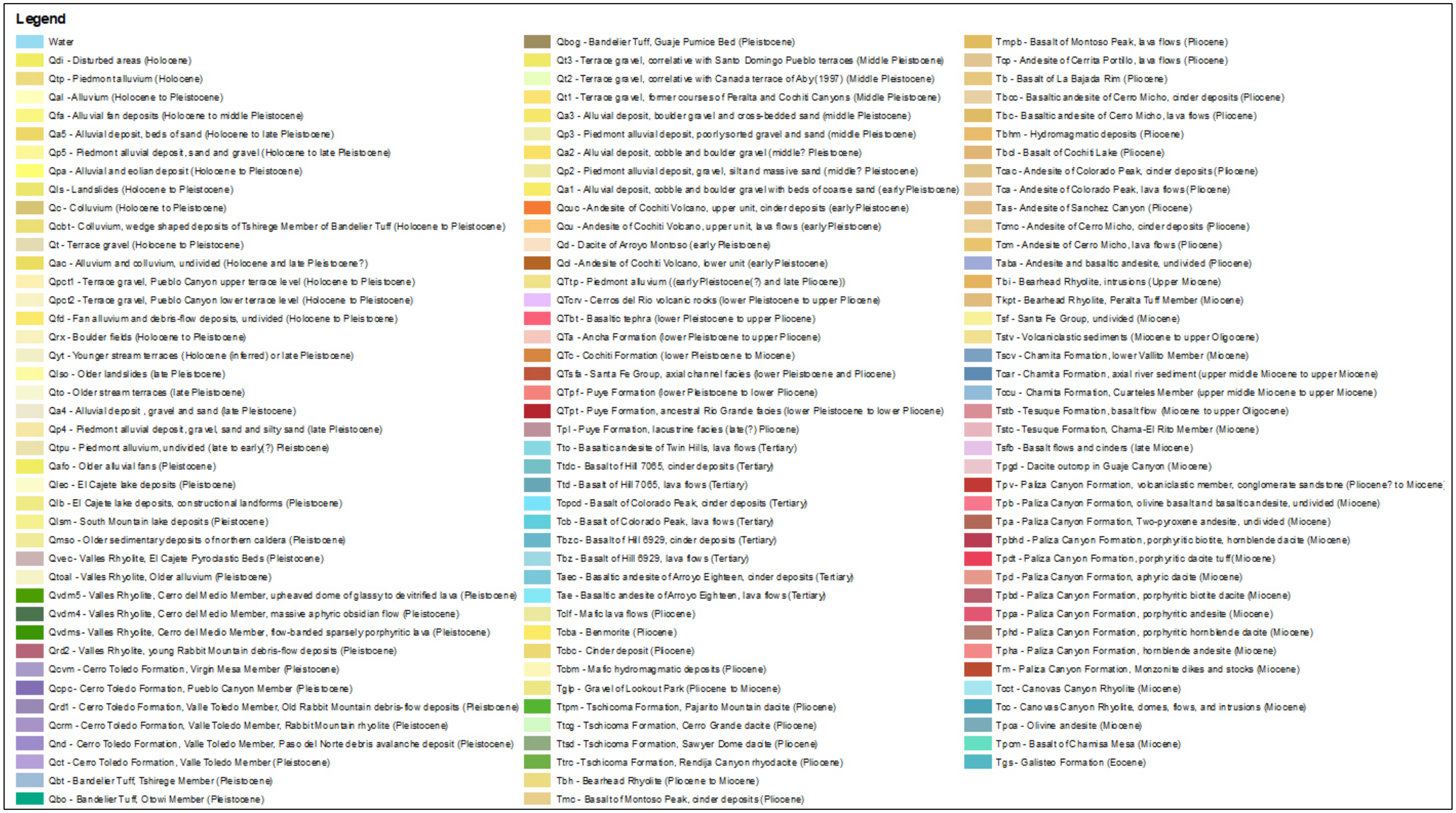


Figure 10. Geologic map legend of BAND, New Mexico.

Table 2. List of BAND stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Alamo Canyon Member, Cerro Toledo Formation	Jacobs and Kelley 2007; Gardner et al. 2010	Type section: in Alamo Canyon from the north side of the canyon at Alamo bend on the southeastern Pajarito Plateau, Sandoval Co., NM.	Pleistocene
Tshirege Member, Bandelier Tuff (Qbt)	Griggs and Hem 1964	Type area: Pajarito Plateau and adjacent lower slopes of the Sierra de los Valles, Los Alamos area, Sandoval Co., NM.	Pleistocene
Tsankawi Pumice Bed, Tshirege Member, Bandelier Tuff	Bailey et al. 1969	Type locality: in vicinity of Tsankawi ruin on Pajarito Plateau [Espanola 15′ Quadrangle], Santa Fe Co., NM. Type area: along south side of Tsankawi Mesa, in secs. 20 and 21, T. 19 N., R. 7 E. [White Rock 7.5′ Quadrangle]; along East Jemez Road in Sandia Canyon, in center of sec. 24, T. 19 N., R. 6 E. [Frijoles 7.5′ Quadrangle, 1984 ed.]; and in roadcuts along NM Route 4 where it crosses Potrillo and Ancho Canyons, [White Rock and Frijoles 7.5′ Quadrangles], Los Alamos and Santa Fe Cos., NM.	Pleistocene

In addition to the designated stratotypes located within BAND, stratotypes located within 48 km (30 mi) of the monument’s boundaries include the Permian Yeso Formation (type section), Meseta Blanca Member of the Yeso Formation (type section), and San Ysidro Formation (type section); Cretaceous Juana Lopez Member of the Mancos Shale (type section and reference section); Eocene Galisteo Formation (type section); Miocene Santa Fe Group (type locality), Tesuque Formation (type section), type sections of the Bishops Lodge, Chama-El Rito, Nambe, Pojoaque, and Skull Ridge Members of the Tesuque Formation, Chamita Formation (type section), Cejita Member of the Chamita Formation (type section and reference section), Cuarteles Member of the Chamita Formation (type section and reference section), Hernandez Member of the Chamita Formation (type section), Vallito Member of the Chamita Formation (type section), Chamisa Mesa Member of the Zia Formation (type section), Bearhead Rhyolite (type locality), Canovas Canyon Rhyolite (type locality), Picuda Peak Member of the Arroyo Ojito Formation (type section), and Paliza Canyon Formation (type area); Miocene–Pleistocene Cochiti Formation (type locality); Pliocene Ceja Formation (reference section), Santa Ana Mesa Member of the Ceja Formation (type section), Totavi Lentil of the Puye Conglomerate (type locality), and Lobato Basalt (type area); Pliocene–Pleistocene Ancha Formation (type section) and Puye Formation (type section); and Pleistocene Pueblo Canyon Member of the Cerro Toledo Formation (type section), Virgin Mesa Member of the Cerro Toledo Formation (type area), Battleship Rock Ignimbrite of the Valles Rhyolite (type section), La Cueva Member of the Bandelier Tuff (type locality), Otowi Member of the Bandelier Tuff (type area and type locality), and Guaje Pumice Bed of the Otowi Member of the Bandelier Tuff (type section).

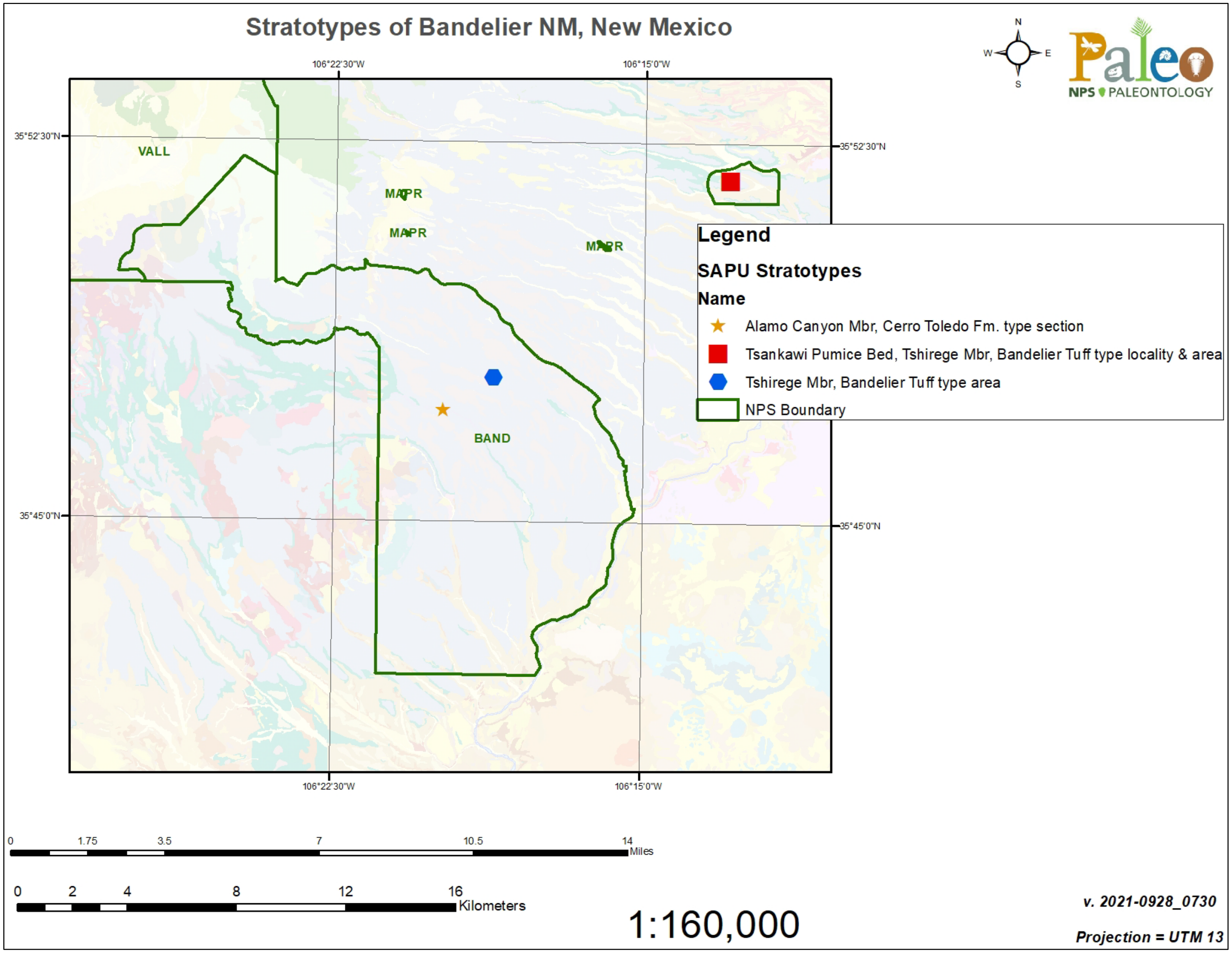


Figure 11. Modified geologic map of BAND showing stratotype locations. The transparency of the geologic units layer has been increased.

The Pleistocene Tshirege Member of the Bandelier Tuff was named by Griggs and Hem (1964) for exposures in the vicinity of the Tshirege ruins where the unit forms a caprock on the Pajarito Plateau. Due to lithologic variations that occur across various localities, Griggs and Hem (1964) designated the type area as the Pajarito Plateau and the adjacent lower slopes of the Sierra de los Valles, New Mexico (Table 2; Figure 11). In the type area, the unit measures approximately 68 m (225 ft) thick and consists of gray- to purplish-gray welded rhyolite tuff containing small fragments of pumice and crystal fragments of sanidine and quartz in a welded ash matrix (Figure 12; Griggs and Hem 1964). Tuffs typically consist of ash-flow deposits with a few thin beds of air-fall pumice in the lower and upper sections. Type area exposures of the Tshirege Member are virtually continuous and show a wide range of welding and devitrification (Griggs and Hem 1964). The Tshirege Member unconformably overlies the Otowi Member of the Bandelier Tuff where it fills eroded channels.

Figure 12. View looking northwest across White Rock Canyon of the Rio Grande at the dissected Pajarito Plateau, type area of the Tshirege Member of the Bandelier Tuff (NPS). The uppermost gray and light brown unit capping the plateau consists of welded rhyolitic tuff of the Tshirege Member.

The Pleistocene Tsankawi Pumice Bed of the Tshirege Member of the Bandelier Tuff was proposed by Bailey et al. (1969) for exposures in the general vicinity of Tsankawi ruin on the Pajarito Plateau, New Mexico. The type locality and type area of the formation are designated along the south side of Tsankawi Mesa, in sections 20 and 21, T. 19 N., R. 7 E. (White Rock 7.5′ Quadrangle); along East Jemez Road in Sandia Canyon, in center of section 24, T. 19 N., R. 6 E. (Frijoles 7.5′ Quadrangle);

and in roadcuts along NM Route 4 where it crosses Potrillo and Ancho Canyons (White Rock and Frijoles 7.5′ Quadrangles) (Table 2; Figures 11 and 13; Bailey et al. 1969). Type area exposures of the Tsankawi Pumice Bed measure from 0.6–1.0 m (2.0–3.5 ft) thick and typically consist of three distinct air fall units: 1) a lower main unit 0.3–0.9 m (1.0–3.0 ft) thick consisting of coarse, crudely bedded ash and pumice lapilli; 2) a thin middle unit 3–5 cm (1–2 in) thick composed of crystal-rich ash; and 3) an upper unit of medium to coarse pumice and ash (Bailey et al. 1969). Typical pumice is rhyolitic in composition, light gray to white in color, with a fibrous structure and silky luster in fresh samples (Bailey et al. 1969). The Tsankawi Pumice Bed overlies the Otowi Member of the Bandelier Tuff and underlies unnamed ash-flows of the Tshirege Member.

Figure 13. Tsankawi Mesa, the type area of the Tsankawi Pumice Bed of the Tshirege Member of the Bandelier Tuff (NPS).

The Pleistocene Alamo Canyon Member of the Cerro Toledo Formation was named by Gardner et al. (2010) after its type section exposure in Alamo Canyon on the southeastern Pajarito Plateau, New Mexico. Located on the north side of the canyon at Alamo Bend, the type section measures about 50 m (164 ft) thick (Table 2; Figure 11; Gardner et al. 2010). The section is composed of a basal fluvial sandy conglomerate, tephra sequence, volcanic breccia, and an upper fluvial sandy conglomerate (Figures 14 and 15; Jacobs and Kelley 2007; Gardner et al. 2010). At the type section, the Alamo Canyon Member underlies the Tsankawi Pumice Bed of the Bandelier Tuff and overlies the Otowi Member of the Bandelier Tuff (Jacobs and Kelley 2007).

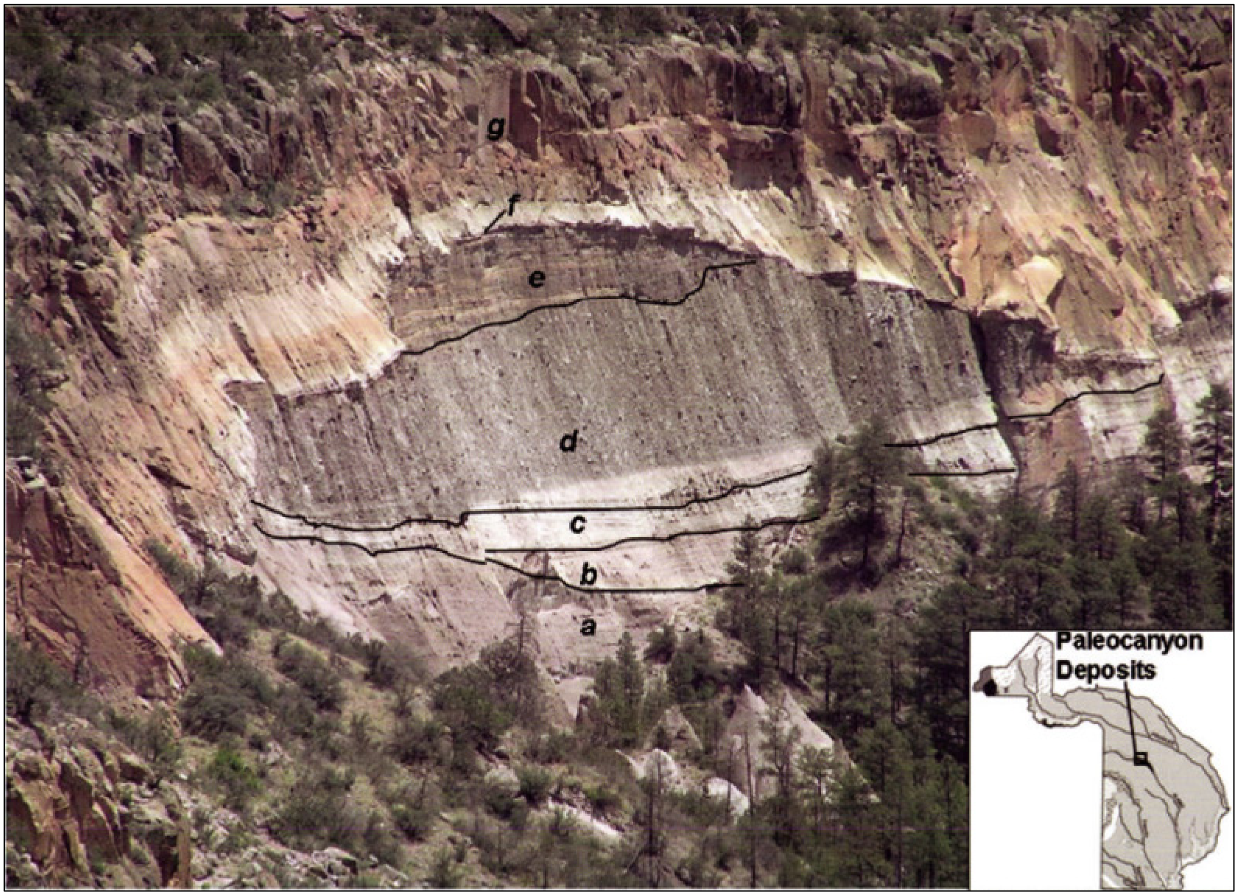


Figure 14. Type section of Cerro Toledo deposits in Alamo Canyon from the north side of the canyon at Alamo Bend. Units are as follows: a, Otowi Member, Bandelier Tuff; b, lower fluvial unit; c, tephra sequence; d, volcanic breccia; e, upper fluvial unit; f, Tsankawi Pumice Bed; g, Tshirege Member, Bandelier Tuff. Units b, c, d, and e constitute the Alamo Canyon Member, Bandelier Tuff. Height of exposure is ~120 m (394 ft). Inset map shows relative location of Alamo Bend. Plate 12 from Jacobs and Kelley (2007) (courtesy of the New Mexico Geological Society).

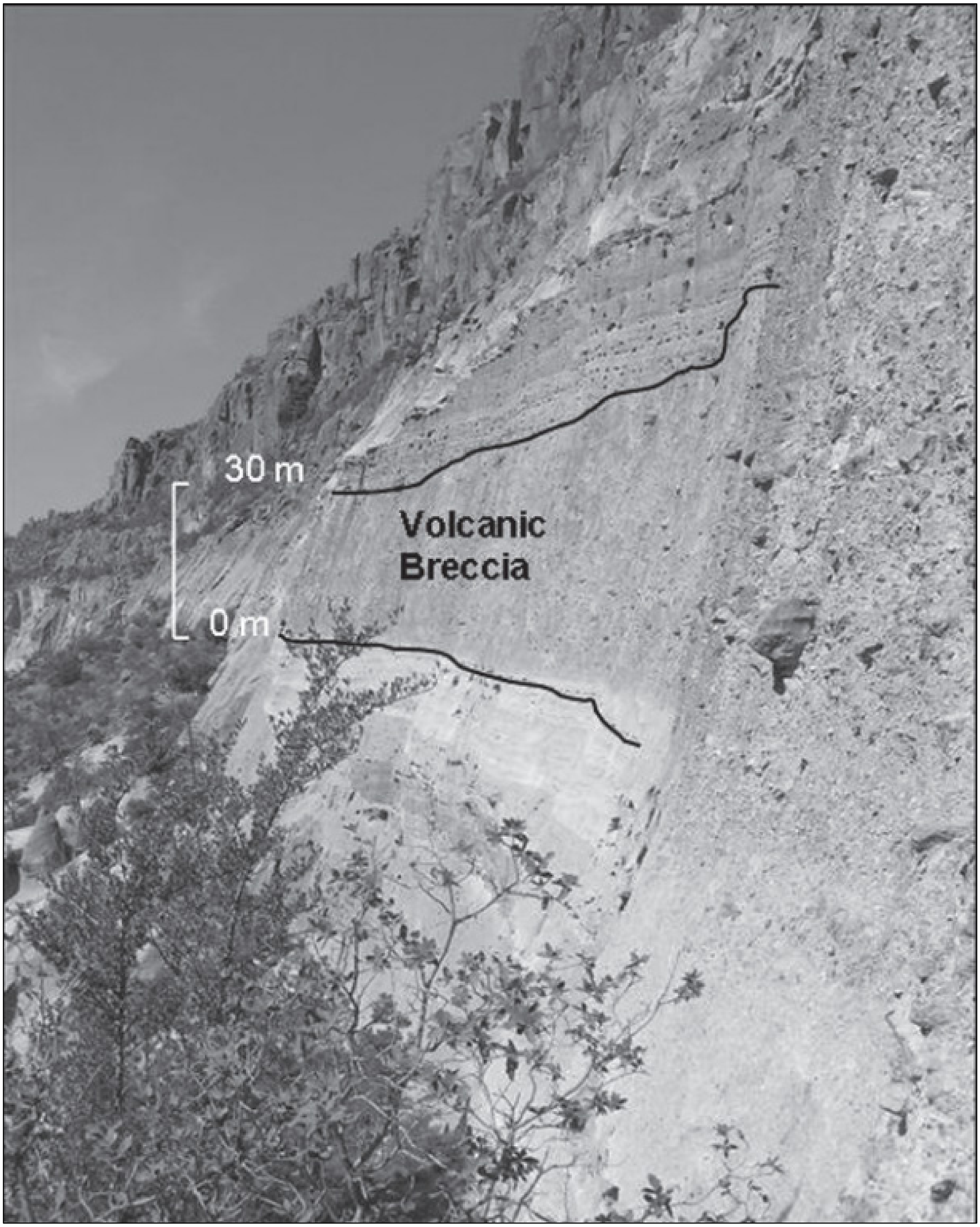


Figure 15. Volcanic breccia at Alamo Bend. Photo was taken on the north side of Alamo Canyon with the view to the northwest (up-canyon). Figure 8 from Jacobs and Kelley (2007) (courtesy of the New Mexico Geological Society).

Canyon De Chelly National Monument (CACH)

Canyon de Chelly National Monument (CACH) is located on Navajo trust land on the outskirts of the town of Chinle in Apache County, northeastern Arizona (Figure 16). Established on February 14, 1931, CACH contains approximately 33,929 hectares (83,840 acres) and preserves one of the longest, continually inhabited American Indian communities in the United States with a history dating back at least 5,000 years (National Park Service 2016a). CACH contains an outstanding collection of archeological and cultural resources that document an occupational history spanning the Archaic through Basketmaker, Ancestral Puebloan, transitional period, historic Navajo and Pueblo, and early European contact (National Park Service 2016a). The canyon system contains alcoves and cliff dwellings that preserve exceptional architecture, as well as one of the largest concentrations of pictographs and petroglyphs in North America.

The geology of CACH is a testament to millions of years of uplift and stream cutting that have exposed the monument's colorful sheer cliff walls. The bedrock of CACH predominantly consists of Paleozoic and Mesozoic sedimentary rocks that have been heavily eroded and incised to form Canyon de Chelly, Canyon del Muerto, and smaller tributary canyons (Figure 17). Units mapped within the national monument include the Pennsylvanian–Permian Supai Formation, Permian Cutler Group, and the Triassic Chinle Formation. The scenic red cliff exposures in CACH consist of the De Chelly Sandstone of the Cutler Group, which rise from the wash to heights of up to 366 m (1,200 ft). Views from the canyon rims look onto spectacular geological features, such as the towering spires of erosion-resistant sandstone and caprock (such as Spider Rock and Face Rock) that stand above the canyon floor (National Park Service 2016b).

Canyon de Chelly National Monument contains three identified stratotypes that represent the early Permian De Chelly Sandstone of the Cutler Group and White House Member of the De Chelly Sandstone, and the Late Triassic Chinle Formation (Table 3; Figure 18). In addition to the designated stratotypes located within CACH, stratotypes located within 48 km (30 mi) of the monument's boundaries include the Permian Fort Defiance Member of the De Chelly Sandstone (type section); Triassic Sonsela Member of the Chinle Formation (type section); Jurassic Lukachukai Member of the Wingate Sandstone (type locality), Rock Point Member of the Wingate Sandstone (type locality), Wanakah Formation (reference section), Beclabito Member of the Wanakah Formation (type section), Horse Mesa Member of the Wanakah Formation (type section), and Todilto Limestone Member of the Wanakah Formation (type locality and reference section); Cretaceous Yale Point Sandstone (type section), Tocito Member of the Gallup Sandstone (type locality), and Crevasse Canyon Formation (type locality); and Oligocene Deza Member of the Chuska Sandstone (type section) and Narbona Pass Member of the Chuska Sandstone (type section).

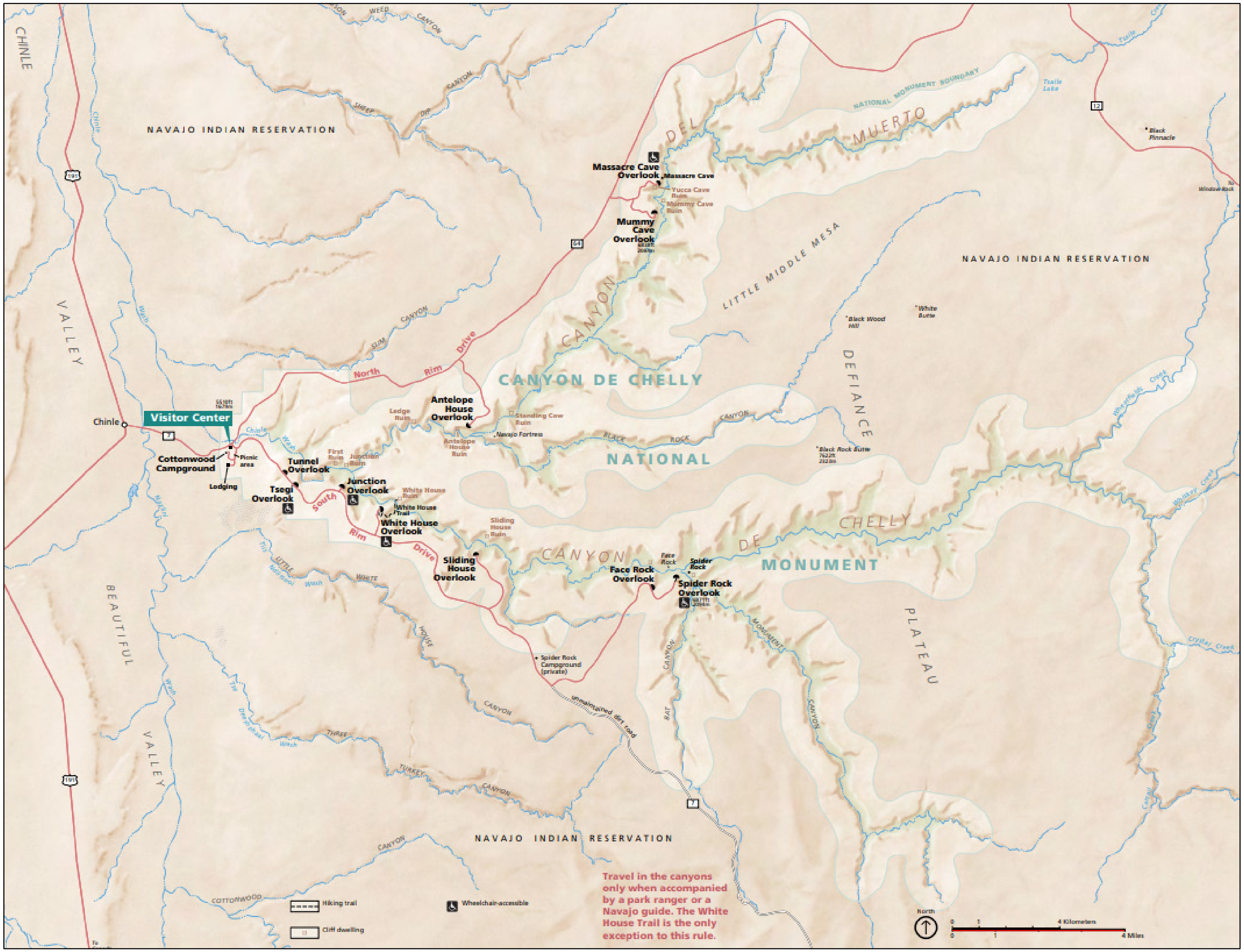


Figure 16. Park map of CACH, Arizona (NPS).

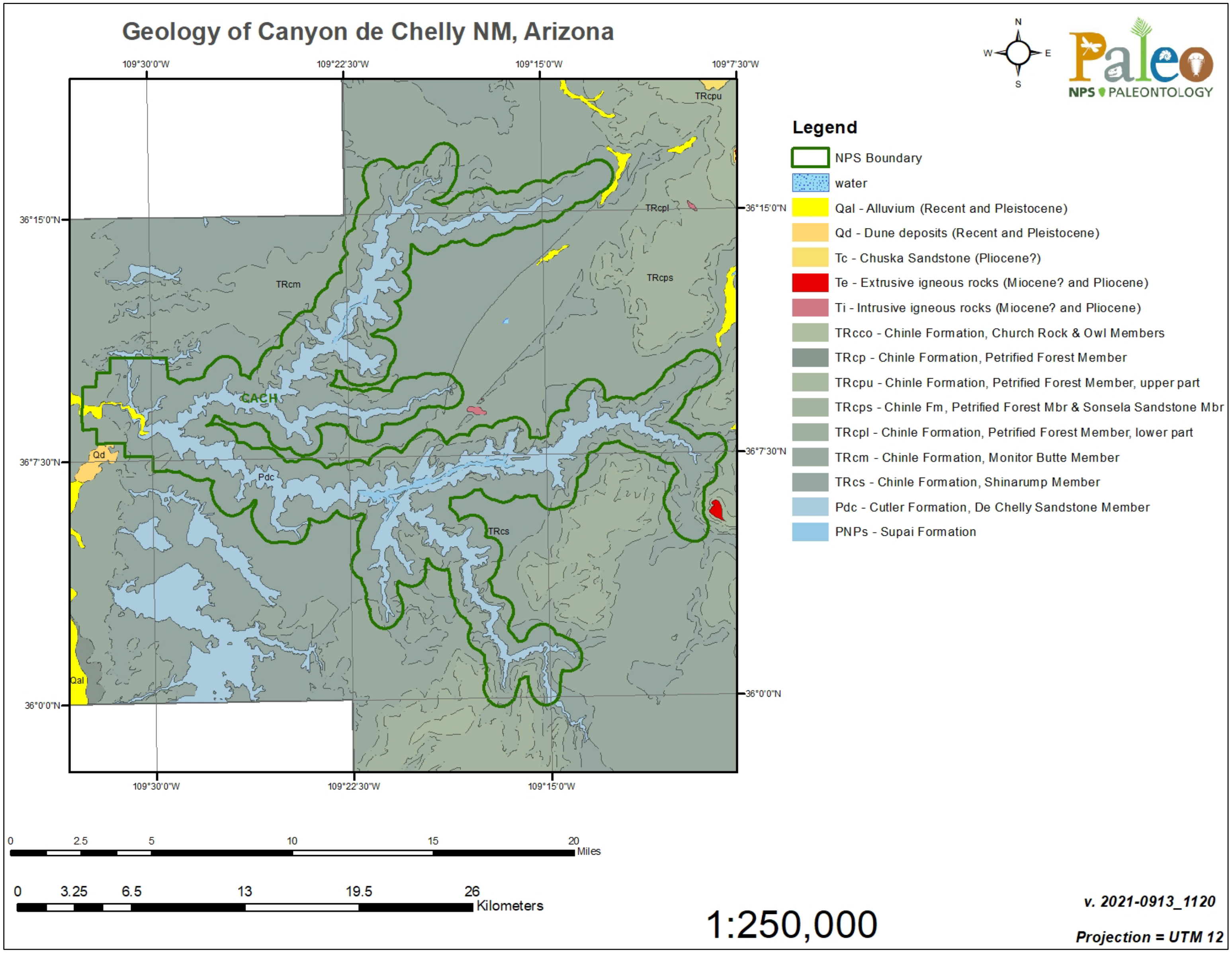


Figure 17. Geologic map of CACH, Arizona.

Table 3. List of CACH stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	**Reference**	**Stratotype Location**	**Age**
Chinle Formation (TRc)	Gregory and Moore 1931	Type locality: Chinle Valley, Apache Co., AZ.	Late Triassic
De Chelly Sandstone, Cutler Group (Pdc)	Gregory 1917; Baars 1973	Type locality: Canyon de Chelly, Apache Co., AZ.	early Permian
White House Member, De Chelly Sandstone	Peirce 1962, 1964	Type section: White House Trail in Canyon de Chelly National Monument, Apache Co., AZ.	early Permian

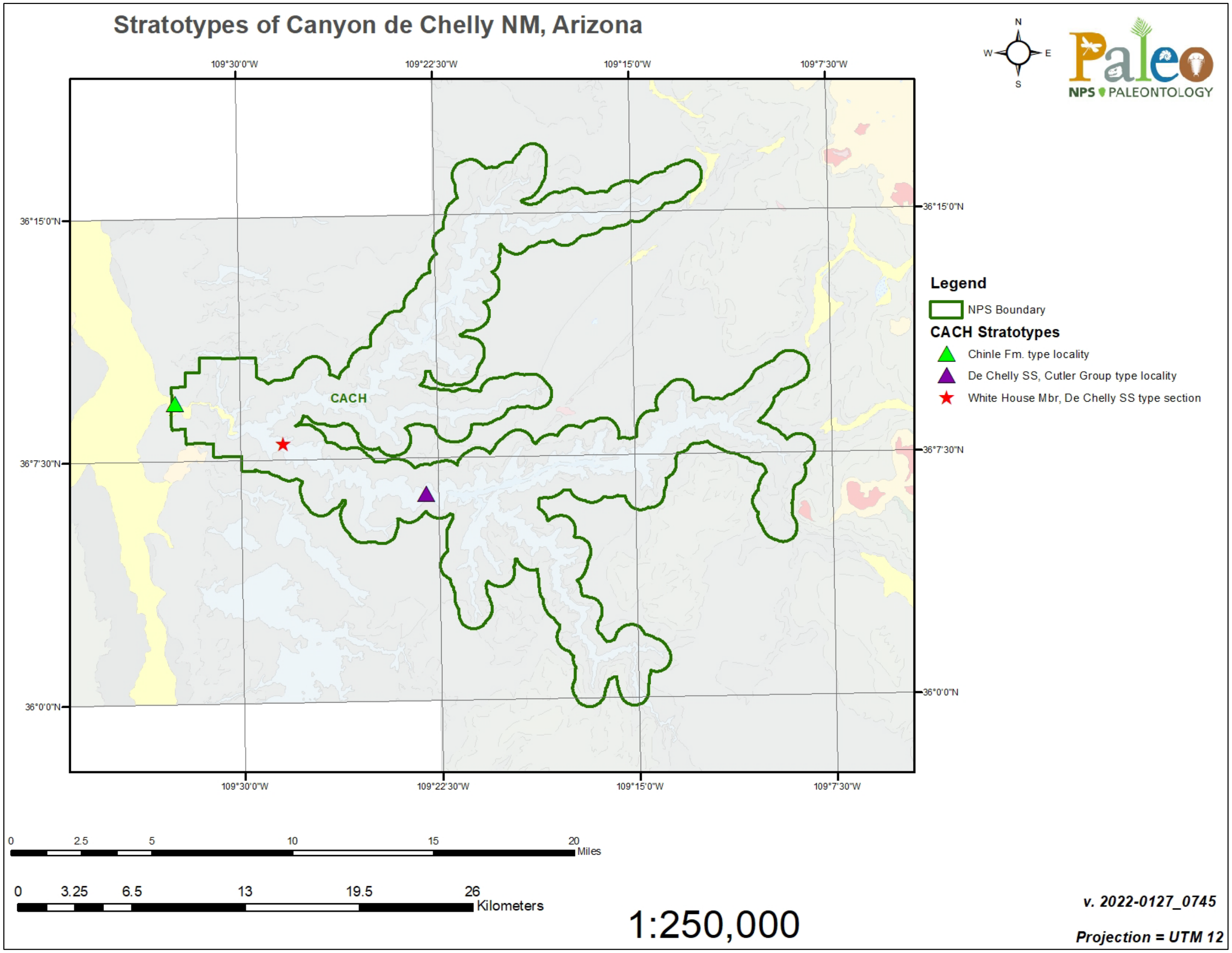


Figure 18. Modified geologic map of CACH showing stratotype locations. The transparency of the geologic units layer has been increased.

The early Permian De Chelly Sandstone of the Cutler Group was first mentioned by Gregory (1915, 1917), who mapped the unit along the type locality in Canyon de Chelly, Arizona (Table 3; Figure 18). The De Chelly Sandstone is approximately 251 m (825 ft) thick at the type locality but thins dramatically on top of the Defiance Uplift between Canyon de Chelly and Hunters Point (Baars 1973). The formation consists of fine-grained, massive, trough cross-stratified eolian (wind-driven) sandstone that has a reddish color derived from orange-red coatings on individual quartz grains (Figure 19; Gregory 1917; Baars 1973; Stanesco 1991). In the type locality, the De Chelly Sandstone overlies the Supai Formation and underlies the Shinarump Member of the Chinle Formation.

Figure 19. Aerial view of Canyon de Chelly National Monument (NPS). The canyon walls consist of red trough cross-bedded sandstone that represent the type locality exposures of the De Chelly Sandstone of the Cutler Group.

The early Permian White House Member is one of five members of the De Chelly Sandstone designated by Peirce (1962, 1964) and named after its type section exposure along the White House Trail in Canyon de Chelly National Monument, Arizona (Table 3; Figure 18). The type section measures approximately 175 m (570 ft) thick and consists of pale reddish-brown, fine-grained, eolian sandstone that displays high-angle cross-stratification with some ripple marks and animal tracks (Figure 20; Peirce 1962, 1964). Near the top of the White House Trail, a pre-Shinarump channel has cut at least 25 m (80 ft) into the De Chelly Sandstone, where the Shinarump Member of the Chinle Formation overlies the White House Member (Peirce 1962). The White House Member overlies the Oak Springs Cliffs Member of the De Chelly Sandstone.

Figure 20. Park visitors hiking down the White House Trail near the type section of the White House Member of the De Chelly Sandstone (NPS).

The Late Triassic Chinle Formation was named by Gregory (1915, 1916, 1917) after its type locality in Chinle Valley, Arizona (Table 3; Figure 18). Type locality exposures of the Chinle Formation measure 360 m (1,182 ft) thick and consists of red shale, shaly sandstone, and greenish-gray to pink limestone conglomerate (Gregory 1916, 1917; Gregory and Moore 1931). At the type locality, Gregory (1917) subdivided the Chinle Formation above the basal Shinarump Conglomerate Member into four informal divisions numbered A, B, C, and D. Upper divisions A and B correspond respectively to what are now called the Rock Point Member and the Owl Rock Member (Martz and Parker 2010). Rocks assigned to Gregory's (1917) division C were later named the Petrified Forest Member of the Chinle Formation by Gregory (1950). The lowermost division D corresponds to strata variously correlated (with much disagreement) to the Monitor Butte, Mesa Redondo, or Bluewater Creek Members of the Chinle Formation (Martz and Parker 2010). The Chinle Formation underlies the Wingate Sandstone and overlies the De Chelly Sandstone of the Cutler Group.

Chaco Culture National Historical Park (CHCU)

Chaco Culture National Historical Park (CHCU) is located about 240 km (150 mi) northwest of Albuquerque in McKinley and San Juan Counties, northwestern New Mexico (Figure 21). Originally proclaimed Chaco Canyon National Monument on March 11, 1907, the park unit was renamed and redesignated on December 19, 1980 (National Park Service 2016a). The historical park encompasses approximately 13,743 hectares (33,960 acres) and protects 13 major Ancestral Puebloan prehistoric sites and hundreds of smaller ones, as well as thousands of recorded archeological sites. The Chacoan civilization flourished between the 9th and 13th centuries and was characterized by remarkable achievements in architecture, designed landscape, craftsmanship, agriculture, social complexity, economic organization, engineering, and astronomy (National Park Service 2015b). The wealth of unique archeological and cultural resources in CHCU is internationally recognized, and the park unit was designated a World Heritage Site on December 8, 1987.

The bedrock geology of CHCU consists of Cretaceous sedimentary rocks that have been deeply incised by the Chaco River and its tributaries. Mapped units within CHCU include the Cliff House Sandstone, Pictured Cliffs Sandstone, Crevasse Canyon Formation, Menefee Formation, and Lewis Shale (Figures 22–25). Most of the Chacoan great houses were constructed along the northern side of Chaco Canyon under vertical cliffs consisting of Cliff House Sandstone (KellerLynn 2015b). The Cliff House Sandstone and the other bedrock units of CHCU were deposited between 100 million and 70 million years ago at a time when the region was inundated by the Western Interior Seaway, a vast sea that flooded the interior of North America. During that time, the site of CHCU was positioned on the western shore of the seaway, which bisected the continent and stretched from the Arctic Ocean to the Gulf of Mexico (KellerLynn 2015b).

There are no designated stratotypes identified within the boundaries of CHCU. There are 14 identified stratotypes located within 48 km (30 mi) of CHCU boundaries, for the Jurassic Iyanbito Member of the Entrada Sandstone (type locality) and Rehoboth Member of the Entrada Sandstone (type section); Cretaceous Hosta Tongue of the Point Lookout Sandstone (type locality), Borrego Pass Lentil of the Crevasse Canyon Formation (type section), Juan Lake Beds of the Allison Member of the Menefee Formation (type section), La Vida Beds of the Allison Member of the Menefee Formation (type section), Bisti Member of the Kirtland Shale (type section), De-na-zin Member of the Kirtland Shale (type area), Hunter Wash Member of the Kirtland Shale (type section), and Naashoibito Member of the Kirtland Shale (type section and reference section); and Paleocene Escavada Member of the Nacimiento Formation (type section), Ojo Encino Member of the Nacimiento Formation (type section), and Penistaja Bed of the Ojo Encino Member of the Nacimiento Formation (type section).

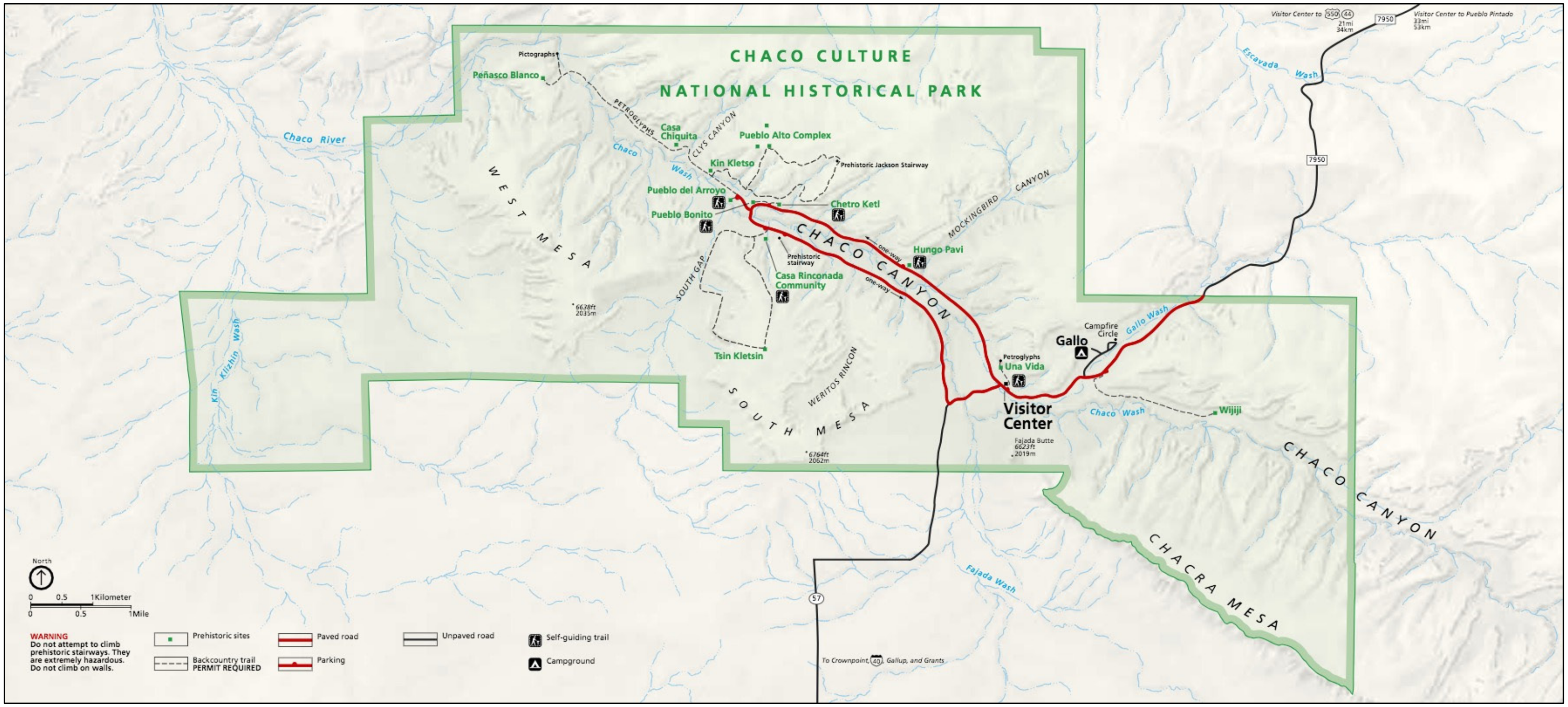


Figure 21. Park map of CHCU, New Mexico (NPS).

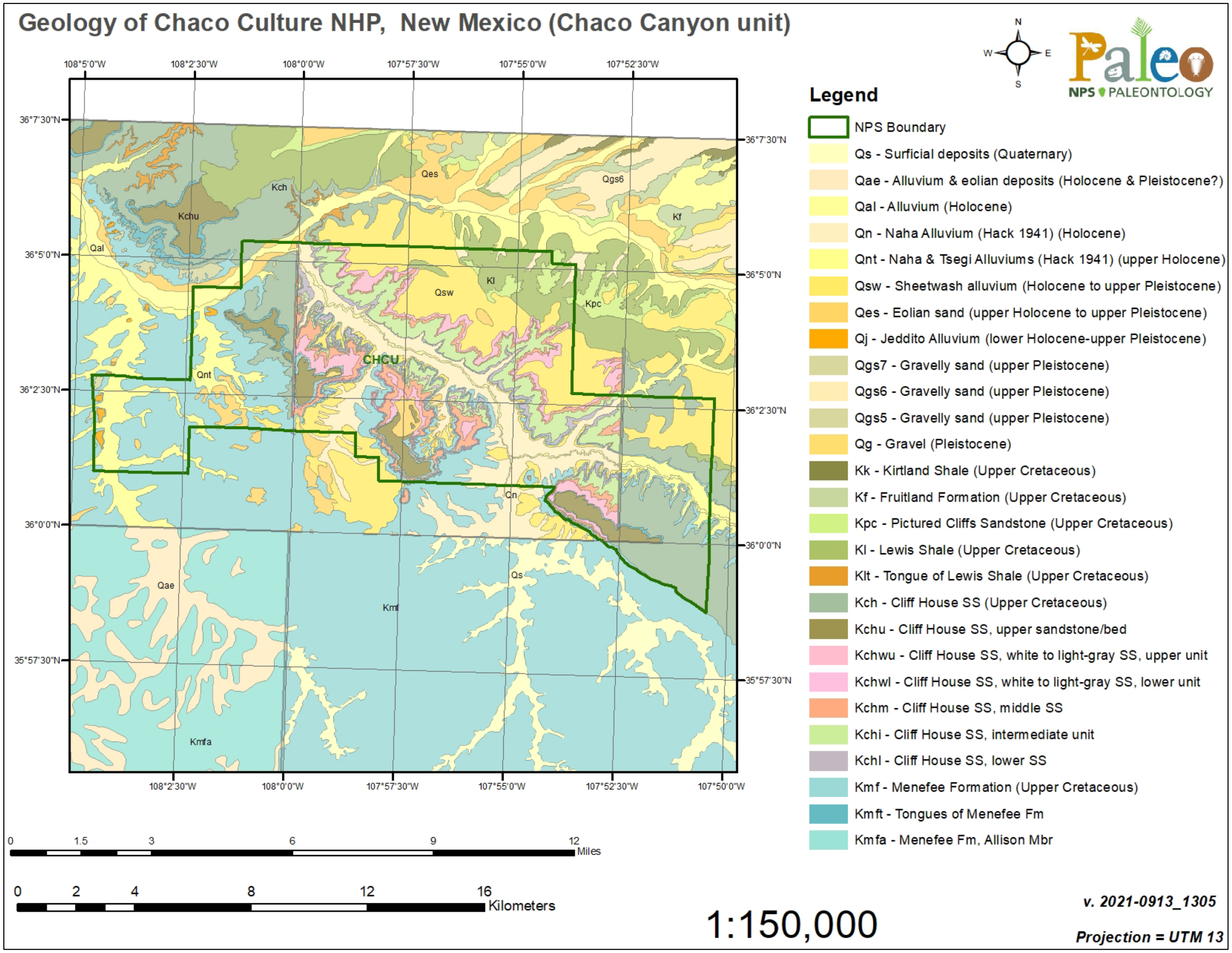


Figure 22. Geologic map of CHCU (Chaco Canyon Unit), New Mexico.

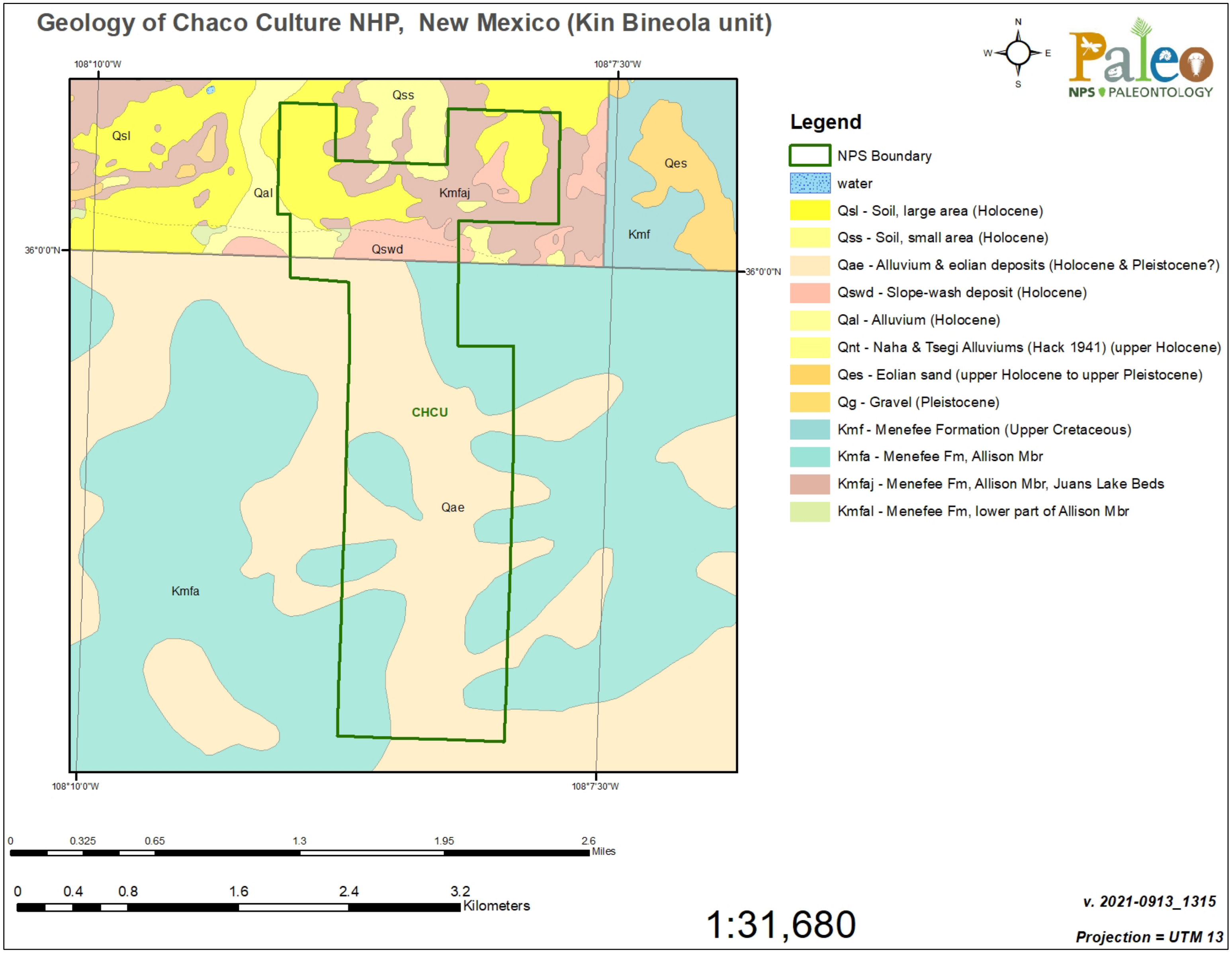


Figure 23. Geologic map of CHCU (Kin Bineola Unit), New Mexico.

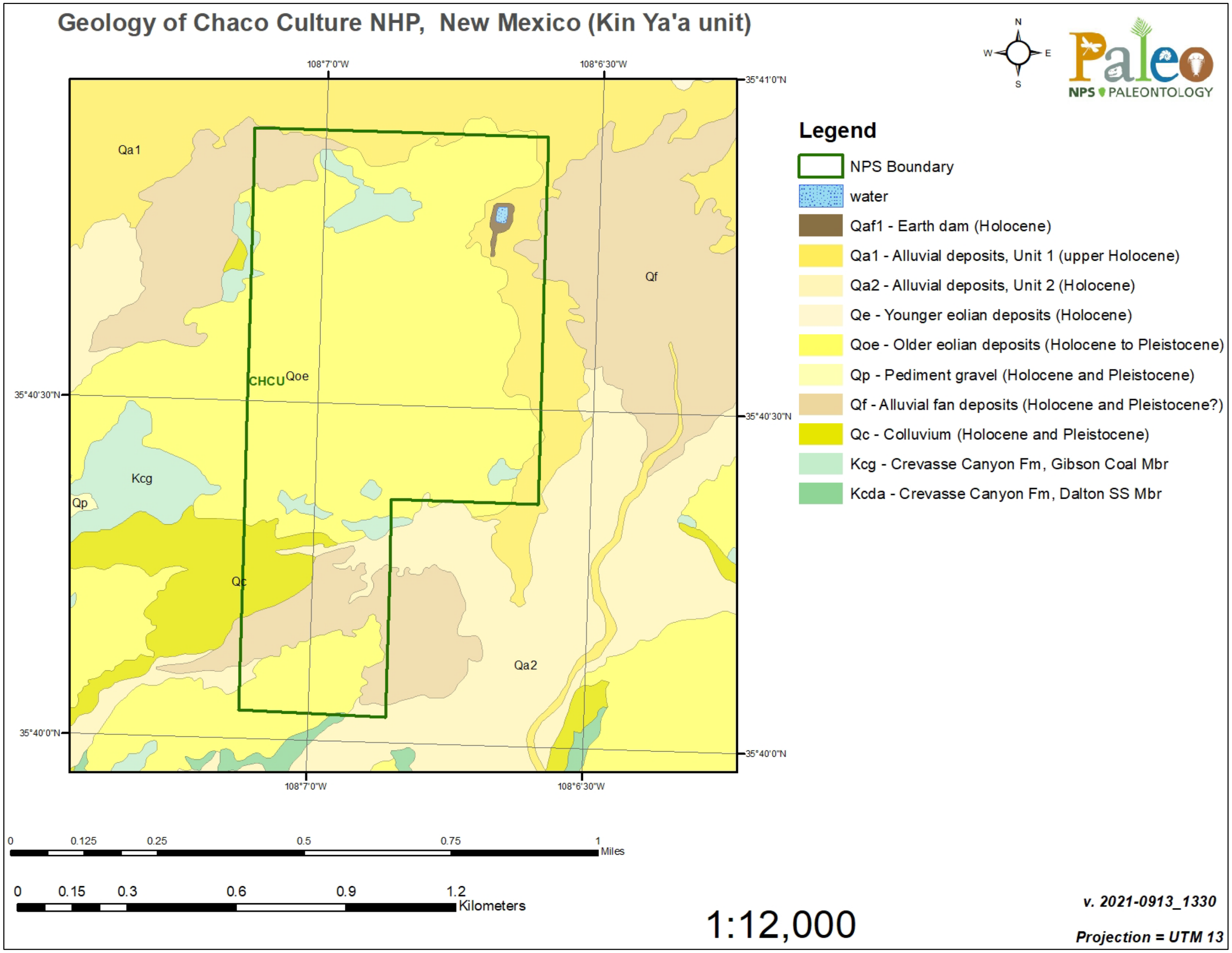


Figure 24. Geologic map of CHCU (Kin Ya'a Unit), New Mexico.

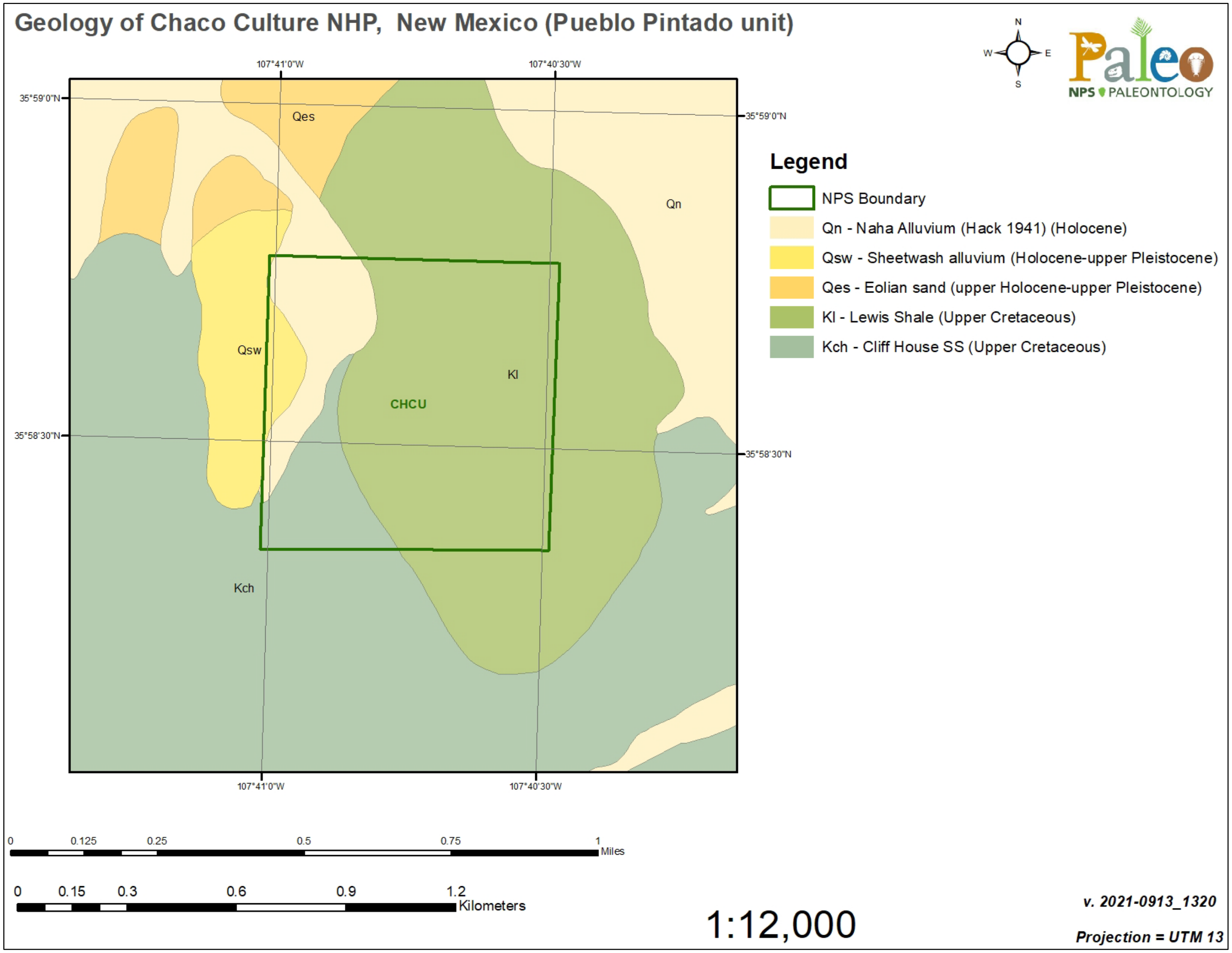


Figure 25. Geologic map of CHCU (Pueblo Pintado Unit), New Mexico.

El Malpais National Monument (ELMA)

El Malpais National Monument (ELMA) protects part of the Zuni–Bandera volcanic field located near the southeastern edge of the Colorado Plateau in Cibola County, west-central New Mexico (Figure 26). Established on December 31, 1987, ELMA preserves approximately 46,261 hectares (114,314 acres) of volcanic landscape featuring cinder cones, extensive lava tube systems, ice caves, the Grants Lava Flow, and the Chacoan great house community of Las Ventanas (National Park Service 2014a, 2016a). Grants Lava Flow is a National Natural Landmark consisting of extrusive lava flows about 51 km (32 mi) long and 29 km (18 mi) wide that contain gigantic pressure ridges, collapse depression ponds, and lava tubes. Early Spanish explorers who encountered the rough lava-flow surfaces named the area "El Malpais", meaning "the Badlands" (KellerLynn 2012a). The black basalt terrain of ELMA is a complex mosaic of lava flows, lava tubes, caves, and associated volcanic features that have been recognized for their geologic importance since the monument was first proposed back in the 1930s.

As part of the Zuni–Bandera volcanic field, ELMA is situated along a zone of crustal weakness called the Jemez lineament, a feature that extends from central Arizona to northeastern New Mexico and contains numerous volcanic fields (KellerLynn 2012a). The Zuni–Bandera volcanic field began erupting in the Pleistocene ~700,000 years ago, but the El Malpais episode occurred within the last 60,000 years. The geology of ELMA can be divided into two main rock groups: 1) sedimentary rocks of Permian, Triassic, Jurassic, and Cretaceous ages (299 million–65 million years old); and 2) young volcanic rocks, most of which erupted in the past 700,000 years (Figure 27; Maxwell 1986). Young volcanic rocks dominate the landscape of the monument. The El Malpais episode contains five main lava flows: the McCartys, Bandera, Hoya de Cibola, Twin Craters, and El Calderon flows (Maxwell 1986). The youngest of these lava flows is the McCarty flow, a 3,900-year-old lava flow that is a widely mapped unit along the eastern portion of the monument and represents the most recent volcanic eruption in New Mexico. Older bedrock units in ELMA occur along the boundaries of the monument and were deposited at a time when shallow seas repeatedly advanced and retreated across the region. Exposures of these older rocks can be seen at the Sandstone Bluff Overlook.

There are no designated stratotypes identified within the boundaries of ELMA. There are nine identified stratotypes located within 48 km (30 mi) of ELMA boundaries, for the Pennsylvanian–Permian Oso Ridge Member of the Abo Formation (type section); Jurassic Acoma Tongue of the Zuni Sandstone (type area); and Cretaceous Clay Mesa Tongue of the Mancos Shale (type section), D-Cross Tongue of the Mancos Shale (type locality), Pescado Tongue of the Mancos Shale (type locality), Paguate Tongue of the Dakota Sandstone (type section), Borrego Pass Lentil of the Crevasse Canyon Formation (type section), Tres Hermanos Sandstone (type locality), and the Atarque Member of the Gallup Sandstone (principal reference section).

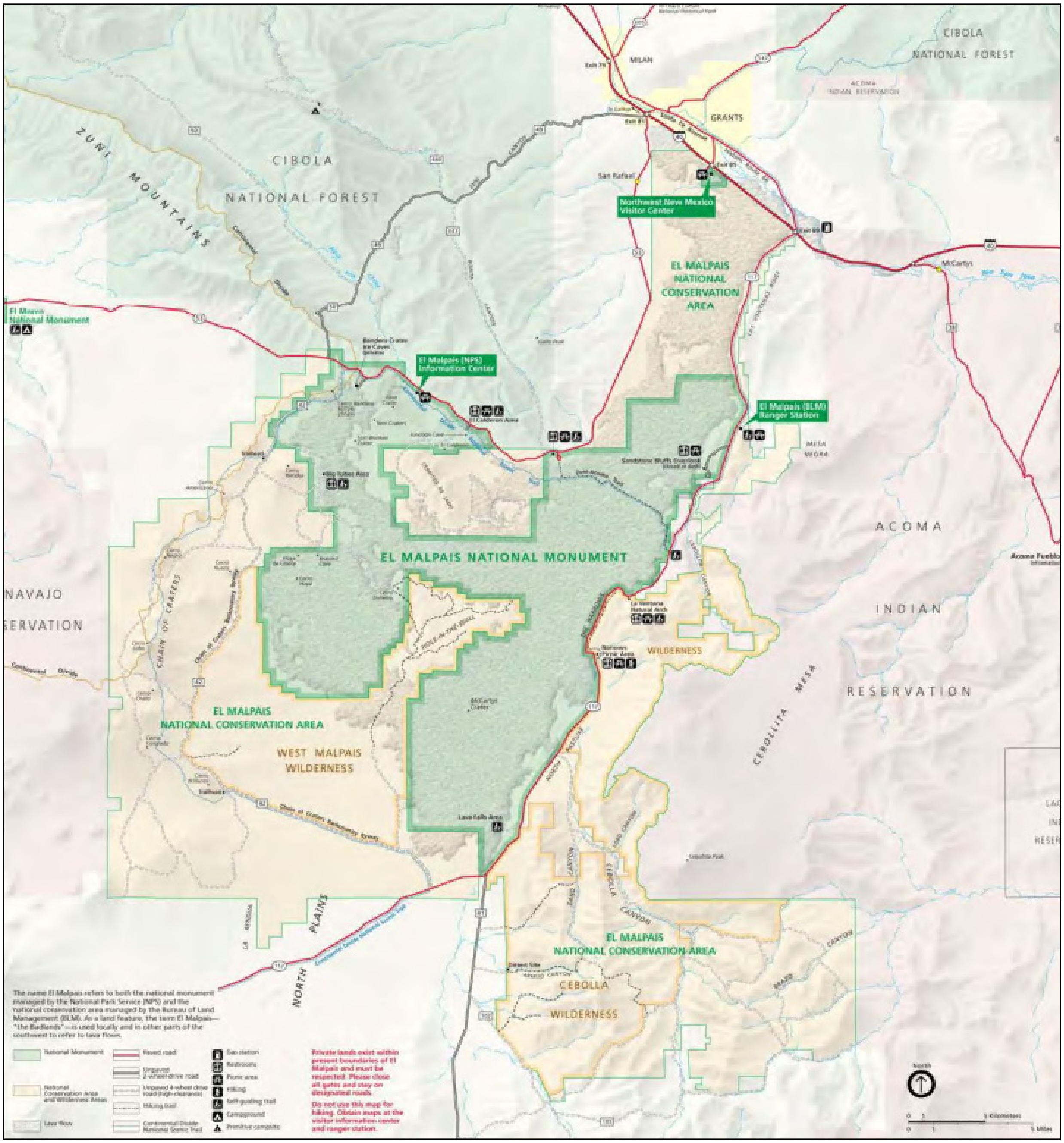


Figure 26. Park map of ELMA, New Mexico (NPS).

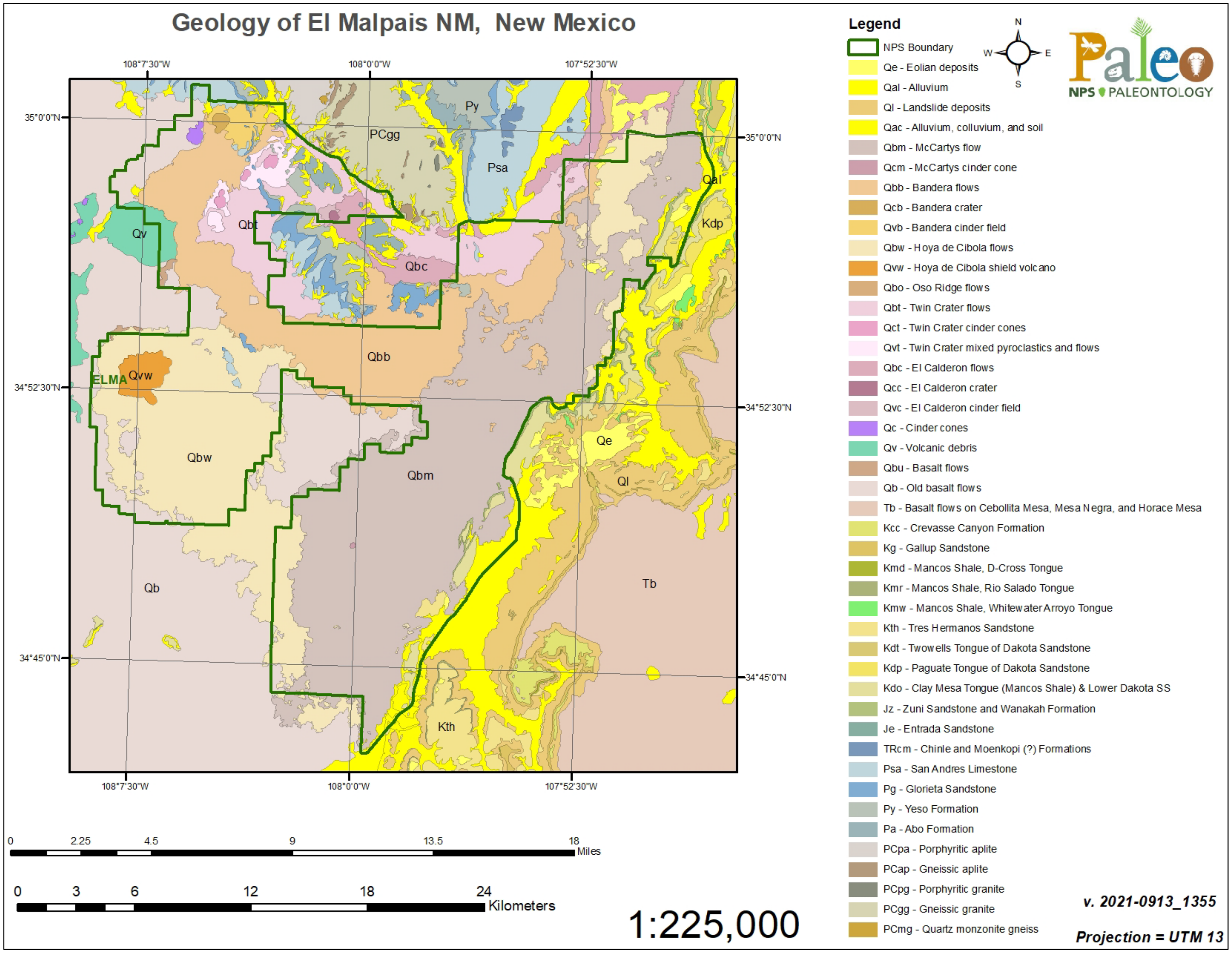


Figure 27. Geologic map of ELMA, New Mexico.

El Morro National Monument (ELMO)

El Morro National Monument (ELMO) is located on the western edge of the Zuni–Bandera volcanic field and southwest of the Zuni Mountains in Cibola County, New Mexico (Figure 28). Established on December 8, 1906, ELMO contains approximately 517 hectares (1,279 acres) and preserves Inscription Rock, its inscriptions, petroglyphs, and Ancestral Puebloan archeological sites (National Park Service 2016a). Inscription Rock is a 70 m (230 ft) tall sandstone monolith with more than 2,000 inscriptions, petroglyphs, and pictographs that document a cultural continuum of more than 1,000 years, from Ancestral Puebloans to Spanish explorers, European American surveyors, pioneers, and military expeditions (National Park Service 2014b). The significant concentration of archeological resources in ELMO includes well-preserved and largely unexcavated pueblo sites atop Inscription Rock. Some of these sites, including the multi-storied Atsinna pueblo, are among the largest 13^{th} and 14^{th} century settlements in the American Southwest. El Morro, meaning “the headland” in Spanish, is a cuesta (tilted mesa)—a landform that slopes upward gently on one side and drops off abruptly on the other. Cliffs bound one flank of El Morro, and the strata of the opposite flank dip into the subsurface (KellerLynn 2012b).

The geology of ELMO consists of Mesozoic sedimentary rocks and Cenozoic basaltic lava flows, alluvium, and eolian sand deposits (Figure 29). The northeastern point of the El Morro cuesta forms the tallest cliffs and exposes the most stratigraphy in the monument. A major portion of the inclined strata of the cuesta consists of the Jurassic Zuni Sandstone, a well-sorted, cross-stratified sandstone deposited in an ancient desert environment by wind-driven processes. Capping the cuesta is a thin layer of Cretaceous Dakota Sandstone, which marks the encroachment of the Western Interior Seaway into the New Mexico area about 96 million years ago (KellerLynn 2012b). The contact between the Zuni Sandstone and overlying Dakota Sandstone marks an unconformity representing a 60-million-year gap in the rock record.

There are no designated stratotypes identified within the boundaries of ELMO. There are four identified stratotypes located within 48 km (30 mi) of ELMO boundaries, for the Pennsylvanian–Permian Oso Ridge Member of the Abo Formation (type section), Jurassic Zuni Sandstone (type locality), and Cretaceous Atarque Member of the Gallup Sandstone (principal reference section) and Pescado Tongue of the Mancos Shale (type locality).

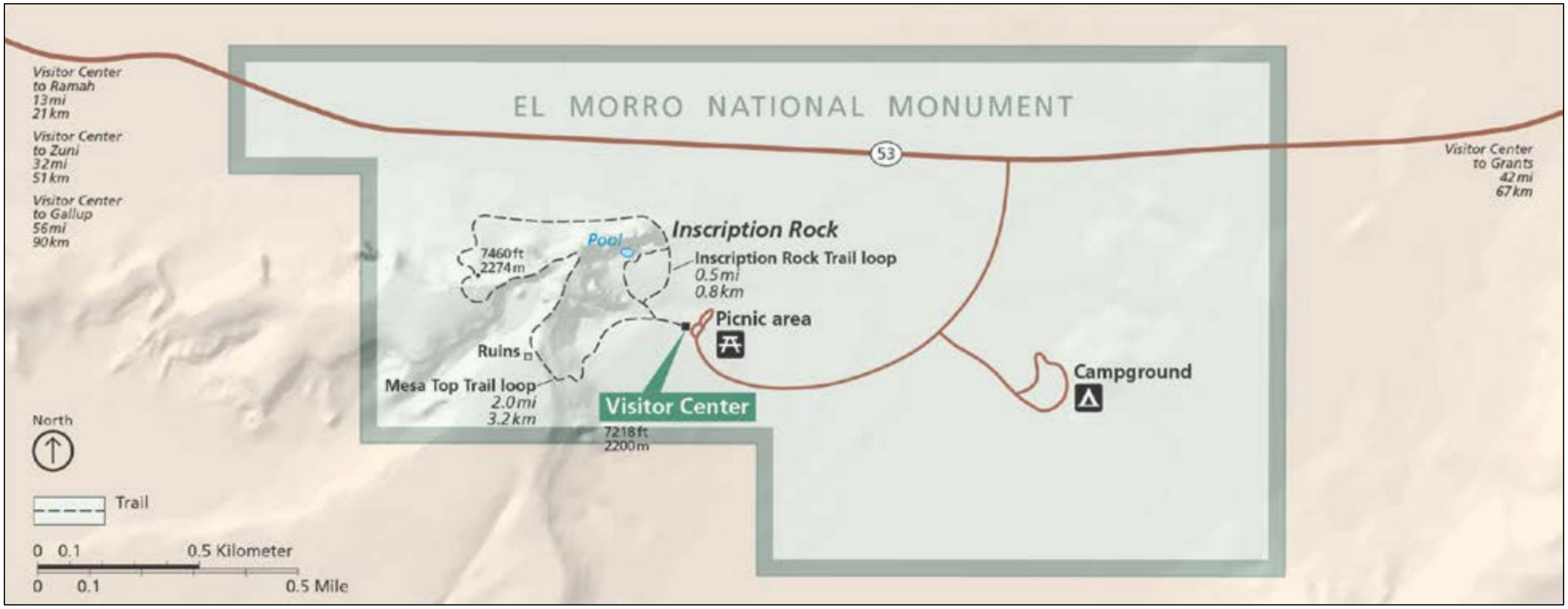


Figure 28. Park map of ELMO, New Mexico (NPS).

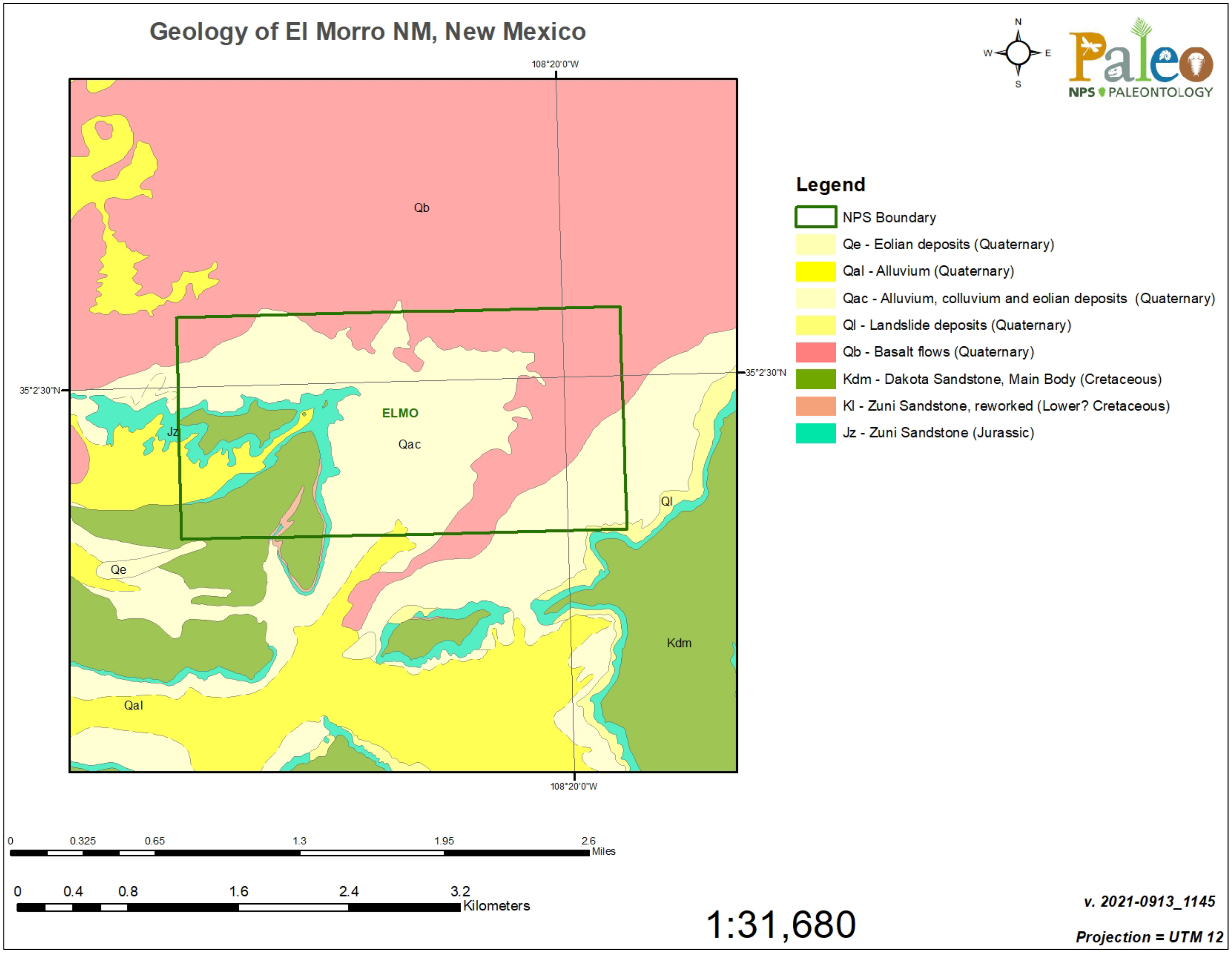


Figure 29. Geologic map of ELMO, New Mexico.

Glen Canyon National Recreation Area (GLCA)

Glen Canyon National Recreation Area (GLCA) is located at the center of the Colorado Plateau and extends from the Orange Cliffs in Utah to Lees Ferry in northernmost Arizona. Established on October 27, 1972, GLCA encompasses about 507,523 hectares (1,254,117 acres) of some of the most rugged canyon country on the Colorado Plateau in Garfield, Kane, San Juan, and Wayne Counties, Utah, and Coconino County, Arizona (National Park Service 2016a). Lake Powell stretches approximately 300 km (186 mi) behind Glen Canyon Dam, and its 3,150 km (1,960 mi) of shoreline and 96 major side canyons provide for diverse land- and water-based recreational activities. The recreation area not only includes Lake Powell but also sections of the Colorado and San Juan Rivers. Other NPS units, including Canyonlands National Park, Capitol Reef National Park, Grand Canyon National Park, and Rainbow Bridge National Monument, also share a boundary with the recreation area (Figure 30; Graham 2016). GLCA preserves a rich history of human presence, adaptation, and exploration that dates back more than 10,000 years (National Park Service 2014c).

The landscape of GLCA includes more than 3,000 m (10,000 ft) of sedimentary rocks that were deposited during the Pennsylvanian Subperiod and Permian Period of the Paleozoic Era and throughout the Mesozoic Era, representing ~300 million years of Earth history (Figures 31 and 32). Geologic formations in GLCA record a complex history that includes several orogenies (mountain-building events), the formation of the supercontinent Pangea, multiple incursions of shallow seas onto North America, vast deserts with Sahara-like sand dunes, the age of the dinosaurs, unique igneous intrusions known as laccoliths, and the carving of the Colorado River system (Graham 2016). The extensive exposures of Mesozoic rocks in GLCA represent one of the best overall Mesozoic stratigraphic sections in the National Park Service, providing exceptional documentation of ancient ecosystems and paleoclimates from about 252 million to 66 million years ago. A diverse assemblage of geologic and geographic features is found in GLCA, including mesas, buttes, cliffs, slickrock, slot canyons, alcoves, hanging gardens, arches, natural bridges, badlands, hoodoos, entrenched meanders, desert varnish, sandstone pipes, and weathering pits.

Glen Canyon National Recreation Area contains seven identified stratotypes that represent the Permian Cedar Mesa Sandstone, Triassic Moody Canyon Member of the Moenkopi Formation, Triassic–Jurassic Glen Canyon Group, and Jurassic Page Sandstone, Carmel Formation, Gunsight Butte Member of the Entrada Sandstone, and Romana Sandstone (Table 4; Figure 33). In addition to the designated stratotypes located within GLCA, stratotypes located within 48 km (30 mi) of the recreation area's boundaries include the Pennsylvanian Honaker Trail Formation (type section and reference section); Permian Kaibab Formation (type locality); type sections of the Triassic Church Rock, Monitor Butte, Moss Back, and Owl Rock Members of the Chinle Formation; type sections of the Jurassic Recapture, Salt Wash, and Westwater Canyon Members of the Morrison Formation, Carmel Formation (reference section), Judd Hollow Tongue of the Carmel Formation (type section), Thousand Pockets Tongue of the Carmel Formation (type section), Escalante Member of the Entrada Sandstone (type locality), Harris Wash Tongue of the Page Sandstone (type section), and White Point Sandstone Member of the Summerville Formation (type section); and type sections of the Cretaceous Drip Tank, John Henry, Smoky Hollow, and Tibbett Canyon Members of the Straight Cliffs

Formation, Kaiparowits Formation (type area), Wahweap Sandstone (type locality), and the Masuk Member of the Mancos Shale (type section).

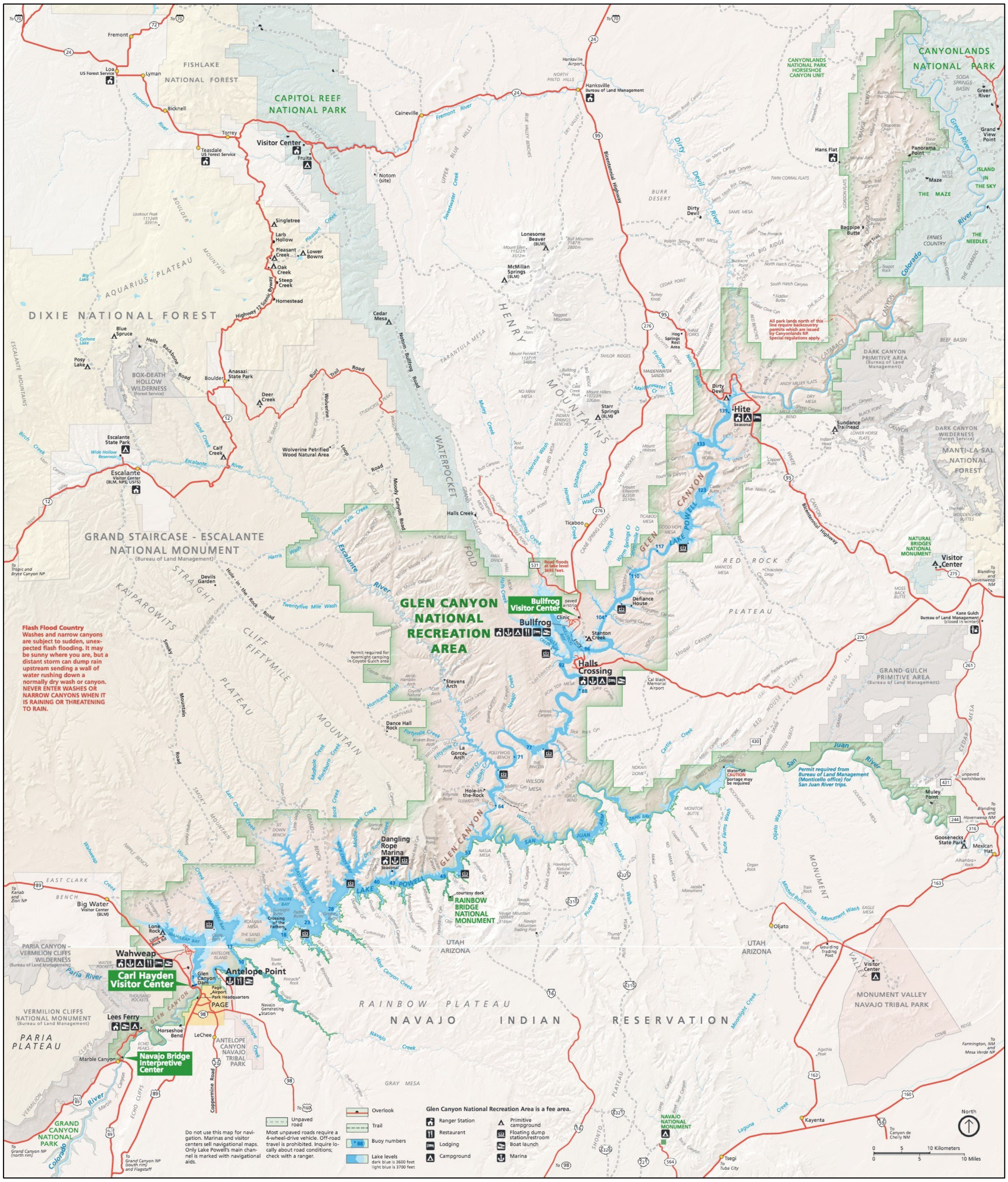


Figure 30. Park map of GLCA, Utah–Arizona (NPS).

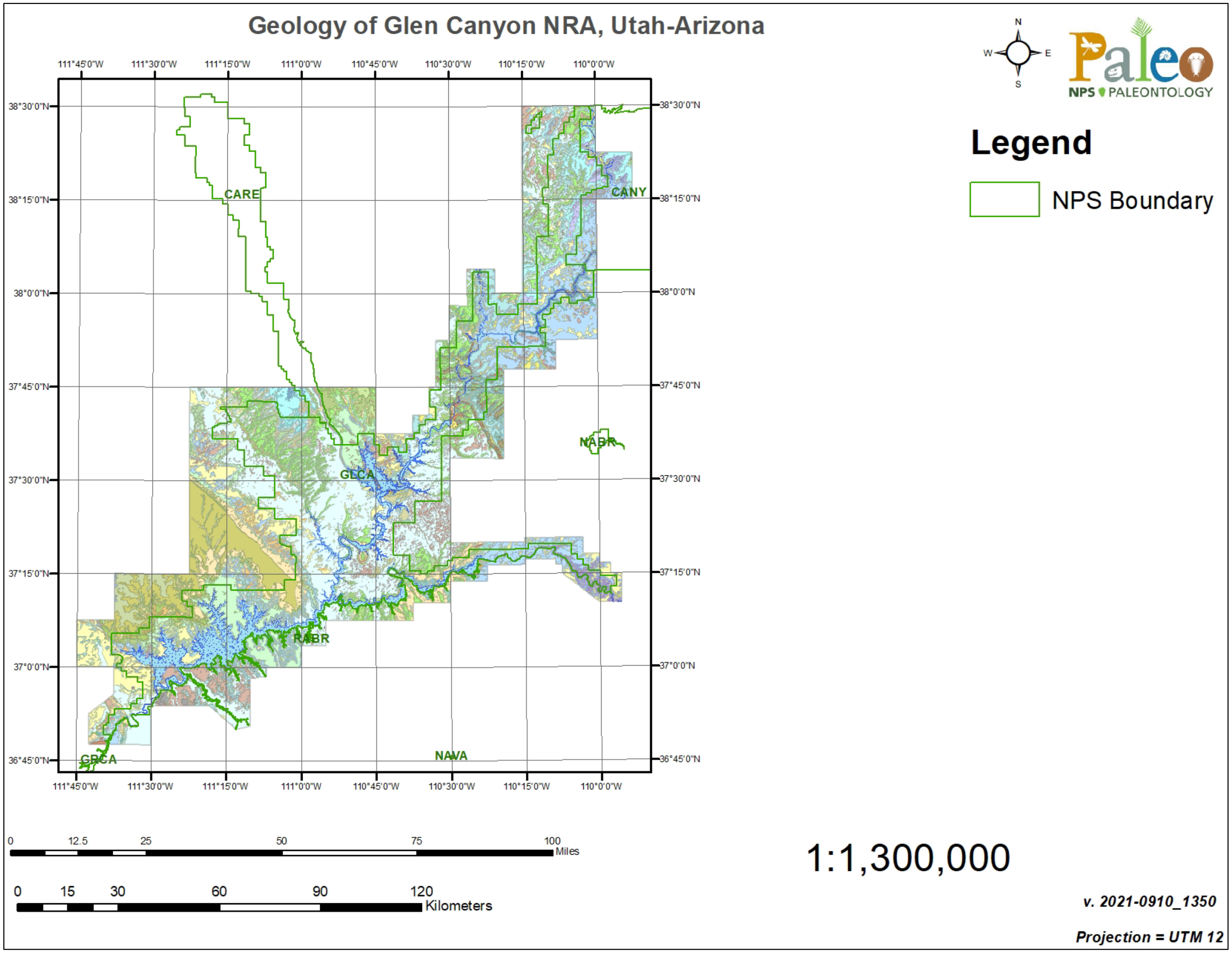


Figure 31. Geologic map of GLCA, Utah–Arizona; see Figure 32 for legend.

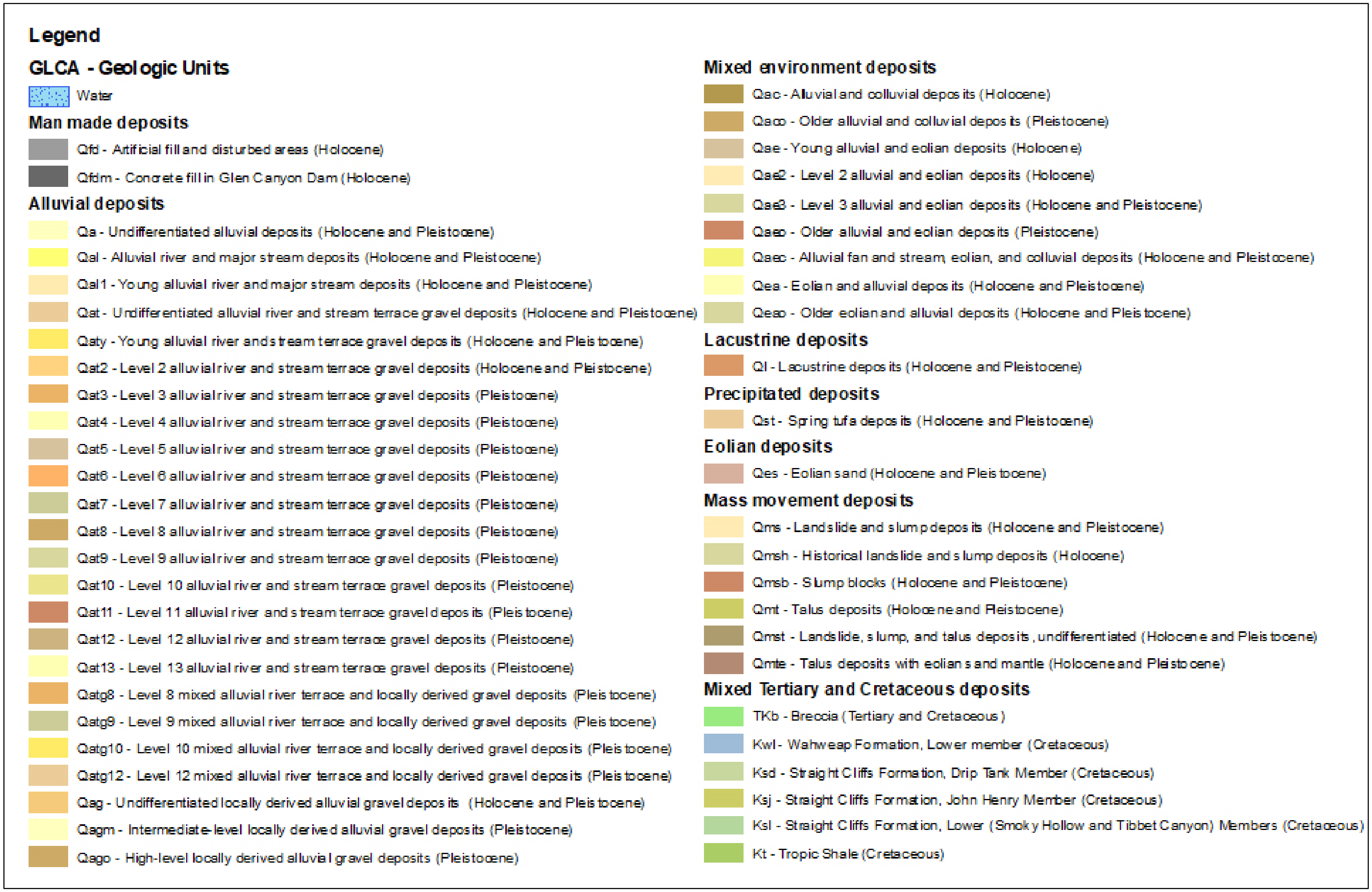


Figure 32. Geologic map legend of GLCA, Utah–Arizona.

Kmf - Mancos Shale, Ferron Sandstone Member (Cretaceous)
Kmt - Mancos Shale, Tununk Shale Member (Cretaceous)
Kd - Dakota Formation (Cretaceous)

Morrison Formation

Jmb - Brushy Basin Member (Jurassic)
Jms - Salt Wash Member (Jurassic)
Jsmt - Tidwell Member of Morrison Formation and/or Summerville Formation (Jurassic)

San Rafael Group

Jr - Romana Sandstone (Jurassic)
Jesu - Summerville Formation and Entrada Sandstone, undivided (Jurassic)
Je - Entrada Sandstone (Jurassic)
Jem - Entrada Sandstone, Middle member (Jurassic)
Jel - Entrada Sandstone, Lower member (Jurassic)
Jcu - Carmel Formation, Upper (Paria River and Winsor) Members (Jurassic)
Jcw - Carmel Formation, Winsor Member (Jurassic)
Jcp - Carmel Formation, Paria River Member (Jurassic)
Jpj - Page Sandstone, Carmel Formation, Judd Hollow Tongue, undivided (Jurassic)
Jpt - Page Sandstone, Thousand Pockets Tongue (Jurassic)
Jcj - Carmel Formation, Judd Hollow Tongue (Jurassic)

Glen Canyon Group

Jn - Navajo Sandstone (Jurassic)
Jnl - Navajo Sandstone, Limestone and dolomite beds (Jurassic)
Jk - Kayenta Formation (Jurassic)
Jks - Kayenta Formation, Springdale Sandstone Member (Jurassic)
JTRw - Wingate Sandstone (Jurassic and Triassic)
JTRmd - Moenave Formation, Dinosaur Canyon Member (Jurassic and Triassic)

Chinle Formation

TRcc - Church Rock Member (Triassic)
TRcop - Owl Rock and Petrified Forest Members (Triassic)
TRcu - Upper (Church Rock, Owl Rock, Petrified Forest, Moss Back) Members (Triassic)
TRcms - Moss Back Member (Triassic)
TRcmn - Monitor Butte Member (Triassic)
TRcs - Shinarump Conglomerate Member (Triassic)

Moenkopi Formation

TRm - main part (Triassic)
TRmh - Hoskinnini Sandstone Member (Triassic)
TRmu - Upper member (Triassic)
TRml - Lower member (Triassic)

Mixed Permian deposits

P - Permian Formations (Kaibab, White Rim, and/or Cedar Mesa) (Permian)
Pk - Kaibab Formation (Permian)
Pt - Toroweap Formation (Permian)
Pco - Coconino Sandstone (Permian)
Phe - Hermit Formation (Permian)

Cutler Group

Pc - Cutler Formation (Permian and Pennsylvanian)
Pwr - White Rim Sandstone (Permian)
Po - Organ Rock Formation (Permian)
Pcm - Cedar Mesa Sandstone (Permian)
PPNcl - Lower Cutler beds (Permian and Pennsylvanian)
PPNhgu - Halgaito Formation, Upper member (Permian and Pennsylvanian)
PPNhgl - Halgaito Formation, Lower member (Permian and Pennsylvanian)
PPNe - Elephant Canyon Formation (Permian and Pennsylvanian)

Hermosa Group

PNht - Honaker Trail Formation (Pennsylvanian)
PNhtu - Honaker Trail Formation, Upper member (Pennsylvanian)
PNhtl - Honaker Trail Formation, Lower member (Pennsylvanian)
PNp - Paradox Formation (Pennsylvanian)

Figure 32 (continued). Geologic map legend of GLCA, Utah–Arizona.

Table 4. List of GLCA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Romana Sandstone (Jr)	Peterson 1988	Type section: northeast side of Crosby Canyon, in SE/4 NE/4 SE/4 sec. 8, T. 43 S., R. 4 E., Kane Co., UT.	Late Jurassic
Gunsight Butte Member, Entrada Sandstone	Thompson and Stokes 1970	Type section: Gunsight Butte on west side of Gunsight Canyon, in secs. 15, 16, 21, and 22, T. 43 S., R. 5 E., Kane Co., UT.	Middle Jurassic
Carmel Formation (Jcw, Jcp)	Peterson and Pipiringos 1979	Reference section: in SW/4 SW/4 sec. 1, SE/4 SE/4 sec. 2, T. 41 N., R. 8 E., Coconino Co., AZ.	Middle Jurassic
Page Sandstone (Jpj, Jpt)	Peterson and Pipiringos 1979	Type section: on the northwest side of Manson Mesa on which the town of Page is situated, about 1 km (0.6 mi) northeast of Glen Canyon Dam [SW/4 NW/4 sec. 19, T. 41 N., R. 9 E.], Coconino Co., AZ.	Middle Jurassic
Glen Canyon Group (Jn, Jk, JTRw, JTRmd)	Reeside et al. 1927; Molenaar 1969	Type locality: Glen Canyon of the Colorado River, Kane Co., UT.	Triassic–Jurassic
Moody Canyon Member, Moenkopi Formation	Blakey 1974	Type section: measured along an east–west line exactly 3.5 km (2.16 mi) due south of the 5728 BM on Horse Pasture Mesa, Circle Cliffs, Garfield Co., UT.	Early–Middle Triassic
Cedar Mesa Sandstone (Pcm)	O’Sullivan 1965	Type locality: Cedar Point, west of Mexican Hat, in sec. 18, T. 41 S. R. 18 E., San Juan Co., UT.	early Permian

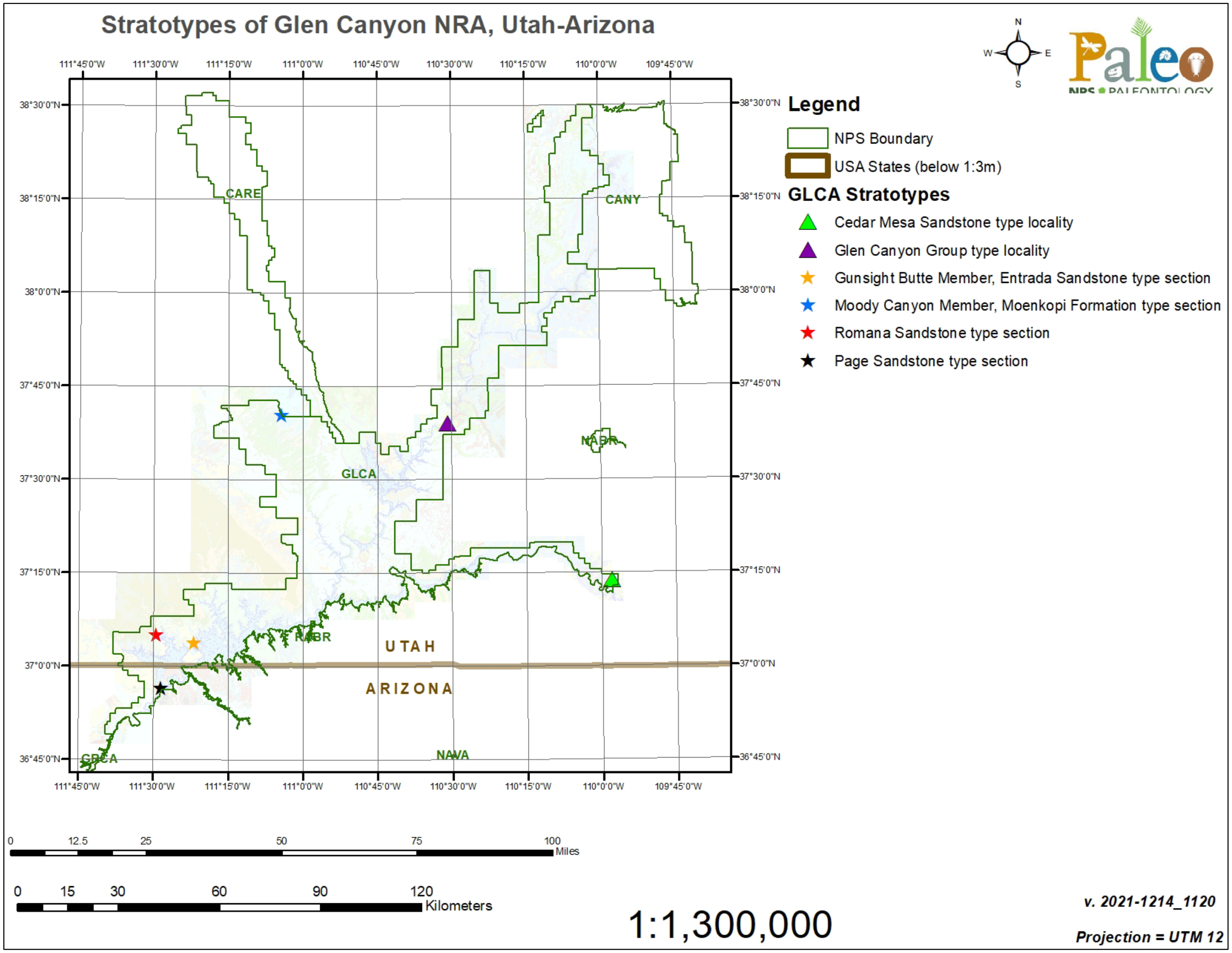


Figure 33. Modified geologic map of GLCA showing stratotype locations. The transparency of the geologic units layer has been increased.

The early Permian Cedar Mesa Sandstone was originally proposed by Baker and Reeside (1929) as a member of the Cutler Formation (now Cutler Group) and named after conspicuous light-colored sandstone exposed in the flat divide extending southward between Lime Creek and Johns Canyon known as Cedar Mesa. The type locality of the formation is designated at Cedar Point, west of Mexican Hat, in section 18, T. 41 S. R. 18 E., San Juan County, Utah (Table 4; Figures 33 and 34; O'Sullivan 1965). Type locality exposures consist of very fine to medium-grained, cross-bedded, grayish-orange sandstone with minor interbedded reddish-brown siltstone that forms thick prominent ledges as much as 38 m (125 ft) thick (O'Sullivan 1965). At the type locality the Cedar Mesa Sandstone overlies the Halgaito Formation and underlies the Organ Rock Formation.

Figure 34. View looking east toward Cedar Point from Muley Point, type locality exposures of the Cedar Mesa Sandstone (DAVID R. VINEYARD).

The Triassic Moody Canyon Member of the Moenkopi Formation was named by Blakey (1974) after its type section exposure in the southwesternmost Circle Cliffs along Moody Creek about 3.2 km (2 mi) north of the head of Moody Canyon, Utah. The type section is measured along an east–west line exactly 3.5 km (2.16 mi) due south of the 5,728 BM (benchmark) on Horse Pasture Mesa in the Circle Cliffs (Table 4; Figure 33). Blakey (1974) noted that the Moody Canyon Member displays impressive continuity and regularity on the Colorado Plateau, predominantly consisting of intercalated siltstone and mudstone with minor beds of dolostone, gypsum, and sandstone (Figure 35). The unit has a maximum measured thickness of 84 m (276 ft) in the Circle Cliffs region (Blakey 1974). The Moody Canyon Member overlies the Torrey Member of the Moenkopi Formation and unconformably underlies the Chinle Formation.

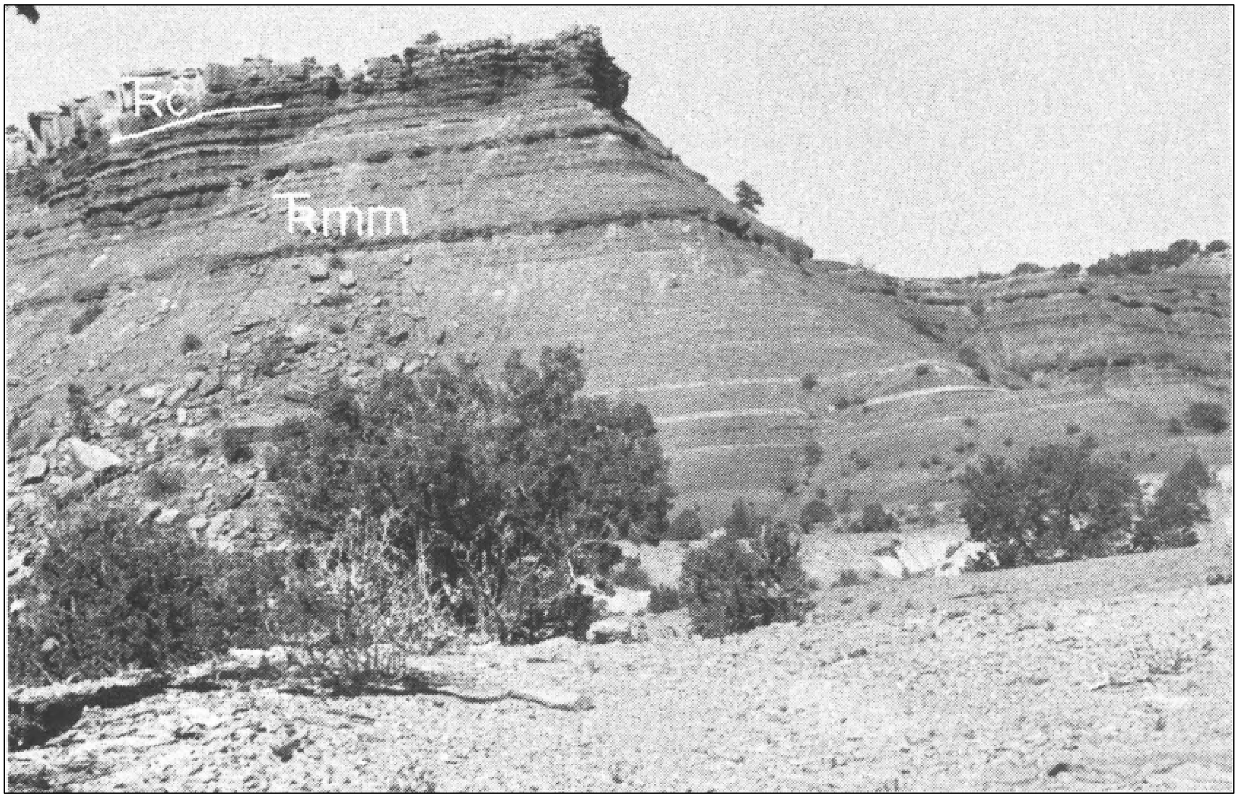


Figure 35. Mudstone facies and ledge- and cliff-forming sandy siltstone and mudstone facies of the Moody Canyon Member (TRmm) in the southern Circle Cliffs near the type section. Two prominent ledges are present throughout the Circle Cliffs. Note how the upper portion forms cliffs where it was protected by the Shinarump Member of the Chinle Formation (TRc). Figure 28E from Blakey (1974) (courtesy of the Utah Geological Survey).

The Triassic–Jurassic Glen Canyon Group was defined by Gilluly and Reeside (1928) and Gregory and Moore (1931) after a thick sequence of sandstones that rests upon the Chinle Formation in eastern Utah. Individual units of the group include, from oldest to youngest, the Moenave Formation, Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. Lithologically, the sequence of strata composing the Glen Canyon Group consists of massive, cross-bedded, cliff-forming sandstones and thin-bedded calcareous sandstone, shale (mudstone), and limestone (Gilluly and Reeside 1928; Gregory and Moore 1931). The type locality of the group is located in Glen Canyon of the Colorado River, in Kane County, Utah (Table 4; Figures 33, 36, and 37; Molenaar 1969 citing Gilluly and Reeside 1928). In the type locality the group is nowhere less than 180 m (600 ft) thick, and in many places it exceeds 610 m (2,000 ft) (Gregory and Moore 1931). The Glen Canyon Group unconformably overlies the Chinle Formation and unconformably underlies the Page Sandstone.

Figure 36. Horseshoe Bend, an entrenched meander of the Colorado River carved into the Navajo Sandstone of the Glen Canyon Group (NPS/TIM HENDERSON). The type locality of the Glen Canyon Group is located along Glen Canyon.

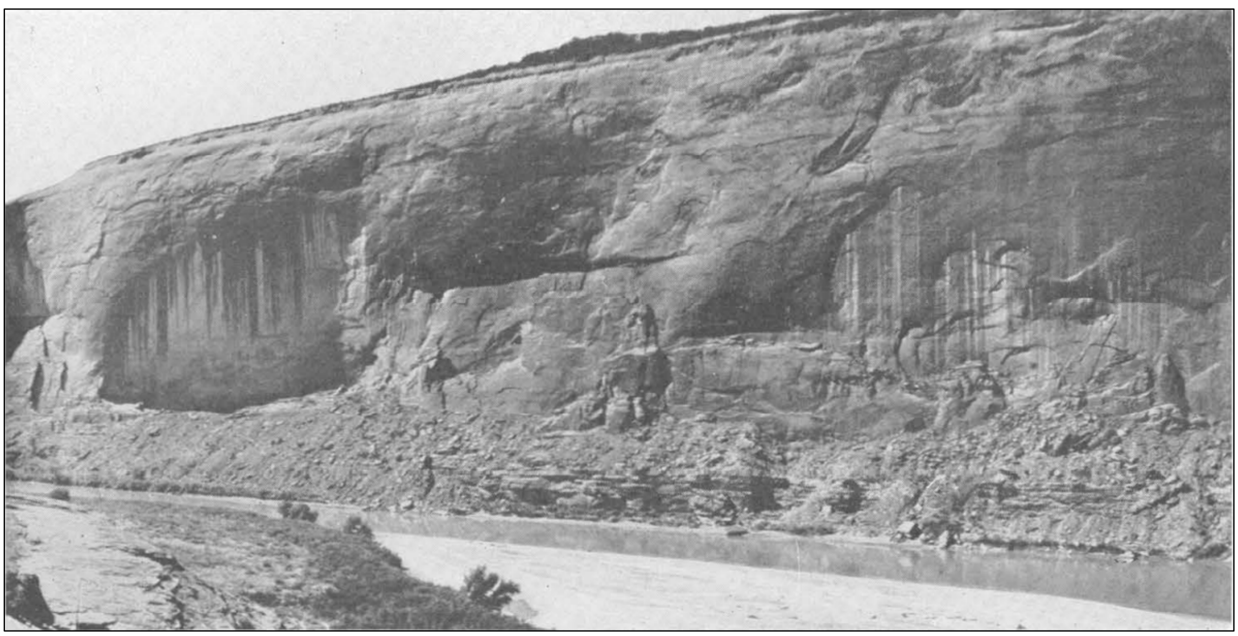


Figure 37. Glen Canyon near the mouth of Warm Springs Creek at Tapestry Wall. The nearly vertical cliff is formed of Navajo Sandstone of the Glen Canyon Group. The underlying Kayenta Formation is exposed near the river level. Plate 10C in Gregory and Moore (1931).

The Jurassic Page Sandstone was formally described by Peterson and Pipiringos (1979) and named after the town of Page in Coconino County, Arizona. Peterson and Pipiringos (1979) measured the type section of the formation on the northwest side of Manson Mesa on which the town of Page is situated, and it is about 1 km (0.6 mi) northeast of Glen Canyon Dam (Table 4; Figures 33, 38, and

39). At the type section the formation is 55.8 m (183 ft) thick and consists largely of reddish-brown to reddish-orange, locally very light gray or grayish-pink eolian sandstone that is fine-grained and well-sorted (Peterson and Pipiringos 1979). Large-scale cross-bedding is common, with cross-bed sets ranging from about 1–6 m (3–20 ft) thick (Peterson and Pipiringos 1979). The Page Sandstone unconformably overlies the Navajo Sandstone and conformably underlies the upper member of the Carmel Formation. The basal contact with the Navajo Sandstone is difficult to distinguish, but the lower Page is commonly slightly darker in color than the Navajo and locally contains lenses of reddish-brown, silty sandstone similar to the Carmel Formation (Anderson et al. 2010).

Figure 38. View looking southeast at the type section of the Page Sandstone near Page, Arizona. The stripped surface in the foreground at the base of the Page (Jp) marks the top of the Navajo Sandstone (JTRn). 2b, measured type section; Jcau, upper member of the Carmel Formation. Figure 18 from Peterson and Pipiringos (1979).

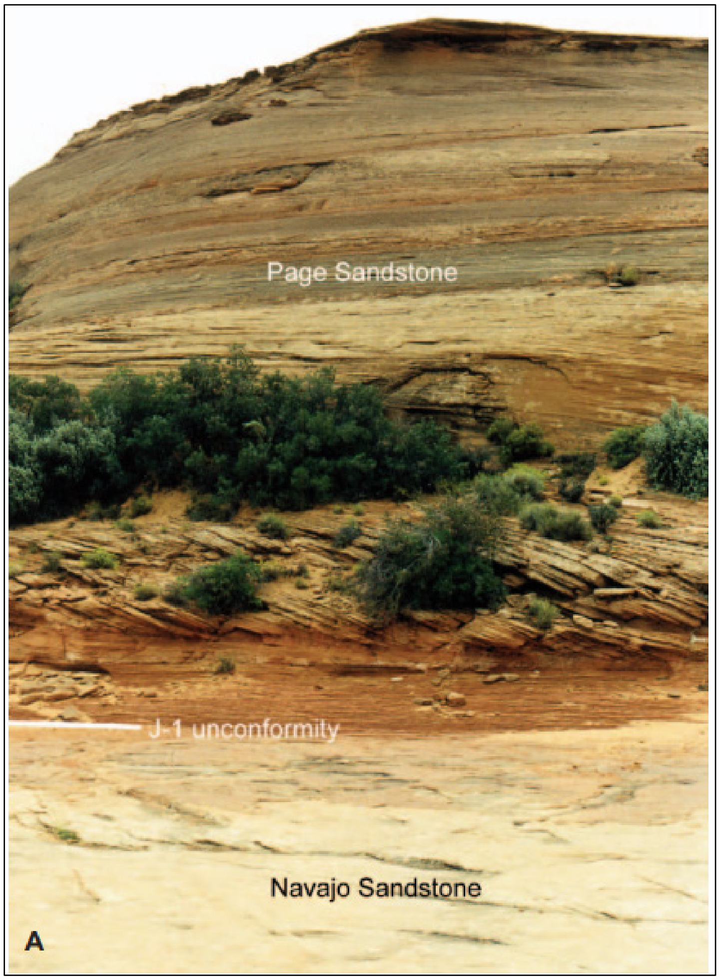


Figure 39. Type section of the Jurassic Page Sandstone unconformably overlying the Navajo Sandstone on the northwest side of Manson Mesa. Figure 28A from Anderson et al. (2010) (courtesy of the Utah Geological Association).

The Jurassic Carmel Formation was first mentioned by Gilluly and Reeside (1928) and named after Mount Carmel, Utah. A reference section by Peterson and Pipiringos (1979) is located within GLCA near a paved road on the west side of Wahweap Creek valley ~5 km (3 mi) north of Hayden Visitor Center at Glen Canyon Dam, in SW/4 SW/4 sec. 1, SE/4 SE/4 sec. 2, T. 41 N., R. 8 E., Coconino County, Arizona (Table 4; Figure 33). The reference section measures 77.7 m (255 ft) thick and consists predominantly of dark reddish-brown sandy mudstone and reddish-brown fine-grained sandstone, with minor beds of grayish-pink limestone (Peterson and Pipiringos 1979). The Carmel Formation unconformably overlies the Navajo Sandstone and underlies the Entrada Sandstone.

The Jurassic Gunsight Butte Member of the Entrada Sandstone was formally proposed by Thompson and Stokes (1970) and named after its type section exposure at Gunsight Butte, on the west side of Gunsight Canyon in secs. 15, 16, 21, and 22, T. 43 S., R. 5 E., Kane County, Utah (Table 4; Figure 33). The type section measures about 145 m (475 ft) thick and is composed of greenish-gray to reddish-brown, very fine to fine-grained, cross-bedded sandstone (Figures 40 and 41; Thompson and Stokes 1970). In southwestern and south-central Utah, the formation is divisible into three main lithofacies that include: 1) a red, silty facies that forms cliffs, hoodoos, and badlands; 2) a red, cross-bedded sandy facies; and 3) a gray, cross-bedded facies that forms buttresses and cliffs (Thompson and Stokes 1970). The Gunsight Butte Member overlies the Carmel Formation and underlies the Cannonville Member of the Entrada Sandstone.

Figure 40. Gunsight Butte on Lake Powell, the type section location of the Gunsight Butte Member of the Entrada Sandstone (NPS).

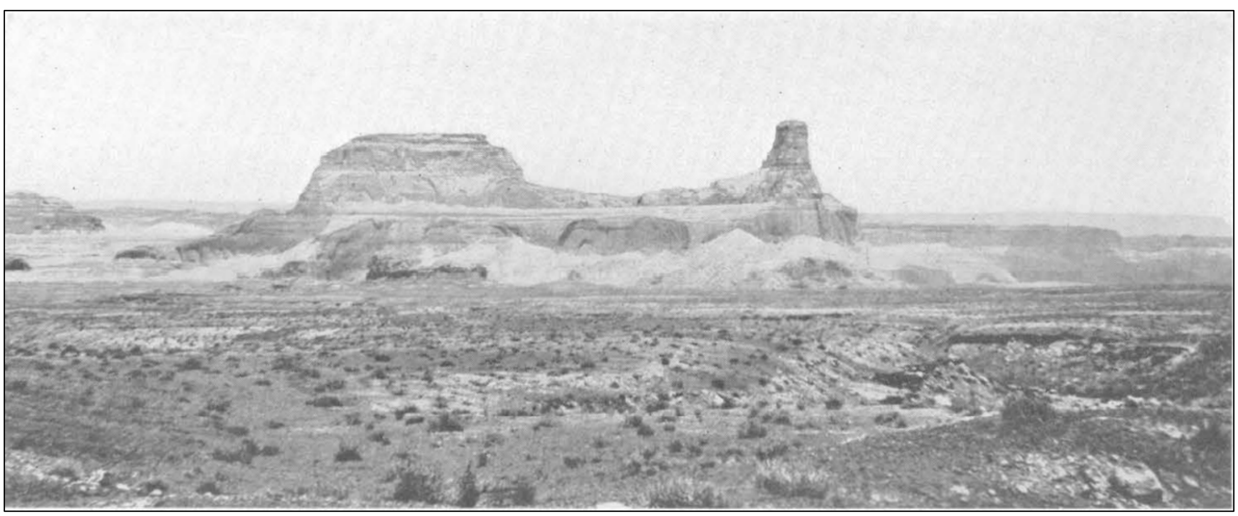


Figure 41. Gunsight Butte is composed of the Morrison, Romana, and Entrada Formations. Plate 10A in Gregory and Moore (1931).

The Jurassic Romana Sandstone was named by Peterson (1988) after Romana Mesa, a promontory on the north side of Lake Powell, Utah. The type section of the Romana Sandstone is located approximately 12 km (7.5 mi) northwest of Romana Mesa on the northeast side of Crosby Canyon, in SE/4 NE/4 SE/4 sec. 8, T. 43 S., R. 4 E., Kane County, Utah (Table 4; Figure 33; Peterson 1988). The formation is 44.2 m (145 ft) thick at the type section and mainly consists of very fine to fine-grained, flat-bedded and cross-bedded gray sandstone (Figure 42; Peterson 1988). At the type section, the Romana Sandstone underlies the Salt Wash Member of the Morrison Formation and overlies the Entrada Sandstone.

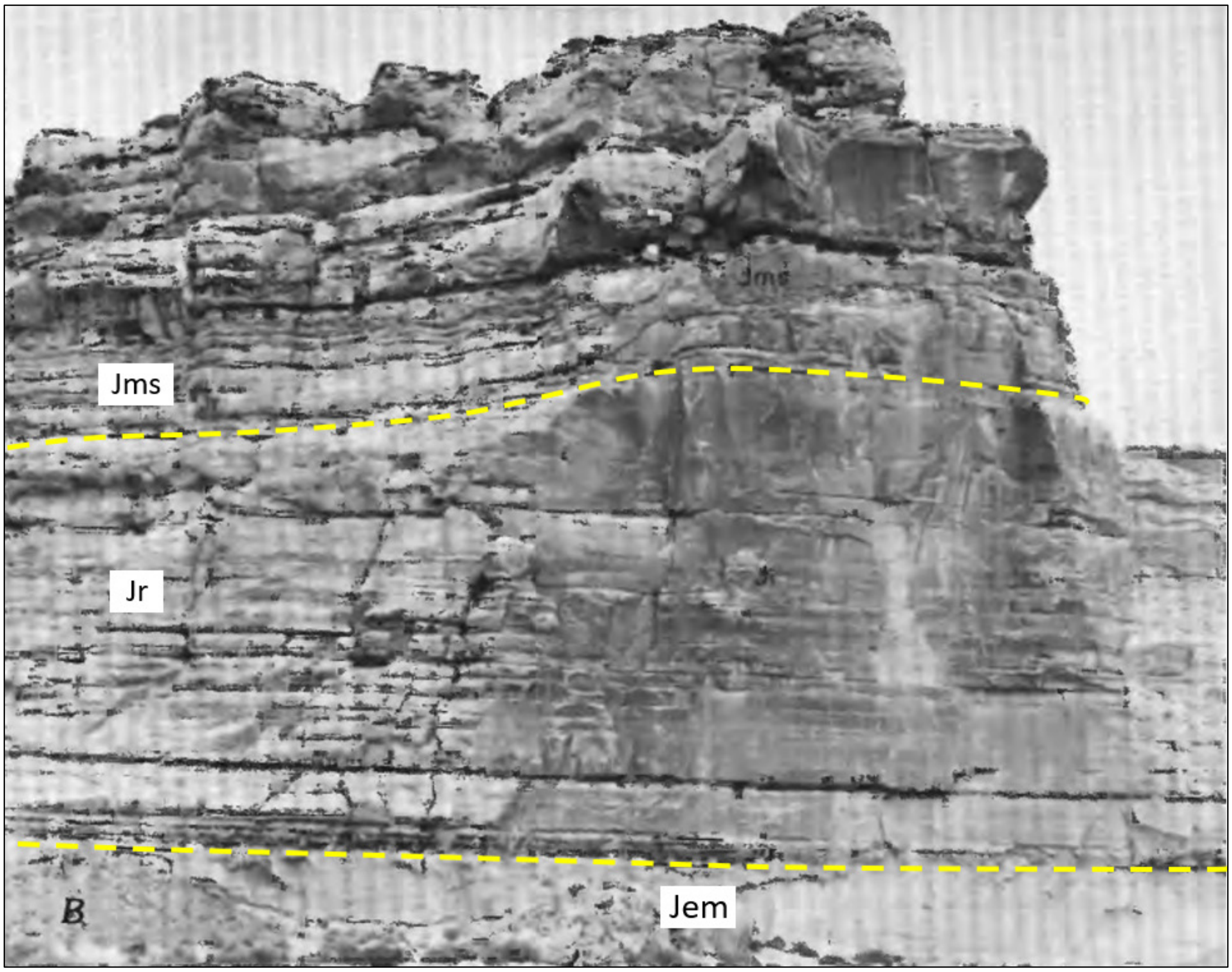


Figure 42. Type section of the Romana Sandstone in Crosby Canyon, southwest side of Kaiparowits Basin in SE/4 sec. 8, T. 43 S., R. 4 E., Kane County, Utah. The type section was measured along the left side of the photographed area. Jr, red marker bed shown near the base of the Romana Sandstone. Jem, middle member of the Entrada Sandstone. Jms, Salt Wash Member of the Morrison Formation. Exposure is 44.2 m (145 ft) thick. Annotated Figure B14 from Peterson (1988).

Grand Canyon National Park (GRCA)

Grand Canyon National Park (GRCA) encompasses 446 km (277 mi) of the Colorado River and adjacent uplands, from the southern terminus of Glen Canyon National Recreation Area to the eastern boundary of Lake Mead National Recreation Area in Coconino and Mohave Counties, Arizona (Figure 43). Established as a national park on February 26, 1919, GRCA protects approximately 486,289 hectares (1,201,647 acres) of one of the planet's most iconic geologic landscapes (Spamer 1989; National Park Service 2016a). Over the last six million years, the Colorado River has carved the Grand Canyon, exposing layers of rock that span more than one-third of Earth's history and record complex tectonic processes and ancient depositional environments. The Grand Canyon is a 1.5 km (0.9 mi)-deep gorge that ranges in width from 500 m to 30 km (0.3 mi to 18.6 mi) and contains a diverse suite of features that include sheer cliffs, buttes, plateaus, spires, mesas, natural arches, slot canyons, and temples. GRCA preserves a wide range of geologic resources including: 1) bedrock exposures ranging from approximately 1.84 billion to 227 million years old; 2) diverse paleontological resources ranging from Precambrian stromatolites to well-preserved Pleistocene vertebrate fossils; 3) surficial deposits; 4) a complex tectonic and erosional history; and 5) Pliocene to Holocene volcanic and variably consolidated surficial deposits (National Park Service 2010; Santucci and Tweet 2021). Strata exposed in GRCA represent six geologic eras (Paleoproterozoic Era to the Cenozoic Era), spanning nearly two billion years of the Earth's 4.6-billion-year history (Figures 44–46; Graham 2020; Karlstrom et al. 2021). GRCA is a keystone in the NPS and internationally recognized as a World Heritage Site (dedicated October 26, 1979).

Cenozoic deposits in Grand Canyon National Park reflect geologically recent processes that carved the current landscape and include fluvial terrace-gravel and alluvial fan deposits, landslide deposits, basalts of Neogene and Quaternary age, important travertine deposits, and cave sediments (Graham 2020). Uplift and erosion during the Cenozoic weathered away nearly all the Mesozoic rock units in the park, with remnants preserved in the far southeastern part of the park (Cedar Mountain) and under Neogene and Quaternary-age basalt flows both north and south of the Grand Canyon.

Paleozoic-age rocks in GRCA represent one of the best-known rock records in the world, consisting of a 910–1,220 m (3,000–4,000 ft)-thick succession responsible for much of the canyon's colorful scenery. The Paleozoic succession consists of sedimentary rocks formed in a variety of depositional environments representing multiple transgressions (relative sea level rise) and regressions (relative sea level fall) and include shallow marine, fluvial, and coastal sand dune settings. Separating the Cambrian Period strata from underlying Precambrian rocks is a major unconformity (John Wesley Powell's "Great Unconformity") that represents as much as 1.2 billion years of missing Earth history (Karlstrom and Timmons 2012).

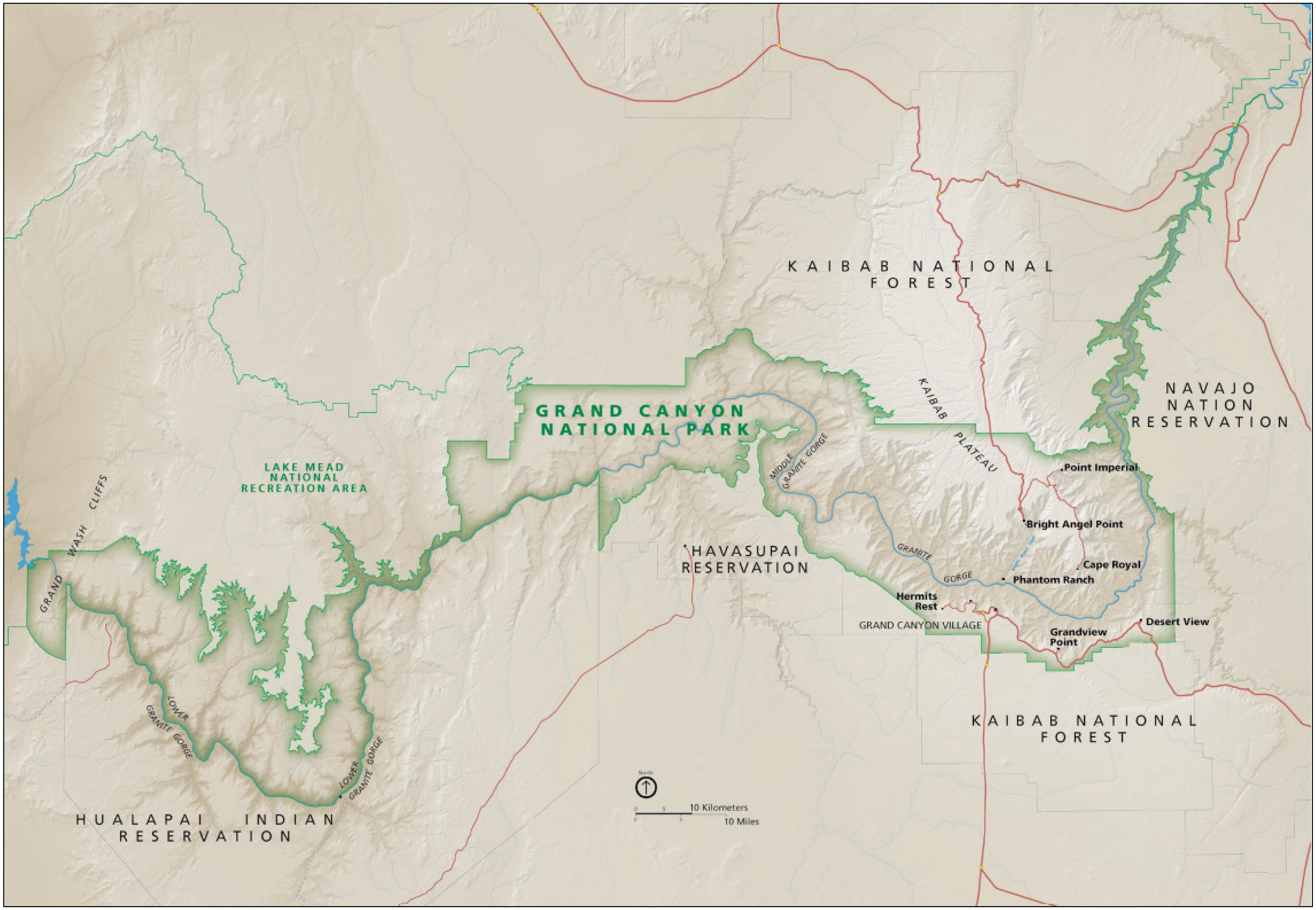


Figure 43. Park map of GRCA, Arizona (NPS).

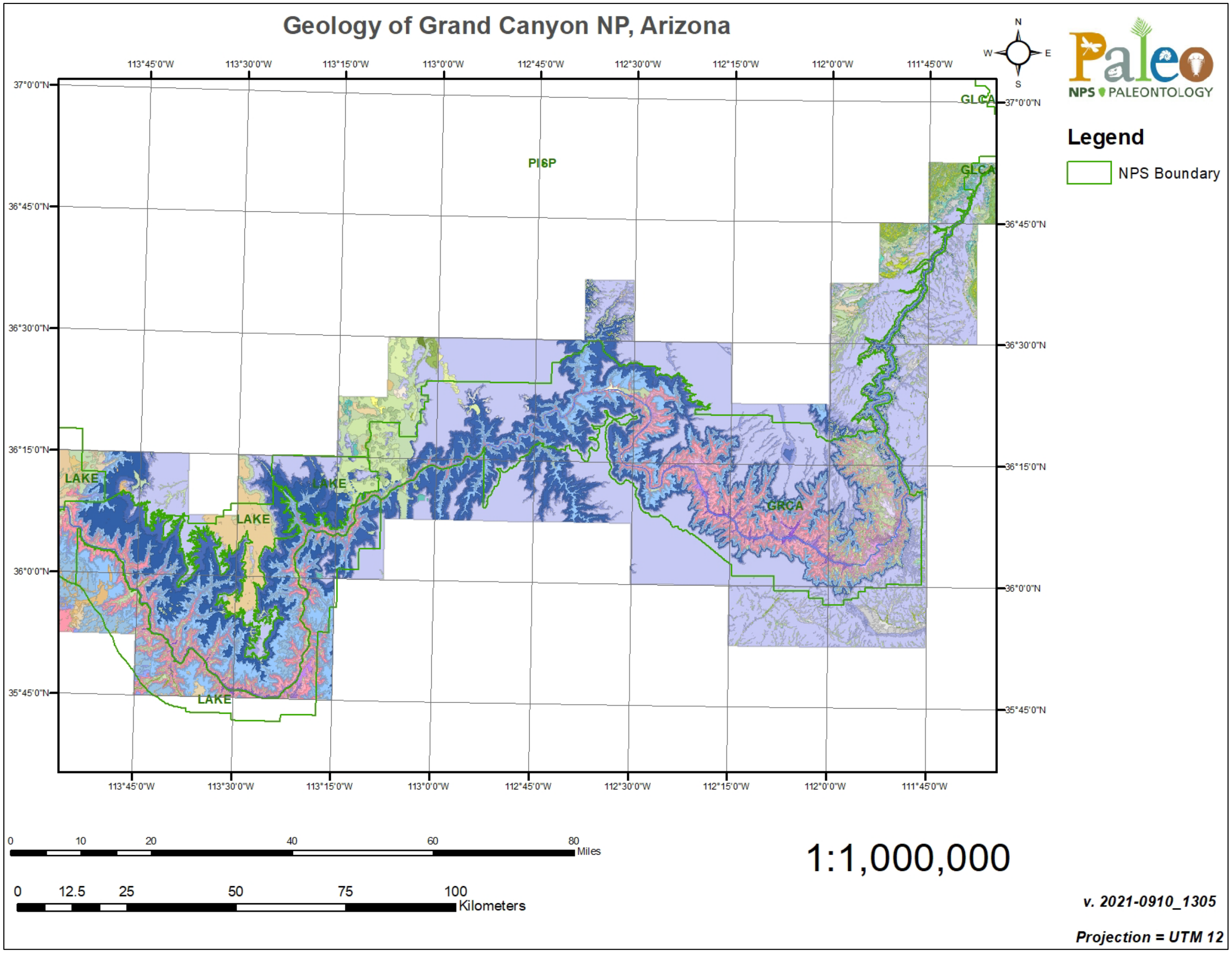


Figure 44. Geologic map of GRCA, Arizona; see Figure 45 for legend.

Legend

- Water
- Qaf - Artificial fill and quarries (Holocene)
- Qs - Stream-channel deposits (Holocene)
- Qf - Floodplain deposits (Holocene)
- Qd - Dune sand and sand sheet deposits, undivided (Holocene)
- Qes - Sand sheet deposits (Holocene)
- Qdp - Parabolic dune deposits (Holocene)
- Qlsp - Little Spring Basalt, pyroclastic deposits (Holocene)
- Qlsb - Little Spring Basalt, basalt flows (Holocene)
- Qg1 - Young terrace-gravel deposits (Holocene and Pleistocene)
- Qtgr - Terrace gravel deposits (Holocene and Pleistocene)
- Qg2 - Intermediate terrace-gravel deposits (Holocene and Pleistocene)
- Qg3 - Old terrace-gravel deposits (Holocene and Pleistocene)
- Qa1 - Young alluvial fan deposits (Holocene and Pleistocene)
- Qa - Alluvial deposits (Holocene and Pleistocene)
- Qa2 - Intermediate alluvial fan deposits (Holocene and Pleistocene)
- Qr - Colorado River gravel and silt deposits (Holocene and Pleistocene)
- Qgy - Young alluvial terrace deposits (Holocene and Pleistocene)
- Qay - Young alluvial fan deposits (Holocene and Pleistocene)
- Qa3 - Old alluvial fan deposits (Holocene, Pleistocene and Pliocene(?))
- Qps - Ponded sediments (Holocene and Pleistocene(?))
- Qae - Mixed alluvium and eolian deposits (Holocene and Pleistocene(?))
- Qv - Valley-fill deposits (Holocene and Pleistocene)
- Qt - Travertine deposits (Holocene and Pleistocene)
- Qtr - Talus and rock-fall deposits (Holocene and Pleistocene)
- Ql - Landslide deposits (Holocene and Pleistocene)
- Qltb - Basalt of Larimore Tank, basalt flows (Pleistocene)
- Qgrp - Basalt of Graham Ranch, pyroclastic deposits (Pleistocene)
- Qgrb - Basalt of Graham Ranch (Pleistocene)
- Qtid - Tuckup Canyon Basalt, intrusive dikes (Pleistocene)
- Qtp - Tuckup Canyon Basalt, pyroclastic deposits (Pleistocene)
- Qtb - Tuckup Canyon Basalt, basalt flow (Pleistocene)
- Qhp - Basalt of Hancock Knolls, pyroclastic deposits (Pleistocene)
- Qhb - Basalt of Hancock Knolls, basalt flows (Pleistocene)
- Qspd - Sage Basalt, pyroclastic deposits (Pleistocene)
- Qsb - Sage Basalt, basalt flows (Pleistocene)
- Qidn - Basalt dikes and necks (Pleistocene)
- Qpyr - Pyroclastic deposits (Pleistocene)
- Qbcr - Basalt flows along the Colorado River (Pleistocene)
- Qi - Basalt of the Uinkaret Plateau, intrusive rocks, south of Mount Trumbull (Pleistocene)
- Qi1 - Basalt of the Uinkaret Plateau, intrusive rocks, north of Mount Trumbull (Pleistocene)
- Qp - Basalt of the Uinkaret Plateau, pyroclastic deposits, south of Mount Trumbull (Pleistocene)
- Qp1 - Basalt of the Uinkaret Plateau, pyroclastic deposits, north of Mount Trumbull (Pleistocene)
- Qb - Basalt of the Uinkaret Plateau, basalt flows, south of Mount Trumbull (Pleistocene)
- Qb1 - Basalt of the Uinkaret Plateau, basalt flows, north of Mount Trumbull (Pleistocene)
- Qp6588 - Basalt of hill 6588, pyroclastic deposits (Pleistocene)
- Qb6588 - Basalt of hill 6588, basalt flows (Pleistocene)
- Qcbb - Basalt of Craigs Knoll and Berry Knoll, basalt flows (Pleistocene)
- Qg4 - Older terrace-gravel deposits (Pleistocene)
- QTi - Hells Hole dikes (Pleistocene or Pliocene(?))
- QTg - Terrace-gravel deposits (Pleistocene and Pliocene(?))
- QTa4 - Older alluvial fan deposits (Pleistocene and Pliocene)
- QTgd - Old gravel deposits (Pleistocene, Pliocene, and middle Miocene)
- QTg4 - Older terrace-gravel deposits (Pleistocene and Pliocene(?))
- QTg5 - Youngest old terrace-gravel deposits (Pleistocene, Pliocene and Miocene)
- Qg5-18 - Oldest terrace-gravel deposits, undivided (Pleistocene and Pliocene(?))
- Tei - Basalt north of Mount Emma, intrusive rocks (Pliocene)
- Tep - Basalt north of Mount Emma, pyroclastic deposits (Pliocene)
- Teb - Basalt north of Mount Emma, basalt flows (Pliocene)
- Tmlb - Basalt of Mount Logan, basalt flows (Pliocene)
- Tbid - Basalt of Bundyville, intrusive dikes (Pliocene)
- Tbb - Basalt of Bundyville, basalt flows (Pliocene)
- Tmb - Basalt of Mount Trumbull, basalt flows (Pliocene)
- Tgs - Gravel and sedimentary deposits (Pliocene to lower Paleocene(?))
- Twi - Whitmore Dike Swarm, intrusive dikes (Pliocene)
- Twb - Whitmore Dike Swarm, basalt flow (Pliocene)
- Tgr - Rocks of the Grand Wash Trough, red siltstone, sandstone, and conglomerate facies (Pliocene and Miocene)
- Tscd - Old stream-channel deposits (Pliocene and Miocene)
- Tsi - Shivwits Basalt, intrusive rocks (Miocene)
- Tsp - Basalt of the Shivwits Plateau, pyroclastic deposits (Miocene)
- Tsb - Shivwits Basalt, basalt flows (Miocene)
- T227i - 227-Mile intrusive (Miocene)
- Tp6i - Dikes of Parashant Canyon and Hundred and Ninetysix Mile Creek (Miocene)
- T2i - Dikes of Colorado River Mile 202 (Miocene)
- Tsgi - Snap Point Basalt and Garrett Dikes, intrusive dikes (Miocene)
- Tsgb - Snap Point Basalt and Garrett Dikes, basalt flows (Miocene)

Figure 45. Geologic map legend of GRCA, Arizona.

- Tgc - Rocks of the Grand Wash Trough, paleozoic-clast conglomerate (Miocene)
- Tgl - Rocks of the Grand Wash Trough, limestone and siltstone facies (Miocene)
- Tgg - Rocks of the Grand Wash Trough, gypsum and gypsiferous siltstone facies (Miocene)
- Tgx - Proterozoic-clast conglomerate facies (Miocene)
- Tc - Volcanic rocks of the Hualapai Plateau, pyroclastic deposits (Miocene)
- Tv - Volcanic rocks of the Hualapai Plateau, andesite flows and basalt flows, undivided (Miocene)
- Ti - Volcanic rocks of the Hualapai Plateau, intrusive dikes (Miocene)
- TKs1 - Old gravel and sedimentary deposits (lower Miocene, Oligocene, Eocene, Paleocene, and Upper Cretaceous)
- Jc - Carmel Formation, undivided (Middle Jurassic)
- Jp - Page Sandstone (Middle Jurassic)
- Jn - Navajo Sandstone (Lower Jurassic)
- Jk - Kayenta Formation, undivided (Lower Jurassic)
- Jks - Kayenta Formation, Springdale Sandstone Member (Lower Jurassic)
- Jm - Moenave Formation and Wingate Sandstone, undivided (Lower Jurassic and Upper Triassic(?))
- TRc - Chinle Formation, undivided (Upper Triassic)
- TRco - Chinle Formation, Owl Rock Member (Upper Triassic)
- TRcp - Chinle Formation, Petrified Forest Member (Upper Triassic)
- TRcs - Chinle Formation, Shinarump Member (Upper Triassic)
- TRm - Moenkopi Formation, undivided (Upper(?), Middle(?) and Lower Triassic)
- TRmu - Moenkopi Formation, upper red member (Middle(?) and Lower Triassic)
- TRms - Moenkopi Formation, Shnabkaib Member (Lower Triassic)
- TRmw - Moenkopi Formation, Wupatki Member (Lower Triassic)
- TRmlm - Moenkopi Formation, lower red member, Virgin Limestone Member, and middle red member, undivided (Lower Triassic)
- TRmt - Moenkopi Formation, Timpoweap Member (Lower Triassic)
- Pk - Kaibab Formation, undivided (Lower Permian)
- Pkh - Kaibab Formation, Harrisburg Member (Lower Permian)
- Pkf - Kaibab Formation, Fossil Mountain Member (Lower Permian)
- Pt - Toroweap Formation, undivided (Lower Permian)
- Ptw - Toroweap Formation, Woods Ranch Member (Lower Permian)
- Ptb - Toroweap Formation, Brady Canyon and Seligman Members, undivided (Lower Permian)
- Pc - Coconino Sandstone (Lower Permian)
- Ph - Hermit Formation (Lower Permian)
- Pe - Esplanade Sandstone (Lower Permian)
- Pep - Esplanade Sandstone and Pakoon Limestone, undivided (Lower Permian)
- PNMs - Wescogame Formation, Manakacha Formation, and Watahomigi Formation, undivided (Pennsylvanian and Upper Mississippian)
- Ms - Surprise Canyon Formation (Upper Mississippian)
- Mr - Redwall Limestone, undivided (Mississippian)
- Dtb - Temple Butte Formation (Upper and Middle Devonian)
- Cm - Muav Limestone (Middle Cambrian)
- Cba - Bright Angel Shale (Middle Cambrian)
- Ct - Tapeats Sandstone (Middle and Lower(?) Cambrian)
- Cs - Sixtymile Formation, undivided (Cambrian)
- Zkw - Kwagunt Formation, Walcott Member (Neoproterozoic)
- Zka - Kwagunt Formation, Awatubi Member (Neoproterozoic)
- Zkcb - Kwagunt Formation, Carbon Butte Member (Neoproterozoic)
- Zgd - Galeros Formation, Duppa Member (Neoproterozoic)
- Zgcc - Galeros Formation, Carbon Canyon Member (Neoproterozoic)
- Zgj - Galeros Formation, Jupiter Member (Neoproterozoic)
- Zgt - Galeros Formation, Tanner Member (Neoproterozoic)
- Zn - Nankoweap Formation, undivided (Neoproterozoic)
- Yi - Unnamed diabase sills and dikes (Mesoproterozoic)
- Yc - Cardenas Basalt (Mesoproterozoic)
- Yd - Dox Formation (Mesoproterozoic)
- Ydo - Dox Formation, Ochoa Point Member (Mesoproterozoic)
- Ydc - Dox Formation, Comanche Point Member (Mesoproterozoic)
- Yds - Dox Formation, Solomon Temple Member (Mesoproterozoic)
- Yde - Dox Formation, Escalante Creek Member (Mesoproterozoic)
- Ys - Shinumo Sandstone, undivided (Mesoproterozoic)
- Yh - Hakatai Shale, undivided (Mesoproterozoic)
- Yb - Bass Formation (Mesoproterozoic)
- Yg - Young granite and pegmatite (Proterozoic)
- Xg - Granite (Paleoproterozoic)
- Xgr - Granite, granitic pegmatite and aplite (Proterozoic)
- Xgd - Granodiorite-gabbro-diorite and granodiorite complexes (Proterozoic)
- Xum - Ultramafic rocks (Paleoproterozoic)
- Xdg - Diorite, gabbro, and anorthosite (Proterozoic)
- Xs - Schist (Proterozoic)
- Xv - Vishnu Schist (Proterozoic)
- Xr - Rama Schist and Gneiss (Paleoproterozoic)
- Xbr - Brahma Schist (Paleoproterozoic)
- Xm - Mafic metavolcanic rocks (Proterozoic)
- Xo - Orthoamphibole schist (Proterozoic)
- Xc - Carbonate and chert (Proterozoic)
- Xec - Elves Chasm pluton (Paleoproterozoic)

Figure 45 (continued). Geologic map legend of GRCA, Arizona.

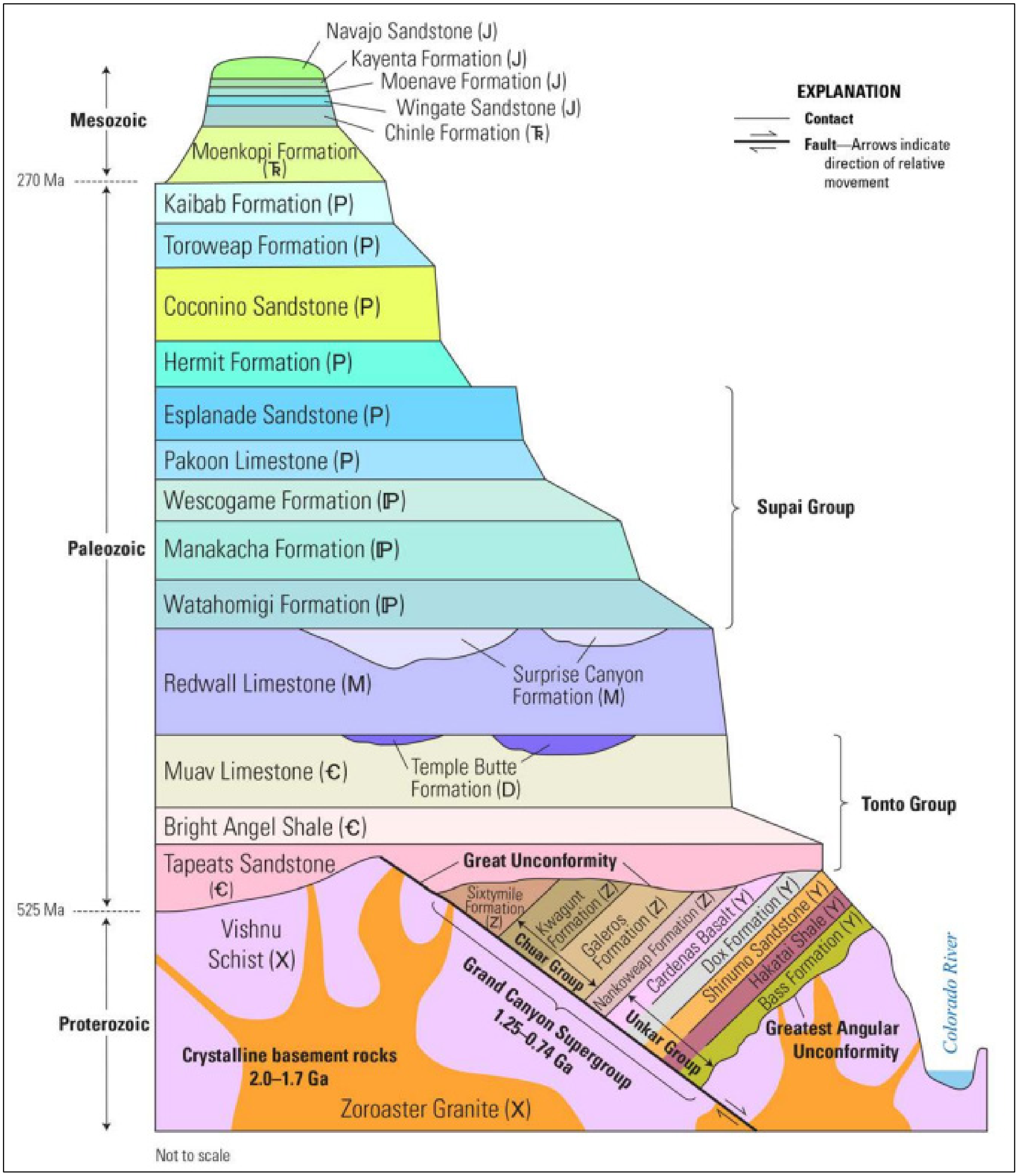


Figure 46. Schematic column showing the stratigraphy and structural relations of geologic formations in the Grand Canyon. Recently, the Sixtymile Formation was proposed to be Cambrian (not Proterozoic) (Karlstrom et al. 2018; 2020) and the Nankoweap Formation was moved into the Chuar Group (Dehler et al. 2017). Mesozoic rocks younger than the Chinle Formation are not found within the boundaries of GRCA, but are present in the immediate vicinity of the park. Figure 2 from Billingsley et al. (2019).

The Mesoproterozoic–Neoproterozoic Grand Canyon Supergroup, found only in GRCA, has an aggregate thickness of 3,650 (12,000 ft) and includes rocks deposited mostly in rift valleys associated with the supercontinent Rodinia. The Upper, Middle, and Lower Granite Gorges of the Grand Canyon contain the oldest bedrock exposures in the park, consisting of Precambrian igneous and metamorphic rocks known as the Vishnu Basement Rocks. The Elves Chasm pluton (1.84 billion years old) is the oldest rock identified in GRCA and is separated from the overlying Granite Gorge Metamorphic Suite by an unconformity representing 90 million years of missing geologic time (Karlstrom et al. 2021). The Granite Gorge Metamorphic Suite (1.75 billion years old) includes the Vishnu, Brama, and Rama Schists. These rocks were later intruded at great depths by granodiorite plutons of the Zoroaster Plutonic Complex (1.74–1.71 billion years old), and by a later group of pegmatite dikes (Cremation pegmatite) and granite plutons (Phantom granite) between 1.69–1.66 billion years ago (Karlstrom et al. 2003, 2021). In the western Grand Canyon, the Quartermaster pluton represents the youngest rocks of the Vishnu Basement Rocks at 1.37 billion years old (Karlstrom et al. 2021).

Grand Canyon National Park contains 54 identified stratotypes that are subdivided into 24 type sections, 16 type localities, 6 type areas, and 8 reference sections (Table 5; Figures 47–50). Many stratotype locations in GRCA are described using the USGS–GCMRC river mile system, which measures distance in miles downstream from the USGS gaging station at Lees Ferry, Arizona (U.S. Geological Survey 2006). In addition to the designated stratotypes located within GRCA, stratotypes located within 48 km (30 mi) of the park's boundaries include the Cambrian Peach Springs Canyon Member of the Muav Formation (type locality); Mississippian Mooney Falls Member of the Redwall Limestone (type section), Surprise Canyon Formation (type section); Pennsylvanian–Permian Supai Group (type section); Pennsylvanian Watahomigi Formation (type section), Manakacha Formation (type section), Wescogame Formation (type section); Permian Esplanade Sandstone (type section), Coconino Sandstone (type section), Seligman Member of the Toroweap Formation (type locality), Kaibab Formation (type locality); Triassic Moenkopi Formation (type section); Jurassic Moenave Formation (type locality), Whitmore Point Member of the Moenave Formation (type section), Dinosaur Canyon Member of the Moenave Formation (type locality), Thousand Pockets Tongue of the Carmel Formation (type section), Judd Hollow Tongue of the Carmel Formation (type section), type sections of the John Henry, Smoky Hollow, and Tibbett Canyon Members of the Straight Cliffs Formation; Miocene Blue Mountain Basalt (type locality); and Pleistocene Little Tanks Basalt (type area), Basalt of Graham Ranch (type area), Sage Basalt (type area), and the Heaton Knolls Basalt (type area).

Table 5. List of GRCA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Tuckup Canyon Basalt (Qtb, Qtp, Qtid)	Billingsley and Hampton 2000	Type area: Tuckup Canyon, central Grand Canyon, in sec. 11, T. 34 N., R. 6 W., northern Mohave Co., AZ.	Pleistocene
Basalt of Hancock Knolls (Qhb, Qhp)	Billingsley and Hampton 2000	Type area: Hancock Knolls, Kanab Plateau, in sec. 20, T. 35 N., R. 6 W., northern Mojave Co., AZ.	Pleistocene
Snap Point Basalt	Billingsley and Wellmeyer 2003	Type area: Snap Point, Shivwits Plateau, in sec. 16, T. 32 N., R. 14 W., Mohave Co., AZ.	Miocene
Fossil Mountain Member, Kaibab Formation (Pkf)	McKee 1938; Sorauf and Billingsley 1991	Type locality: Bass Trail on Fossil Mountain, Coconino Co., northern AZ.	early Permian
Toroweap Formation (Pt)	McKee 1938; Rawson and Turner 1974	Type section: in Brady Canyon, an eastern side canyon of Toroweap (Tuweep) Valley, about 14 km (9 mi) above the mouth and 13 km (8 mi) north of Colorado River, Mohave Co., AZ.	early Permian
Brady Canyon Member, Toroweap Formation (Ptb)	Sorauf and Billingsley 1991	Type locality: in Brady Canyon, on the eastern side of Toroweap Valley about 20.6 km (12.8 mi) north of the Colorado River, Mohave Co., northern AZ.	early Permian
Hermit Formation (Ph)	Noble 1922	Type locality: Hermit basin, Grand Canyon, Coconino Co., northern AZ.	early Permian
Redwall Limestone (Mr)	Darton 1910	Type locality: Redwall Canyon, in the Shinumo drainage basin on the north side of Grand Canyon, Coconino Co., northern AZ.	Mississippian
Horseshoe Mesa Member, Redwall Limestone	McKee 1963	Type section: Horseshoe Mesa, Coconino Co., AZ.	Mississippian
Thunder Springs Member, Redwall Limestone	McKee 1963	Type section: in cliff west of springs at head of Thunder River about 3.2 km (2 mi) north of Colorado River, Coconino Co., AZ.	Mississippian
Whitmore Wash Member, Redwall Limestone	McKee 1963	Type section: east side of Whitmore Wash Valley, on the upthrown side of the Hurricane Fault, about 0.4 km (0.25 mi) north of Colorado River, Mohave Co., AZ.	Mississippian
Temple Butte Formation (Dtb)	Walcott 1883; McKee 1974	Type section: at Temple Butte on the west side of the Colorado River a few miles below its junction with the Little Colorado River, Coconino Co., AZ.	Middle–Late Devonian
Tonto Group (Cm, Cba, Ct)	Noble 1922; Elston 1989a; Rose 2011	Type section (Noble): measured along the South Bass Trail, Coconino Co., AZ. Type section (Rose): measured in Blacktail Canyon, lat. 36°14′25″ N., long. 112°26′21″ W., Coconino Co., AZ.	early–middle Cambrian
Muav Formation (Cm)	Noble 1914, 1922; McKee 1945	Type locality: Muav Canyon, Coconino Co., AZ.	middle Cambrian

Table 5 (continued). List of GRCA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Havasu Member, Muav Formation	McKee 1945	Type locality: near the mouth of Havasu Canyon, on the south side of Kanab Plateau [Tuckup Canyon 15′ Quadrangle], Coconino Co., northwestern AZ.	middle Cambrian
Kanab Canyon Member, Muav Formation	McKee 1945	Type locality: at the mouth of Kanab Canyon, where it is lowest massive cliff-forming unit, not far above the level of the Colorado River [Kanab Point 15′ Quadrangle], Mohave and Coconino Cos., northwestern AZ.	middle Cambrian
Lava Falls Tongue, Muav Formation	McKee 1945	Type locality: about 1.6 km (1 mi) east of Lava Falls at the foot of Toroweap Canyon, Coconino Co., northwestern AZ.	middle Cambrian
Bright Angel Formation (Cba)	McKee 1945	Type locality: exposures in the cliffs of Bright Angel Canyon, AZ.	middle Cambrian
Tapeats Sandstone (Ct)	Noble 1914; Molenaar 1969	Type locality: Tapeats Creek, Coconino Co., AZ.	early(?)–middle Cambrian
Grand Canyon Supergroup (Zk*, Zg*, Yd*, Ys, Yh, Tb)	Powell 1876; Molenaar 1969	Type locality: Grand Canyon, AZ.	Mesoproterozoic–Neoproterozoic
Sixtymile Formation (Cs)	Ford and Breed 1973	Type section: cliffs on the north side of the upper part of Sixty Mile Canyon, Coconino Co., AZ. Reference section: top of Nankoweap Butte, Awatubi Canyon, Coconino Co., AZ.	early–middle Cambrian
Chuar Group	Walcott 1883; Molenaar 1969	Type locality: Chuar Valley, Coconino Co., AZ.	Neoproterozoic
Kwagunt Formation (Zkw, Zka, Zkcb)	Ford and Breed 1973	Type area: Kwagunt Canyon, in the northern slopes of which the formation is fully exposed, Coconino Co., AZ.	Neoproterozoic
Walcott Member, Kwagunt Formation (Zkw)	Ford and Breed 1973	Type section: head of Walcott Glen and upper part of Nankoweap Butte, Coconino Co., AZ.	Neoproterozoic
Awatubi Member, Kwagunt Formation (Zka)	Ford and Breed 1973	Type section: Awatubi Canyon, Coconino Co., AZ. Reference section: southeast slope of Nankoweap Butte, Coconino Co., AZ.	Neoproterozoic
Carbon Butte Member, Kwagunt Formation (Zkcb)	Ford and Breed 1973	Type section: Carbon Butte, Coconino Co., AZ. Reference section: south fork of Nankoweap Canyon, Coconino Co., AZ	Neoproterozoic
Galeros Formation (Zgd, Zgcc, Zgj, Zgt)	Ford and Breed 1973	Type area: Galeros Promontory, which overlooks the southern part of the Chuar outcrops in Chuar and Carbon Canyons, Coconino Co., AZ.	Neoproterozoic

Table 5 (continued). List of GRCA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Duppa Member, Galeros Formation (Zgd)	Ford and Breed 1973	Type section: below Duppa Butte in Kwagunt Canyon, Coconino Co., AZ.	Neoproterozoic
Carbon Canyon Member, Galeros Formation (Zgcc)	Ford and Breed 1973	Type section: Carbon Canyon west fork and mid-Chuar Canyon, Coconino Co., AZ.	Neoproterozoic
Jupiter Member, Galeros Formation (Zgj)	Ford and Breed 1973	Type section: below Jupiter Temple in lower part of Chuar Canyon, Coconino Co., AZ.	Neoproterozoic
Tanner Member, Galeros Formation (Zgt)	Ford and Breed 1973	Type section: overlooking Tanner Rapids in the cliffs of Basalt Canyon, Coconino Co., AZ. Reference section: lower end of Chuar Canyon, Coconino Co., AZ	Neoproterozoic
Nankoweap Formation (Zn)	Van Gundy 1951	Type section: Basalt Canyon, on the north side of the Colorado River just south of its intersection with the Little Colorado River, Coconino Co., AZ.	Neoproterozoic
Ferruginous Member, Nankoweap Formation	Elston and Scott 1976	Type section: in the graben at the Tanner Canyon rapids, Coconino Co., AZ.	Neoproterozoic
Unkar Group (Yd*, Ys, Yh, Yb)	Walcott 1894; Molenaar 1969	Type locality: Unkar Valley, Coconino Co., AZ.	Mesoproterozoic
Dox Formation (Yd, Ydo, Ydc, Yds, Yde)	Noble 1914; Beus et al. 1974	Type section: beneath Dox Castle in a tributary to Shinumo Creek, Coconino Co., AZ	Mesoproterozoic
Ochoa Point Member, Dox Formation (Ydo)	Stevenson and Beus 1982	Type section: in an unnamed stream on the southwest side of Ochoa Point, a promontory west of Basalt Canyon, northwest side of the Colorado River [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic
Comanche Point Member, Dox Formation (Ydc)	Stevenson and Beus 1982	Type section: exposures in the bed of unnamed creek tributary to Tanner Canyon, 1.6 km (1 mi) west of Comanche Point, southeast side of the Colorado River between Tanner Canyon and Comanche Creek [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic
Solomon Temple Member, Dox Formation (Yds)	Stevenson and Beus 1982	Type section: 2.4 km (1.5 mi) northeast of Solomon Temple, south of Unkar Creek [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic
Escalante Creek Member, Dox Formation (Yde)	Stevenson and Beus 1982	Type section: Escalante Creek [Vishnu Temple 15′ Quadrangle], Coconino Co., AZ.	Mesoproterozoic
Shinumo Sandstone (Ys)	Noble 1914; Molenaar 1969	Type locality: Shinumo Creek canyon, Coconino Co., AZ.	Mesoproterozoic

Table 5 (continued). List of GRCA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Hakatai Shale (Yh)	Noble 1914; Beus et al. 1974	Type section: Hakatai Canyon, Coconino Co., AZ.	Mesoproterozoic
Bass Formation (Yb)	Noble 1914; Beus et al. 1974	Type section: in Hotauta Canyon, on the north side of the Colorado River [Shinumo Quadrangle], Coconino Co., northern AZ.	Mesoproterozoic
Hotauta Conglomerate Member, Bass Formation	Noble 1914; Molenaar 1969	Type locality: in Hotauta Canyon, on the north side of the Colorado River [Shinumo Quadrangle], Coconino Co., northern AZ.	Mesoproterozoic
Zoroaster Granite	Campbell and Maxson 1938; Barnes 1989	Type area: exposures between Zoroaster and Cremation Canyons, Coconino Co., AZ.	Paleoproterozoic
Vishnu Schist (Xv)	Campbell and Maxson 1938; Ilg et al. 1996	Type locality: in lower canyon of Vishnu Creek, Coconino Co., AZ. Reference section: Vishnu Canyon, Coconino Co., AZ.	Paleoproterozoic
Rama Schist and Gneiss (Xr)	Ilg et al. 1996	Reference sections: 1) for higher-grade quartzofeldspathic gneisses, ~1 km (0.6 mi) downstream from Hance Canyon in the core of the Sockdolager antiform; 2), for the massive, metamorphosed lapilli-crystal tuffs, in Shinumo Creek ~6 km (3.7 km) from the Colorado River; and 3), for quartz-eye metarhyolite, near river mile 127 [measured downstream from Lee's Ferry]	Paleoproterozoic

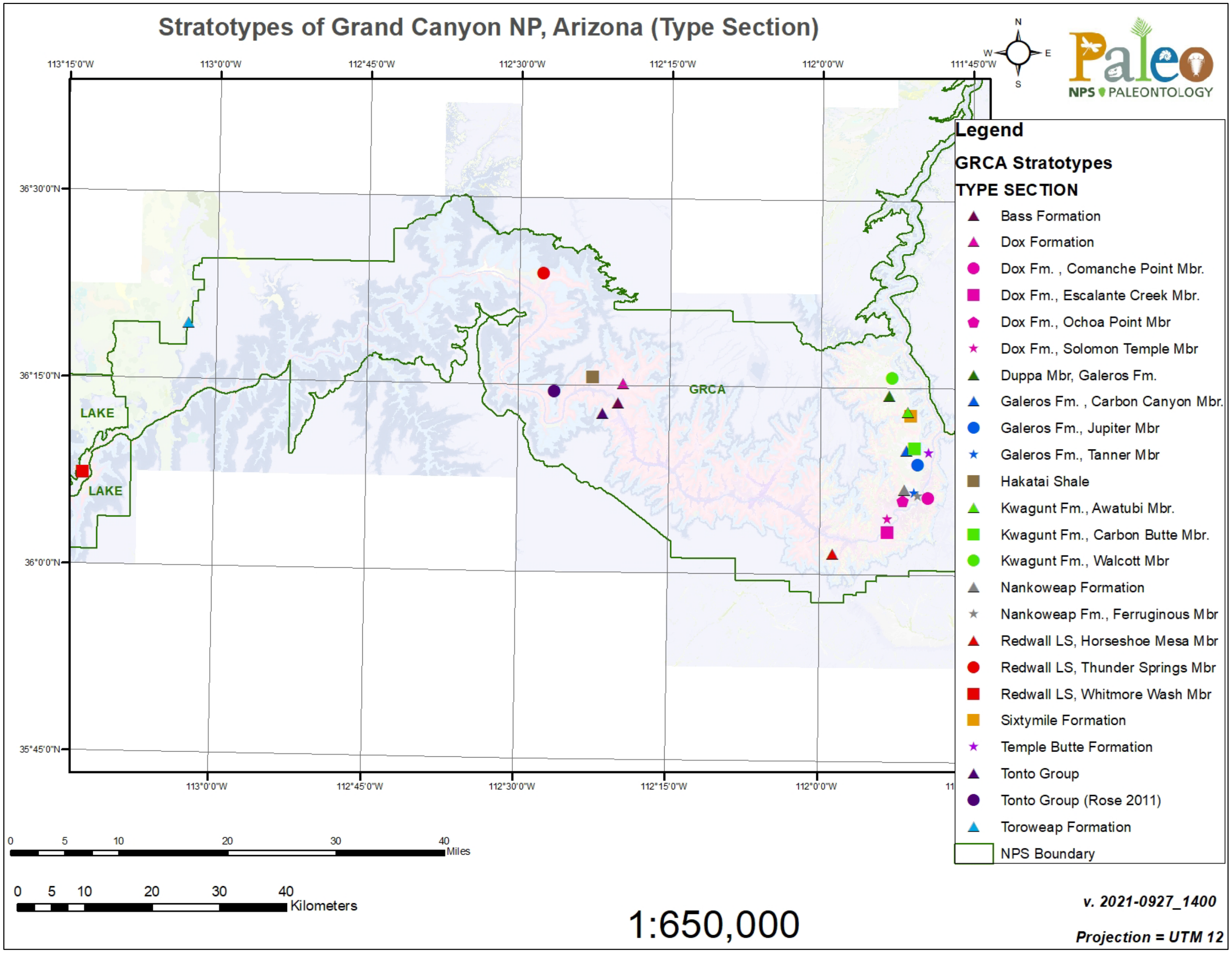


Figure 47. Modified geologic map of GRCA showing type section locations. The transparency of the geologic units layer has been increased.

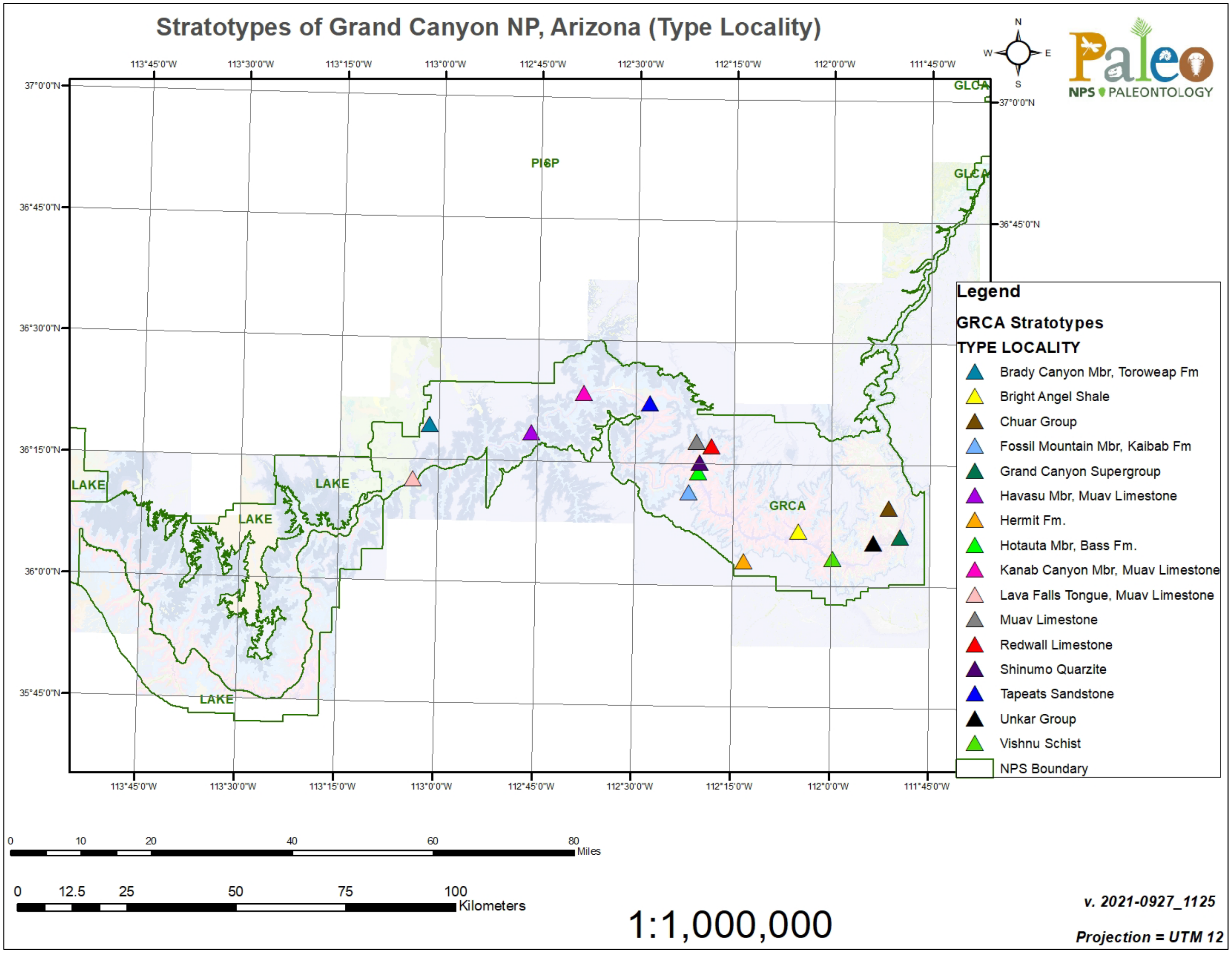


Figure 48. Modified geologic map of GRCA showing type locality locations. The transparency of the geologic units layer has been increased.

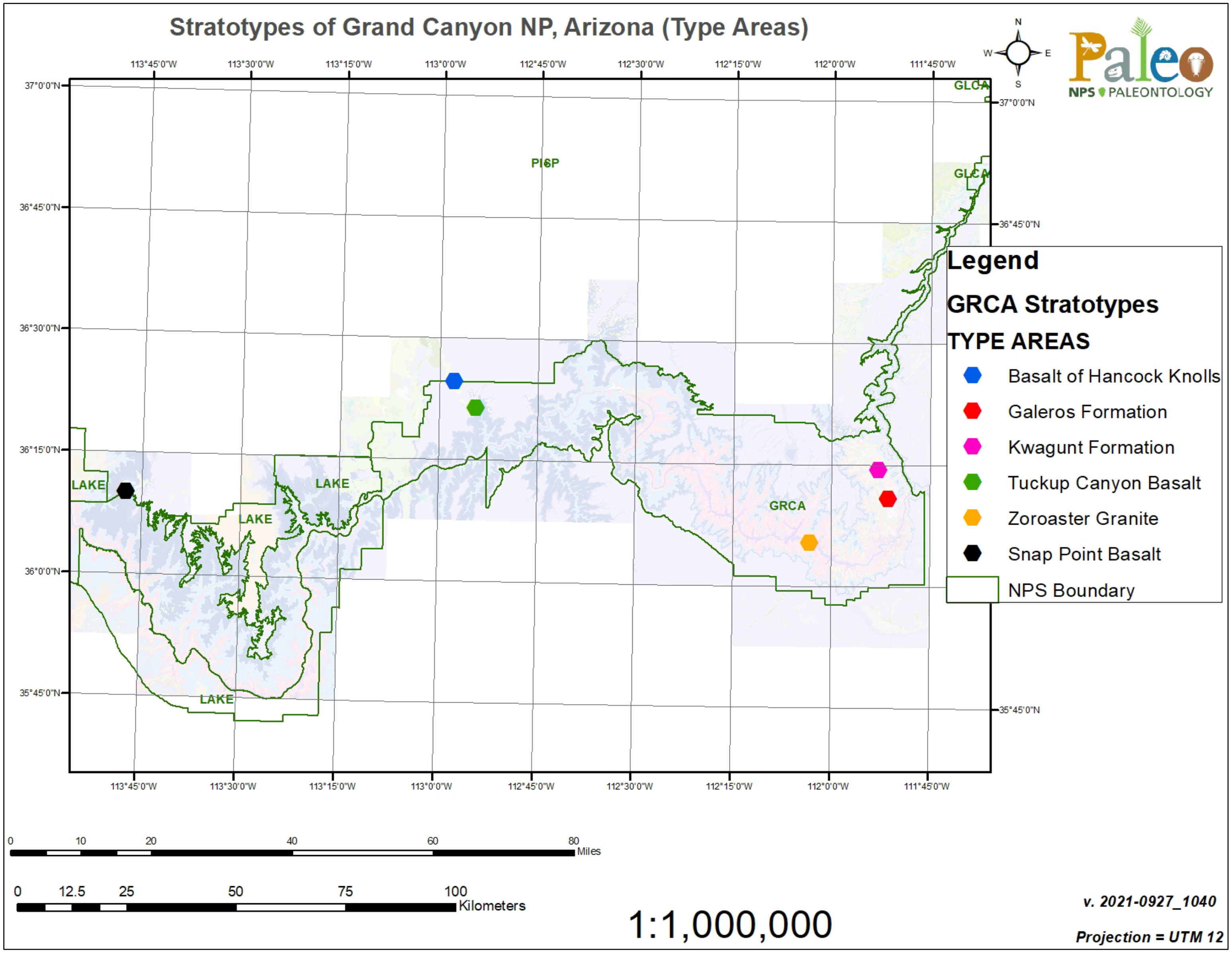


Figure 49. Modified geologic map of GRCA showing type area locations. The transparency of the geologic units layer has been increased.

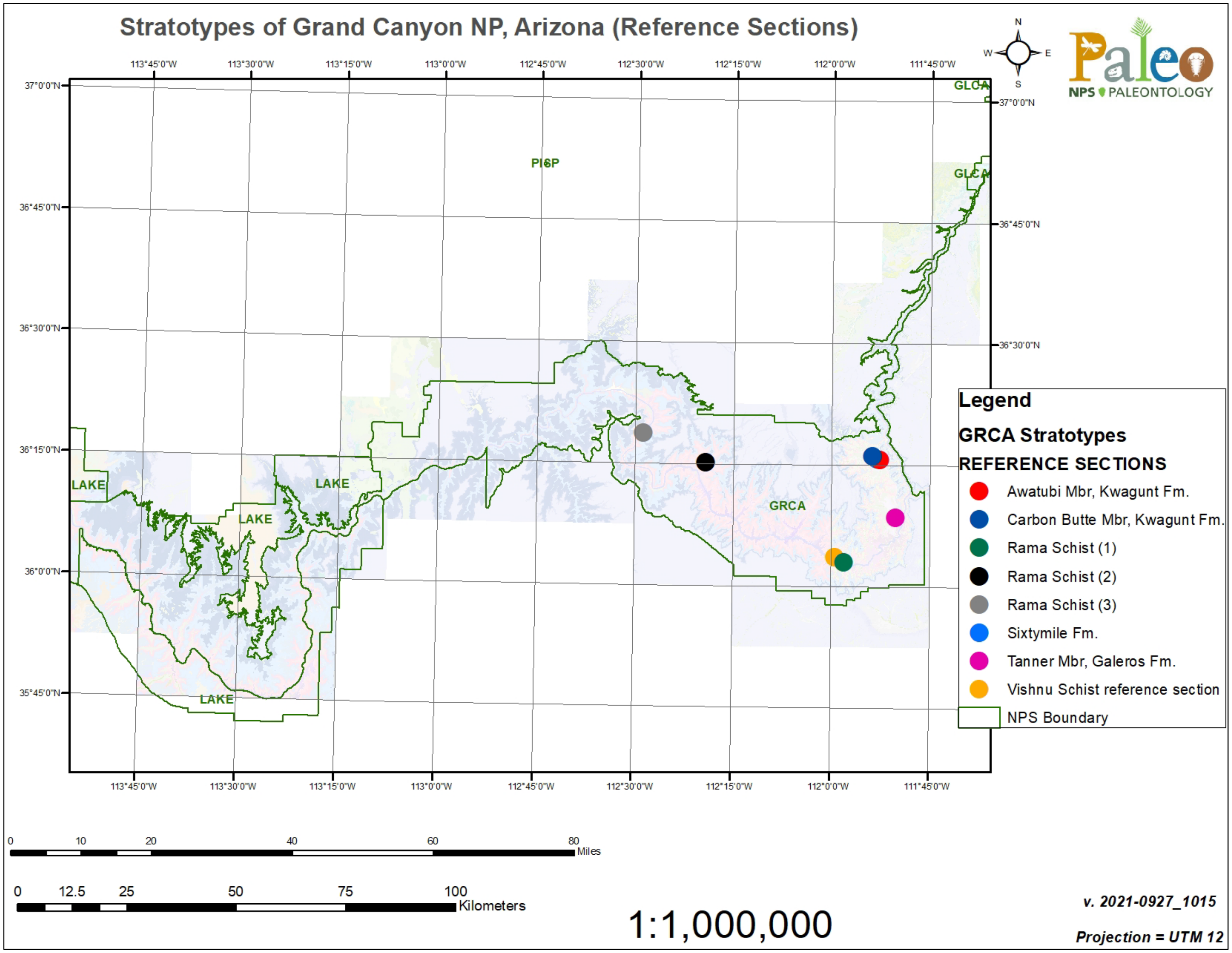


Figure 50. Modified geologic map of GRCA showing reference section locations. The transparency of the geologic units layer has been increased.

Vishnu Basement Rocks

The Paleoproterozoic Rama Schist of the Granite Gorge Metamorphic Suite was first mentioned by Maxson (1968) to describe approximately one billion-year-old basalts of the Mesoproterozoic Grand Canyon Supergroup. The designation by Maxson (1968) would later be abandoned when these basalts were formally named the "Cardenas Basalt" by Ford et al. (1972) and Elston (1989b). A new usage of the term "Rama" in Ilg et al. (1996) describes quartzofeldspathic schist and gneiss, meta-rhyolites, and injected pegmatite named after the Rama Shrine, located near the core of the Sockdolager antiform, Arizona. Three reference sections for the Rama Schist are designated at the following locations within GRCA (Figure 50): 1) for higher-grade quartzofeldspathic gneisses located ~1 km (0.6 mi) downstream from Hance Canyon in the core of the Sockdolager antiform (Figure 51); 2) for the massive, metamorphosed lapilli-crystal tuffs, in Shinumo Creek ~6 km (3.7 km) from the Colorado River; and 3) for quartz-eye meta-rhyolite near river mile 127 (Table 5; Figure 52; Ilg et al. 1996). The Rama Schist is locally interlayered with the mafic Brahma Schist (Ilg et al. 1996).

Figure 51. Pegmatite dikes in the Rama Schist near the reference section in the core of the Sockdolager antiform, on the south bank of river mile 80.5. Photograph EM04 from Billingsley et al. (2019).

Figure 52. Exposures of river-polished amphibolitic Rama Schist on the west (left) bank of the Colorado River at mile 128.8. Photograph CM06 from Billingsley et al. (2019).

The Paleoproterozoic Vishnu Schist of the Granite Gorge Metamorphic Suite was first described as the "Vishnu terrane" by Charles Doolittle Walcott, who named the exposures after the Vishnu Temple, Arizona. Walcott (1890, 1894) described the basement complex as consisting of bedded quartzite and schists greater than 305 m (1,000 ft) thick that unconformably underlie the Grand Canyon Group (now Grand Canyon Supergroup) in northern Arizona. Ilg et al. (1996) described the Vishnu Schist as consisting of meta-sedimentary pelitic schist and quartz-biotite-muscovite schists that show thick sections (km-scale) of rhythmically banded layers, with locally well-preserved relict bedding and graded bedding. The type locality of the Vishnu Schist is designated in the lower canyon of Vishnu Creek in the Grand Canyon region (Table 5; Figures 48 and 53; Campbell and Maxson 1938). The type locality accounts "*...for all variations in character from relatively pure quartzites to highly micaceous schists are present, as well as some of the rather unique concretionary forms which seem to be distinctive of certain horizons of the Vishnu series*" (Campbell and Maxson 1938, p. 362). An additional reference section of the Vishnu Schist is located in Vishnu Canyon, Arizona (Table 5; Figure 50; Ilg et al. 1996). The contacts between the Vishnu Schist and Brahma Schist are considered generally concordant (Ilg et al. 1996).

Figure 53. Type locality exposures of the Vishnu Schist at the mouth of Cottonwood Creek, south side of river mile 81.1. Photograph EM10 from Billingsley et al. (2019).

The Paleoproterozoic Zoroaster Granite of the Zoroaster Plutonic Complex was originally referred to as “Zoroaster Gneiss” in Campbell and Maxson (1933), who named the unit after exposures in the narrow canyon of Zoroaster Creek in the Grand Canyon region. The type area of the Zoroaster Granite is designated as the exposures between Zoroaster and Cremation Canyons in Coconino County, Arizona (Table 5; Figure 49; Barnes 1989 citing Campbell and Maxson 1938). The type area exposes one of the single largest masses of the Zoroaster Granite, which is a little more than 1.6 km (1 mi) across and composed of pink to red, microcline-rich, coarse-grained granite (Figure 54; Campbell and Maxson 1938). The Zoroaster Granite intrudes older rocks of the Granite Gorge Metamorphic Suite and is separated from the younger rocks of the Unkar Group by the “Great Nonconformity”, a contact that can represent up to 500 million years of missing geologic time (Karlstrom and Timmons 2012; Karlstrom et al. 2021).

Figure 54. View looking west and downriver at type area exposures of the Zoroaster Granite on the south side of river mile 85.7. Exposures represent the lower part of the Zoroaster Granite “island” consisting of pegmatite and granite intrusions into black Vishnu Schist. Photograph EM15 from Billingsley et al. (2019).

Grand Canyon Supergroup

The Mesoproterozoic–Neoproterozoic Grand Canyon Supergroup was originally referred to as the “Grand Canyon Schist” by John Wesley Powell (1876) and “Grand Canyon Group” by Charles Doolittle Walcott (1883, 1894) before it was redesignated by Elston and Scott (1976). The Grand Canyon Supergroup is a >3.6 km (>2.2 mi)-thick sequence of strata consisting of the Unkar Group at its base, Chuar Group, and until recently the Sixtymile Formation of the Tonto Group (Elston 1989b, 1989c; Timmons et al. 2007; Dehler et al. 2017; Karlstrom et al. 2020). The type locality of the supergroup is located in GRCA, where the only known exposures occur in the eastern and central parts of the Grand Canyon (Table 5; Figures 48 and 55; Molenaar 1969 citing Powell 1876; Elston 1989b, 1989c). Type localities of the component Unkar and Chuar Groups are also located in GRCA, in Unkar Valley and Chuar Valley, respectively (Table 5; Figure 48; Molenaar 1969). The Grand Canyon Supergroup unconformably overlies (“Great Nonconformity”) basement rocks of the Vishnu Schist and unconformably underlies (“Great Angular Unconformity”) the Tonto Group (Karlstrom and Timmons 2012).

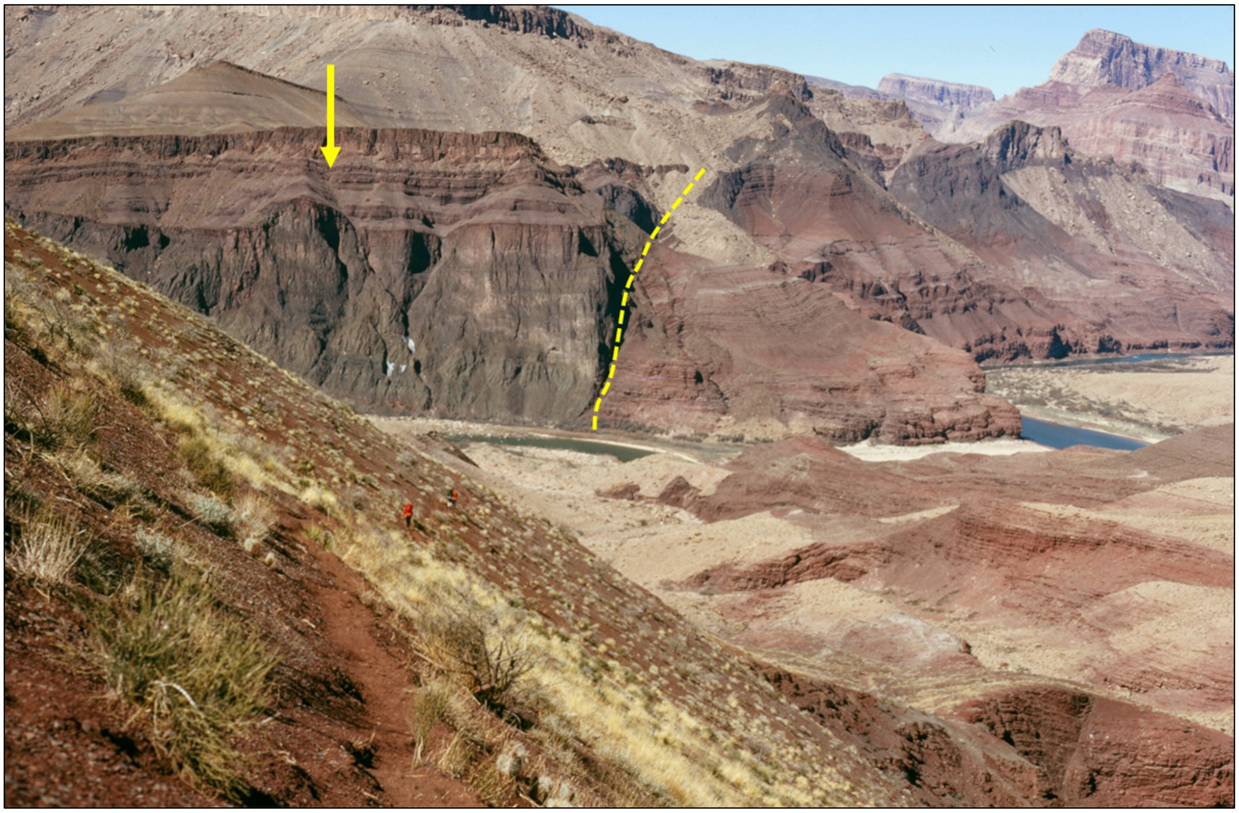


Figure 55. View north down Tanner Canyon from Tanner Trail toward Butte Fault (yellow dashed line) at river mile 69.0. Grand Canyon Supergroup exposures consisting of Cardenas Basalt of the Unkar Group (black cliff on the left side of fault), overlain by ledges of the Nankoweap Formation (type section of the Ferruginous Member marked by yellow arrow), with upper slopes consisting of the Tanner Member of the Galeros Formation of the Chuar Group. Red strata of the Dox Formation comprise the trail in the foreground and located to the right of the fault. Note the people for scale. Annotated photograph EF59 from Billingsley et al. (2019).

The Mesoproterozoic Unkar Group of the Grand Canyon Supergroup was originally referred to as the "Unkar Terrane", the lowest division of the Grand Canyon Group (now Grand Canyon Supergroup) by Walcott (1894). Noble (1914) revised Walcott's descriptions, referred to the Unkar as a group, and recognized five formations within the Unkar Group: 1) Hotauta Conglomerate (now a member of the Bass Formation); 2) Bass Limestone; 3) Hakatai Shale; 4) Shinumo Sandstone; and 5) Dox Sandstone. Additional revisions by Elston and Scott (1976) and Elston (1989b) introduced the Cardenas Basalt. The type locality of the Unkar Group is Unkar Valley in Coconino County, Arizona (Table 5; Figures 48, 56, and 57; Molenaar 1969 citing Walcott 1894). As the oldest group of the Grand Canyon Supergroup, the Unkar Group lies above the "Great Nonconformity" at the top of the Vishnu Schist and unconformably underlies the Chuar Group.

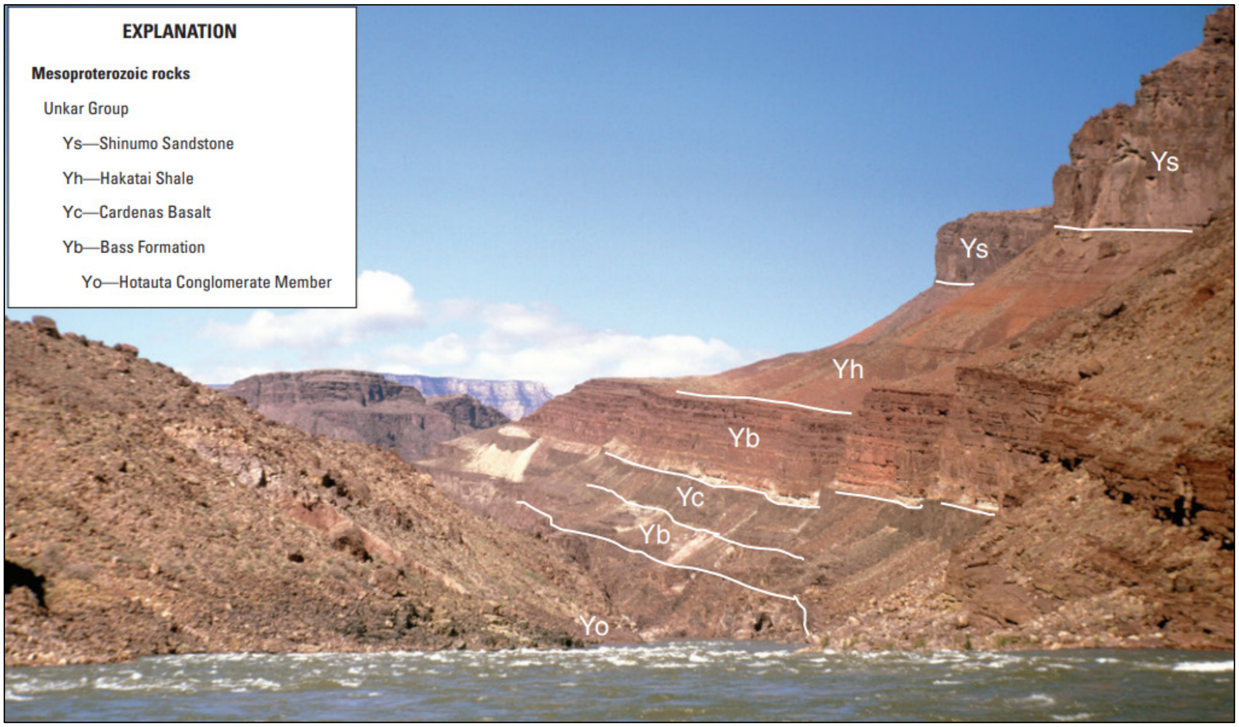


Figure 56. View looking west and downriver at a sequence of the Unkar Group from river mile 77.5. Figure 3 from Billingsley et al. (2019).

Figure 57. View looking northwest and downriver toward the Basalt Canyon Fault on the north side of river mile 69.2. The Dox Formation is present on the left side of the fault and the Cardenas Basalt is present on the right side. Photograph EF58 from Billingsley et al. (2019).

The Mesoproterozoic Bass Formation was named by Noble (1914) after exposures in Bass Canyon on the south side of the Colorado River, Arizona. The type section of the formation is located in Hotauta Canyon, on the north side of the Colorado River in Coconino County, Arizona (Table 5; Figures 47, 58, and 59; Beus et al. 1974 citing Noble 1914). The type section measures approximately 93 m (305 ft) thick and consists of blue slate, white crystalline limestone, and red calcareous shales and limestones (Noble 1914). Subsequent studies show that the predominant lithology of the Bass Formation is gray to reddish-gray dolomite interbedded with arkose and sandy dolomite interbedded with intraformational breccias or conglomerates (Beus et al. 1974; Billingsley et al. 2012). Typical sedimentary structures of the formation include symmetrical ripple marks, desiccation cracks, and small-scale normal and reverse graded bedding (Beus et al. 1974). The Bass Formation conformably underlies the Hakatai Shale and overlies the “Great Nonconformity” above the Vishnu Basement Rocks.

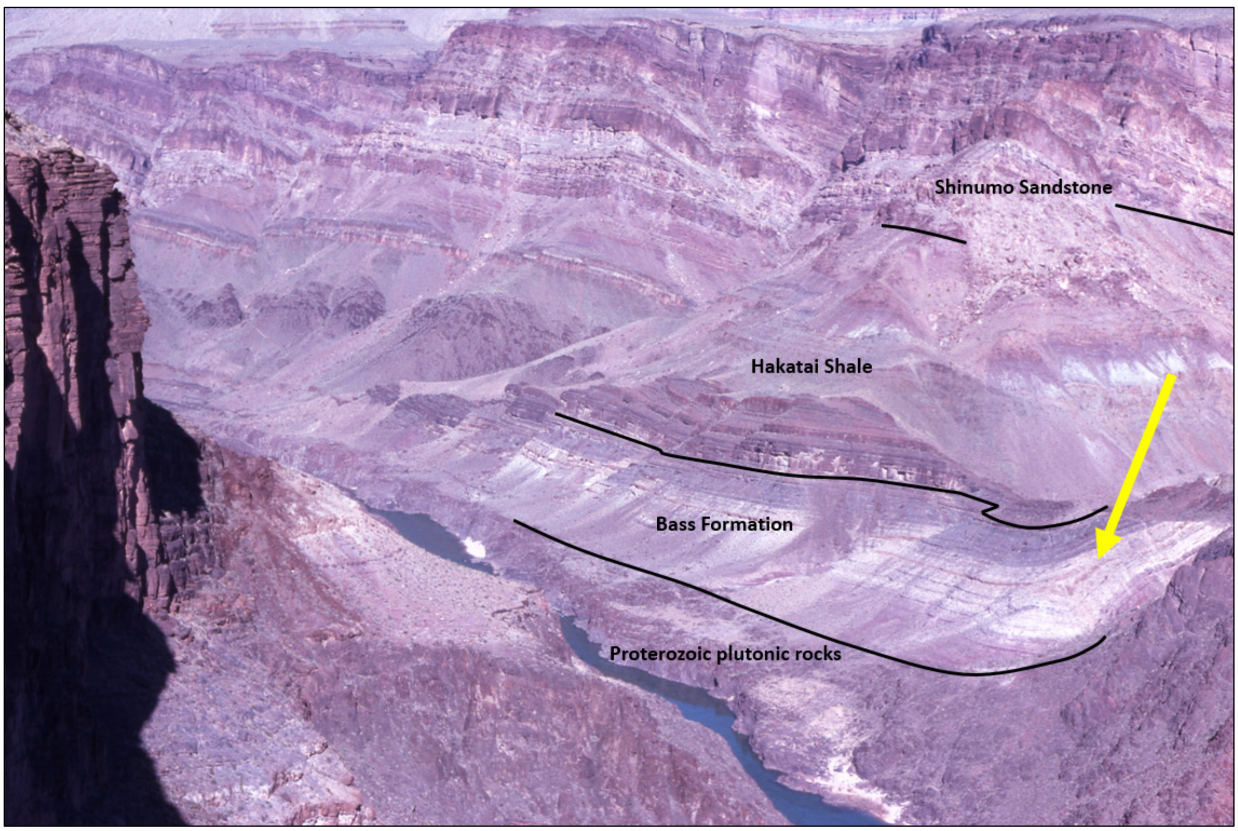


Figure 58. Type locality exposures of the Bass Formation. View looking north along the Tonto Trail just west of river mile 107.6 toward the Wheeler Fold in the Bass Formation (white beds indicated by yellow arrow) on the north side of river mile 108.1. Tilted strata above the Bass Formation include reddish slopes and ledges of the Hakatai Shale and upper brown cliffs of the Shinumo Sandstone. Annotated photograph ES178 from Billingsley et al. (2019).

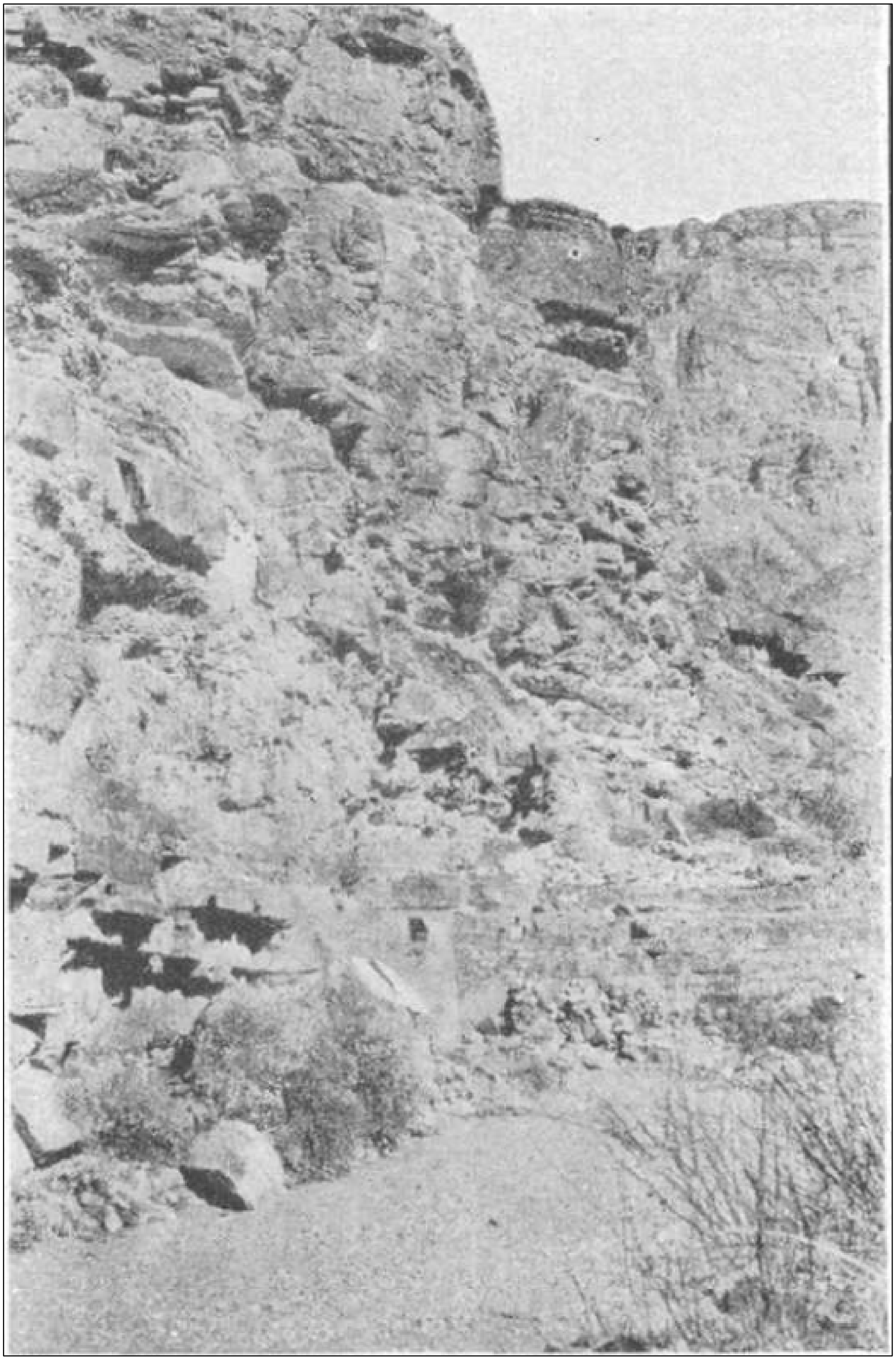


Figure 59. Type locality exposures of the Bass Limestone and Hotauta Conglomerate Member in Hotauta Canyon on the north side of the Colorado River. Plate 10A from Noble (1914).

The Mesoproterozoic Hotauta Conglomerate Member of the Bass Formation was originally proposed as the “Hotauta Conglomerate” by Noble (1914) and named after its type locality exposures in Hotauta Canyon, on the north side of the Colorado River in Coconino County, northern Arizona (Table 5; Figures 48 and 59; Molenaar 1969 citing Noble 1914). At the type locality, the Hotauta Conglomerate Member is a thin unit approximately 2 m (6 ft) thick that occurs locally at the base of the Bass Formation and typically consists of an assortment of rounded, gravel-sized clasts of chert, granite, quartz, plagioclase, and micro-pegmatites in a quartz sand matrix (Noble 1914; Beus et al. 1974; Billingsley et al. 2012). The Hotauta Conglomerate Member overlies the “Great Nonconformity” above the Vishnu Basement Rocks.

The Mesoproterozoic Hakatai Shale was named by Noble (1914) after its type section exposure in Hakatai Canyon in Coconino County, Arizona (Table 5; Figure 47; Beus et al. 1974 citing Noble 1914). The type section of the formation measures approximately 177 m (580 ft) thick and consists of red argillaceous shale that grades upward into arenaceous red shale and sandstone (Noble 1914). The Hakatai Shale is among the most colorful formations in the Grand Canyon, ranging from bright orange to purple and containing sedimentary structures that include mud cracks, ripple marks, and tabular-planar cross-bed structures (Beus et al. 1974; Billingsley et al. 2012). The Hakatai Shale occurs conformably above the Bass Formation and unconformably below the Shinumo Sandstone.

The Mesoproterozoic Shinumo Sandstone was originally proposed by Noble (1914) as the “Shinumo Quartzite” and named after its type locality exposures in the canyon of Shinumo Creek, Coconino County, Arizona (Table 5; Figures 48 and 60; Molenaar 1969 citing Noble 1914). Type locality exposures measure 477 m (1,564 ft) thick and predominantly consist of fine-grained, white to purplish-brown, cliff-forming, cross-bedded sandstone and quartzite (Figure 61; Noble 1914). Other sedimentary structures present in the Shinumo Sandstone include tabular-planar cross-bedding, ripple marks, clay galls, load casts, rare mud cracks, and contorted bedding (Beus et al. 1974). The Shinumo Sandstone unconformably overlies the Hakatai Shale and conformably underlies the Dox Formation.

The Mesoproterozoic Dox Formation was originally named the “Dox Sandstone” by Noble (1914) after its type section exposure beneath Dox Castle in a tributary to Shinumo Creek in Coconino County, Arizona (Table 5; Figures 47 and 62; Beus et al. 1974 citing Noble 1914). Stevenson and Beus (1982) subdivided the Dox Formation into the four members, in ascending order the Escalante Creek Member, Solomon Temple Member, Comanche Point Member, and Ochoa Point Member. The type section measures 700 m (2,297 ft) thick and consists of two distinct intervals: 1) a basal interval of greenish-gray micaceous shaly sandstone (Escalante Creek Member); overlain by 2) red to reddish-brown shaly sandstone (Solomon Temple Member) (Figure 63; Noble 1914, Stevenson and Beus 1982). Both divisions contain cross-bedding and ripple marks, with the upper sandstone interval displaying well-preserved mud cracks (Noble 1914). Beus et al. (1974) and Stevenson and Beus (1982) consider the thickness of the type section to be excessive since only the lowermost two members of the Dox Formation are present. At the type section, the Dox Formation conformably overlies the Shinumo Sandstone and unconformably underlies the Tapeats Sandstone.

Figure 60. View from the Tonto Trail looking northeast toward Shinumo Creek, type locality of the Shinumo Sandstone, just southwest of river mile 109.2. Rocks of the Unkar Group overlie the Vishnu Schist. Photograph ES180 from Billingsley et al. (2019).

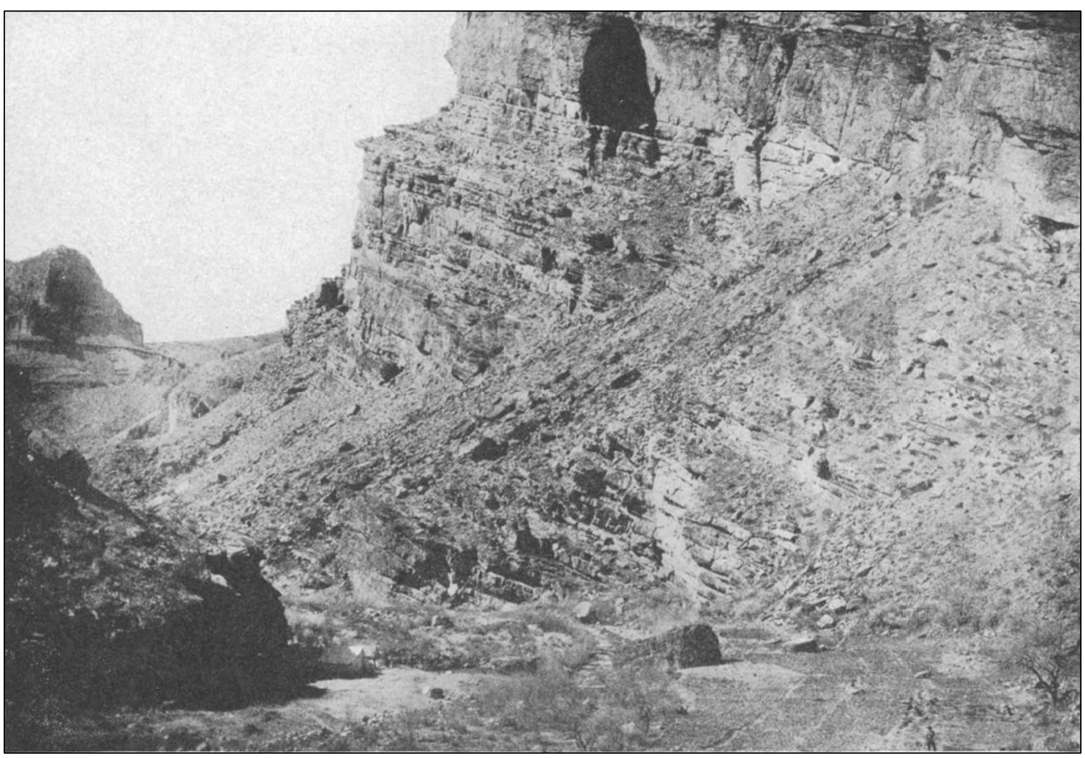


Figure 61. Type locality exposures of the Shinumo Sandstone in the canyon of Shinumo Creek. Plate 12B from Noble (1914).

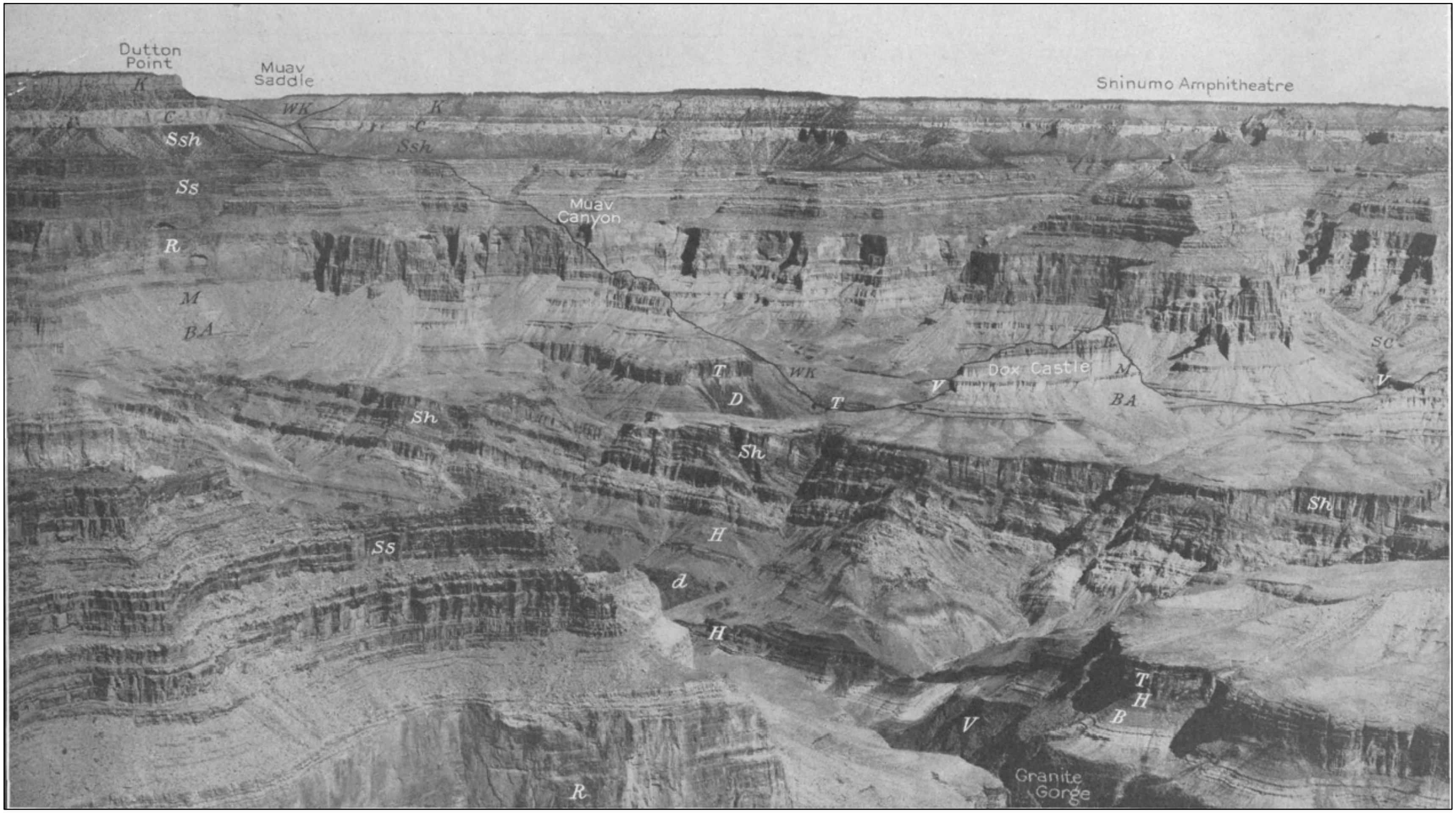


Figure 62. View northward across the Grand Canyon from the end of Grand Scenic Divide. The type section exposure of the Dox Formation is below Dox Castle along Shinumo Creek. SC, Shinumo Creek; V, Vishnu Schist; B, Bass Formation; H, Hakatai Shale; Sh, Shinumo Sandstone; D, Dox Formation; d, Diabase intrusive; T, Tapeats Sandstone; BA, Bright Angel Formation; M, Muav Formation; R , Redwall Limestone: Ss, sandstone of Supai Group; Ssh, shale of Supai Formation (now considered the Hermit Formation); C, Coconino Sandstone; K, Kaibab Formation; WK, West Kaibab fault. Plate 11 from Noble (1914).

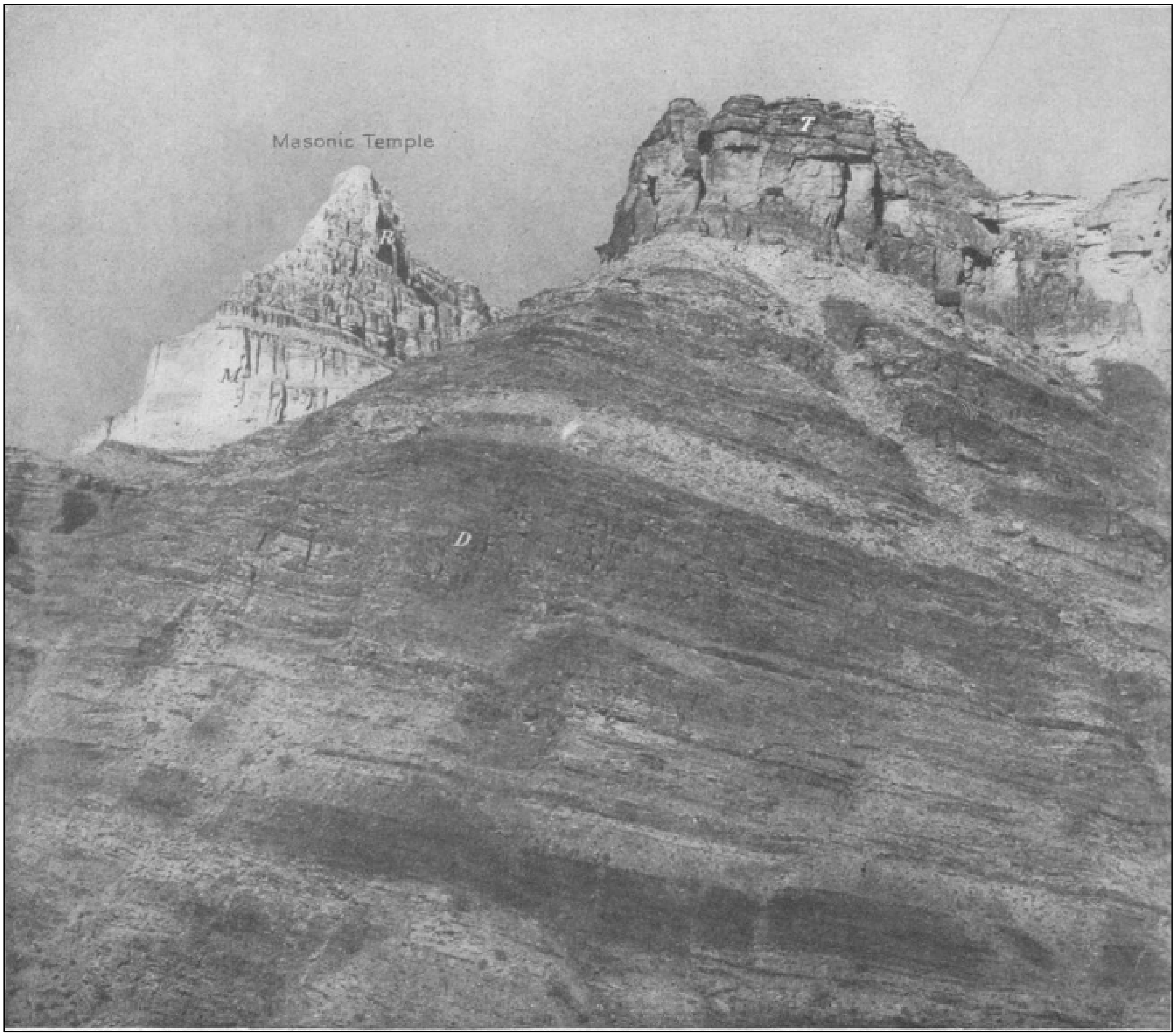


Figure 63. Type section of the Dox Formation in the canyon of Shinumo Creek, unconformably overlain by Tapeats Sandstone. D, Dox Sandstone; T, Tapeats Sandstone; M, Muav Formation; R, Redwall Limestone. Pinnacle of Masonic Temple in the left background. Plate 13B from Noble (1914).

The Mesoproterozoic Escalante Creek Member is the lowermost member of the Dox Formation proposed by Stevenson and Beus (1982), who named the unit after its type section along Escalante Creek in Coconino County, Arizona (Table 5; Figures 47 and 64). The type section measures 390 m (1,280 ft) thick and is subdivided into four distinct lithologies that include (in ascending order): 1) white to grayish-tan, friable, medium-grained sandstone, 73 m (240 ft) thick; 2) green to greenish-brown shale, mudstone, and sandstone, 80 m (262 ft) thick; 3) resistant, cliff-forming calcareous sandstone, 96 m (315 ft) thick; and 4) interbedded brown to gray siltstone, 140 m (459 ft) thick (Stevenson and Beus 1982). The Escalante Creek Member conformably occurs between the underlying Shinumo Sandstone and overlying Solomon Temple Member of the Dox Formation.

Figure 64. View looking southwest and downriver toward the type locality exposures of the Escalante Member of the Dox Formation from river mile 73.6. The lower canyon walls consist of the Escalante Member and the overlying Solomon Temple Member which forms the upper slopes. Note the rafts for scale. Photograph ES149 from Billingsley et al. (2019).

The Mesoproterozoic Solomon Temple Member of the Dox Formation was proposed by Stevenson and Beus (1982) and named after Solomon Temple, a prominent butte in eastern Grand Canyon. The type section is 2.4 km (1.5 mi) northeast of Solomon Temple, south of Unkar Creek in Coconino County, Arizona (Table 5; Figure 47; Stevenson and Beus 1982). The type section is a 280-m-thick (919 ft) succession of red siltstone and sandstone, with the lower 215 m (705 ft) consisting of a monotonous slope-forming sequence of alternating red to reddish-brown, fine-grained sandstone and red to maroon shaly, micaceous siltstone (Figure 65; Stevenson and Beus 1982). Common sedimentary structures of the member include micro-cross-laminations, ripple marks, load casts, flute casts, and irregular scour marks (Stevenson and Beus 1982; Billingsley et al. 2012). The Solomon Temple Member overlies the Escalante Creek Member and underlies the Comanche Point Member of the Dox Formation.

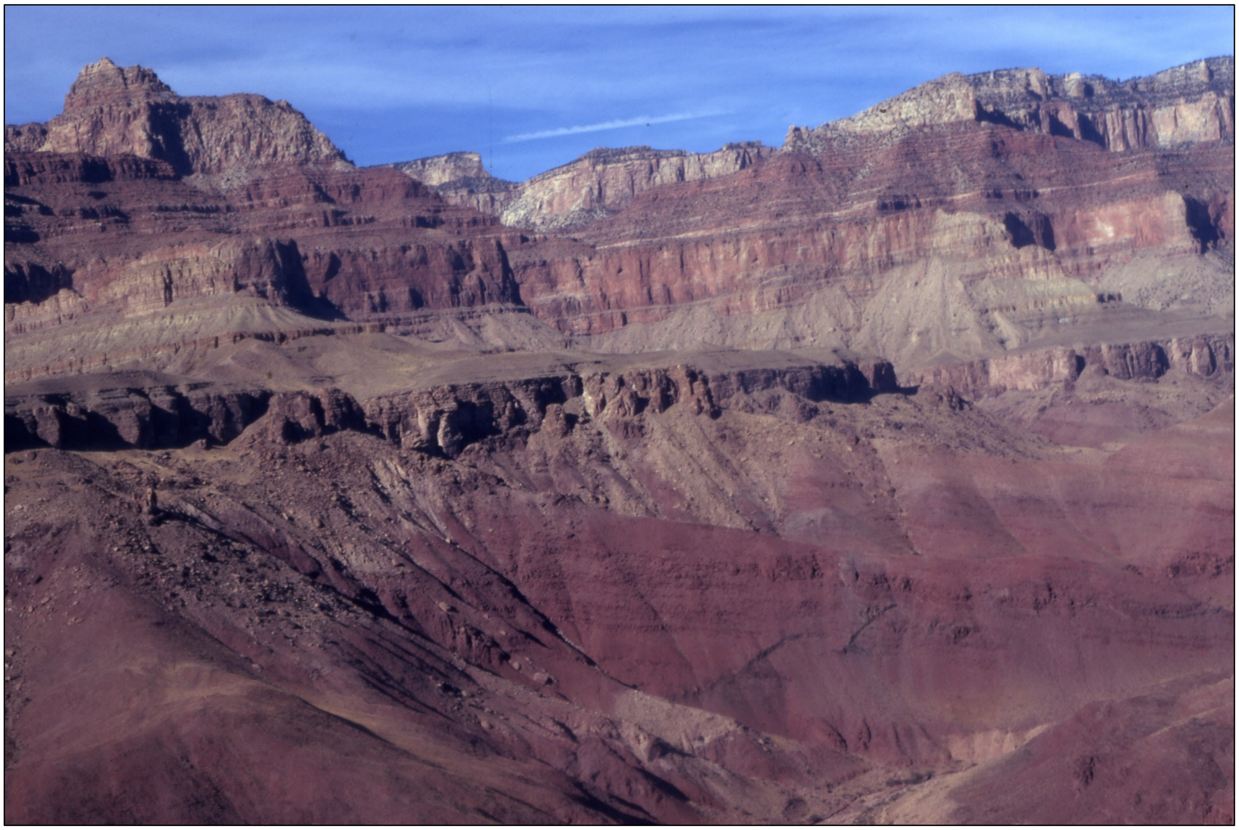


Figure 65. Aerial view northwest toward the west side of Unkar Creek Canyon about 3.2 km (2 mi) west of river mile 72.5. Lower red slopes consist of the Solomon Temple Member of the Dox Formation, overlain by the Tapeats Sandstone, Bright Angel Formation, Muav Formation, Temple Butte Formation, and Redwall Limestone. Photograph EI07 from Billingsley et al. (2019).

The Mesoproterozoic Comanche Point Member of the Dox Formation was named by Stevenson and Beus (1982) after Comanche Point, a promontory of the southeast side of the Colorado River. Stevenson and Beus (1982) designated the type section in the bed of an unnamed creek tributary to Tanner Canyon, 1.6 km (1 mi) west of Comanche Point, on the southeast side of the Colorado River between Tanner Canyon and Comanche Creek in Coconino County, Arizona (Table 5; Figure 47). The type section measures 155 m (509 ft) thick and is comprised of a cyclic succession of red siltstone and thin interbedded quartz sandstone (Stevenson and Beus 1982). In the type section, the Comanche Point Member is characterized by five laterally continuous marker beds of white to greenish-white interbedded sandstone and mudstone distinguishable against an otherwise reddish-brown, slope-forming mudstone (Figures 66 and 67; Stevenson and Beus 1982). Typical sedimentary structures of the member include ripple marks, mud cracks, salt crystal casts, low-angle cross-bedding, and wavy-bedding. The Comanche Point Member overlies the Solomon Temple Member and underlies the Ochoa Point Member of the Dox Formation.

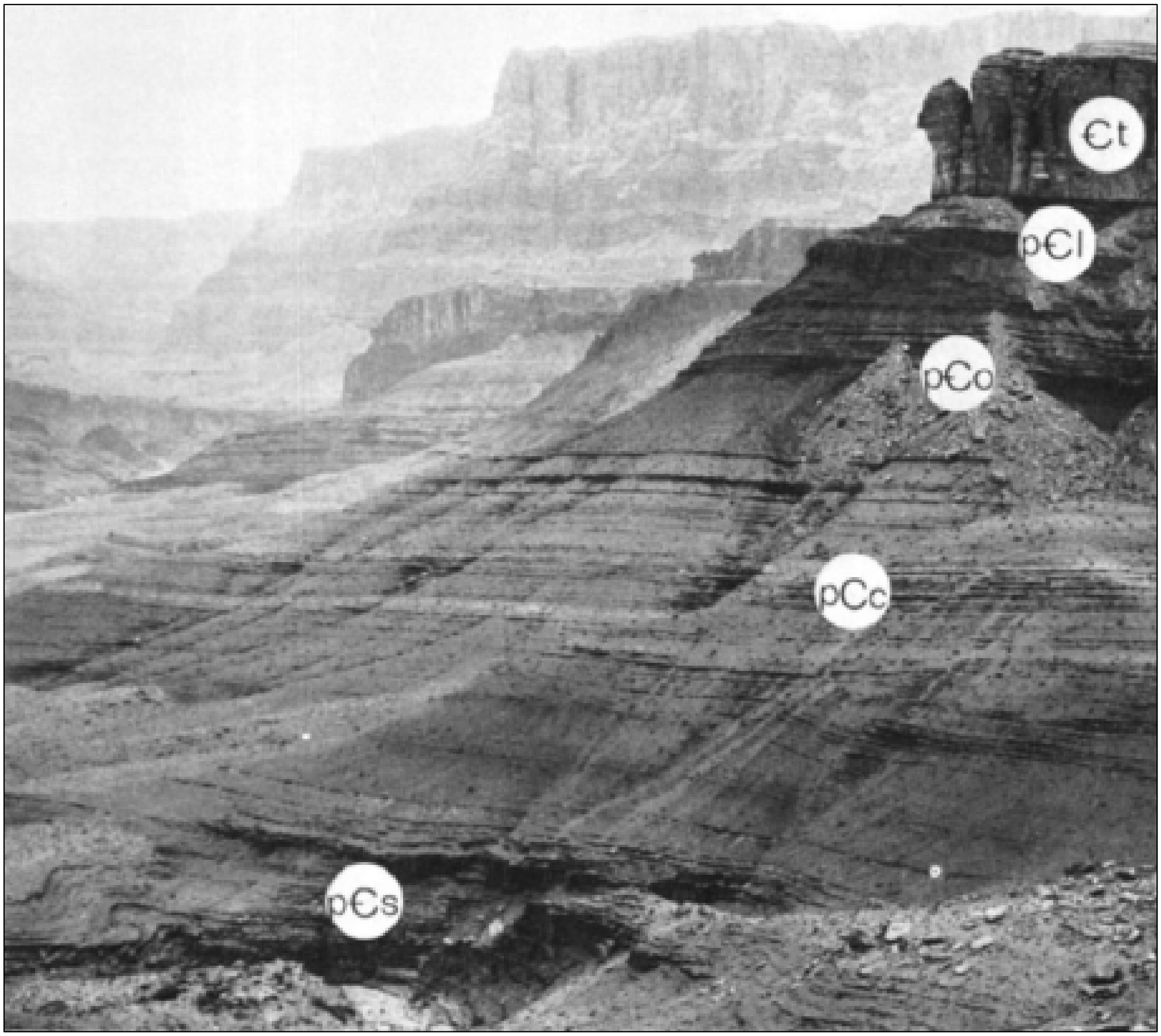


Figure 66. View looking north-northeast at the type section of the Comanche Point Member beneath Comanche Point. PCs, Solomon Temple Member; PCc, Comanche Point Member; PCo, Ochoa Point Member; PCl, Cardenas Basalt; Ct, Tapeats Sandstone. Figure 6 from Stevenson and Beus (1982).

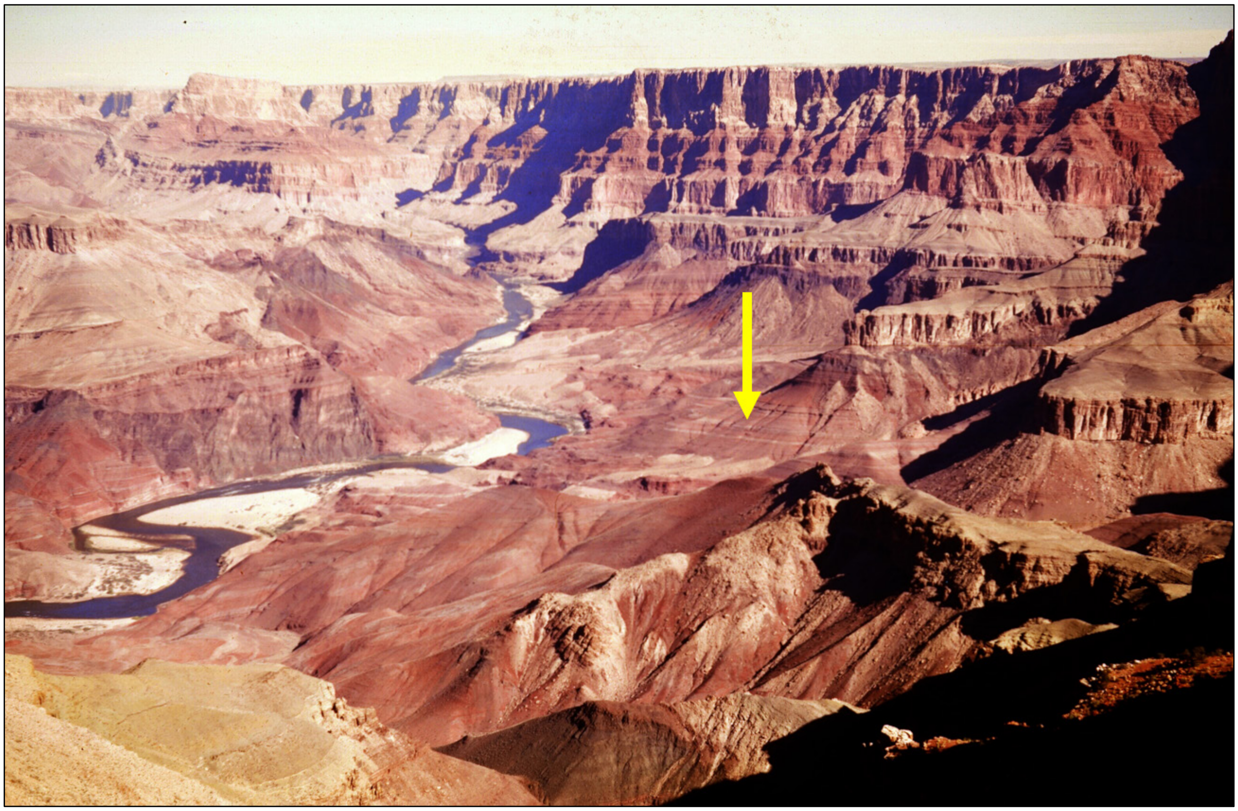


Figure 67. View looking north from Cardenas Butte toward the type section of the Comanche Point Member (yellow arrow), about 1.6 km (1 mi) southeast of river mile 70.0. Annotated photograph EL32 from Billingsley et al. (2019).

The Mesoproterozoic Ochoa Point Member is the uppermost and thinnest member of the Dox Formation designated by Stevenson and Beus (1982). The member is named after its type section exposure, located in an unnamed stream on the southwest side of Ochoa Point, a promontory west of Basalt Canyon, on the northwest side of the Colorado River in Coconino County, Arizona (Table 5; Figure 47; Stevenson and Beus 1982). At the type section the member is 76 m (249 ft) thick and consists of a lower interval comprised of slope-forming, reddish-brown micaceous siltstone and interbedded sandstone. The upper section is composed of thicker interbeds of red sandstone that form steep slopes or cliffs (Figure 68; Stevenson and Beus 1982). Common sedimentary structures include mud cracks, salt-crystal casts, ripple marks, and small-scale cross-beds (Stevenson and Beus 1982; Billingsley et al. 2012). The Ochoa Point Member overlies the Solomon Temple Member and underlies the Cardenas Basalt.

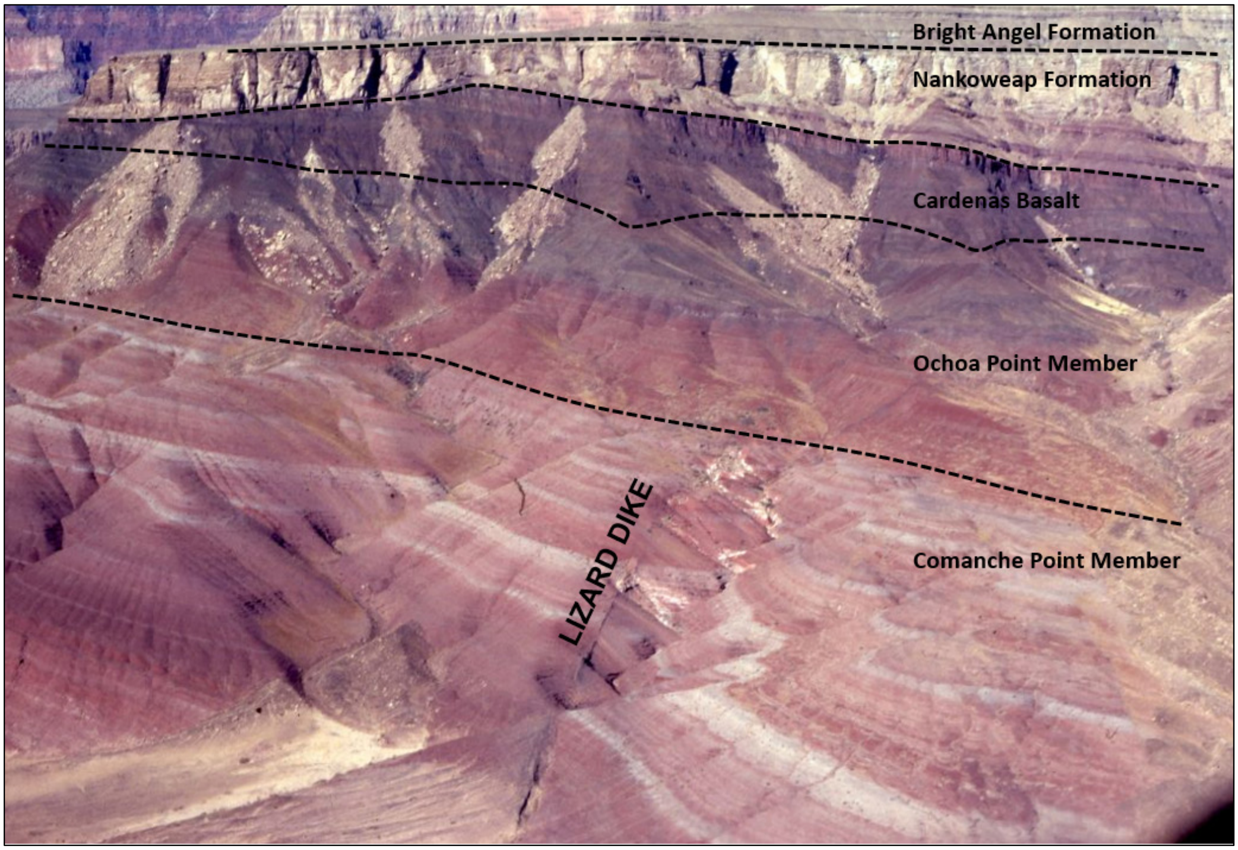


Figure 68. Aerial view northwest at the type section exposure of the Ochoa Point Member on the north side of river mile 71.6. The dark linear feature cutting across the Comanche Member in the lower middle photograph is the Lizard Dike composed of Cardenas Basalt. Annotated photograph EI04 from Billingsley et al. (2019).

The Neoproterozoic Chuar Group of the Grand Canyon Supergroup was first described by Walcott (1883, 1894) and consists of a 1,637 m-thick (5,371 ft) succession of predominantly very fine grained sedimentary rocks. More than half the strata of the group consists of organic-rich, gray to black mudstone and siltstone (Reynolds et al. 1989). Ford and Breed (1973) subdivided the Chuar Group into three formations, from oldest to youngest the Galeros, Kwagunt, and Sixtymile Formations. The Sixtymile Formation was subsequently removed from the Chuar Group by Elston (1979) and established as a unit of the Tonto Group by Karlstrom et al. (2020). Recent work by Dehler et al. (2017) assigned the Nankoweap Formation to the Chuar Group. The type locality of the Chuar Group is in Chuar Valley in the eastern Grand Canyon, Arizona (Table 5; Figures 48 and 69; Molenaar 1969 citing Walcott 1883). Exposures of the Chuar Group are also found in Nankoweap, Kwagunt, Awatubi, Sixtymile, Carbon, and Basalt Canyons (Ford and Breed 1973). The Chuar Group disconformably overlies the Unkar Group and unconformably underlies the Sixtymile Formation.

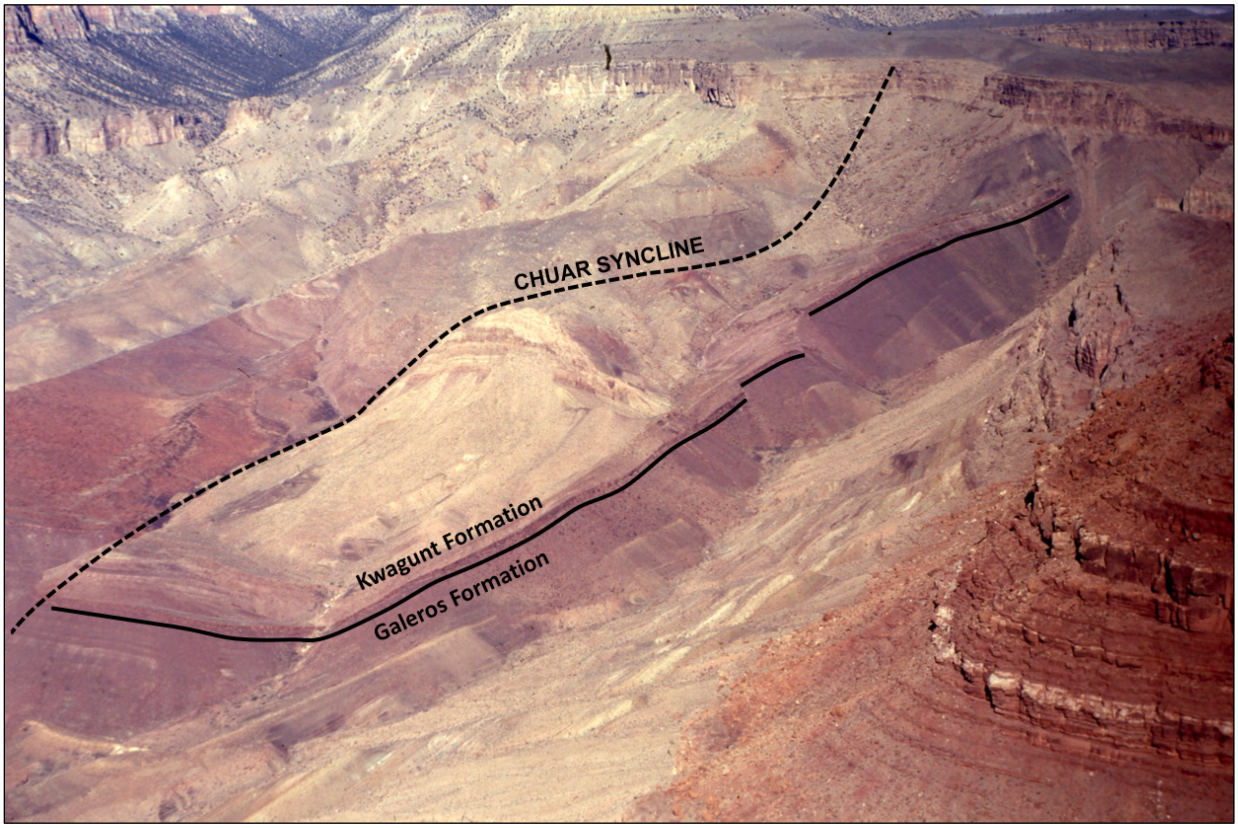


Figure 69. Aerial view looking northwest toward Carbon Butte in the Chuar syncline (dashed line marks fold axis), and type locality exposures of the Chuar Group. Carbon Butte is composed of the light-colored limestone and shale/mudstone of the Galeros Formation and overlying red sandstone and light-colored limestone of the Kwagunt Formation. Temple Butte is in the right foreground. Photograph EL29 from Billingsley et al. (2019).

The Neoproterozoic Nankoweap Formation was originally proposed as the "Nankoweap Group" by Van Gundy (1934) to describe a sequence of sedimentary rocks that were well-exposed in Nankoweap Valley, Arizona. The Nankoweap Formation is divided into two members: 1) a lower ferruginous member composed of finely laminated, very fine grained, reddish-brown sandstone; and 2) an upper member consisting of non-stratified and non-cemented purplish-red sand and silt with irregularly distributed, pebble- to cobble-size chert (Elston and Scott 1976). Van Gundy (1934, 1951) designated the type section of the Nankoweap Formation in Basalt Canyon, on the north side of the Colorado River just south of its confluence with the Little Colorado River (Table 5; Figure 47). The type section measures 100 m (330 ft) thick and consists of thin-bedded, light-brown, purple, and white, medium- to coarse-grained sandstone, red sandstone alternating with red and gray sandy shale, and thin-bedded gray sandstone (Figure 70). This latter sandstone grades into and is capped by a pure-white, very fine grained quartz sandstone (Van Gundy 1951). Ripple marks, mud cracks, trough cross-bedding, and soft-sediment deformation are common sedimentary structures found throughout the formation (Van Gundy 1951; Billingsley 2012). Recent work by Dehler et al. (2017) assigned the Nankoweap Formation to the Chuar Group. The Nankoweap Formation unconformably occurs between the underlying Unkar Group and overlying Galeros Formation.

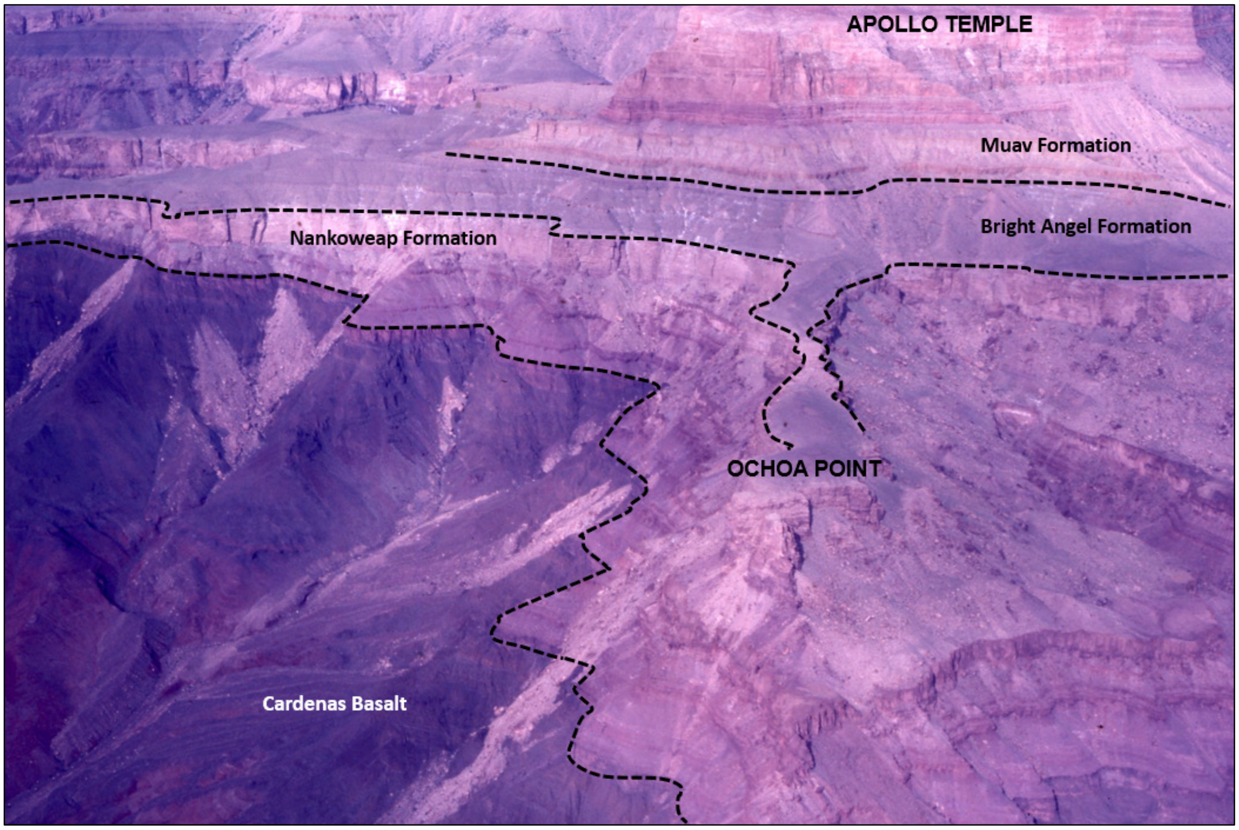


Figure 70. Aerial view looking northwest at Ochoa Point, about 2.1 km (1.3 mi) northwest of river mile 70.5. Exposures of the Nankoweap Formation cap the shelf in the foreground and are near the type section. Dark rocks of the Cardenas Basalt underlie the Nankoweap Formation and form the Basalt Cliffs to the left of the photo. Annotated photograph EL33 from Billingsley et al. (2019).

The Neoproterozoic Ferruginous Member of the Nankoweap Formation was named by Elston and Scott (1976) after exposures west of Tanner Canyon that rest above a ferruginous weathered zone of the underlying Cardenas Basalt. The type section of the member is located in the graben at the Tanner Canyon rapids in Coconino County, Arizona (Table 5; Figure 47; Elston and Scott 1976). The type section is 13 m (43 ft) thick and consists of finely laminated, very fine grained, light-reddish-brown sandstone. Resistant strata of the lower two-thirds of the member are very well cemented by hematite and cap the sheer cliff that overlooks the rapids (Elston and Scott 1976). The unit appears to be confined within the area of the graben, pinching out on the east and thinning to the west (Elston and Scott 1976). At the type section, the Ferruginous Member disconformably overlies the Cardenas Basalt and underlies an unnamed upper member of the Nankoweap Formation.

The Neoproterozoic Galeros Formation was proposed by Ford and Breed (1973) and named after its type area exposures near the Galeros promontory in the eastern Grand Canyon, Arizona (Table 5; Figure 49). The Galeros Formation consists of shale, siltstone, sandstone, and dolomite that are interpreted as lacustrine or marine in origin (Ford and Breed 1973; Elston 1989c; Billingsley et al. 2012). It is subdivided into four members that include from youngest to oldest the Tanner, Jupiter, Carbon Canyon, and Duppa Members. An aggregate thickness of the Galeros Formation in the type area is about 1,302 m (4,272 ft) (Ford and Breed 1973). The Galeros Formation unconformably overlies the Nankoweap Formation and conformably underlies the Carbon Butte Member of the Kwagunt Formation.

The Neoproterozoic Tanner Member is the oldest member assigned to the Galeros Formation by Ford and Breed (1973), who named the unit after its type section overlooking Tanner Rapids in the cliffs of Basalt Canyon, Arizona (Table 5; Figure 47). The type section measures 195 m (640 ft) thick and is composed of massive, coarsely crystalline dolomite at its base and almost exclusively shale above (Figure 71). The dolomite forms the topmost cliffs overlooking the mouth of Basalt Canyon and Tanner Rapids (Ford and Breed 1973). An additional reference section is designated by Ford and Breed (1973) at the lower end of Chuar Canyon, where the unit is 212 m (697 ft) thick and predominantly consists of shale (Table 5; Figure 50). The Tanner Member unconformably overlies the Nankoweap Formation and underlies the Jupiter Member of the Galeros Formation.

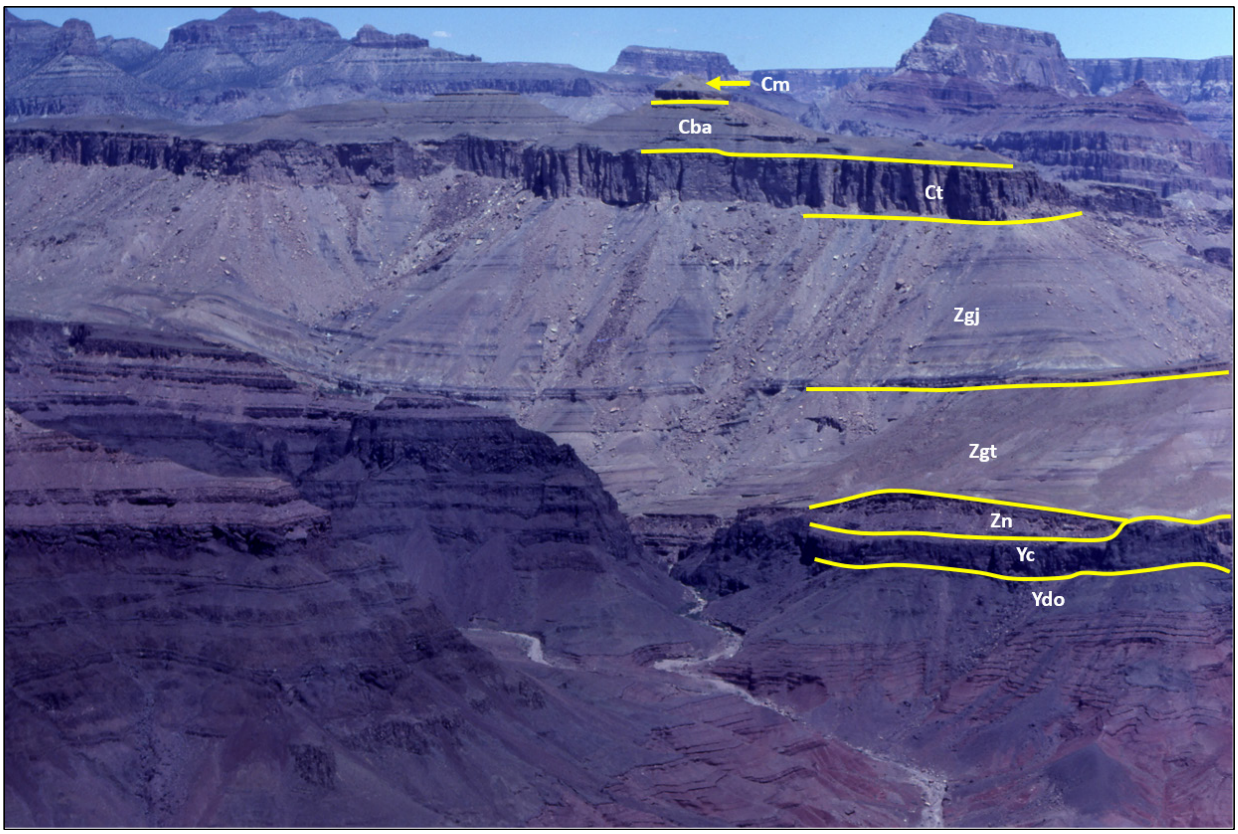


Figure 71. Aerial view looking north toward Basalt Canyon at the type section exposure of the Tanner Member of the Galeros Formation, about 1.6 km (1 mi) north of river mile 70.1. Ydo, Ochoa Point Member of Dox Formation; Yc, Cardenas Basalt; Zn, Nankoweap Formation; Zgt, Tanner Member of Galeros Formation; Zgj, Jupiter Member of Galeros Formation; Ct, Tapeats Sandstone; Cba, Bright Angel Formation; Cm, Muav Formation. Annotated photograph ES141 from Billingsley et al. (2019).

The Neoproterozoic Jupiter Member of the Galeros Formation was proposed by Ford and Breed (1973) and named after Jupiter Temple in the eastern Grand Canyon, Arizona. The type section is designated by Ford and Breed (1973) below Jupiter Temple in the lower part of Chuar Canyon, where the formation is 462 m (1,516 ft) thick (Table 5; Figures 47, 72, and 73). The type section consists predominantly of vari-colored shale that overlie stromatolitic and argillaceous limestone containing frequent lenses of flat-pebble conglomerate (Ford and Breed 1973). The Jupiter Member overlies the Tanner Member and underlies the Carbon Canyon Member of the Galeros Formation.

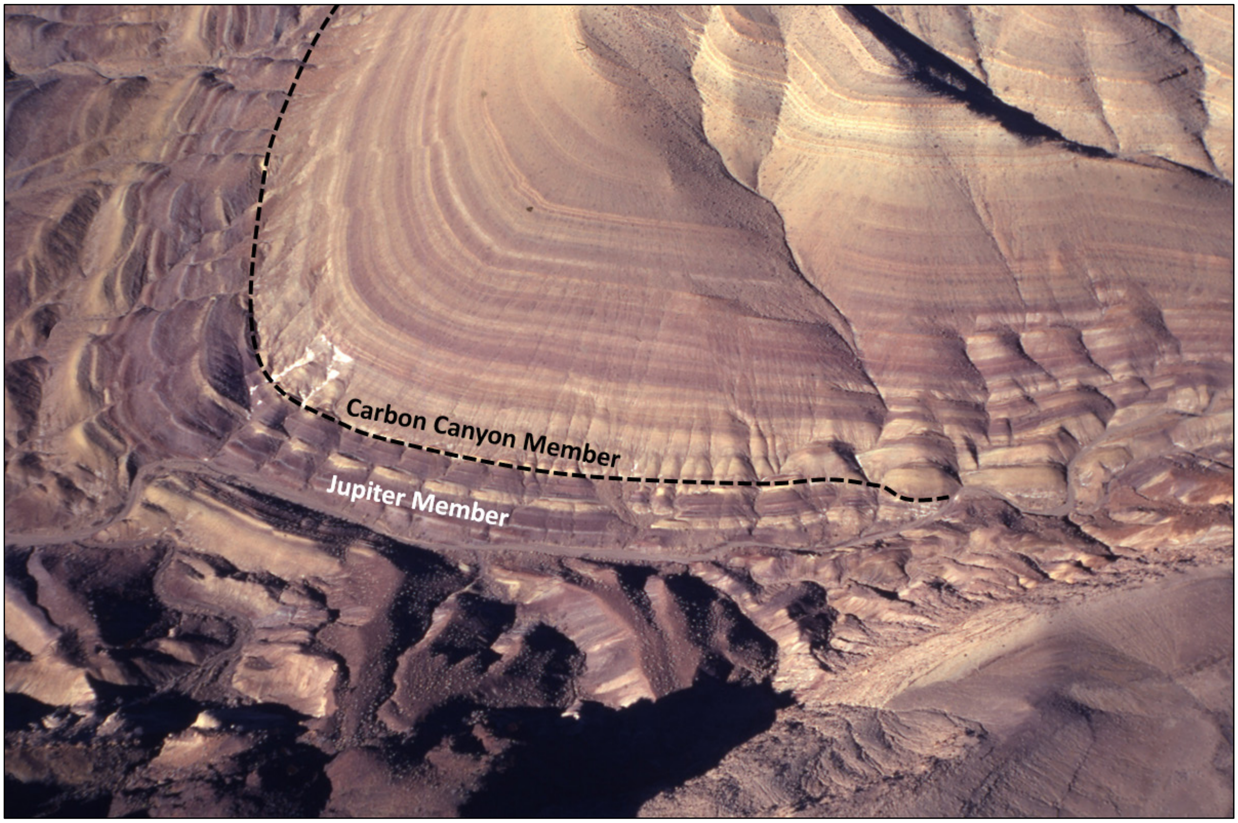


Figure 72. Type section exposure of the Jupiter Member of the Galeros Formation. Aerial view is northwest toward Chuar syncline on the north side of Chuar Creek, Lava Canyon, 1.6 km (1 mi) west of river mile 65.1. Annotated photograph EF46 from Billingsley et al. (2019).

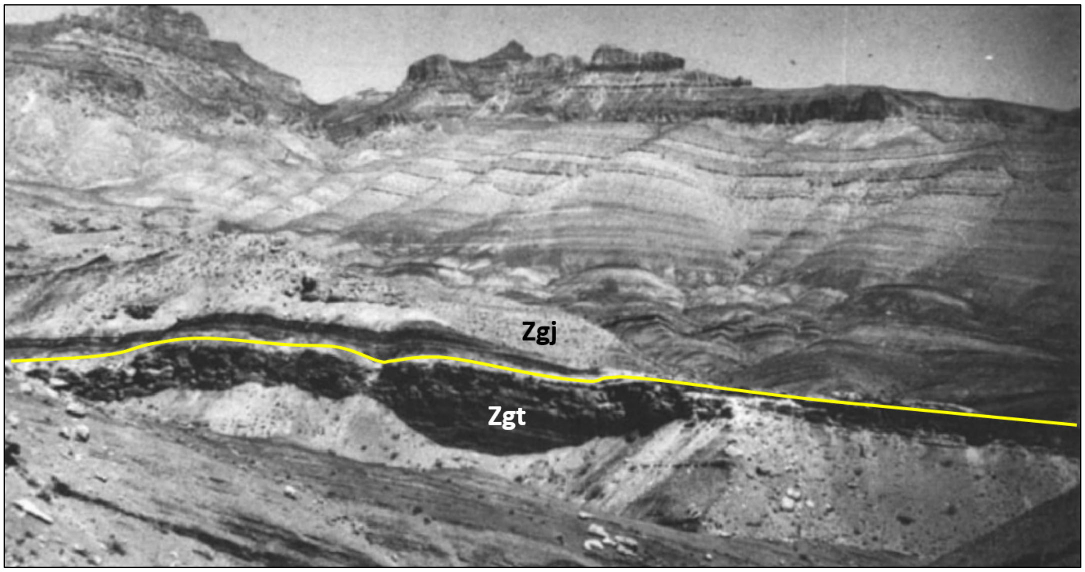


Figure 73. Lower Chuar Canyon looking north. Shale of the Tanner Member (Zgt) in the foreground overlooked by crags of stromatolitic limestone and colored shale/mudstone of the Jupiter Member (Zgj). Annotated Figure 5 from Ford and Breed (1973) (courtesy of the Geological Society of America).

The Neoproterozoic Carbon Canyon Member of the Galeros Formation was named by Ford and Breed (1973) after its type section exposure in the west fork of Carbon Canyon and mid-Chuar Canyon, Arizona (Table 5; Figure 47). At the type section the member measures 471 m (1,546 ft) thick and consists of a rapid, cyclic alternation of limestone and shale beds a few meters or feet thick with some thin argillaceous sandstone beds (Figures 74 and 75; Ford and Breed 1973). Common sedimentary structures found in sandstone beds include ripple marks, cross-bedding, and mud crack casts (Billingsley et al. 2012). The Carbon Canyon Member overlies the Jupiter Member and underlies the Duppa Member of the Galeros Formation.

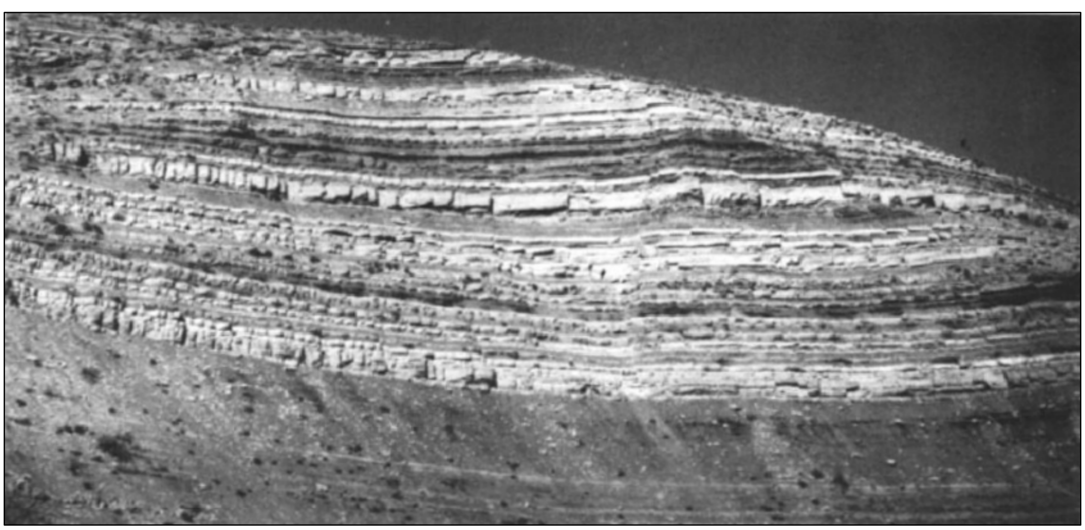


Figure 74. Chuar Canyon. Alternating limestone–shale/mudstone succession of the Carbon Canyon Member. Figure 6 from Ford and Breed (1973) (courtesy of the Geological Society of America).

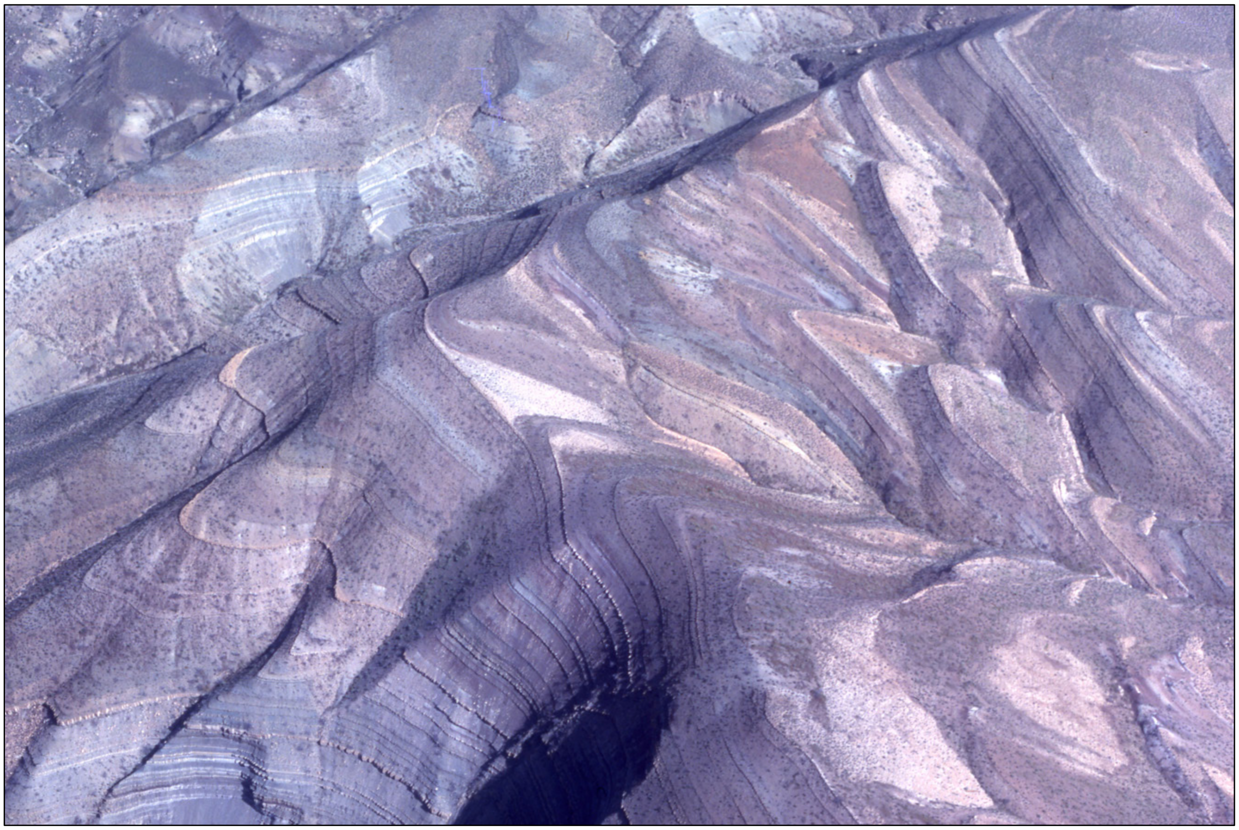


Figure 75. Aerial view looking northwest toward the type section of the Carbon Canyon Member of the Galeros Formation, on the north side of Carbon Creek about 4.8 km (3 mi) west of river mile 63.0. Photograph ES135 from Billingsley et al. (2019).

The Neoproterozoic Duppa Member is the youngest member of the Galeros Formation proposed by Ford and Breed (1973), who named the unit after its type section exposure below Duppa Butte in Kwagunt Canyon, Arizona (Table 5; Figure 47). The type section measures 174 m (570 m) thick and is composed of purple to gray micaceous shale, thin beds of limestone, and calcareous siltstone (Ford and Breed 1973). The Duppa Member overlies the Carbon Canyon Member of the Galeros Formation and underlies the Carbon Butte Member of the Kwagunt Formation.

The Neoproterozoic Kwagunt Formation was proposed by Ford and Breed (1973) and named after excellent exposures in the northern slopes of Kwagunt Canyon, Arizona. The type area is designated at Kwagunt Canyon where the formation has an aggregate thickness of approximately 675 m (2,215 ft) (Table 5; Figure 49; Ford and Breed 1973). Ford and Breed (1973) subdivided the formation into three formal members that include from oldest to youngest the Carbon Butte, Awatubi, and Walcott Members. Major lithologies of the members include limestone, mudstone, and dolomite that are interpreted as lacustrine or possibly tidal flat in origin (Elston 1989c). The Kwagunt Formation conformably overlies the Galeros Formation and unconformably underlies the Sixtymile Formation.

The Neoproterozoic Carbon Butte Member is the oldest member assigned to the Kwagunt Formation by Ford and Breed (1973), who named the unit after its type section exposure at Carbon Butte, Arizona (Table 5; Figure 47). At the type section the member measures 76 m (252 ft) thick and forms a prominent shelf of red sandstone surrounding Carbon Butte, but also includes overlying shale and some thinner sandstone beds (Figure 76; Ford and Breed 1973). An additional reference section is located along the south fork of Nankoweap Canyon, where the member measures 60 m (198 ft) thick (Table 5; Figure 50; Ford and Breed 1973). The sandstone interval of the Carbon Butte Member is 29 m (94 ft) thick and represents the only thick sandstone in the Chuar Group (Ford and Breed 1973). Common sedimentary structures include mud cracks, ripple marks, and abundant soft-sediment deformation features (Ford and Breed 1973; Billingsley et al. 2012). The Carbon Butte Member overlies the Duppa Member of the Galeros Formation and underlies the Awatubi Member of the Kwagunt Formation.

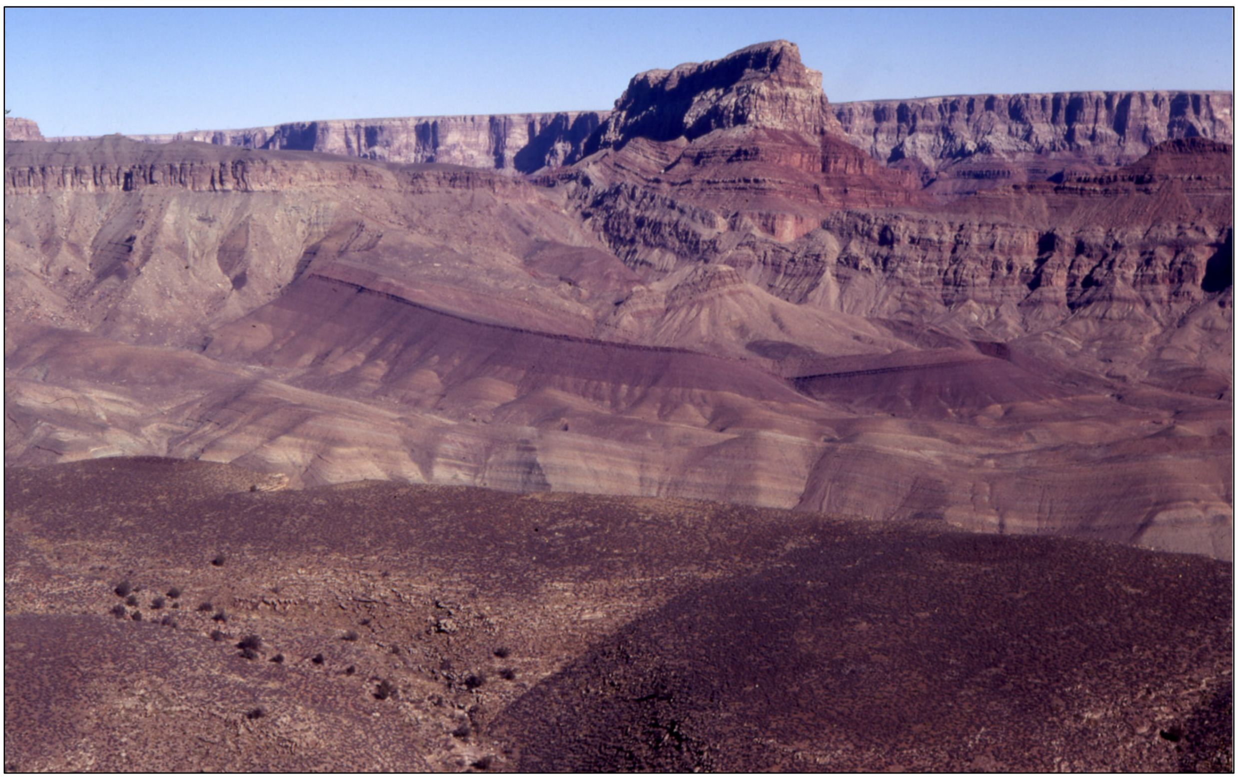


Figure 76. Aerial view looking east toward the type section of the Carbon Butte Member at Carbon Butte. The type section measures 76 m (252 ft) thick and consists predominantly of red sandstone that forms a prominent shelf around the butte. Cropped photograph EM30 from Billingsley et al. (2019).

The Neoproterozoic Awatubi Member of the Kwagunt Formation was named by Ford and Breed (1973) after its type section exposure in the upper reaches of Awatubi Canyon, Arizona (Table 5; Figure 47). The type section measures approximately 355 m (1,167 ft) thick and consists of a conspicuous basal stromatolitic limestone containing fossil biohermal dome features with overlying vari-colored shale, siltstone, and sandstone (Figure 77; Ford and Breed 1973). Ford and Breed (1973) assigned an additional reference section on the southeastern slope of Nankoweap Butte where the member is 344 m (1,128 ft) thick (Table 5; Figures 50 and 78). The Awatubi Member overlies the Carbon Butte Member and underlies the Walcott Member of the Kwagunt Formation.

Figure 77. A stromatolite bioherm from the base of the Awatubi Member seen from above Chuar Canyon. Note person for scale. Figure 9 from Ford and Breed (1973) (courtesy of the Geological Society of America).

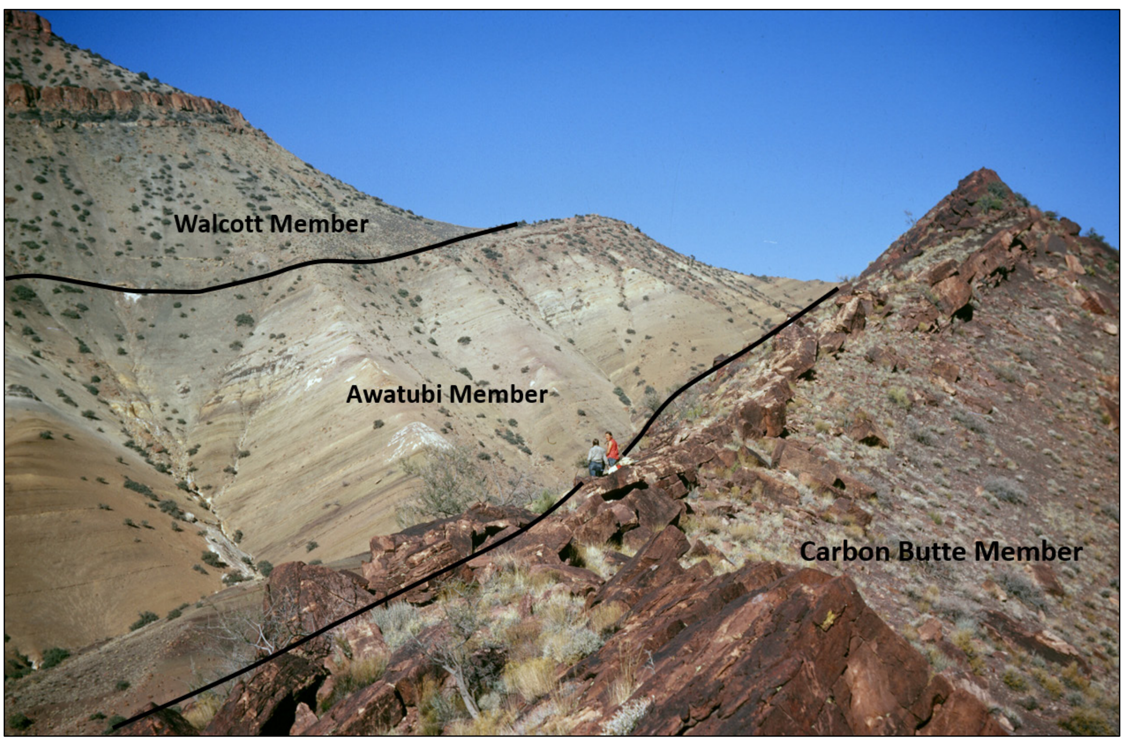


Figure 78. Reference section exposure of the Awatubi Member of the Kwagunt Formation in the upper reaches of Walcott Glen. View is looking northwest toward the southeast side of Nankoweap Butte. Walcott Member (upper gray slope) overlying the Awatubi Member (lower tan slope), with Carbon Butte Member (red ledge). Annotated photograph ES84 from Billingsley et al. (2019).

The Neoproterozoic Walcott Member is the youngest member assigned to the Kwagunt Formation by Ford and Breed (1973). It is named after its type section exposure at the head of Walcott Glen and the upper part of Nankoweap Butte, Arizona (Table 5; Figures 47, 79, and 80). The type section measures 255 m (838 ft) thick and consists of a conspicuous basal "Flaky Dolomite", a buff-weathering dolomite 2.5 m (8 ft) thick that is overlain by blue-gray shale containing distinctive beds of black chert (Ford and Breed 1973). The Walcott Member overlies the Awatubi Member of the Kwagunt Formation and unconformably underlies the Sixtymile Formation.

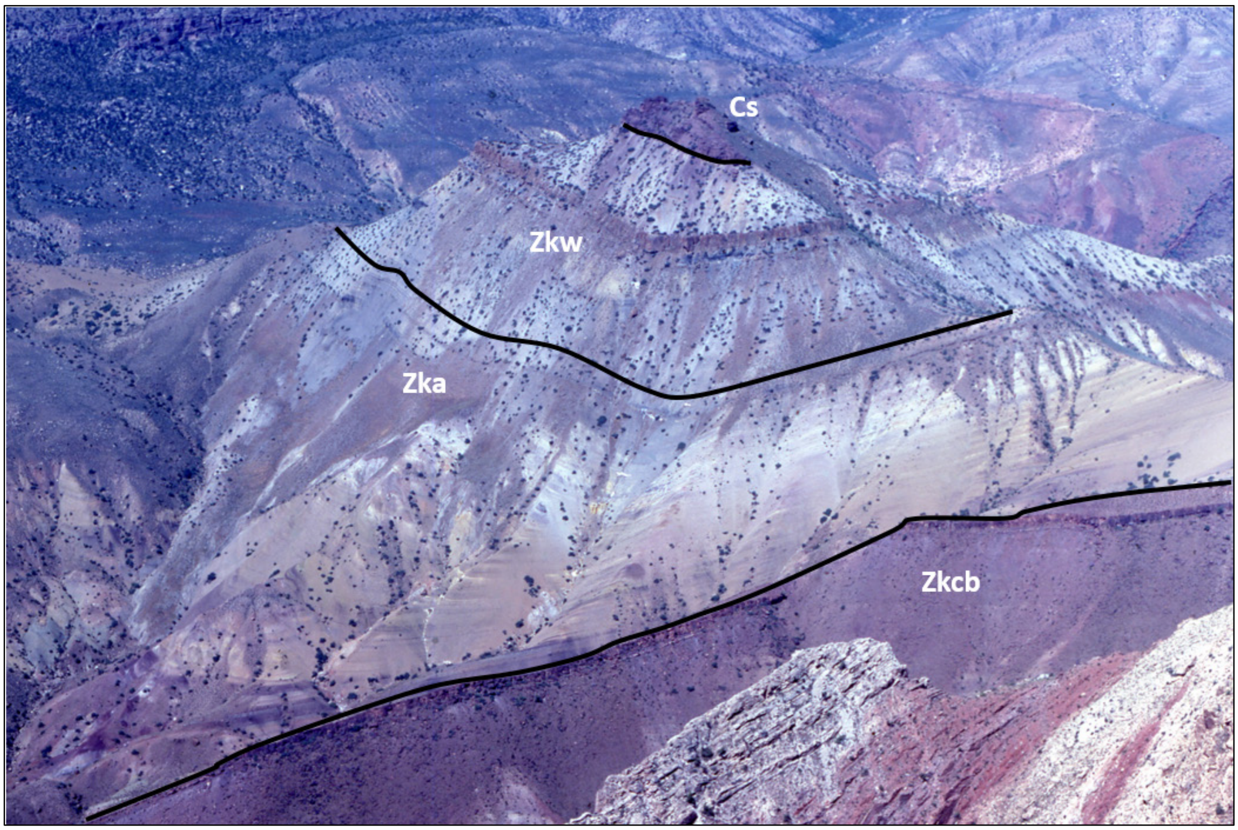


Figure 79. Aerial view looking northwest toward the type section of the Walcott Member of the Kwagunt Formation on the southeast side of Nankoweap Butte. The upper white slope, brown ledge, and white slope of Walcott Member (Zkw), is underlain by a lower tan slope of Awatubi Member (Zka) and then by a dark red ledge of Carbon Butte Member (Zkcb). Nankoweap Butte is capped by reddish-brown breccias of the Sixtymile Formation (Cs). Annotated photograph ES82 from Billingsley et al. (2019).

Figure 80. Nankoweap Butte looking northeast, with lower Nankoweap Canyon in far left; Walcott Glen is in shadow to right. Slopes in the lower foreground and lower right are in shale of Awatubi Member. Prominent ledges toward the top of the Butte are massive dolomite of the Walcott Member. The summit cap is breccia and sandstone of the Sixtymile Formation (reference section). Figure 10 from Ford and Breed (1973) (courtesy of the Geological Society of America).

Layered Paleozoic Rocks

The Cambrian Tonto Group was first mentioned by Gilbert (1874, 1875) to describe a sequence of Paleozoic sedimentary strata in the Grand Canyon. A recent revision to the Tonto Group by Karlstrom et al. (2020) added to the base the Sixtymile Formation, redated to the Cambrian, and distinguished the Frenchman Mountain Dolostone from rocks formerly assigned to the upper Muav Formation. The type section of the group is located along the South Bass Trail and consists of a 363-m-thick (1,192 ft) sequence of the Tapeats Sandstone, Bright Angel Formation, and Muav Formation (Table 5; Figure 47; Elston 1989a citing Noble 1922). Rose (2011) acknowledged the Paleozoic section along the South Bass Trail by Noble (1922) but noted that it was published before the rules for stratigraphic nomenclature were codified. Therefore, Rose (2011) described a secondary type section at Blacktail Canyon, Arizona (lat. 36°14′25″ N., long. 112°26′21″ W.), where the Tonto Group is 256 m (840 ft) thick (Table 5; Figure 47). The type sections of Noble (1922) and Rose (2011) are both bounded by unconformities with the underlying Vishnu Basement Rocks and overlying Temple Butte Formation.

The Cambrian Sixtymile Formation was formally proposed by Ford and Breed (1973) and named after its type section exposure in the cliffs on the north side of the upper part of Sixty Mile Canyon, Arizona (Table 5; Figure 47). The base of the type section is sharp, consisting of intraformational breccia beds resting on eroded shales of the underlying Walcott Member of the Kwagunt Formation. Overlying the basal breccia beds is massive, fine-grained red sandstone and a second upper interval of breccia beds (Ford and Breed 1973; Billingsley et al. 2012). An additional reference section is designated at the top of Nankoweap Butte in Awatubi Canyon, where the formation makes up the topmost 36 m (120 ft) of the butte (Table 5; Figures 50, 79, and 80; Ford and Breed 1973). The Sixtymile Formation unconformably occurs between the underlying Walcott Member and the overlying Tapeats Sandstone.

The Cambrian Tapeats Sandstone is the oldest formation assigned to the Tonto Group by Noble (1914, 1922). It was first described from the Shinumo Quadrangle in the central Grand Canyon, Arizona. Type locality exposures of the formation are located along Tapeats Creek and consist of white and reddish-brown cross-bedded sandstone with a maximum measured thickness of 86 m (285 ft) (Table 5; Figures 48 and 81; Molenaar 1969 citing Noble 1914). Throughout the type locality and much of the central and eastern Grand Canyon, the Tapeats Sandstone shows little lithologic variation (Noble 1914; Elston 1989a). At the type locality, the Tapeats Sandstone unconformably overlies ("Great Angular Unconformity") Proterozoic-age rocks and conformably underlies the Bright Angel Formation.

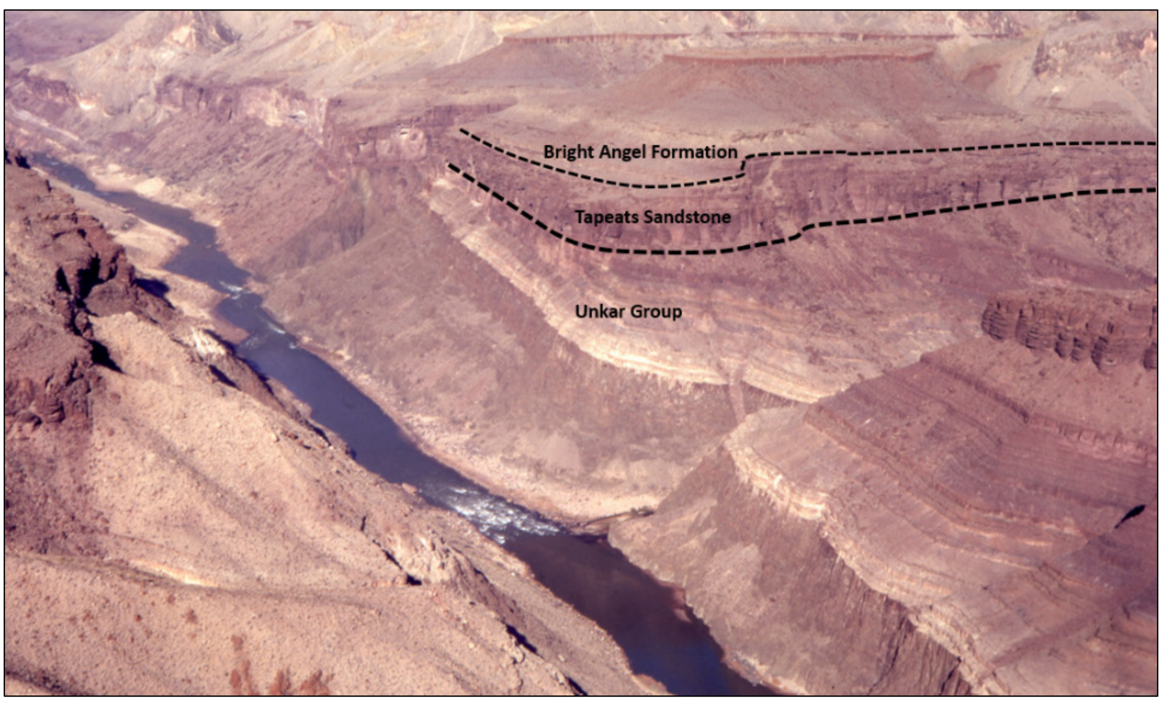


Figure 81. View looking northwest at type locality exposures of the Tapeats Sandstone at the mouth of Tapeats Creek (Thunder River) at river mile 134.5. Horizontal rocks of the Tapeats Sandstone unconformably overlie tilted strata of the Unkar Group on the north side of Tapeats Rapid. The Bright Angel Formation caps the mesa. Annotated photograph CS19 from Billingsley et al. (2019).

The Cambrian Bright Angel Formation was named by Noble (1914, 1922) and first described from the Shinumo Quadrangle in the central Grand Canyon, Arizona. The type locality of the formation is located in the cliffs of Bright Angel Canyon, where it predominantly consists of green, fossiliferous sandy shale with lesser amounts of sandstone and limestone (Table 5; Figure 48; McKee 1945 citing Noble 1914). Thickness of the Bright Angel Formation in the type locality is 99 m (325 ft) (McKee 1945). The Bright Angel Formation occurs conformably between the underlying Tapeats Sandstone and overlying Muav Formation.

The Cambrian Muav Formation is the youngest formation assigned to the Tonto Group by Noble (1914, 1922) and first described from the Shinumo Quadrangle in central Grand Canyon, Arizona. The formation is subdivided into eight members and associated tongue units that include, in ascending order, the Rampart Cave Member (and associated Elves Chasm Tongue), Sanup Plateau Member (and associated Garnet Canyon Tongue), Spencer Canyon Member (and associated Lava Falls Tongue), Peach Springs Member (and associated Parashant Tongue and Boucher Tongue), Kanab Canyon Member, Gateway Canyon Member, Havasu Member, and Yampai Cliffs Member (McKee 1945; Wood 1966). The type locality of the Muav Formation is designated in Muav Canyon, in which the lower part of the formation is particularly well exposed (Table 5; Figures 48 and 82; McKee 1945 citing Noble 1914). Exposures in the type locality are 137–145 m (450–475 ft) thick and consist of cliff-forming, fossiliferous, dark gray to orange-red limestone that has a characteristic mottled appearance imparted by numerous thin beds or lenses of shaly material (Noble 1914; Billingsley et al. 2012). The Muav Formation conformably overlies the Bright Angel Formation and unconformably underlies the Temple Butte Formation.

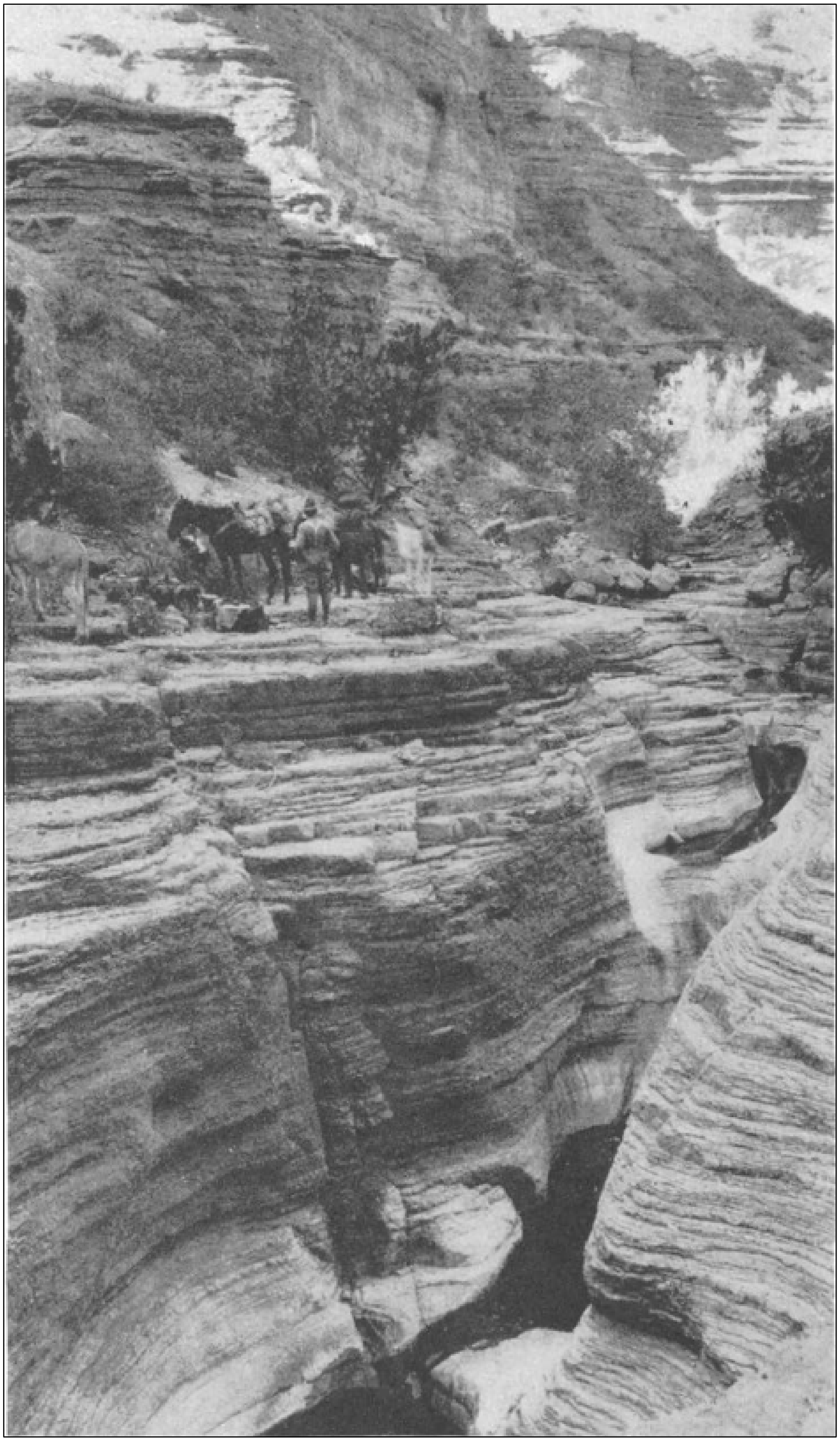


Figure 82. Type locality exposures of the Muav Formation in Muav Canyon. Plate 15A from Noble (1914).

The Cambrian Lava Falls Tongue of the Muav Formation was named by McKee (1945) after its type locality exposures about 1.6 km (1 mi) east of Lava Falls at the foot of Toroweap Canyon, Arizona (Table 5; Figures 48 and 83). Type locality exposures measure about 5 m (17.5 ft) thick and consist of three units: 1) a rusty brown, basal ledge-forming dolomitic limestone; 2) slope-forming green shale and brown siltstone; and 3) an upper cliff-forming carbonate unit (McKee 1945). The Lava Falls Tongue overlies the Sanup Plateau Member and underlies the Peach Springs Member of the Muav Formation.

Figure 83. View looking west toward Lava Falls and Lava Falls Rapids near the type locality of the Lava Falls Tongue of the Muav Formation at river mile 178.2. Person is resting on the Esplanade Sandstone. Photograph CI33 from Billingsley et al. (2019).

The Cambrian Kanab Canyon Member is the lowermost subdivision of the Muav Formation throughout the eastern part of the Grand Canyon. It was named by McKee (1945). The type locality of the member is designated at the mouth of Kanab Canyon, Arizona, where it is the lowest massive cliff-forming unit not far above the level of the Colorado River (Table 5; Figure 48; McKee 1945). Type locality exposures measure 44 m (143 ft) thick and consist of a single massive cliff of gray mottled limestone (Figure 84; McKee 1945). The Kanab Canyon Member overlies the Peach Springs Member and underlies the Gateway Canyon Member of the Muav Formation.

Figure 84. Type locality exposures of the Kanab Canyon Member. View looking south toward travertine seeps on the west side of Kanab Creek that issue from Kanab Canyon and Peach Springs Canyon Members of the Muav Formation, about 2.3 km (1.4 mi) north of river mile 144. Photograph CW36 from Billingsley et al. (2019).

The Cambrian Havasu Member is the youngest member of the Muav Formation assigned by McKee (1945) and named after its type locality exposures near the mouth of Havasu Canyon, on the south side of Kanab Plateau, Arizona (Table 5; Figure 48). Type locality exposures of the member are composed of reddish-pink, mottled limestone and dolomite that form a sheer cliff overlying a narrow bench that is marked by a flat-pebble conglomerate (McKee 1945). The thickness of the member is about 30 m (100 ft) throughout much of the Grand Canyon, but in the extreme western portion it averages closer to 36 m (120 ft) (McKee 1945). The Havasu Member overlies the Gateway Canyon Member of the Muav Formation and its upper contact is not known.

The Devonian Temple Butte Formation was originally named the “Temple Butte Limestone” by Walcott (1883) to describe sedimentary rocks underlying the Redwall Limestone in the eastern Grand Canyon. The type section of the formation is located at Temple Butte, on the west side of the Colorado River a few kilometers or miles below its junction with the Little Colorado River, Arizona (Table 5; Figures 47 and 85; McKee 1974 citing Walcott 1883). Exposures of the Temple Butte Formation in the eastern Grand Canyon are typically less than 30 m (100 ft) thick and represent scattered remnants filling channels and depressions eroded into the underlying Muav Formation (McKee 1974). The Temple Butte Formation is predominantly composed of gray, medium- to fine-grained, crystalline dolomite with minor sandy dolomite and sandstone beds with basal channel-fill strata commonly comprised of sandy to silty reddish-purple dolomite (Beus and Billingsley 1989). The Temple Butte Formation unconformably occurs between the underlying Muav Formation and overlying Redwall Limestone.

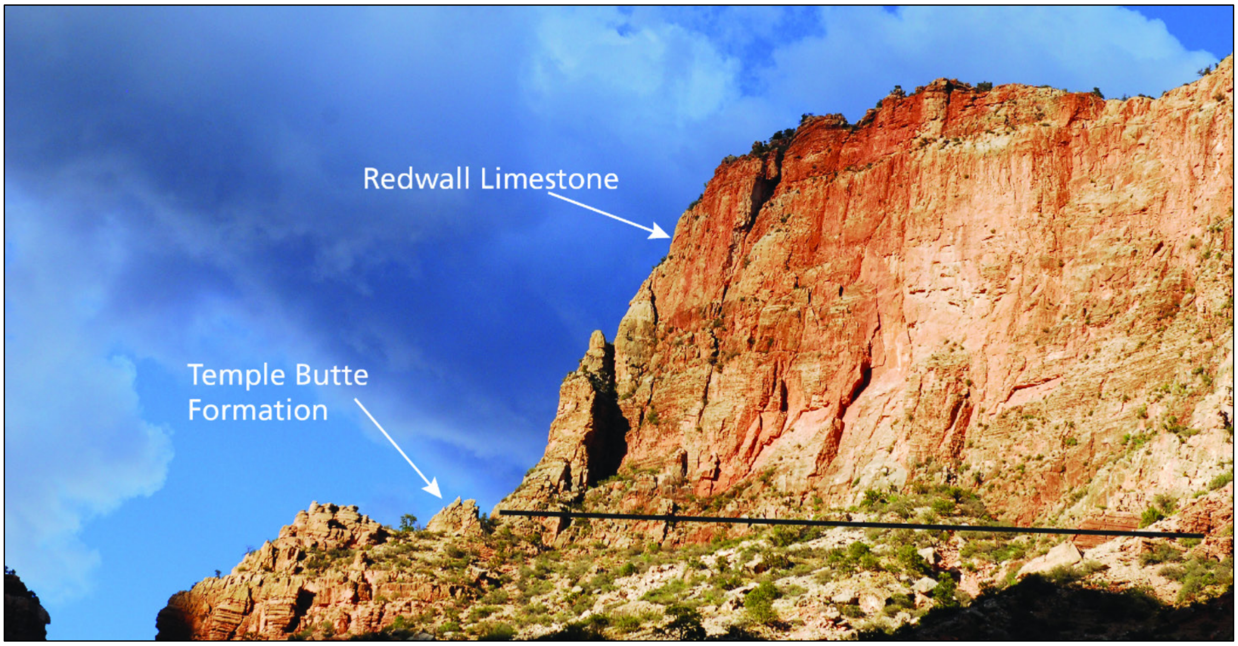


Figure 85. Exposures of the Temple Butte Formation at Temple Butte near river mile 63.0 (NPS/KIRSTEN M. CALDRON). A massive cliff of Redwall Limestone overlies a slope composed of the Temple Butte Formation.

The Mississippian Redwall Limestone was named by Gilbert (1875) to describe the prominent red cliffs on either side of the Grand Canyon, Arizona. The type locality of the unit is located in Redwall Canyon, in the Shinumo drainage basin on the north side of the Grand Canyon (Table 5; Figure 48; Darton 1910). Type locality exposures consist of light gray massive limestone that form sheer cliffs approximately 244 m (800 ft) thick (Darton 1910). The red color of the formation is derived from iron oxides washed down from the overlying Supai Group (McKee 1974). At the type locality, the Redwall Limestone unconformably underlies the Supai Group and unconformably overlies either the Temple Butte Formation or the Muav Formation where the Temple Butte Formation is missing.

The Mississippian Whitmore Wash Member is the oldest subdivision of the Redwall Limestone proposed by McKee (1963). The unit is named after its type section exposure on the east side of Whitmore Wash Valley, on the upthrown side of the Hurricane Fault about 0.4 km (0.25 mi) north of Colorado River, Arizona (Table 5; Figures 47 and 86; McKee 1963). The type section measures 31 m (101 ft) thick and consists of uniformly fine-grained, thick-bedded, cliff-forming dolomite that displays conspicuous medium-scale cross-bedding in a few places (McKee 1963, 1974). The Whitmore Wash Member unconformably overlies the Temple Butte Formation and underlies the Thunder Springs Member of the Redwall Limestone.

Figure 86. Aerial view looking north toward the Hurricane Fault and the type section of the Whitmore Wash Member of the Redwall Limestone. Only part of the foremost main arm of the Hurricane Fault is shown with the dashed line. Exposures consist of basal red cliffs of the Muav Formation (Cm), overlain by the Temple Butte Formation (Dtb), and the Whitmore Wash Member of the Redwall Limestone (Mr) located to the right of the fault. Annotated photograph WF05 from Billingsley et al. (2019).

The Mississippian Thunder Springs Member of the Redwall Limestone was proposed by McKee (1963) and named after its type section exposure in the cliff west of the springs at the head of Thunder River (Tapeats Creek), about 3.2 km (2 mi) north of the Colorado River, Arizona (Table 5; Figures 47 and 87). The type section consists of thin alternating beds and elongate lenses of chert and carbonate rock approximately 42 m (138 ft) thick (McKee 1963, 1974). The Thunder Springs Member occurs between the underlying Whitmore Wash and overlying Mooney Falls Members of the Redwall Limestone.

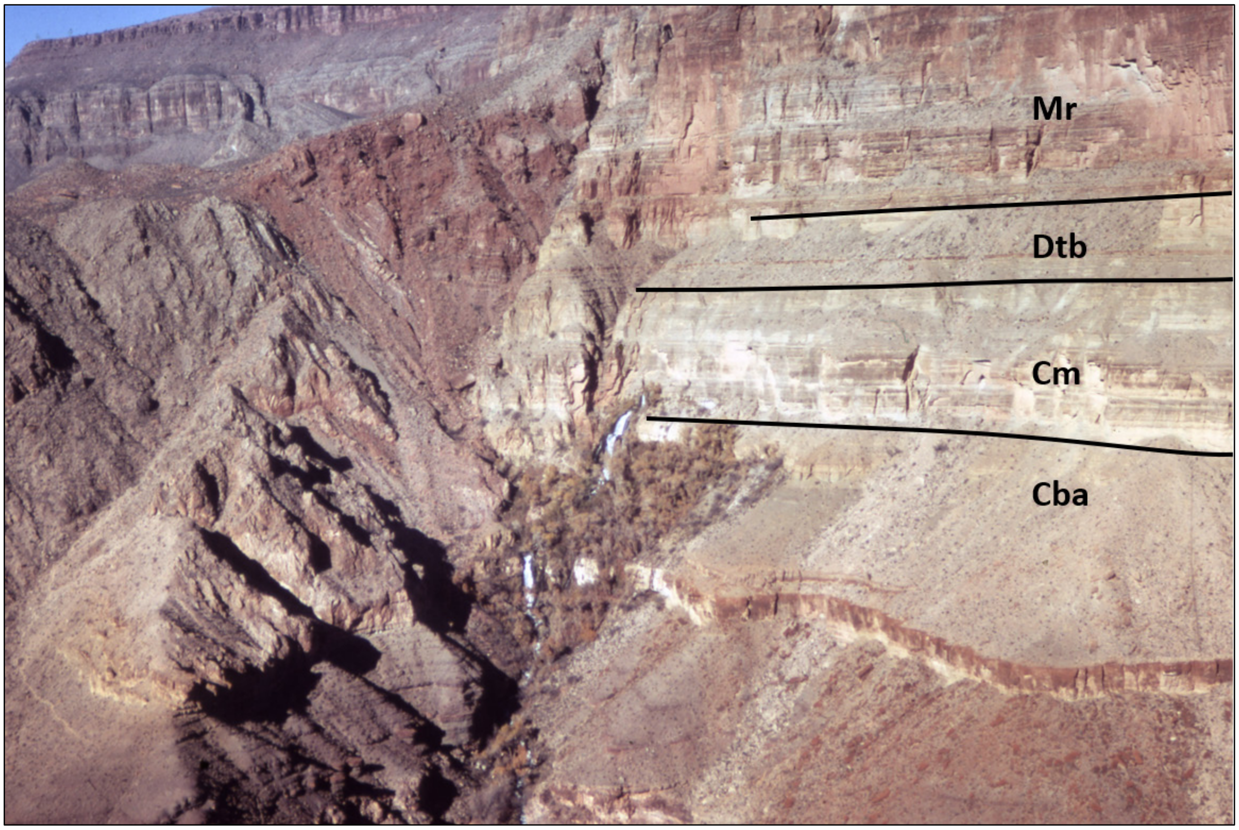


Figure 87. Aerial view looking northwest toward the type section exposure of the Thunder Springs Member at Thunder Spring on the west side of Tapeats Creek about 3.2 km (2 mi) north of river mile 134.3. Basal slopes that discharge waterfalls consist of the Bright Angel Formation (Cba), overlain by white cliffs of the Muav Formation (Cm), thin light-colored slopes of the Temple Butte Formation (Dtb), and upper red cliffs of the Redwall Limestone (Mr). Annotated photograph CW16 from Billingsley et al. (2019).

The Mississippian Horseshoe Mesa Member is the youngest subdivision of the Redwall Limestone and was named by McKee (1963) after its type section exposure located at Horseshoe Mesa below Grandview Point on the south side of the Grand Canyon, Arizona (Table 5; Figure 47). The Horseshoe Mesa Member is a relatively thin unit that ranges from 11 m (38 ft) thick at the type section to 38 m (125 ft) to the west (McKee 1963). The unit is characteristically thin-bedded and commonly weathers to form receding ledges that stand in contrast to the cliff-forming limestone of the underlying Mooney Falls Member (McKee 1974). The lithology of the Horseshoe Mesa Member predominantly consists of aphanitic limestone, fine-grained and oolitic limestone, with localized zones of thin-bedded chert lenses near the base (McKee 1963, 1974). At the type section, the Horseshoe Mesa Member overlies the Mooney Falls Member and unconformably underlies the Supai Group.

The Permian Hermit Formation was originally proposed as the "Hermit Shale" by Noble (1922), who redescribed a sequence of sandy shales (mudstones) and sandstones initially included as part of the Supai Group. The formation is named after its type locality exposures in the Hermit Basin of the

Grand Canyon, Arizona (Table 5; Figures 48 and 88). Type locality exposures range from 81–97 m (267–317 ft) thick and consist of deep brick-red shaly siltstone interbedded with fine-grained friable sandstone that characteristically form benches or shelves (Noble 1922; McKee 1974; Beus and Billingsley 1989). Silty sandstone beds may exhibit ripple marks or trough cross-bedding, and plant fossils are widespread and locally abundant throughout the formation (Beus and Billingsley 1989). The Hermit Formation unconformably occurs between the underlying Supai Group and overlying Coconino Sandstone.

Figure 88. View looking west at type locality exposures of the Hermit Formation from Hermit Trail on the South Rim. Lower red strata of the Supai Group (Ps) overlain by the Hermit Formation (Ph), Coconino Sandstone (Pc), Toroweap Formation (Pt), and capped by the Kaibab Formation (Pk). Annotated photograph ES166 from Billingsley et al. (2019).

The Permian Toroweap Formation was proposed by McKee (1938) and named after excellent exposures in Toroweap Valley, Arizona. McKee (1938) designated the type section in Brady Canyon, an eastern side canyon of Toroweap Valley, about 14 km (9 mi) above the mouth and 13 km (8 mi) north of the Colorado River (Table 5; Figure 47). The type section measures 129 m (425 ft) thick and consists of four main lithologies in ascending order: 1) brown to gray, thin- to thick-bedded, sandy, fossiliferous limestone that weathers to form rounded, slopes and cliffs; 2) reddish yellow to white, fine-grained, calcareous sandstone that weathers to rounded exposures; 3) blue chert; and 4) thin black shale/mudstone near the top (McKee 1938). The formation has subsequently been subdivided into the Woods Ranch, Brady Canyon, and Seligman Members, all distinguishable west of Marble Canyon (Sorauf and Billingsley 1991). The Toroweap Formation overlies the Coconino Sandstone and unconformably underlies the Kaibab Formation.

The Permian Brady Canyon Member is the middle cliff-forming member of the Toroweap Formation first mentioned in Sorauf (1962) and formally described by Sorauf and Billingsley (1991). The type locality of the member is designated in Brady Canyon, on the eastern side of Toroweap Valley about 20.6 km (12.8 mi) north of the Colorado River, Arizona (Table 5; Figure 48; Sorauf and Billingsley 1991). Type locality exposures measure 66 m (218.5 ft) thick and consist of gray, fossiliferous marine limestone that varies from thin- to thick-bedded (Sorauf and Billingsley 1991). The base of the member is placed where the first carbonate appears above the horizontally bedded sandstone or bedded gypsum of the Seligman Member (Rawson and Turner 1974). The Brady Canyon Member occurs between the overlying Woods Ranch and underlying Seligman Members of the Toroweap Formation.

The Permian Fossil Mountain Member of the Kaibab Formation was first described as the informal "beta member" of the Kaibab Formation by McKee (1938) before it was renamed by Sorauf (1962) and formally described by Sorauf and Billingsley (1991). The type locality of the unit is located along the Bass Trail on Fossil Mountain, Arizona (Table 5; Figure 48; Sorauf and Billingsley 1991). Type locality exposures are 64 m (211 ft) thick and predominantly composed of slope- to cliff-forming, fossiliferous, yellowish gray limestone that contains scattered nodules and lenses of white chert (McKee 1938; Sorauf and Billingsley 1991). The Fossil Mountain Member unconformably overlies the Toroweap Formation and underlies the Harrisburg Member of the Kaibab Formation.

Cenozoic Volcanics

The Miocene Snap Point Basalt was formally proposed by Billingsley and Wellmeyer (2003) and is named after its type area exposures at Snap Point, on the Shivwits Plateau, Arizona (Table 5; Figures 49 and 89). The Snap Point Basalt originated from a dike source near the highest part of Snap Point and consists of two dark gray, alkali-olivine basalt flows, one that flowed east about 2.4 km (1.5 mi) down drainage and another that flowed west down the steep erosional escarpment of the upper Grand Wash Cliffs (Billingsley and Wellmeyer 2003). Thickness of the basalt flows ranges from 3–10 m (10–30 ft) (Billingsley and Wellmeyer 2003). In the Grand Wash Trough the Snap Point Basalt underlies young alluvial fan deposits, where erosion has removed most of the alluvial deposits to form an inverted topographic feature (formed due to differential erosion leaving behind more resistant rock) called Nevershine Mesa (Billingsley and Wellmeyer 2003).

Figure 89. View looking north toward Snap Point and type area exposures of the Snap Point Basalt. Exposed section consists of basal Hermit Formation (red strata), Toroweap Formation (lower gray cliffs), and Kaibab Formation (top gray cliff), overlain by the Snap Point Basalt (black). Cropped photograph W144 from Billingsley et al. (2019).

The Pleistocene Basalt of Hancock Knolls was informally named by Billingsley and Hampton (2000) after its type area at Hancock Knolls in the Kanab Plateau, Arizona (Table 5; Figure 49). The unit is subdivided into a basal interval 1–27 m (3–90 ft) thick consisting of gray, finely crystalline alkali-olivine basalt flows overlain by an upper interval 12–107 m (40–350 ft) thick composed of red to reddish-black cinder and scoriaceous basaltic fragments (Billingsley and Hampton 2000). The Basalt of Hancock Knolls may represent the same eruptive phase as the Tuckup Canyon Basalt based on coalescing lava flows and the alignment of eruptive features in upper Tuckup Canyon (Billingsley and Hampton 2000).

The Pleistocene Tuckup Canyon Basalt was mentioned in Billingsley (1970) and formally described by Billingsley and Hampton (2000). The type area is designated in Tuckup Canyon, central Grand Canyon, Arizona (Table 5; Figures 49, 90, and 91; Billingsley and Hampton 2000). Billingsley and Hampton (2000) subdivided the formation into three units, in ascending order: 1) gray, finely crystalline alkali-olivine basalt flows 1–7.5 m (3–25 ft) thick; 2) pyroclastic deposits comprised of red to reddish-gray cinders and scoriaceous basalt 60 m (200 ft) thick; and 3) intrusive dikes consisting of dark-gray, finely crystalline alkali-olivine basalt that are 0.4–1 m (1–3 ft) wide. The Tuckup Canyon Basalt may represent the same eruptive phase as the Basalt of Hancock Knolls based on coalescing lava flows and the alignment of eruptive features in upper Tuckup Canyon (Billingsley and Hampton 2000).

Figure 90. View looking west toward the type area exposures of the Tuckup Canyon Basalt from the east rim of Tuckup Canyon. The black featureless Tuckup Canyon Basalt flow overlies the Esplanade Sandstone. Cropped photograph CI23 from Billingsley et al. (2019).

Figure 91. North-facing view toward the south end of the Tuckup Canyon Basalt flow over Esplanade Sandstone. Photograph CI24 from Billingsley et al. (2019).

Hubbell Trading Post National Historic Site (HUTR)

Hubbell Trading Post National Historic Site (HUTR) is located just off Arizona State Highway 264 approximately 1.6 km (1 mi) west of Ganado and 89 km (55 mi) northwest of Gallup, New Mexico in Apache County, Arizona (Figure 92). Established on August 28, 1965, HUTR encompasses about 65 hectares (160 acres) and preserves the oldest continuously operated trading post on the Navajo Nation (National Park Service 2016a). The history of the trading post begins in approximately 1874, when Anglo-European trader William Leonard established a trading post in the Ganado Valley. Using “squatter’s rights”, Juan Lorenzo Hubbell purchased the Leonard post and later filed for a homestead claim. As the Navajo Nation lands were expanded in 1880, the land Hubbell acquired would become one of few privately owned parcels of land within the boundaries of the Navajo Nation. The national historic site consists primarily of a historic vernacular landscape from the period (1878–1967) that the trading post was actively run by the Hubbell family. During the first half of the 20^{th} century, Hubbell built an economic empire consisting of more than 20 trading posts that was able to influence the production and development of traditional designs that remain in use today (National Park Service 2007).

The geology of HUTR consists of Mesozoic and Cenozoic sedimentary rocks spanning from ~225 million years ago to the present. The bedrock underlying the historic site is composed of sandstone and claystone of the Triassic Monitor Butte Member of the Chinle Formation, overlain by a veneer of Quaternary alluvium (Figure 93). Immediately surrounding HUTR are the Triassic Petrified Forest and Sonsela Members of the Chinle Formation, as well as Miocene–Pliocene-age terrace, eolian, and upper Bidahochi Formation deposits. The Pueblo Colorado Wash cuts through the northernmost part of HUTR, while the remainder of the national historic site consists of leveled terraces, rising from north to south, from which native vegetation was removed for farming and raising livestock (National Park Service 2007).

There are no designated stratotypes identified within the boundaries of HUTR. There is one identified stratotype located within 48 km (30 mi) of HUTR boundaries, for the Miocene–Pliocene Bidahochi Formation (reference section).

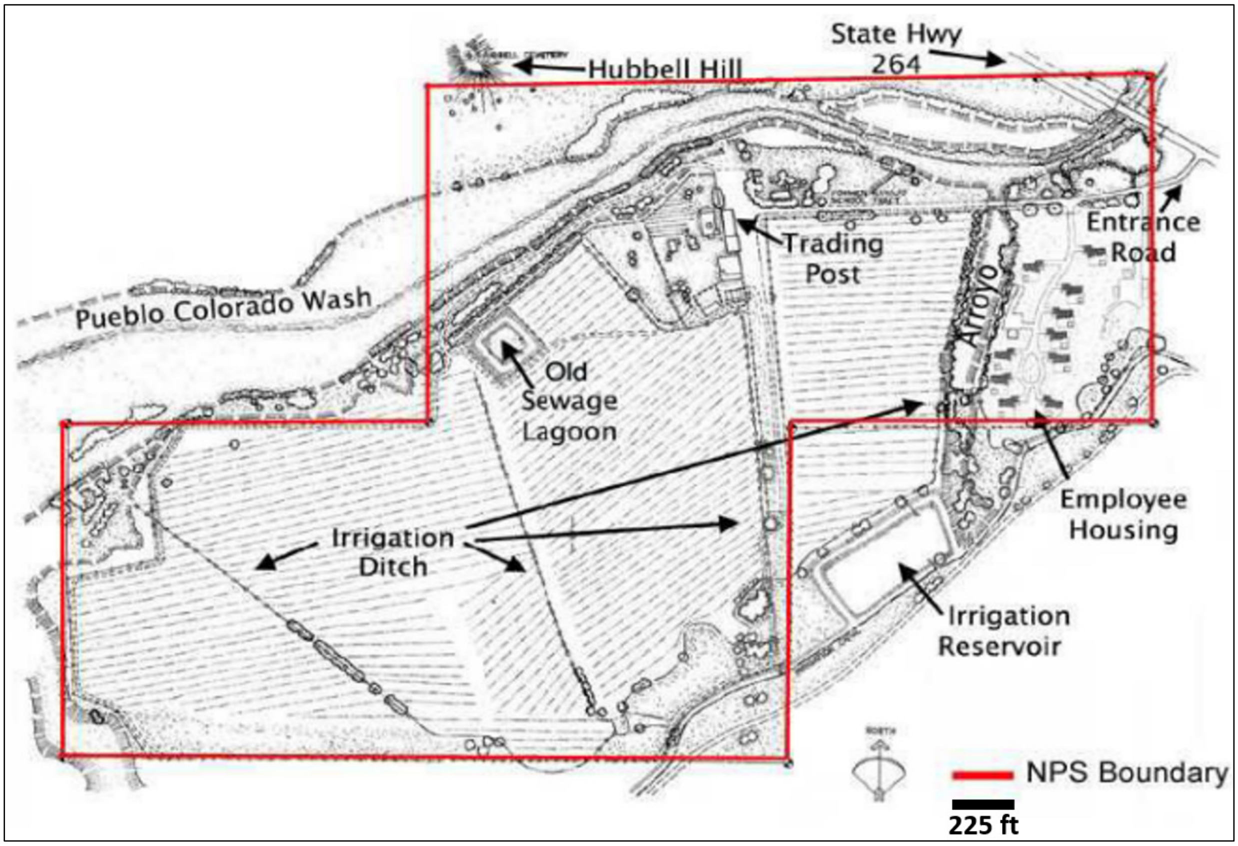


Figure 92. Park map of HUTR, Arizona (NPS).

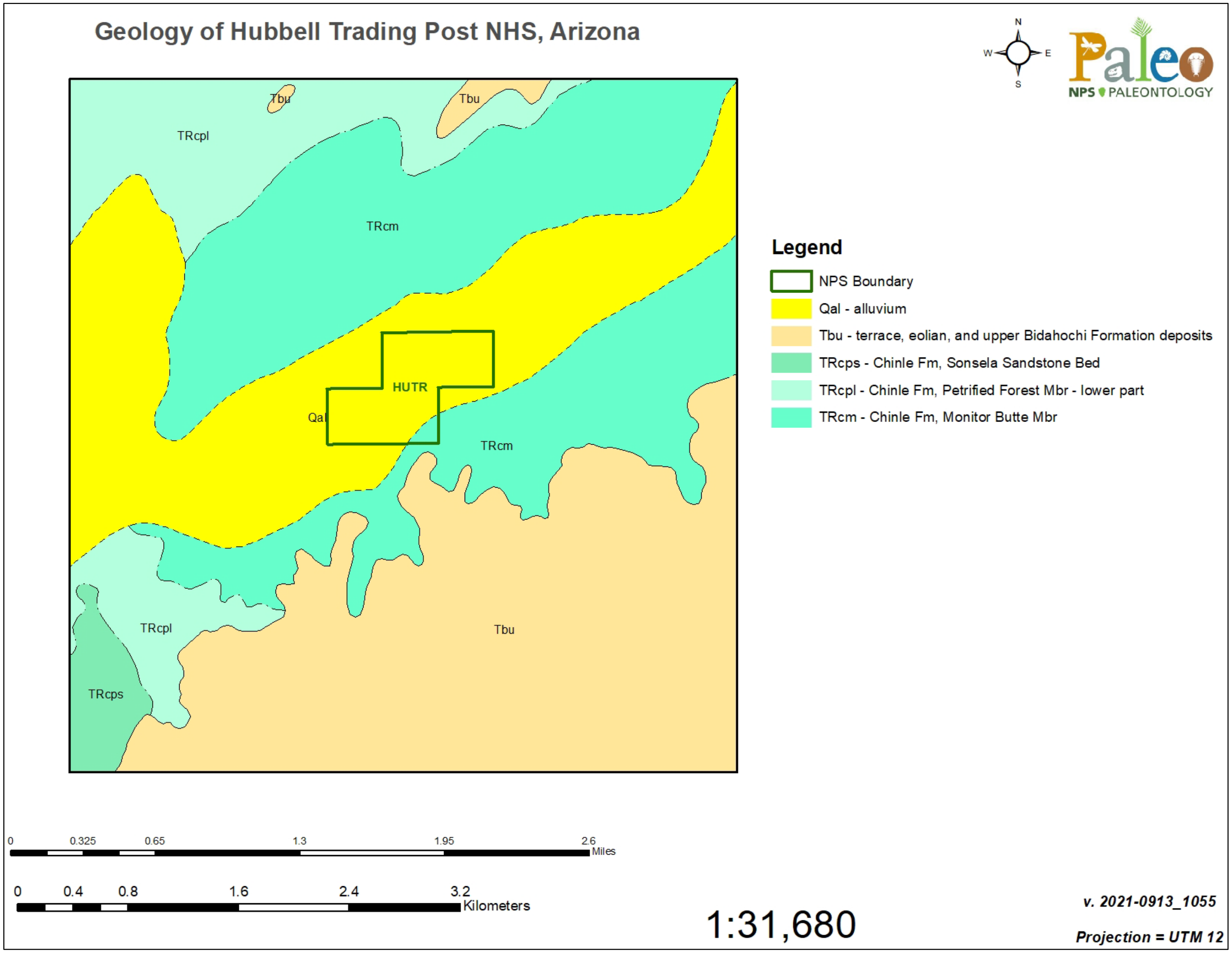


Figure 93. Geologic map of HUTR, Arizona.

Mesa Verde National Park (MEVE)

Mesa Verde National Park (MEVE) is located in Montezuma County, southwestern Colorado near the Four Corners region where Arizona, Colorado, New Mexico, and Utah meet (Figure 94). Established on June 29, 1906, MEVE contains approximately 21,240 hectares (52,485 acres) of an archeological landscape that includes more than 600 well-preserved prehistoric cliff dwellings and more than 5,000 archeological sites (National Park Service 2016a). Ancestral Puebloans inhabited the park region from about 550 to 1300 CE, and numerous sites throughout MEVE provide insights into Ancestral Puebloan culture including Far View Sites, the Mesa Top Loop, Step House, the Badger House Community at Wetherill Mesa, Cliff Palace, Balcony House, Long House, and Spruce Tree House. The boundaries of MEVE include about 1,347 km^2 (520 mi^2) of deeply dissected tableland on the Colorado Plateau, including about 32 km (20 mi) of hiking trail scattered throughout the park (Graham 2006). In recognition of its valuable cultural resources, MEVE was among the first sites designated a United Nations Educational Scientific and Cultural Organization (UNESCO) World Heritage Cultural Site on September 6, 1978.

Mesa Verde National Park encompasses roughly 210 km^2 (81 mi^2) of Mesa Verde, a broad and deeply dissected, flat-topped mesa with numerous north–south-trending, steep-sided canyons. Mapped geologic units within the park include rocks of the Cretaceous Mesaverde Group (Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone) and Mancos Shale, and younger Quaternary surficial deposits (Figure 95). The notable massive cliffs and alcoves of MEVE consist of porous, erosion-resistant sandstones of the Cliff House Sandstone. The slopes beneath the cliffs are less resistant and composed of siltstone, mudstone, or shale of the Menefee Formation. Because the underlying strata of the Menefee Formation is less permeable than the overlying Cliff House Sandstone, groundwater flows along the contact of the two formations and emerges as springs or seeps along the canyon walls (Graham 2006). The alcoves and cliff dwellings of the Ancestral Puebloans are the result of these springs and seeps as they were an important source of water.

Mesa Verde National Park contains five identified stratotypes that represent the Cretaceous Mancos Shale, Cortez Member of the Mancos Shale, Mesaverde Group, Point Lookout Sandstone, and Cliff House Formation (Table 6; Figure 96). In addition to the designated stratotypes located within MEVE, stratotypes located within 48 km (30 mi) of the park's boundaries include the Cretaceous Montezuma Valley Member of the Mancos Shale (type section) and the Menefee Formation (type locality).

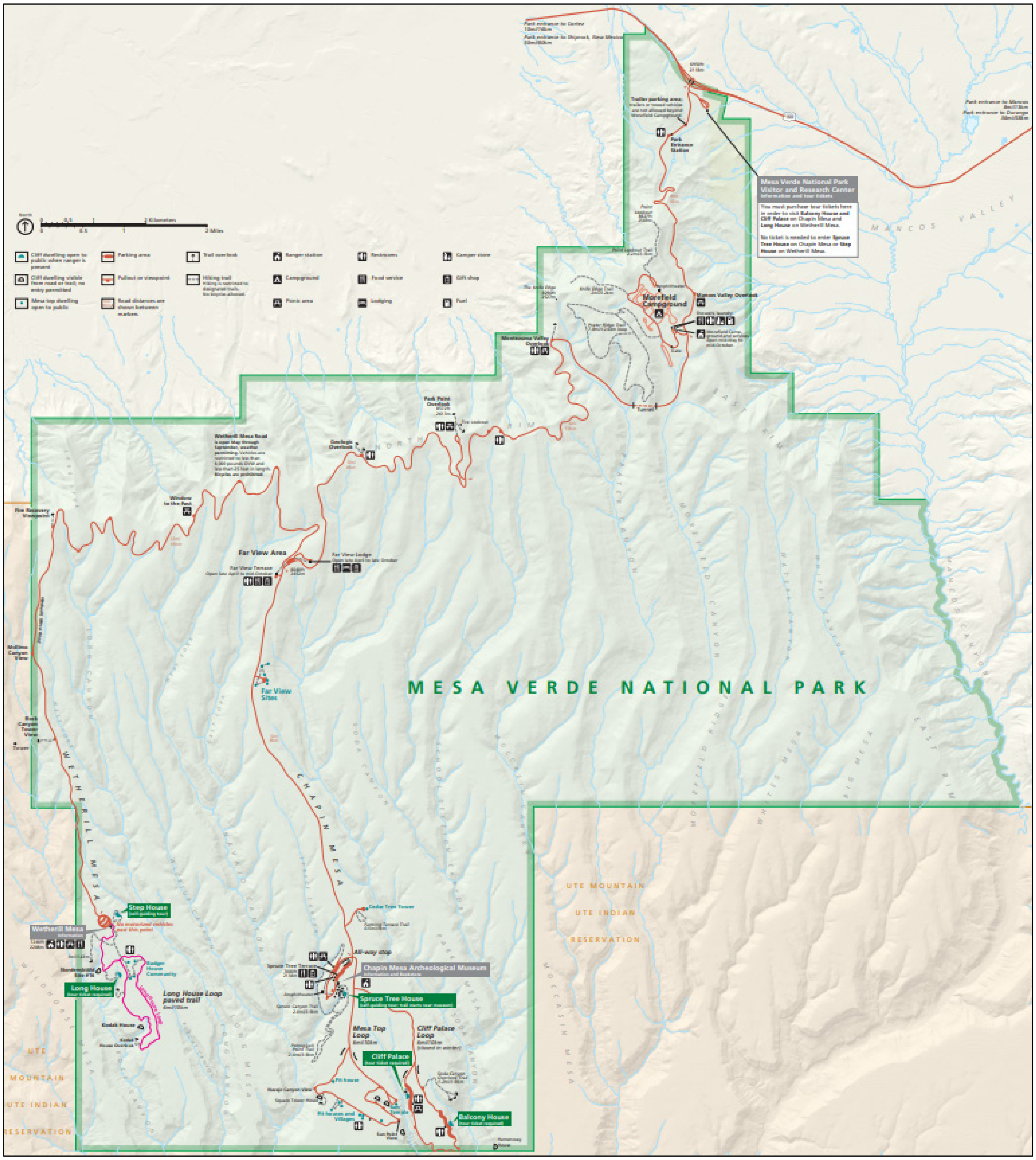


Figure 94. Park map of MEVE, Colorado (NPS).

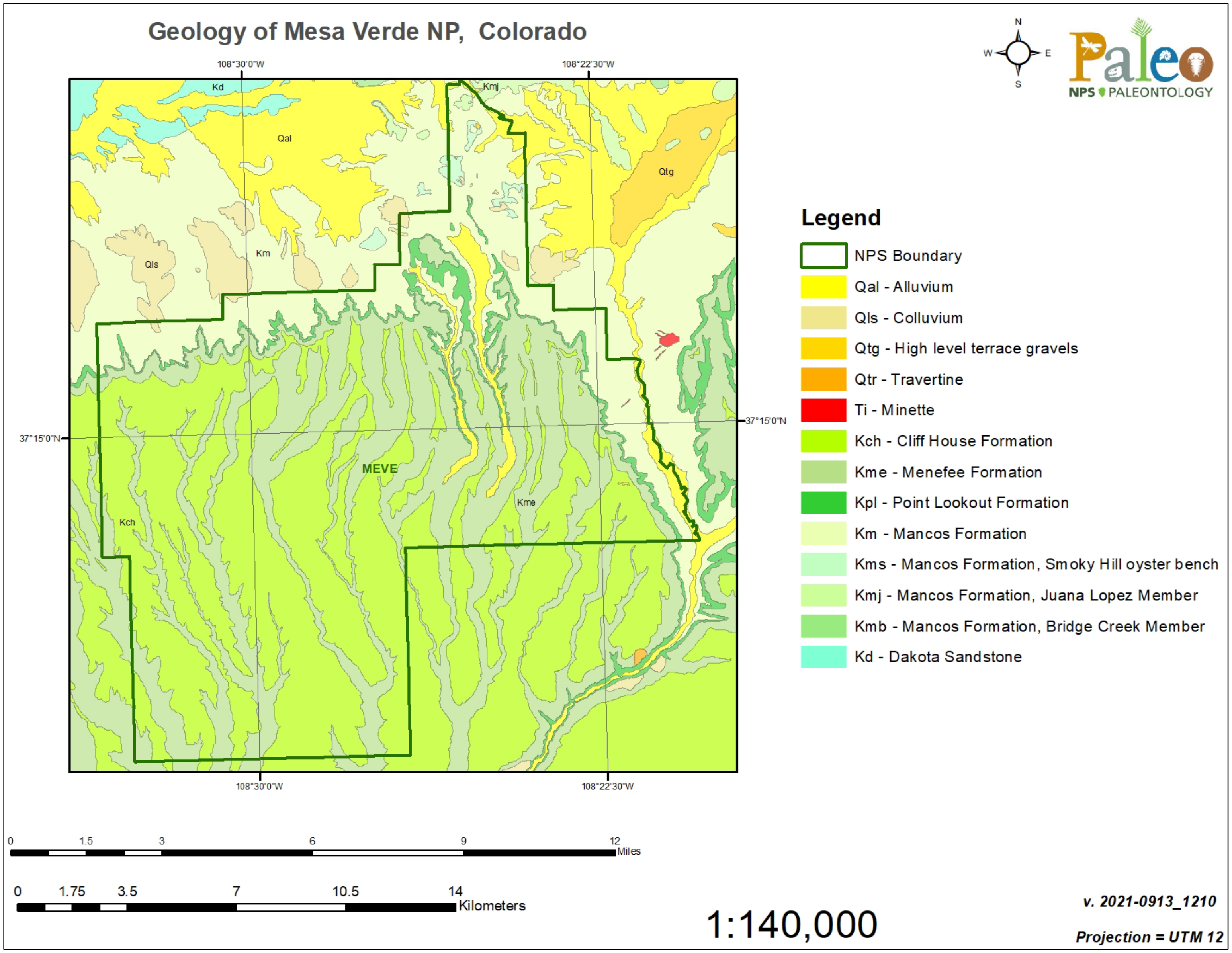


Figure 95. Geologic map of MEVE, Colorado.

Table 6. List of MEVE stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Mesaverde Group (Kch, Kme, Kpl)	Collier 1919; Dubiel 2013	Type locality: Mesaverde National Park in southwestern CO.	Late Cretaceous
Cliff House Formation (Kch)	Collier 1919; Lochman-Balk 1967	Type locality: Echo Cliffs in MEVE, Montezuma Co., CO.	Late Cretaceous
Point Lookout Sandstone (Kpl)	Collier 1919; Lochman-Balk 1967	Type locality: Cliffs at Point Lookout, about 12 km (7.5 mi.) SW of Mancos, Montezuma Co., CO.	Late Cretaceous
Mancos Shale (Km, Kms, Kmj)	Leckie et al. 1997	Principal reference section (composite): transect extending from sec. 19 and 20, T. 36 N., R. 14 W., north of MEVE, to sec. 5, T. 35 N., R. 14 W. at the base of the sandstone cliffs of Point Lookout within the park, Montezuma Co., CO.	Late Cretaceous
Cortez Member, Mancos Shale	Leckie et al. 1997	Type section: in the western half of sec. 5, T. 35 N., R. 14 W., Montezuma Co., CO.	Late Cretaceous

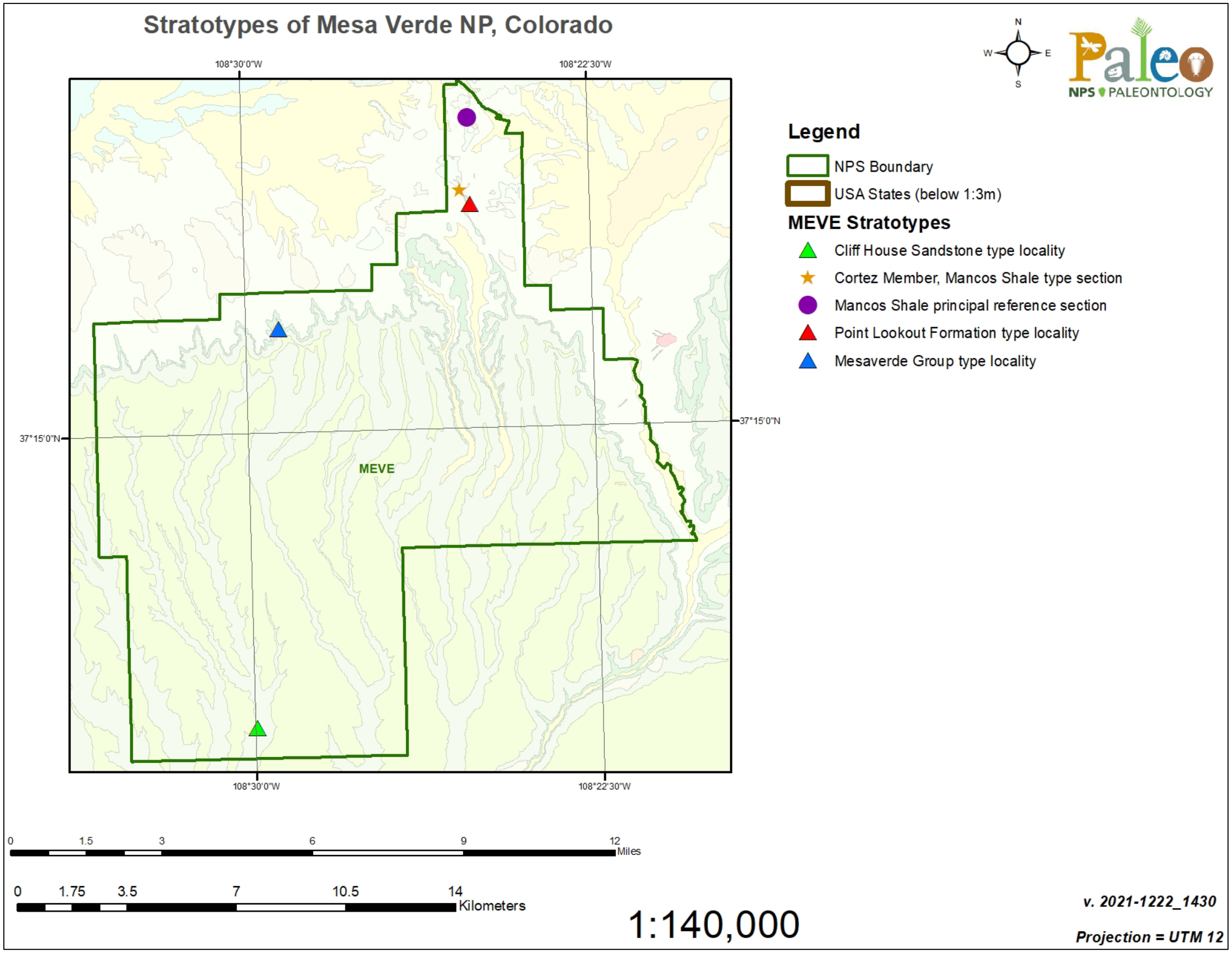


Figure 96. Modified geologic map of MEVE showing stratotype locations. The transparency of the geologic units layer has been increased.

The Cretaceous Mancos Shale was first proposed by Cross in Cross and Purington (1899) and named from its characteristic occurrence in Mancos Valley and around the town of Mancos, Colorado. A principal reference section for the Mancos Shale is located in northern MEVE along a transect extending from sec. 19 and 20, T. 36 N., R. 14 W., north of MEVE, to sec. 5, T. 35 N., R. 14 W. at the base of the sandstone cliffs of Point Lookout within the national park (Table 6; Figures 96 and 97; Leckie et al. 1997). The section measures 682 m (2,237 ft) thick and is subdivided into eight members, from oldest to youngest the Graneros, Bridge Creek, Fairport, Blue Hill, Juana Lopez, Montezuma Valley, Smoky Hill, and Cortez Members (Leckie et al. 1997). The Mancos Shale is predominantly composed of non-calcareous and calcareous shale, with minor amounts of sandstone, sandy mudstone, and limestone (Leckie et al. 1997). At the principal reference section, the Mancos Shale overlies the Dakota Sandstone and underlies the Point Lookout Sandstone.

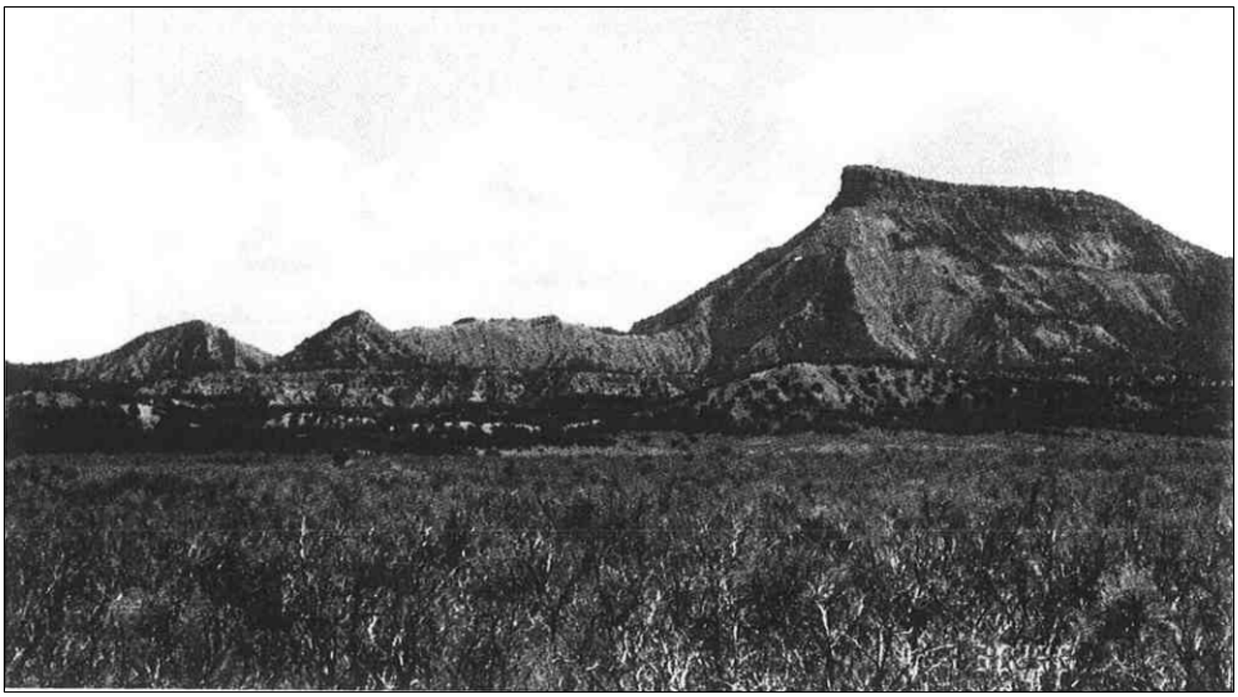


Figure 97. Mancos Shale principal reference section as viewed from the northwest. Point Lookout forms the prominent erosional headland at the north end of Mesa Verde National Park. Low slopes in the foreground are capped by orange-weathering calcarenite beds of the upper Juana Lopez Member of the Mancos Shale. Behind these slopes and in front of the long erosional ridge extending below Point Lookout is a continuous, horizontal bench marking the contact between the Smoky Hill and Cortez Members of the Mancos Shale. Figure 3 from Leckie et al. (1997) (courtesy of the New Mexico Geological Society).

The Cretaceous Cortez Member of the Mancos Shale was named by Leckie et al. (1997) after the nearby city of Cortez, Colorado. The type section of the member is in the shaly slopes exposed beneath the northern rim of Mesa Verde, in the western half of sec. 5, T. 35 N., R. 14 W., in Montezuma County, Colorado (Table 6; Figure 96; Leckie et al. 1997). The type section consists of two coarsening-upward sequences. The lower coarsening-upward package is composed of calcareous shale overlain by silty calcareous shale containing an increasing abundance of sandstone up-section (Leckie et al. 1997). The second coarsening-upward sequence consists of silty to sandy shale that transitions upward into interbedded sandstone and sandy shale (Leckie et al. 1997). The Cortez Member conformably occurs between the underlying Smoky Hill Member of the Mancos Shale and overlying Point Lookout Sandstone.

The Cretaceous Mesaverde Group was originally mentioned by Holmes (1877) and revised by Collier (1919) to include the Cliff House Sandstone, Menefee Formation, and Point Lookout Sandstone. The type locality of the group is located in MEVE (Figure 96; Table 6; Dubiel 2013 citing Collier 1919). In the vicinity of Mancos, the group is between 305–366 m (1,000–1,200 ft) thick and composed of a basal massive sandstone (Point Lookout Sandstone), middle interval of sandstone, shale, and coal (Menefee Formation), and an upper sequence of compact, cliff-forming sandstone (Cliff House Sandstone) (Figure 98; Collier 1919). The Mesaverde Group overlies the Mancos Shale and underlies Quaternary-age alluvium.

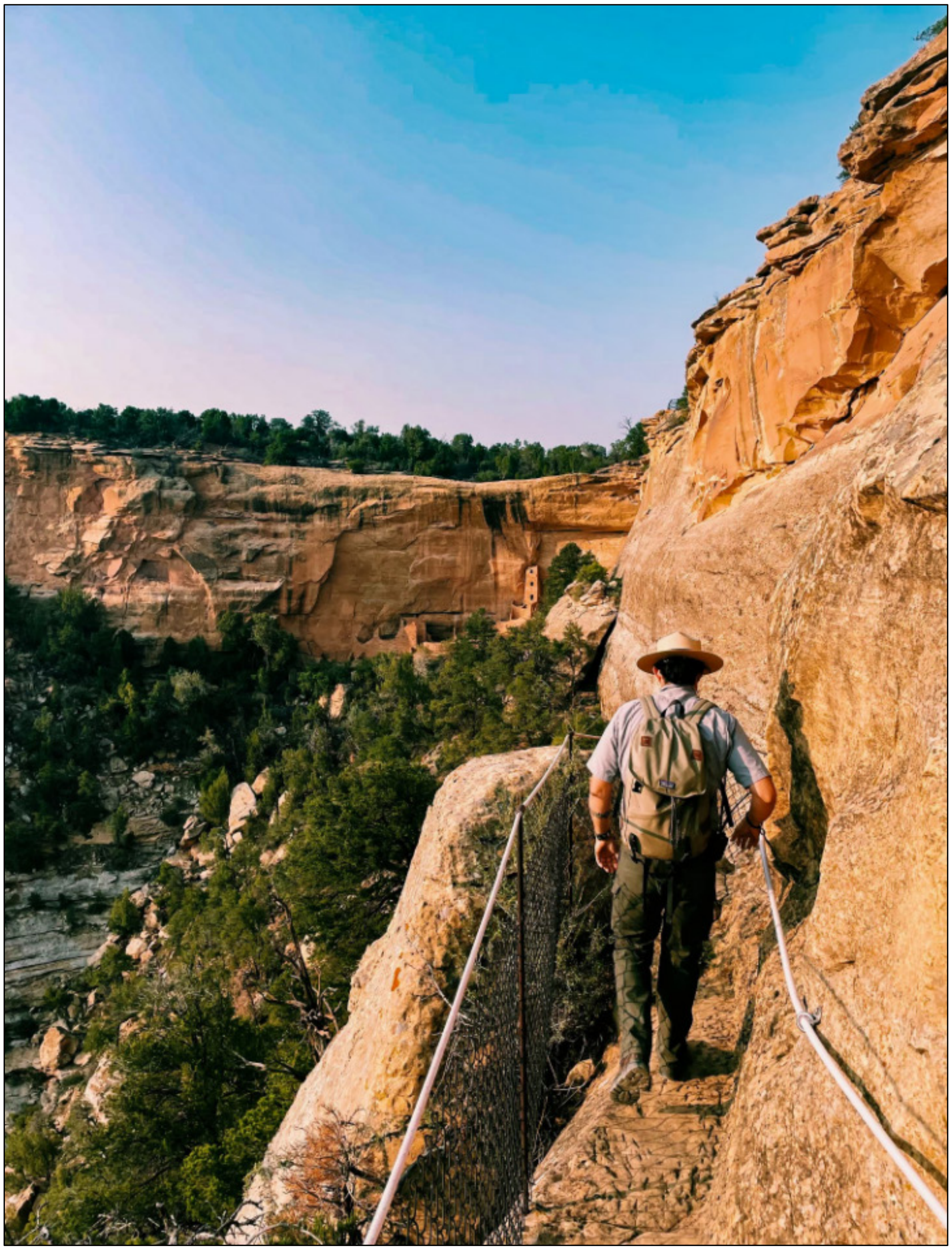


Figure 98. A ranger walks along a narrow stone walkway on the restricted trail to Square Tower House (NPS). Upper cliffs consist of the Cliff House Sandstone of the Mesaverde Group.

The Cretaceous Point Lookout Sandstone was named by Collier (1919) and included as the lowermost unit of the Mesaverde Group. The type locality of the formation is located in the cliffs at Point Lookout, about 12 km (7.5 mi) southwest of Mancos, Colorado (Table 6; Figures 96 and 99; Lochman-Balk 1967 citing Collier 1919). Type locality exposures consist of tan, massive sandstone with minor shale lenses that measure approximately 76–91 m (250–300 ft) thick (Collier 1919). At the type locality the Point Lookout Sandstone underlies the Menefee Formation and overlies the Mancos Shale.

Figure 99. Type locality exposures of the Point Lookout Sandstone at Point Lookout (NPS). Lower slopes consist of the Mancos Formation, overlain by the Point Lookout Sandstone (gray lower cliff), and capped by the Menefee Formation (light brown upper cliff).

The Cretaceous Cliff House Sandstone was named by Collier (1919) and included as the uppermost unit of the Mesaverde Group. The type locality of the formation is located in the Echo Cliffs at MEVE, Colorado (Table 6; Figure 96; Lochman-Balk 1967 citing Collier 1919). Type locality exposures consist of compact sandstone more than 122 m (400 ft) thick forming the sheer cliffs in the canyons around the cliff houses of the park (Collier 1919). The Cliff House Sandstone overlies the Menefee Formation.

Navajo National Monument (NAVA)

Navajo National Monument (NAVA) is located in the heart of the western part of the Navajo Nation in Coconino and Navajo Counties, northeastern Arizona (Figure 100). Established on March 20, 1909, NAVA encompasses approximately 146 hectares (360 acres) and preserves three cliff dwelling complexes (Betatakin, Keet Seel, and Inscription House) constructed by the Ancestral Puebloans (National Park Service 2016a). These Ancestral Puebloan dwellings are considered among the largest and most intact pre-contact structures in the American Southwest, built in natural alcoves eroded into the sandstone walls of the Tsegi Canyon system. The cliff dwelling complexes in NAVA represent a significant part of the long span of human habitation of the area and hold profound cultural importance and meaning for contemporary people, particularly the Hopi, Zuni, Navajo, and San Juan Southern Paiute (National Park Service 2017).

Navajo National Monument is situated in Tsegi Canyon, a primary drainage of the eastern part of the Shonto Plateau, part of the larger Colorado Plateau Physiographic Province. Tsegi Canyon contains three major branches and numerous tributary canyons that have deeply incised into Triassic–Jurassic strata (Figures 101 and 102). The notable dwelling complexes of NAVA are constructed in sandstone cliffs of the Jurassic Navajo Sandstone, a porous and permeable unit that serves as a regional aquifer. Springs and seeps are associated with the basal contact between the cliff-forming Navajo Sandstone and the underlying siltstones and sandstones of the Jurassic Kayenta Formation. Geologic factors such as the presence of springs and seeps, large cross-beds in the Navajo Sandstone, and vertical fractures that serve as conduits for water all contribute to the formation of alcoves utilized by the Ancestral Puebloan people (Graham 2007).

There are no designated stratotypes identified within the boundaries of NAVA. There are five identified stratotypes located within 48 km (30 mi) of NAVA boundaries, for the Triassic Church Rock Member of the Chinle Formation (type section) and Owl Rock Member of the Chinle Formation (type section); Jurassic Cow Springs Sandstone (type section and type locality) and Kayenta Sandstone (type locality); and the Holocene Tsegi Alluvium (type locality).

Figure 100. Regional map of NAVA, Arizona (NPS).

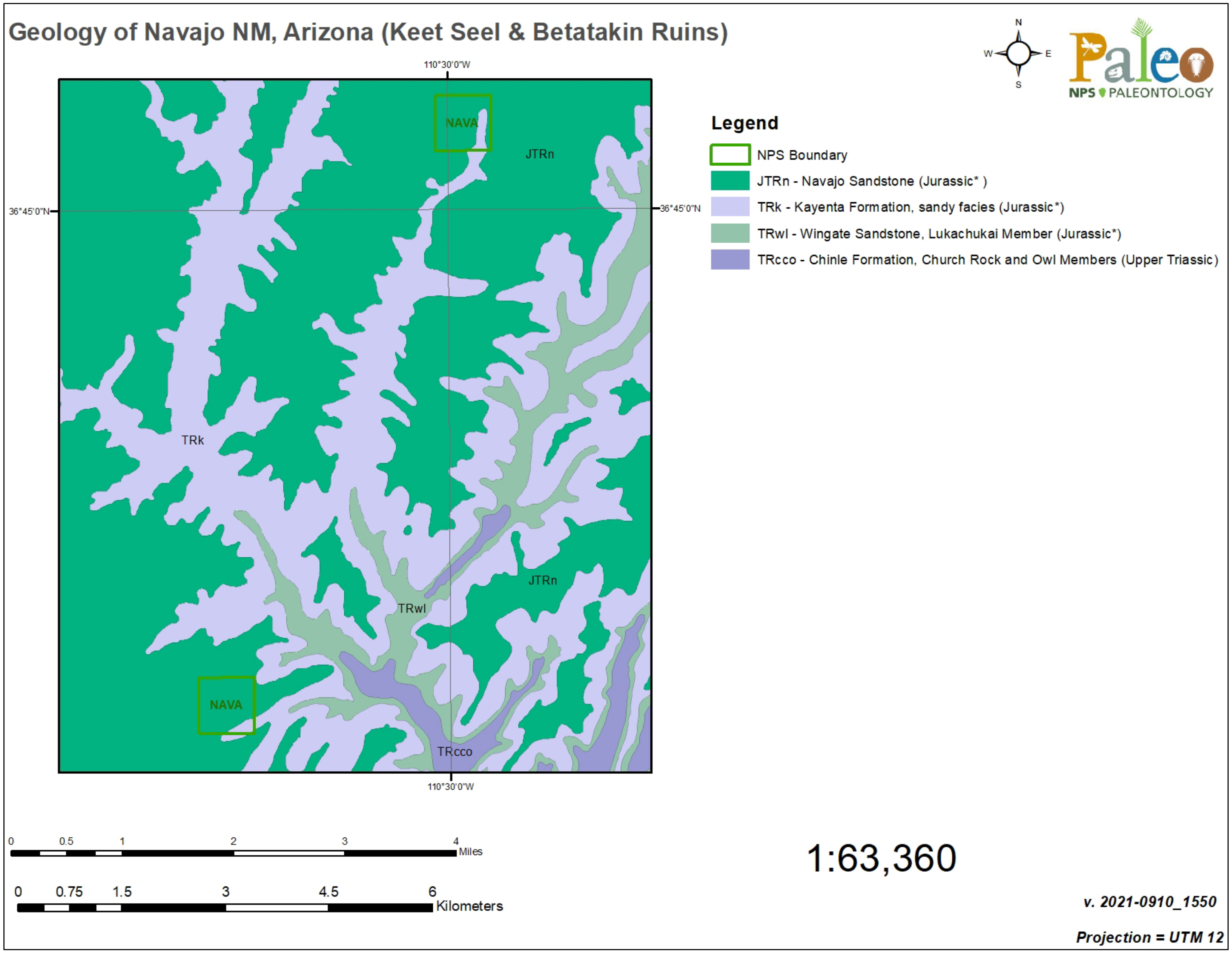


Figure 101. Geologic map of NAVA (Keet Seel and Betatakin Ruins units), Arizona. Note: the source map interpreted the Navajo Sandstone as Triassic–Jurassic in age but it is now known to be solely Jurassic.

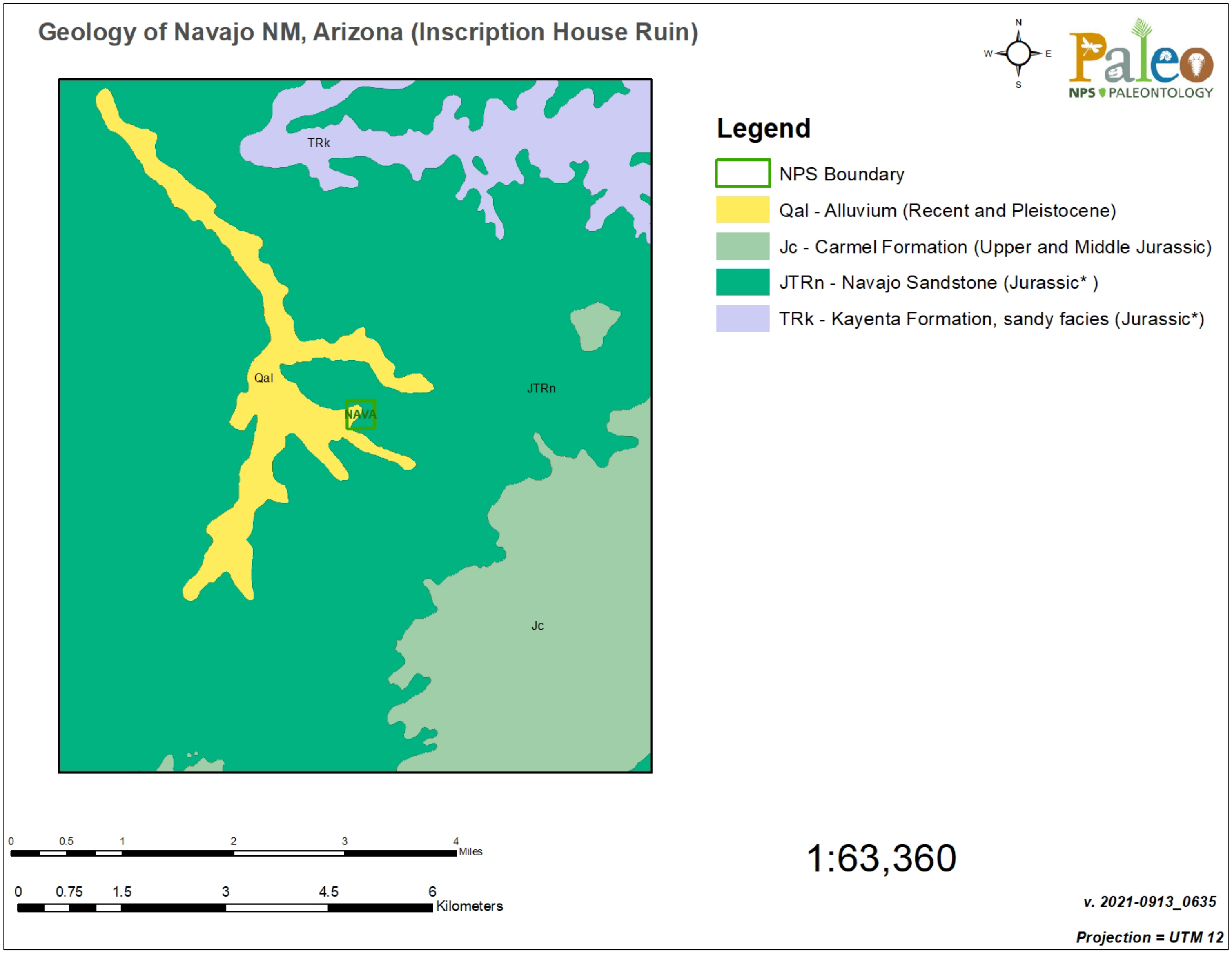


Figure 102. Geologic map of NAVA (Inscription House Ruin Unit), Arizona. Note: the source map interpreted the Navajo Sandstone as Triassic–Jurassic in age but it is now known to be solely Jurassic.

Petrified Forest National Park (PEFO)

Petrified Forest National Park (PEFO) is located about 160 km (100 mi) east of Flagstaff in Apache and Navajo Counties, Arizona (Figure 103). Originally established as a national monument on December 8, 1906, PEFO was redesignated a national park on December 9, 1962 (National Park Service 2016a). PEFO encompasses approximately 89,603 hectares (221,416 acres) and protects globally significant fossils, including petrified wood and one of the most comprehensive records of Late Triassic vertebrate evolution in North America (National Park Service 2015c). The national park contains one of the largest and most colorful concentrations of mineralized fossil wood in the world, including petrified logs of ancient conifer species that are more than 58 m (190 ft) long.

The geology of PEFO primarily consists of the Late Triassic Chinle Formation (and associated members) and the Miocene–Pliocene Bidahochi Formation (Figures 104). Paleontological resources of the Chinle Formation and Bidahochi Formation have yielded more than 700 paleontological sites in the park, making PEFO a world-renowned natural laboratory for paleontology. The park's petrified wood and other Upper Triassic fossils are considered globally significant because they document a diverse suite of terrestrial ecosystems during "the dawn of dinosaurs" between 223–208 million years ago (KellerLynn 2010; Ramezani et al. 2011). Multi-hued badland hills, flat-topped mesas, and buttes of the Painted Desert are primarily composed of sandstones, conglomerates, and mudstones of the Chinle Formation that record fluvial deposition in an ancient river basin. The stratigraphic nomenclature of the Chinle Formation in PEFO has undergone a number of revisions since the early 1990s. The accepted terminology for the members of the Chinle Formation found at PEFO are as follows, from oldest to youngest: the Mesa Redondo Member, Blue Mesa Member, Sonsela Member, Petrified Forest Member, and Owl Rock Member (Figure 105; Martz et al. 2012). The contact between the Chinle Formation and Bidahochi Formation is an unconformity that represents a gap in the rock record of ~190 million years.

Petrified Forest National Park contains 39 identified stratotypes that are subdivided into 12 type sections and 27 reference sections (Table 7; Figures 106 and 107). In addition to the designated stratotypes located within PEFO, stratotypes located within 48 km (30 mi) of the park's boundaries include the Triassic Holbrook Member of the Moenkopi Formation (type area) and Mesa Redondo Member of the Chinle Formation (type section), and the Miocene–Pliocene Bidahochi Formation (reference section).

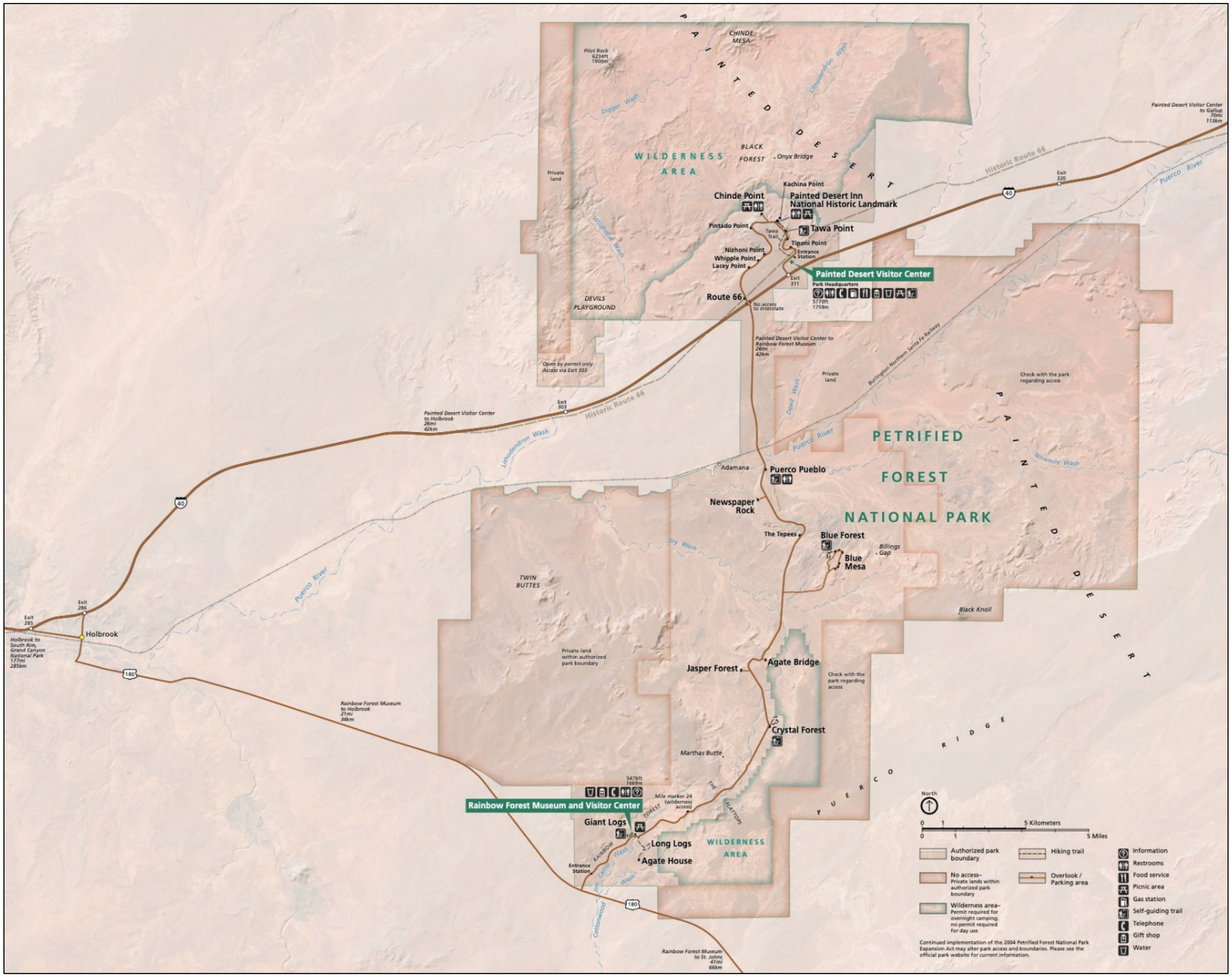


Figure 103. Park map of PEFO, Arizona (NPS).

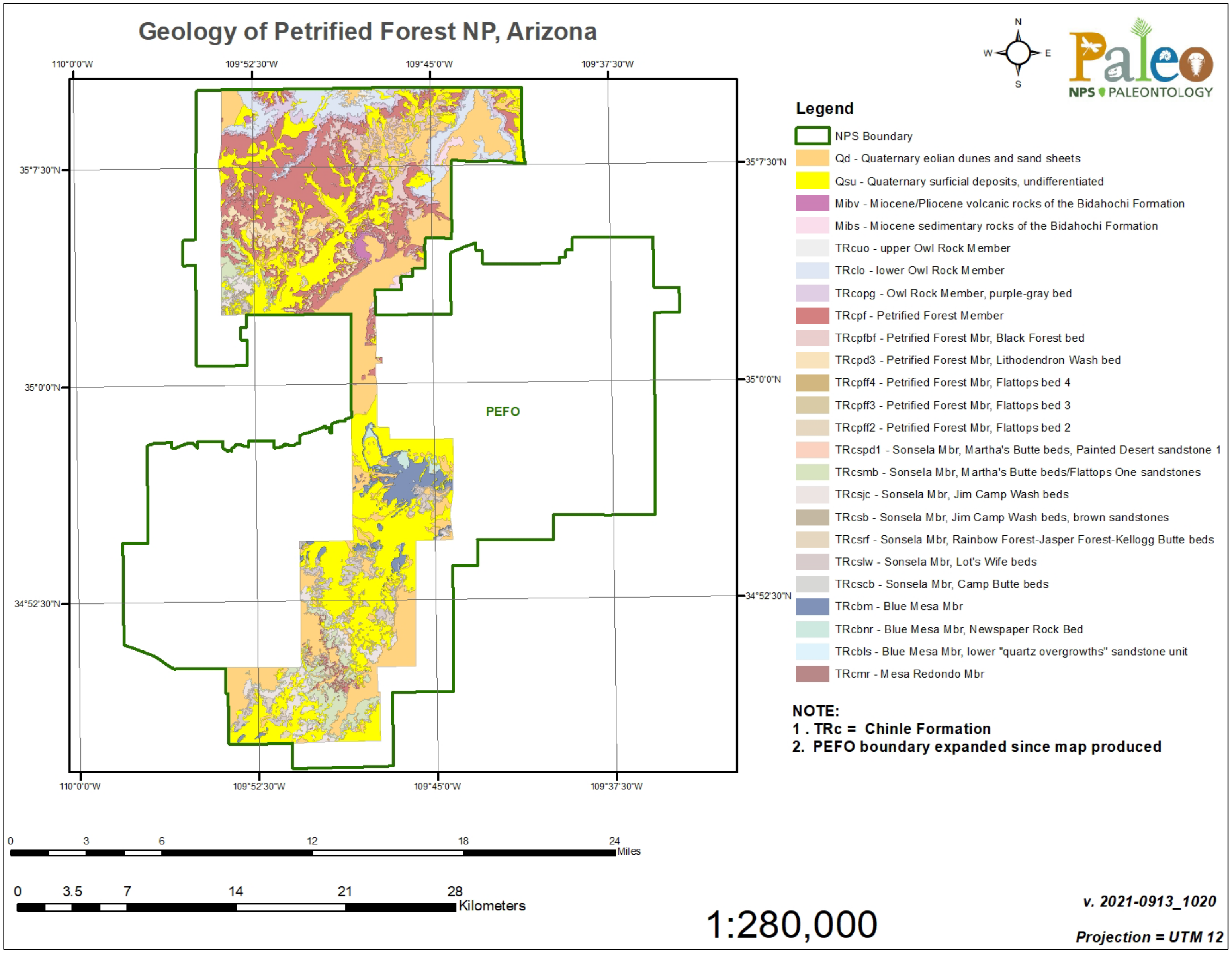


Figure 104. Geologic map of PEFO, Arizona. Note: PEFO has expanded since the creation of the geologic map.

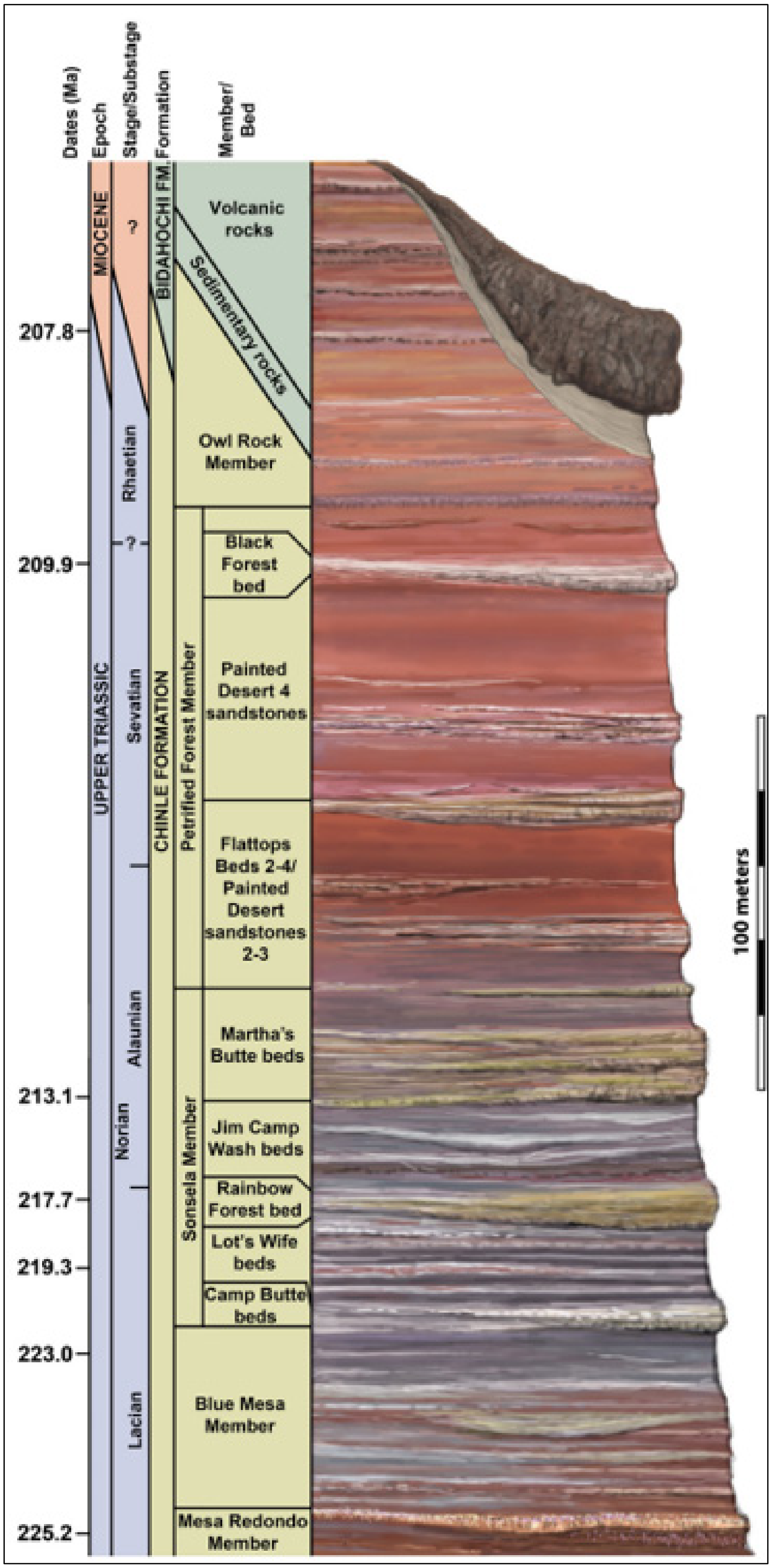


Figure 105. Lithostratigraphic column for PEFO. Figure 3 from Martz et al. (2012) (courtesy of the Arizona Geological Survey).

Table 7. List of PEFO stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Painted Desert Member, Petrified Forest Formation, Chinle Group (*now obsolete and considered the Petrified Forest Member of the Chinle Formation*)	Lucas 1993; Heckert and Lucas 2002	Type section (composite): 1) SE/4 NE/4 sec. 11, T. 19 N., R. 23 E.; 2) W/2 NW/4 SW/4 sec. 34, T. 20 N., R. 24 E.; and 3) NW/4 sec. 9 and SW/4 sec. 4, T. 20 N., R. 24 E., Apache Co., AZ.	Late Triassic
Black Forest Bed, Petrified Forest Member, Chinle Formation (TRcpfbf)	Ash 1992	Type section: below Kachina Point and about 40 m (131 ft) west of the trail leading into the Painted Desert Section of PEFO, in SW/4 SW/4 SW/4, sec. 33, T. 20 N., R. 24 E., Apache Co., AZ.	Late Triassic
Lithodendron Wash Bed, Petrified Forest Member, Chinle Formation (TRcpd3)	Heckert and Lucas 2002	Type section: Chinde Point II section, in NW/4 SE/4 NE/4, sec. 33, T. 20 N., R. 24 E., Apache Co., AZ.	Late Triassic
Flattops Bed 4, Petrified Forest Member, Chinle Formation (TRcpff4)	Cooley 1957; Roadifer 1966; Murry and Long 1989; Heckert and Lucas 2002	Type section: Flattops west section, in SW/4 NE/4 NW/4 sec. 32, T. 17 N., R. 24 E., Apache Co., AZ. Reference sections: 1) S/2 SE & SW/4, sec. 32, T. 17 N., R. 24 E., Apache Co., AZ (Cooley 1957); 2) SE/4 SW/4 sec. 32, T. 17 N., R. 24. E., Apache Co., AZ (Roadifer 1966); and 3) sec. 32, T. 17 N., R. 24 E., at approx. lat. 34°49′50″ N, long. 109°48′48″ W., Apache Co., AZ (Murry and Long 1989).	Late Triassic
Flattops Bed 3, Petrified Forest Member, Chinle Formation (TRcpff3)	Cooley 1957; Roadifer 1966; Murry and Long 1989; Heckert and Lucas 2002	Type section: Flattops west section, in SW/4 NW/4 sec. 32, T. 17 N., R. 24 E., Apache Co., AZ. Reference sections: 1) S/2 SE & SW/4, sec. 32, T. 17 N., R. 24 E., Apache Co., AZ (Cooley 1957); 2) SE/4 SW/4 sec. 32, T. 17 N., R. 24. E., Apache Co., AZ (Roadifer 1966); and 3) sec. 32, T. 17 N., R. 24 E., at approx. lat. 34°49′50″ N, long. 109°48′48″ W., Apache Co., AZ (Murry and Long 1989).	Late Triassic

Table 7 (continued). List of PEFO stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Flattops Bed 2, Petrified Forest Member, Chinle Formation (TRcpff2)	Cooley 1957; Roadifer 1966; Murry and Long 1989; Heckert and Lucas 2002	Type section: Flattops west section, in NE/4 NE/4 sec. 31, T. 17 N., R. 24 E., Apache Co., AZ. Reference sections: 1) S/2 SE & SW/4, sec. 32, T. 17 N., R. 24 E., Apache Co., AZ (Cooley 1957); 2) SE/4 SW/4 sec. 32, T. 17 N., R. 24. E., Apache Co., AZ (Roadifer 1966); and 3) sec. 32, T. 17 N., R. 24 E., at approx. lat. 34°49′50″ N, long. 109°48′48″ W., Apache Co., AZ (Murry and Long 1989).	Late Triassic
Flattops Bed 1, Petrified Forest Member, Chinle Formation (TRcsmb)	Woody 2006	Type section: section Mountain Lion Mesa 1 – UTM Zone 12S, E608482, N3857866, NAD 27. Reference sections: 1) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27; 2) section Agate Mesa West 1 – UTM Zone 12S, E607822, N3860933, NAD 27; 3) section Old 180 4 – UTM Zone 12S, E608325, N3850628, NAD 27; 4) section Crystal Forest – UTM Zone 12S, E610591, N3859345, NAD 27; and 5) section Dry Wash N – UTM Zone 12S, E610014, N3856388, NAD 27.	Late Triassic
Sonsela Member, Chinle Formation (TRcsrf, TRcsb, TRcsjc, TRcsmb, TRcspd1)	Woody 2006	Reference sections: 1) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27; and 2) section Mountain Lion Mesa 1 – UTM Zone 12S, E608482, N3857866, NAD 27.	Late Triassic
Agate Bridge Bed, Sonsela Member, Chinle Formation	Heckert and Lucas 2002	Type section: just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge, northwest of Giant Logs in N/2 SW/4 SW/4 to NW/4 NW/4 SW/4 sec. 35, T. 17 N., R. 23 E., Navajo Co., AZ. Reference section: units 7–11 of Murry and Long's (1989) "Sonsela section", north of Agate Bridge, Apache Co., AZ.	Late Triassic

Table 7 (continued). List of PEFO stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Jim Camp Wash Beds, Sonsela Member, Chinle Formation (TRcsjc, TRcsb)	Heckert and Lucas 2002; Woody 2006	Type section: just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge, northwest of Giant Logs in N/2 SW/4 SW/4 to NW/4 NW/4 SW/4 sec. 35, T. 17 N., R. 23 E., Apache Co., AZ. Reference sections: 1) section Agate Mesa West 1 – UTM Zone 12S, E607822, N3860933, NAD 27; 2) section Mountain Lion Mesa 1 – UTM Zone 12S, E608482, N3857866, NAD 27; 3) section Dry Wash North – UTM Zone 12S, E610014, N3856388, NAD 27; and 4) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27.	Late Triassic
Jasper Forest Bed, Sonsela Member, Chinle Formation (TRcsrf)	Martz and Parker 2010	Reference section: the capping sandstone at Agate Mesa, best exposed on the northern face, Apache Co., AZ.	Late Triassic
Rainbow Forest Bed, Sonsela Member, Chinle Formation (TRcsrf)	Cooley 1957; Heckert and Lucas 2002; Woody 2006	Type section: just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge, northwest of Giant Logs in N/2 SW/4 SW/4 to NW/4 NW/4 SW/4 sec. 35, T. 17 N., R. 23 E., Apache County, AZ. Reference sections (Woody 2006): 1) section Lots Wife – UTM Zone 12S, E610276, N3862740, NAD 27; 2) section Old 180 W – UTM Zone 12S, E602742, N3853275, NAD 27; 3) section Blue Mesa 1 – UTM Zone 12S, E614277, N3866793, NAD 27; and 4) section Camp Butte – UTM Zone 12S, E612581, N3867223, NAD 27. Reference section (Heckert and Lucas 2002): 5) unit 3 of Cooley's (1957) Rainbow Forest Sandstone, in W/2 S/2 NW/2 to W/2 N/2 NW/2 sec. 1, T. 16 N., R. 23 E., Navajo Co., AZ.	Late Triassic
Blue Mesa Member, Chinle Formation (TRcbm)	Heckert and Lucas 2002; Woody 2006	Type section (composite): from the Haystacks (units 1–8 in the SW/4 SW/4 SE/4 sec. 21) through the Teepees (units 9–11 in the SW/4 NW/4 SW/4 NE/4 sec. 22); and "Camp's Butte" (units 12–15, SE/4 NW/4 SW/4 sec. 23) to the Blue Mesa area proper (units 16–21 in the E/2 SE /4 SE/4 SW/4 sec. 23) in T. 18 N., R. 24 E., Apache Co., AZ.	Late Triassic
Newspaper Rock Bed, Blue Mesa Member, Chinle Formation (TRcbnr)	Heckert and Lucas 2002	Type section: Newspaper Rock Section in the SE/4 SE/4 NW/4 sec. 16, T. 18 N., R. 24 E., Apache Co., AZ.	Late Triassic

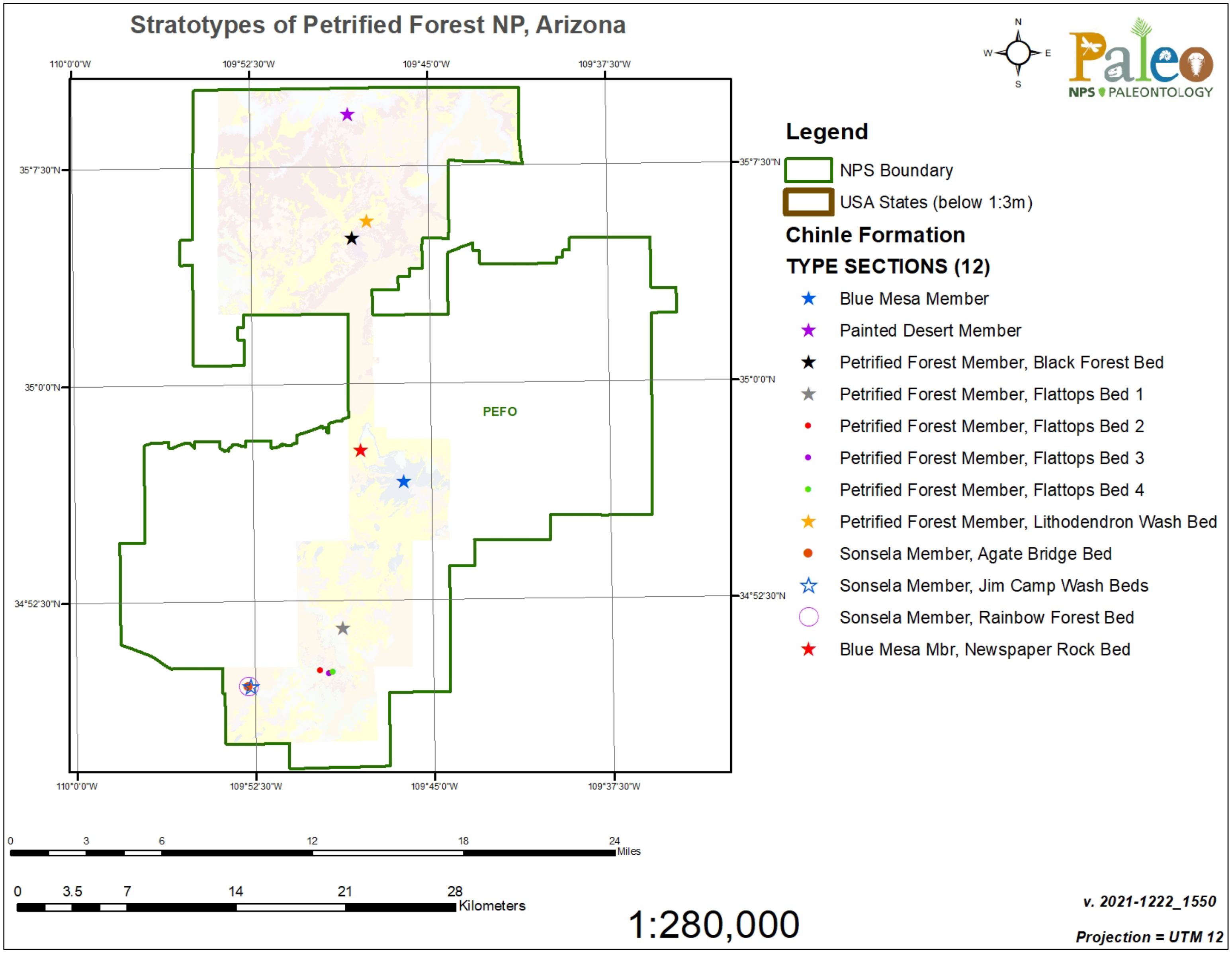


Figure 106. Modified geologic map of PEFO showing type section locations. The transparency of the geologic units layer has been increased.

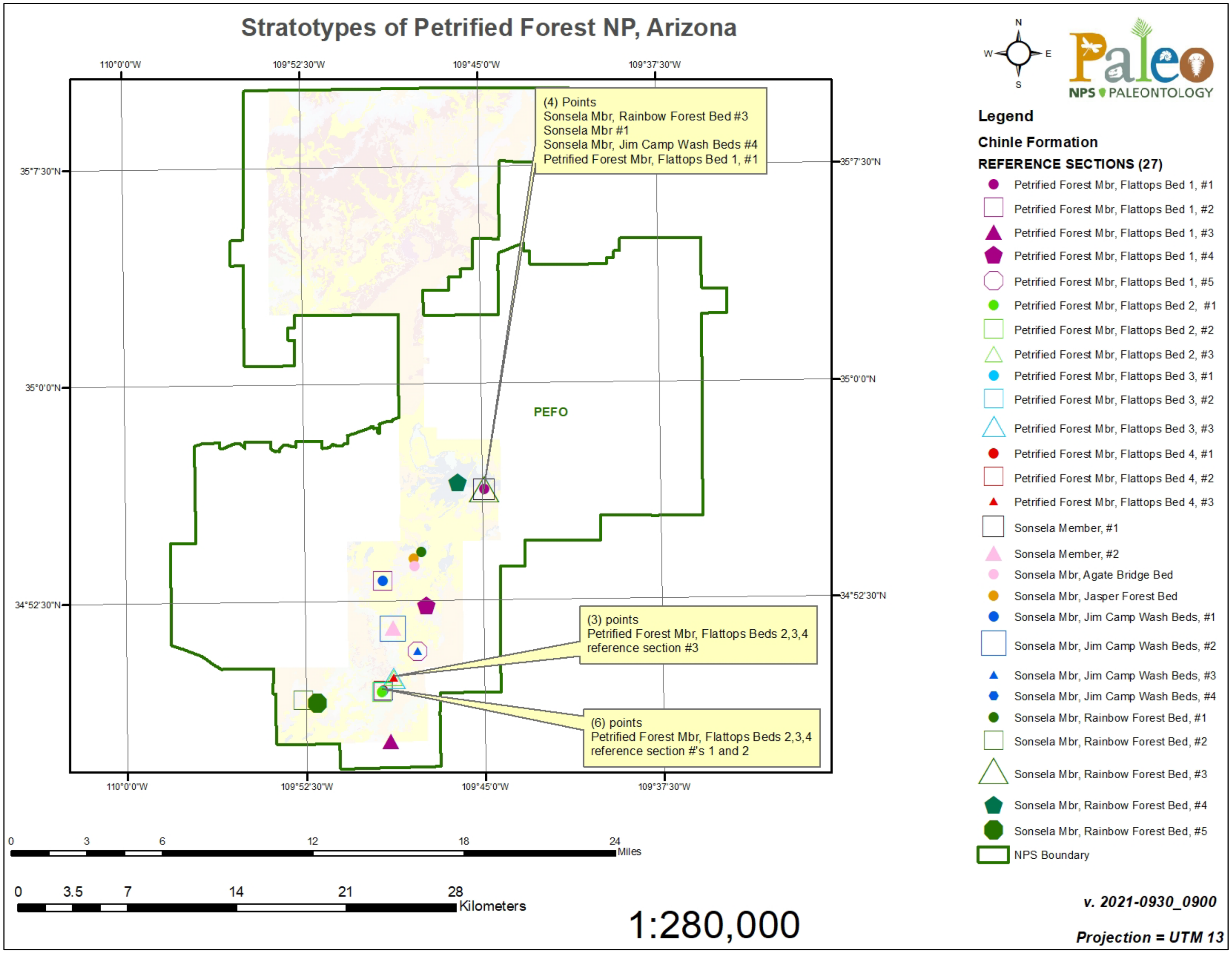


Figure 107. Modified geologic map of PEFO showing reference section locations. The transparency of the geologic units layer has been increased.

The Triassic Blue Mesa Member of the Chinle Formation was originally assigned to the Petrified Forest Formation of Lucas (1993) and named after exposures at Blue Mesa in Petrified Forest National Park, Arizona. The type section is a composite of measured sections: from the Haystacks (SW/4 SW/4 SE/4 sec. 21) through the Teepees (SW/4 NW/4 SW/4 NE/4 sec. 22); and "Camp's Butte" (SE/4 NW/4 SW/4 sec. 23) to the Blue Mesa area proper (E/2 SE /4 SE/4 SW/4 sec. 23) in T. 18 N., R. 24 E., Arizona (Table 7; Figure 106; Lucas 1993; Heckert and Lucas 2002). It should be noted that measurements from the Blue Mesa area proper are considered part of the Sonsela Member and were removed by Woody (2006), yielding a modified type section thickness of 57+ m (187+ ft). The type section measures 77.7 m (255 ft) thick and consists of bluish-gray to purple and white mudstone interbedded with several sandstone beds of varying thickness and lateral continuity (Figure 108; Heckert and Lucas 2002). The Blue Mesa Member overlies the Mesa Redondo Member and underlies the Sonsela Member of the Chinle Formation (Marsh et al. 2019; Rasmussen et al. 2021).

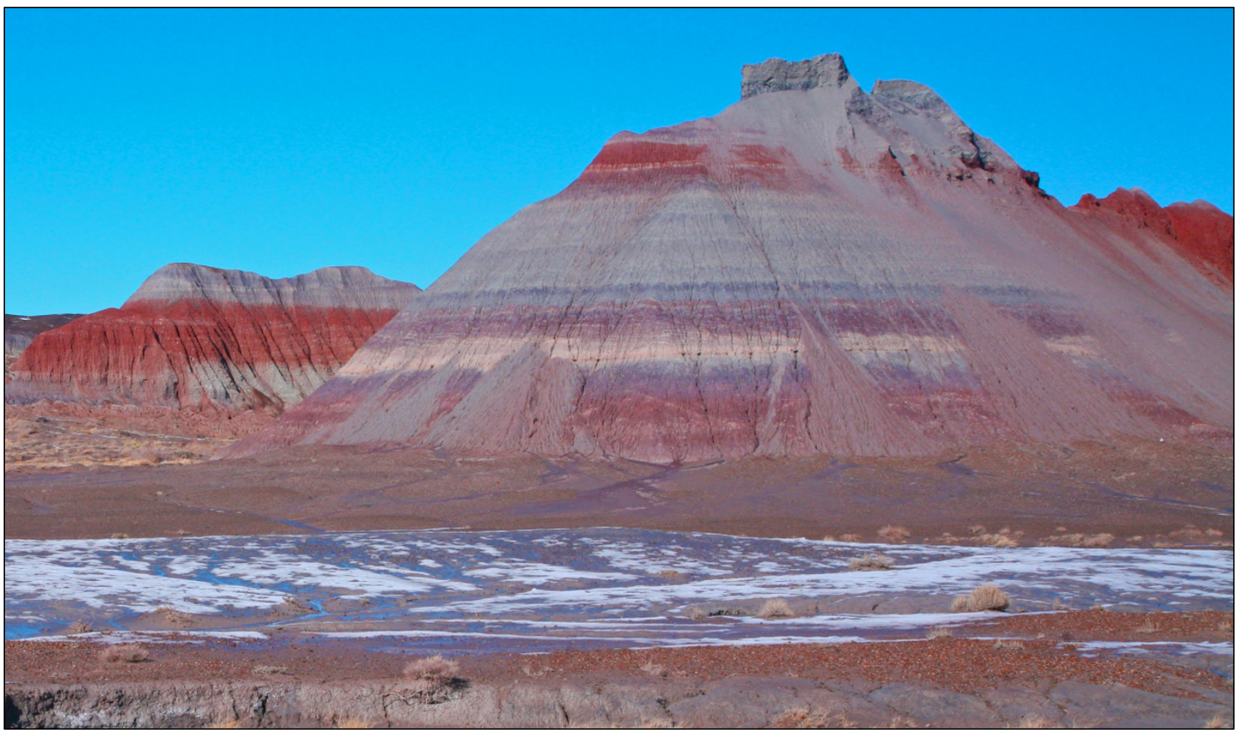


Figure 108. Colorful, banded mudstone and sandstone beds of the lower Blue Mesa Member and associated Newspaper Rock Bed of the Chinle Formation (NPS).

The Triassic Newspaper Rock Bed of the Blue Mesa Member of the Chinle Formation was originally described as the "Newspaper sandstone bed" by Cooley (1957) and named after Newspaper Rock along the south side of Rio Puerco in PEFO, Arizona (Figure 109). Cooley's term "Newspaper Rock" was coined after an excellent group of American Indian petroglyphs that are carved into the unit. Heckert and Lucas (2002) renamed the unit and designated the type section as the Newspaper Rock section in the SE/4 SE/4 NW/4 sec. 6, T. 18 N., R. 24 E., Apache County, Arizona. It appears that the published type section location in Heckert and Lucas (2002) is misreported as there are no Triassic outcrops in section 6, let alone the Newspaper Rock Bed—it is likely that the authors meant section

16 which is within PEFO where Newspaper Rock is located (Table 7; Figure 106; A. Marsh, PEFO lead paleontologist, pers. comm., 2021). At the type section the Newspaper Rock Bed measures 8.7 m (29 ft) thick and consists of moderately well-indurated, cliff-forming, ripple-laminated, very fine to fine-grained, sub-angular to sub-rounded, micaceous quartz arenites (Figure 109; Heckert and Lucas 2002). The basal contact of the Newspaper Rock Bed is erosional, where the unit fills scours in a series of light gray, grayish blue, and reddish purple bentonitic mudstones (Cooley 1957; Heckert and Lucas 2002). Although the upper contact is generally missing, the Newspaper Rock Bed underlies discontinuous Quaternary deposits and grades upward into the middle Blue Mesa Member south of the type section (Heckert and Lucas 2002).

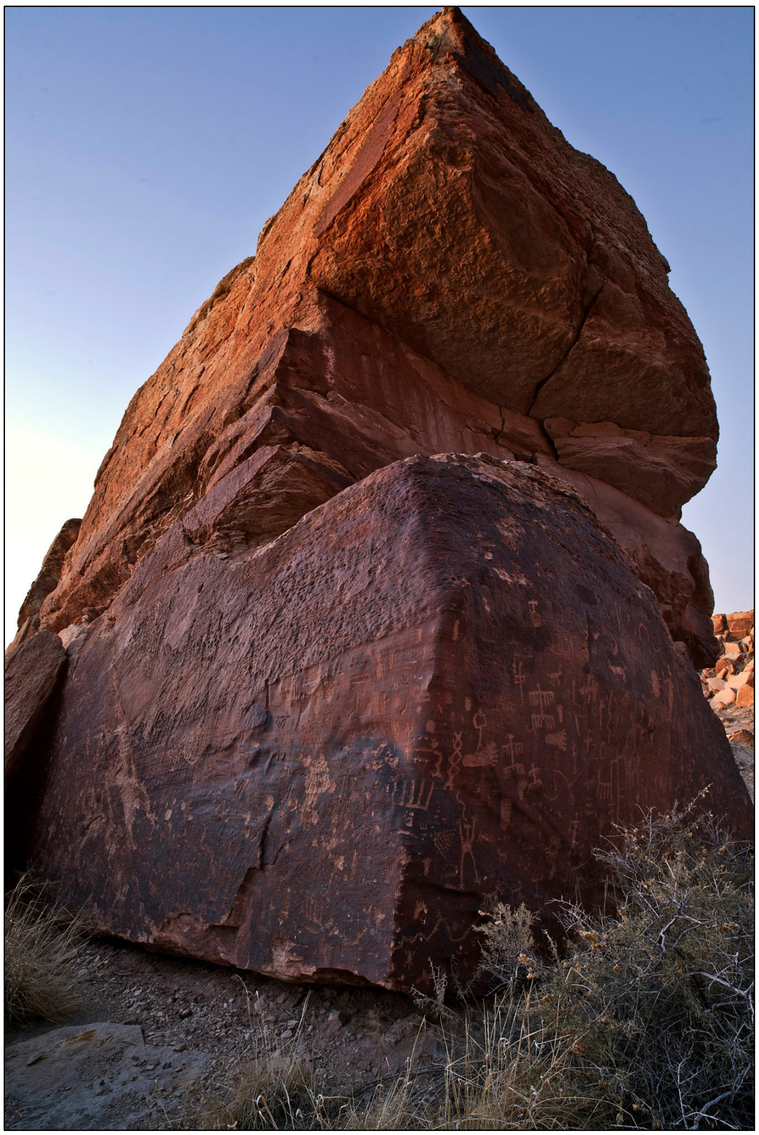


Figure 109. Petroglyphs carved in sandstone at Newspaper Rock, near the type section of the Newspaper Rock Bed of the Blue Mesa Member of the Chinle Formation (NPS/ANDREW KEARNS).

The Triassic Sonsela Member of the Chinle Formation was named by Akers et al. (1958) after the Sonsela Buttes on the eastern flank of the Defiance Uplift, Arizona. The Sonsela Member has undergone rigorous stratigraphic revision since the early 2000s, with a more recent subdivision that includes five units: 1) Camp Butte beds; 2) Lot's Wife beds; 3) sandstone and locally abundant conglomerate of the Jasper Forest bed/Rainbow Forest bed; 4) a heterogeneous slope-forming sequence of mudstone, sandstone, and conglomerate of the Jim Camp Wash beds; and 5) upper sheet-like deposits of multi-storied sandstone and conglomerate of the Martha's Butte beds (Martz and Parker 2010). The uppermost subdivision of the member was formerly assigned to the Flattops 1 bed of Woody (2006) and Agate Bridge Bed of Heckert and Lucas (2002). Two reference sections are situated within PEFO at the following locations (all are NAD 27, UTM Zone 12S): 1) section Blue Mesa 1, E614277, N3866793; and 2) section Mountain Lion Mesa 1, E608482, N3857866 (Table 7; Figure 107; Woody 2006). The Sonsela Member in the Blue Mesa 1 section has a thickness of 42.1 m (138 ft) and consists of the Rainbow Forest bed, Jim Camp Wash beds, and the Flattops 1 bed (Figure 110; Woody 2006). The Mountain Lion Mesa 1 section measures 36 m (118 ft) thick and is composed of the Jim Camp Wash beds and Flattops 1 bed (Woody 2006). The Sonsela Member overlies the Blue Mesa Member and underlies the Petrified Forest Member of the Chinle Formation.

Figure 110. Purple, blue, and gray banded strata of the Camp Butte beds, Lot's Wife beds, and Jasper Forest bed of the Sonsela Member of the Chinle Formation along the Blue Mesa Trail (NPS).

The Triassic Rainbow Forest bed of the Sonsela Member of the Chinle Formation was previously referred to as the "Rainbow Sandstone" by Cooley (1957) before it was named by Heckert and Lucas

(2002). The unit is named after its type section exposure located just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge and just northwest of Giant Logs, Arizona (Table 7; Figure 106). The type section consists of 2.25 m (7.4 ft) of white to pinkish-gray conglomeratic sandstone that contains rip-up clasts of light gray mudstone (Heckert and Lucas 2002). Heckert and Lucas (2002) assigned unit 3 of Cooley's (1957) Rainbow Forest Sandstone as a reference section for the Rainbow Forest bed (Table 7; Figure 107). Woody (2006) designated four additional reference sections within PEFO at the following locations (all are NAD 27, UTM Zone 12S): 1) section Lots Wife – E610276, N3862740; 2) section Old 180 W – E602742, N3853275; 3) section Blue Mesa 1 – E614277, N3866793; and 4) section Camp Butte – E612581, N3867223 (Table 7; Figure 107). The Rainbow Forest bed hosts an extensive "forest" of petrified logs and is the main wood-bearing horizon both inside and outside of PEFO (Heckert and Lucas 2002). It is worth noting that the Rainbow Forest bed is likely a correlative, lateral equivalent of the Sonsela sandstone bed (Martz and Parker 2010). The Rainbow Forest bed underlies the Jim Camp Wash beds of the Sonsela Member and overlies the Blue Mesa Member of the Chinle Formation.

The Triassic Jasper Forest bed of the Sonsela Member of the Chinle Formation was named by Martz and Parker (2010) after exposures near Jasper Forest in PEFO, Arizona. A reference section for the unit is located at Agate Mesa, where it forms a capping sandstone best exposed on the northern face (Table 7; Figure 107; Martz and Parker 2010). The reference section measures approximately 10–15 m (33–49 ft) thick and comprises texturally mature, multi-storied, cross-bedded conglomeratic sandstone (Martz and Parker 2010). The Jasper Forest bed occurs between the underlying Lot's Wife beds and overlying Jim Camp Wash beds of the Sonsela Member.

The Triassic Jim Camp Wash beds of the Sonsela Member of the Chinle Formation were formally named by Heckert and Lucas (2002) and assigned as the middle unit of the Sonsela Member. The type section is located just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge and just northwest of Giant Logs in PEFO, Arizona (Table 7; Figure 106; Heckert and Lucas 2002). At the type section the Jim Camp Wash beds measure 29.9 m (98 ft) thick and consist of slope-forming interbedded bentonitic mudstone and lithic sandstone, with lesser amounts of conglomerate and calcrete nodules (Heckert and Lucas 2002). In the type section region, strata of the unit can be traced along the cliffs north of Rainbow Forest, and around the drainages of Jim Camp Wash and Cottonwood Wash (Martz and Parker 2010). Additional reference sections are located at the following locations within PEFO (all are NAD 27, UTM Zone 12S): 1) section Agate Mesa West 1, E607822, N3860933; 2) section Mountain Lion Mesa 1, E608482, N3857866; 3) section Dry Wash North, E610014, N3856388; and 4) section Blue Mesa 1, E614277, N3866793 (Table 7; Figure 107; Woody 2006). The Jim Camp Wash beds gradationally overlie the Jasper Forest/Rainbow Forest bed and underlie the Martha's Butte beds of the Sonsela Member.

The Triassic Agate Bridge Bed was proposed by Heckert and Lucas (2002) as the uppermost unit of the Sonsela Member of the Chinle Formation. The unit has been abandoned by subsequent authors, redescribed as the Flattop 1 bed in Woody (2006) and more recently as the Martha's Butte beds by Martz and Parker (2010). The type section of the Agate Bridge Bed is designated just northwest of Rainbow Forest, about 11 km (7 mi) southwest of Agate Bridge and just northwest of Giant Logs, Arizona (Table 7; Figure 106; Heckert and Lucas 2002). At the type section the unit measures 6.6 m (22 ft) thick and consists of yellowish gray to light olive gray, trough cross-bedded sandstone with minor amounts of conglomerate (Heckert and Lucas 2002). Heckert and Lucas (2002) assign units 7–11 of Murry and Long's (1989) "Sonsela section" north of Agate Bridge as a reference section for the unit (Table 7; Figure 107). However, this is likely an incorrect correlation attempt made over 18 km (11 mi) and these beds are probably in what is now the Lot's Wife beds (W. Parker, PEFO research stewardship and science program manager, pers. comm., 2021). The Agate Bridge Bed underlies the Painted Desert Member of the Chinle Formation and overlies the Jim Camp Wash beds. Although extensive revision of the Sonsela Member has since removed the Agate Bridge Bed in subsequent studies, it is included in this inventory for reference.

The Triassic Flattops Bed 1 of the Sonsela Member of the Chinle Formation was originally described as the "Camp Wash Zone" of Roadifer (1966) before it was redescribed as the "Flattops Sandstone #1" of Billingsley (1985a), "Flattops 1 bed" of Woody (2006), and the "Martha's Butte beds" of Martz and Parker (2010). It is worth noting that Billingsley (1985a) rejected Roadifer's (1966) concept of a "Camp Wash Zone", renamed the unit "Flattops Sandstone #1", and then renumbered Flattops 1, 2, and 3 as Flattops 2, 3, and 4. The unit is named after exposures in the Flattops area in southern PEFO. The type section is designated in Woody's (2006) Mountain Lion Mesa 1 section [NAD 27, UTM Zone 12S, E608482, N3857866] located in Apache County, Arizona (Table 7; Figure 106). At the type section the Flattops Bed 1 measures approximately 7.9 m (26 ft) thick and is composed of tan to yellowish-gray, cross-bedded sandstone with local lenses of conglomerate (Woody 2006). Additional reference sections for the unit within PEFO are found at the following locations (all are NAD 27, UTM Zone 12S): 1) section Blue Mesa 1 – E614277, N3866793; 2) section Agate Mesa West 1 – E607822, N3860933; 3) section Old 180 4 – E608325, N3850628; 4) section Crystal Forest – E610591, N3859345; and 5) section Dry Wash N – E610014, N3856388 (Table 7; Figure 107; Woody 2006). The Flattops Bed 1 overlies the Jim Camp Wash beds and is equivalent to the Agate Bridge Bed of Heckert and Lucas (2002) and the Martha's Butte beds of Martz and Parker (2010).

The Triassic Flattops Bed 2 of the Petrified Forest Member of the Chinle Formation was originally described as "Flattops Sandstone #1" by Roadifer (1966) and named after the Flattops area in southern PEFO. The type section of the unit is designated at the Flattops west section of Heckert and Lucas (2002), located in NE/4 NE/4 sec. 31, T. 17 N., R. 24 E., Arizona (Table 7; Figures 106, 111, and 112). At the type section the unit is approximately 6.6 m (22 ft) thick and predominantly consists of brownish-gray, cross-bedded, very fine to medium-grained arkosic sandstone that is readily traceable across much of the Flattops area (Heckert and Lucas 2002). Various sections reported by Cooley (1957), Roadifer (1966), and Murry and Long (1989) at the Flattops are designated as reference sections, where the Flattops Bed 2 is as much as 11.4 m (37 ft) thick (Figure 107; Table 7; Heckert and Lucas 2002). Flattops Bed 2 overlies the Sonsela Member and underlies Flattops Bed 3 of the Petrified Forest Member.

Figure 111. The Flattops in southern PEFO, composed of sandstone and conglomeratic sandstone of the Flattops beds of the Petrified Forest Member of the Chinle Formation (NPS).

Figure 112. Eroded landscape of the Flattops in southern PEFO, consisting of the Martha's Butte beds of the Sonsela Member and Flattops Bed 1, as well as the lower part of the Petrified Forest Member (NPS).

The Triassic Flattops Bed 3 of the Petrified Forest Member of the Chinle Formation was originally described as the "Flattops Sandstone 2" in Cooley (1957) and Roadifer (1966) and named after the Flattops area in southern PEFO. The type section of the unit is designated at the Flattops west section of Heckert and Lucas (2002) in SW/4 NW/4 sec. 32, T. 17 N., R. 24 E., Arizona (Table 7; Figures 106, 111, and 112). The type section exposure measures 6.2 m (20 ft) thick and consists of yellowish-gray to brownish-gray, cross-bedded, very fine to fine-grained sandstone overlying a basal olive gray, fine- to coarse-grained, conglomeratic sandstone (Heckert and Lucas 2002). Sections reported by Cooley (1957), Roadifer (1966), and Murry and Long (1989) at the eastern Flattops are designated as reference sections (Table 7; Figure 107; Heckert and Lucas 2002). Flattops Bed 3 occurs between the underlying Flattops Bed 2 and overlying Flattops Bed 4 of the Petrified Forest Member.

The Triassic Flattops Bed 4 of the Petrified Forest Member of the Chinle Formation was originally described as the "Flattops Sandstone #3" in Cooley (1957) and Roadifer (1966) and renamed by Billingsley (1985a) after the Flattops area in southern PEFO. The type section of the unit is designated at the Flattops west section of Heckert and Lucas (2002) in SW/4 NE/4 NW/4 sec. 32, T. 17 N., R. 24 E., Arizona (Table 7; Figures 106, 111, and 112). At the type section the unit measures about 3.4 m (11 ft) thick and is comprised of pale red to grayish-red, very fine to fine-grained sandstone that is locally interbedded with a cherty mudstone-pebble conglomerate (Heckert and Lucas 2002). Common sedimentary structures include trough cross-bedding and ripple marks. Sections reported by Cooley (1957), Roadifer (1966), and Murry and Long (1989) at the eastern Flattops are designated as reference sections (Table 7; Figure 107; Heckert and Lucas 2002). Flattops Bed 4 overlies the section of the Petrified Forest Member that includes the Flattops Bed 3 and the upper contact is not preserved, as the unit caps the Flattop mesas and is not regionally traceable.

The Triassic Painted Desert Member of the Petrified Forest Formation (Chinle Group) was proposed by Lucas (1993) for widespread exposures in the Painted Desert region of northern PEFO. Extensive revision of the Chinle Formation has since removed the Painted Desert Member in subsequent studies, where these units would otherwise occur in the Petrified Forest Member (Woody 2006; Martz and Parker 2010). As defined by Heckert and Lucas (2002), the superseded Painted Desert Member included Flattops Bed 2–4 (ascending), the Lithodendron Wash Bed, and the Black Forest Bed. The type section represented a composite of sections located in T. 19 N., R. 23 E. and T. 20 N., R. 24 E., Arizona (Table 7; Figure 106; Lucas 1993; Heckert and Lucas 2002). At the type section the member measured 147.2 m (483 ft) thick and was primarily composed of grayish-red mudstone with numerous sandstone beds expressed as thin, persistent benches (Lucas 1993; Heckert and Lucas 2002). The Petrified Forest Member conformably overlies the Sonsela Member and underlies the Owl Rock Member of the Chinle Formation.

The Triassic Lithodendron Wash Bed of the Painted Desert Member of the Chinle Formation was originally described by Billingsley (1985a) as the "Painted Desert Sandstone 3" and renamed by Heckert and Lucas (2002) after exposures along the margins of Lithodendron Wash in the Painted Desert region of PEFO. The type section of the unit is located at the Chinde Point II section of Heckert and Lucas (2002) in NW/4 SE/4 NE/4, sec. 33, T. 20 N., R. 24 E., Arizona (Table 7; Figure 106). The type section measures 2.5 m (8 ft) thick and consists of alternating bands of pale greenishyellow and pale red, very fine to fine-grained sandstone with localized conglomerate at the base of the unit (Heckert and Lucas 2002). The Lithodendron Wash Bed caps the mesa tops in the Painted Desert and forms a prominent bench beneath Chinde Point and Kachina Point at the type section (Heckert and Lucas 2002). The Lithodendron Wash Bed overlies the Sonsela Member and underlies the Black Forest Bed of the Petrified Forest Member.

The Triassic Black Forest Bed of the Painted Desert Member of the Chinle Formation was first mentioned as the "Black Forest Tuff" by Billingsley (1985b), renamed by Ash (1992), and assigned to the Painted Desert Member by Heckert and Lucas (2002). The type section of the unit is located below Kachina Point and about 40 m (131 ft) west of the trail leading into the Painted Desert section of PEFO, Arizona (Table 7; Figure 106; Heckert and Lucas 2002). At the type section the unit measures 7.7 m (25 ft) thick and is composed of hardened calcrete-pebble conglomerate and softer reworked tuff (Heckert and Lucas 2002). The Black Forest Bed occurs in the upper Petrified Forest Member underlying the Owl Rock Member of the Chinle Formation (Martz et al. 2012).

Petroglyph National Monument (PETR)

Petroglyph National Monument (PETR) is located along a 27 km (17 mi)-stretch of Albuquerque's West Mesa volcanic escarpment situated 11 km (7 mi) west of downtown Albuquerque in Bernalillo County, New Mexico (Figure 113). Authorized on June 27, 1990, PETR contains approximately 2,917 hectares (7,209 acres) and protects one of the largest concentrations of Rio Grande-style rock images in North America (National Park Service 2016a). The monument features more than 20,000 petroglyphs (prehistoric or historic rock carvings), more than 350 archeological sites that have revealed a history of human occupation of more than 12,000 years, and significant geologic resources. Dormant fissure volcanoes, volcanic cinder cones, lava flows, and dramatic surface erosional features at PETR have helped geologists better understand the formation of the Rio Grande Rift Valley and how natural landforms have influenced culture over time (KellerLynn 2017).

Petroglyph National Monument is situated within the Rio Grande Rift, a major crustal extension (pulling apart of Earth's crust) feature that stretches about 1,000 km (600 mi) from northern Mexico to central Colorado. Dynamic crustal extensional processes associated with the Rio Grande Rift resulted in thick packages of sedimentary deposits (Santa Fe Group), but also thinned and weakened the crust, producing numerous volcanic fields throughout New Mexico. The geology of the monument has been heavily influenced by the development of the rift, consisting of four major groupings of rock, from oldest to youngest 1) Pliocene–Pleistocene(?)-age sedimentary rocks of the Santa Fe Group that were deposited as basin fill (primarily sand and gravel) in the Rio Grande Rift; 2) formations associated with the development of the Rio Grande River and its tributaries; 3) basaltic lava flows and near-vent deposits that make up the Albuquerque volcanic field; and 4) recent active-stream valley deposits (Figure 114; KellerLynn 2017). Pleistocene-age lava flows of the Albuquerque volcanic field dominate the landscape of the monument, including a chain of dormant fissure volcanoes, cinder cones, spatter cones, and volcanic vents.

There are no designated stratotypes identified within the boundaries of PETR. There are 18 identified stratotypes located within 48 km (30 mi) of PETR boundaries, for the Pennsylvanian Los Moyos Limestone (two reference sections) and Sol se Mete Member of the Wild Cow Formation (reference section); Miocene Chamisa Mesa Member of the Zia Formation (type section), Cerro Conejo Formation (type locality), and Picuda Peak Member of the Arroyo Ojito Formation (type section); Pliocene Ceja Formation (type section) and type sections of the Atrisco, Rio Puerco, and Santa Mesa Members of the Ceja Formation; Pleistocene Lomatas Negras Formation (type section and reference section), Edith Formation (type section and principal reference section), Los Duranes Formation (type section), Menaul Member of the Los Duranes Formation (reference section), and Arenal Formation (type section); and the Holocene Los Padillas Formation (type section).

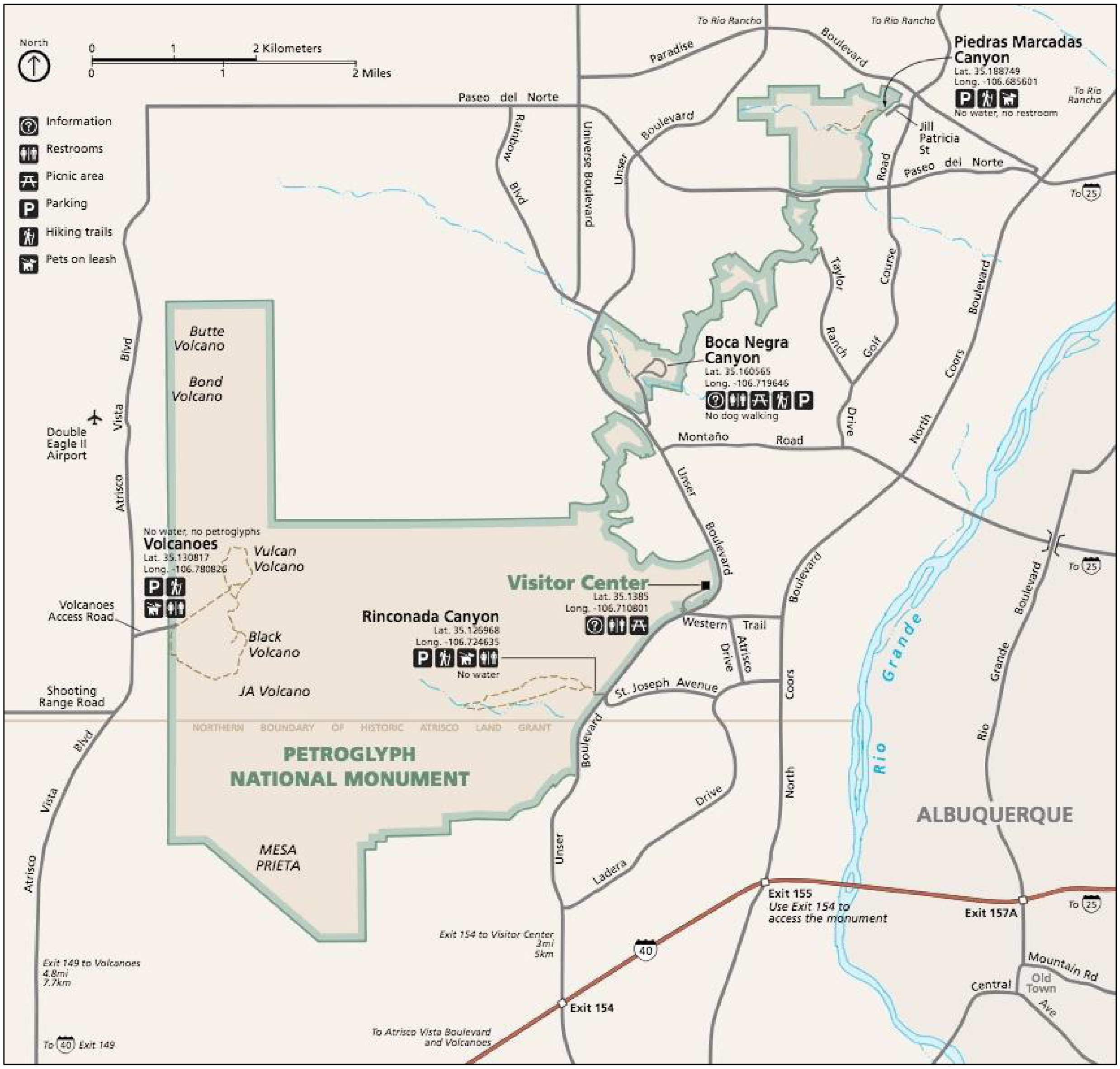


Figure 113. Park map of PETR, New Mexico (NPS).

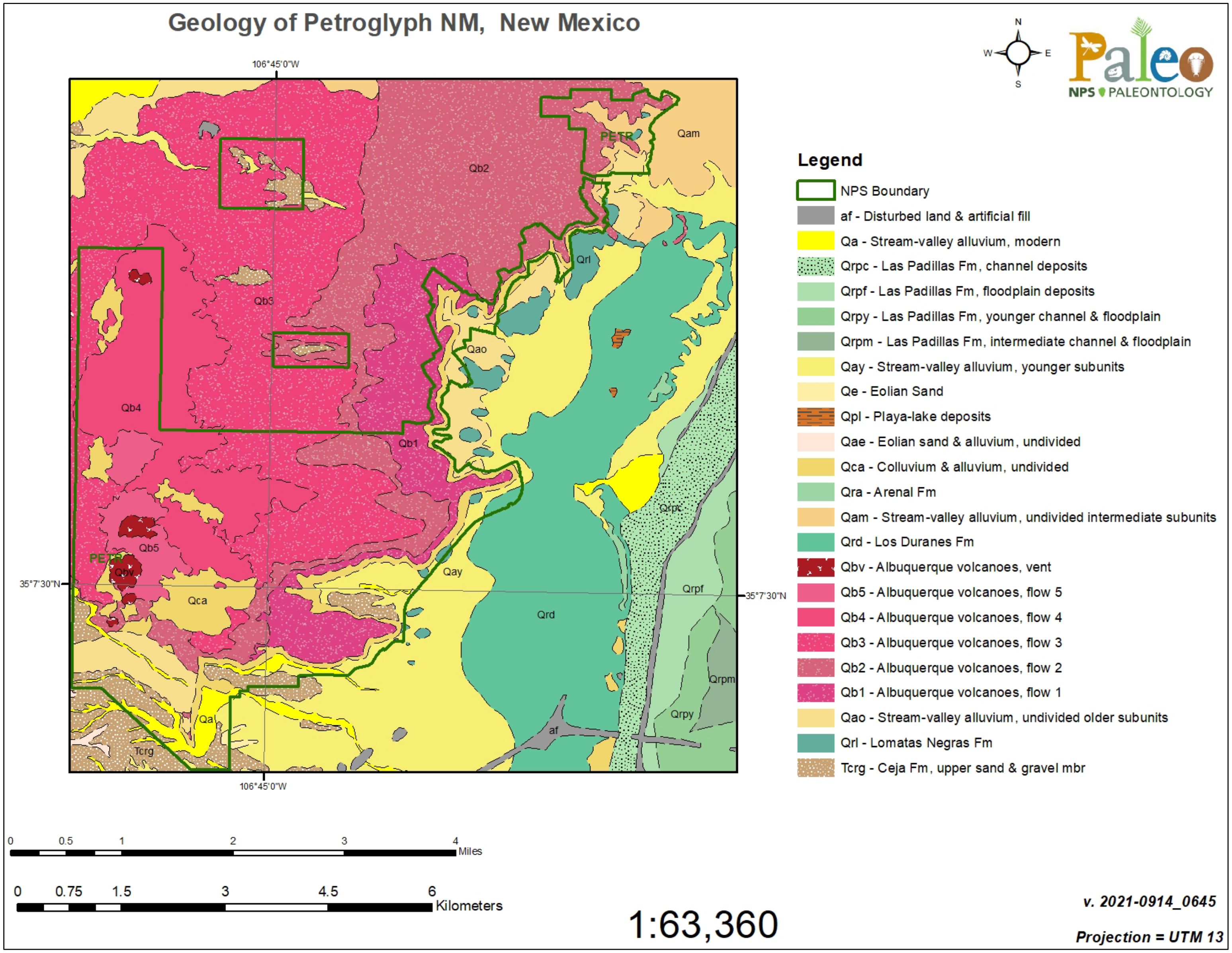


Figure 114. Geologic map of PETR, New Mexico.

Rainbow Bridge National Monument (RABR)

Rainbow Bridge National Monument (RABR) is located in a southern canyon arm of Lake Powell adjacent to Glen Canyon National Recreation Area in San Juan County, southern Utah (Figure 115). Established on May 30, 1910, RABR contains 105 hectares (160 acres) and protects one of the world's largest natural bridges that rises 88 m (290 ft) above the canyon floor (National Park Service 2016a). Situated approximately 13 km (8 mi) upstream from the confluence of Bridge Creek with the Colorado River, Rainbow Bridge lies in remote canyon country. The formation of Rainbow Bridge is the result of continuous stream erosion that has slowly carved the bridge completely out of sandstone over many years. The natural bridge is considered sacred to several American Indian tribes, including the Hopi Tribe, Kaibab Paiute Tribe, Navajo Nation, San Juan Southern Paiute Tribe, Pueblo of Zuni, and the Ute Mountain Ute Tribe (White Mesa Band) (National Park Service 2014b).

The geology of RABR entirely consists of the Early Jurassic Kayenta Formation and Navajo Sandstone. Rainbow Bridge and the surrounding cliffs consist entirely of Navajo Sandstone, with underlying Kayenta Formation exposed beneath the bridge and within the channel of Bridge Creek (Figure 116). The formation of Rainbow Bridge involved a combination of tectonic and erosional processes, including regional uplift, development of structural fractures and joints in the rock, erosive forces of wind and water, and lithology (Sproul 2001; Graham 2009). Regional uplift of the Colorado Plateau rejuvenated the erosive power of rivers, allowing them to incise channels through the Navajo Sandstone. Tight meandering curves preserved in the rock slowly weather into holes (windows) that widen into features such as Rainbow Bridge.

There are no designated stratotypes identified within the boundaries of RABR. There are four identified stratotypes located within 48 km (30 mi) of RABR boundaries, for the Triassic Church Rock Member of the Chinle Formation (type section) and Monitor Butte Member of the Chinle Formation (type section and type locality), and the Cretaceous Smoky Hollow Member of the Straight Cliffs Formation (type section).

Figure 115. Regional map of RABR, Utah (NPS).

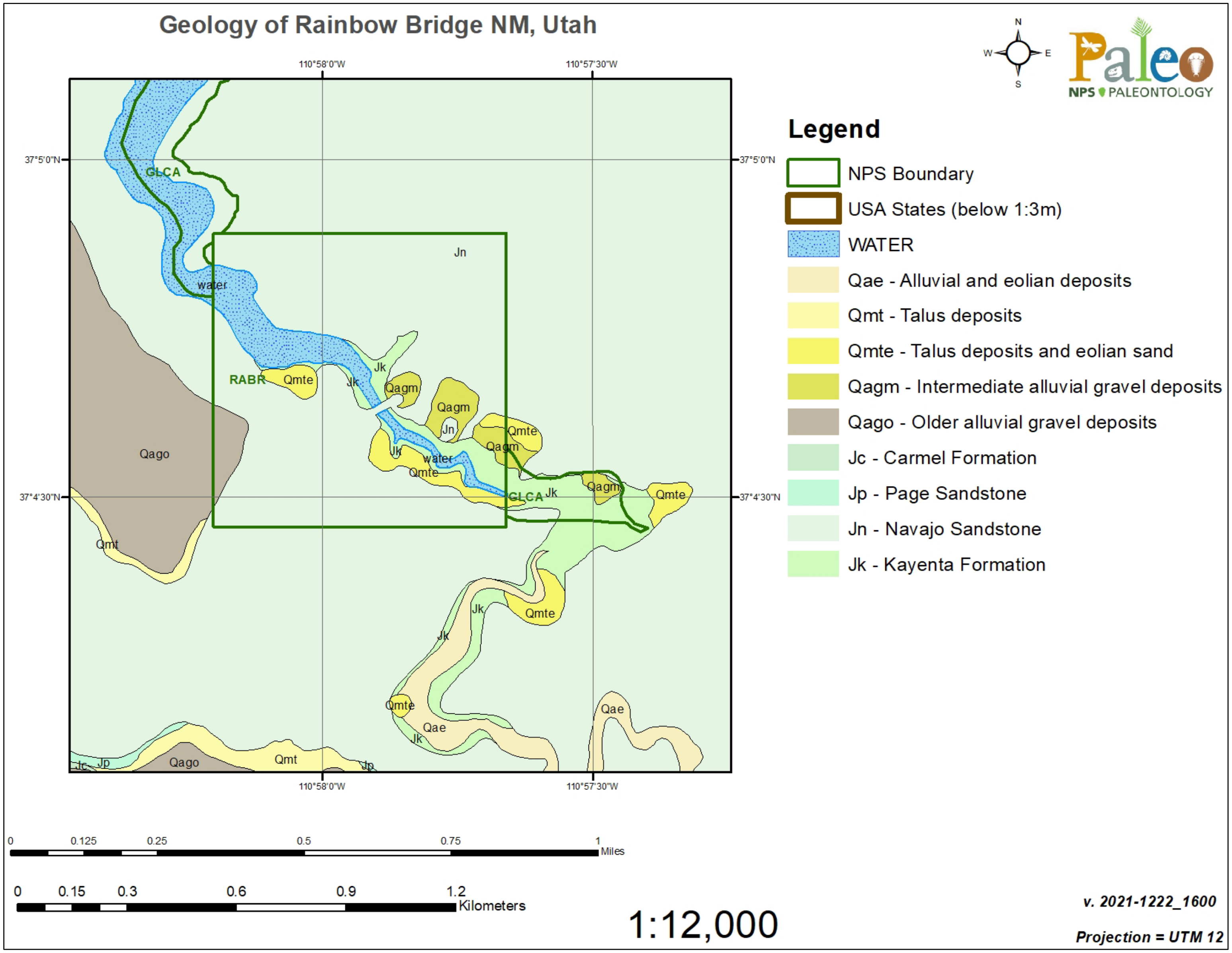


Figure 116. Geologic map of RABR, Utah.

Salinas Pueblo Missions National Monument (SAPU)

Salinas Pueblo Missions National Monument (SAPU) is located about 80 km (50 mi) southeast of Albuquerque and consists of three non-contiguous units (Abó, Gran Quivira, and Quarai) in Socorro and Torrance Counties, central New Mexico (Figure 117). Originally authorized as Gran Quivira National Monument on November 1, 1909, the monument was expanded and later renamed Salinas National Monument in 1980 before its current name was established on October 28, 1988 (National Park Service 2016a). The national monument contains approximately 433 hectares (1,071 acres) and preserves three Puebloan villages, four of the best-preserved 17th century Spanish mission churches in the United States, and 19th and 20th century rancheros (National Park Service 2016a). The largely unexcavated sites at Abó, Gran Quivira, and Quarai are part of an expansive regional complex of early to late pueblo history sites interwoven with Archaic history, trade routes, and a long-standing tradition of cultural diversity (National Park Service 2014d).

The regional geologic setting of SAPU encompasses the Rio Grande Rift, Manzano Mountains, Estancia Basin, and Chupadera Mesa (KellerLynn 2018). Mapped units throughout the monument include Permian-age sedimentary rocks of the Abo, Arroyo de Alamillo, and San Andres Formations, Tertiary igneous dikes, and Quaternary stream alluvium and eolian sand deposits (Figures 118–120). The colorful Permian "red beds" consist of red, orange, yellow, and pinkish white sandstone and mudstone interbedded with gray limestone, sandstone, and gypsum. Pueblos and churches in SAPU were predominantly built from these Permian-age red sandstones and gray limestones. At the Gran Quivira unit, Tertiary mafic igneous dikes intrude Permian strata of the Chupadera Mesa, deforming the overlying layers into many small anticlinal structures that the pueblo and mission were constructed upon.

Salinas Pueblo Missions National Monument contains two identified stratotypes that represent the Permian Abo Formation and the Cañon de Espinoso Member of the Abo Formation (Table 8; Figure 121). In addition to the designated stratotypes located within SAPU, stratotypes located within 48 km (30 mi) of the monument's boundaries include the Pennsylvanian Wild Cow Formation (type section), La Casa Member of the Wild Cow Formation (type section), Pine Shadow Member of the Wild Cow Formation (type section), Sol de Mete Member of the Wild Cow Formation (type section and reference section), and Los Moyos Limestone (type section and two reference sections); Permian Scholle Member of the Abo Formation (type section), Yeso Formation (type section and type locality), and Torres Member of the Yeso Formation (type locality); and the Miocene Arroyo de Alamillo Formation (type section).

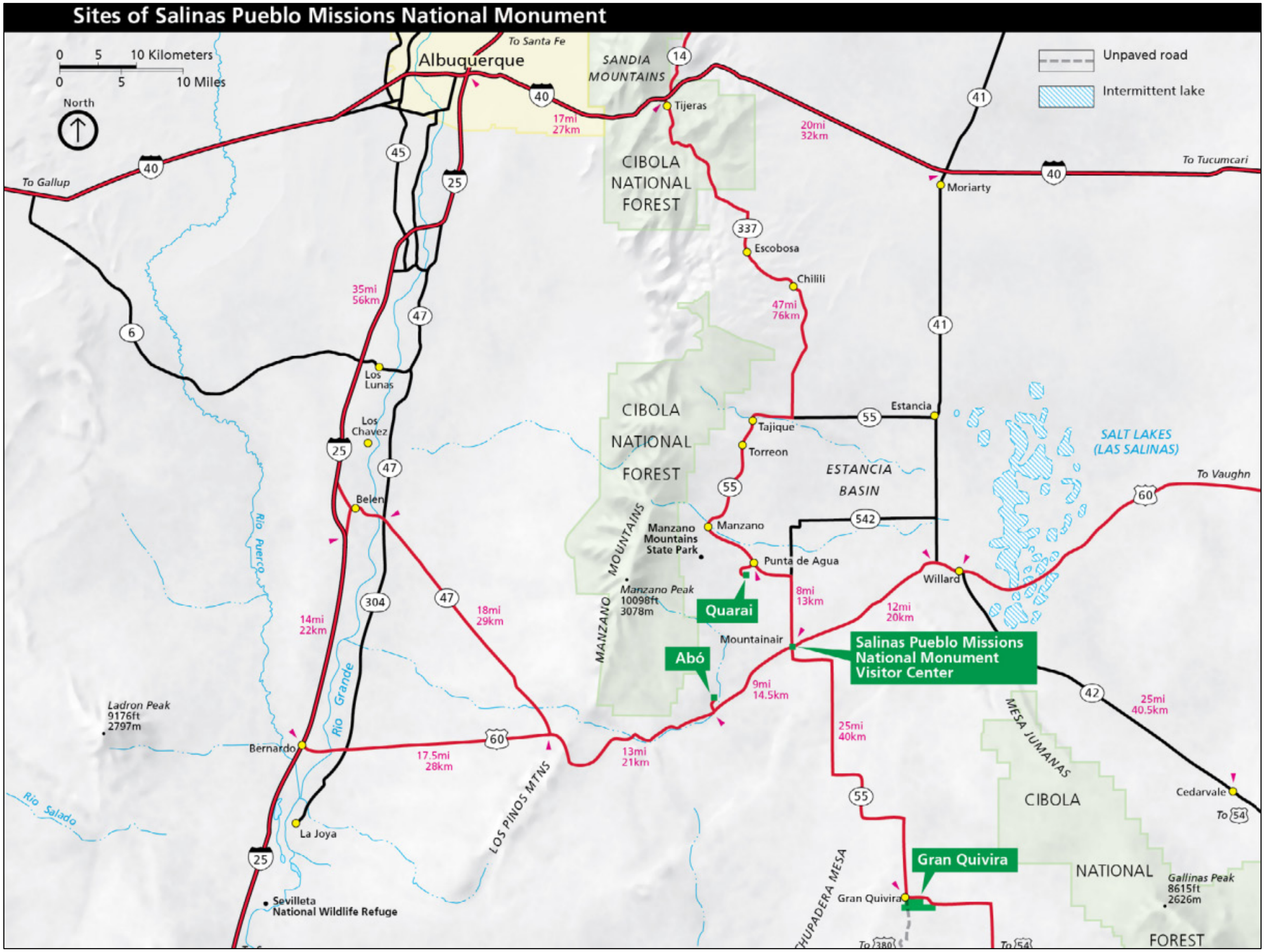


Figure 117. Regional map of SAPU, New Mexico (NPS).

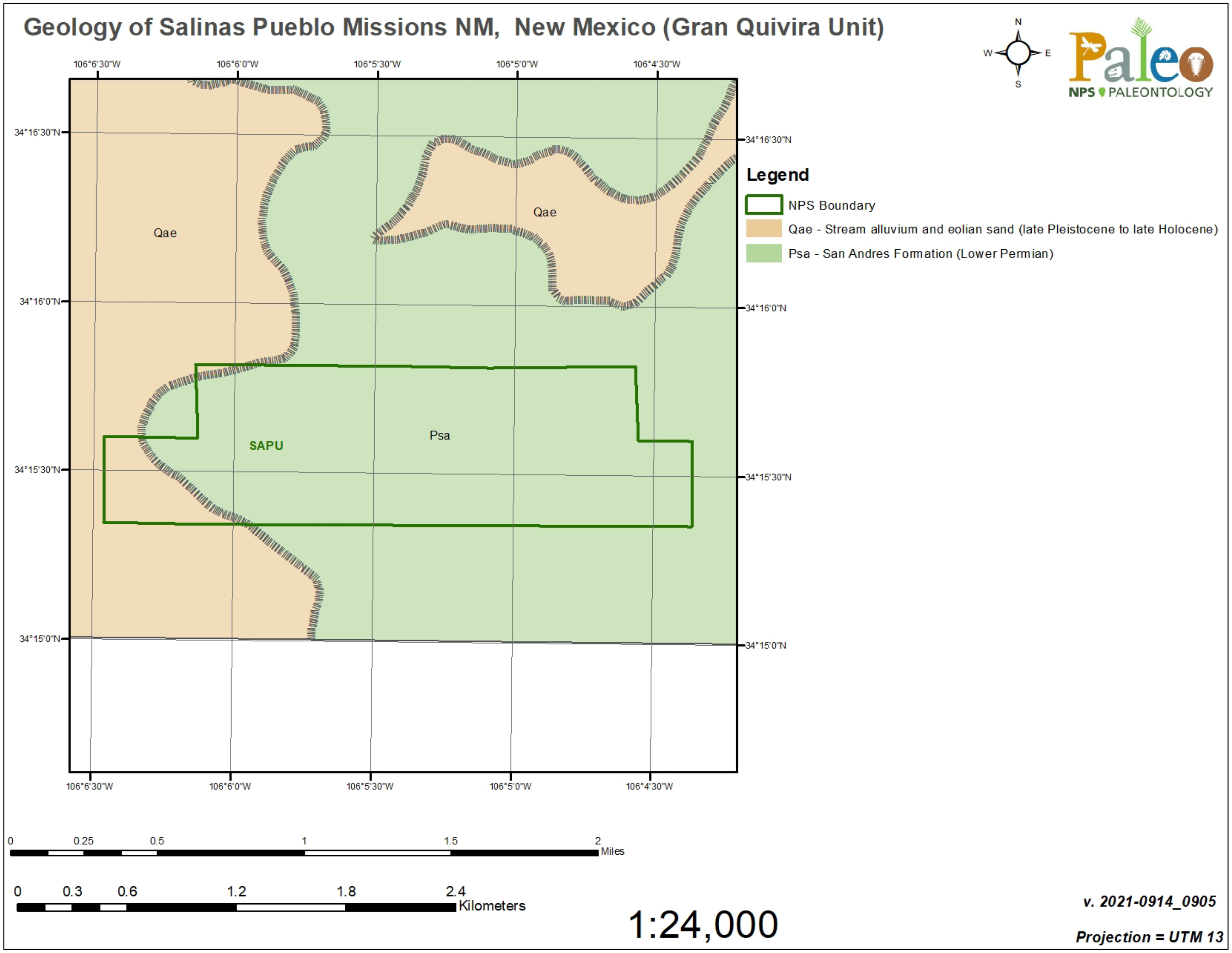


Figure 118. Geologic map of SAPU (Gran Quivira Unit), New Mexico.

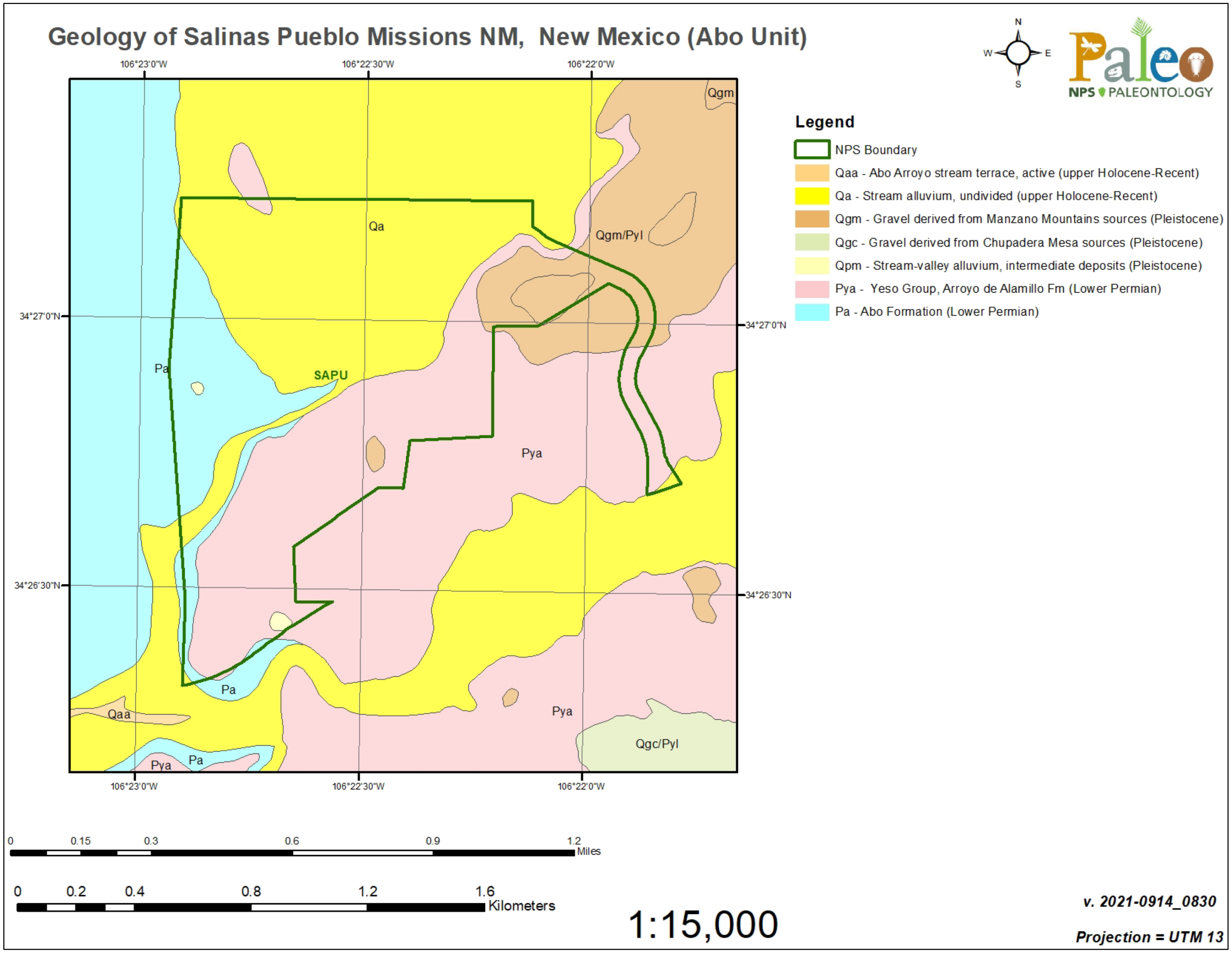


Figure 119. Geologic map of SAPU (Abo Unit), New Mexico.

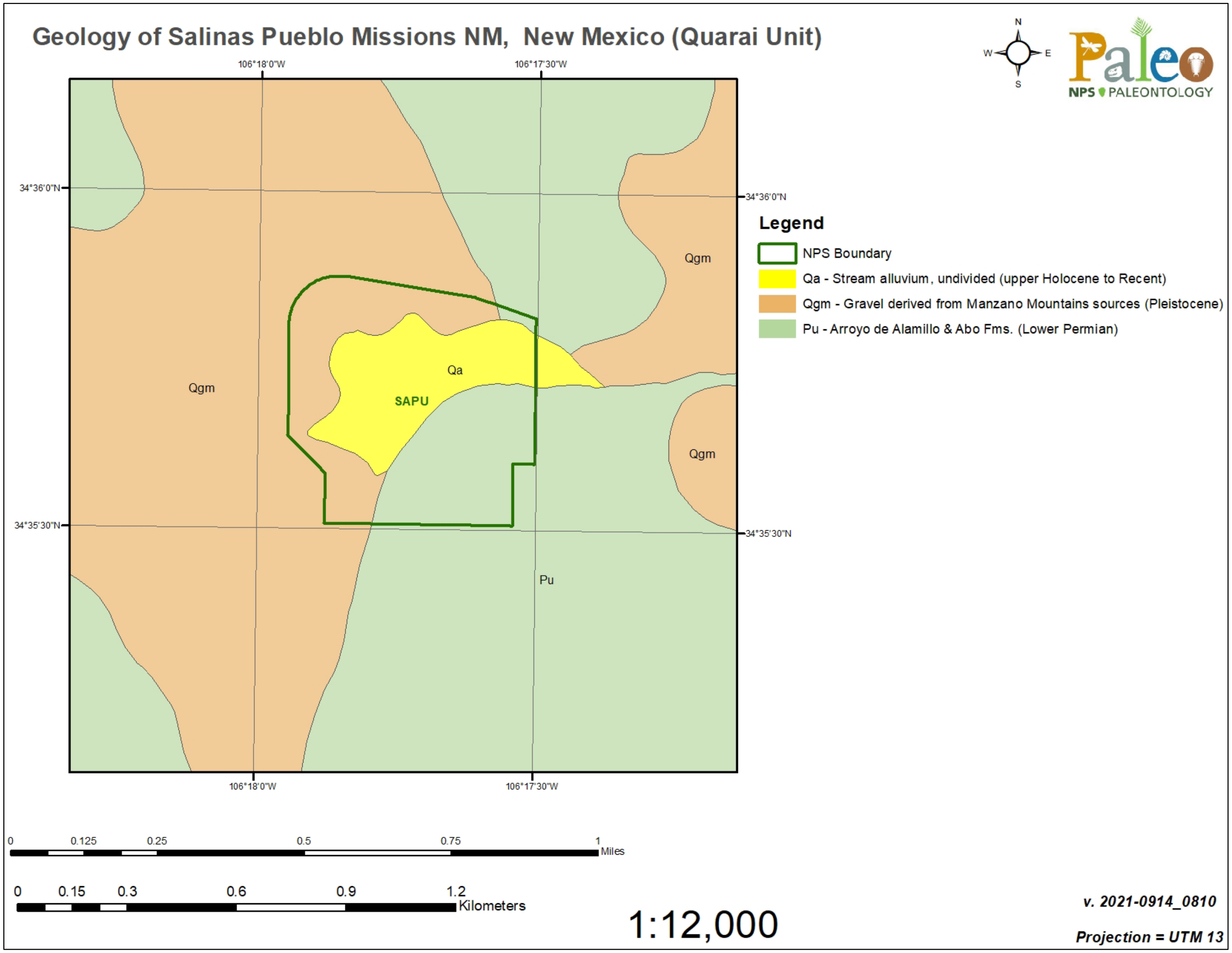


Figure 120. Geologic map of SAPU (Quarai Unit), New Mexico.

Table 8. List of SAPU stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Abo Formation (Pa)	Lee 1909; Lucas et al. 2005	Type section: between Priest Canyon and the Abo Mission Ruins in Abo Canyon, southern Manzano Mountains. Bottom of section measured in sec. 3, T. 2 N., R. 5 E.; top measured in secs. 35–36, T. 3 N., R. 5 E., Torrance Co., NM.	early Permian
Cañon de Espinoso Member, Abo Formation (Pa)	Lucas et al. 2005	Type section: measured near the top of the Abo type section (units 22–68 of the Abo type section) in secs. 35–36, T. 3 N., R. 5 E., Torrance Co., NM.	early Permian

The Permian Abo Formation was named by Lee (1909) and derives its name from Abo Canyon at the southern end of the Manzano Mountains, New Mexico. The type section is designated between Priest Canyon and the Abó Mission Ruins in the southern Manzano Mountains in Torrance County, New Mexico (Table 8; Figure 121; Needham and Bates 1943; Lucas et al. 2005). The formation is about 300 m (984 ft) thick at the type section and is subdivided into two informal intervals: 1) a basal slope-forming mudstone broken by thin ledges of trough cross-bedded sandstone and conglomerate; and 2) an upper interval of slope-forming mudstone interbedded with siltstone and numerous thin ledges of ripple laminated sandstone (Lucas et al. 2005). The Abo Formation overlies the Bursum Formation and underlies the Yeso Group.

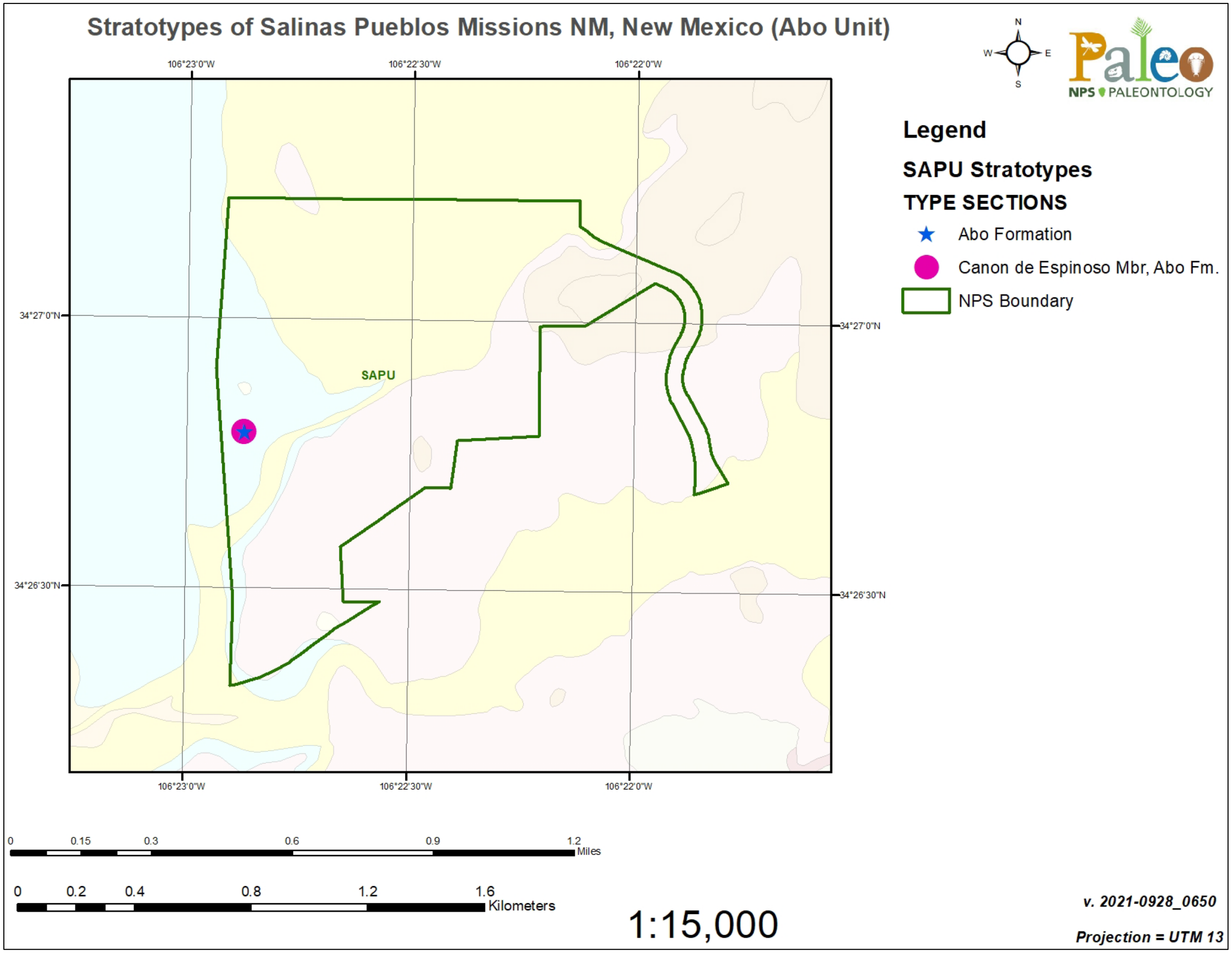


Figure 121. Modified geologic map of SAPU showing stratotype locations. The transparency of the geologic units layer has been increased.

The Permian Cañon de Espinoso Member of the Abo Formation was proposed by Lucas et al. (2005) for exposures that occur in a small canyon of that name in central New Mexico. Lucas et al. (2005) designated the type section of the member near the top of the Abo Formation type section (units 22–68 of the Abo type section) in the southern Manzano Mountains in Torrance County (Table 8; Figures 121 and 122). At the type section the unit measures approximately 166 m (545 ft) thick and consists of slope-forming mudstone interbedded with siltstone and numerous thin ledges of ripple laminated sandstone (Lucas et al. 2005). The Cañon de Espinoso Member overlies the Scholle Member of the Abo Formation and underlies the Yeso Group.

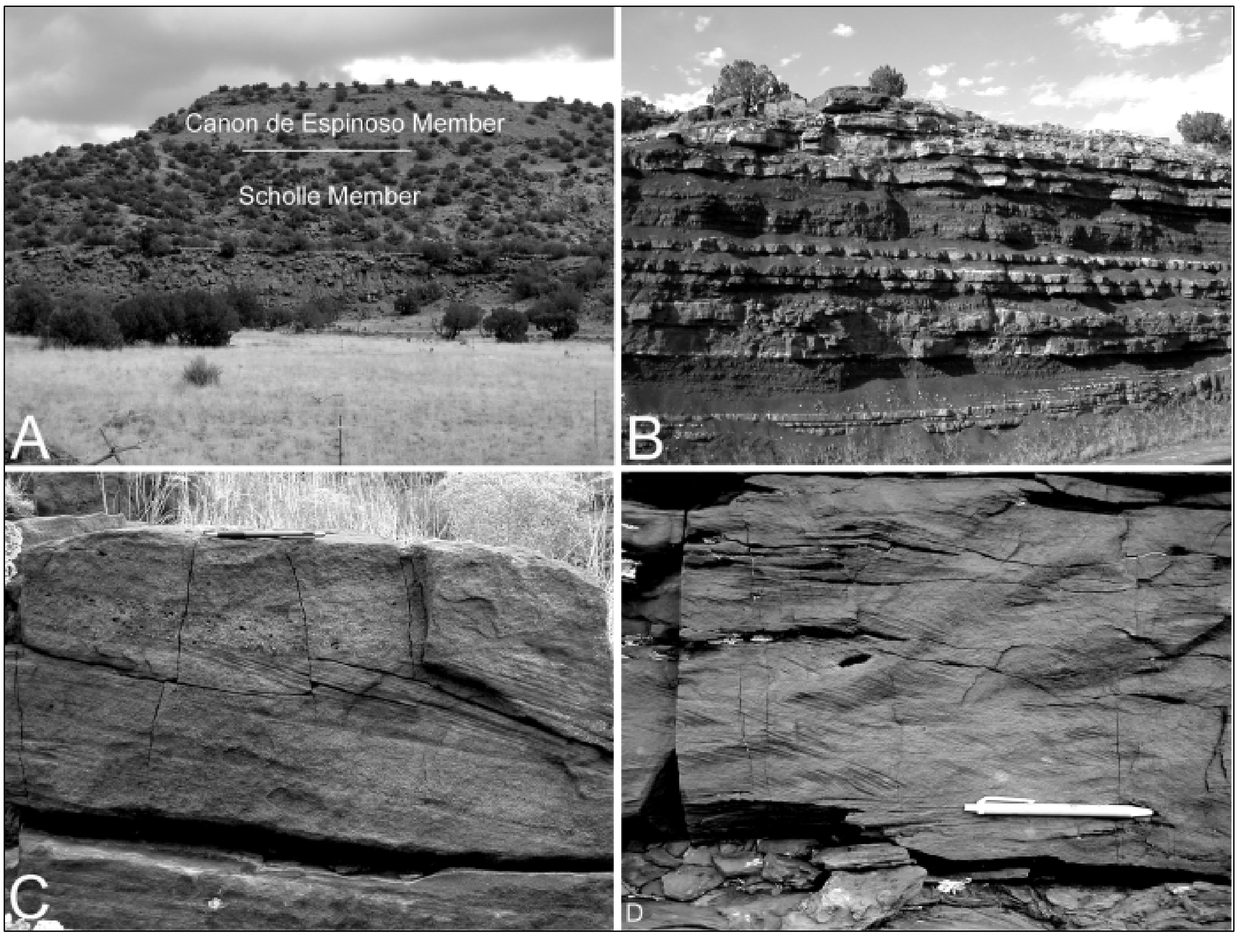


Figure 122. Photographs of the type section of the Abo Formation. **A.** Overview of lower part of section, which is type section of Scholle Member. **B.** Overview of part of upper part of section, which is part of type section of Cañon de Espinoso Member. **C.** Characteristic trough cross-bedded conglomeratic sandstone of Scholle Member. **D.** Characteristic climbing-ripple laminated sandstone of Cañon de Espinoso Member. Figure 6 from Lucas et al. (2005) (courtesy of the New Mexico Museum of Natural History and Science).

Sunset Crater Volcano National Monument (SUCR)

Sunset Crater Volcano National Monument (SUCR) is located approximately 32 km (20 mi) northeast of Flagstaff in Coconino County, northern Arizona (Figure 123). Originally proclaimed as Sunset Crater National Monument on May 26, 1930, the monument was renamed on November 16, 1990 (National Park Service 2016a). The national monument encompasses 1,230 hectares (3,040 acres) of stark, black volcanic landscape and was established to preserve and protect the colorful 305 m (1,000 ft)-high cinder cone and surrounding Bonito Lava Flow, ice cave, cinder fields, spatter cones, lava tubes, and squeeze-ups (National Park Service 2015d). The numerous volcanic features contained within SUCR represent a microcosm of the volcanic activities that have shaped the surrounding landscape since the late Miocene (~6 million years ago). Sunset Crater Volcano National Monument represents the Colorado Plateau's most recent volcanic eruption, forming around 1085 CE when a series of earthquakes and volcanic eruptions brought the dormant San Francisco volcanic field back to life (Thornberry-Ehrlich 2005; Alfano et al. 2019).

The geology at SUCR is dominated by volcanic rock, with the ground surface covered by lava flows, volcanic ash, and cinder deposits (Figure 124). Sunset Crater Volcano is the youngest, best-preserved cinder cone in the San Francisco volcanic field and is part of a 10-km-long chain of young volcanoes that includes Rows of Cones, Gyp Crater, and Vent 512 (Blaylock 1996). Cinder cones such as Sunset Crater Volcano are relatively small structures that form quickly (months to years) as gas-charged frothy blobs of basalt magma rise quickly to the surface and erupt as upward spray or lava fountains. Sunset Crater Volcano represents an interesting case of highly explosive (Sub-Plinian scale) volcanism with several eruptive phases and intermittent episodes of lava discharge (Alfano et al. 2019). Regionally, nearly all the mountains and hills between the Grand Canyon and Flagstaff represent extinct volcanoes of the San Francisco volcanic field (Thornberry-Ehrlich 2005). Sunset Crater Volcano and its relatively undeveloped landscape provide important scientific opportunities to study ecological succession and adaptation in an arid volcanic landscape.

There are no designated stratotypes identified within the boundaries of SUCR. There are two identified stratotypes located within 48 km (30 mi) of SUCR boundaries, representing the type sections of the Permian Cave Spring Sandstone and Harding Point Sandstone Members of the Coconino Sandstone.

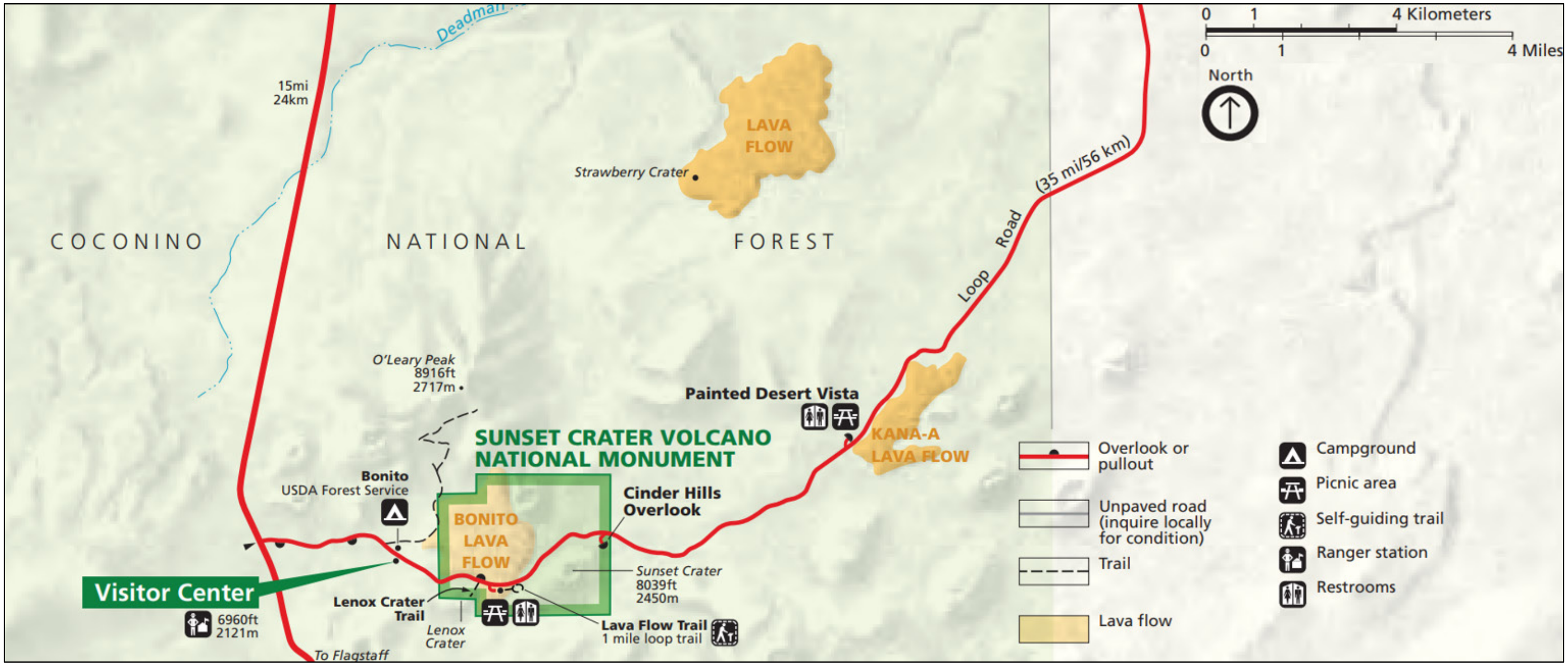


Figure 123. Park map of SUCR, Arizona (NPS).

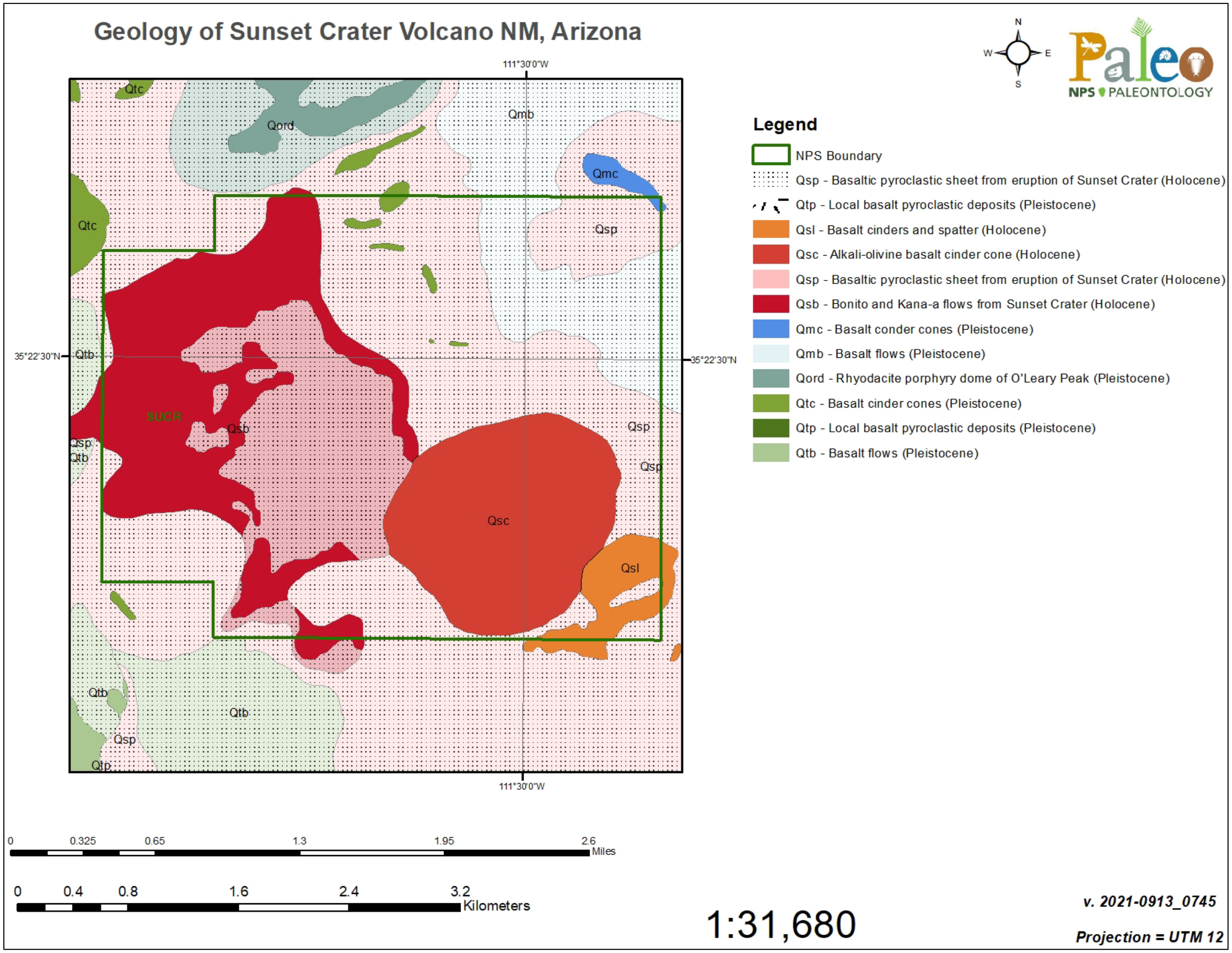


Figure 124. Geologic map of SUCR, Arizona.

Valles Caldera National Preserve (VALL)

Valles Caldera National Preserve (VALL) is located in the Jemez Mountains in Rio Arriba and Sandoval Counties, northern New Mexico (Figure 125). The national preserve was established on July 25, 2000 and added to the National Park System on December 14, 2014. Valles Caldera National Preserve contains 36,017 hectares (89,000 acres) of valley meadows, lush forested volcanic domes, meandering valley streams, and old-growth ponderosa pine groves situated within the 22 km (13.6 mi)-wide Valles Caldera (National Park Service 2016a). Resulting from one of only three supervolcanoes that have erupted in the last 2 million years in the United States, the Valles Caldera was formed during the Pleistocene about 1.23 million years ago (Nasholds 2020). The caldera still displays signs of volcanic life, with active geothermal systems that include hot springs and boiling sulfuric acid fumaroles. The large grassland meadows (or “valles” in Spanish) juxtaposed against forested volcanic domes provides a distinctive landscape. Ecosystems within VALL reflect the topographic mosaic combined with abundant rainfall and rich soils to support a great diversity of animals, plants, fungi, and other organisms including several thousand elk and healthy populations of mountain lions, bears, and coyotes (National Park Service 2018). The region of VALL has historic and cultural connections to various American Indian tribes, who used the caldera for thousands of years to hunt, fish, gather various plants for food, medicine, and ceremonies, and collect materials for tools such as obsidian.

The geology of Valles Caldera National Preserve is the resurgent Valles Caldera and its near-perfect ring of roughly 15 post-caldera lava dome and flow eruptions (Goff 2009; Goff et al. 2011). The formation of Valles Caldera and the earlier Toledo Caldera occurred 1.23 and 1.64 million years ago, respectively, resulting from two explosive eruptions that produced large pyroclastic flows that produced the Pleistocene Bandelier Tuff. Large quantities of pyroclastic material were ejected, causing the crust above the emptied magma chamber to collapse into the bowl-shaped depression seen today. Following the caldera-forming eruption, rejuvenation of the magma chamber has uplifted the caldera floor to form a resurgent dome (Redondo Peak) and produced at least 15 smaller eruptions that form the ring of post-caldera lava flows and domes (Goff et al. 2011). Mapped units throughout VALL predominantly belong to the Pleistocene Tewa Group and include rhyolite domes, lava flows, pyroclastic flows, fallout tephras, and a variety of volcaniclastic deposits that represent the Valles–Toledo caldera complex (Figures 126 and 127; Gardner et al. 2010).

Valles Caldera National Preserve contains 12 identified stratotypes that represent the Pleistocene Valle Toledo Member of the Cerro Toledo Formation and the Valles Rhyolite, as well as the Deer Canyon, Redondo Creek, Cerro del Medio, Cerros del Abrigo, Cerro Santa Rosa, Cerro San Luis, Cerro Seco, San Antonio Mountain, South Mountain, and East Fork Members of the Valles Rhyolite (Table 9; Figure 128). In addition to the designated stratotypes located within VALL, stratotypes located within 48 km (30 mi) of the preserve’s boundaries include the Permian Yeso Formation (type section), Meseta Blanca Member of the Yeso Formation (type section), and San Ysidro Formation (type section); Cretaceous Juana Lopez Member of the Mancos Shale (type section and reference section); Paleocene Nacimiento Formation (type locality) and Arroyo Chijuillita Member of the Nacimiento Formation (type section); Eocene San Jose Formation (type area) and type sections of the

Cuba Mesa, Llaves, and Regina Members of the San Jose Formation; Miocene Santa Fe Group (type locality), Tesuque Formation (type section), type sections of the Bishops Lodge, Chama-El Rito, Nambe, Pojoaque, and Skull Ridge Members of the Tesuque Formation, Chamita Formation (type section), Cejita Member of the Chamita Formation (reference section), Cuarteles Member of the Chamita Formation (type section and reference section), Hernandez Member of the Chamita Formation (type section), Vallito Member of the Chamita Formation (type section), Bearhead Rhyolite (type locality), Canovas Canyon Rhyolite (type locality), Paliza Canyon Formation (type area), Chamisa Mesa Member of the Zia Formation (type section), and Picuda Peak Member of the Arroyo Ojito Formation (type section); Miocene–Pleistocene Cochiti Formation (type locality); Pliocene Totavi Lentil of the Puye Conglomerate (type locality), Lobato Basalt (type area), Ceja Formation (reference section), and Santa Ana Mesa Member of the Ceja Formation (type section); Pliocene–Pleistocene Ancha Formation (type section) and Puye Formation (type section); and Pleistocene Battleship Rock Ignimbrite of the Valles Rhyolite (type section), La Cueva Member of the Bandelier Tuff (type locality), Otowi Member of the Bandelier Tuff (type area and type locality), Guaje Pumice Bed of the Otowi Member of the Bandelier Tuff (type section), Pueblo Canyon Member of the Cerro Toledo Formation (type section), and the Virgin Mesa Member of the Cerro Toledo Formation (type area).

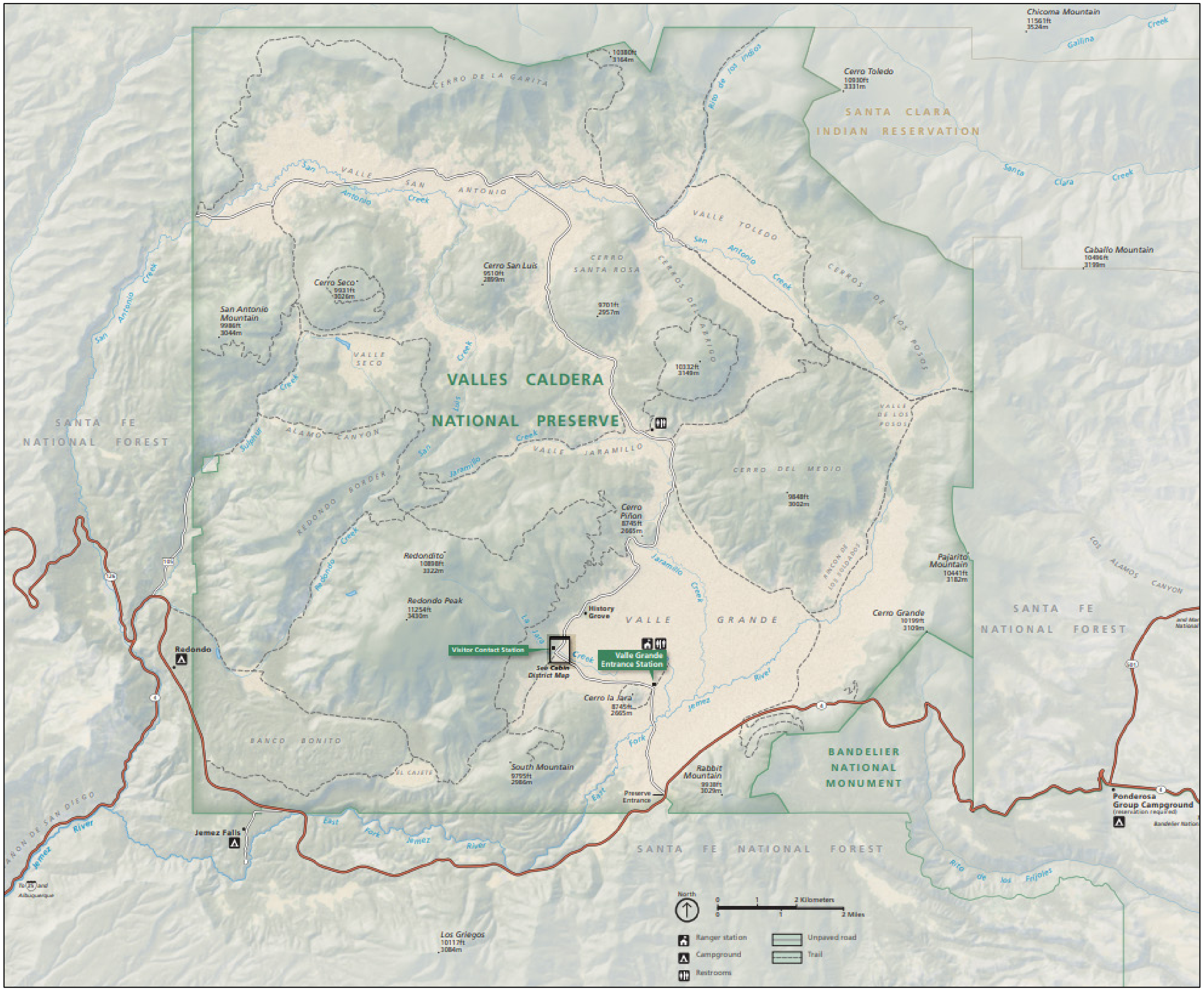


Figure 125. Park map of VALL, New Mexico (NPS).

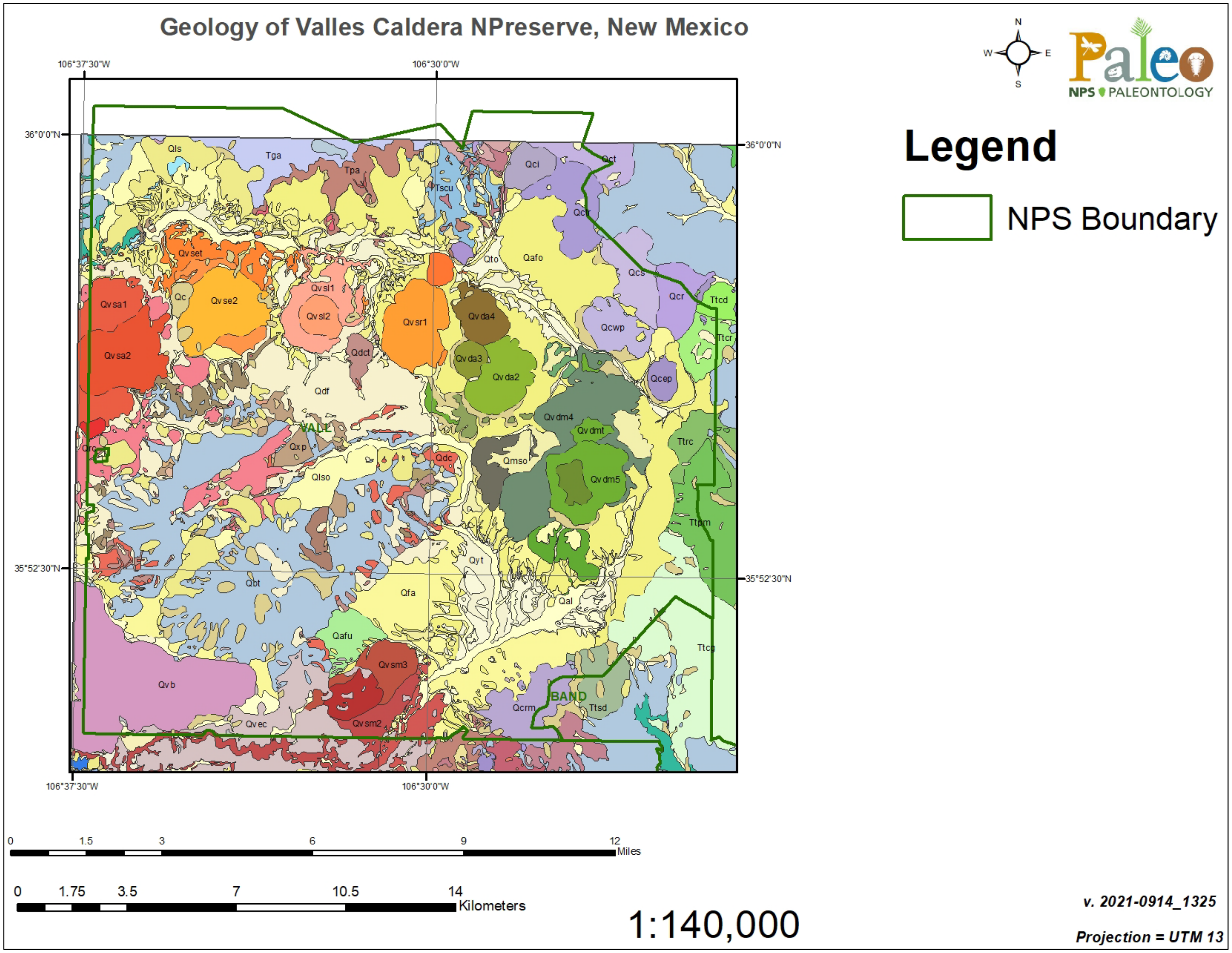


Figure 126. Geologic map of VALL, New Mexico; see Figure 127 for legend.

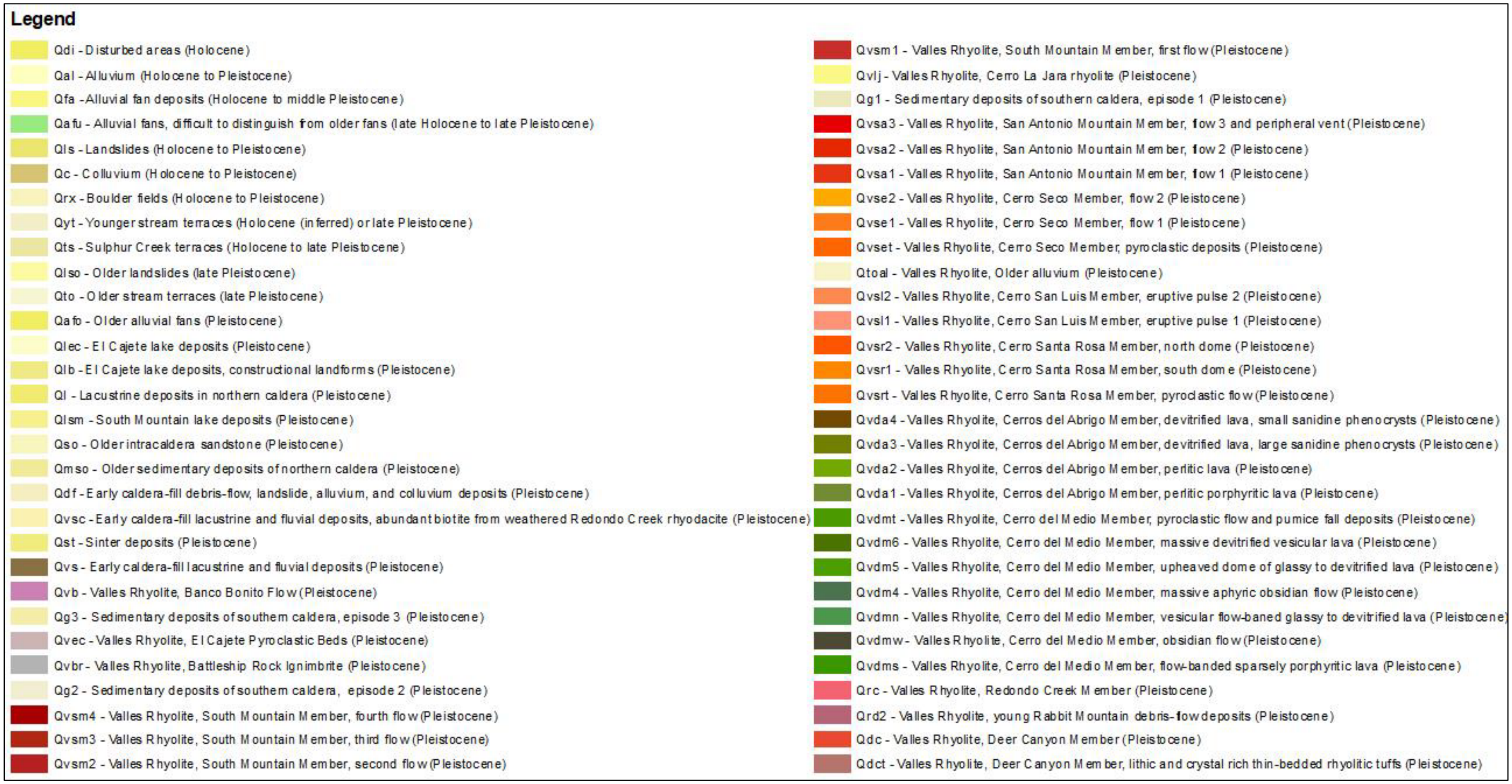


Figure 127. Geologic map legend of VALL, New Mexico.

Qcvm - Cerro Toledo Formation, Virgin Mesa Member (Pleistocene)
Qcpc - Cerro Toledo Formation, Pueblo Canyon Member (Pleistocene)
Qcr - Cerro Toledo Formation, aphyric rhyolite (Pleistocene)
Qcrt - Cerro Toledo Formation, Valle Toledo Member, Rhyolite tuff (Pleistocene)
Qcws - Cerro Toledo Formation, Valle Toledo Member, Warm Springs rhyolite (Pleistocene)
Qctq - Cerro Toledo Formation, Valle Toledo Member, Cerro Trasquilar rhyolite (Pleistocene)
Qrd1 - Cerro Toledo Formation, Valle Toledo Member, Old Rabbit Mountain debris-flow deposits (Pleistocene)
Qcs - Cerro Toledo Formation, Valle Toledo Member, Sierra de Toledo rhyolite (Pleistocene)
Qctr - Cerro Toledo Formation, Valle Toledo Member, Turkey Ridge rhyolite (Pleistocene)
Qcrm - Cerro Toledo Formation, Valle Toledo Member, Rabbit Mountain rhyolite (Pleistocene)
Qcrmt - Cerro Toledo Formation, Valle Toledo Member, Rabbit Mountain rhyolite, bedded tuff (Pleistocene)
Qct - Cerro Toledo Formation, Valle Toledo Member (Pleistocene)
Qcep - Cerro Toledo Formation, Valle Toledo Member, East Los Posos rhyolite (Pleistocene)
Qci - Cerro Toledo Formation, Valle Toledo Member, Indian Point rhyolite (Pleistocene)
Qcnp - Cerro Toledo Formation, Valle Toledo Member, Paso del Norte rhyolite (Pleistocene)
Qcnpt - Cerro Toledo Formation, Valle Toledo Member, Paso del Norte rhyolite, lithic rich tuff (Pleistocene)
Qcnr - Cerro Toledo Formation, Valle Toledo Member, north caldera rim intrusion (Pleistocene)
Qcwp - Cerro Toledo Formation, Valle Toledo Member, West Los Posos rhyolite (Pleistocene)
Qbx - Bandelier Tuff, vent and/or hydrothermal breccia (Pleistocene)
Qbt - Bandelier Tuff, Tshirege Member (Pleistocene)
Qxbo - Bandelier Tuff, caldera-collapse breccia, Bandelier Tuff, Otowi Member (Pleistocene)
Qxt - Bandelier Tuff, caldera-collapse breccia, Tschicoma and Puye Formations (Pleistocene)
Qxpt - Bandelier Tuff, caldera-collapse breccia, Paliza Canyon Formation dacite tuff (Pleistocene)
Qxp - Bandelier Tuff, caldera-collapse breccia, Paliza Canyon Formation andesite and volcaniclastic materials (Pleistocene)
Qxsf - Bandelier Tuff, caldera-collapse breccia, Santa Fe Group (Pleistocene)
Qxr - Bandelier Tuff, caldera-collapse breccia, Ritito Formation (Pleistocene)
Qxa - Bandelier Tuff, caldera-collapse breccia, Abo Formation and Yeso Group (Pleistocene)
Qxm - Bandelier Tuff, caldera-collapse breccia, Madera Formation (Pleistocene)
Qbo - Bandelier Tuff, Otowi Member (Pleistocene)
QTpf - Puye Formation (lower Pleistocene to lower Pliocene)

Ttqc - Tschicoma Formation, upper Quemazon Canyon dacite (Pliocene)
Ttcb - Tschicoma Formation, Caballo Mountain dacite (Pliocene)
Ttpm - Tschicoma Formation, Pajarito Mountain dacite (Pliocene)
Ttcg - Tschicoma Formation, Cerro Grande dacite (Pliocene)
Ttsd - Tschicoma Formation, Sawyer Dome dacite (Pliocene)
Ttcr - Tschicoma Formation, Cerro Rubio dacite (Pliocene)
Ttcd - Tschicoma Formation, dacite intrusion north of Cerro Rubio (Pliocene)
Ttsc - Tschicoma Formation, Santa Clara Canyon dacite (Pliocene)
Ttpd - Tschicoma Formation, Tschicoma Peak area dacite and rhyodacite, undivided (Pliocene)
Ttrc - Tschicoma Formation, Rendija Canyon rhyodacite (Pliocene)
Tbh - Bearhead Rhyolite (Pliocene to Miocene)
Tscu - Chamita Formation, Hernandez Member (Miocene)
Tghd - La Grulla Formation, hornblende dacite and rhyodacite (Miocene)
Tgbhd - La Grulla Formation, porphyritic biotite, hornblende rhyodacite (Miocene)
Tgb - La Grulla Formation, olivine basalt (Miocene)
Tga - La Grulla Formation, porphyritic andesite and dacite, undivided (Miocene)
Tpgd - Dacite outcrop in Guaje Canyon (Miocene)
Tpv - Paliza Canyon Formation, volcaniclastic member, conglomerate sandstone (Pliocene? to Miocene)
Tpvs - Paliza Canyon Formation, volcaniclastic member, sandstone (Pliocene? to Miocene)
Tpb - Paliza Canyon Formation, olivine basalt and basaltic andesite, undivided (Miocene)
Tpa - Paliza Canyon Formation, Two-pyroxene andesite, undivided (Miocene)
Tpbhd - Paliza Canyon Formation, porphyritic biotite, hornblende dacite (Miocene)
Thb - Paliza Canyon Formation, hydrothermal breccia (Miocene)
Tpdt - Paliza Canyon Formation, porphyritic dacite tuff (Miocene)
Tpbd - Paliza Canyon Formation, porphyritic biotite dacite (Miocene)
Tpha - Paliza Canyon Formation, hornblende andesite (Miocene)
Ta - Abiquiu Formation (Miocene to Oligocene)
TRcs - Shinarump Formation (Triassic)
TRm - Moenkopi Formation (Triassic)
Pg - Glorieta Sandstone (Permian)
Py - Yeso Group (Permian)

Figure 127 (continued). Geologic map legend of VALL, New Mexico.

Table 9. List of VALL stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Valles Rhyolite (Qv*)	Griggs and Hem 1964	Type locality: rhyolite domes in Valles Caldera in west-central part of Los Alamos area, Sandoval Co., NM.	Pleistocene
East Fork Member, Valles Rhyolite	Gardner et al. 2010	Type area: composite of type areas of constituent units (Banco Bonito, Battleship Rock, and El Cajete), centered at approx. lat. 35°50′ N., long. 106°35′ W. [in Jemez Springs, Redondo Peak, Valle San Antonio, and Seven Springs 7.5′ Quadrangles], Sandoval Co., NM.	Pleistocene
South Mountain Member, Valles Rhyolite (Qvsm1, Qvsm2, Qvsm3, Qvsm4)	Gardner et al. 2010	Type area: a northeast-trending rectangular area about 5 km (3 mi) long and 2 km (1.35 mi) wide, centered on UTM 13S, 361850E 3966750N, NAD 27, Sandoval Co., NM.	Pleistocene
San Antonio Mountain Member, Valles Rhyolite (Qvsa1, Qvsa2, Qvsa3)	Gardner et al. 2010	Type area: designated as the area defined by roughly a 3 km (1.86 mi) radius about UTM 13S, 354180E 3978100N, NAD 27, Sandoval Co., NM.	Pleistocene
Cerro Seco Member, Valles Rhyolite (Qvset, Qvse1, Qvse2)	Gardner et al. 2010	Type area: designated as the rectangular area defined with the northwest corner at UTM 13S, 356050E 3981750N, and the southeast corner at UTM 13S, 359600E 3977300N, NAD 27, Sandoval Co., NM.	Pleistocene
Cerro San Luis, Valles Rhyolite (Qvsl1, Qvsl2)	Gardner et al. 2010	Type area: the area of about 1.5 km (1 mi) radius around UTM 13S, 361400E 3979100N, NAD 27, Sandoval Co., NM.	Pleistocene
Cerro Santa Rosa Member, Valles Rhyolite (Qvsr1, Qvsr2, Qvsrt)	Gardner et al. 2010	Type area: the north–northeast-trending chain of hills, about 3.5 km (2.2 mi) long and less than 2 km (1.25 mi) wide, centered at UTM 13S, 3664350E 3979000N, NAD 27, Sandoval Co., NM.	Pleistocene
Cerros del Abrigo Member, Valles Rhyolite (Qvda1, Qvda2, Qvda3, Qvda4)	Gardner et al. 2010	Type area: an area of about 1–2 km (~0.5–1 mi) radius centered about UTM 13S, 366475E 3977650N, NAD 27, Sandoval Co., NM.	Pleistocene
Cerro del Medio Member, Valles Rhyolite (Qvdm1, Qvdm2, Qvdm3, Qvdm4, Qvdm5, Qvdm6, Qvdmt)	Gardner et al. 2010	Type area: an area of 2–3 km (~1–2 mi) radius about UTM 13S, 368800E 3974250N, NAD 27, Sandoval Co., NM.	Pleistocene
Redondo Creek Member, Valles Rhyolite (Qrc)	Bailey et al. 1969	Type locality: in steep slopes on west side of Sulphur Creek, between Sulphur Springs and La Cueva [Jemez Springs 15′ Quadrangle], Sandoval Co., NM.	Pleistocene

Table 9 (continued). List of VALL stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Deer Canyon Member, Valles Rhyolite (Qdc, Qdct)	Bailey et al. 1969	Type area: Deer Canyon, southwest side of Redondo Border [Jemez Springs 15′ Quadrangle], Sandoval Co., NM.	Pleistocene
Valle Toledo Member, Cerro Toledo Formation (Qct)	Griggs 1964; Gardner et al. 2010	Type area: on the northeast side of Valles Caldera in steep forested northwest-trending ridge, the Sierra de Toledo, between Rito de los Indios and Valle de los Posos, Sandoval Co., NM. Type area expanded to include vicinity of Valle Toledo.	Pleistocene

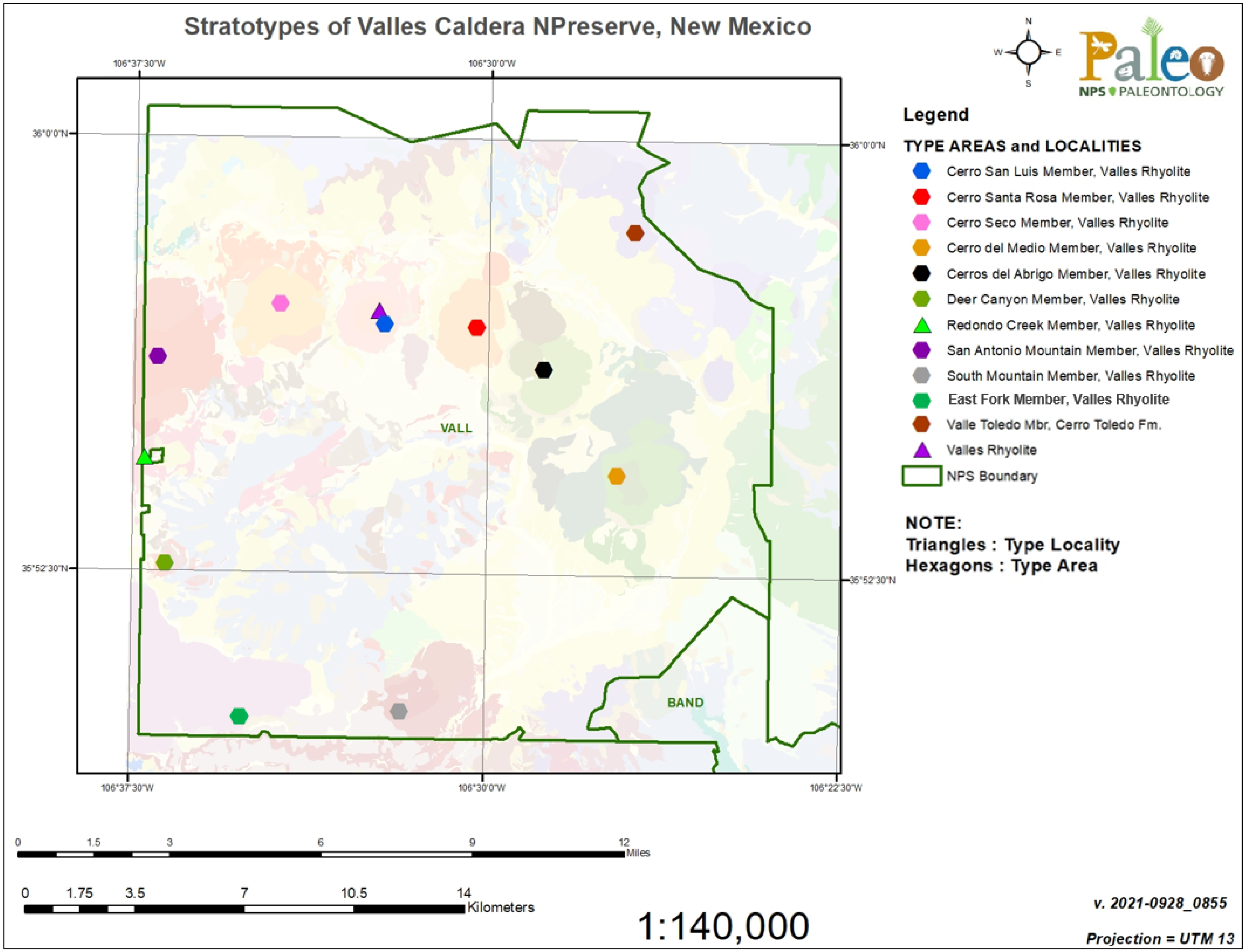


Figure 128. Modified geologic map of VALL showing stratotype locations. The transparency of the geologic units layer has been increased.

The Pleistocene Valle Toledo Member is the youngest member of the Cerro Toledo Formation proposed by Gardner et al. (2010) and replaces the former "Cerro Toledo Rhyolite" defined by Griggs (1964). The type area is designated on the northeast side of the Valle–Toledo caldera complex on a steep forested northwest-trending ridge, the Sierra de Toledo, between Rito de los Indios and Valle de los Posos, New Mexico (Table 9; Figure 128 and 129; Griggs 1964). Gardner et al. (2010) expanded the type area to include the vicinity of Valle Toledo. Type area exposures consist of rhyolitic domes and extra-caldera sequences dominated by pyroclastic deposits (Gardner et al. 2010). The Valle Toledo Member overlies the Virgin Mesa Member of the Cerro Toledo Formation and underlies the Tshirege Member of the Bandelier Tuff.

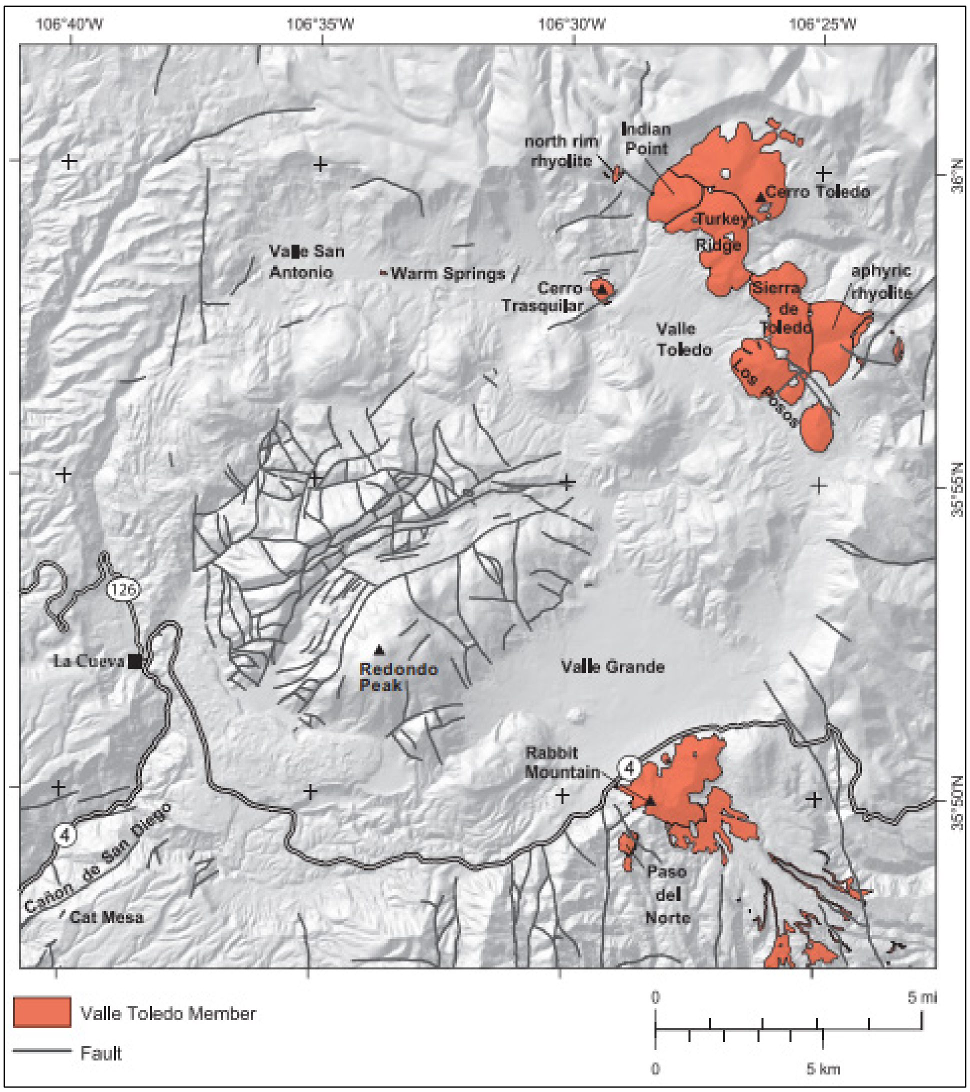


Figure 129. Shaded relief map of the Valles–Toledo caldera complex showing the Valle Toledo Member of the Cerro Toledo Formation and some geographic features of the caldera complex. Figure 5 from Gardner et al. (2010) (courtesy of the New Mexico Bureau of Geology and Mineral Resources).

The Pleistocene Valles Rhyolite was proposed by Griggs and Hem (1964) for a voluminous series of rhyolitic tuffs and lavas that mark the terminal stage of volcanism in the Jemez Mountains. The formation is subdivided into ten formal members that include, from oldest to youngest, the Deer Canyon, Redondo Creek, Cerro del Medio, Cerros del Abrigo, Cerro Santa Rosa, Cerro San Luis, Cerro Seco, San Antonio Mountain, South Mountain, and East Fork Members (Gardner et al. 2010). Type locality exposures of the Valle Rhyolite consist of the rhyolite domes in the Valle–Toledo caldera complex in the west-central part of the Los Alamos area (Table 9; Figure 128; Griggs and Hem 1964). While smaller domes of the formation are nearly circular to elliptical in shape, the larger domes are composite masses of multiple domes (Griggs and Hem 1964). The Valles Rhyolite exhibits lithological zoning, with a slightly weathered outer rind of pumice and pumiceous glass with an interior of slightly porous, light-gray rhyolite that contains interstitial obsidian (Griggs and Hem 1964). The Valles Rhyolite overlies the Bandelier Tuff and underlies young Holocene-age alluvium.

The Pleistocene Deer Canyon Member of the Valles Rhyolite was named by Bailey et al. (1969) after its type area exposures at Deer Canyon on the southwest side of Redondo Border (Table 9; Figures 128 and 130). Type area exposures occur in the central part of the Valle–Toledo caldera complex and consist of volcanic domes, rhyolitic tuffs, and breccias that have a maximum thickness of approximately 30 m (100 ft) (Bailey et al. 1969). At most localities the Deer Canyon Member overlies sedimentary caldera fill which in turn overlie the Tshirege Member of the Bandelier Tuff. The Deer Canyon Member underlies the Redondo Creek Member of the Valles Rhyolite.

The Pleistocene Redondo Creek Member of the Valles Rhyolite was named by Bailey et al. (1969) after its type locality in the steep slopes on the west side of Sulphur Creek, between Sulphur Springs and La Cueva (Table 9; Figures 128 and 130). Type locality exposures occur in the central and western parts of the Valles–Toledo caldera complex and consist of rhyolitic domes, dikes, lava flows, and perlitic flow breccias with a thickness of about 152 m (500 ft) (Bailey et al. 1969). The Redondo Creek Member overlies both the Deer Canyon Member and unnamed sedimentary caldera fill and unconformably underlies the now-superseded Valle Grande Member of the Valles Rhyolite (Gardner et al. 2010).

The Pleistocene Cerro del Medio Member of the Valles Rhyolite was proposed by Gardner et al. (2010) and named after the Cerro del Medio, a cluster of hills and mountains in the eastern part of the Valle–Toledo caldera complex. Gardner et al. (2010) designated the type area as a 2–3 km (~1–2 mi) radius zone in the Cerro del Medio centered about UTM 13S, 368800E 3974250N, NAD 27 (Table 9; Figures 128 and 130). Type area exposures have a maximum thickness of about 260 m (853 ft) and consist of rhyolitic lava flows, pyroclastic deposits, and obsidian. According to Gardner et al. (2010), the Cerro del Medio Member represents a rhyolite flow and dome complex that records at least six distinct phases of eruptive activity. The base of the Cerro del Medio Member is not exposed, but the unit presumably overlies early sedimentary caldera fill and underlies the Cerros del Abrigo Member of the Valles Rhyolite (Gardner et al. 2010).

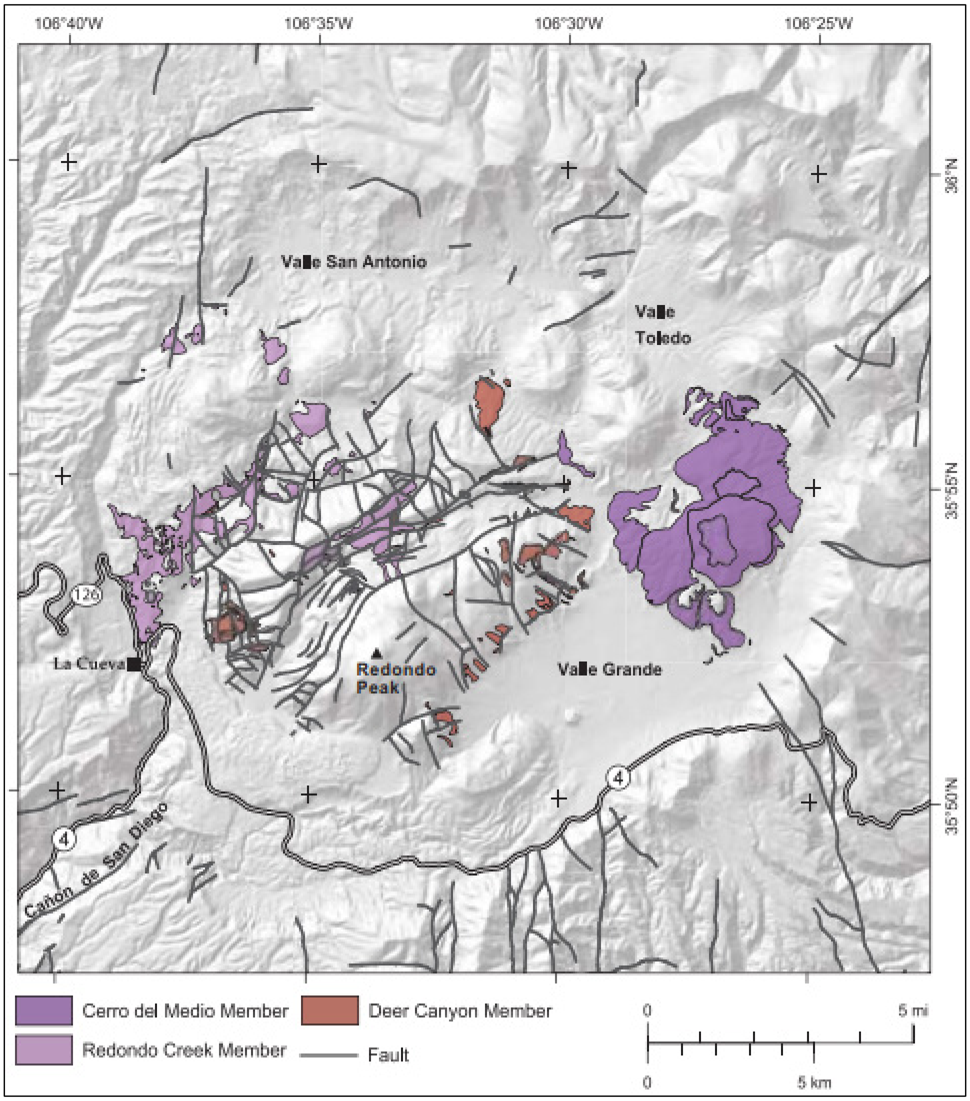


Figure 130. Shaded relief map of the Valles–Toledo caldera complex showing type area flows and beds of the Cerro del Medio, Redondo Creek, and Deer Canyon Members of the Valles Rhyolite and some geographic features of the caldera complex. Figure 8 from Gardner et al. (2010) (courtesy of the New Mexico Bureau of Geology and Mineral Resources).

The Pleistocene Cerros del Abrigo Member of the Valles Rhyolite was named by Gardner et al. (2010) after the Cerros del Abrigo hills in the northeastern region of the Valle–Toledo caldera complex. The type area of the member is designated as a 1–2 km (~0.5–1 mi) radius zone of the Cerros del Abrigo centered about UTM 13S, 366475E 3977650N, NAD 27 (Table 9; Figures 128 and 131; Gardner et al. 2010). Type area exposures represent a complex of four dome and flow sequences of finely porphyritic rhyolite that have a maximum thickness of about 405 m (1,329 ft) (Gardner et al. 2010). Contact relations of the Cerro del Abrigo Member are largely obscured by younger sedimentary deposits, but the unit is known to overlie the Cerro del Medio Member in the southern type area (Gardner et al. 2010).

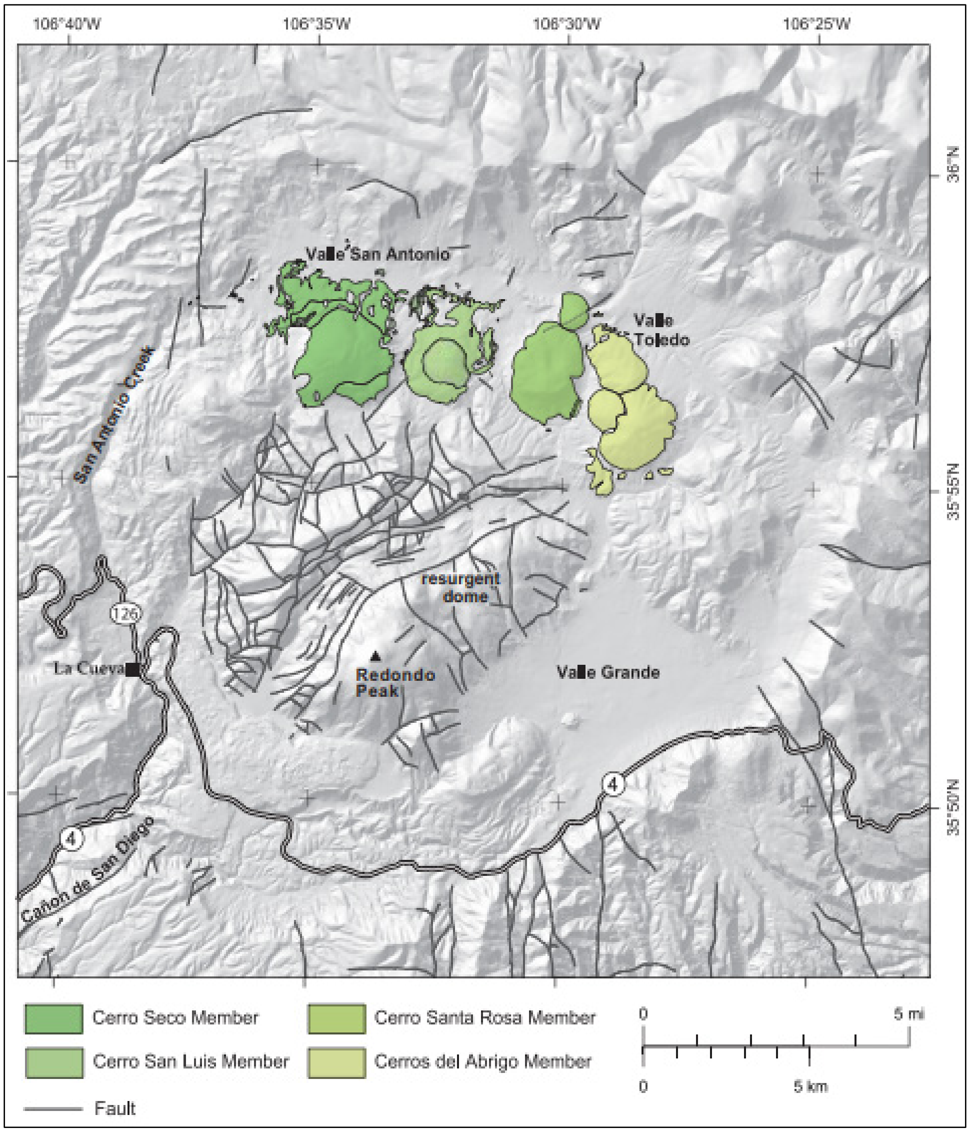


Figure 131. Shaded relief map of the Valles–Toledo caldera complex showing type area flows and beds of the Cerro Seco, Cerro San Luis, Cerro Santa Rosa, and Cerros del Abrigo Members of the Valles Rhyolite and some geographic features of the caldera complex. Figure 9 from Gardner et al. (2010) (courtesy of the New Mexico Bureau of Geology and Mineral Resources).

The Pleistocene Cerro Santa Rosa Member of the Valles Rhyolite was proposed by Gardner et al. (2010) and named after Cerro Santa Rosa, a hill located in the north-central region of the Valle–Toledo caldera complex. Gardner et al. (2010) designated the type area as a north–northeast-trending chain of hills about 3.5 km (2.2 mi) long and less than 2 km (1.25 mi) wide centered at UTM 13S, 3664350E 3979000N, NAD 27 (Table 9; Figures 128 and 131). Type area exposures are composed of at least two rhyolite domes, lava flows, and pyroclastic deposits with a maximum thickness of approximately 150 m (492 ft) (Gardner et al. 2010). Rocks of the member mostly consist of white to gray porphyritic rhyolite with glassy, pumiceous textures (Gardner et al. 2010). The Cerro Santa

Rosa overlies the Cerros del Medio Member and underlies the Cerro San Luis Member of the Valles Rhyolite.

The Pleistocene Cerro San Luis Member of the Valles Rhyolite was proposed by Gardner et al. (2010) and named after the Cerro San Luis in the north-central portion of the Valle–Toledo caldera complex. The type area of the member is designated as a 1.5 km (1 mi) radius zone of the Cerro San Luis centered around UTM 13S, 361400E 3979100N, NAD 27 (Table 9; Figures 128 and 131; Gardner et al. 2010). Type area exposures consist of flow-banded, pumiceous, porphyritic rhyolite with a maximum measured thickness of about 325 m (1,066 ft) (Gardner et al. 2010). The Cerro San Luis Member overlies Cerro Santa Rosa Member in the eastern type area and underlie the Cerro Seco Member of the Valles Rhyolite.

The Pleistocene Cerro Seco Member of the Valles Rhyolite was named by Gardner et al. (2010) after Cerro Seco in the north-central region of the Valles–Toledo caldera complex. Gardner et al. (2010) designated the type area of the member as the rectangular region defined with the northwest corner at UTM 13S, 356050E 3981750N, and the southeast corner at UTM 13S, 359600E 3977300N, NAD 27 (Table 9; Figures 128 and 131). Type area exposures have a maximum thickness of approximately 375 m (1,230 ft) and consist of porphyritic rhyolite and pyroclastic deposits interbedded with white laminated mudstone containing desiccation cracks (Gardner et al. 2010). The Cerro Seco Member overlies deposits of both the Cerro San Luis Member of the Valles Rhyolite and Valle Toledo Member of the Cerro Toledo Formation and its upper contact is obscured by erosion (Gardner et al. 2010).

The Pleistocene San Antonio Member of the Valles Rhyolite was proposed by Gardner et al. (2010) and named after San Antonio Mountain in the northwestern region of the Valles–Toledo caldera complex. The type area of the member is defined by roughly a 3 km (1.86 mi) radius zone centered about UTM 13S, 354180E 3978100N, NAD 27 (Table 9; Figures 128 and 132). Exposures in the type area exceed 510 m (1,673 ft) thick and comprise a porphyritic rhyolite flow and dome center consisting of a partial ring of older lava flows that are intruded by younger domes (Gardner et al. 2010). The San Antonio Member underlies lacustrine and inferred deltaic deposits and overlies the Redondo Creek Member of the Valles Rhyolite, debris-flow deposits from the Valles Caldera resurgent dome, and older lacustrine deposits (Gardner et al. 2010).

The Pleistocene South Mountain Member of the Valles Rhyolite was named by Gardner et al. (2010) after South Mountain in the southern area of the Valles–Toledo caldera complex immediately south and southeast of Redondo Peak. The type area is designated as a northeast-trending rectangular area about 5 km (3 mi) long and 2 km (1.35 mi) wide, centered on UTM 13S, 361850E 3966750N, NAD 27 (Table 9; Figures 128 and 132; Gardner et al. 2010). Exposures in the type area have a maximum thickness of 450 m (1,476 ft) at South Mountain and consist of porphyritic rhyolite domes, lava flows, and pyroclastic deposits that record at least five eruptive episodes (Gardner et al. 2010). Lava flows of the member are dispersed for at least 10 km (6 mi) west of the type area. The South Mountain Member underlies the East Fork Member of the Valles Rhyolite and overlies sedimentary caldera fill and older landslide, fluvial, and lacustrine deposits.

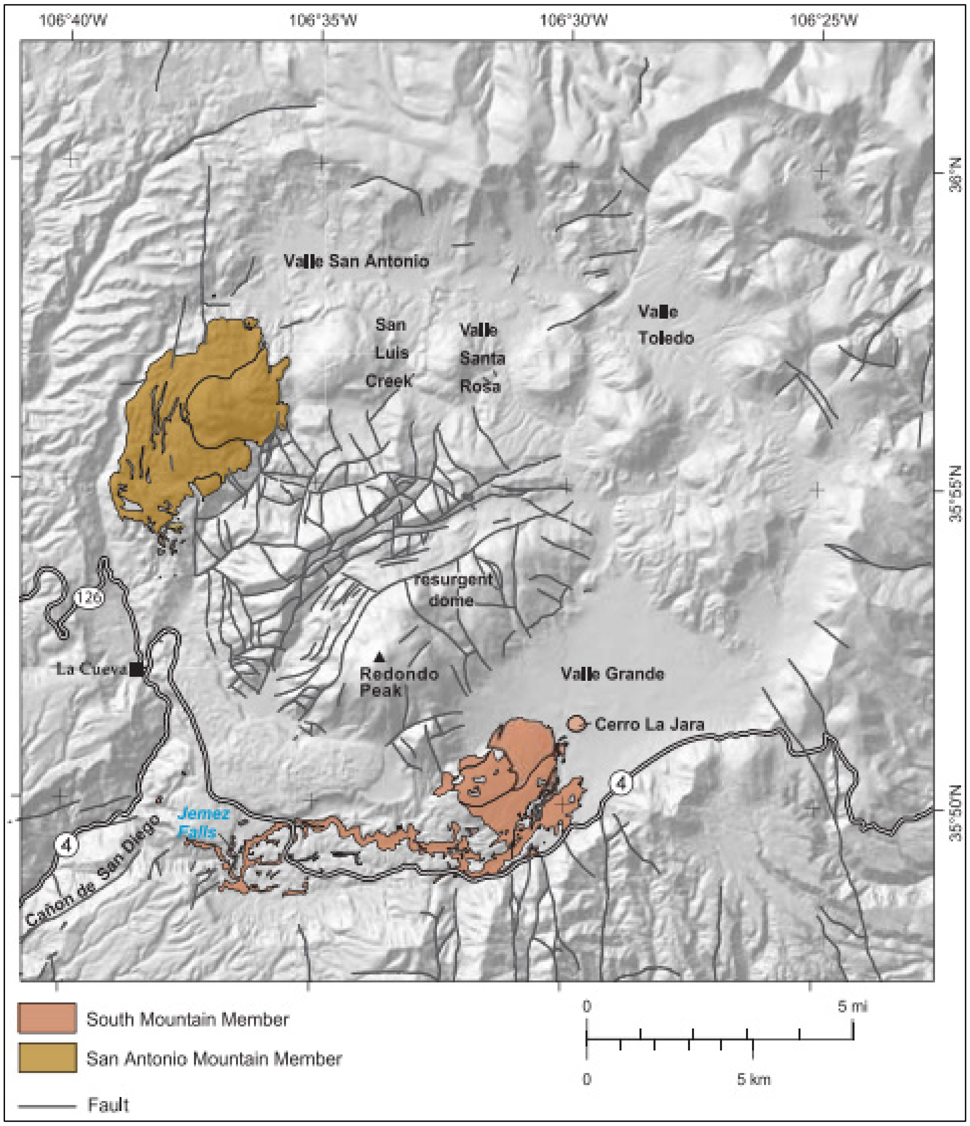


Figure 132. Shaded relief map of the Valles–Toledo caldera complex showing type area flows and beds of the South Mountain and San Antonio Mountain Members of the Valles Rhyolite and some geographic features of the caldera complex. Figure 10 from Gardner et al. (2010) (courtesy of the New Mexico Bureau of Geology and Mineral Resources).

The Pleistocene East Fork Member of the Valles Rhyolite was proposed by Gardner et al. (2010) and derives its name from the East Fork of the Jemez River. The member represents the most recent eruptive sequence within the Valles Caldera that occurred about 75,000–68,000 years ago (Reneau et al. 1996; Gardner et al. 2010; Zimmerer et al. 2016; Nasholds 2020). Gardner et al. (2010) designated the type area of the member to encompass a composite of type areas of superseded constituent units (Banco Bonito, Battleship Rock, and El Cajete Members of Bailey et al. 1969), centered at approximately lat. 35°50′ N., long. 106°35′ W. along the southwestern margin of the Valles–Toledo caldera complex (Table 9; Figures 128 and 133). Type area exposures consist of rhyolitic ash-flow deposits (Battleship Rock units), rhyolitic pumice lapilli and blocks (El Cajete units), and a porphyritic obsidian flow that fills the southwestern moat of Valles Caldera (Banco Bonito units) (Bailey et al. 1969; Gardner et al. 2010). Core hole data reveals a 298 m (978 ft) thick sequence of the East Fork Member that is comprised of several lava flows, four welded tuff horizons, and relatively minor pyroclastic fallout beds (Gardner et al. 2010). The East Fork Member overlies the South Mountain Member and its upper contact is unknown.

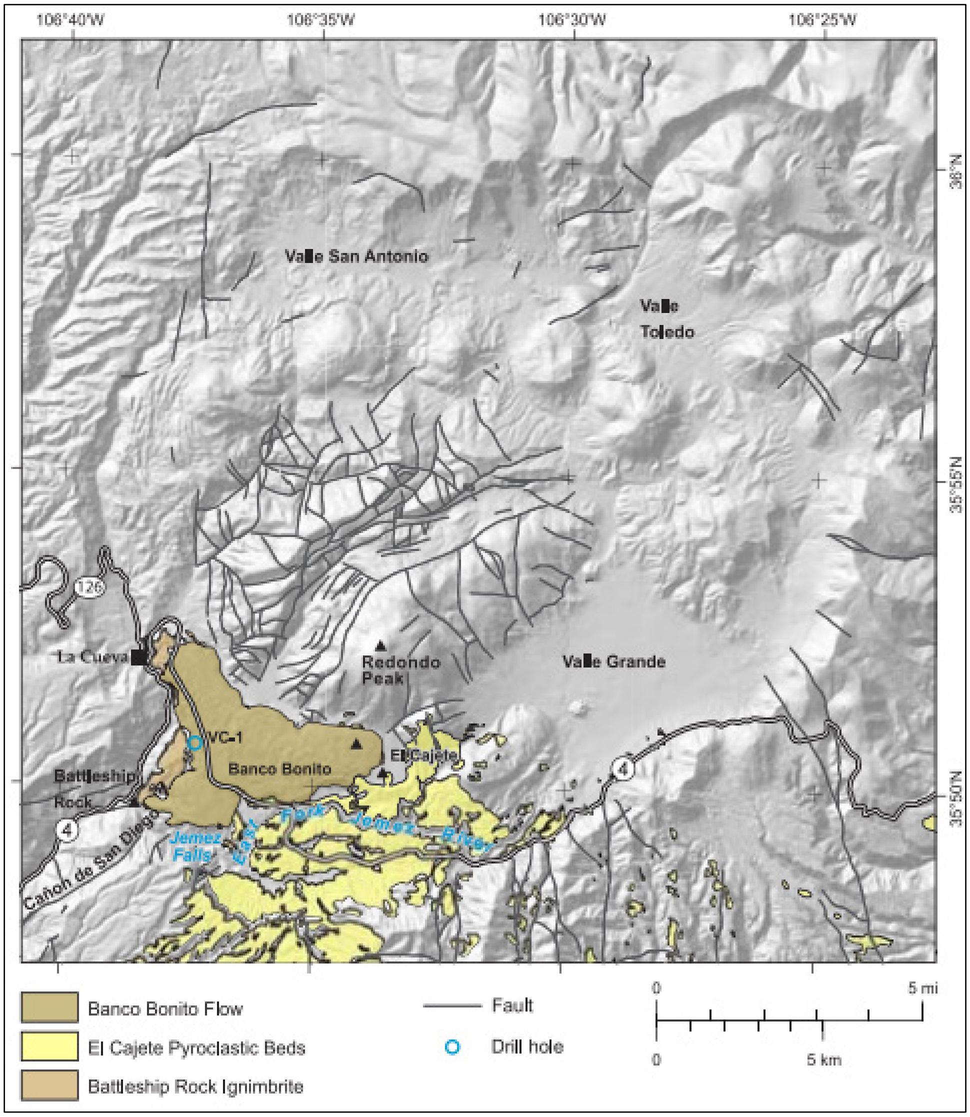


Figure 133. Shaded relief map of the Valles–Toledo caldera complex showing type area flows and beds of the East Fork Member of the Valles Rhyolite and some geographic features of the caldera complex. Figure 11 from Gardner et al. (2010) (courtesy of the New Mexico Bureau of Geology and Mineral Resources).

Walnut Canyon National Monument (WACA)

Walnut Canyon National Monument (WACA) is located just 16 km (10 mi) from downtown Flagstaff in Coconino County, Arizona (Figure 134). Authorized on November 30, 1915, WACA encompasses nearly 1,428 hectares (3,529 acres) and protects a high concentration of well-preserved Northern Sinagua cliff dwellings, pit houses, and other cultural resources situated in deeply incised canyon topography (National Park Service 2016a). Cliff dwellings in WACA are located in the upper third of Walnut Canyon, named after the Arizona walnut trees that grow along the floor of the canyon (Graham 2008). The Northern Sinagua people constructed the cliff dwellings and pit houses about 800 years ago in shallow alcoves of relatively soft sandstone nestled under harder, more resistant ledges of limestone. The cliff dwellings and rich biological communities in WACA hold traditional cultural importance for numerous American Indian tribes in the American Southwest.

The geology of WACA is predominantly controlled by Walnut Canyon and the entrenched segment of Walnut Creek that has incised into relatively horizontal layers of Paleozoic limestone and sandstone. Walnut Canyon averages 402 m (1,320 ft) wide from rim-to-rim and reaches a maximum depth of 122 m (400 ft) at the western (upstream) boundary (Graham 2008). Incision of the canyon has revealed resistant gray limestone of the Permian Kaibab Formation in the upper walls and rim, with light tan, cross-bedded sandstone exposures of the Toroweap Formation and Coconino Sandstone underneath (Figure 135; Graham 2008). Sandstones such as the Coconino Sandstone not only served as protective alcove shelters for the Northern Sinagua but represent an important regional aquifer.

There are no designated stratotypes identified within the boundaries of WACA. There are six identified stratotypes located within 48 km (30 mi) of WACA boundaries, for the Permian Schnebly Hill Formation (type section), type sections of the Bell Rock, Rancho Rojo, and Sycamore Pass Members of the Schnebly Hill Formation, and the type sections of the Cave Spring Sandstone and Harding Point Sandstone Members of the Coconino Sandstone.

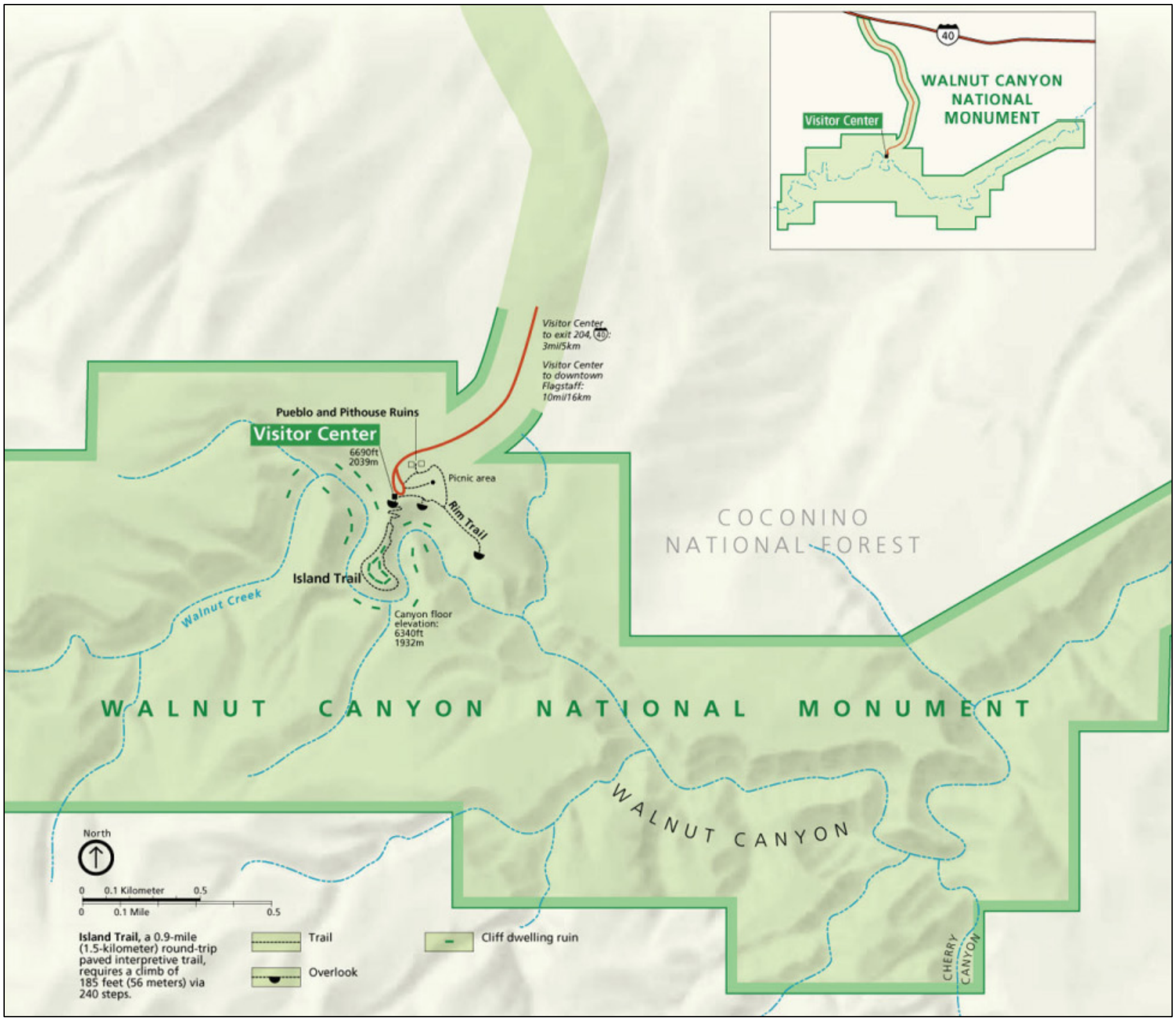


Figure 134. Park map of WACA, Arizona (NPS).

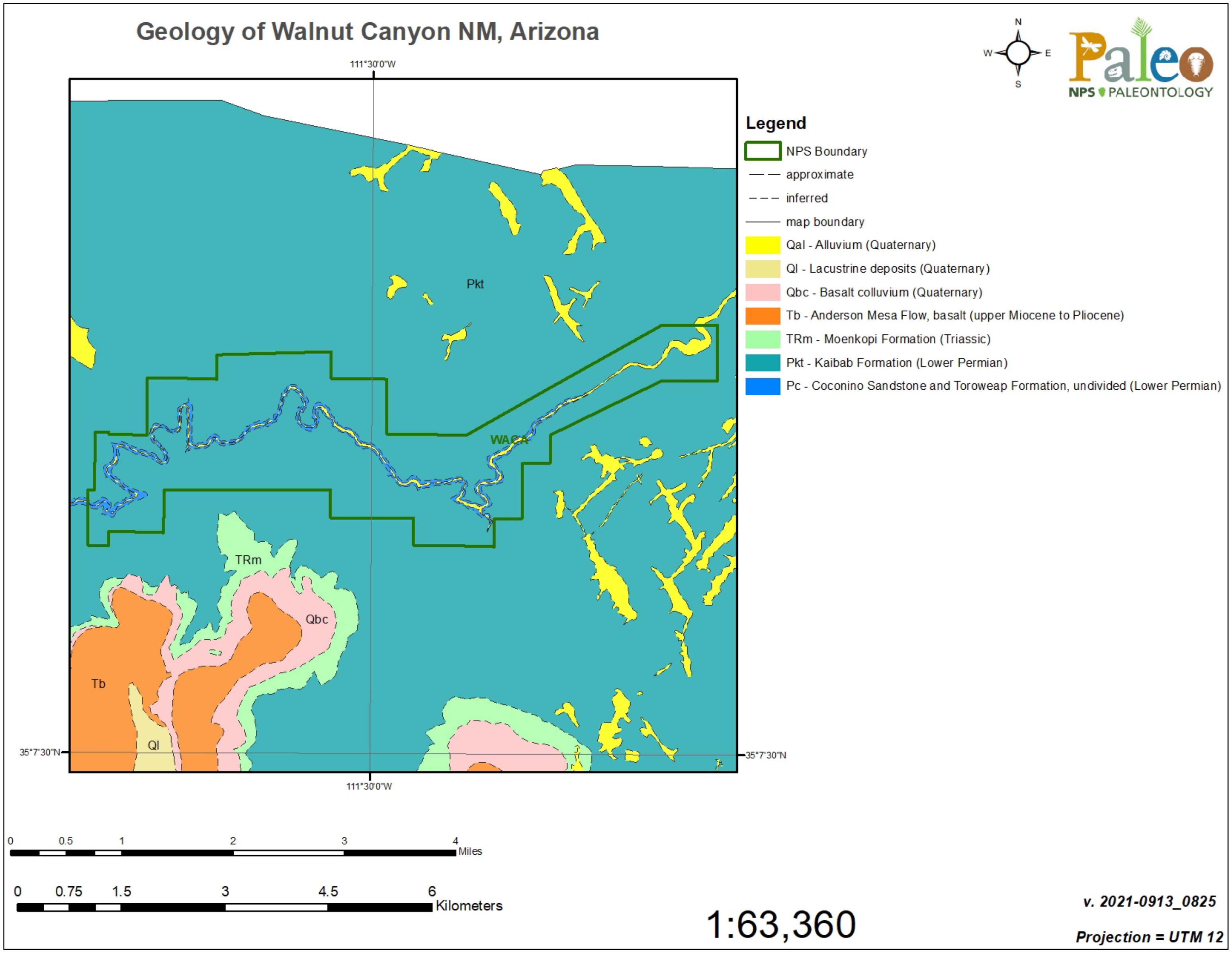


Figure 135. Geologic map of WACA, Arizona.

Wupatki National Monument (WUPA)

Wupatki National Monument (WUPA) is located about 42 km (26 mi) north of Flagstaff in Coconino County, Arizona (Figure 136). Proclaimed on December 9, 1924, WUPA contains approximately 14,334 hectares (35,422 acres) and preserves more than 2,700 archeological sites distributed across the Painted Desert landscape on the southwestern Colorado Plateau (Ort et al. 2008; National Park Service 2016a). Sites mostly date to the 12th and 13th centuries and range in size from lithic and sherd scatters, to small single-room field houses, to several large, prominent free-standing pueblos containing 50 to 100 rooms (National Park Service 2015e). The monument was originally authorized in 1924 to protect the Citadel and Wupatki Pueblos that were built by a culture archeologists refer to as the Northern Sinagua, but subsequent boundary adjustments over the years have encompassed additional pueblos (Graham 2011). The region of WUPA was home, at various times, to several American Indian tribes and preserves a tangible record of clan migrations and extensive trading practices through the centuries.

The geologic landscape of WUPA predominantly consists of lower Permian (299–270 million years ago) and Lower Triassic (252–245 million years ago) sedimentary rocks (Figure 137). In eastern WUPA, red sandstone and siltstone exposures of the Triassic Moenkopi Formation stand in vivid contrast to the gray limestone outcrops in western WUPA. The Northern Sinagua people primarily utilized the reddish sandstone of the Moenkopi Formation as principal building blocks for their pueblos. In the western portion of WUPA, Permian-age strata of the Kaibab and Toroweap Formations constitute the extensive Antelope Prairie and form cliffs and ledges of calcareous sandstone and cherty limestone. Pliocene and Pleistocene-age basaltic lava flows occur as erosion-resistant caprock on several mesas in the western and southern areas of the monument, sourced from volcanic eruptions in the San Francisco volcanic field located south of the monument (Graham 2011). The major geologic structure in WUPA is the Black Point Monocline, a northeast–southwest-trending asymmetric fold that bisects the monument and separates Permian units from younger Triassic strata.

Wupatki National Monument contains one identified stratotype, for the Triassic Wupatki Member of the Moenkopi Formation (Table 10; Figure 138). In addition to the designated stratotype located within WUPA, stratotypes located within 48 km (30 mi) of the monument's boundaries include the Triassic Moenkopi Formation (type section), Jurassic Moenave Formation (type locality) and Dinosaur Canyon Member of the Moenave Formation (type locality), and the Cretaceous Blue Point Tongue of the Toreva Formation (type section).

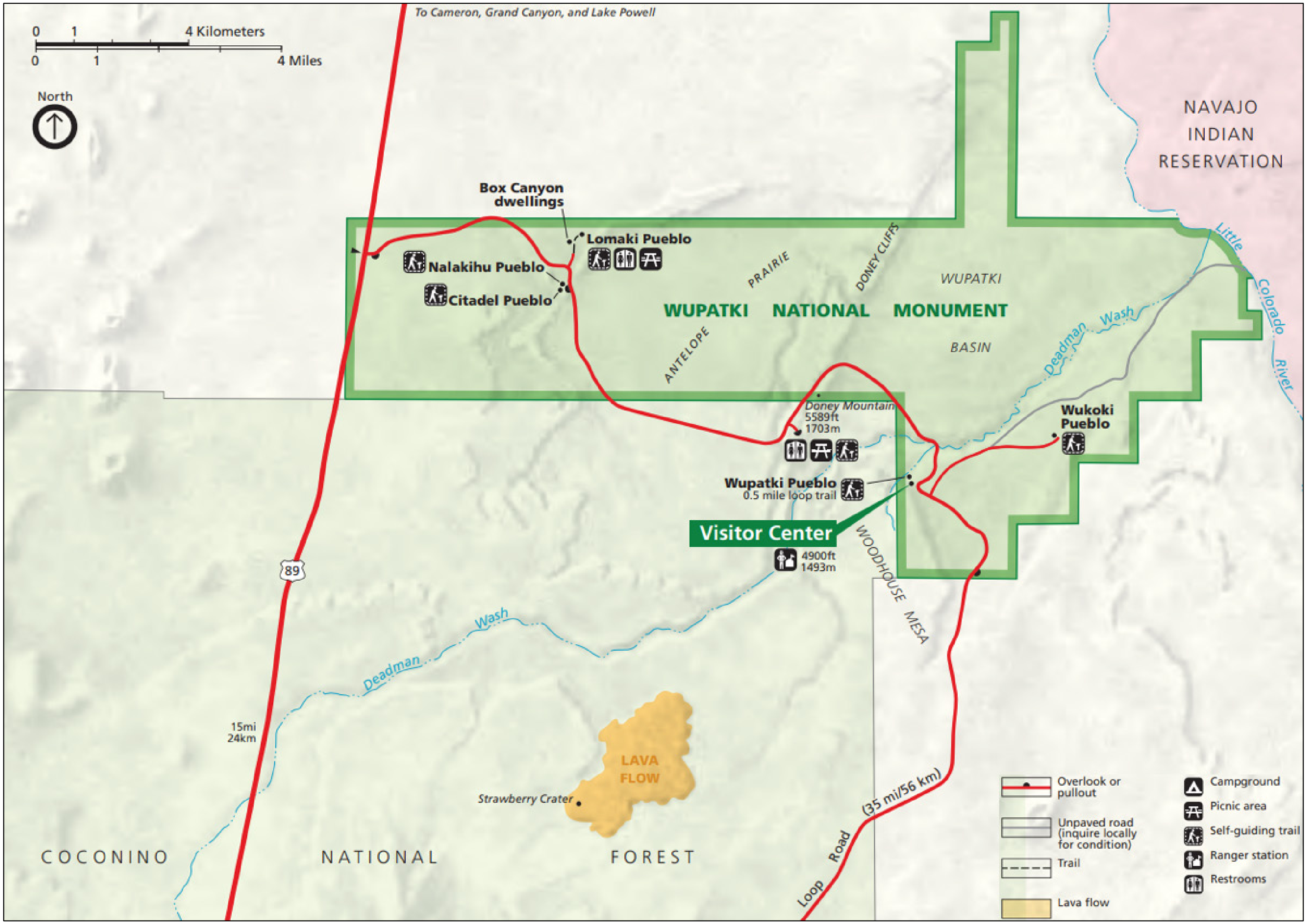


Figure 136. Park map of WUPA, Arizona (NPS).

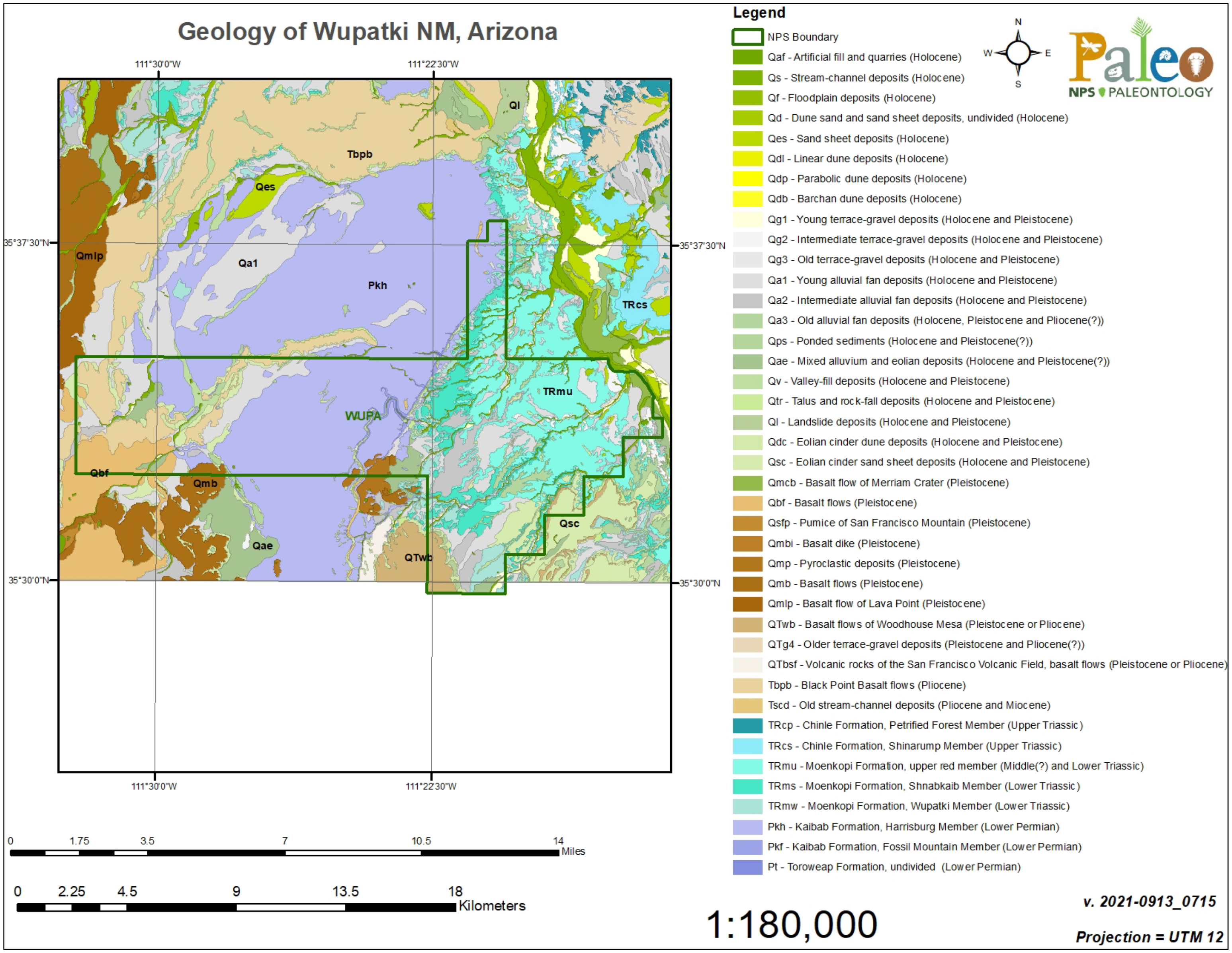


Figure 137. Geologic map of WUPA, Arizona.

Table 10. List of WUPA stratotype units sorted by age with associated reference publications and locations.

Unit Name (map symbol)	Reference	Stratotype Location	Age
Wupatki Member, Moenkopi Formation (TRmw)	Akers et al. 1958	Type area: near Wupatki Pueblo, Coconino Co., AZ.	Early Triassic

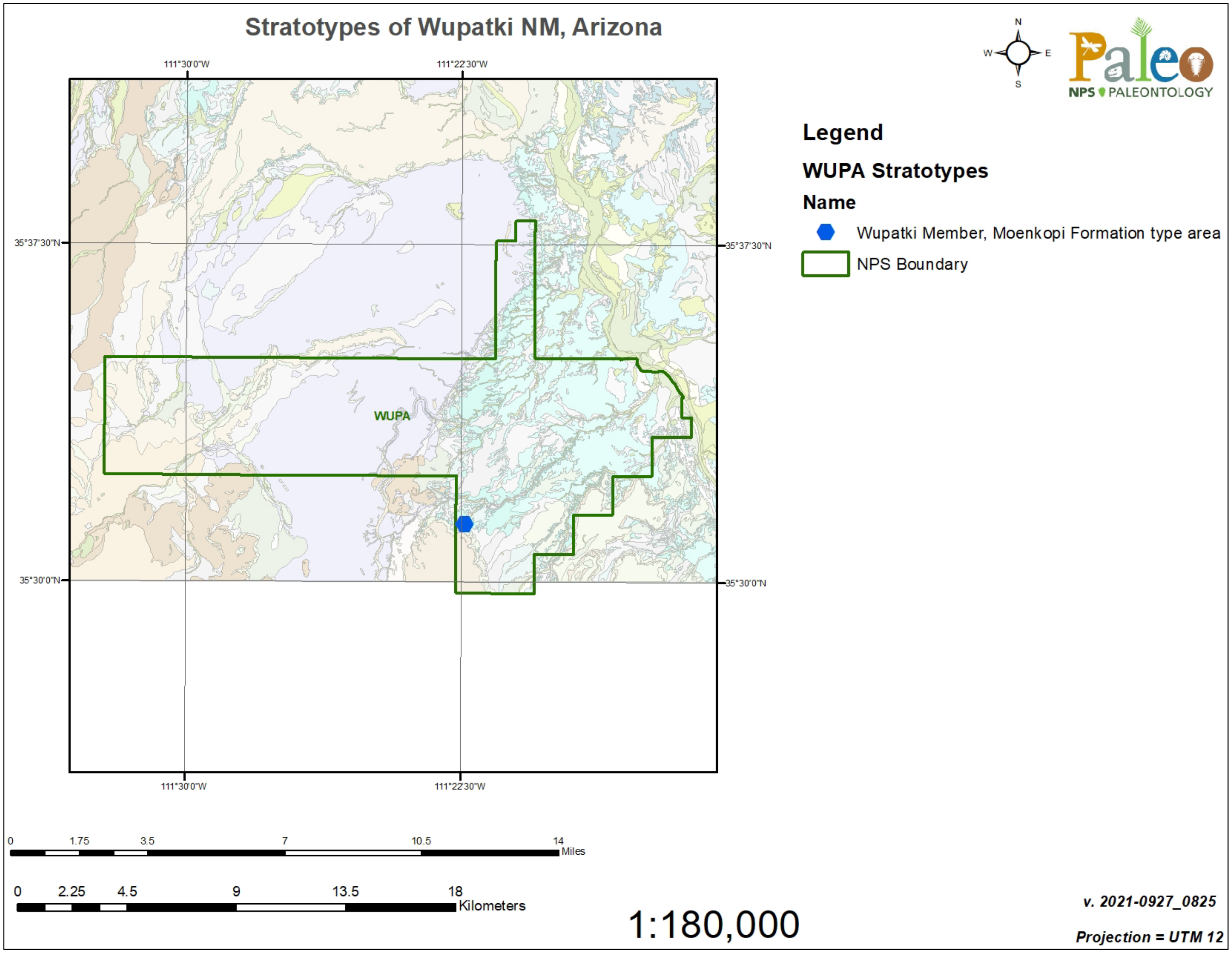


Figure 138. Modified geologic map of WUPA showing stratotype locations. The transparency of the geologic units layer has been increased.

The Triassic Wupatki Member of the Moenkopi Formation was proposed by McKee (1951, 1954) to describe a sequence of red beds in the Winslow–Holbrook area, Arizona. The type area of the unit is located near Wupatki Pueblo, where the member is 29 m (95 ft) thick and composed of slope-forming, reddish-brown siltstone, sandy siltstone, silty sandstone, and an upper unit of fine-grained sandstone (Table 10; Figures 138 and 139; Akers et al. 1958). Common sedimentary structures include ripple marks and salt casts in the silty sandstone beds and trough cross-bedding in the upper sandstone (Akers et al. 1958). The Wupatki Member unconformably overlies the Kaibab Formation and underlies the Moqui Member of the Moenkopi Formation.

Figure 139. Wupatki Pueblo near the type area of the Wupatki Member of the Moenkopi Formation (NPS).

Yucca House National Monument (YUHO)

Yucca House National Monument (YUHO) is situated on the gently sloping eastern flank of Sleeping Ute Mountain, near the margin of the Montezuma Valley west of the Mesa Verde scarp in Montezuma County, southwestern Colorado (Figure 140). Authorized on December 19, 1919, YUHO contains approximately 13 hectares (34 acres) and preserves an unexcavated 13th century Ancestral Pueblo community center that offers opportunities for archeological research and interpretation (National Park Service 2016a). Yucca House is a prehistoric ruin generally referred to as a "valley pueblo", composed of a multi-story masonry pueblo that includes a well-preserved Great House, multiple towers in small plazas, a bi-wall structure, a significant number of kivas, and a ceremonial plaza containing a great kiva, partially enclosed by an imposing wall to the north (National Park Service 2015f). A distinctive mix of architectural features suggest that different groups of American Indians occupied the same site contemporaneously, with an initial occupation ranging from 1050–1150 CE followed by a later occupation from 1225–1300 CE.

The bedrock geology underlying Yucca House National Monument predominantly consists of the Upper Cretaceous Juana Lopez Member of the Mancos Shale (Figure 141). Sediments of the Juana Lopez Member were originally deposited in the Western Interior Seaway as it inundated the Four Corners area. Well-preserved marine fossils such as ammonites, bivalves, and oysters have been reported in the unit and are a testament to marine deposition (Leckie et al. 1997). Local fossiliferous limestone from the Juana Lopez Member provided building stone for ancient structures within the monument (Thornberry-Ehrlich 2013). The southernmost portion of YUHO overlies calcareous shale/mudstone of the Montezuma Valley Member of the Mancos Shale, which shares similar depositional conditions to the Juana Lopez Member.

There are no designated stratotypes identified within the boundaries of YUHO. There are two identified stratotypes located within 48 km (30 mi) of YUHO boundaries, for the Cretaceous Montezuma Valley Member of the Mancos Shale (type section) and Menefee Formation (type locality).

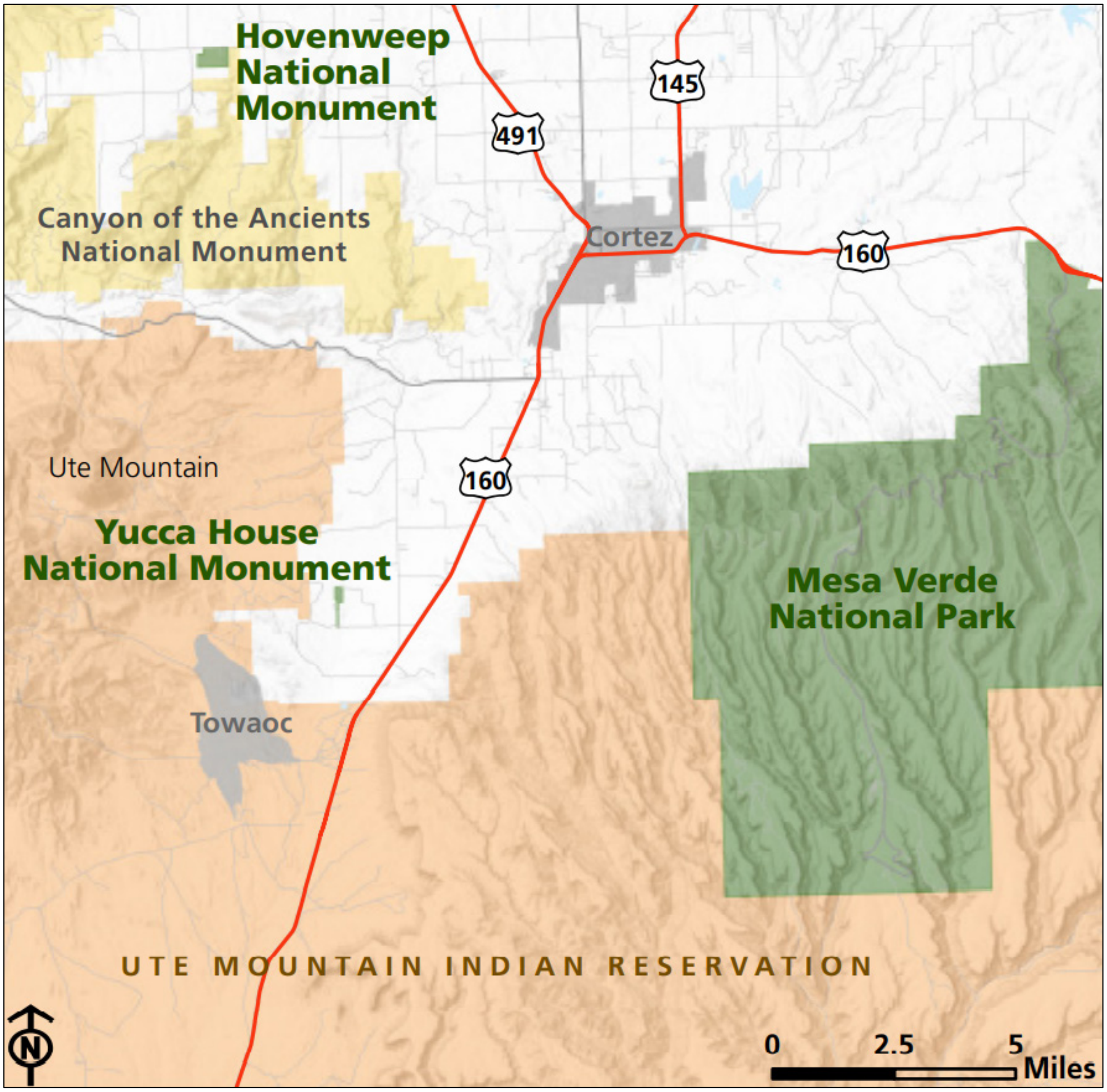


Figure 140. Regional map of YUHO, Colorado (NPS).

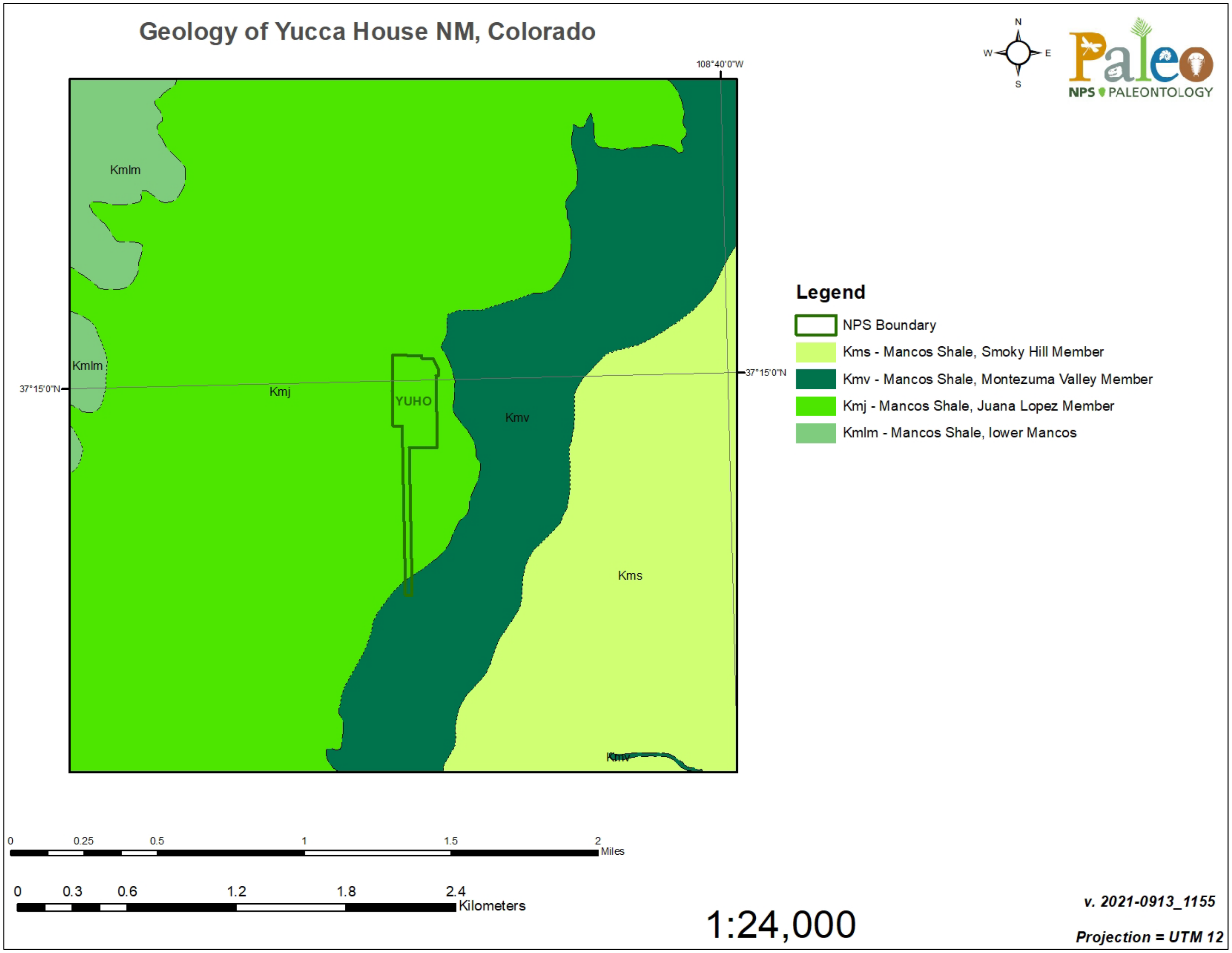


Figure 141. Geologic map of YUHO, Colorado.

Recommendations

1) The NPS Geologic Resources Division should work with park and network staff to increase their awareness and understanding about the scientific, historic and geologic heritage significance of geologic stratotypes (type sections/localities/areas, reference sections, lithodemes). *Stratotypes represent unique geologic exposures and should be considered extremely important to protect for the advancement of the scientific community for future generations.*

2) Once the SCPN Geologic Type Section Inventory report is finalized, the NPS Geologic Resources Division should schedule a briefing for the staff of the SCPN and respective network parks.

3) The Mesoproterozoic Cardenas Basalt of the Unkar Group is named from Cardenas Butte in a westward bend of the Colorado River below the mouth of the Little Colorado River in the Grand Canyon (Keyes 1938). A full sequence of the formation is well exposed at the base of Cardenas Butte. Although the Cardenas is a widely mappable unit throughout GRCA, it currently lacks a formal designated stratotype. It is recommended that a stratotype designation of the unit be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of this unit; and C) help safeguard these exposures.

4) Numerous members of the Cambrian Muav Formation and Bright Angel Formation originally assigned by McKee (1945) are located in GRCA but currently do not have formally designated stratotypes, including 1) Spencer Canyon Member of the Muav Formation; 2) Sanup Plateau Member of the Muav Formation; 3) Rampart Cave Member of the Muav Formation; 4) Parashant Tongue of the Muav Formation; 5) Garnet Canyon Tongue of the Muav Formation; 6) Elves Chasm Tongue of the Muav Formation; 7) Boucher Tongue of the Muav Formation; 8) Flour Sack Member of the Bright Angel Formation; and 9) Tincanebits Tongue of the Bright Angel Formation. It is recommended that stratotype designations of these units be made in order to: A) provide a standard reference for scientific research; B) educate park staff and visitors about the geoheritage significance of these units; and C) help safeguard these exposures.

5) The NPS Geologic Resources Division should work with park and network staff to ensure they are aware of the location of stratotypes in park areas. This information would be important to ensure that proposed park activities or development would not adversely impact the stability and condition of these geologic exposures. Preservation of stratotypes should not limit availability for future scientific research but help safeguard these exposures from infrastructure development.

6) The NPS Geologic Resources Division should work with park and network staff, the U.S. Geological Survey, state geological surveys, academic geologists, and other partners to formally assess potential new stratotypes as to their significance (international, national, or statewide), based on lithology, stratigraphy, fossils or notable features using procedural code outlined by the North American Commission on Stratigraphic Nomenclature.

7) From the assessment in (6), NPS staff should focus on registering new stratotypes at state and local government levels where current legislation allows, followed by a focus on registering at federal and state levels where current legislation allows.

8) The NPS Geologic Resources Division should work with park and network staff to compile and update a central inventory of all designated stratotypes and potential future nominations.

9) The NPS Geologic Resources Division should ensure the park-specific Geologic Type Section Inventory Reports are widely distributed and available online.

10) The NPS Geologic Resources Division should work with park and network staff to regularly monitor geologic type sections to identify any threats or impacts to these geologic heritage features in parks.

11) The NPS Geologic Resources Division should work with park and network staff to obtain good photographs of each geologic type section within the parks. In some cases, where there may be active geologic processes (rock falls, landslides, coastal erosion, etc.), the use of photogrammetry may be considered for monitoring of geologic type sections. GPS locations should also be recorded and kept in a database when the photographs are taken.

12) The NPS Geologic Resources Division should work with park and network staff to consider the collection and curation of geologic samples from type sections within respective NPS areas. Samples collected from type section exposures can be useful as reference specimens to support future studies, especially where stratotypes may be lost through natural processes or human activities.

13) The NPS Geologic Resources Division should work with park and network staff to utilize selected robust internationally and nationally significant type sections as formal teaching/education sites and for geotourism so that the importance of the national- and international-level assets are more widely (and publicly) known, using information boards and walkways.

14) The NPS Geologic Resources Division should work with park and network staff in developing conservation protocols of significant type sections, either by appropriate fencing, walkways, and information boards or other means (e.g., phone apps).

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Appendix A: Source Information for GRI Maps of SCPN Parks

AZRU

- GMAP 115: Ward, A.W. 1990. Geologic map emphasizing the surficial deposits of the Farmington 30′ X 60′ Quadrangle, New Mexico and Colorado. U.S. Geological Survey, Reston, Virginia. Miscellaneous Investigations Series Map I-1978. Scale 1:100,000. Available at: https://ngmdb.usgs.gov/Prodesc/proddesc_10056.htm (accessed January 4, 2022).
- GMAP 41612: Brown, D. R., and W. J. Stone. 1979. Geologic map of Aztec Quadrangle, San Juan County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Hydrogeologic Sheet 1. Scale 1:62500.
- GMAP 41613: Gillam, M. L. 1998. Geomorphic map of the lower Animas River Valley, San Juan County, Colorado (Plate 1b). Unpublished Plate 1b. Scale 1:50,000.
- GMAP 73376: Dames & Moore. 1979. Coal resource occurrence and coal development potential maps of the Flora Vista Quadrangle, San Juan County, New Mexico. U.S. Geological Survey, Washington, D.C. Open-File Report 79-1116. Scale 1:24,000. Available at: https://pubs.er.usgs.gov/publication/ofr791116 (accessed January 4, 2022).
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BAND

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- GMAP 6633: Kempter, K. A., S. Kelley, J. Gardner, S. Reneau, D. Broxton, F. Goff, A. Levine, and C. Lewis. 1998. Geologic map of the Guaje Mountain Quadrangle, Los Alamos and Sandoval Counties, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open-File Geologic Map 55. Scale 1:24,000.
- GMAP 7218: Lynch, S. D., G. A. Smith, and A. J. Kuhle. 2004. Geologic map of the Canada Quadrangle, Sandoval County, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open-File Geologic Map 85. Scale 1:24,000.

- GMAP 7224: Goff, F., J. N. Gardner, and S. L. Reneau. 2002. Geologic map of the Frijoles Quadrangle, Los Alamos and Santa Fe Counties, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. Open-File Geologic Map 42. Scale 1:24,000.
- GMAP 7225: Goff, F., S. L. Reneau, S. Lynch, C. J. Goff, J. N. Gardner, P. Drakos, and D. Katzman. 2005. Geologic map of the Bland Quadrangle, Los Alamos and Sandoval Counties, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open-File Geologic Map 112. Scale 1:24,000.
- GMAP 7226: Goff, F., J. N. Gardner, S. L. Reneau, and C. J. Goff. 2008. Geologic map of the Redondo Peak Quadrangle, Sandoval County, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Open-File Geologic Map 111. Scale 1:24,000.
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- GMAP 75593: Thompson, R. A., M. R. Hudson, R. R. Shroba, S. A. Minor, and D. A. Sawyer. 2011. Geologic map of the Montoso Peak Quadrangle, Santa Fe and Sandoval Counties, New Mexico. U.S. Geological Survey, Reston, Virginia. Scientific Investigations Map 3179. Scale 1:24,000. Available at: https://pubs.usgs.gov/sim/3179/ (accessed January 4, 2022).

CACH

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Appendix B: Geologic Time Scale

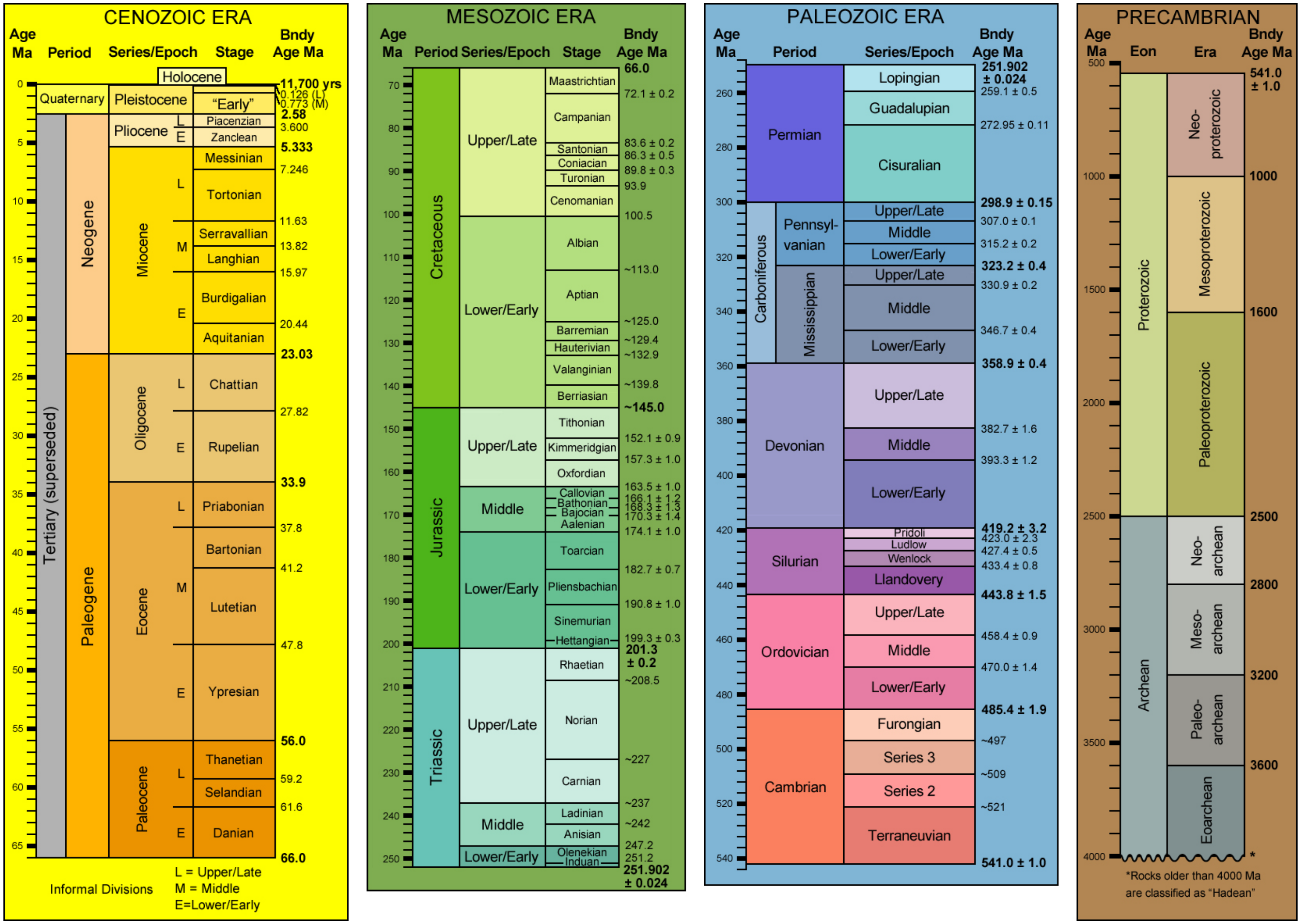

Figure B1. Geologic Time Scale. **Ma**=Millions of years old. **Bndy Age**=Boundary Age. Layout after 1999 Geological Society of America Time Scale (https://www.geosociety.org/documents/gsa/timescale/timescl-1999.pdf). Dates after Gradstein et al. (2020).

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