Prepared in cooperation with the Navajo Nation

Preliminary Bedrock and Surficial Geologic Map of the West Half of the Sanders 30' x 60' Quadrangle, Navajo and Apache Counties, Northern Arizona

By Lee Amoroso, Susan S. Priest, and Margaret Hiza-Redsteer

Digital database by Susan S. Priest

Pamphlet to accompany

Open-File Report 2014-1124

2014

U.S. Department of the Interior
U.S. Geological Survey

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Introduction

The bedrock and surficial geologic map of the west half of the Sanders 30' x 60' quadrangle was completed in a cooperative effort of the U.S. Geological Survey (USGS) and the Navajo Nation to provide regional geologic information for management and planning officials. This report provides baseline geologic information that will be useful in future studies of groundwater and surface water resources, geologic hazards, and the distribution of soils and plants.

Field work on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for, and receive, a permit from the Navajo Nation Minerals Department, P.O, Box 1910, Window Rock, Arizona 86515, (928) 871-6587.

The west half of the Sanders quadrangle encompasses approximately 2,509 km^2 (980 mi^2) within Navajo and Apache Counties of northern Arizona and is bounded by lat 35°30' to 35° N., long 109°30' to 110° W. The majority of the land within the map area lies within the Navajo Nation. South of the Navajo Nation, private and State lands form a checkerboard pattern east and west of Petrified Forest National Park (fig. 1, map sheet 2).

The geologic map of the west half of the Sanders quadrangle was prepared by the USGS Navajo Land Use Planning Project in cooperation with the Navajo Nation and funded through the USGS National Cooperative Geologic Mapping Program to provide connectivity to the regional geologic framework of the Grand Canyon area of northern Arizona. The geologic map will benefit local, state, federal, Navajo, and private land resource managers who direct environmental and land management programs such as range management, biological plant and animal studies, flood control, water resource investigations, and natural hazards associated with sand dune mobility. The geologic information will support ongoing and future geologic investigations and associated scientific studies within the west half of the Sanders quadrangle.

Map Scale

Although the nominal scale of a USGS 30′ x 60′ topographic quadrangle is 1:100,000, we present the bedrock and surficial geologic map of the west half of the Sanders quadrangle at 1:50,000 scale to preserve geologic features that were mapped and compiled at the 1:24,000-scale but are too detailed to show at 1:100,000 scale. For plotting purposes, sheet 1 is the geologic map and sheet 2 contains a List of Map Units, Correlation of Map Units, and an Explanation of Map Symbols. In some areas, the details may be hard to read on plotted maps, but because the map is available digitally, any difficulty in the more detailed areas of the map may be viewed by using the geodatabase or viewing the PDF with magnification. This pamphlet contains a description of map units applicable to map sheet 1.

Geography

The western half of the Sanders quadrangle lies within the southern Colorado Plateau geologic province and contains several physiographic regions: the Hopi Buttes (Tsézhin Bií), Padres Mesa, Petrified Forest National Park, and Chinde Mesa (fig. 1). The ephemeral Puerco River originates within western New Mexico and drains southwest to join the Little Colorado River just east of Holbrook, Arizona, southwest of the map area. The uplands east of the Hopi Buttes are drained by moderate- to large-size washes that empty into the Puerco River and include Pueblo Colorado Wash, Steamboat Wash, Wide Ruins Wash, Digger Wash, Little Lithodendron Wash, Leroux Wash, Sabita Wash, Crazy Creek, Dead Wash and Twin Wash, as well as Black Creek and its tributaries (fig. 1). The northern portion of Wide Ruins Wash lies along a northeasterly strike valley formed along the western flank of the Defiance Uplift. Elevations range from 2,044 m (6,700 ft) on the uplands southwest of Klagetoh to about 1,634 m (5,360 ft) at the Puerco River south-southeast of the Petrified Forest National Park.

Settlements within the west half of the Sanders quadrangle include Klagetoh, Tanner Springs, Wide Ruins, and Navajo (fig. 1). The northern portion of the Petrified Forest National Park is located in the southern part of the map area. Not shown are the small communities of Greasewood Springs about 1.6 km (1 mi) and Ganado about 22.5 km (14 mi) north of the map area (map sheet 1).

Interstate Highway 40 runs diagonally across the south-central part of the quadrangle and provides access to that area of the reservation; State Highway 191 provides access to the eastern part of the map area and Klagetoh north of the map. Navajo Highway 15 crosses the northwestern corner of the quadrangle. Unimproved dirt roads provide access to remote parts of the Navajo Reservation. Some roads are maintained by the Navajo Nation Roads Department in Window Rock, Arizona, while others are locally maintained by Chapter Governments (Indian Wells, Greasewood Springs, Klagetoh, Wide Ruins, and Nahata Dziil Chapters). Four-wheel-drive vehicles are recommended for driving on dirt roads of the Navajo Nation due to mud or snow in the winter months and sandy conditions in the spring and summer. Extra water and food is also highly recommended for travel in this region.

Previous Work

The general geology of the map area was first described by Gregory (1917) and Darton (1925). More detailed investigations started in the middle to late 1950s by McKee (1954); Akers and others (1958); and Cooley (1959). A study of the hydrogeology of the Navajo and Hopi Indian Reservations of Arizona, New Mexico, and Utah from 1946 through the mid-1960s resulted in a geologic map that covers a portion of the Sanders quadrangle (Cooley and others, 1969; map 6 of 9; 1:125,000 scale). This map was not registered to a topographic base map at the time because a base larger than 1:250,000 scale did not exist. Another report from that hydrogeology study described the uppermost Triassic and Jurassic rocks of the Navajo country (Harshbarger and others, 1957). Two regional studies of the Chinle and Moenkopi formations in the Colorado Plateau region cover a portion of the west half of the Sanders quadrangle and were useful in understanding lateral variations in these formations (Repenning and others, 1969; Stewart and others, 1972a,b). More recent mapping and interpretations of the Chinle Formation in the area of Petrified Forest National Park were useful in compiling the bedrock geology (Dubiel, 1989 a,b; Deacon, 1990; Murry, 1990; Ash, 1992; Dubiel, 1994; Lucas and others, 1997; Heckert and Lucas, 2002; Woody, 2006, Martz and Parker, 2010; Trendell and others, 2012). Recent work in Petrified Forest National Park has greatly improved the isotopic age of the Chinle Formation (about 225 Ma at the base of the Petrified Forest Member and the top of the member is younger than ~208 Ma; Riggs and others, 2003; Ramezani and others, 2011).

A master's thesis of the stratigraphy and the correlation and age of the ash beds of the Bidahochi Formation in the Hopi Buttes (Tsézhin Bií) volcanic field and east of the Hopi Buttes was produced by

Dallegge (1999). Ort and others (1998) summarize the sedimentary and volcanic history of the Bidahochi Formation, including several locations in the northwestern half of the map area.

Howell's maps and descriptions of the Cenozoic deposits of the Chetoh Country, Arizona and New Mexico (Howell, 1959), were useful in revealing that not all old fluvial deposits are a part of the Bidahochi Formation and helped to understand the extent of valley-fill deposits west of the Defiance Plateau in the eastern half of the map area.

Structural and tectonic features within the west half of the Sanders quadrangle are described in detailed maps of the Colorado Plateau by Kelley and Clinton (1960). A more detailed description of shallow folds in the Navajo South 1:24,000 quadrangle (Brown and Lauth, 1961) was used in the preparation of this map.

The surficial geology and approximate ages of the deposits were estimated by adapting previous work on soil development in the arid to semiarid southwest. Surficial geologic mapping in the Mojave Desert and on the southwestern portion of the Colorado Plateau (Amoroso and Miller, 2012; Amoroso and others, 2004; Mahan and others, 2006) were used to develop landscape morphology/soil development/age relations for the southern Colorado Plateau. Ellwein's work on eolian and alluvial deposits and other Quaternary landforms in the Petrified Forest National Park (Ellwein, 1997) was used to quantify changes in soil development for deposits of Late Pleistocene and Holocene age in the map area. Additional age control came from age determinations (radiocarbon and uranium-series dating) within and near the map area and are detailed in the unit descriptions. These methods result in classification of surficial deposits based on the spans of time during which the sediments were laid down; that is a geochronologic rather than a chronostratigraphic classification. The deposit age interpretations generally match those used in the Winslow 30' x 60' quadrangle, Arizona (Billingsley, personal commun., 2012), which adjoins the western border of the map area.

Geologic Setting

In the west half of the Sanders quadrangle, Mesozoic bedrock is nearly flat lying except near folds (fig. 1). A shallow Cenozoic erosional basin that developed about 20 Ma in the western part of the map area cut across late Paleozoic and Mesozoic rocks that were subsequently filled with flat-lying Miocene and Pliocene mudstone and argillaceous sandstone and fluvial sediments of the Bidahochi Formation and associated volcanic rocks of the Hopi Buttes volcanic field (Ort and others, 1998; fig. 2, map sheet 2). The Bidahochi rocks are capped by Pliocene(?) and Pleistocene fluvial sediments and Quaternary eolian and alluvial deposits. Erosion along northeast-southwest-oriented drainages have exposed elongated ridges of Bidahochi Formation (Tbu and Tbl) and basin-fill deposits (Qvf) that are exposed through shallow eolian cover of similarly oriented longitudinal dunes (Qdl4). Stokes (1964) concluded that the accumulation of longitudinal sand bodies and the development of confined parallel drainages are simultaneous processes resulting in parallel sets of drainages and ridges oriented along the prevailing southwest wind direction on the southern Colorado Plateau.

General Surficial Geology

Alluvial deposits (Qa1, Qa2, Qa3, Qa4, Qvf, QTa) are common surficial units in the map area. They are composed of materials eroded from nearby hillslopes by mass movement and surface wash or delivered from up-gradient areas by surface water. These deposits are usually composites of several different deposits that cannot be shown at map scale, for example, alluvial deposits with a small amount of eolian cover, two alluvial deposits of different ages, or alluvial deposits that have been incised by small washes.

Stream channel, flood, terrace and wash deposits (Qs, Qf, Qg1, Qg2, Qg3, QTg4) are characterized as fluvial deposits, including terraces and channels that drain the higher terrain and deliver water and sediment to the fluvial system. They are a significant feature of the map area although most are not visible at the map scale.

Valley-axis deposits (Qv2, Qv3) that are produced by a combination of several different geomorphic processes—fluvial, alluvial, and eolian deposition—are found in low-relief areas. Valley-axis deposits are composite units whose features are not easily shown at map scale. Flanking alluvial fan and wash deposits generally grade into valley-axis deposits.

Talus and rockfall deposits (Qtr) and landslide deposits (Ql) are types of mass-movement deposits resulting from physical weathering of steep bedrock exposures. Debris-flow deposits are also included in this category. Many of these deposits, as well as older alluvium (Qa3, Qa4) and colluvium-covered (Qc) slopes, are commonly underlain by or contain laminar-layered impermeable pedogenic carbonates that promote rapid saturation of the material, which enhances mass movement potential (Wells and others, 1982).

Eolian deposits (Qd1, Qd2, Qd3, Qd4, Qdb2, Qdl2, Qdl3, Qdl4, Qdp2 and Qdp4) are the most areally extensive surface deposits in the west half of the Sanders quadrangle. Present-day eolian processes rework the fine-grain fraction of fluvial sediments in washes and redeposit them on nearby terraces and adjacent surficial deposits or bedrock as either dunes, sand sheets, or as mixed eolian-alluvial deposits. The Pleistocene and early Holocene eolian deposits may result from the same geomorphic processes on a longer time scale or other processes, such as enhanced bedrock weathering, that might be responsible for the formation of large sand sheet deposits (Qd4 and Qdl4). Strong winds, capable of sand transport, are common on the southern Colorado Plateau during the passage of weather fronts during the fall, winter, and spring months.

Groundwater springs, in the west half of the Sanders quadrangle, are found where permeable sediments overlie a lower permeability or impermeable substrate, such as eolian sands over Bidahochi Formation claystones or Mesozoic bedrock. Groundwater may also come to the surface via joints and fractures or faults in Mesozoic and Cenozoic bedrock. Inactive groundwater features (Qgw2 and Qgw3) are difficult to identify on aerial photography because of their small size and similar hue to the Bidahochi Formation and other surficial deposits. As a result, the identified springs were found while conducting field work. There are likely other groundwater deposits that were not identified.

Ponded deposits (Qps) form small playas and accumulate in interior drainage depressions where local drainages have deposited fine-grained sediments. Ponded deposits are found mostly within dunes and sand-sheet areas but are also found on younger alluvial deposits.

Paleozoic Rocks

In the eastern quarter of the west half of the Sanders quadrangle (fig. 1), the Defiance Uplift (or Plateau), is a partially-eroded, asymmetrical anticline that exposes the early Permian De Chelly Sandstone and the Organ Rock Formation. In the western part of the map area, the De Chelly Sandstone and underlying Organ Rock Formation may be present in the subsurface but available well data showed that no drilling penetrated to a depth where the formation might be encountered (Jamie Macy, USGS, oral commun., 2011).

Mesozoic Rocks

Headward erosion of the Puerco River and its tributaries has exposed about 548 m (1,800 ft) of Mesozoic sedimentary rock strata in the western and central part of the west half of the Sanders quadrangle (map sheet 1). The Mesozoic rocks are, from oldest to youngest, the Chinle Formation (Upper Triassic), the Moenave Formation (Lower Jurassic), and the Kayenta Formation (Lower Jurassic).

Chinle Formation

The Triassic Chinle Formation forms spectacular vistas in Petrified Forest National Park and other locations in the southern portion of the map area (map sheet 1). Regionally, the Chinle Formation is composed of three formal members: in ascending order, the Shinarump, the Petrified Forest, and the Owl Rock Members (Cooley, 1959; Stewart and others, 1972). Two members are exposed in the map area: the Petrified Forest and the Owl Rock Members. Informally named marker units within the Petrified Forest Member include the Black Forest bed of Billingsley (1985), Flattops sandstone beds of Billingsley (1985), Sonsela sandstone bed of Akers and others (1958), and formal Newspaper Rock Sandstone Bed (Cooley, 1959; Billingsley, 1985). Hereafter these units are referred to by their informal unit names without accompanying citations.

The Petrified Forest Member is the colorful middle part of the Chinle Formation and forms the spectacular reddish-brown and greenish-gray badlands, as seen at the Painted Desert view point northwest of the Painted Desert Visitor Center. Extensive outcrops are found in the southwestern part of the west half of the Sanders quadrangle, and smaller exposures are found along the Puerco River (fig. 1). Akers and others (1958) and Stewart and others (1972a) subdivided the Petrified Forest Member into three parts: upper and lower parts separated by the Sonsela sandstone bed, based on lithologic and color differences. Later authors have proposed subdividing this interval into a Petrified Forest Member above the Sonsela sandstone bed and a lower part renamed the Blue Mesa member (Heckert and Lucas, 2002; Woody, 2006). The boundaries between the three parts of the Petrified Forest Member are variable and gradational throughout the west half of the Sanders quadrangle and are herein mapped as the Petrified Forest Member of the Chinle Formation. Thin to thick, ledge-forming sandstones within the Petrified Forest Member include the Black Forest bed, Flattops sandstone beds, Sonsela sandstone bed (which includes the Flattops sandstone #1 of Breed and Billingsley, 1979; Billingsley, 1985), and the Newspaper Rock Sandstone Bed.

The Owl Rock Member of the Chinle Formation overlies the Petrified Forest Member. The contact between the Owl Rock and Petrified Forest members is highly gradational, both laterally and vertically. The contact is marked at or near the base of the lowest limestone bed of the Owl Rock Member. The Owl Rock Member, exposed only in the west-central part of the map area southeast of Hopi Buttes, forms resistant limestone beds which cap Chinde Mesa northeast of Pilot Rock (fig. 1). The Owl Rock Member consists of a sequence of grayish-brown, light-reddish-brown, and greenish-gray, ledge-forming limestone beds (some rich with nodular chert) interbedded with reddish-purple and pale-reddish-brown, slope-forming calcareous siltstone and sandstone. Previously, the carbonate and underlying claystone have been interpreted to represent cyclic deposition in ephemeral lakes. Recent work has established that many of these carbonate and claystone sequences represent depositional hiatuses and long periods of soil formation (pedogenic carbonates) and groundwater carbonates (Lucas and others, 1997; Heckert and Lucas, 2002; Tanner and Lucas, 2006). At some locations, as many as six limestone beds that form flat ledge outcrops are present within the Owl Rock Member. The contact between the Petrified Forest and Owl Rock members is about 3 m (11 ft) below the base of the lowest limestone bed of the Owl Rock Member.

The contact between the Owl Rock Member and overlying Moenave Formation is unconformable and marked by a sharp contrast in color and lithology between the brown to grayish-brown siltstone of the Owl Rock and the orange-red sandstone of the Moenave. This regional unconformity is known as the J-O unconformity and separates Triassic from the overlying Jurassic rocks of the Glen Canyon Group (Pipiringos and O’Sullivan, 1978).

Moenave Formation

Pale-yellowish-orange, reddish-orange, and orange-pink slope-forming siltstone and sandstone deposits of the Moenave Formation unconformably overlie the Owl Rock Member of the Chinle Formation in the far western portion the west half of the Sanders quadrangle (map sheet 1).

The white-gray and light-red sandstones mapped as the upper sandstone member of the Moenave Formation (Jms) in the Winslow quadrangle do not appear to be present in the map area owing to a facies change to red sandy siltstone (Billingsley, written commun., 2012).

The Moenave Formation commonly weathers as a reddish-orange slope east of Hopi Buttes (map sheet 1). Much of the upper portion of the Moenave Formation has been removed by Tertiary erosion and is unconformably overlain by dark-brown and white mudstone and argillaceous sandstone deposits of the lower Bidahochi Formation.

Kayenta Formation

The reddish-brown and reddish-orange, slope-forming siltstone and reddish-brown and grayish-pink, cliff-forming sandstone sequence of the Kayenta Formation (Jk) unconformably overlies the Moenave Formation. The Kayenta Formation is poorly exposed and mostly covered by various and numerous surficial deposits.

Just north of the map area between Greasewood and Ganado, the Kayenta Formation is considerably thicker than deposits in the map area and is conformably overlain by the Entrada Sandstone. The Kayenta Formation and Entrada Sandstone are unconformably overlain by the Bidahochi Formation (Amoroso and others, 2012). The same Tertiary erosional surface appears to have cut higher into the Mesozoic section north of the map area.

Cenozoic Sedimentary and Volcanic Rocks

The Miocene sedimentary and volcanic rocks of the Hopi Buttes volcanic field and the Pliocene sedimentary rocks found farther east are important because they contain critical landscape information about the early erosional development of this part of the Colorado Plateau.

Remnants of Pliocene(?) Older valley fill (Tvf) found along Wide Ruins Wash (fig. 1) and more extensive Pleistocene deposits (Qvf) lie unconformably on the upper fluvial member of the Bidahochi Formation that marks the end of extensive deposition of fluvial sediments into a shallow Cenozoic erosional basin.

Bidahochi Formation

The Bidahochi Formation was originally defined and separated into three informal members by Repenning and Irwin (1954) and Shoemaker and others (1957, 1962): in descending order, an upper fluvial member, a middle volcanic member, and a lower mudstone and argillaceous sandstone member (Miocene and Pliocene). These subdivisions are based on a reference section at White Cone Peak, a landmark about 6.5 km (4 mi) northeast of White Cone, Arizona, just northwest of the map area. For mapping purposes, the original middle volcanic member has been redefined by Billingsley (written commun., 2012) as the volcanic rocks of the Hopi Buttes volcanic field, based on field observations and recent studies and measured sections published by Dallegge and others (1998, 2001, 2003) and Ort and others (1998).

The upper fluvial member of the Bidahochi Formation (Pliocene) is present from east of Pueblo Colorado Wash to the west and south of the Defiance Plateau (fig. 1 and map sheet 1) and consists of cross-bedded, poorly to moderately cemented, fine- to medium-grained clayey sandstone and siltstone with minor amounts of claystone and volcanic ash (Dallegge, 1999).

The lower mudstone and argillaceous sandstone member is present within the Hopi Buttes area (map sheet 1), and, just to the east and northeast of Hopi Buttes, it unconformably overlies the lower part of the Moenave Formation (Jm) in the northwestern part of the map area. In the subsurface, east of Pueblo Colorado Wash, the lower mudstone and argillaceous sandstone member overlies the Kayenta Formation (Jk) and other erosionally truncated Mesozoic units in the subsurface. The age of the Bidahochi Formation is Miocene and Pliocene (~16 to ~5 Ma) based on vertebrate fossil faunas including amphibians, rodents, camels (Morgan and White, 2005), fossil fish (Spencer and others, 2008), geochronology (Dallegge and others, 2003) and paleomagnetic studies (Lindsey and others, 1984), though there is little age control of the fluvial member.

Several authors hypothesize that a lake of considerable extent may have persisted in the Bidahochi basin for at least a portion of the time during deposition of the Bidahochi Formation (Blackwelder, 1934; Meek and Douglass, 2001; Scarborough, 2001). Fossil evidence suggests that ephemeral lakes or perhaps a vigorous river system may have existed in the Bidahochi basin. Uyeno and Miller (1965) suggest a large, permanent aquatic habitat associated with swift-flowing rivers, based on fossil fish found in the Bidahochi fluvial member deposits (sample sites 5–20 km [3–12 mi] west and northwest of Wood Chop Mesa). Other fish fossils at White Cone Peak, about 10 km (6 mi) north of Wood Chop Mesa, are found in distal fluvial, overbank, or deltaic lacustrine deposits (Spencer and others, 2008). Fish fossils at The Coliseum (20 km [12 mi] southwest of Wood Chop Mesa) are within a white 1-m-thick (3-ft-thick) lacustrine deposit that interfingers with thick volcanic tuffaceous ash and pyroclastic surge and air-fall deposits (Tc). Dallegge and others (2003) presented evidence that no large paleolake occupied the Bidahochi basin. A significant inflow of water would be required to maintain an extensive lake of adequate size and duration to deposit the fine-grained clastics and clays of the lower Bidahochi Formation member. Because the depositional basin persisted for more than 9 Ma, any river would have quickly filled the basin with sediment; the stratigraphic and geochronologic evidence suggest a very low sedimentation rate. Both White (1991) and Vazquez (1998) reported evidence, such as mud cracks beneath the volcanic ash deposits, suggesting that the Hopi Buttes maar eruptions occurred in ephemeral lake or playa settings rather than in an extensive lake (at least in the Hopi Buttes area).

Field observations of the Bidahochi Formation by George Billingsley (U.S. Geological Survey) and Dr. Michael Ort (Northern Arizona University) suggest that the lower and upper Bidahochi Formation is one depositional unit that is correlative across the landscape but is found at different elevations. The lower mudstone and argillaceous sandstone deposits were likely deposited at the same time as the upper fluvial deposits. The upper fluvial deposits contain numerous eolian and fluvial sandstone lenses that were likely deposited upland and downwind of the lower lacustrine playa deposits in the Hopi Buttes area, making both the upper and lower Bidahochi units time equivalent and deposited simultaneously at different elevations. North of White Cone, Arizona, along State Highway 77, the white upper fluvial member of the Bidahochi Formation appears to be interbedded, intertonguing, or locally disconformable within the upper part of the lower green and red mudstone and argillaceous sandstone member with no apparent unconformity between these units and is considered Miocene and Pliocene (Billingsley and others, 2013). If there is an interbedded relation between the lower mudstone and argillaceous sandstone and upper fluvial members to the east in the Sanders quadrangle, the age constraints on the mudstone and argillaceous sandstone member already cited suggest that the fluvial member may also be latest(?) Miocene to Pliocene age.

Volcanic Rocks of the Hopi Buttes

The volcanic rocks of the Hopi Buttes volcanic field were described by Williams (1936) and well documented by White (1991). The original middle volcanic member of the Bidahochi Formation (Repenning and Irwin, 1954; Shoemaker and others, 1957, 1962) was redefined for mapping purposes as the volcanic rocks of the Hopi Buttes volcanic field by Billingsley and others (2013). The volcanic rock types are not mapped in detail, because of multiple intertonguing, cross-cutting, unconformities, and overlapping complexities between eruptional events that distributed a variety of volcanic rock types in different parts of the Hopi Buttes as shown by Vazquez (1998, 1999), Hooten (1999) and Hooten and Ort (2002). This map follows the methodology of Billingsley (written commun., 2012)—the volcanic rocks are subdivided into intrusive dikes, plugs, or necks (Ti), volcanic-crater sediment deposits (Tm), mafic monchiquite and basanite flows (Tm) as defined by Vazquez and Ort (2006) and Vazquez (1998), mafic tuff-and-ash deposits (Tmt), and mixed monchiquite and basanite flows and tuff deposits, undivided (Tmu).

Billingsley and others (2013) believe there is sufficient justification for separating the volcanic rocks from the original middle volcanic member of the Bidahochi Formation: (1) the volcanic and associated volcanic crater sediment rocks can be mapped as separate rock types, (2) the thin deposits of volcanic ash and tuff that separated the original upper and lower Bidahochi Formation at White Cone Peak landmark are absent northeast of the landmark, (3) the volcanic deposits are interbedded within the lower Bidahochi Formation (about 50 m [165 ft] below the top of White Cone landmark) and at several discontinuous horizons, (4) the volcanic rocks either overlie or are adjacent to Triassic, Jurassic, and Cretaceous rocks at different locations throughout the Hopi Buttes, (5) the volcanic rocks are unevenly distributed with variable thicknesses and numerous local unconformities, (6) the volcanic crater sedimentary (Tc) deposits are interbedded with or overlain by other volcanic deposits locally disconnected from Bidahochi sediments at multiple topographic horizons above and below Bidahochi horizons throughout the volcanic field, and (7) the volcanic crater sediments may not be connected to the Bidahochi Formation.

The age of volcanic rocks in the Hopi Buttes volcanic field range between 7.5 to 6.5 Ma (Vazquez, 1998, 1999; Vazquez and Ort, 2006). Vazquez (1999) obtained $^{40}Ar/^{39}Ar$ ages of 7.21±0.45 Ma, 6.99±0.75 Ma, 6.53±0.69 Ma, and 6.81±0.06 Ma from different vents near Wood Chop Mesa in the northeastern part of the Hopi Buttes. Thus, an average age of 7 Ma for the volcanic rocks of the Hopi Buttes in this area is consistent with the underlying lower mudstone and argillaceous sandstone of the Bidahochi Formation at White Cone Peak and Wood Chop Mesa that has a $^{40}Ar/^{39}Ar$ age of 13.71±0.08 Ma (Dallegge and others, 1998).

Surficial Unit Stratigraphic Nomenclature

This report describes the Mesozoic and late Tertiary bedrock and Quaternary surficial deposits of the west half of the Sanders 30’ x 60’ quadrangle. Quaternary map units are defined using surface morphology and landscape position, degree of soil development, and depth of incision (the height of deposit surfaces above active drainages). The distribution of Quaternary deposits on this map is based on a reconnaissance level of mapping, which is primarily based on aerial photograph interpretation; the ages assigned to Quaternary deposits are based on field descriptions and geochronology farther west in the Mojave Desert.

Classification of the Quaternary geologic units and surficial deposits and the ages assigned are based on previous work in the western Mojave Desert (Amoroso and Miller, 2012; Mahan and others, 2006). The relative ages of the units are presented youngest to oldest. For example, a Qx1 deposit is active, a Qx2 deposit is young, a Qx3 deposit is intermediate age, and a Qx4 deposit is old. The 'x' is a placeholder for geomorphic process or landscape position such as 'a' for alluvium, Qae' for mixed alluvial/eolian deposit, ‘g’ for terrace gravel-wash deposit, ’ d’ for eolian (dune) deposit, ‘v’ for valley-axis deposit, and 'gw' for groundwater deposit. Unless observed in the field and specifically mapped, a given age of surficial deposit may be composed of different subunits. For example, alluvial units may have significant contributions from eolian or mass-wasting processes. Mapped surficial geologic units may be a composite of two units: either one unit overlying another or a combination of two different units. The unit is labeled by the most prevalent deposit type.

Active aggradation surfaces (Qx1) have received deposition within the last few decades or centuries. They are characterized by unconsolidated sediment and are prone to flooding and sediment transport. They are typically unvegetated or moderately vegetated and have microtopography, such as prominent gravel bars with intervening swales of fine-grained materials or debris-flow lobes and levees. Active surfaces cover a small area on alluvial fans and usually form discrete channels. Young surfaces (Qx2) are middle and early Holocene to latest Pleistocene age. They are abandoned or receive sediment infrequently. These surfaces are characterized by loose to slightly compacted sediment. Soils are thin with incipient to weak development characterized by a sandy vesicular (Av) horizon over a weak cambic horizon (Bw). Soils with Stage I carbonate morphology are present on the older (Qx2) deposits. Young surfaces are moderately vegetated and show smoother microtopography than active surfaces with low to moderate relief bar and swale. Desert pavement is not present, but the clasts may show some desert varnish and rubification (reddening) on the clast undersides. Intermediate-age surfaces (Qx3) are Middle and Late Pleistocene in age and have been abandoned for tens of years to several hundred thousand years. Sediments are slightly to moderately compact. These surfaces may have moderately to well-developed desert pavement with moderate to strong desert varnish on clasts. The surface microtopography is nearly flat; the original bar and swale form has been eroded. There may be as much as 4 m of erosional incision into these deposits. Moderate to strong pedogenesis has resulted in a silty Av horizon beneath the desert pavement. There is moderate to strong Bt horizon development (enhanced clay content), and the sediment may show from Stage I+ to III+ carbonate morphology (Gile and others, 1981; Machette, 1985). Old surfaces (Qa4) are early and Middle Pleistocene in age and have been abandoned for many hundreds of thousands of years. Erosion has modified the original deposit and soils by removing as much as several meters of sediment to expose the underlying pedogenic carbonate so that the surface has considerable carbonate litter and ballena-form interfluves. There may be as much as 10 m (33 ft) of incision into these deposits. Strong pedogenesis results in Stage III to IV carbonate morphology. Extremely old surfaces (QTx) are early Pleistocene to late Pliocene in age and have been abandoned for many hundreds of thousands of years to a million years or more. Erosion has removed many meters of sediment exposing the pedogenic carbonate. Reworking of the surface deposits and eolian inputs may result in veneers of younger sediments overlying QTx. There may be as much as tens of meters of incision into these deposits. Moderate pedogenesis results in Stage II+ to III+ carbonate morphology. The lesser degree of pedogenesis seen in QTx deposits suggests that some portion of the deposit, including older soil horizons, had been eroded away prior to the formation of the observed soil horizons. Time-dependent processes used to evaluate surficial unit age, such as pedogenesis, desert varnish development, and the vertical separation of different age deposits, were best judged from field relations.

Geologic Hazards

Soil Problems

Expansive soils and collapsible soils cause significant damage to infrastructure and buildings in the southwestern United States. There is a strong relation between geomorphology and surficial deposit characteristics and the engineering properties of soils that can be used to identify potential soil problem locations (Amoroso, 2001). Deposit age, composition, and location can guide planners where the potential for soil problems exist and suggest further geotechnical investigation when designing roads and buildings. Collapsible soils are characterized by a granular, honeycomb structure with small to moderate amounts of silt and clay that collapse when wetted (hydrocompaction). These soils are found in alluvial fans, sand dunes, and volcanic tuff deposits (Barton, 1994; Dudley, 1970; Houston and others, 1988). Holocene deposits in the southwestern United States have distinctive geotechnical properties, because these soils contain minor amounts of clay and calcium carbonate cement that support the granular structure. Researchers have suggested that these deposits are susceptible to collapse upon wetting (Beckwith and Hansen, 1982). The Qx1 and Qx2 deposits, because of their observed composition, may have the potential to be collapsible soils (small amounts of soil carbonate are found in even the young deposits). Expansive soils contain clays that change their volume with water content, which results in differential soil heave (Selby, 1993). This is a common problem in northern Arizona; the shrinking and swelling of montmorillonite clays in the Petrified Forest Member of the Chinle Formation (Stewart and others, 1972a) damages roads and building foundations, where these clay-bearing rocks are near or at the surface. Geotechnical soil testing to see how soils behave under load would be required to identify if soils are susceptible to collapse or expansion (Lutenegger and Saber, 1988; Selby, 1993).

Flooding Potential

The potential exists for sustained rainstorms to flood roads, buildings, and other infrastructure. This geologic map is a guide for planning purposes. Flooding is generally confined to stream channels (Qs) and adjacent flood plains (Qf), as well as smaller active washes. Flotsam observed on older terraces (Qg1 and Qg2) suggest that these may be inundated during larger flood events. The lack of flotsam or other geomorphic indicators of flooding on Qg3 terraces that were examined may suggest that these surfaces have a low potential for flooding. Further, detailed studies would be needed to determine the flooding potential of land near drainages.

Vegetation

The major plant species, typically found on surficial deposits in the west half of the Sanders quadrangle, are listed in the description of map units; the list is not all-inclusive. Some plants are indirect indicators of deposit age, parent material, or geomorphic process. Soil properties control the distribution and vigor of plants. For example, a high clay and silt content of thicker Av horizons results in low infiltration of precipitation, which restricts vegetation; shallow carbonate horizons are impermeable causing periodic high-water saturation in the shallow subsurface that is not tolerated by some plants; or high salt content of playas may restrict plants to salt-tolerant species. The swelling clays of the Petrified Forest Member of the Chinle Formation and in the Bidahochi Formation make it difficult for plants to germinate. The usage of common and scientific names follows Epple (1995). The Thomas and others (2009) report on plants found in Petrified Forest National Park was useful to check plant distributions on different surficial deposits.

Descriptions of Rocks, Sediments, and Soils

Surficial unit descriptions in the pamphlet are formatted as follows: (1) grain size, sorting, rounding, and composition; (2) sedimentary structures and degree of consolidation; (3) surface morphology; (4) soil development; (5) inset relations and landscape position; (6) common vegetation; (7) human implications and impacts; and (8) diagnostic features. The primary surficial deposit categories are grouped by depositional process with the units listed from youngest to oldest.

Bedrock map units are described by color, internal organization and structure (bedding, laminations, ripple marks), cementation, contacts, and the presence of other features, such as mottling, distinctive gravels, petrified wood, and the thickness of the unit.

Soil colors were described using Munsell Soil Color Charts (Munsell, 2000) and colors are for dry samples. Rock colors were described using the Rock Color Chart (Goddard and others, 1980). The rock colors indicated are for a weathered surface unless otherwise noted. The descriptions of soil carbonate morphology follows Gile and others (1981) and Machette (1985). General soil properties were described using Schoeneberger and others (2002).

DESCRIPTION OF MAP UNITS

SURFICIAL UNITS

Surficial units are alluvial, eolian, fluvial, and groundwater deposits that unconformably overlie the Mesozoic and Cenozoic bedrock units.

ANTHROPOGENIC DEPOSITS

Qaf **Anthropomorphic features or other land disturbances (latest Holocene)—**Surficial material moved for mining, construction, and agriculture that is extensively disturbed, making landforms and deposits difficult to classify. On this map, the majority of small Qaf features are dams, stock tanks, and ponds

ALLUVIAL DEPOSITS

Qa1 **Active alluvial fan deposits (latest Holocene)—**Moderately to poorly sorted sand, gravel, and pebble clasts to 30 cm in diameter with no soil development. Alluvium has coarser texture near hillslopes or reworked from older coarse-grained deposit; average grain size decreases downslope. Alluvium is poorly to moderately bedded and loose; channel bars of sand and gravel are as high as 50 cm. Qa1 deposits lie 10–30 cm above or grade to active channels with few vertical cutbanks and may be inset into unit Qa2. Unit is sparsely to well vegetated with various perennial shrubs, such as rubber rabbitbrush (Ericameria nauseosa), sand sagebrush (Artemisia filifolia), galleta grass (Pleuraphis jamesii), alkali sacaton grass (Sporobolus airoides), and in some places invasive Russian thistle (Salsola tragus). Alluvial fan deposits characterized by surfaces that are active and have received deposits within the last few decades. Prone to inundation and flooding during and after heavy rains. Diagnostic features: actively aggrading, geomorphic features grading to, or adjacent to, an active wash or stream-channel (Qs)

Qa2 **Young alluvial fan deposits (middle and early Holocene)—**Moderately to poorly sorted sand, silt, gravel, and clasts to 50 cm in diameter. Bar and swale micro-topography averages 20 cm in height (and as much as a maximum of 30 cm) and decreases down fan. Surfaces lie 10–90 cm above active channels and may be inset into unit Qa3. These deposits show little or no soil development; older deposits may show development of a weak cambic horizon (slightly redder hue than underlying sediment) or disseminated filamentous or pinpoint calcium carbonate. Unit is sparsely vegetated with various perennial shrubs, such as rubber rabbitbrush (Ericameria nauseosa), sand sagebrush (Artemisia filifolia) galleta grass (Pleuraphis jamesii), alkali sacaton grass (Sporobolus airoides), and in some places invasive Russian thistle (Salsola tragus). Surface may be flooded during and after heavy rains. Active on a centennial time scale. Diagnostic features: alluvial fans formed downslope of drainage basins. Include terraces along younger to active channels too small to show at map scale. No pavement or desert varnish development

Qa3 **Intermediate-age alluvial fan deposits (early Holocene and Late Pleistocene)—**Moderately to poorly sorted sand, silt, and clay with gravel and clasts to 60 cm in diameter. Poorly bedded to massive, weakly to moderately consolidated. Surface may have slight to well-developed desert pavements, scattered to widespread pedogenic carbonate debris, or may exhibit a polygonal pattern that is the result of shrink-swell fissures developed in an exposed Av horizon. Bar and swale micro-topography is subdued to 10 cm in height, though the surface is generally flat and incised by shallow to moderate channels. Surfaces are an average of 250 cm above active channels and may be inset into unit Qa4 or older units. Where incised, most deposits will preserve a vertical or near vertical scarp or exposure. These deposits show moderate to strong soil development, well-developed platy to blocky Av horizons as much as 7 cm thick and moderate cambic B horizon development (7.5 to 5YR hue) with platy to blocky peds as much as 4 cm and Stage I+ carbonate development. Older Qa3 deposits have argillic Bt (to 2.5YR hue) with angular, prismatic peds or may have carbonate litter from exhumed calcic horizons. Some mid- to Late Pleistocene soils have Stage II to III+ pedogenic carbonate morphology (Machette, 1985). Unit is moderately vegetated with perennial shrubs including rubber rabbitbrush (*Ericameria nauseosa*), Four-wing Saltbush (*Atriplex canescens*), mound saltbush (Atriplex obovata), galleta grass (*Pleuraphis jamesii*), and alkali sacaton grass (*Sporobolus airoides*) along with other annuals and grasses. Both one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) are found in the upland areas. Surface is rarely flooded. Diagnostic features: old alluvial fans generally confined to the hillside or as veneers of reworked alluvium derived from older deposits, flat surfaces with moderate to strong pavement development and well-developed desert varnish

Qa4 **Old alluvial fan deposits (Late and middle Pleistocene)—**Moderately to poorly sorted sand, gravel, and clasts to 60 cm in diameter. Deposits are characterized by deeply incised or heavily carbonate-cemented fan. Many surfaces have been stripped down to the well-indurated soil carbonate or are littered with carbonate debris; eroded interfluves form ballenas with little or no carbonate debris. Poorly bedded to massive, well consolidated. Qa4 surfaces are found an average of 9 m above active channels and may be inset into late Tertiary units. Where incised, most deposits will preserve a vertical or near vertical scarp or exposure. These deposits show strong soil development. Qa4 deposits have Stage IV and Stage V carbonate morphology but the soil horizons are generally eroded (Machette, 1985). Younger deposits that overlie Qa4 and contain an Av horizon and cambic B horizon may be developed on the eroded or reworked Qa4 deposit. Unit is moderately vegetated with perennial shrubs including rubber rabbitbrush (*Ericameria nauseosa*), sand sagebrush (*Artemisia filifolia*), Four-wing Saltbush (*Atriplex canescens*), mound saltbush (*Atriplex obovata*), galleta grass (*Pleuraphis jamesii*), and alkali sacaton grass (*Sporobolus airoides*) along with other annuals and grasses. Both one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) are found in the upland areas. Surface is rarely flooded. Diagnostic features: degraded alluvial fans generally confined to the upper piedmont. Stage IV to V pedogenic carbonate may be exposed at the surface

Qvf **Younger valley-fill deposits (middle and early Pleistocene?)—**Light-brown, fine- to medium-grained sands with minor amounts of coarse-grained sand, pebbles of quartzite and chert, and cobbles of Mesozoic bedrock. Locally, deposits of sub-rounded to angular clasts of sandstone are found in planar beds and channels eroded into the upper portions of the deposit. Appears as a light-hued scarp or ridge crest over the more muted light-brown hue of the upper Bidahochi Formation fluvial deposits (Tbu). Distinguished from fluvial Tbu deposits by the presence of Stage II to III+ pedogenic carbonate development. Easily discerned from the underlying variegated Chinle Formation deposits. Qvf lies on the moderately to deeply eroded upper Bidahochi Formation just west of Wide Ruins wash and on the lower Chinle Formation farther to the west. Well exposed along Highway 191 north from Chambers to Klagetoh (fig. 1). Qvf is moderately eroded and is more deeply eroded near the active drainage network; this is evident where the pedogenic horizons are partially removed or absent. In places, Qvf is overlain by Qd4 and (or) Qdl4, which means it is likely older than ~200 ka. May be related to QTa or possibly younger. Unit derived from erosion of the exposed bedrock of the Defiance Plateau (primarily the De Chelly Sandstone) and sediments were deposited on a land surface tens of meters above the modern drainage network as valley-fill deposits or perhaps pediment fans on the western flank of the Defiance Plateau. Diagnostic features: light-hued fluvial deposit with soil development found only on mesa and ridge tops near the Defiance Plateau

QTa **Extremely old alluvial deposits (early Pleistocene and late Pliocene)—**Moderately to poorly sorted sand, gravel, and cobbles that include ubiquitous reworked Shinarump Member and Chinle Formation gravels, and clasts as much as 30 cm in diameter derived from Mesozoic bedrock highlands to the northeast. Thin to thick bedded, with low-angle cross-beds, to massive, slightly to well consolidated. In many places these deposits cap the high interfluves created by the present drainage system and unconformably overly the Petrified Forest Member of the Chinle Formation in the southwestern part of the quadrangle. The deposit is obscured by eolian deposits in most areas. On the west side of Padres Mesa, QTa overlies both the Petrified Forest Member and the lower and upper parts of the Bidahochi Formation (Tbl and Tbu). The paleo-drainage system may have been abandoned for many hundreds of thousands of years to perhaps several million years. Evidence of soil development is not always preserved. There are QTa deposits, capped by Qdl4, north and west of Twin Wash in the southwestern part of the quadrangle that preserve Stage III+ carbonate morphology (Machette, 1985) including rhyzoliths as much as 40 cm long. North of I-40 and east of Dead Wash (fig. 1, southwestern corner of the map area) QTa contains clasts with remnants of partial to complete pedogenic coatings, implying at least Stage III carbonate morphology. This suggests that, in other places where QTa is exposed, the upper portion of the original deposit, including soil horizons, has been eroded or reworked. Surfaces range from ballena remnants to planar landforms as much as 20 m above the modern drainages. There are sedimentological, geomorphic, and pedogenic similarities between QTa and Qvf lateral continuity or interfingering was not found. Commonly covered with galleta grass (*Pleuraphis jamesii*) and alkali sacaton grass (*Sporobolus airoides*), as well as sagebrush (*Artemisia bigelovii, A. tridentata*), mound saltbush (*Atriplex obovata*), and some Four-wing Saltbush (*Atriplex canescens*). Widely-spaced one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) are found in the upland areas. Diagnostic features: degraded, dissected remnants of abandoned surfaces found well above modern drainages

VALLEY-AXIS DEPOSITS

Qv2 **Older young valley-axis deposits (middle and early Holocene)—**Fine to coarse sand and small gravels. These deposits grade into the distal portions of Qa2 fans and mixed alluvial/eolian deposits (Qae2). Degree of soil development is similar to Qa2. Prone to flooding after heavy rains. Found in broad, low-relief valley-axis locations characterized by anastomosing ephemeral washes, low-relief interfluves, and widely distributed eolian deposits (primarily sheet sand deposits). Many areas modified by agricultural activities. Slightly to moderately vegetated with black greasewood (*Sarcobatus vermiculatus*), rubber rabbitbrush (*Ericameria nauseosa*), and one of several saltbush species (*Atriplex spp.*) and invasive Russian thistle (*Salsola tragus*). Annuals and several species of grasses. Diagnostic features: found between uplands, prone to flooding after heavy rains

Qv3 **Intermediate-age valley-axis deposits (early Holocene and Late Pleistocene)—**Fine to coarse sand, small gravels, and cobbles. These deposits are found along valley axis locations characterized by abandoned anastomosing washes and moderate-relief interfluves. These deposits grade into the distal portions of Qa3 fans. Degree of soil formation is similar to Qa3 and may show Stage II to III carbonate morphology (Machette, 1985). Younger eolian deposits (primarily sheet sands) may overlie these deposits. Desert pavement may be developed on the interfluves. Rarely flooded, incised by active washes as much as 200 cm deep. Many areas modified by agricultural activities. Thinly vegetated with black greasewood (*Sarcobatus vermiculatus*), rubber rabbitbrush (*Ericameria nauseosa*), and one of several saltbush species (*Atriplex spp.*) and invasive Russian thistle (*Salsola tragus*). Annuals and several species of grasses. Diagnostic features: found adjacent to distal alluvial fan deposits, may be flooded after heavy rains

STREAM CHANNEL, FLOOD, TERRACE, AND WASH DEPOSITS

Qs **Stream-channel deposits (latest Holocene)—**Light brown, light-reddish-brown, and off-white sands, silts, and minor amounts of clay. Cobbles of locally derived rock fragments as much as 30 cm diameter and pebbles of bedrock, chert, and quartzite pebbles. Grades into adjacent Qf deposits or may include Qf deposits where map scale cannot show detail. No soil development. Generally not vegetated except for islands and some channel margins. Commonly seen are salt cedar (*Tamarix ramosissima*), coyote willow (*Salix exigua*), and Fremont Cottonwood (*Populus fremontii*) along the lower reaches of larger washes and the Puerco River. Diagnostic features: elongate, active channels that generally increase in width down-channel

Qf **Flood-plain deposits (latest Holocene)—**Reddish-brown, brown, and light-brown silt, clay, and fine- to medium-grained sands with minor amounts of gravel and cobbles. This is the floodplain of the active (Qs) channels. Mapping of smaller Qf deposits may include Qs deposits. Floods on a 1–10-year average. None to little soil development (weak cambic). Vegetated with salt cedar (*Tamarix ramosissima*), rubber rabbitbrush (*Ericameria nauseosa*), and Fremont Cottonwood (*Populus fremontii*) and in some places invasive Russian thistle (*Salsola tragus*). Diagnostic features: elongate, terraces that parallel active channels, generally increase in width down channel

Qg1 **Young terrace-wash deposits (late Holocene)—**Moderately to poorly sorted sand, sandy gravel, and clasts as much as 105 cm in diameter, depending on gradient and size of the drainage basin. Coarser-grained deposits are found near steep terrain or where washes cross boulder- to cobble-bearing parent materials; poorly to moderately bedded and loose. Alluvial terrace/wash deposits characterized by surfaces and channels that are active and have received deposits within the last few decades. May include stream channel and floodplain deposits where these features are too small to present at the mapping scale. May be overlain by eolian deposits, found along larger washes and drainages. Channel bars as much as 40 cm in height. Smaller alluvial wash tracts are generally included in young alluvial fan deposits unit (Qa1). The age of these deposits range from recent to approximately 200 years old. This deposit shows very little to no soil development. Unit may be moderately vegetated with rubber rabbitbrush (*Ericameria nauseosa*), greasewood (*Sarcobatus vermiculatus*), desert sumac (*Rhus microphylla*), and several species of saltbush (*Atriplex canescens, A. confertifolia, A. obovata*), as well as annuals. Salt cedar (*Tamarix ramosissima*) is found along the lower reaches of major washes. Prone to channelized flow and flooding during and after heavy rains. Diagnostic features: narrow, elongate channels and terraces that parallel modern washes, generally increase in width down channel

Qg2 **Older young terrace-wash deposits (middle and early Holocene)—**Moderately sorted to poorly sorted sand and silt, sandy gravel, and clasts as much as 30 cm in diameter. Deposits are coarser grained near steep terrain or in washes where they cross boulder- to cobble-bearing parent materials. Poorly to moderately bedded, loose to poorly consolidated, deposits may be as much as 200 cm above active channel and may contain channel bars as much as 30–40 cm in height. Strath terraces, such as those cut into the Moenave Formation near Wood Chop Mesa, are included in this classification. Smaller alluvial wash tracts that cannot be shown at map scale are generally included with younger alluvial fan deposits (Qa1 and Qa2). Younger deposits show slight soil development (typically development of a redder hue); older deposits may show some Av development including polygonal surface features. The B horizon shows a redder hue than the parent material and may show some clay/silt accumulation and filamentous or blebs of soil carbonate; to Stage I+ carbonate morphology (Machette, 1985). The age of these deposits are estimated to be greater than 200 years to approximately 4 ka. The younger age is based on optically stimulated luminescence (OSL) dating of a young eolian dune near Two Mill Tank (fig. 1, west-central part of the map area; 270±90 years, T. Rittenour, oral commun., 2009) overlying a Qg2 terrace and ^{14}C dating of charcoal in a Qg2 terrace deposit in the nearby Winslow 30' x 60' quadrangle yielding a calendric age of 739±39 yr B.P. (J. McGeehin, oral commun.,2009). Unit sparsely to moderately vegetated with black greasewood (*Sarcobatus vermiculatus*), rubber rabbitbrush (*Ericameria nauseosa*), and one of several saltbush species (*Atriplex spp.*), as well as annuals. Prone to channelized flow and flooding during and after heavy rains. Active on a centennial time scale based on burial or erosion of late 19th and early 20th century trails and structures. Diagnostic features: narrow, elongate geomorphic features that generally parallel active washes, generally increase in width down channel

Qg3 **Intermediate-age terrace-wash deposits (early Holocene and latest Pleistocene)—** Moderately to poorly sorted sand and silt, sandy gravel, and clasts as much as 20 cm in diameter, primarily as terrace deposits along and above Qg1 and Qg2 washes and as discontinuous wash remnants. Strath terraces cut into indurated deposits or bedrock, such as terraces along the Puerco River cut into the Chinle Formation (Ŧcp and Ŧcs), are included in this unit. Deposits are coarser grained near steeper terrain and may be 3–5 m above the active channel along washes. These deposits may be as much as 5–7 m above the active channel of the Puerco River (fig. 1). Poorly to moderately bedded, poorly to moderately consolidated. Channel bars as much as 30 cm in height. Younger deposits show no soil development (similar to Qa2), older deposits may show Av horizons as much as 3 cm thick and weak to moderate B horizon development and as much as Stage II+ soil carbonate morphology similar to Qa3 (Machette, 1985). Unit sparsely to moderately vegetated with black greasewood (*Sarcobatus vermiculatus*), rubber rabbitbrush (*Ericameria nauseosa*), and one of several saltbush species (*Atriplex spp.*). Prone to channelized flow and flooding during and after heavy rains. Diagnostic features: narrow, elongate geomorphic remnant feature (that may be discontinuous) along larger washes and the Puerco River

QTg4 **Extremely old terrace-gravel deposits (early Pleistocene and Pliocene)—**Parent material is moderately to poorly sorted sand and silt, sandy gravel, and clasts exposed along high terraces adjacent to major washes. Clasts are primarily Mesozoic sandstones and highly resistant quartzites and cherts, probably recycled Shinarump Member of the Chinle Formation conglomerates. Discontinuous exposures occur along Pueblo Colorado and Steamboat Washes. Deposits appear white to light gray in aerial photographs. The deposits are pedogenic carbonate rich (carbonate morphology Stage III+) to a depth of more than 150 cm; clasts are uniformly coated with pedogenic carbonate. Carbonate horizons are at the surface suggesting some erosion of overlying soil horizons and may explain the lack of laminar horizons expected for these deposits. These deposits are found 25 to 28 m (82 to 92 ft) above the modern stream channel. Diagnostic features: discontinuous fluvial sand, gravel, and cobble deposits tens of meters above the modern channel

EOLIAN DEPOSITS

Qd1 **Young eolian deposits (late Holocene)—**Moderately sorted to well-sorted, very fine to fine sand and silt; sediments are unconsolidated. Active eolian sand dune and sheet deposits that show evidence of recent movement; may be as much as 2.5 m thick. These deposits do not have significant vegetative cover and can migrate during winter and spring wind storms, filling washes and rendering roads impassable. Little or no soil development other than they may show significant soil carbonate accumulation downwind of drainages. An OSL sample collected from a dune overlying a Qg2 terrace near Two Mill Tank (fig. 1, west-central part of the map area) yielded an age of 270±90 years (T. Rittenour, oral commun., 2009). This dune had a horizon weakly cemented with calcium carbonate at 65 cm from the surface. Young eolian deposits are vegetated with rubber rabbitbrush (*Ericameria nauseosa*), joint fir-Mormon tea (*Ephedra sp.*), and one of several saltbush species (*Atriplex spp.*). There are several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: eolian deposits on Qg1 and Qg2 terraces and burial of older deposits

Qdp1 **Young parabolic dune deposits (late Holocene)—**Moderately sorted to well-sorted, very fine to fine sand and silt. Sediments are unconsolidated. Active eolian parabolic sand dune deposits with evidence of recent migration. Dunes form as the underlying eolian deposit is eroded. May be vegetated with rubber rabbitbrush (*Ericameria nauseosa*), joint fir-Mormon tea (*Ephedra sp.*), and one of several saltbush species (*Atriplex spp.*). There are several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: eolian deposits having an elongated U shape with the arms pointing upwind (to the southwest)

Qd2 **Older young eolian deposits (middle and early Holocene)—**Moderately sorted to well-sorted sand and silt; sediments are unconsolidated. Inactive eolian sand deposits. Little or no soil development but may show significant soil carbonate accumulation downwind of dry lakes and large washes. Vegetated with rubber rabbitbrush (*Ericameria nauseosa*), saltbush (*Atriplex canescens.*), mound saltbush (*Atriplex obovata*), and joint fir-Mormon tea (*Ephedra sp.*). There are several grass species:

galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: eolian deposits on Qg2 terraces and burial of older deposits

Qdb2 **Older young barchan dune deposits (middle and early Holocene)—**Moderately sorted to well-sorted, fine to very fine sand and silt; sediments are unconsolidated. Generally inactive eolian barchan dune deposits. Deposited downwind of large washes. Little or no soil development but may show significant soil carbonate accumulation downwind of dry lakes and large washes. Sparsely vegetated with rubber rabbitbrush (*Ericameria nauseosa*), saltbush (*Atriplex canescens.*), and joint fir-Mormon tea (*Ephedra sp.*). There are several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: dunes whose arms point upwind (to the southwest)

Qdl2 **Older young linear dune deposits (middle and early Holocene)—**Moderately sorted to well-sorted, fine to very fine sand and silt; sediments are unconsolidated. Derived from erosion and reworking of Qd4 and Qdl4 deposits. Generally inactive eolian linear dune deposits. Little or no soil development but may show significant soil carbonate accumulation downwind of dry lakes and large washes. Vegetated with rubber rabbitbrush (*Ericameria nauseosa*), saltbush (*Atriplex canescens*), and joint fir-Mormon tea (*Ephedra sp.*). There are several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: linear eolian deposits on Qg2 terraces and burial of bedrock and older surficial deposits

Qdp2 **Older young parabolic dune deposits (middle and early Holocene)—**Moderately sorted to well-sorted sand and silt; sediments are unconsolidated. Inactive eolian sand deposits. Dunes form from reworking of underlying eolian deposit. Little or no soil development but may show significant soil carbonate accumulation downwind of dry lakes and large washes. Vegetated with rubber rabbitbrush (*Ericameria nauseosa*), saltbush (*Atriplex canescens.*), and joint fir-Mormon tea (*Ephedra sp.*). There are several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: eolian deposits having an elongated U shape with the arms pointing upwind (to the southwest)

Qd3 **Intermediate-age eolian deposits (early Holocene and latest Pleistocene)—**Moderately sorted to well-sorted, fine-grained to very fine grained sand and silt. Inactive eolian sand sheet and dune deposits. Some soil development with soil carbonate as filaments and blebs and as much as Stage I+ carbonate morphology (Machette, 1985). Some pedogenic clay accumulation (Bt) is light reddish yellow (Munsell soil color 5YR 6/8 to 7.5YR 7/6); blocky to sub-blocky peds show firm to very firm consistency. Vegetated with rubber rabbitbrush (*Ericameria nauseosa*), joint fir-Mormon tea (*Ephedra sp.*), mound saltbush (Atriplex obovata), and one of several saltbush species (*Atriplex spp.*). There were several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: eolian deposits on bedrock and burial of older surficial deposits

Qdl3 **Intermediate-age linear dune deposits (early Holocene and latest Pleistocene)—**Moderately sorted to well-sorted, fine to very fine sand and silt. Generally inactive eolian linear dune deposits. Loose to slightly consolidated. Minor soil development with soil carbonate as filaments and blebs and as much as Stage I+ carbonate morphology (Machette, 1985). Some light-reddish-yellow (Munsell soil color 5YR 6/8 to 7.5YR 7/6) pedogenic clay accumulation; blocky to sub-blocky peds show firm to very firm consistency. Vegetated with rubber rabbitbrush (*Ericameria nauseosa*), joint fir-Mormon tea (*Ephedra sp.*), and one of several saltbush species (*Atriplex spp.*). There were several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua spp*.). Diagnostic features: linear eolian deposits on Qg3 terraces and burial of bedrock and older surficial deposits

Qdp4 **Old parabolic dune deposits (Late Pleistocene)—**Moderately sorted to well-sorted sand and silt. Inactive eolian sand dune deposits. Parabolic dunes formed from partially eroded Qd4 and Qdl4 deposits; further erosion may have eroded one of the parabolic arms. Slightly to moderately consistent. Deposits show moderate to strong soil development, including argillaceous (Bt, Btk) and Stage II and III soil carbonate morphology (Bwk and Bk) as seen in Qa4, Qd4, and Qdl4 deposits (Machette, 1985). Commonly covered with galleta grass (*Pleuraphis jamesii*), blue grama grass (*Bouteloua gracilis*), and alkali sacaton grass (*Sporobolus airoides*), as well as sagebrush (*Artemisia bigelovii, A. tridentata*). Both one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) are found in the upland areas. Diagnostic features: eolian deposits having an elongated U shape with the arms pointing upwind (to the southwest)

Qd4 **Old eolian deposits (Late and middle Pleistocene)—**Moderately sorted to well-sorted, fine to very fine grained sand and silt. Inactive eolian sand dune deposits. This deposit may represent multiple intervals of sand deposition and erosion. Deposits show moderate to strong soil development including argillaceous (Bt and Btk, Munsell soil color 5YR 5/6 to 10 YR 7/8) and pedogenic carbonate showing Stage II and III carbonate morphology to a depth of 100 cm (Bwk and Bk) similar to those observed in Qa4, Qae4, and Qdl4 deposits (Machette, 1985). Shows incision from 1 to 2 m deep. An OSL sample collected near Steamboat Wash from an eolian sandsheet just beneath a Stage II pedogenic carbonate horizon (depth 88 cm) yielded an age of 16.67±1.29 ka (T. Rittenour, oral commun., 2011). There is a strong Btk or Bk soil horizon associated with these deposits in the eastern portion of the west half of the quadrangle; the Stage III carbonate morphology suggests these eolian deposits are approximately 200 to 80 kya (table 2 in Machette, 1985; warm, semi-arid climate). Commonly covered with galleta grass (*Pleuraphis jamesii*), blue grama grass (*Bouteloua gracilis*), and alkali sacaton grass (*Sporobolus airoides*), as well as sagebrush (*Artemisia bigelovii, A. tridentata*), mound saltbush (*Atriplex obovata*), and some Four-wing Saltbush (*Atriplex canescens*). Both one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) occur in upland areas. Diagnostic features: eolian deposits on bedrock and burial of older surficial deposits

Qdl4 **Old linear dune deposits (Late and middle Pleistocene)—**Moderately sorted to well-sorted, fine to very fine sand and silt. Generally inactive eolian sand dune deposits. This deposit may represent multiple intervals of sand deposition and erosion. Deposits show moderate to strong soil development including argillaceous Bt (10R 6/2 to 10R 4/6) and Btk horizons (10YR 8/2 to 10YR 7/4) and Stage II and III pedogenic carbonate horizons (Bwk and Bk, 10YR 8/2 to 10R 8/2) as seen in Qa4, Qd4, and Qdl4 deposits (Machette, 1985). Shows incision from 1 to 3 m deep. There is a strong Bt or Btk (reddish brown, 5YR 3/4 to 5/4) or Bk soil horizon associated with these deposits in the eastern portion of the west half of the quadrangle; the Stage III carbonate morphology suggests these eolian deposits are approximately 200 to 80 kya (table 2 in Machette, 1985; warm, semi-arid climate). Commonly covered with galleta grass (*Pleuraphis jamesii*), blue grama grass (*Bouteloua gracilis*), and alkali sacaton grass (*Sporobolus airoides*), as well as sagebrush (*Artemisia bigelovii, A. tridentata*), mound saltbush (*Atriplex obovata*), and some Four-wing Saltbush (*Atriplex canescens*). Both one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) are found in the upland areas. Diagnostic features: linear eolian deposits on Qd4 sheet sands

MIXED ALLUVIAL AND EOLIAN DEPOSITS

Qae1 **Young mixed alluvial and eolian deposits (latest Holocene)—**Moderately sorted to well-sorted, fine- to medium-grained sand, silt, and small clasts. Generally flat bedded to massive. Active mixed alluvial and eolian deposits. Little or no soil development. Grades into Qa1 and Qd1 deposits. Unit is sparsely vegetated with various perennial shrubs such as rubber rabbitbrush (*Ericameria nauseosa*), sand sagebrush (*Artemisia filifolia*) galleta grass (*Pleuraphis jamesii*), alkali sacaton grass (*Sporobolus airoides*), and scattered one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) in the upland areas. Diagnostic features: generally found along distal portions of alluvial fans downwind of washes or other drainages

Qae2 **Older young mixed alluvial and eolian deposits (late and middle Holocene)—**Moderately sorted to well-sorted, fine- to medium-grained sand, silt, and small clasts. Generally flat bedded to massive. Inactive mixed alluvial and eolian deposits. Some surface clasts are varnished but there is no desert pavement development. Little or no soil development; soil carbonate in matrix may show weak to moderate reaction to hydrochloric acid, Stage I carbonate morphology (Machette, 1985). Grades into Qa2 and Qd2 deposits. May be incised to a depth of 0.5 to 3 m controlled by the distance to washes. An OSL sample collected from a deposit near Betty Well yielded an age of 1.34±0.20 ka (T. Rittenour, oral commun., 2009). Unit is sparsely vegetated with various perennial shrubs such as rubber rabbitbrush (*Ericameria nauseosa*), sand sagebrush (*Artemisia filifolia*), galleta grass (*Pleuraphis jamesii*), alkali sacaton grass (*Sporobolus airoides*), and widely spaced one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) in the upland areas. Diagnostic features: generally found along the distal portions of alluvial fans downwind of washes or other drainages

Qae3 **Intermediate-age mixed alluvial and eolian deposits (early Holocene and latest Pleistocene)—**Moderately sorted to well-sorted, fine- to medium-grained sand and silt and clasts as much as 20 cm. Generally flat bedded to massive. Inactive mixed eolian and alluvial deposits. Some surface clasts are varnished and may show moderate desert pavement development. Deposits show little to moderate soil development including argillaceous Bt and pedogenic carbonate horizons as seen in Qa3 deposits. May show incision from 1 to 3 m deep. Unit is sparsely vegetated with various perennial shrubs such as rubber rabbitbrush (*Ericameria nauseosa*), sand sagebrush (*Artemisia filifolia*), mound saltbush (*Atriplex obovata*), Four-wing Saltbush (*Atriplex canescens*), galleta grass (*Pleuraphis jamesii*), alkali sacaton grass (*Sporobolus airoides*), and widely spaced one-seed juniper (*Juniperus monosperma*) and sagebrush (*Artemisia bigelovii, A. tridentata*) in the upland areas. Diagnostic features: generally found along the distal portions of alluvial fans downwind to washes or other drainages

Qae4 **Old mixed alluvial and eolian deposits (Late and middle Pleistocene)—**Characterized by interbedded sandy pebble to cobble-sized alluvium composed of monchiquite debris shed from the buttes interbedded with fine-grained eolian sand. Inactive mixed eolian and alluvial deposits. Found primarily adjacent to the Hopi Buttes. These deposits were identified as Dilkon deposits, which underlie the Dilkon terrace surface (Sutton, 1974), in the Winslow quadrangle to the west (Billingsley, written commun., 2012). Away from the buttes, thin beds or individual locally derived clasts of Mesozoic bedrock may be found interbedded with fine sands. Grades laterally into Qa4, Qd4, and Qdl4 deposits. Deposits show moderate to strong soil development, including argillaceous (Bt, Btk; reddish brown, 5YR 3/4 to 5YR 5/4) and Stage III to Stage III+ pedogenic carbonate development shown in Bk horizons in Qa4, Qd4, and Qdl4 deposits. May show incipient to moderate desert pavement development. Shows incision from 2 to 5 m deep. Age constraints for these deposits are from the degree of soil development, OSL geochronology, a calibrated carbonate rind proxy, and U-series dating. The Stage III soil carbonate suggests this alluvial deposit is approximately 200 to 80 kya (see table 2 in Machette, 1985, to compare the climate of the Sanders quadrangle with the warm, semi-arid climate of the Albuquerque-Socorro-Las Cruces areas, NM). An OSL sample collected from eolian beds beneath monchiquite clast-rich alluvium with a Stage III carbonate soil near Montezuma's Chair, about 50 km west in the Winslow quadrangle, yielded an age greater than 100 ka. Though the carbonate-rind thickness-numerical age proxy (Amoroso, 2006) does not have calibrations from the Colorado Plateau area, monchiquite clasts from the Montezuma's Chair site were measured to estimate the deposit age. The rind thickness measurements suggest that the alluvial deposit was greater than 90 ka (Amoroso, 2006). U-series age determinations (Paces and others, 2004) were made on carbonate coatings on monchiquite clasts from the Montezuma's Chair site. These show the alluvium overlying the eolian beds to be 64.4 to 59.5 ka (J. Paces, oral commun., 2010). The age of the alluvium beneath the Dilkon terrace surface are therefore inferred to be Late Pleistocene. Commonly covered with galleta grass (*Pleuraphis jamesii*), blue grama grass (*Bouteloua gracilis*), and alkali sacaton grass (*Sporobolus airoides*), as well as Four-wing Saltbush (*Atriplex canescens*), mound saltbush (*Atriplex obovata*), and sagebrush (*Artemisia bigelovii, A. tridentata*). Diagnostic features: generally found adjacent to the Hopi Buttes and other high relief uplands

PONDED SEDIMENT DEPOSITS

Qps **Ponded sediment deposits (Holocene and Pleistocene)—**Composed of fine sand, silt, and clay with polygonal cracking; salts may be present as efflorescences or as weak cements. Deposits active to inactive. Surfaces are flat and prone to flooding; surface water may pond on these low permeability materials. Generally barren of vegetation. Diagnostic features: flat-lying deposits in an area of internal drainage

GROUNDWATER DISCHARGE DEPOSITS

Qgw2 **Older young groundwater spring deposits (middle and early Holocene)—**White (10YR 8/1) efflorescence on sands and gravels. Weakly consolidated groundwater carbonates (tufa); forms a mound at the site of former groundwater discharge. Deposits are difficult to identify on aerial photographs because of their small size and are found during field work. A single mound was identified within a maar crater in the Greasewood Spring quadrangle. Sparsely to moderately vegetated with small annuals and shrubs. Diagnostic features: commonly forms light-colored mound constructed of tufa

Qgw3 **Intermediate-age groundwater spring deposits (early Holocene and latest Pleistocene)—** Silt and fine sand, some groundwater carbonates; compact and thin bedded to massive in zones of former groundwater discharge. Identified by ground litter of strongly indurated, micritic groundwater carbonates (tufa) overlying light-greenish-gray (5G 8/1), fine sand and greenish-gray (5GY 6/1), waxy clay. Also appears as white (N9) seeps at the contact of Qae4 and the underlying bedrock. Sparsely vegetated with annuals and small shrubs. Diagnostic features: commonly forms light-colored mound constructed of tufa or efflorescence at the edges of the Qae4 where it overlies lower permeability or impermeable bedrock

COLLUVIAL, LANDSLIDE, AND OTHER HILLSLOPE DEPOSITS

Qc **Young and intermediate-age colluvial deposits (Holocene and Pleistocene)—**Hillslope deposits composed of cobbles, gravel, and sand that are thicker than 2 m and covering a large area; generally poorly vegetated. Generally forms by a combination of slope wash and mass movement to accumulate at slope angles of ~29º to ~11º; grades downslope into alluvial fan deposits. May show soil development including as much as Stage III carbonate development and clay-rich B horizons. Diagnostic features: discontinuous deposits found on upper hillslopes

Qtr **Talus and rockfall deposits (Holocene and Pleistocene)—**Accumulations of coarse rock debris found below cliffs; size ranges from small clasts to 5+ m boulders. Generally accumulates at slope angles of ~36º to ~30º (Selby, 1993). May be clast supported or matrix supported where voids between clasts filled with eolian sands and finer rock materials. Grades downslope into colluvial deposits (Qc). Diagnostic features: discontinuous cobble to boulder deposits found below cliffs

Ql **Landslide deposits (Holocene and Pleistocene)—**Landslide deposits of clasts to 2.5-m boulders that may have sandy or sandy-clay matrix. Deposits thicker than 2 m cover a wide area. Deposits form by translational, rotational movement or slumping of rock or sediment masses. May show soil development including as much as Stage III pedogenic carbonates and minor to thick Bt horizons. Diagnostic features: rock masses that show evidence of downslope movement, found on the steep slopes of many of the Hopi Buttes

VOLCANIC ROCKS

Volcanic rocks of the Hopi Buttes volcanic field (Miocene)—In the northwestern corner of the west half of the Sanders quadrangle. Originally defined as the middle volcanic member of the Bidahochi Formation (Repenning and Irwin, 1954; Shoemaker and others, 1962). These rocks are redefined as volcanic rocks of the Hopi Buttes volcanic field (Miocene) because they form a mappable sequence of volcanic rocks that may, in part, be time equivalent to deposits of the lower or middle part of the Miocene Bidahochi Formation (Billingsley, written commun., 2012).

Ti **Intrusive dikes (Miocene)**—Black, dark-gray, and brown intrusive monchiquite, basanite, and unsorted scoriaceous and palagonitic tuff; highly eroded. Include clinopyroxene, pyroxenite inclusions in limburgite, and olivine phenocrysts (Lewis, 1973). Two small dikes lie on either side of Arrowhead Butte (just south of the Hopi Buttes label; a small dike is located at the eastern end of an unnamed butte 3.5 km west-southwest of Twin Buttes; one large dike, 24 m (78 ft) wide and 188 m (620 ft) long, is located roughly half way between Twin Buttes and Wood Chop Mesa; and a second large dike, 74 m (240 ft) wide and 800 m (2,620 ft) long, is located some distance from other volcanic features about 4 km east-southeast of Twin Buttes (fig 1). These are aligned along north- and northwest-trending bedrock fractures and joints

Tc **Volcanic-crater sedimentary deposits (Miocene)—**Found within circular maar crater vent depressions that display inward-dipping stratified pyroclastic and surge deposits interbedded with lacustrine sedimentary deposits. Consists of undivided epiclastic and lacustrine volcanic and fluvial sedimentary rocks of gray, light-yellow, tan to white claystone; thin-bedded calcareous siltstone and sandstone; globular or bedded travertine and groundwater deposits; and gypsum interbedded with variable interbedded pyroclastic and mafic gray tuff and white ash and sandstone. Unit is moderately sorted and commonly shows intense soft-sediment deformation. Thickness, 3–49+ m (10–160+ ft)

Tm **Mafic monchiquite and basanite flows (Miocene)—**Black, dark-gray, and medium-brown porphyritic monchiquite and basanite. Contain olivine, clinopyroxene, and phlogopite phenocrysts. Thick monchiquite flows display prominent columnar cooling joints. Thickness, 5 to 58+ m (16 to 190+ ft)

Tmt **Mafic tuff-and-ash deposits (Miocene)—**Gray and white palagonite-rich, lithic tuff with pyroclasts of porphyritic monchiquite or basanite fragments containing phenocrysts and glomerocrysts of clinopyroxene, olivine, and some phlogopite. Include palagonitic tuffs containing welded ash to lapilli tuff, local bomb-rich layers, and multiple deposits of fallout and surge deposits (Hooten and Ort, 2002). Outcrops south of Pueblo Colorado Wash on the Sanders-Winslow quadrangle boundary (map sheet 1). Thickness, 18–67+ m (60–220+ ft)

Tmu **Monchiquite and basanite flow and tuff deposits, undivided (Miocene)—**Gray or brown monchiquite and basanite flows interbedded with mafic tuff and ash deposits. Contain abundant phenocrysts of clinopyroxene, olivine, and phlogopite. Include several mixed flows and pyroclastic deposits from multiple volcanic eruptions in northwest half of Hopi Buttes area (map sheet 1). Include abundant kaersutite megacrysts near top of some bedded deposits in Wood Chop Mesa area. ^{40}Ar/^{39}Ar age on kaersutite, 6.81±0.06 Ma, just east of the maar crater deposits on northern end of Wood Chop Mesa (fig. 1; Vazquez, 1998). Thickness, 9–46+ m (30–150+ ft)

SEDIMENTARY ROCKS

Cenozoic, Mesozoic, and Paleozoic sedimentary rocks (Cretaceous, Tertiary, Jurassic, Triassic, and Leonardian-North-American-Stage Permian)

Tvf **Older valley-fill deposits (Pliocene?)—**Slope- and minor cliff-forming sandstone, light-reddish-brown to light-brown, fine- to medium-grained, low-angle cross-bedded to flat-bedded fluvial sandstone. Includes sub-rounded to angular clasts of local bedrock in basal portion. Moderately consolidated with silica and calcareous cement. Unconformably overlying the Petrified Forest Member of the Chinle Formation. Unit forms small outcrops in the northeastern portion of map along Wide Ruins Wash (fig. 1). Extends eastward up the topographic slope on western flank of the Defiance Plateau Uplift to about the erosional limit of the Petrified Forest Member. These deposits appear to postdate Tbu and are related to the deposits on the early Black Point surface (Akers, 1962)

Bidahochi Formation (Pliocene and Miocene)—The Bidahochi Formation consists of three informal members as defined by Repenning and Irwin (1954) and Shoemaker and others (1957, 1962), which are, in descending order, upper fluvial member (Pliocene), middle volcanic member (Miocene), and lower mudstone and argillaceous sandstone member (Miocene). The Bidahochi Formation was redefined by G.H.Billingsley (written commun., 2012) to include only two of the original members, the upper fluvial member and the lower mudstone and argillaceous sandstone member.

The lower member (Tbl) is associated with Miocene volcanic rocks in the Winslow 30' x 60' quadrangle to the west (G.H. Billingsley, written commun., 2012) and is considered to be Miocene age in the west half of the Sanders quadrangle as well

Tbu **Upper fluvial member (Pliocene)**—Slope- and minor cliff-forming clastic deposits. Upper fluvial member lies unconformably on either the lower mudstone and argillaceous sandstone member of the Bidahochi Formation, or the Petrified Forest Member of the Chinle Formation. Some of the fluvial materials are locally derived from weathering of Hopi Buttes volcanic deposits. Tbu is composed of white (N9), grayish-orange-pink (5YR 7/2), moderate-brown (5YR 4/4) and light-brown (5YR 6/4), fine- to medium-grained, and coarse-grained sandstone with minor interbedded siltstone. Includes minor amounts of light-brown (5YR 6/4), and greenish-gray (5GY 6/1) claystone. Sandstones are thin bedded to planar, tabular, and show low-angle to high-angle-planar, tabular cross-beds. Unit is partly cemented with calcite and silica and is poorly to moderately consolidated. In the southeastern part of the map area, QTa alluvium unconformably overlies the fluvial member. Thickness, 84–165 m (275–540 ft)

Tbl **Lower mudstone and argillaceous sandstone member (Miocene)**—Slope- and minor cliff-forming, thin-bedded lacustrine mudstone, claystone, sandstone, and air-fall volcanic ash deposits. Basal gravel lag of quartzite, chert, and petrified wood, probably derived from reworking of the Shinarump Member of the Chinle Formation found to the northeast. Soft claystone and siltstone beds are easily eroded below cliffs of volcanic rocks in Hopi Buttes area, resulting in landslide (Ql) or talus and rock fall (Qtr) deposits. Lowermost beds include red claystone (5R 5/4) and light-greenish-gray (5GY 8/1) claystone overlain by white (N9) and grayish-orange-pink (10R 8/2) siltstone, marlstone, and claystone with minor light-gray (N7) sandstones and thin light-gray (N8) silicic ash beds. Sanidine minerals from a felsic vitric ash bed in lower part of Tbl at Triplets Mesa (informally named by Dallegge and others, 1998) located just north of Wood Chop Mesa yield a $^{40}Ar/^{39}Ar$ age of 13.71 ±0.08 Ma. Unit unconformably overlies reddish-brown siltstone and sandstone of Kayenta Formation (Jk) and lower orange beds of the Moenave Formation (Jm) east and northeast of the Hopi Buttes. Tbl unconformably overlies the Owl Rock and Petrified Forest Members of the Chinle Formation farther east in the map area, marking an extensive Tertiary erosional surface that cuts across Mesozoic rocks. Thickness, 32–83 m (105–272 ft)

GLEN CANYON GROUP

The Glen Canyon Group overlies the Triassic Chinle Formation and, on the southern Colorado Plateau, includes the Jurassic Moenave Formation (Jm) (Wingate Sandstone in Utah and northeastern Arizona; not present in the Sanders quadrangle), Kayenta Formation (Jk), and Navajo Sandstone (not present in the map area). The contact between the Moenave and Chinle Formations is arbitrarily placed at a lithologic, slope, and color change between moderate-red and light-greenish-gray claystone and sandstone and gray limestone of the underlying Owl Rock Member of the Chinle Formation (T̵Rco) and overlying pale-yellowish-orange mudstone, siltstone, and sandstone of the Moenave Formation (Jm).

Jk **Kayenta Formation (Lower Jurassic)**—Moderate-reddish-orange (10R 6/6) to moderate-reddish-brown (10R 4/6), brown, and light-brown (5YR 4/4 to 5YR 6/4), with minor grayish-pink (5R 8/2), slope- and cliff-forming, fluvial cross-bedded, channel form and flat-bedded (20–200 cm thick) claystone, siltstone, and fine-grained silty sandstone. Near the Hopi Buttes, Jk is mostly covered by landslide (Ql) and talus and rock fall (Qtr); elsewhere it is largely covered by the Bidahochi Formation, or surficial Qae4/Qdl4 deposits. Contact with underlying pale-yellowish-orange (10YR 8/6) sandstone of Moenave Formation (Jms) is gradational and marked at topographic and lithologic change between slope-forming Kayenta Formation and underlying cliff or ledge-forming Moenave Formation. An unknown thickness of the Kayenta Formation has been removed by late Tertiary erosion. Thickness, 12–23 m (40–75 ft)

Jm **Moenave Formation (Lower Jurassic)—**Pale-yellowish-orange (10YR 8/6), moderate-reddish-orange (10R 6/6), and moderate-orange-pink (5YR 8/4), slope-forming, flat-bedded, low-angle cross-bedded, primarily fluvial, fine- to coarse-grained siltstone and silty sandstone. Much of the Moenave Formation was removed by Tertiary erosion east and southeast of the Hopi Buttes, where it is unconformably overlain by pale-brown (5YR 5/2), pinkish-gray (5YR 8/1), and pale-reddish-brown (10R 5/4) claystone and siltstone of the lower Bidahochi Formation (Tbl). Unit is unconformably overlain by moderate-reddish-orange (10R 6/6) to moderate-reddish-brown (10R 4/6) siltstone and sandstone of the Kayenta Formation (Jk) east of the Hopi Buttes (map sheet 1). Sharp contact with underlying Owl Rock Member of the Chinle Formation (Ꞧco). Thickness, 14–38 m (45–125 ft)

Chinle Formation (Upper Triassic)—Includes the Owl Rock and Petrified Forest members. The lower Shinarump Member is not present in the western part of the Sanders quadrangle (Stewart, 1972a).

Ꞧco **Owl Rock Member (Upper Triassic)—**Grayish-red (10R 4/2), moderate-red (5R 4/6), and pale-reddish-brown 10 R 5/4), with minor light-greenish-gray (5G 8/1) shale and siltstone-forming slopes as much as 15 ft thick overlying the ledge-forming nodular limestone interbedded with grayish-red-purple (5RP 4/2) and pale-reddish-brown (10R 5/4) calcareous claystone, siltstone, and sandstone. Most limestone beds are medium gray (N5) to brownish gray (5YR 4/1); some appear brecciated and recemented with carbonate and laminated chert. Beds are laterally persistent for thousands of meters, and the carbonates are slightly to very silty, sandy, and argillaceous. Some beds are pale red (5R 6/2) with light-gray (N7) nodules 0.5 to 1.5 m (1 to 5 ft) thick. Limestone beds are separated by claystone and sandy claystone that shows considerable mottling and variegation with some root traces. Gradational and arbitrary contact with underlying Petrified Forest Member (Ꞧcp) placed at the lowest limestone or nodular calcareous very light gray siltstone (N8) in slope below lowest limestone bed. The Owl Rock Member is restricted to the west-central portion of the map area. Thickness, 58–67 m (190–220 ft)

Ꞧcp **Petrified Forest Member (Upper Triassic)—**Reddish-gray (10R 6/1) to grayish-purple 5RP 4/2), moderate-red (5R 4/4) to reddish-brown (10R 4/6), light-greenish-gray (5GY 8/1) to light-olive (10Y 5/4), and grayish-blue 5PB 5/2) slope-forming claystone and siltstone interbedded with grayish-pink (5R 8/2) to pale-orange (10YR 8/2), coarse-grained, lenticular sandstone. Includes lenticular, large-scale alluvial channel features that exhibit large-scale low-angle trough-cross-bedding. Silicified logs and wood fragments are common in white or yellow-white sandstone beds. Bluish-white (5B 9/1) and pale-red (10R 6/2) claystone beds weather into rounded hills or slopes with shrinking and swelling of montmorillonite clays creating a popcorn texture on the surface. The contact with the underlying Shinarump Member (Ћcs) is covered. Thickness, 107–131 m (350–430 ft)

Ћcpb **Black Forest bed of Billingsley, 1985 (Upper Triassic)—**Pale pink (5 RP 8/2) and pale red-purple (5RP 6/2) shale and mudstone along with reworked tuffaceous sediments overlying moderate brown (5 YR 3/4) limestone-pebble conglomerate (on weathered surface). Black silicified wood is present just above and within the conglomerate bed. Unit is present only in the northern portion of Petrified Forest National Park and eastward to west of Dead Wash as a local channel fill within the Petrified Forest Member; it may be covered by slope debris north of the park boundary. Thickness, 1–10.5 m (3.3–35 ft)

Ћcpf **Flattops sandstone beds of Billingsley, 1985, undivided (Upper Triassic)—**Pale-red (5 R 6/2), brownish-gray (5 YR 4/1), and pale-yellowish-brown, very fine to medium grained, sub-rounded sandstone beds (10 YR 6/2) that weather to light brown (5 YR 6/4) on fresh surface. Includes as much as three distinct sandstone beds in southern part of Petrified Forest National Park and vicinity south of the map area. Includes pebble conglomerate in the basal portion of the bed and trough, low- to high-angle cross-bedded and planar sandstone beds; slightly calcareous. Silicified logs and log fragments are common. Appears as one or more laterally continuous beds within the Petrified Forest Member. Aggregate thickness of the three beds, 15–21 m (25–69 ft)

Ћcps **Sonsela sandstone bed of Akers and others, 1958 (Upper Triassic)—**Pale_yellowish-orange (10 YR 8/6), grayish-orange-pink (5 YR 7/2), and grayish-brown (5 YR 3/2) sandstone on weathered sandstone surfaces. Includes interbedded grayish-purple (5 P 4/2) to grayish-blue-green (5 BG 5/2) mudstone; some mottling is present. Predominantly medium- to coarse-grained sandstone beds to more than 3 m (10 ft) thick with planar to tabular, cross-bedded, and minor to massive horizontally stratified, thin- to thick-bedded conglomerates (as much as 6 m thick). Includes some interbedded mudstone and siltstone beds. Silicified logs and log fragments are common. Rhyzoliths and carbonate nodules are evidence that soil formation took place prior to lithification. Includes the lowest Flattop Sandstone (#1) of Billingsley (1985). Outcrops are found from Petrified Forest National Park eastward along Interstate 40 to the Defiance Plateau. Thickness, 28–75 m (92–246 ft)

Ћcpn **Newspaper Rock Sandstone Bed of Chinle Formation (Upper Triassic)—**Pale greenish-yellow (10 Y 8/2) to grayish-yellow-green (5 GY 7/2), very fine- to fine-grained sandstone on fresh exposures. Weathers dark yellowish brown (10 YR 4/2) on desert-varnish-coated surfaces. Located in the southwestern portion of Petrified Forest National Park and southwest of the map area. Appears as a localized, laterally continuous bed within the lower part of the Petrified Forest Member. Thickness, 3–9 m (10–30 ft)

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