Prepared in cooperation with the Navajo Nation

Bedrock and Surficial Geologic Map of the Satan Butte and Greasewood 7.5' Quadrangles, Navajo and Apache Counties, Northern Arizona

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Pamphlet to accompany

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Introduction

The bedrock and surficial geologic map of the Satan Butte and Greasewood 7.5' quadrangles 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 geologic map of the Satan Butte and Greasewood 7.5' quadrangles 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 map area encompasses approximately 314 km^2 (123 mi^2) within Navajo and Apache Counties of northern Arizona and is bounded by lat 35°37'30" to 35°30' N., long 109°45' to 110° W. This geologic map will benefit local, Arizona, 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 Ganado 30' x 60' quadrangle.

Map Scale

The map was compiled at 1:24,000 scale using a combination of 1:40,000 color aerial photography (flown in 2005), digital orthophotos, and field checking. The map is presented in one panel at the 1:24,000 scale. The map sheet contains a Correlation of Map Units and a List of Map Units that includes an explanation of map symbols. This pamphlet contains a Description of Map Units.

Geography

The Satan Butte and Greasewood 7.5' quadrangles lie within the southern Colorado Plateau geologic province (herein called the Colorado Plateau) within the northeastern portion of the Hopi Buttes (Tsézhin Bií) located in the Satan Butte quadrangle (fig. 1). Large ephemeral drainages, Pueblo Colorado Wash and Steamboat Wash, originate north of the map area on the Defiance Plateau and Balakai Mesa respectively. Elevations range from 1,930 m (6,330 ft) at the top of Satan Butte to about 1,787 m (5,860 ft) at Pueblo Colorado Wash where it exits the southwest corner of the Greasewood quadrangle.

The only settlement within the map area is Greasewood, Arizona, on the north side of Pueblo Colorado Wash (fig. 1). Navajo Highway 15 crosses both quadrangles and joins State Highway 264 northwest of Ganado. Unimproved dirt roads provide access to remote parts of the Navajo Reservation (fig. 1). Some roads are maintained by the Navajo Nation Roads Department in Window Rock, Arizona, while others are locally maintained by Chapter Governments (Greasewood Springs, Steamboat, and Cornfields 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 months. Extra water and food is also highly recommended for travel in this region.

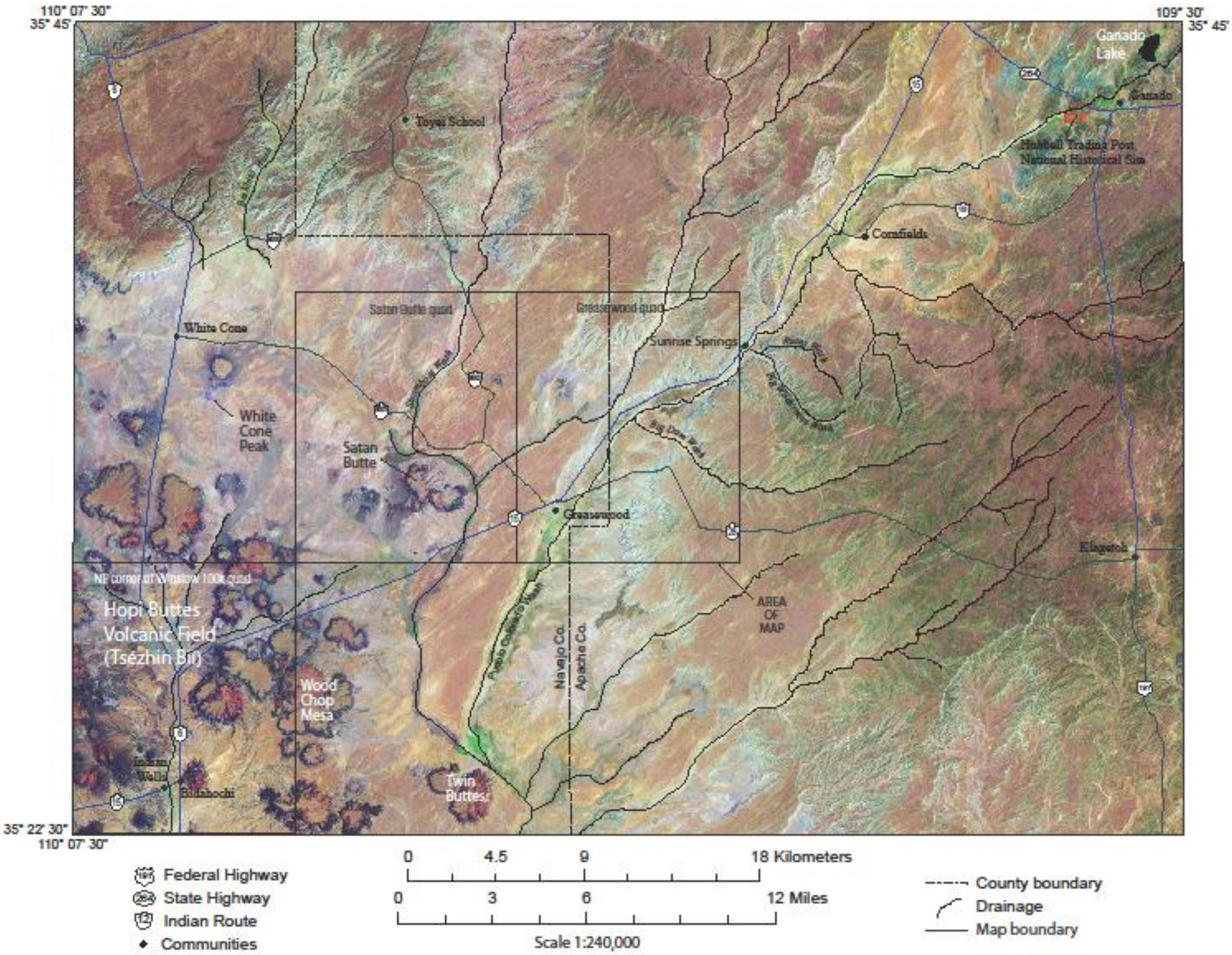

Figure 1. Map of the Satan Butte (left) and Greasewood (right) 7.5' quadrangles, Arizona, showing physiographic, cultural, and geologic locations mentioned in the text.

Previous Studies

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 (Cooley and others, 1969) that covers the map area (map #6 of 9; 1:125,000 scale). This map was not registered to a topographic base because a base larger than 1:250,000 scale did not exist. Another report resulting from that hydrogeology study described the uppermost Triassic and Jurassic rocks of the Navajo country (Harshbarger and others, 1957). A master's thesis of the stratigraphy and the correlation and age of the ash beds of the Bidahochi Formation at the Hopi Buttes (Tsézhin Bií) Volcanic Field and to the east was produced by Dallegge (1999). Ort and others (1998) summarizes the sedimentary and volcanic history of the Bidahochi Formation including several locations in the northwestern part of the Sanders 30' x 60' quadrangle. Structural and tectonic features within the Satan Butte and Greasewood 7.5' quadrangles are described in the Kelley and Clinton (1960) detailed maps of the Colorado Plateau.

The mapped surficial geology was interpreted and approximate ages of the deposits estimated by adapting previous work on soil development in the Mojave Desert and on the southwestern portion of the Colorado Plateau (Amoroso and Miller, 2006; Amoroso and others, 2004; Mahan and others, 2006). This includes mapping in the Sanders 30' x 60' quadrangle immediately south of the Satan Butte and Greasewood quadrangles that is still in progress. These studies in spatially adjacent landscapes were used to develop soil development/age relations for the southern Colorado Plateau. The deposit-age interpretations generally match the consistency and detail of the Winslow 30' x 60' quadrangle, Arizona (G.H. Billingsley, written commun.2012), which is southwest of the Satan Butte and Greasewood quadrangles.

Geologic Setting

In the Satan Butte and Greasewood quadrangles, the flat-lying Moenave Formation is the only Mesozoic bedrock exposed at the surface. A shallow Cenozoic erosional basin, late Miocene or older (Elston and Young, 1991), was cut across Mesozoic rocks (see cross section A–A'). This basin was subsequently filled with flat-lying Miocene and Pliocene lacustrine and fluvial sediments of the Bidahochi Formation and associated with volcanic rocks of the Hopi Buttes Volcanic Field (Ort and others, 1998) that unconformably overlie Triassic strata (see cross section A–A'). These deposits were later overlain by alluvial and eolian surficial deposits; not all surficial deposits are shown in cross section A–A'.

General Surficial Geology

Alluvial deposits (Qa1, Qa2, Qa3) mantling piedmonts between the bedrock hills and the valley axes are common in the Satan Butte and Greasewood quadrangles. They are composed of materials eroded from nearby hillsides or delivered from up-gradient areas by drainages. These deposits are usually composites of several different units that cannot be shown at the map scale, for example, alluvial fans that have a small amount of eolian cover or that have been incised by small drainages.

Mixed alluvial and eolian deposits (Qae1, Qae2, Qae3, and Qae4) are found near bedrock highlands and drainages. They are mixtures of alluvium and eolian sediments; either of these constituents may be the major fraction. This includes dune deposits overlying alluvium that cannot be shown at the map scale. Qae4 is restricted to the area around Satan Butte and is composed of volcanic and sedimentary rock clasts interbedded with eolian sands. These eolian sands grade into Qd4 and Qdl4 deposits.

Valley-axis deposits are found in low-relief areas that lie between uplands. These deposits (Qv2) are composed of units produced under several different geomorphic processes: fluvial, alluvial, and eolian. Valley-axis deposits are composite units because the individual 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 mass-movement deposits that result from physical weathering of steep bedrock exposures. Debris flow deposits are also included in this category. These deposits as well as the colluvium-covered (Qc) slopes are commonly underlain by or contain laminar-layered impermeable pedogenic carbonates that promote rapid saturation of the material enhancing mass movement potential (Wells and others, 1982).

Broad areas are covered by eolian deposits in the Satan Butte and Greasewood quadrangles (Qd1, Qd2, Qd3, Qd4, Qdl3, Qdl4, Qdp1, Qdp2, and Qdp4). Present day eolian processes rework the minor fine-grained fraction of fluvial sediments and deposit them on nearby terraces as either dunes or as mixed eolian-alluvial deposits. The Pleistocene and early Holocene eolian deposits may be the result of the same geomorphic processes on a larger, long-term scale, or other processes may be responsible for the formation of the large sand-sheet deposits (Qd4 and Qdl4). Strong winds, capable of sand transport over large distances, are common on the southern Colorado Plateau during the passage of weather fronts during the fall, winter, and spring months. Ponded deposits (Qps) that include small playas and depressions are located where local drainages deposit fine-grained sediments in the inter-dune areas.

Mesozoic Rocks

Erosion along Pueblo Colorado Wash and Steamboat Wash has exposed small outcrops of the Moenave Formation (Lower Jurassic). Other Mesozoic sedimentary rocks are present under the Bidahochi and Moenave Formations and surficial deposits.

Moenave Formation

The Moenave Formation (Jm) is poorly exposed in the Satan Butte and Greasewood quadrangles; the few exposures are along cliffs bordering Pueblo Colorado Wash and Steamboat Wash (fig. 2). Pale-yellowish-orange, reddish-orange and orange-pink, slope-forming siltstone and sandstone deposits of the Moenave Formation unconformably overly the Owl Rock Member of the Chinle Formation (not exposed in these quadrangles but found in the western portion of the Sanders 30' x 60' quadrangle to the south.

The Moenave Formation commonly weathers as a reddish-orange slope to the east of the Hopi Buttes. Remnants of reddish-white fluvial sandstones of the Kayenta Formation unconformably overly the Moenave Formation in several exposures on the northwest side of Pueblo Colorado Wash between Greasewood and Sunrise Springs (fig. 1), but they are too small to show on the map. Much of the upper portion of the Moenave Formation has been removed by Tertiary erosion and is now unconformably overlain by red, dark-brown, and white mudstone and argillaceous sandstone deposits of the lower Bidahochi Formation (Tbl). The Moenave Formation is 92–134 m (300–440 ft) thick in the Winslow quadrangle to the southwest and 4–38 m (45–125 ft) thick in the Sanders quadrangle to the south. The Moenave Formation in the Satan Butte and Greasewood quadrangles is 9–21 m (30–70 ft) thick.

Figure 2. The upper (Tbu) and lower (Tbl) members of the Miocene and Pliocene Bidahochi Formation lying unconformably on the Jurassic Moenave Formation (Jm). The upper fluvial member consists of slope-forming light green and brown claystones and clayey sandstones and cliff-forming light brown cross-bedded sandstones. There are no volcanic rocks from the Hopi Buttes Volcanic Field in this area. The lower member consists of mudstone and

argillaceous sandstone and a few extrabasinal felsic volcanic tephra beds. The topple block has rotated and translated downslope probably due to backwasting of the Moenave Formation that consequently removed the supporting buttress at the base of the cliff.

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.

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, these included 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 section reference at White Cone Peak, a natural landmark about 4 mi (6.5 km) northeast of White Cone, Arizona, just southwest of the map area.

The upper fluvial member (Tbu) of the Miocene and Pliocene Bidahochi Formation is present to the north and east of Pueblo Colorado Wash (fig. 2). The fluvial member consists of crossbedded, 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, argillaceous sandstone, and volcanic ash member (Tbl) is present within the Hopi Buttes area and just to the east and northeast and unconformably overlies the lower part of the Moenave Formation (Jm) in the northwestern part of the Sanders quadrangle. East of Pueblo Colorado Wash, the lower lacustrine member overlies the Kayenta Formation (Jk) and other erosionally truncated Mesozoic units in the subsurface. 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 age of the Bidahochi Formation is middle Miocene and Pliocene (~16 to ~5 Ma) based on vertebrate fossil faunas including amphibians, rodents, beaver, and 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.

There are some hypotheses that a lake of considerable extent may have persisted in the Bidahochi basin for at least a portion of the time Bidahochi Formation sediments were being deposited (Blackwelder, 1934; Meek and Douglass, 2001; Scarborough, 2001). Some 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 from fossil fish found in the Bidahochi fluvial member; the sample sites are 5–20 km (3–12 mi) west and northwest of Woodchop Mesa. The fish fossils at White Cone Peak (fig. 1) are found in distal fluvial, overbank or deltaic lacustrine deposits (Spencer and others, 2008). The fish fossils at the Coliseum 20 km (12 mi) southwest of Woodchop Mesa are within white, 1-m-thick (3-ft-thick) lacustrine sediments that are interbedded with thick volcanic tuffaceous ash and pyroclastic surge and air-fall deposits. Dallegge and others (2003) cited lines of evidence that no large paleolake occupied the Bidahochi basin. A significant inflow of water would be required to maintain an extensive lake large enough to deposit the fine-grained clastics and clays of the lower portion of the Bidahochi Formation member. Because the depositional basin persisted for more than 9 Ma, a 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 eruption deposits, suggesting that the Hopi Buttes maar eruptions occurred in ephemeral lake or playa settings rather than an extensive lake (at least in the area of the Hopi Buttes).

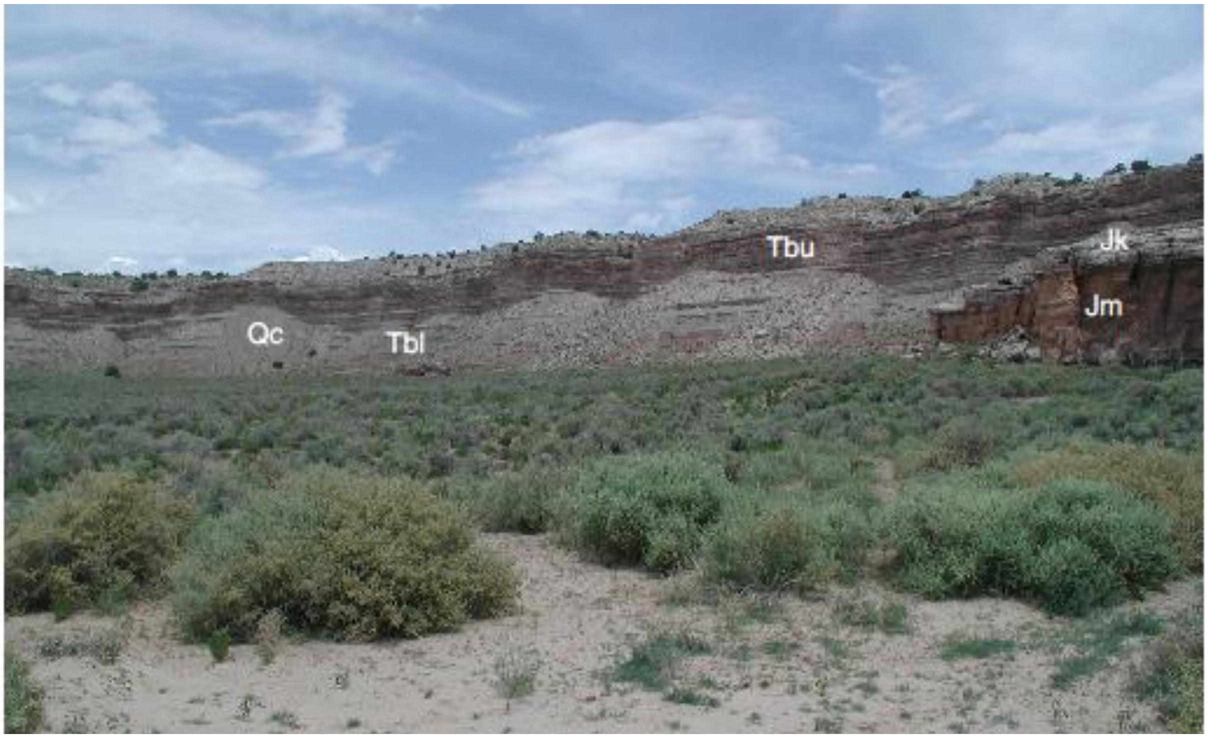

Figure 3. Looking northwest at Miocene and Pliocene upper fluvial member (Tbu, cliff former) and lower mudstone and argillaceous sandstone member (Tbl, slope former) of the Bidahochi Formation overlying the Jurassic Moenave Formation (Jm), which is seen in the orange-brown cliff-forming sandstone at the far right in the middle distance. A thin bed of white sandstone of the Jurassic Kayenta Formation (Jk) caps the sandstones of the Moenave Formation. The Kayenta Formation outcrops are poorly exposed and of limited extent. As a result, they are not shown on the geologic map. Colluvial deposits (Qc) are seen covering the middle and lower slopes of the escarpment. Mixed alluvial and eolian sands (Qae2) are seen in the foreground covered with black greasewood (*Sarcobatus vermiculatus*) and four-wing saltbush (*Atriplex canescens*).

Field observations of the Bidahochi Formation by George Billingsley and Michael Ort (Northern Arizona University) suggest that the lower and upper Bidahochi Formation (Tbl and Tbu) can be correlated across the landscape but at different elevations at different sites. The mudstone and argillaceous member was likely deposited at the same time as the upper fluvial member. The upper fluvial member contains numerous eolian and fluvial sandstone lenses that are likely deposited upland and downwind of the lower lacustrine playa deposits of the Hopi Buttes, making both the upper and lower Bidahochi Formation members time equivalent but deposited 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 green and red beds of the lower mudstone and argillaceous sandstone member with no apparent unconformity between these units and is considered Miocene and Pliocene age (G.H. Billingsley, written commun.2012). If there is an interbedded relation between the lacustrine and fluvial sedimentary deposits to the east in the Sanders quadrangle, the age constraints on the mudstone and argillaceous sandstone member already cited suggests that the fluvial member may be middle Miocene to Pliocene age.

Volcanic Rocks of the Hopi Buttes

The volcanic rocks of the Hopi Buttes Volcanic Field are described by Williams (1936) and are also 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 (written commun.2012), because they (1) form a mappable sequence of related volcanic rock types, (2) are time equivalent with parts of the lower Bidahochi Formation, and (3) are interbedded only within the lower part of the Bidahochi Formation and do not regionally separate the upper and lower portions of the Bidahochi Formation east of the Hopi Buttes.

The volcanic rock types are not mapped in detail because of multiple intertonguing, crosscutting, overlapping, and unconformity complexities between eruption events that distributed a variety of volcanic rock types throughout the Hopi Buttes as shown by Vazquez (1998, 1999), Hooten (1999), and Hooten and Ort (2002). Mapping of Satan Butte and Greasewood quadrangles follows the methodology of Billingsley (G.H. Billingsley, written commun.2012). The volcanic rock types are volcanic crater sediment deposits (Tc), mafic monchiquite and basanite flows (Tm) as defined by Vazquez and Ort (2006), mafic tuff and ash deposits (Tmt), and mixed monchiquite and basanite flows with tuff deposits (Tmu).

The age of volcanic rocks in the Hopi Buttes Volcanic Field range between 7.5–6.5 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. An average age of 7 Ma for the volcanic rocks of the Hopi Buttes in this area is consistent with an older age determined for an ash found in the underlying lower mudstone and argillaceous sandstone member of the Bidahochi Formation at White Cone Peak and Woodchop Mesa. The $^{40}Ar/^{39}Ar$ age of this extrabasinal ash is 13.71±0.08 Ma (likely from the southwestern Nevada volcanic field; Dallegge, 1999).

Stratigraphic Nomenclature

This report describes the Mesozoic and late Tertiary bedrock and Quaternary surficial deposits of the Satan Butte and Greasewood 7.5' quadrangles. Quaternary map units are defined using the surface morphology and landscape position, the degree of soil development, and the depth of incision (the height of deposit surfaces above active drainages). The distribution of Quaternary deposits on this map shows a reconnaissance level of mapping. The ages assigned to Quaternary deposits are primarily 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, 2006; 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, where the xis a placeholder for geomorphic process or landscape position such as a for alluvium, ae for mixed alluvial/eolian, g for terrace-wash deposit, d eolian (dune), and v for valley-axis deposit. Unless observed in the field and specifically mapped, a given age 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, and the unit is labeled by the most prevalent deposit type.

Active aggradation surfaces (Qx, Qs, Qf) 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 significant 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 but are abandoned or receive sediment infrequently. These surfaces are characterized by loose to slightly compact sediments. 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 can be seen in the older (Qx2) deposits. Young surfaces are moderately vegetated and show smoother microtopography 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 Late Pleistocene to early Holocene in age and have been abandoned for tens to a hundred thousand years. Sediments are slightly to moderately compact. These surfaces may have moderately developed 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 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 (significant clay) and the sediment may show from Stage I+ to III+ carbonate morphology (Gile and others, 1981; Machette, 1985).

Old surfaces (Qx4) are middle and Late Pleistocene in age and have been abandoned for several hundred thousand years. Erosion has modified the original deposit and soils by removing as much as several meters of sediment and, thus, may have exposed the pedogenic carbonate horizon. There may be as much as 10 m of incision into these deposits. Strong pedogenesis results in Stage III to Stage IV carbonate morphology and moderate to strong Bt and Btk (clay-rich) horizons (figs. 4, 5).

Figure 4. Late Pleistocene sand-sheet deposit (Qd4) unconformably overlying the lower mudstone and argillaceous sandstone member (Tbl) of the Bidahochi Formation. A moderate Btk soil horizon has developed in the sand sheet that resulted from clay and calcium carbonate accumulation (pedogenesis) in the subsurface. The small white spots at the base of the Btk horizon are carbonate nodules that likely formed around plant roots. Where road surfaces have worn down to the Btk horizon, the clays can become very slippery when wet. Notebook is 20 cm tall.

Figure 5. Stage III pedogenic carbonate morphology (Machette, 1985) developed in a fluvial gravel deposit. This is a terrace (QTg4) located 15 m above the modern channel of Pueblo Colorado Wash. Largest clasts are 25 cm across.

Geologic Hazards

Soil Problems

Expansive soils and collapsible soils cause significant damage to infrastructure and structures 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 to where potential 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 wet (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 Hansed, 1982). The Qx1 and Qx2 deposits, because of their observed soil carbonate and clay content, may have the potential to be collapsible soils.

Expansive soils contain clays that change their volume with water content, resulting in differential soil heave (Selby, 1993). 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. The geologic map may be a guide for planning purposes. Flooding is generally confined to stream channels (Qs), adjacent flood plains (Qf), and alluvial deposits (Qa1), as well as smaller active washes. Flotsam observed on older terraces (Qg1, Qg2) suggests inundation during some larger flood events. The lack of flotsam or other geomorphic indicators of flooding on Qg3 terraces 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 species typically found on surficial deposits in the Satan Butte and Greasewood quadrangles 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 will control the distribution and vigor of plants. For example, the high clay and silt content of thicker Av horizons results in low infiltration of precipitation, restricting 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 restricts plants to salt-tolerant species. The swelling clays of the Bidahochi Formation make it difficult for plants to germinate. The usage of common and scientific names follows Epple (1995). Thomas and others (2009) was useful to check plant distributions on surficial deposits.

Descriptions of Rocks, Sediments, and Soils

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, and (7) human implications and impacts, and (8) diagnostic features. The primary categories are grouped by depositional process with the units listed from youngest to oldest.

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

DESCRIPTION OF MAP UNITS

[Some units on the map are too small to distinguish the color for unit identification. These units are labeled where possible. Unlabeled units are attributed in the geodatabase]

SURFICIAL DEPOSITS

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 stock tanks and ponds

ALLUVIAL DEPOSITS

Qa1 **Active alluvial fan deposits (latest Holocene)**—Moderately to poorly sorted sand, gravel, and clasts to 25 cm in diameter. Alluvium has coarser texture near hillslopes or where derived from older coarse-grained deposits that are being reworked; average grain size decreases downslope. The alluvium is poorly to moderately bedded and loose; channel bars are as high as 35 cm. No soil development. 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 are 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 40 cm in diameter. Poorly bedded to massive; loose to poorly consolidated. Bar and swale microtopography averages 20 cm in height (to a maximum of 30 cm) and decreases down fan. Surfaces lie 10–80 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*), black greasewood (*Sarcobatus vermiculatus*), galleta grass (*Pleuraphis jamesii*), alkali sacaton grass (*Sporobolus airoides*), and in some places invasive Russian thistle (*Salsola tragus*). Deposits characterized by surfaces that receive material infrequently but 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. Diagnostic features: no soil development, desert 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 45 cm in diameter. Poorly bedded to massive; weakly to moderately consolidated. Surface may have slightly developed 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 200 cm above active channels. 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 thick as 6 cm, and moderate cambic B horizon development (7.5 to 5 YR hue) with platy to blocky peds to 4 cm and Stage I+ carbonate development. Older Qa3 deposits have argillic Bt (to 2.5 YR 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 various perennial shrubs such as rubber rabbitbrush (*Ericameria nauseosa*), Four-wing Saltbush (*Atriplex canescens*), mound saltbush (*Atriplex obovata*), galleta grass (*Pleuraphis jamesii*), and alkali sacaton grass (*Sporobolus airoides*) as well as 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 during and after heavy rains. Diagnostic features: characterized by surfaces that have been abandoned for tens to hundreds of thousands of years. 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 30 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 40 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 overlying soil horizons are generally eroded away (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 poorly vegetated with various perennial shrubs such as 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 during and after heavy rains. Diagnostic features: degraded alluvial fans generally confined to the edge of higher terrain; Stage IV to V pedogenic carbonate exposed at the surface

VALLEY-AXIS DEPOSITS

Qv2 **Older young valley-axis deposits (middle and early Holocene)**—Sand to small gravels in broad, low-relief valley-axis locations characterized by inactive anastomosing ephemeral washes, low-relief interfluves, and rare to widely distributed eolian deposits (primarily coppice mounds). 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 in heavy rains, 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: deposits found in valley bottoms between upland areas

WASH AND STREAM-CHANNEL 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 to 30 cm diameter and pebbles of bedrock, chert, and quartzite pebbles. Grades into adjacent Qf deposits. 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. Diagnostic features: elongate, active channels that generally increase in width down channel

Qf **Floodplain 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) deposits. Floods on a 1- to 10- year average. None to very little soil development (weak cambic development). Vegetated with salt cedar (*Tamarix ramosissima*), rubber rabbitbrush (*Ericameria nauseosa*), Fremont Cottonwood (*Populus fremontii*) and, in some places, invasive Russian thistle (*Salsola tragus*). Diagnostic features: found adjacent to active drainages, usually well covered with vegetation

Qg1 **Young terrace-wash deposits (late Holocene)**—Moderately to poorly sorted sand, sandy gravel, and clasts to 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. Channel bars to 40 cm in height. Smaller alluvial wash tracts are generally included in young alluvial fan deposits (Qa1). 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 that are too small to be visible at map scale. The age of these deposits range from modern to approximately 200 years old. 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 washes and terraces that generally increase in width downchannel

Qg2 **Older young terrace-wash deposits (middle and early Holocene)**—Moderately to poorly sorted sand and silt, sandy gravel, and clasts to 30 cm in diameter. Deposits are coarser grained near mountain fronts, steep alluvial fans, or 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 to 20–40 cm in height. Smaller alluvial wash tracts that cannot be shown at the mapping scale are generally included with younger alluvial fan deposits (Qa1, 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 carbonate 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 kya. The lower end of the estimated age range is based on Optically-stimulated Luminescence (OSL) dating of a young eolian dune near Two Mill Tank (in the western central part of the Sanders 30' x 60' quadrangle; 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 (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 washes and terraces that generally increase in width down channel

Qg3 **Intermediate-age terrace-wash deposits (early Holocene and latest Pleistocene)**—Parent material is moderately to poorly sorted sand and silt, sandy gravel, and clasts to 20 cm in diameter, primarily as terrace deposits along and above Qg1 and Qg2 washes and as discontinuous wash remnants. Deposits are coarser grained near steeper terrain and may be 2–3 m above the active channel along washes. Poorly to moderately bedded; poorly to moderately consolidated. Channel bars to 30 cm in height. Younger deposits show no soil development (similar to Qa2); older deposits may show Av horizons to 3 cm thick and weak to moderate B horizon development to 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

QTg4 **Extremely old terrace-gravel deposits (early Pleistocene and Pliocene)**—Parent material is moderately to poorly sorted sand and silt, sandy gravel, and clasts (to 25 cm) exposed along discontinuous high terraces along Pueblo Colorado and Steamboat Washes. Clasts are primarily Mesozoic sandstones and highly resistant quartzites and cherts that may be recycled conglomerates from the Shinarump Member of the Chinle Formation. Deposits appear white to light gray in aerial photos. The deposits are pedogenic and carbonate-rich (carbonate morphology Stage III+) to a depth of more than 150 cm; clasts are uniformly coated with pedogenic carbonate (fig. 5). Carbonate horizons are at the surface, suggesting some weathering or erosion of overlying soil horizons, and may explain the lack of laminar horizons expected for these deposits. Found 1.5–15 m (5–49 ft) above the modern channel. Diagnostic features: discontinuous sand, gravel, and cobbles found well above drainages

EOLIAN DEPOSITS

Qd1 **Young eolian deposits (late Holocene)**—Moderately sorted to well-sorted, very fine to fine sand and silt; sediments are loose. Eolian sand-dune and sheet deposits that are active and show evidence of recent migration may be as much as 2.5 m thick. Active sands that 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, but 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 (west-central part of Sanders 30' x 60' quadrangle) yielded an age of 270±90 years (T. Rittenour, oral commun., 2009). This dune had a horizon weakly cemented with calcium carbonate 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.), as well as several grass species, galleta grass (*Pleuraphis jamesii*), and several types of grama (*Bouteloua* spp.). Diagnostic features: eolian deposits on Qg1 and Qg2 terraces and burial of older deposits

Qd2 **Older young eolian deposits (middle and early Holocene)**—Moderately sorted to well-sorted sand and silt; sediments are loose. Eolian sand-sheet and dune deposits are generally inactive. 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.), as well as several grass species, galleta grass (*Pleuraphis jamesii*), and several types of grama (*Bouteloua* spp.). Diagnostic features: eolian deposits on Qg2 terraces and burial of older deposits

Qd3 **Intermediate-age eolian deposits (early Holocene and latest Pleistocene)**—Moderately sorted to well-sorted, fine-grained to very fine grained sand and silt. Eolian sand-sheet and dune deposits are generally inactive. Some soil development that includes soil carbonate as filaments and blebs to Stage I+ carbonate morphology (Machette, 1985). Some pedogenic clay accumulation (Bt); 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.). Several grass species include galleta grass (*Pleuraphis jamesii*) and several types of grama (*Bouteloua* spp.). Diagnostic features: eolian dune and sheet-sand deposits that are vegetated and appear stabilized

Qd4 **Old eolian deposits (Late and middle Pleistocene)**—Moderately sorted to well-sorted, fine-grained to very fine grained sand and silt. Shows incision from 1–2 m deep. Eolian sand-dune and sand-sheet deposits that are inactive. This sand-sheet deposit is areally extensive, covering a large portion of the southern Navajo Nation. 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 seen in Qa4, Qae4, and Qdl4 deposits (Machette, 1985). An OSL sample collected near Steamboat Wash (just south of the Satan Butte quadrangle) from an eolian sand sheet 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 (fig. 4). The Stage III carbonate morphology suggests these eolian deposits are approximately 200–80 kya (see table 2 in Machette, 1985, warm, semi-arid climate). Commonly covered with galleta grass (*Pleuraphis jamesii*), blue grama (*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: extensive, stabilized sand-sheet deposits

Qdl3 **Intermediate-age linear dune deposits (early Holocene and latest Pleistocene)**—Moderately sorted to well-sorted, fine-grained to very fine grained sand and silt. Eolian linear dune deposits are generally inactive. Some soil development shown by soil carbonate as filaments and blebs to 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.). Several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama (*Bouteloua* spp.). Diagnostic features: linear dune deposits oriented southwest-northeast found on the extensive Qd4 sand sheet

Qdl4 **Old linear dune deposits (Late and middle Pleistocene)**—Moderately sorted to well-sorted, fine-grained to very fine grained sand and silt. This deposit may represent multiple intervals of sand deposition and erosion and is now generally inactive. Shows incision from 1–3 m deep. Deposits show moderate to strong soil development, including argillaceous Bt (10R 6/2 to 10R 4/6) and Btk (10YR 8/2 to 10YR 7/4) horizons, 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). The Stage III carbonate morphology suggests these eolian deposits are at most approximately 200–80 kya (see table 2 in Machette, 1985, warm, semi-arid climate). Commonly covered with galleta grass (*Pleuraphis jamesii*), blue grama (*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 dune deposits oriented southwest-northeast lies over old extensive sand sheet

Qdp1 **Young parabolic dune deposits (late Holocene)**—Moderately sorted to well-sorted, very fine grained to fine-grained sand and silt; sediments are loose. Eolian parabolic sand-dune deposits are active and show 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.). Several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama grass (*Bouteloua* spp.). Diagnostic features: eolian deposits have an elongated 'U' shape with the arms pointing upwind (to the southwest)

Qdp2 **Older young parabolic dune deposits (middle and early Holocene)**—Moderately sorted to well-sorted sand and silt; sediments are loose. Eolian sand deposits are generally inactive. Dunes form as underlying eolian deposit is eroded. 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.). Several grass species: galleta grass (*Pleuraphis jamesii*) and several types of grama (*Bouteloua* spp.). Diagnostic features: eolian deposits have an elongated ‘U’ shape with the arms pointing upwind (to the southwest)

Qdp4 **Old parabolic dune deposits (Late Pleistocene)**—Moderately sorted to well-sorted sand and silt. Eolian parabolic dune deposits are generally inactive. Parabolic dunes formed from partially eroded Qd4 and Qdl4 deposits; further erosion may have eroded one of the parabolic arms. 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 (*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 have an elongated 'U' shape with the arms pointing upwind (to the southwest)

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. Mixed alluvial and eolian deposits that are generally active. 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*), black greasewood (*Sarcobatus vermiculatus*), 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 (middle and early Holocene)**—Moderately sorted to well-sorted, fine- to medium-grained sand and silt and small clasts. Generally flat bedded to massive. Mixed alluvial and eolian deposits that are generally inactive. Some surface clasts are varnished but no desert pavement development. Little or no soil development; soil carbonate in matrix may show weak to moderate reaction to HCl; Stage I carbonate morphology (Machette, 1985). Grades into Qa2 and Qd2 deposits. May be incised to a depth of 0.5–3 m; the amount of incision is controlled by the distance to washes. An OSL sample collected from a deposit near Betty Well (located in the Sanders 30' x 60' quadrangle) 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*), black greasewood (*Sarcobatus vermiculatus*), 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: found along the distal portions of alluvial fans adjacent to washes

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 up to 20 cm. Generally flat bedded to massive. Some surface clasts are varnished and may show moderate desert pavement development. Mixed eolian and alluvial deposits that are inactive. May show incision from 1–3 m deep. Deposits show little to moderate soil development including argillaceous Bt and pedogenic carbonate horizons as seen in Qa3 deposits. 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: found along the distal portions of alluvial fans adjacent to washes

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 eolian sand. Mixed eolian and alluvial deposits that are inactive. May show incipient to moderate desert pavement development. Shows incision from 2–5 m deep. Found only in the area of Satan Butte. Identified by Sutton (1974) as Dilkon deposits lying on the Dilkon terrace (Sutton, 1974) and are identified in the Winslow 30' x 60' quadrangle to the southwest (Dilkon deposits, QTd, G.H. Billingsley, written commun.2012). Grades laterally into Qd4 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 Qd4 deposits. Age constraints for these deposits come from soil development, OSL geochronology, a calibrated carbonate rind proxy, and U-series dating. The Stage III soil carbonate suggests this alluvium is approximately 200–80 kya (Machette, 1985, see table 2 to compare the climate of the Satan Butte 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 southwest in the Winslow 30' x 60' 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. Rind thickness measurements suggest that the alluvial deposit was greater than 90 ka old (Amoroso, 2006). U-series age determinations (^{230}Th/U; Paces and others, 2004 for methods used) were made on carbonate coatings on monchiquite clasts from the Montezuma's Chair site. The results show that the alluvium overlying the eolian beds was estimated to be 59.5–64.4 ka old (J. Paces, oral commun., 2010). Commonly covered with galleta grass (*Pleuraphis jamesii*), blue grama (*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: 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 are active or do not regularly receive sediments. 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

COLLUVIAL, LANDSLIDE, AND OTHER HILLSLOPE DEPOSITS

Qc **Young and intermediate-age colluvial deposits (Holocene and Pleistocene)**—Composed of clasts, gravel, and sand that are thicker than 2 m and covering a wide area of the upper hillslope, generally poorly vegetated. Generally forms by a combination of slope wash and mass movement to accumulate at slope angles of ~29º to ~11º; grades into alluvial fan deposits down slope. May show soil development to 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 ~30º to ~36º (Selby, 1993). May be clast supported or matrix supported where voids between clasts filled with eolian sands and finer rock materials. May show soil development to Stage III carbonate development and clay-rich B horizons. 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 are thicker than 2 m and cover a wide area. Deposits form by translational, rotational movement or slumping of rock or sediment masses. May show soil development to 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 (Tsézhin Bií)

BEDROCK UNITS

VOLCANIC ROCKS

Volcanic rocks of the Hopi Buttes (Tsézhin Bií) Volcanic Field in the southern portion of the Satan Butte quadrangle (Miocene and Pliocene) were 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 to Pliocene Bidahochi Formation (G.H. Billingsley, written commun.2012).

Tc **Volcanic-crater sedimentary deposits (Miocene)**—Consists of undivided epiclastic and lacustrine volcanic and fluvial sedimentary rocks of gray, light-yellow, or 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, some interbedded with sandstone. Bedded ash and tuffaceous conglomerate and sandstone deposits are moderately sorted and commonly show intense soft-sediment deformation. Found within circular maar crater vent depressions that display inward-dipping stratified pyroclastic and surge deposits interbedded with lacustrine sedimentary deposits. The 1-m-thick (3-ft-thick) sandy sediments within the Coliseum diatreme between Indian Wells and Dilkon, west of the Sanders 30' x 60' quadrangle, contain fish fossils (Uyeno and Miller, 1965), implying a fluvial connection to the upper Bidahochi Formation southeast of Satan Butte. Thickness, 5–45+ m (16–148+ 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, 24–40+ m (79–131+ 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). One outcrop in the Satan Butte quadrangle on the southwest flank of Satan Butte. Thickness, 18+ m (59+ ft)

Tmu **Mixed monchiquite and basanite flows 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 the Satan Butte area. 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 the northern end of Wood Chop Mesa (fig. 1; Vazquez, 1998). Thickness, 8–36+ m (26–118+ ft)

SEDIMENTARY ROCKS

Bidahochi Formation (Pliocene and Miocene)—The Bidahochi Formation was defined by Repenning and Irwin (1954) and Shoemaker and others (1957, 1962) as three informal members in descending order: upper fluvial member, middle volcanic member, and lower mudstone and argillaceous sandstone member (Pliocene and Miocene). The Bidahochi Formation has been redefined by Billingsley (written commun. 2012) to include only two of the original members: the upper fluvial member (Tbu) and the lower mudstone and argillaceous sandstone member (Tbl). The lower portion of the Bidahochi Formation (Tbl) is associated with Miocene volcanic rocks in the Winslow 30' x 60' quadrangle geologic map to the west (G.H. Billingsley, written commun., 2012) and is considered Miocene age in the Sanders quadrangle as well, because these members interfinger and are approximately the same age. The middle volcanic member has been redefined by Billingsley (written commun. 2012) as volcanic rocks of the Hopi Buttes Volcanic Field

Tbu **Upper fluvial member (Pliocene)**—Slope- and minor cliff-forming clastic deposit. Upper fluvial member lies conformably on the lower mudstone and argillaceous sandstone member (Tbl), the volcanic rocks of the Hopi Buttes Volcanic Field, or the Moenave Formation. Some of the fluvial materials are locally derived from weathering of Hopi Buttes Volcanic Field 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, some coarse-grained sandstone and minor siltstone. Minor amounts of light brown (5YR 6/4) and greenish gray (5GY 6/1) claystone. Sandstones are thin-bedded to planar, tabular sandstones showing low-angle to high-angle planar, tabular cross beds. Cemented with calcite and silica in part; poorly to moderately consolidated. Found north and east of Pueblo Colorado Wash in the map area. Thickness, 30–90 m (98–295 ft)

Tbl **Lower mudstone and argillaceous sandstone member (Miocene)**—Slope- and minor cliff-forming lacustrine and air-fall volcanic deposit. Basal gravel lag of quartzite, chert, and petrified wood, probably derived from reworking of the Shinarump Member, is seen in some exposures. Uppermost beds are moderate-red (5R 5/4) and greenish-gray (5GY 6/1) claystones and minor siltstones. Soft claystone and siltstone beds are easily eroded below cliffs of volcanic rocks in Hopi Buttes area resulting in mass-movement deposits: landslide (Ql) or talus and rock fall (Qtr). Lowermost beds are moderate-red claystone (5R 5/4) overlain by white (N9) and grayish-orange-pink (10R 8/2) siltstone, marlstone, and claystone with minor light-gray (N7) sandstones along with thin, silicic ash beds. Light-greenish-gray (5GY 8/1) claystone, pinkish-gray (5YR 8/1) mudstone and siltstone, gray sandstone, and thin-bedded conglomerate, all primarily of lacustrine origin with thin light-gray (N8) silicic ash tuff beds in lower part. Sanidine minerals from a felsic vitric ash bed in lower part of unit at Triplets Mesa (informally named by Dallegge and others, 1998) just north of Wood Chop Mesa yield a $^{40}Ar/^{39}Ar$ age of 13.71±0.08 Ma (Dallegge, 1998). Unit unconformably overlies reddish-brown siltstone and sandstone of the Moenave Formation (Jm) east and northeast of Hopi Buttes. Unit unconformably overlies Owl Rock and Petrified Forest Members of the Chinle Formation in the subsurface farther east in the map area. This depositional contact marks an extensive Tertiary erosional surface cutting across Mesozoic rocks. Thickness, 22–98 m (72–321 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 though not present in the map area), Kayenta Formation (Jk) present in small outcrops along Pueblo Colorado Wash that were not mapped, and Navajo Sandstone (also not present in the map area). The Moenave Formation in the southern Colorado Plateau is considered Jurassic and not late Triassic as in southern Utah, on the basis of correlation and paleogeographic reconstruction (Edwards, 1985; Clemmensen and others, 1989). The map contact between 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 (Ꞧco) and overlying pale-yellowish-orange mudstone, siltstone, and sandstone of the Moenave Formation (Jm).

Jm **Moenave Formation (Lower Jurassic)**—Pale-reddish-brown (10R 5/4), moderate-reddish-brown (10R 4/6), and very pale orange (10YR 8/2) on fresh surfaces of cliff- and slope-forming, flat-bedded and 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). Unconformably overlain by the lower member of the Bidahochi Formation. Sharp contact with underlying Owl Rock Member of the Chinle Formation in the Sanders 30' x 60' quadrangle. Thickness, 9–21 m (30–70 ft)

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