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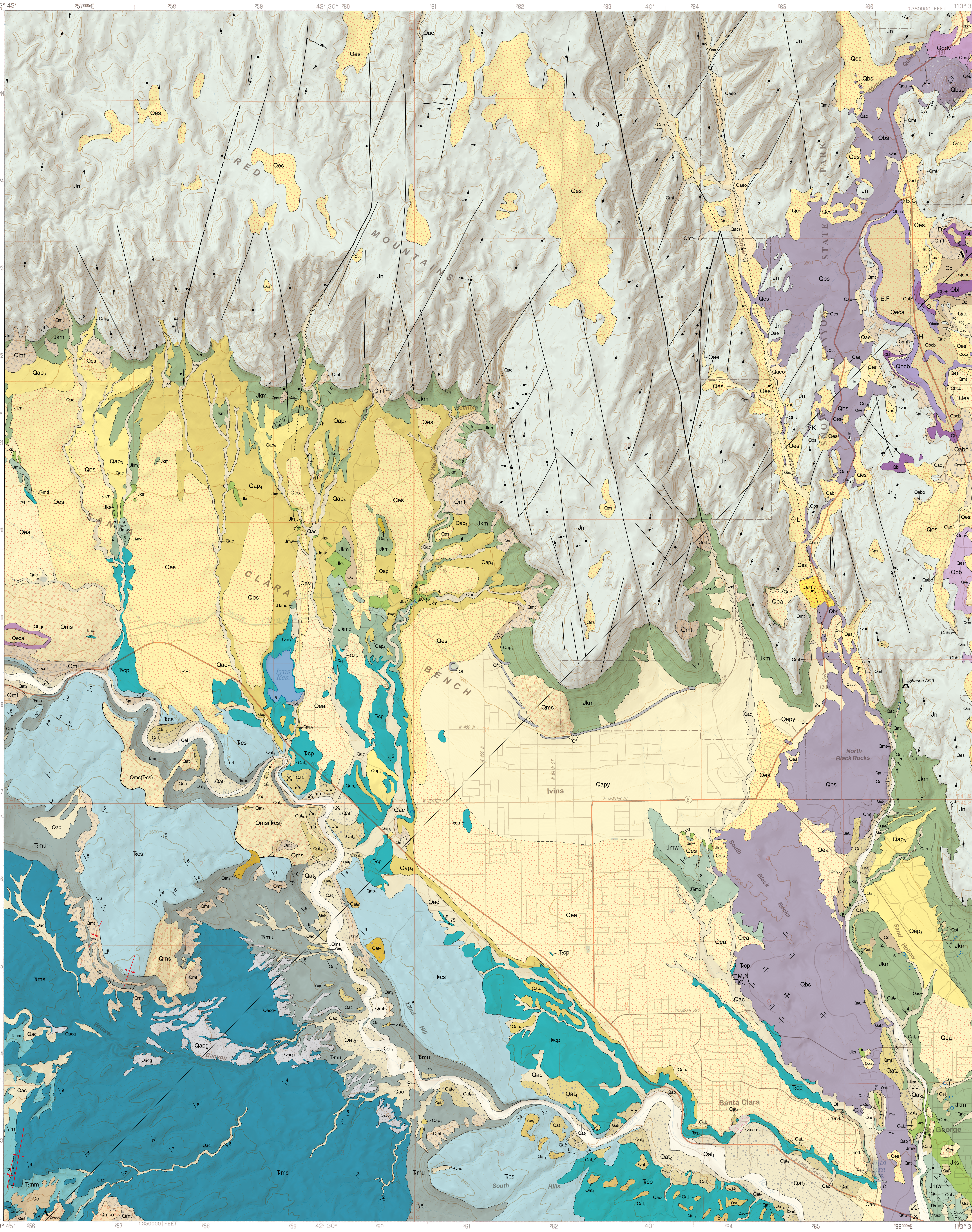

SCALE 1:24,000

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1 0.5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET

APPROXIMATE MEAN DECLINATION, 2015

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UTAH

QUADRANGLE LOCATION

GEOLOGIC MAP OF THE SANTA CLARA QUADRANGLE, WASHINGTON COUNTY, UTAH

by

Grant C. Willis and Janice M. Hayden

2015

1	2	3
4		5
6	7	8

1. Gunlock
2. Veyo
3. Saddle Mountain
4. Shivwits
5. Washington
6. Jarvis Peak
7. White Hills
8. Saint George

ADJOINING 7.5' QUADRANGLE NAMES

Topographic base compiled from multiple sources:
Contours generated from National Elevation Dataset 10 m DEM (2014)
PLSS and Transportation from AGRC (2014)
Hydrology from National Hydrography Dataset (2014)
UTM and Lat/Lon grid from USGS Topographic Map (1986)
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1866

Project Manager: Robert F. Biek
GIS and Cartography: Zachary W. Anderson and J. Buck Ehler

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This map was created from Geographic Information System (GIS) data.

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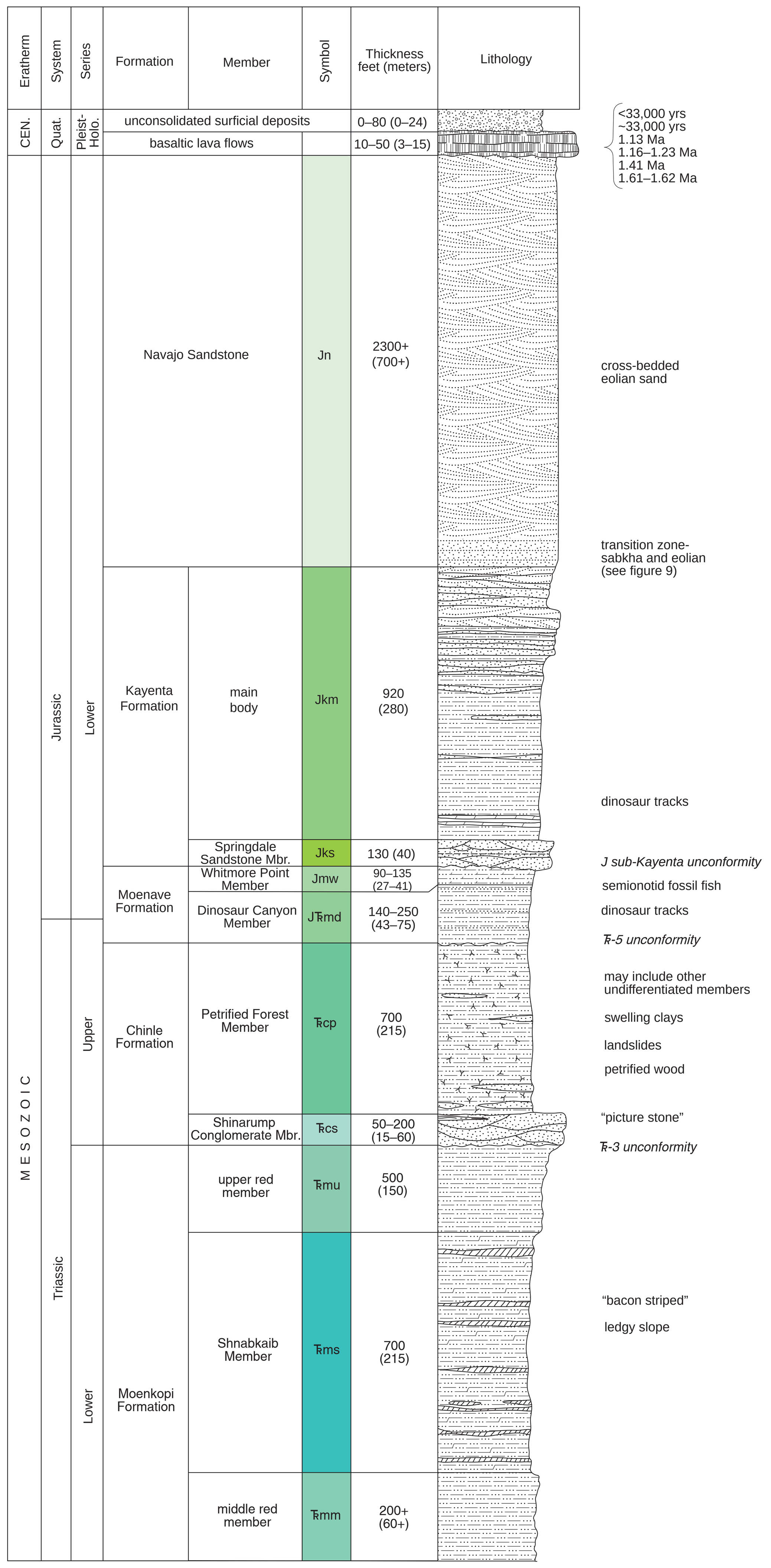
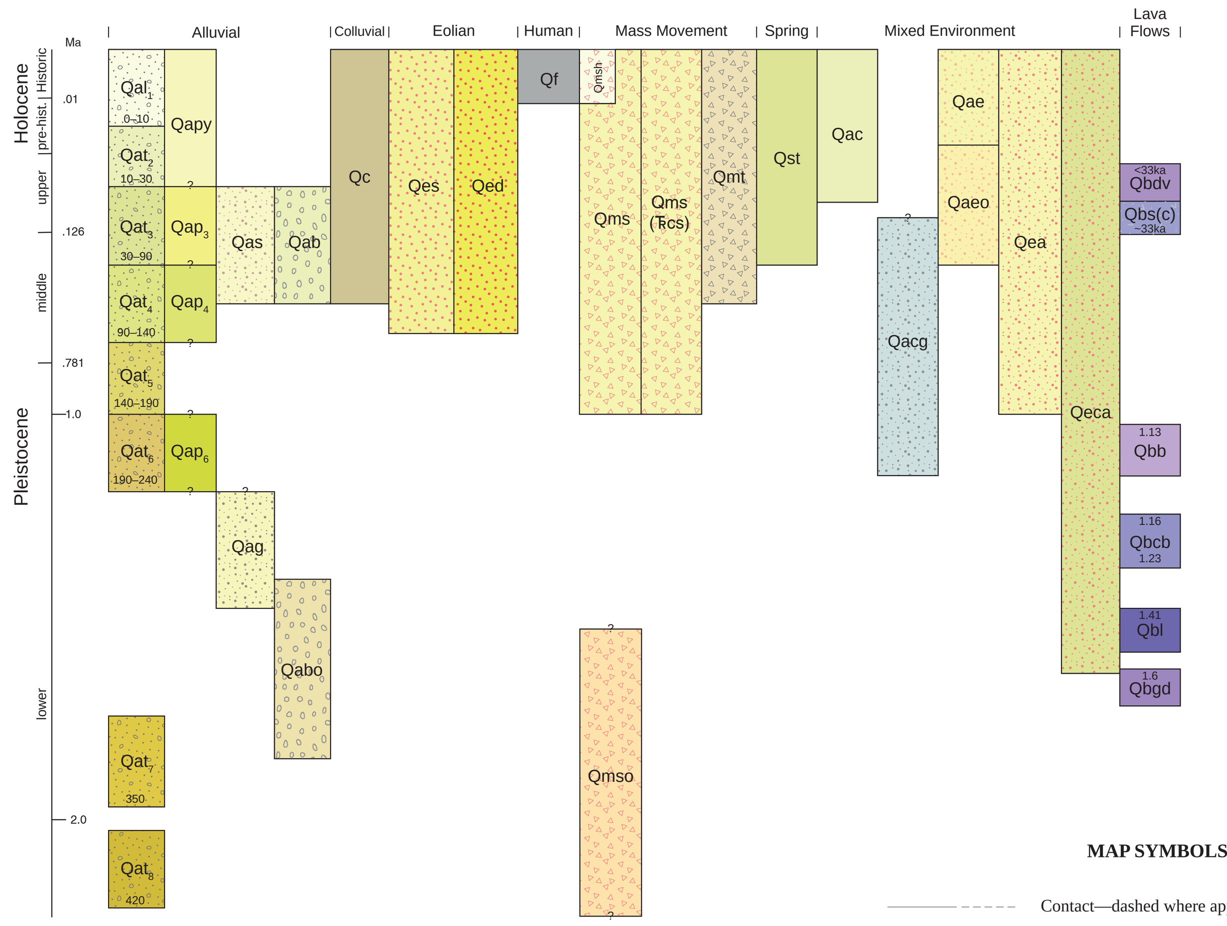
LITHOLOGIC COLUMN



CORRELATION OF MAP UNITS



MAP SYMBOLS

Contact—dashed where approximately located

High-angle fault—dashed where approximately located, dotted where concealed, bar and ball on down-thrown side

Landslide—main scarp

Lineament—mapped from aerial photographs and field mapping (only most prominent shown)

Axial trace of fold—dotted where concealed, arrows on trace show direction of plunge

Anticline

Syncline

Strike and dip of bedding

Strike and dip of joint

Inclined

Near-vertical

Gravel or road-fill pit

Rock quarry—primarily basalt for riprap and landscape stone

Spring

Rock arch

Cinder cone vent

Basaltic dike—arrow and number show dip direction and dip of dike

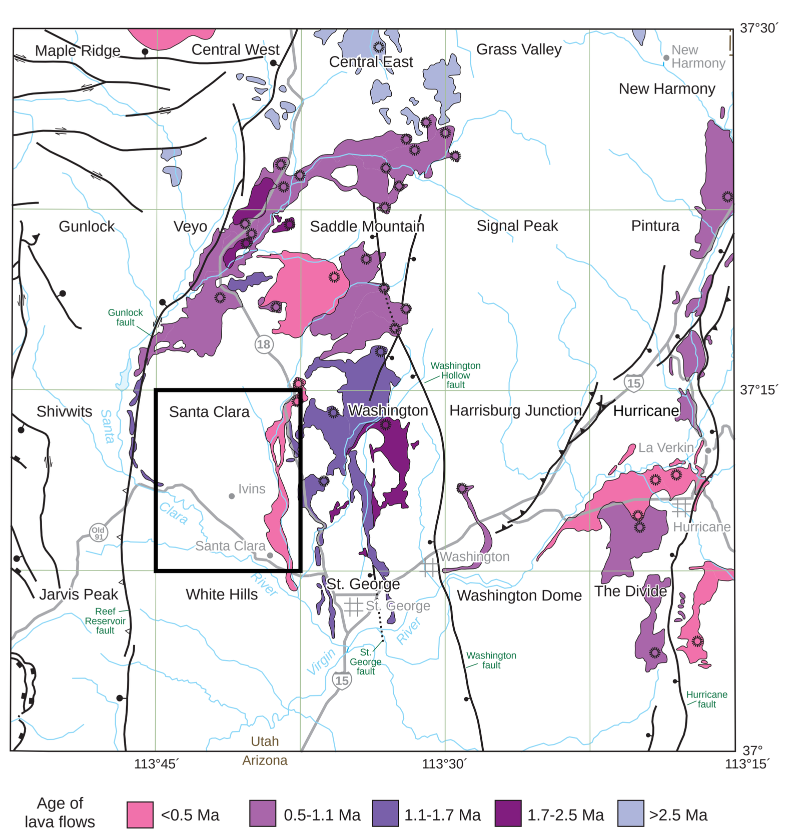
Sample location (letters refer to table 1)

A Navajo Sandstone geochemistry (appendix A)

G Basaltic lava flow—isotopic age or geochemistry (table 1)

M ^{14}C or OSL age (table 1)

INDEX MAP



Index map of the Santa Clara quadrangle area showing major highways, quadrangle names, young basalt flows grouped by age, cinder cones (starburst pattern), and major faults.

Table 1. *Summary and map label of geochronology and geochemistry samples from the Santa Clara quadrangle, Washington County, Utah.*

UGS Sample Number	Map Unit	Map Unit Label	Map Location Label	Longitude (DD)	Latitude (DD)	UTM_N	UTM_E	Age (Ma or cal yr.)	Reference	Reference Notes
Geochronology										
VR42-08	Cedar Bench flow	Qbcb	G	-113.6314	37.2195	4122263	266515	1.16±0.03 Ma	UGS and USGS (2014)	Whole rock $^{40}Ar/^{39}Ar$; USGS Laboratory
SC100605-1	sand under Santa Clara flow	Qbs/Qac	M	-113.6557	37.1502	4114637	264143	32,600±400 cal yr	UGS and USU-LL (2014)	charcoal, ^{14}C, Beta-Analytic, see lab data in footnotes
SC030207-1	sand under Santa Clara flow	Qbs/Qac	N	-113.6557	37.1502	4114637	264143	40,030±2500 cal yr	UGS and USU-LL (2014)	sand, OSL, USU-LL
SC030207-2	sand under Santa Clara flow	Qbs/Qac	O	-113.6555	37.1497	4114580	264159	40,390±2490 cal yr	UGS and USU-LL (2014)	sand, OSL, USU-LL
SC030207-3	sand under Santa Clara flow	Qbs/Qac	P	-113.6555	37.1497	4114580	264159	40,610±2930 cal yr	UGS and USU-LL (2014)	sand, OSL, USU-LL
Geochemistry										
SC0302	Navajo Sandstone	Jn	A	-113.6272	37.2494	4125779	266983		appendix A (booklet)	iron content analysis
SC-1	Cedar Bench flow	Qbcb	E	-113.6374	37.2202	4122363	265982		Biek and Ehler (2007)	see reference for data
SC-1a	Cedar Bench flow	Qbcb	F	-113.6374	37.2202	4122363	265982		Biek and Ehler (2007)	see reference for data
SC-3	Cedar Bench flow	Qbcb	B	-113.6339	37.2303	4123478	266323		Biek and Ehler (2007)	see reference for data
SC-3a	Cedar Bench flow	Qbcb	C	-113.6339	37.2303	4123478	266323		Biek and Ehler (2007)	see reference for data
SC111506-1	Cedar Bench flow	Qbcb	I	-113.6334	37.2142	4121682	266318		Biek and Ehler (2007)	see reference for data
SC1107	Cedar Bench flow	Qbcb	H	-113.6322	37.2163	4121920	266433		Biek and Ehler (2007)	see reference for data
SC111506-2	Lava Ridge flow	Qbl	J	-113.6342	37.2143	4121697	266252		Biek and Ehler (2007)	see reference for data
SC-6	Lava Ridge flow	Qbl	D	-113.6283	37.2275	4123143	266812		Biek and Ehler (2007)	see reference for data
92N2	Santa Clara flow	Qbsc	L	-113.6481	37.1975	4119863	264969		Biek and Ehler (2007)	see reference for data
92N3	Santa Clara flow	Qbsc	K	-113.6461	37.2069	4120909	265172		Biek and Ehler (2007)	see reference for data
92N9	Santa Clara flow	Qbsc	Q	-113.6392	37.1363	4113060	265569		Biek and Ehler (2007)	see reference for data

Notes:

See references for full data and laboratory reports

Cedar Bench flow was called Snow Canyon Overlook flow in Willis and Higgins (1996)
Geochronologic data discussed in Biek and others (2010)
Latitude and longitude based on NAD27 for SC samples
DD – Decimal degree
Northing – meters north; Easting - meters east; UTM NAD27 zone 12
Geochemistry lists samples from this quadrangle; most flows have additional analyses from adjacent quadrangles not listed here (see Biek and Ehler, 2007, for analyses from UGS projects from 1980s–2007)
USU-LL – Utah State University Luminescence Laboratory
Ma = millions of years ago
cal yr = calendar year before present (1950)
SC100605-1
Analysis by Beta Analytic, Inc.; Analytical data: Beta Lab #210950
Calendar conversion following Fairbanks and others (2005)
Measured Radiocarbon Age: 27,200 ± 250 BP; $^{13}C/^{12}C$ Ratio: -20.5 o/oo
Conventional Radiocarbon Age: 27,270 ± 250 BP; Calendar Years Conversion: 32,594±308

Figure 1. *Sandstone in the middle part of the Navajo Sandstone in Snow Canyon State Park shows sub-planar cross-bed bounding surfaces on a large scale, but is dominated by cross-bedding when examined in detail. The primary color is medium reddish brown, which is caused by a thin patina of hematite (iron-oxide) that coats each sand grain; acidic (organic) water migrating through the rock reduces (bleaches) and then transports the reddish iron-oxide (hematite), leaving the sandstone pale yellowish gray to grayish white. Upon encountering oxidizing fluid (fresh water), the iron is immediately precipitated as goethite and hematite in dense ironstone pods, bands, nodules, or round balls (Navajo berries or Moqui marbles).*

Figure 2. *View northeastward across much of the Santa Clara quadrangle (fore and middle ground) toward the Pine Valley Mountains (background on right side). The blocky ledge in the foreground is the Shinarump Conglomerate Member of the Chinle Formation; it is commonly quarried for building and landscaping stone. It is overlain by dark reddish-brown to gray, banded, slope-forming Petrified Forest Member. Reddish-brown cliffs and ledges are weakly bleached sandstone of the upper Kayenta and lower Navajo Formations. The stark white sandstone in the distance is highly bleached upper Navajo Sandstone. Black basalt of the Santa Clara flow spreads out across the Moenave and Kayenta Formations in the lowlands.*

Figure 3. *View northeastward through a gap between the Navajo Sandstone and the Santa Clara basalt cinder cone toward the snow-covered Pine Valley Mountains. This sandstone was probably originally entirely medium reddish brown due to a uniform patina of hematitic iron oxide that evenly coated individual grains. Organic fluid migrating through the rock reduced the iron, allowing it to be transported in solution until encountering oxidizing fluids, which caused the iron to immediately precipitate in concentrated ironstone bands, blebs, and nodules ("berries"), leaving most of the rock very pale yellowish gray to white. The Santa Clara basalt flow forms the dark sage brush-covered flats near the highway. The slightly younger Diamond Valley flow forms the black band just behind the Santa Clara flow.*

Figure 4. *A rain-on-snow event in uplands north of the St. George area in January 2005 caused the Santa Clara River to swell from normal discharge of 6 cfs (cubic feet per second) to 6200 cfs (0.17-175 cubic meters per second). Flooding destroyed homes, infrastructure, and farmland. Before (left) and after (right) photos provided by Cory Cram of the Washington County Water Conservancy District.*

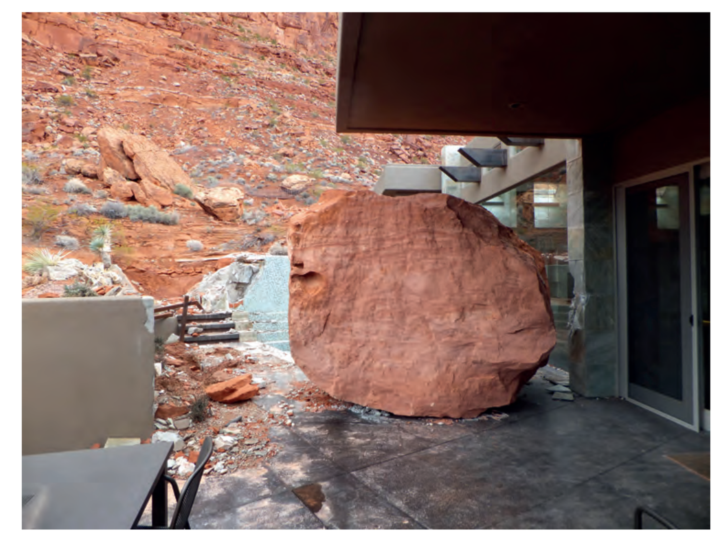


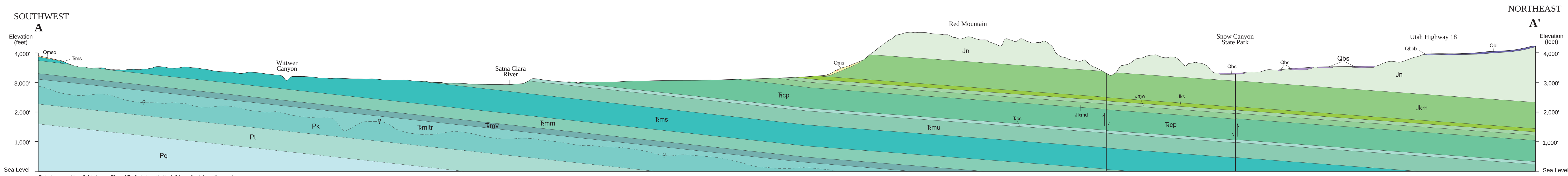
Figure 5. *In January 2013, a boulder from the base of the Navajo Sandstone split off the cliff at top of photo and tumbled down the slope, bounced over a fence, and rolled through two rebar-reinforced concrete walls before being stopped by the pillar of a house in the Kachina Cliffs neighborhood of the Entrada development near the east side of the quadrangle. Though damaged, the pillar prevented the boulder from crashing through the large glass windows.*

Figure 6. *Landslides are a significant concern in the quadrangle. Though the Kayenta and Moenkopi and other formations can slide, of most concern are members of the Chinle Formation. In this photograph, the Truman Drive landslide primarily involves the Petrified Forest Member of the Chinle and overlying terrace gravel. It has slid and expanded several times over the last few decades, and currently (2014) three homes have been condemned (Lund and others, 2007, 2008). The main (head) scarp is the vertical face that has advanced toward the houses. The pillars are concrete caissons from a failed earlier attempt to stabilize the slide. Truman Drive is the narrow slope near the right edge of the photo; it has been abandoned and now is used for a drainage line installed to move water away from the slide.*

Figure 7. *Thick alluvial sediment directly underlying basalt of the Santa Clara flow in the south-central part of the quadrangle. A piece of charcoal from just under the basalt yielded an age of about 32,600 cal yr B.P., and the sediment yielded OSL ages of about 40,000 yr (table 1).*

Figure 8. *Johnson Arch in Snow Canyon State Park in the east-central part of the quadrangle is eroded into a fin in the lower part of the Navajo Sandstone.*

Figure 9. *The basal part of the Navajo Sandstone is dominated by planar bedding rather than cross bedding typical of the main part of the formation. The planar bedding, combined with frosted grains and other eolian features, indicates that the sand was blown onto a flat sahbka-like environment. The contact with the Kayenta Formation is gradational in most areas but here is fairly sharp and is just visible at the base of the lowest cliff.*



GEOLOGIC MAP OF THE SANTA CLARA QUADRANGLE, WASHINGTON COUNTY, UTAH

by Grant C. Willis and Janice M. Hayden

UTAH DNR GEOLOGICAL SURVEY

MAP 271DM
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2015

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by Grant C. Willis and Janice M. Hayden

SCALE: 1:24,000

Cover photo: *Northeast view across much of the Santa Clara quadrangle toward the Pine Valley Mountains.*

ISBN: 978-1-55791-905-2

MAP 271DM
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CONTENTS

GEOLOGIC MAP OF THE SANTA CLARA QUADRANGLE, WASHINGTON COUNTY, UTAH

by Grant C. Willis and Janice M. Hayden

SUMMARY

The Santa Clara quadrangle is in the St. George basin of southwestern Utah and is popular for its scenery of vivid red and white sandstone contrasting with black basaltic lava flows, particularly at Snow Canyon State Park located in the northeast part of the quadrangle (index map, plate 2; figure 1). The quadrangle is in the transition zone between the Basin and Range Province to the west and the Colorado Plateau to the east and contains structural elements of both (Hamblin, 1970b; Hintze, 1986; Biek and others, 2010). It is near the leading edge of the Late Cretaceous–Paleocene Sevier orogenic thrust belt and a basal blind thrust fault is postulated in underlying Cambrian strata. The rocks have been compressed into the west limb of the broad, poorly defined, gently north-northeast plunging St. George syncline (Cordova,1978; called the Pine Valley Mountain syncline in some publications, e.g., Hintze, 1986), resulting in a dip of about four to seven degrees to the northeast across the quadrangle (figure 2). This movement partially shattered brittle rock and produced a set of widely spaced, subparallel joints and deformation band shear zones that mostly trend north-northwest in the brittle, massively bedded Jurassic Navajo Sandstone (Davis, 1999) (plate 1). Compression and subsequent extensional deformation created localized and more closely spaced sets of parallel joints that trend mostly northeast. These two intersecting joint sets, along with the uniform nature of the cross-bedded Navajo Sandstone, control the weathering pattern of the rock and contribute to the intricate landscape of Snow Canyon State Park. Locally, steeper dips are associated with complex folds in the highly gypsiferous Shnabkaib Member of the Moenkopi Formation; these may be due to minor disharmonic folding during the Sevier orogeny or to nonstructural movement and dissolution of gypsum. Axes of larger folds in the Shnabkaib, which locally deform overlying formations, are shown on the map (plate 1). The transition zone is also part of the active southern segment of the Intermountain Seismic Belt, which coincides with the boundary between relatively thin crust and lithosphere of the Basin and Range Province and thicker, more stable crust of the Colorado Plateau (Arabasz and Julander, 1986; Lund and others, 2008). The zone consists of a series of down-to-the-west normal faults that step down from the Colorado Plateau into the Basin and Range Province. The quadrangle sits on an intermediate structural block bounded on the west by the Grand Wash–Gunlock fault, with a stratigraphic displacement of about 3000 feet (900 m) near Gunlock and about 1500 feet (450 m) near the Utah-Arizona border (Hintze, 1986; Hammond, 1991), and bounded on the east by the Hurricane fault, with offset of 3600 to 4900 feet (1100–1500 m) (Biek and others, 2010). The block is also cut by smaller faults, including the Washington and St. George faults, both east of the quadrangle (Hayden and Willis, 2011; Willis and Hayden, in press), and smaller unnamed faults within the quadrangle.

The upper three members of the Lower Triassic Moenkopi Formation—the middle red, Shnabkaib, and upper red—with about 1400 feet (425 m) of section exposed in the southwest corner of the map, are the oldest exposed rocks in the quadrangle. They are unconformably overlain by the Shinarump Conglomerate and Petrified Forest Members of the Upper Triassic Chinle Formation, which combined are 750 to 900 feet (230–275 m) thick (figure 2). Other poorly defined and undifferentiated members of the Chinle Formation may be present but have not been defined in this area (see discussion in unit description and in Biek and others, 2010). Uppermost Triassic and Lower Jurassic strata crop out in the northeast half of the quadrangle and consist of the Dinosaur Canyon and Whitmore Point Members of the Moenave Formation, 230 to 385 feet (70–120 m) thick; Springdale Sandstone Member and the main body of the Kayenta Formation, 1050 feet (320 m) thick; and Navajo Sandstone with 2300 feet (700 m) (most of the formation) exposed.

Located in the northern part of the Western Grand Canyon basaltic field, which extends across northwestern Arizona, southwestern Utah, and southeastern Nevada (Hamblin, 1963, 1970a, 1987; Best and Brimhall, 1970, 1974; Best and others, 1980; Smith and others, 1999; Johnson and others, 2010), the quadrangle includes six Quaternary basalt flows that followed stream drainages from vents mostly north and east of the map area (Biek and others, 2010; Hayden, in press; Willis and Hayden, in press) (plate 2, index map). The cinder cone and vent for the Santa Clara lava flow are in the northeast corner of the quadrangle (figure 3). Because of continued regional uplift and subsequent erosion of adjacent sedimentary rocks, drainages next to these flows are actively incising such that older flows cap successively higher ridges, forming inverted valleys (Hamblin, 1963, 1970a, 1987; Hamblin and others, 1981). Continued relative uplift and incision are also documented by

multiple levels of terrace alluvium with thick calcic soil (indicating relatively old age) along the Santa Clara River and its tributaries, and by other dissected alluvial surfaces.

GEOLOGIC RESOURCES

Geologic resources include gravel from alluvial terrace deposits and stone from bedrock sources. Minor gypsum, copper mineralization, and ironstone are also present. Water resources are increasingly important as population increases and development continues. The Utah Geological Survey website at http://geology.utah.gov provides additional information on geologic resources in the area.

Gravel, Sand, Road Fill, and Riprap

Gravel, sand, road fill, and riprap are in high demand in the St. George area because of rapid growth. Gravel, essential for construction, is the most widely utilized resource in the quadrangle. The primary deposits are in alluvial terrace deposits near the Santa Clara River. Low-level deposits ($Qat_{2\text{-}4}$) are preferred since these deposits have less calcic soil (caliche) than the older, higher-level deposits. The caliche makes quarrying more difficult, and makes the gravel less desirable for concrete and asphalt. Several deposits have been covered by development and are no longer accessible. Terrace alluvium in the Sand Hollow area along the east edge of the map ($Qat_{3,4}$) and alluvial boulder deposits (Qab, Qabo) also contain gravel and unconsolidated materials suitable as road fill. Boulders from the Chinle and Kayenta Formations, basalt flows, colluvium, and talus are commonly used as riprap along rivers and washes. Several pits for talus blocks have been opened adjacent to the basalt-capped ridges. Road-fill has been acquired from several surficial deposits in the quadrangle. However, like the gravel, many of these sources are being blocked by development. Sand for local uses has been obtained from eolian sand deposits (Qes, Qed, Qea) within the quadrangle.

Building Stone

Early settlers used blocks of sandstone from the Kayenta Formation and from jointed basalt flows for building walls and foundations. Blocks from the Shinarump Conglomerate and other resistant units are popular for use as landscaping stones and in retaining walls (figure 2). No building stone quarries are active within the quadrangle at the time of this publication except where rocks excavated during construction of homes and roads on hillsides are reused for landscaping and to build retaining walls.

Ornamental Stone

Petrified wood from the Petrified Forest Member of the Chinle Formation is used to construct monuments, decorate rock gardens and fireplace mantles, and to sell as curiosities in gift shops. "Picture rock" or "landscape stone" from the Shinarump Conglomerate and lower Petrified Forest Members of the Chinle Formation is polished into ornamental spheres, coasters, and clock bases, and is cut into slabs that are mounted in picture frames. Picture rock is well-lithified sandstone with extensive Liesegang banding that imparts alternating light-brown, dark-brown, and orangish-brown swirls, waves, bands, and other patterns in the rock. In cut pieces these complexly intertwined bands resemble landscape silhouettes. Currently, no quarries for this stone are active within the quadrangle, but several outcrops of picture rock exist.

Gypsum

The Shnabkaib Member of the Moenkopi Formation (₸ms) and gypsiferous tufa deposits (Qacg) both contain bedded gypsum. Beds are generally less than 10 feet (3 m) thick and typically contain multiple sandstone (₸ms) or sand and gravel (Qacg) partings. We have not conducted tests for quality or purity on samples from the quadrangle.

Metals

No metallic resources are known to have been produced from the quadrangle, but minor malachite and chrysocolla mineralization is present in a small outcrop of the Whitmore Point Member of the Moenave Formation in the SW1/4, section 4, T. 42 S., R. 16 W. The overlying Springdale Sandstone Member of the Kayenta Formation is a known host of silver, copper, and uranium in the Silver Reef area about 15 miles (24 km) northeast of the quadrangle (James and Newman, 1986; Proctor and Brimhall, 1986; Biek and Rohrer, 2006). Thick, discordant lenses of dark-brown to brownish-black ironstone are locally common in the Navajo Sandstone in Snow Canyon. The iron, mostly in the form of hematite and goethite, fills interstitial pore space between sand grains. Samples yielded as high as 21 percent iron oxide (appendix A).

Oil and Natural Gas

No exploratory drilling for oil or gas has been done in the Santa Clara quadrangle. The nearest production was from the Virgin oil field, 20 miles (32 km) northeast of St. George, adjacent to Zion National Park. It produced 195,000 barrels (31,000 m^3) of oil from 30 wells, although over 200 wells were drilled (Eppinger and others, 1990). Oil was derived from a sandstone and vuggy limestone interval 1 to 8 feet (0.3–2.4 m) thick in the uppermost part of the Timpoweap Member of the Triassic Moenkopi Formation, with minor production from the Pennsylvanian Callville Limestone. These formations also underlie the Santa Clara quadrangle, but have not been tested.

Geothermal Resources

The quadrangle is in an area with geothermal potential (Mabey and Budding, 1985; Budding and Sommer, 1986; Blackett and Wakefield, 2004; also see Utah Geological Survey website at http://geology.utah.gov/emp/geothermal/index.htm). A few warm springs occur within about 20 miles (30 km) of the Santa Clara quadrangle, but the only warm spring in the quadrangle is Snow Spring, in Snow Canyon State Park, a small spring with discharge at 70°F (21°C) (near the lower limit for classification as a thermal spring). Veyo Hot Spring, about 11 miles (18 km) north of the quadrangle, discharges at 90°F (32.2°C). A water well drilled near the cinder cone in Big Sand flats just east of the quadrangle may have encountered hot water (possibly steam) at about 900 feet (270 m) (Pete Tolman, verbal communication, 1995), but no testing has been reported and elevated temperatures have not been verified. Elevated temperatures in a few area springs are the result of deep circulation of groundwater driven by topographic relief and normal geothermal gradients and are not related to late Quaternary basalt vents in the area; basalt ascends from depths of many miles from near the base of the lithosphere through relatively small pipe-like conduits, which cool quickly after eruptions and do not produce long-lasting near-surface elevated temperatures (Smith and others, 2009). On a cold morning in January 2010, a state park employee observed a small white haze in the northern part of the park (first thought to be smoke). Closer investigation revealed that a small lava tube with an opening of about 3 by 2 feet (1 x 0.6 m) was venting warm, moist vapor measured at 65°F (18°C) (verbal communication, Jenny D. Stucki, Snow Canyon State Park naturalist, 2010). The warm air was probably caused by residual heat from summer solar heating of the basalt, but possibly may indicate warm sub-basalt groundwater welling upward along deep fractures.

Water

Water is of great importance in the St. George area since the population is rapidly increasing and much of the valley receives less than 8 inches (20 cm) of precipitation per year (Cordova and others, 1972; Cordova, 1978; Clyde, 1987; Horrocks-Carollo Engineers, 1993; Utah Division of Water Resources, 1993; Hurlow, 1998; Western Regional Climate Center: www.wrcc.dri.edu; accessed May 14, 2014). Water resources of the map area are discussed in Hurlow (1998); additional resources and links are available at http://geology.utah.gov/utahgeo/water/index.htm.

Cordova and others (1972), Sandberg and Sultz (1985), and Hurlow (1998) summarized flow data on perennial streams in the area and reported on surface-water quality in the central Virgin River basin. The only perennial stream in the quadrangle, the Santa Clara River, flows from northwest to southeast across the southwest corner of the quadrangle and is extensively used for agriculture and culinary water. Flows on the river vary tremendously as illustrated by data from the U.S. Geological Survey stream gauge at the town of Gunlock about 8 miles (13 km) upstream of the quadrangle (www.waterdata.usgs.gov, accessed August 21, 2013). There, average annual flow is about 20 cubic feet per second (cfs) (0.6 cubic meters per second [cms]). Daily mean spring to early summer flow is about 70 to 200 cfs (2–5.6 cms), late summer is about 15 to 40 cfs (0.4–1.1 cms), and fall is about 5 to 20 cfs (0.14–0.57 cms). Peak flow recorded near Santa Clara during flood events was 6390 cfs (181 cms) in 1966, 6200 cfs (165 cms) in 2005, and 7730 cfs in 2010 (219 cms) (Lund and others, 2007; www.waterdata.usgs.gov, accessed August 21, 2013). A few other washes have small spring-fed seeps that flow at the surface for short distances.

The Santa Clara River controls base level in the quadrangle and the unconfined potentiometric surface slopes toward the river from both the northeast and the southwest (Cordova and others, 1972; Cordova, 1978; Clyde, 1987; Hurlow, 1998). Important aquifers in the quadrangle are in the Moenkopi, Chinle, Moenave, Kayenta, and Navajo Formations, and in thin unconsolidated deposits. Of these, the Navajo aquifer (which includes the upper part of the Kayenta Formation) is the most important. It consists of about 2300 feet (700 m) of fractured and porous, well-sorted, fine- to medium-grained sandstone exposed throughout much of the northern half of the quadrangle (figure 1). The primary recharge area for the Navajo aquifer is limited to the Navajo outcrop belt (Freethey, 1993) since the overlying Temple Cap and Carmel Formations form a barrier that mostly seals the Navajo from surface waters. Recharge is primarily from precipitation on the Navajo and from streams crossing the Navajo that originate in the Pine Valley and Bull Valley Mountains to the northeast and north. Wells in the Navajo aquifer in Snow Canyon and below Gunlock Reservoir to the northwest of the quadrangle are a major source of domestic water for the area (Horrocks-Carollo Engineers, 1993; Willis and Higgins, 1996; Hurlow, 1998). Several small springs issue from near the top of the Kayenta Formation in the northern part of the quadrangle. The gradational Navajo-Kayenta contact zone separates underlying, low-porosity, muddy siltstone and sandstone from overlying, fractured, porous sandstone and forms the base of the Navajo aquifer. The springs, primarily used for irrigation, issue from where south-flowing water "spills" over this natural threshold. Many small springs also issue from sandy intervals in the lower and middle parts of the Kayenta Formation and the Dinosaur Canyon Member of the Moenave Formation. In general, water is fresh and of high quality in the Navajo and Kayenta aquifers, but has higher total dissolved solids concentrations ranging up to saline in older formations. Water quality in unconsolidated-sediment aquifers varies considerably depending upon local conditions.

GEOLOGIC HAZARDS

Geologic hazards pose a risk to people's safety and have caused significant damage to roads and structures in the St. George/Santa Clara area, and concern increases as development continues. Expansive, soluble, and collapsible soil and rock; earthquakes; flooding and debris flows (figure 4); rockfalls (most from sandstone and basalt ledges above steep slopes) (figure 5); landslides (figure 6); and earthquakes have caused millions of dollars in damage as well as injuries and deaths in the St. George area in recent years, and the Santa Clara quadrangle includes many areas of concern (Hilburn and others, 2006; Lund and others, 2008; Biek and others, 2010; Lund and others, 2010; Knudsen and others, 2013, and references therein). Radon gas is of significant concern in the area, especially in areas of the Chinle Formation or deposits derived from it (Solomon, 1992a, 1992b); volcanic eruptions and other geologic hazards are also possible. Geologic hazards in the area are shown on a series of maps and discussed in detail in Lund and others (2008). The Utah Geological Survey website at http://geology.utah.gov/utahgeo/hazards/index.htm provides additional information and resources on geologic hazards.

The Petrified Forest Member of the Chinle Formation, which is widespread throughout the quadrangle, has caused many problems in southwest Utah, including in and near Santa Clara City (Christenson, 1992; Lowe, 1992; Lund and others, 2007, 2008). Locally known as "blue clay," the formation contains abundant smectitic clays that expand or swell when wetted. Lund and others (2007) noted specific incidents of major landslides and foundation damage linked to this unit, including the Truman Drive landslide along the bluffs north of downtown Santa Clara (figure 6). Geotechnical studies are recommended anywhere this formation or soils derived from it are suspected.

Also of recent note in the quadrangle is flooding. A heavy rain-on-snow event in higher elevations north of the quadrangle in January 2005 caused the Santa Clara River to swell from 6 cfs to 6200 cfs peak flow (0.17–175 cms) (www.waterdata.usgs.gov, accessed August 21, 2013). The resulting flood (including the Virgin River, which joins the Santa Clara River just downstream of the quadrangle), caused $225 million in damage to local infrastructure and personal property, including damaging or destroying 28 homes (figure 4) (Hilburn and Hunt, 2006; Wilkowske and others, 2006). Daily mean flow on the Santa Clara River during this event was 3300 cfs (93 cms) on January 10th. Much of the damage was due to erosion of Qat_2 terrace alluvium, but lateral river-channel migration also undercut the edges of some Qat_3 terrace deposits even though the deposits were well above the high water line. In 2005, local officials armored river banks adjacent to developed property and channelized the river with basalt-boulder levees (not mapped) that protected property during an even larger flood event in 2010 in which peak flow on December 21st was 7730 cfs (219 cms) and mean daily flow was 4340 cfs (123 cms) (www.waterdata.usgs.gov, accessed August 21, 2013). Flooding continues to be a concern along both major and minor drainages in the quadrangle.

DESCRIPTION OF MAP UNITS

QUATERNARY

Alluvial Deposits

Qal_1 **Stream alluvium** (Holocene) – Stratified, moderately to well-sorted clay, silt, sand, and gravel deposits in large, active drainages; in addition to locally derived sandstone and basalt, clasts are quartzite, limestone, and igneous rocks derived from outside the quadrangle; mapped along the Santa Clara River, which flows southeast from near the middle of the western edge of the quadrangle; also mapped along Sand Hollow Wash; includes alluvial-fan and colluvial deposits too small to map separately, and alluvial-terrace deposits up to 10 feet (3 m) above modern channels; 0 to 10 feet (0–6 m) exposed but channel fill may be tens of feet thicker.

Qat_2–Qat_8

Terrace alluvium (Holocene to lower Pleistocene) – Moderately to well-sorted sand, silt, clay, and pebble to boulder gravel that forms flat to gently sloping surfaces at several levels above modern river and stream floodplains; clasts, up to about 8 inches (20 cm) in diameter with a few in excess of 12 inches (30 cm), are subrounded to well rounded and many are imbricated; most clasts are quartzite, limestone, basalt, or intrusive igneous rocks exotic to the quadrangle, indicating a source several miles upstream; locally, angular boulders or blocks from local sources are incorporated into the deposits; eolian sand and silt are common on the terrace deposits; map unit commonly includes colluvium drapped down-slope from terraces; important local source of sand and gravel; all levels have some soil development and most terraces have a calcic soil (caliche) layer or horizon that is thicker in older deposits (as much as stage VI—see description of carbonate soil morphology stages in Birkeland and others, 1991); large terrace benches are developed or cultivated along the Santa Clara River; deposited primarily in stream-channel and floodplain environments; most extensive near the Santa Clara River where the river has progressively shifted northeast down the dip slope of the resistant Shinarump Conglomerate by preferentially cutting into the overlying non-resistant Petrified Forest Member and leaving "stair-step" terrace deposits; thickness varies from 0 to 30 feet (0–9 m); subscript denotes height above active drainages: level 2 deposits are mostly 10 to 30 feet (3–9 m), level 3 deposits are 30 to 90 feet (9–25 m), level 4 deposits are 90 to 140 feet (25–40 m), level 5 deposits are 140 to 190 feet (40–55 m), and level 6 deposits are 190 to 240 feet (55–73m) above the modern drainages; one exposure of a level 7 deposit is mapped at 350 feet (107 m) and one exposure of a level 8 deposit, mapped in section 2, T. 42 S., R. 17 W., is 420 feet (128 m) above the river and is capped by a stage VI calcic soil (caliche) that forms a blocky ledge over 8 feet (2.4 m) thick.

Hereford and others (1996), working upstream on Virgin River deposits near the town of Rockville, determined that terrace deposits less than about 30 feet (9 m) above the active river channel (mapped as Qal_1 and some Qat_2) are late Holocene in age (probably less than 1000 years old) and are related to short-term (decades to a few hundred years) cyclic changes from incision to deposition in the "modern" river channel (some higher Qat_2 remnants may be from older cycles). They showed that the river cycles through episodes of incision and backfilling of a few tens of feet with associated channel widening, meander shifts, and channel narrowing that are controlled primarily by short-term changes in climate and in the frequency, intensity, and duration of major storms. They also estimated that most higher (older) river-terrace deposits, mapped as $Qat_{3–8}$, are late Pleistocene and older. Although these older deposits have not been dated directly, their ages can be estimated using long-term incision rates determined from the age of basaltic lava flows and relative height above the current drainage level, combined with the amount of soil development and degree of lithification (Willis and Biek, 2001; Biek and others, 2010). The average long-term incision rate along the Santa Clara River, based on the Gunlock–Dammeron Valley North lava flow just north of the river channel in the middle of the western edge of the quadrangle and projecting to the Cedar Bench lava flow (called Airport lava flow in some preceding publications; e.g. Willis and Biek, 2001), is about 190 feet per million years (60 m/myr). While many uncertainties must be taken into consideration, such as incision rates that have probably varied and movement on nearby faults that may affect calculations, this suggests that Qat_3 deposits are mostly about 150,000 to 450,000 years old, but locally may be younger; Qat_4 – about 450,000 to 750,000 years old; Qat_5 – about 750,000 to 1 million years old; Qat_6 – about 1 to 1.3 million years old; Qat_7 – about 1.8 million years old; and Qat_8 – about 2.2 million years old.

Qapy, $Qap_{3,4,6}$

Pediment-mantle alluvium (Holocene to lower Pleistocene) – Poorly sorted, angular- to subrounded, gravel- to boulder-sized, pale- to moderate-reddish-orange sandstone clasts deposited as debris flows and alluvium shed from the upper part of the Kayenta Formation and Navajo Sandstone; boulders near mountains are angular and as much as 20 feet (6 m) in diameter whereas those near the river are subrounded and up to 2 feet (0.6 m) in diameter; typically blanketed by loose eolian sand (Qes) and mixed eolian sand and alluvium (Qea) that are mapped separately where extensive; mapped in four levels based on elevation above and amount of dissection by washes that cross them; numbers are inferred correlation with terrace alluvium since many local washes are not graded to the Santa Clara River (no deposits correlative with terrace levels 5 and 7 were recognized); youngest deposits (Qapy) are approximately correlative with terrace levels 1 and 2 and locally 3; they cover a broad gentle slope north of Ivins, are not significantly incised, and parts are active surfaces that were periodically flooded by debris flows and flash floods until a series of debris catchment dikes (Qf) were constructed; in older deposits, lower parts of most washes cut into and expose bedrock; oldest level (Qap_6) caps prominent hill in NW1/4 section 25, T. 41 S., R. 17 W. as sole remnant of probably once-extensive deposits at that level; form broad benches that slope southward from the base of the Red Mountains toward the Santa Clara River in the central part of the quadrangle and toward Sand Hollow in the eastern part; surfaces cut across the easily eroded lower part of the Kayenta Formation, Moenave Formation, and Petrified Forest Member of the Chinle Formation, forming a broad strike valley through the middle of the quadrangle; thickness increases northward from 0 to 80 feet (0–24 m).

Qas, Qag

Alluvial silt and sand (Qas) and gravel (Qag) beneath lava flows (upper to lower Pleistocene) – Poorly to moderately sorted, clay- to boulder-size, stream-deposited sediment exposed as small, isolated outcrops beneath lava flows; generally obscured by talus, colluvium and landslide deposits; alluvial sand and silt (Qas), mapped near the base of the Santa Clara flow near the southeast corner of the quadrangle, consists of fine-grained, pale-reddish-gray sand, silt, and clay, with some stringers of grit and fine gravel; similar alluvial deposits too small to map are exposed beneath the edges of the Santa Clara flow in several other areas, one of which yielded an optically stimulated luminescence (OSL) age of about 40,000 calendar years (see Qbs discussion), suggesting that the sand is part of older mixed alluvial and eolian sediment adjacent to ancestral Snow Canyon wash deposited well before emplacement of the flow; poorly exposed gravel deposit (Qag), mapped only in the SW1/4 section 15, T. 41 S., R. 16 W., consists of moderately sorted boulders, cobbles, and pebbles heavily coated with calcic soil (caliche) in a muddy matrix derived from sedimentary and igneous rocks exposed north of the quadrangle; it appears to overlie the Lava Ridge lava flow and underlie the Cedar Bench lava flow but locally part may actually overlie both flows; about 20 feet (6 m) thick.

Qab,Qabo

Boulder terrace alluvium (upper to lower Pleistocene) – Cobble to boulder-size, subangular to subrounded clasts up to about 1.5 feet (0.5 m) in diameter in a muddy to sandy matrix; moderately sorted; clasts, many exotic to the quadrangle, are sourced from lava flows, intrusive igneous rocks, and sedimentary strata; deposits are more poorly sorted and contain more silt and muddy matrix, and clasts are less rounded than in terrace alluvium (Qat); mapped in Snow Canyon and on the bench east of Snow Canyon; divided into younger (Qab) and older (Qabo) units since they cannot be directly correlated to current drainages or numbered terrace deposits; younger deposits (Qab) were probably deposited prior to the Santa Clara lava flow dated at about 33,000 cal yr B.P. (see map unit Qbs); older boulder terraces (Qabo) were probably deposited prior to the 1.4 Ma Lava Ridge lava flow and may represent stream deposits in an ancestral Snow Canyon; 0 to 40 feet thick (0–12 m).

Colluvial Deposits

Qc **Colluvium** (Holocene to middle Pleistocene) – Poorly sorted, angular to rounded blocks up to several feet in diameter in a muddy silt and clay to sandy matrix; covers many low to moderate slopes throughout the quadrangle; deposited by sheet wash, debris flows, and slope creep; mapped deposits are gradational with and locally include eolian, talus, and alluvial deposits; unmapped thin and discontinuous colluvium is common on most low and moderate slopes in the quadrangle; 0 to 20 feet (0–6 m) thick.

Eolian Deposits

Qes, Qed

Eolian sand and sand dunes (Holocene to middle Pleistocene) – Well- to very well sorted, fine- to very fine grained, well-rounded, mostly quartz sand; derived from weathering of the Navajo Sandstone and the Kayenta Formation; accumulates in irregular hummocky mounds on the gently sloping pediment benches in the central part of the quadrangle and in depressions and protected areas on the Navajo Sandstone; sand deposits (Qes) are 0 to 20 feet (0–6 m) thick; poorly developed dunes (Qed) up to 50 feet (0–15 m) thick form near the mouth of Snow Canyon where the sand is locally more extensive.

Artificial Deposits

Qf **Human-emplaced fill and disturbed areas** (Historical) – Artificial fill from human activity emplaced in small dams for reservoirs and flood-catchment basins, road base, dikes, and other projects, and large excavated and disturbed areas; extensive throughout the quadrangle but most not mapped to avoid obscuring natural geologic relationships and because they change with each new construction project; fill ranges from engineered and compacted deposits to general borrow materials and should be anticipated in all developed areas, many of which are shown on the topographic base map; generally 0 to 20 feet (0–6 m) thick, but locally thicker.

Mass-Movement Deposits

Qms, Qmsh, Qmso, Qms(Ŧcs)

Landslides (Holocene to lower Pleistocene) – Extremely poorly sorted, clay- to boulder-sized, chaotic debris with blocks of rotated strata up to several hundred feet across that have slid down slopes and form chaotic, hummocky mounds; developed primarily on steep slopes with competent capping units; slide masses involve overlying bedrock formations, talus, and basalt; meteoric and irrigation water that percolates down through the fractured rock and weakens the impermeable clay is a major factor contributing to landslide development; even landslides with subdued morphology (suggesting that they are older, weathered, and may not have experienced large-scale movement recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003); thickness highly variable, but is generally 10 to 80 feet (3–25 m).

A weak zone in the lower part of the main body of the Kayenta Formation forms the basal detachment surface of the Red Mountain landslide complex, which consists of a large, mostly jumbled and chaotic mass of Navajo and upper Kayenta Formations in the north-central part of the quadrangle; primary bedding still evident in some blocks indicates toreva-like (back-tilted) movement. A landslide covering a northeast-facing slope near the west-central quadrangle border consists mostly of basalt blocks from the Gunlock–Dammeron Valley North lava flow and has a slip surface on the clay-rich Petrified Forest Member of the Chinle Formation. Landslides, including smaller slides that are not mapped, are common along the bluff overlooking downtown Santa Clara (section 15 and 16, T. 42 S., R. 16 W.). They involve alluvium and colluvium as well as bedrock strata that are sliding on the Petrified Forest Member of the Chinle Formation and have moved repeatedly in historical times, damaging roads and buildings (see Geologic Hazards discussion) (Christenson, 1992; Lowe, 1992; Lund and others, 2007, 2008). Much of the bench edge and slope is unstable. Perhaps the most active is the Truman Drive landslide (Qmsh, NW¼ section 16) which, in spite of engineering attempts to stabilize the slide, has now expanded to include some of adjacent Truman Drive and, as of 2013, caused three homes to be condemned (figure 6).

Extremely poorly sorted, chaotic debris with angular blocks up to 30 feet (9 m) across derived from the Shinarump Conglomerate Member of the Chinle Formation (Qmso) cap three knolls in the southwest part of the quadrangle that are more than 400 feet (120 m) above nearby washes. The nearest Shinarump outcrop is about 0.5 miles (0.8 km) to the east and at a lower elevation, so the blocks must have slid from and are the last remnants of older Shinarump outcrops to the south or west that have long since retreated or eroded away. In the west-central part of the quadrangle, large masses of Shinarump Conglomerate (Qms[T̄Rcs]) are sliding on inclined clayey beds in the upper red member of the Moenkopi Formation and in the lower part of the Shinarump. They are common where water percolates through fractures in the sandstone and weakens clay layers, and where the toe of the inclined Shinarump has been undercut by the Santa Clara River. They are recognizable as blocks that are slightly rotated and at lower elevations than nearby non-slumped strata, similar to those described by Hintze and Hammond (1994) in the Shivwits quadrangle, west of the study area; slickensides with multi-directional lineations at the base of the sandstone indicate that blocks commonly slide on the upper red member of the Moenkopi Formation.

Qmt **Talus** (Holocene to middle Pleistocene) – Very poorly sorted, angular boulders with minor fine-grained interstitial sediment that has accumulated on and at the base of steep slopes; consists mostly of basalt blocks that roll down slopes as the underlying and supporting softer red beds of the Navajo and Kayenta Formations erode; also includes blocks of Navajo Sandstone that rest on Kayenta Formation slopes, and blocks of the Shinarump Conglomerate Member of the Chinle Formation that accumulate on the upper red member of the Moenkopi Formation; talus boulders are commonly used as riprap along rivers and washes; only large deposits are mapped, but talus boulders are common on and at the base of all steep slopes in the quadrangle; rock falls and rolling boulders are a significant hazard in the quadrangle (figure 5); locally, masses of talus have moved as landslides and are mapped as landslide deposits (Qms); 0 to 20 feet (0–6 m) thick.

Spring Deposits

Qst **Spring tufa** (Holocene to middle Pleistocene) – Pale-gray, pale-yellowish-gray, or pale-reddish-gray calcareous tufa; typically laminar to botryoidal with abundant vugs; some outcrops have a soft, powdery weathered surface whereas others are more resistant and weather to a rough surface with a jagged pinnacle-like texture; forms small, resistant mounds and locally drapes down slopes beneath the many small springs common in the eastern part of the quadrangle; 0 to 20 feet (0–6 m) thick.

Mixed-Environment Deposits

Qac **Mixed alluvium and colluvium** (Holocene to upper Pleistocene) – Poorly to moderately sorted, clay- to boulder-sized sediment mapped in minor drainages; alluvium is transported along washes during heavy rainstorms whereas colluvium is derived by slope creep from side slopes; locally incised up to 30 feet (10 m); gradational with and includes stream alluvium (Qal_1), colluvium (Qc), and eolian sand (Qes) deposits too small to map separately; 0 to 10 feet (0–3 m) thick.

Qae, Qaeo

Mixed alluvium and eolian sand ((Holocene to middle Pleistocene) – Moderately to well-sorted, clay- to sand-sized sediment of alluvial origin that locally includes abundant eolian sand and minor pebble- to small-boulder gravel; mapped primarily in Snow Canyon where eolian sediment is reworked by ephemeral streams and mixed with alluvium; younger deposits (Qae) have minor calcic soil (caliche) development whereas older deposits (Qaeo) have extensive caliche development, are typically dissected 10 to 30 feet (3–9 m), and are isolated by incising washes; smaller Qaeo deposits are mapped with Qae deposits; typically 0 to 30 feet (0–9 m) thick, but may thicken locally.

Qacg **Gypcrete and alluvium** (upper to lower Pleistocene) – Pale-gray to pinkish-gray, punky, gypsiferous tufa (gypcrete) that forms a resistant ledge up to 10 feet (3 m) thick; caps a sloping irregular surface cut across the Shnabkaib and upper red members of the Moenkopi Formation in the southwest part of the quadrangle; similar in appearance to a thick calcic soil (caliche) layer; deposited directly on bedrock in most areas, but locally overlies (and is mapped with) alluvial mud, sand, and gravel in paleochannels; alluvium consists mostly of mud and sand, but locally contains gravel lenses with boulders up to about 2 feet (0.6 m) in diameter; gypcrete cap and alluvial deposits are incised up to 140 feet (43 m) by deep narrow washes; locally the gypcrete drapes down slopes and is only incised 30 to 40 feet (9–12 m); the gypsum is derived from the Shnabkaib Member of the Moenkopi Formation, which has abundant gypsum in beds and veins; up to 80 feet (26 m) thick.

Qea **Mixed eolian sand and alluvium** (Holocene to lower Pleistocene) – Well-sorted eolian sand locally reworked by alluvial processes and locally including minor alluvial clay to gravel; contains thick calcic soil horizons (caliche) that indicate long periods of accumulation; commonly covered by and gradational with eolian sand that is mapped separately where extensive (Qes); mapped separately in central part of quadrangle where well exposed and masks pediment-mantle deposits; 0 to 20 feet (0–6 m) thick.

Qeca **Eolian and alluvial deposits with thick calcic soil (caliche) on lava flows** (Holocene to lower Pleistocene) – Eolian silt, sand, and clay, and alluvial gravel with very thick calcic soil (caliche) development (to stage VI of Birkeland and others, 1991) deposited on lava flows; calcic soils are in more advanced stage on older flows, exhibiting laminar layers and platy structures, pisoliths, and multiple generations of incipient brecciation and recementation; deposited by streams that flowed on top of resistant lava flows before shifting to and incising less-resistant Jurassic sedimentary rock adjacent to the flows; most deposits are now isolated by deep incision of streams but eolian silt, sand, and clay continue to accumulate on the flows, allowing thick calcic soil to develop; thickness varies from 0 to 15 feet (0–5 m).

Basaltic Lava Flows

Six basaltic lava flows are mapped in the quadrangle: the Santa Clara lava flow, Diamond Valley lava flow, Big Sand lava flow, Cedar Bench lava flow (called Snow Canyon Overlook flow by Willis and Higgins, 1996), Lava Ridge lava flow, and Gunlock–Dammeron Valley North lava flow. Each is a different age and at a different stage of topographic inversion, forming inverted valleys as first described in detail by Hamblin (1963, 1970a, 1987) and Hamblin and others (1981). After lava flows blocked drainages, streams commonly reestablished themselves on top of the flows, as evidenced by thin gravel deposits. Eventually, most streams shifted to or were replaced by streams in softer sedimentary bedrock along the flanks of flows. Continued incision left the resistant lava flows isolated as elevated, sinuous ridges called inverted valleys; thus, flows that were valley floors now cap ridges. Since most small basaltic volcanoes are monocyclic, meaning that each vent produces only one eruptive cycle that probably lasted less than a year to as much as a few tens of years, the resistant flows document the local drainage pattern as it existed when the flow erupted. This inversion is best seen well downstream of the eruptive vent where the flow followed well-established drainages. In some places rugged paleotopographic terrain and incomplete incision led to unusual relationships; for example, near the northeast edge of the Santa Clara quadrangle a portion of the Lava Ridge lava flow cascaded into a topographically lower valley west of the valley containing the main flow. Soon after, the slightly younger Cedar Bench lava flow that forms the ridge of the Snow Canyon overlook flowed down the lower western valley, partially covering the Lava Ridge flow (Hayden, 2011b). Continued differential erosion has now left part of the Lava Ridge flow higher in elevation than adjacent Cedar Bench flow outcrops, and part lower than and capped by the Cedar Bench flow, which can cause difficulties in mapping. Similar apparent disparities are common with other flows in the area.

Long-term incision rates for the St. George area are calculated using isotopic ages for these lava flows and their height above major drainages (Willis and Biek, 2001) (also see discussion in map unit Qat). The calculations reconfirm and expand on many of the findings of Hamblin and others (1981), who similarly documented incision rates in the St. George basin. However, the old axiom that "the higher the lava flow is above the current drainage, the older it is" is only valid when comparing flows on the same part of the same structural block, and, as just described, where unusual paleotopographic conditions did not exist (Willis and Biek, 2001; Biek and others, 2010). For example, southeast of the quadrangle the lower reaches of Middleton and Washington Black Ridges, capped by the Lava Ridge and Washington lava flows, respectively, are classic inverted valleys (Willis and Hayden, in press). These two flows are about 5 miles (8 km) apart and both flowed into a well-graded stretch of the ancestral Virgin River, but they are on two different structural blocks, separated by the Washington fault. The Washington flow stands about twice as high above the present Virgin River as the Lava Ridge flow, yet $^{40}Ar/^{39}Ar$ ages show that it is about 500,000 years younger than the Lava Ridge flow. The greater topographic inversion of the younger flow is directly attributable to its position on the footwall (upthrown part) of a separate, relatively more elevated structural block. Thus, position on structural blocks is important when estimating relative ages of lava flows based on the amount of topographic inversion.

Flows consist of multiple cooling units that mostly range from a few feet to a few tens of feet thick, each unit representing a pulse of magma separated by enough time for cooling, but not significant weathering, to occur. Numerous workers have described the lava flows and their tectonic setting and petrogenesis, and proposed that the geochemical variability between individual lava flows could be explained by their derivation from the partial melting of compositionally heterogeneous lithospheric mantle, and by fractional crystallization (Hamblin, 1963, 1970a, 1987; Best and others, 1966, 1980; Best and Brimhall, 1970, 1974; Hamblin and Best, 1970; Lowder, 1973; Leeman, 1974; Hamblin and others, 1981; Nelson and Tingey, 1997; Nusbaum and others, 1997; Smith and others, 1999; Downing, 2000; and Biek and others, 2010). Analytical data for samples from flows in and near the quadrangle include major and trace-element geochemistry (table 1; Biek and Ehler, 2007; Biek and others, 2010) and chronologic ages (table 1; Biek and others, 2010 and open-file reports referenced therein; Utah Geological Survey and U.S. Geological Survey, 2014; Utah Geological Survey and Utah State University Luminescence Laboratory, 2014). Rock names are derived from the total alkali vs. silica diagram of LeBas and others (1986).

Qbdv **Diamond Valley lava flow** (upper Pleistocene) – Dark-brownish-black to black subalkaline basalt that contains abundant small olivine and rare plagioclase phenocrysts in an aphanitic groundmass (Faust, 2005; Faust and Smith, 2005); iridescent sheen preserved on many protected surfaces; chemically and petrographically similar to the much more voluminous Santa Clara lava flow; no reliable isotopic age data but limited field relationships, including possible overlap of flow lobes, morphology of its cinder cone (just northeast of the northeast corner of the quadrangle), and slightly sharper and better-defined features on its flow surface suggest that it may be slightly younger than the Santa Clara lava flow (figure 3); generally 10 to 30 feet (3–9 m) thick, but locally thicker where it fills paleotopographic lows.

Qbs, Qbsc

Santa Clara lava flow and cinder cone (upper Pleistocene) – Dark-brownish-black to black subalkaline basalt (Qbs) that has a distinctly higher iron content than other flows in the area and contains abundant small olivine phenocrysts in an aphanitic groundmass; has predominantly jagged aa surface; together with the nearby chemically similar Diamond Valley lava flow, is one of the two youngest flows in the St. George basin; an iridescent sheen is locally present on protected surfaces; erupted from a vent at cinder cone (Qbsc) in the northeast corner of quadrangle, flowed southwest through a pass in a sandstone ridge, then spread out (figure 3); lobes cascaded into Snow Canyon through several gaps and open joints in the sandstone, rejoining to form one main flow in the lower part of the canyon before spreading out over a large flat area in the central and southern parts of the quadrangle (figures 1 and 2); has a few poorly developed lava tubes, some collapsed; distal end of the flow is just a few hundred feet south of the quadrangle; displays limited poorly developed topographic inversion; amount of local inversion is not a good indicator of age in the case of very young flows such as this since streams displaced from their channels can quickly cut deep gorges along the flanks of flows as they seek to return to their normal base level; for example, in section 34, T. 41 S., R 16 W., a stream bed on top of the flow plunges approximately 40 feet (12 m) over a vertical nick point into a gorge along the edge of the flow; attempts at $^{40}Ar/^{39}Ar$ dating yielded unreliable ages, probably because of insufficient argon due to the young age of the flow (UGS unpublished data); charcoal, discovered in loose sand about 2 inches (5 cm) beneath the flow and presumably from a root burned as the flow overran it, yielded an age of 32,600 ± 300 cal yr B.P. (27,270 ± 250 ^{14}C yr B.P.) (Willis and others, 2006), while the sand itself yielded optically stimulated luminescence (OSL) ages of about 40,000 cal yr B.P. (figure 7; table 1; Utah Geological Survey and Utah State University Luminescence Laboratory, 2014); we consider the ^{14}C age to most closely reflect the age of the flow; the slightly older age of the sand, if accurate, suggests that it is from older sediment that had been buried for a few thousand years before emplacement of the flow (Willis and others, 2006; Biek and others, 2010); lava flow is typically 10 to 30 feet (3–9 m) thick, but locally thicker where it fills paleotopographic lows.

Qbb **Big Sand lava flow** (lower Pleistocene) – Dark-reddish-gray to dark-brownish-gray basaltic trachyandesite, locally with large quartz and plagioclase and small olivine phenocrysts; contains abundant rafts of scoria and cinders that were apparently transported in the flow; erupted from a vent at a cinder cone about 1 mile (1.5 km) east of the quadrangle and is mapped near center of eastern edge; flow and cone have thick stage V to VI calcic soil (caliche) development (Birkeland and others, 1991); yielded an $^{40}Ar/^{39}Ar$ plateau age of 1.13 ± 0.05 Ma (1.111 ± 0.007 Ma isochron) (Biek and others, 2010); generally 10 to 50 feet (3–15 m) thick.

Qbcb **Cedar Bench lava flow** (lower Pleistocene) – Dark-greenish-gray to brownish-black trachybasalt with small phenocrysts of clinopyroxene and olivine; prevalent columnar jointing; strongly weathered along joints, forming a mottled texture; caps the broad bench east of Snow Canyon; previously called Snow Canyon Overlook lava flow (Willis and Higgins, 1996; Willis and Biek, 2001) but, because of similar geochemistry and position, is now considered the southern extension of the Cedar Bench lava flow (Biek and others, 2010); directly overlies the older Lava Ridge lava flow with the contact well exposed in the wash just west of Highway 18 in SW¼ section 15, T. 41 S., R. 16 W. where a few feet of alluvial gravel (Qag) is poorly exposed between the two flows; two cooling units are well exposed along the southeast edge of the flow; erupted from vents at two overlapping cinder cones about 5 miles (8 km) east-northeast of the northeast corner of the quadrangle; yielded $^{40}Ar/^{39}Ar$ plateau ages of 1.23 ± 0.01 Ma and 1.16 ± 0.03 Ma (Biek and others, 2010) (slightly older than the less reliable K-Ar age of 1.07 ± 0.04 Ma reported by Hamblin and others, 1981) that fit well with regional incision rates (Willis and Biek, 2001); typically 10 to 30 feet (3–9 m) thick.

Qbl **Lava Ridge lava flow** (lower Pleistocene) − Moderate- to dark-gray to dark-brownish-gray basaltic trachyandesite with prominent euhedral plagioclase phenocrysts up to 0.4 inch (1 cm) wide, common pyroxene and small olivine phenocrysts; moderate to prevalent columnar jointing; most of the lava flowed south in a valley just east of the quadrangle, but a portion of the lava overtopped the main valley to cascade westward into a lower valley near Snow Canyon State Park and now underlies the younger Cedar Bench lava flow; erupted from a group of heavily weathered cinder cones on Lava Ridge, about 2 miles (3 km) east of the quadrangle (Willis and Hayden, in press); samples from Middleton Black Ridge in the St. George quadrangle, which petrographic and limited geochemical data suggest is the southern extension of the Lava Ridge lava flow (Biek and others, 2010), yielded a K-Ar age of 1.5 ± 0.1 Ma (Best and others, 1980) and an $^{40}Ar/^{39}Ar$ age of 1.41 ± 0.01 Ma (Biek and others, 2010); 20 to 40 feet (6–12 m) thick.

Qbgd **Gunlock–Dammeron Valley North lava flow** (lower Pleistocene) – Dark-gray basaltic trachyandesite to trachybasalt with common, small olivine phenocrysts; crude columnar jointing; source unknown, but is at least 2 miles (3 km) east of Veyo and 5 miles (8 km) north of the quadrangle where it may be concealed by the younger Saddle Mountain lava flow (Biek and others, 2010); the Dammeron Valley North flow yielded $^{40}Ar/^{39}Ar$ plateau ages of 1.62 ± 0.02 Ma (1.63 ± 0.03 Ma isochron) (UGS and NMGRL, 2008) and 1.65 ± 0.02 Ma (1.67 ± 0.04 Ma preliminary isochron) (Biek and others, 2010); Embree (1970) mapped and described vertical and lateral chemical variation of the Gunlock lava flow, the age, geochemistry, and petrology of which suggest it is simply the distal part of the Dammeron Valley North flow of Biek and others (2010) and Hayden (in press); the Gunlock part of this lava flow yielded a K-Ar age of 1.6 ± 0.11 Ma (Hintze and Hammond, 1994) and an $^{40}Ar/^{39}Ar$ plateau age of 1.61 ± 0.07 Ma (Biek and others, 2010); flowed down ancestral channel of the Santa Clara River; distal end is preserved near the center of the west side of the quadrangle; typically 10 to 50 feet (3–15 m) thick.

unconformity

JURASSIC

Navajo Sandstone

Jn **Navajo Sandstone** (Lower Jurassic) – Moderate-reddish-orange to moderate-reddish-brown to pale-yellowish-white, massively cross-bedded, poorly to moderately well-cemented sandstone with well-sorted, well-rounded, fine- to medium-grained, frosted quartz sand grains; has cross-bed sets bounded by planar surfaces; forms cliffs except where highly jointed and fractured where forms steep rubbly slopes; exposed across northern third of map area; lower interval is mostly planar bedded with crinkle bedding, tepee structures, and mineral casts formed by the growth of minerals such as halite (Sansom, 1992), indicative of eolian sand on a sahbka playa; locally strongly bleached to pale yellowish gray to white (figures 1 and 3); has common ironstone bands and concretions; cut by prominent joints, the dominant set of which trends north-northwest and consists of mostly parallel fractures that weather as open depressions, though some conjugate joints trend northeast; some joints stand out in positive relief due to slower weathering of strong siliceous and calcareous recementation of localized joint breccia; forms the principal aquifer in the area (Clyde, 1987; Hurlow, 1998; Heilweil and others, 2000, 2002; Rowley and Dixon, 2004; Rowley and others, 2004); springs develop at lower contact with Kayenta Formation; Johnson Arch is eroded into the lower part of the Navajo along joints near a spring in the southern part of Snow Canyon State Park (figure 8); deposited in a vast coastal and inland dune field with prevailing winds principally from the north, and in rare interdunal ephemeral lakes and playas (Blakey, 1994; Peterson, 1994); much of the sand may originally have been transported to areas north and northwest of Utah via a transcontinental river system that tapped Grenvillian-age (about 1.0 to 1.3 billion-year-old) crust involved in Appalachian orogenesis of eastern North America, and then remobilized into a vast down-wind dune field (Dickinson and Gehrels, 2003, 2009; Rahl and others, 2003; Reiners and others, 2005); lower contact with main body of Kayenta Formation is gradational and locally the transition zone between the two formations, which reaches its maximum thickness of about 300 feet (100 m) in the Red Cliffs area northeast of the quadrangle, can make the contact difficult to pick (Willis and Higgins, 1996; Biek, 2003) (figure 9); lower contact corresponds to the base of lowest thick to massively bedded, vertically jointed sandstone, which is commonly planar bedded rather than cross-bedded as is typical of the main part of the formation, and above the highest thick interval of thin-bedded siltstone, mudstone, or interbedded siltstone and thin muddy sandstone; map unit includes areas of weathered sandstone regolith and Quaternary eolian sand that may be blown into crude dunes too small to map separately; only lower 2300 feet (700 m) is present in the quadrangle, but total thickness in this area is approximately 2500 feet (760 m).

The Navajo Sandstone has not been directly dated in this area, but the minimum age is constrained by $^{40}Ar/^{39}Ar$ isotopic ages on volcanic ash in the immediately overlying Temple Cap Formation exposed just outside of the quadrangle that range from about 171 to 173 Ma (Kowallis and others, 2001; Sprinkel and others, 2009; Doelling and others, 2013). Since the Temple Cap and Navajo are separated by the J-1 unconformity, upper beds of the Navajo are Toarcian to Pliensbachian (likely older than 175 Ma, and probably older than 180 Ma). The maximum age of the Navajo and underlying Kayenta Formation are contrained by the age of the underlying Whitmore Point Member of the Moenave Formation, making the lower Navajo and Kayenta both Sinemurian in age (see Jmw discussion and Hintze and Kowallis, 2009).

As indicated by limited unaltered outcrops in the quadrangle, fine-grained intervals in the Navajo and underlying Kayenta Formation, and outcrops to the west, the primary unaltered color of the Navajo is moderate red to moderate reddish brown due to a uniform hematitic iron patina that coats all grains. However, many outcrops in the quadrangle are mostly pale yellowish gray to nearly white due to extensive alteration (bleaching) and migration (leaching) of the hematitic patina (figures 1, 2, 3, and 9). The west wall of middle Snow Canyon displays a spectacular pattern of interfingering red and white alteration (figure 1). This alteration represents a complex and extensive reaction front between chemically oxidizing and reducing fluids in the subsurface with the primary direction of bleaching fluid migration to the south or southwest (Beitler and others, 2005; Nielsen and Chan, 2009; Nielsen, 2010). Bleaching or whitening of the rock occured after lithification and was caused by acidic water (probably acidized by fluid derived from organic or volcanic rock or sediment) that reduced and dissolved hematitic minerals that coat and bind sand grains, leaving the sandstone very pale yellow to white (close to the natural color of the quartz grains) and very friable; the reduced iron migrated short to moderate distances through the rock—upon encountering slightly more oxided water the iron precipitated as concentrated bands and concretions of dark-yellowish-brown to brownish-black iron or iron manganese oxides (goethite, hematite, and other iron-manganese minerals); bleaching in the middle and upper part of the formation is closely linked with precipitation of dark-colored iron oxide bands and concretions in the lower part of the formation (Nielsen and Chan, 2009; Nielsen, 2010); Nielsen and Chan proposed that the precipitation of brightly colored, secondary iron oxide near parallel, high-angle, generally north-northeast-trending joints in the upper part of the Navajo Sandstone was a distinct later episode of alteration. These joints commonly weather out into positive relief due to concentration of resistant secondary siliceous, calcareous, and iron-manganese oxide cement. Analyses of representative samples demonstrate the strong reduction, migration, and re-precipitation of iron and manganese oxides—selected samples from in and near the quadrangle indicate that white, strongly bleached sandstone contains less than 0.5% iron oxides whereas adjacent, very dark brownish-black ironstone contains up to 21% iron oxides and 5% manganese oxides; "typical" moderate-reddish-brown sandstone has 1 to 2% iron oxides (appendix A).

Kayenta Formation

Jkm **Main body of Kayenta Formation** (Lower Jurassic) – Reddish-brown to moderate-reddish-brown to pale-red, thin-bedded siltstone and mudstone with sericite on some bedding surfaces interbedded with very fine to fine-grained, planar to lenticular, mottled sandstone with climbing ripples; upper surface of sandstone ledges is commonly bioturbated; includes minor intraformational pebble conglomerate near the base and three 2- to 6-inch (5–15 cm) thick beds of light-pinkish-gray to light-olive-gray, micritic limestone at about 85 feet (26 m), 105 feet (31 m) and 110 feet (33 m) above the base; light-gray siltstone marker bed about 30 feet (9 m) below the top extends across the quadrangle; generally coarsens upward; forms steep, ledgy slope to ledgy cliff that is locally covered by talus (figure 9); commonly jointed; lower contact with the Springdale Sandstone Member is conformable and gradational and is placed at the base of laterally continuous, thin-bedded, reddish-brown, fine-grained silty sandstone that overlies the Springdale Sandstone cliff; quarried from Red Hills east of the quadrangle by early settlers for building stone; deposited in distal river, playa, and minor lacustrine environments (Tuesink, 1989; Blakey, 1994; Peterson, 1994); 920 feet (280 m) thick in exposures just southeast of the quadrangle (Hayden and Willis, 2011).

Jks **Springdale Sandstone Member of Kayenta Formation** (Lower Jurassic) – Mostly pale-reddish-brown to pale-grayish-yellow, moderately sorted, fine- to medium-grained, medium- to very thick bedded, ledge- to small cliff-forming sandstone, and minor, thin, discontinuous lenses of intraformational conglomerate and thin interbeds of moderate-reddish-brown or greenish-gray mudstone and siltstone; has large lenticular and wedge-shaped, low-angle cross-bedding; secondary color banding that varies from concordant to discordant to cross-beds is common in the sandstone; locally exhibits minor copper and uranium mineralization (James and Newman, 1986); contains locally abundant petrified and carbonized fossil plant remains; theropod tracks common in upper horizon, known as the Springdale mega-tracksite (Lucas and others, 2005; Hamblin and others, 2006); produced silver at the Silver Reef mining district 15 miles (24 km) to the northeast (James and Newman, 1986; Proctor and Shirts, 1991; Biek and Rohrer, 2006); resistant to erosion, it forms isolated outcrops that protrude from beneath surficial deposits in the central part of the quadrangle and is well exposed in major washes; unconformable lower contact with the Whitmore Point Member of the Moenave Formation is placed at the base of the massive sandstone cliff above a slope of interbedded mudstone and claystone; deposited in braided-stream and minor floodplain environments in Early Jurassic time (Clemmensen and others, 1989; Blakley, 1994; Peterson, 1994; DeCourten, 1998; Lucas and Tanner, 2006, 2007; Lucas and others, 2011); 130 feet (40 m) thick northwest of Red Mountain and north of Ivins.

J-sub Kayenta unconformity

Blakey (1994) and Marzolf (1994) proposed a major regional unconformity at the base of the Springdale Sandstone, thus restricting the Moenave Formation to the Dinosaur Canyon and Whitmore Point Members. Subsequent work by Lucas and Heckert (2001), Molina-Garza and others (2003), and Lucas and Tanner (2006) also suggested that the Springdale Sandstone unconformably overlies the Whitmore Point Member and is more closely related to and should be the basal member of the Kayenta Formation (also see Biek and others, 2010).

JURASSIC/TRIASSIC

Moenave Formation

Jmw **Whitmore Point Member** (Lower Jurassic) – Interbedded, pale-reddish-brown, greenish-gray, and grayish-red mudstone, claystone, and limestone with thin-bedded, moderate-reddish-brown, very fine to fine-grained sandstone and siltstone; sandstone and siltstone commonly thin bedded to laminated in lenticular or wedge-shaped beds; claystone and mudstone are generally planar bedded and weather into expansive soil; contains several 2- to 6-inch (5–15 cm) thick, bioturbated, cherty, very light gray to yellowish-gray, dolomitic limestone beds with algal structures, some altered to jasper, and fossil fish scales of semionotids (Hamilton, 1984; Milner and Kirkland, 2006; Milner and Spears, 2007; Milner and others, 2012); nonresistant and poorly exposed locally in washes and where uncovered by construction; one construction area in the St. George quadrangle, now called the St. George Dinosaur Discovery Site at Johnson Farm, revealed exceptionally well-preserved theropod tracks (*Eubrontes* and *Grallator*) near the base of the member, including swim tracks (Kirkland and Milner, 2006; Milner and others, 2006; Milner and Spears, 2007; Milner and others, 2012), a variety of invertebrate fossils and trace fossils (Lucas and Milner, 2006; Lucas and others, 2006; Schudack, 2006; Lucas and others, 2011; Milner and others, 2012), plant fossils (Tidwell and Ash, 2006), and rare dinosaur remains (Milner and Kirkland, 2007; Milner and others, 2012); Cornet and Waanders (2006) described diagnostic palynomorphs in the Whitmore Point Member; these paleontologic studies constrain the Whitmore Point to the lowermost Jurassic (Hettangian), which also helps bracket the age of the Kayenta and Navajo Formations; lower, conformable contact is placed at a pronounced break in slope at the base of the lowest light-gray, thin-bedded, dolomitic limestone and above the thicker bedded sandstone and siltstone ledges of the Dinosaur Canyon Member; deposited in low-energy lacustrine and fluvial environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998; Milner and Kirkland, 2006; Milner and others, 2012); 90 to 135 feet (27–41 m) thick.

JTRmd **Dinosaur Canyon Member** (Lower Jurassic to Upper Triassic) – Interbedded, generally thin-bedded, moderate-reddish-brown to moderate-reddish-orange, very fine to fine-grained sandstone, very fine grained silty sandstone, and lesser siltstone and mudstone with laminated cross-beds; uniformly colored; ripples and mud cracks common; forms ledgy slope; regionally forms the base of Vermilion Cliffs step of the Grand Staircase (Gregory, 1950) but here is poorly exposed in stream channels or by construction; regionally, a thin chert-pebble conglomerate bed marks the unconformable base of the unit, but in this area it is more common to have a 1.5- to 2-foot-thick (0.5–0.6 m) gypsum bed with local chert pebbles; in other places the unconformable lower contact is placed at a prominent color and lithology change from reddish-brown siltstone above to pale-greenish-gray mudstone of the Petrified Forest Member of the Chinle Formation below; deposited on broad, low floodplain that was locally shallowly flooded (fluvial mud flat) (Clemmensen and others, 1989; Blakey, 1994;

Peterson, 1994; DeCourten, 1998); 140 to 250 feet (43–75 m) thick (Kirkland and Milner, 2006).

TR-5 unconformity

Pipiringos and O'Sullivan (1978) showed this unconformity at the Jurassic-Triassic boundary and called it the J-0 unconformity. Molina-Garza and others (2003), Kirkland and Milner (2006), Lucas and Tanner (2007), and Lucas and others (2011) showed that the Jurassic-Triassic boundary is within the Dinosaur Canyon Member of the Moenave Formation and that this basal Moenave unconformity is Late Triassic in age and called it the TR-5 unconformity.

TRIASSIC

Chinle Formation

Ѓcp **Petrified Forest Member** (Upper Triassic) (may include other undifferentiated members) – Highly variegated, light-brownish-gray, pale-greenish-gray, to grayish-red-purple, smectitic shale, mudstone, siltstone, and claystone, with several lenticular interbeds of pale-yellowish-brown, cross-bedded, resistant sandstone up to 10 feet (3 m) thick; pebble to small cobble conglomerate near base; clasts are primarily chert and quartzite; contains minor chert, nodular limestone, very thin coal seams and lenses as much as 0.5 inch (1 cm) thick, and locally abundant, brightly colored fossilized wood; shale weathers to a "popcorn" surface with abundant mudcracks due to expansive clays and causes road and building foundation problems; weathers to badland topography (figure 2); prone to landsliding along steep hillsides; local primary source for radon (Solomon, 1992a, 1992b); forms well-developed strike valley that extends northwest to southeast across the quadrangle adjacent to the more resistant cliffs of the Shinarump Conglomerate Member; well exposed only where protected from weathering by resistant capping deposits, where dissected by washes, and in slump headwalls; lower contact with the Shinarump Conglomerate Member is placed at the base of the purplish-gray claystone slope and above a prominent sandstone and conglomerate ledge; deposited in the Late Triassic (Norian-Carnian) in lacustrine, flood-plain, and fluvial environments of a back-arc basin formed inland of a magmatic arc associated with a subduction zone along the west coast of North America, with a significant portion of sediment supplied by volcanic ash (Stewart and others, 1972b; Dickinson and others, 1983; Blakey and others, 1993; Lucas, 1993; Dubiel, 1994; DeCourten, 1998; Lucas and Tanner, 2007); 700 feet (215 m) thick as estimated from map relationships where both upper and lower contacts exposed.

Working in Petrified Forest National Park in Arizona, Billingsley (1985) divided the Petrified Forest Member into upper and lower members separated by the Sonsela Sandstone bed. Heckert and Lucas (2002) expanded the Sonsela Member into three major packages of rock, proposed an unconformable surface at the base, and renamed the lower bentonitic beds Blue Mesa Member and the upper bentonitic beds Painted Desert Member. Woody (2006) doubted the existence of a single unconformable surface at the base of the Sonsela Member and retained the name Petrified Forest Member for the upper beds. Martz and Parker (2010) agreed that the expanded base of the Sonsela Member consists of discontinuous lenses of sandstone and conglomerate that are complexly interbedded with the Blue Mesa as five major packages of rock. These members have not yet been established in southwest Utah although discontinuous sandstone and conglomerate beds are locally present—evidence is not conclusive if these sandstone and conglomerate beds represent the Sonsela Member, thereby making the lower smectitic beds the Blue Mesa Member, or if they are simply sandstones within the Petrified Forest Member, as currently mapped. In addition, beds equivalent to the Owl Rock and Monitor Butte Members may be present but these members are not mapped because of poorly defined contacts and discontinuous exposures (Biek and others, 2010).

Ѓcs **Shinarump Conglomerate Member** (Upper Triassic) – Varies from grayish-orange to moderate-yellowish-brown, medium- to coarse-grained sandstone with locally well-developed limonite bands ("picture stone" or "landscape rock") to moderate-brown pebbly conglomerate with subrounded clasts of quartz, quartzite, and chert; conglomerate is well developed in the southeast corner of the quadrangle; mostly thick- to very thick bedded with both planar and low-angle cross-stratification, although thin, platy beds with ripple cross-stratification occur locally; strongly jointed with common slickensides on many joint surfaces; weathering along major northeast-trending joints forms repeated rectangular blocks and straight, narrow gaps in the rock a few inches to several feet wide and locally more than 50 feet (15 m) deep (figure 2); contains poorly preserved petrified wood, commonly replaced in part by iron-manganese oxides; rare, poorly preserved three-toed dinosaur tracks are present in conglomerate beds on Land Hill (Lockley and Milner, 2006) although the track may actually be from a quadrupedal animal rather than a biped (Andrew R.C. Milner, verbal communication, March 14, 2013); forms a dark-brown to moderate-yellowish-brown resistant ledge to small cliff above the Moenkopi Formation—thus caps the Chocolate Cliffs step of the Grand Staircase

(Gregory, 1950); forms Land Hill and South Hills that stretch northwest to southeast across the southern third of the quadrangle; commonly slumped on non-resistant upper Moenkopi Formation; lower unconformable contact is drawn at the base of the small cliff above slope-forming, reddish-brown siltstone of the upper red member of the Moenkopi Formation; variable in composition and thickness because it represents deposition over Late Triassic paleotopography in stream channels from sources far to the south and southwest (Stewart and others, 1972b; Blakey and Gubitosa, 1983; Dubiel, 1994); ranges from 50 to 200 feet (15–60 m) thick.

TR-3 unconformity (Pipiringos and O'Sullivan, 1978)

Moenkopi Formation

TRmu **Upper red member** (Lower Triassic) – Moderate-reddish-brown to moderate-reddish-orange, thin- to medium-bedded siltstone and very fine grained sandstone with some thin gypsum beds and abundant discordant gypsum stringers; ripples common in the siltstone; locally includes 20-foot-thick (6 m), fine-grained, resistant sandstone near base; where the basal sandstone is thickened, weathering and slope retreat of overlying units is slowed, creating resistant points on the cuestas; well exposed in the southwest part of the quadrangle as steep slope with at least one prominent sandstone ledge beneath resistant caprock of Shinarump Conglomerate; conformable lower contact is gradational and drawn where reddish-brown mudstone of the upper red member grades into greenish-gray, gypsiferous siltstone of the Shnabkaib Member; deposited in Early Triassic (Olenekian-Induan) in very low relief tidal-flat and coastal-plain environments in which sea level changes of a few feet translated into shoreline changes of many tens of miles (Stewart and others, 1972a; Blakey and others, 1993; Dubiel, 1994); probably does not extend into Middle Triassic in this area (Spencer Lucas, New Mexico Museum of Natural History and Science, verbal communication, 2005), though it may in areas to the east (Chadwick and Brand, 2013); measured at 496 feet (151 m) thick in section 24, T. 42 S., R. 17 W., thus considered about 500 feet (150 m) thick throughout the quadrangle; greater thickness than in the St. George quadrangle may be due to picking a lower gypsum bed as the basal contact.

TRms **Shnabkaib Member** (Lower Triassic) – Light-gray to pale-red gypsiferous siltstone with several thin interbeds of dolomitic, unfossiliferous limestone near the base; alternating light- and dark-colored strata create a "bacon-striped" appearance; resistant limestone and nonresistant siltstone beds form ledge-slope topography making the lower portion slightly more resistant to erosion than the upper portion, which is very gypsiferous and weathers to a powdery soil forming a strike valley in the southwest corner of the quadrangle; unusually well exposed in Wittwer Canyon; gypsum dissolution causes local settlement, collapse, and piping; conformable and gradational lower contact is placed where predominantly light-gray, unfossiliferous, dolomitic limestone beds that mark the base of the Shnabkaib Member are underlain by moderate-red siltstone of the middle red member; deposited on a broad coastal shelf of low relief in a variety of supratidal, intertidal, and subtidal environments (Stewart and others, 1972a; Lambert, 1984; Paull and Paull, 1994); 688 feet (210 m) thick in sections 24 and 27, T. 42 S., R 17 W., thus generally considered about 700 feet (215 m) thick throughout the quadrangle, much thinner than 900- to 1000-foot (270–300 m) thicknesses common in the St. George quadrangle (Hayden and Willis, 2011), probably at least partially due to picking the upper contact on a different bed, but also possibly due to depositional thinning.

TRmm **Middle red member** (Lower Triassic) – Interbedded moderate-red to moderate-reddish-brown siltstone, mudstone, and thin-bedded, very fine grained sandstone with thin interbeds and veinlets of greenish-gray to white gypsum; forms slope; poorly exposed in washes in the southwest corner of the quadrangle; deposited in a tidal-flat environment (Stewart and others, 1972a; Dubiel, 1994); measured 404 feet (123 m) thick in section 27, T. 42 S., R. 17 W. just south of the quadrangle, however, only the upper 200 feet (60 m) is exposed in the quadrangle.

Subsurface Units

TRmv **Virgin Limestone Member of the Moenkopi Formation** – Shown on cross section only. Thickness from Hayden (2011a).

TRmltr **Lower red, Timpoweap, and Rock Canyon Conglomerate Members of the Moenkopi Formation –** Shown on cross section only. Thickness from Hayden (2011a).

unconformity

PERMIAN

Pk **Kaibab Formation** – Shown on cross section only. Thickness from Hayden (2011a).

Pt **Toroweap Formation** – Shown on cross section only. Thickness from Hayden (2011a).

Pq **Queantoweap Sandstone** – Shown on cross section only. Thickness from Hammond (1991).

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REFERENCES

Arabasz, W.J., and Julander, D.R., 1986, Geometry of seismically active faults and crustal deformation within the Basin and Range–Colorado Plateau transition in Utah, *in* Mayer, L., editor, Extensional tectonics of the southwestern United States—a perspective on processes and kinematics: Geological Society of America Special Paper 208, p. 43–74.

Ashland, F.X., 2003, Characteristics, causes, and implications of the 1998 Wasatch Front landslides, Utah: Utah Geological Survey Special Study 105, 49 p.

Beitler, B., Parry, W.T., and Chan, M.A., 2005, Fingerprints of fluid flow—chemical diagenetic history of the Jurassic Navajo Sandstone, southern Utah, U.S.A.: Journal of Sedimentary Research, v. 75, p. 547–561.

Best, M.G., and Brimhall, W.H., 1970, Late Cenozoic basalt types in the western Grand Canyon region, *in* Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geology Society Guidebook to the Geology of Utah, no. 23, p. 57–74.

Best, M.G., and Brimhall, W.H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geological Society of America Bulletin, v. 85, no. 11, p. 1677–1690.

Best, M.G., Hamblin, W.K., and Brimhall, W.H., 1966, Preliminary petrology and chemistry of late Cenozoic basalts in the western Grand Canyon region: Brigham Young University Geology Studies, v. 13, p. 109–123.

Best, M.G., McKee, E.H., and Damon, P.E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1035–1050.

Biek, R.F., 2003, Geologic map of the Harrisburg Junction quadrangle, Washington County, Utah: Utah Geological Survey Map 191, 42 p., 2 plates, scale 1:24,000.

Biek, R.F., and Ehler, J.B., 2007, Whole-rock major- and trace-element geochemical data for basaltic rocks in the St. George 30′ x 60′ quadrangle and adjacent areas, Washington, Iron, and Kane Counties, Utah: Utah Geological Survey Open-File Report 500, 1 plate, variously paginated, compact disk.

Biek, R.F., and Rohrer, J.C., 2006, Geology, mining history, and reclamation of the Silver Reef mining district, Washington County, Utah, *in* Bon, R.L., Gloyn, R.W., and Park, G.M., editors, Mining districts of Utah: Utah Geological Association Publication 32, p. 479–512.

Biek, R.F., Rowley, P.D., Hayden, J.M., Hacker, D.B., Willis, G.C., Hintze, L.F., Anderson, R.E., and Brown, K.D., 2010, Geologic map of the St. George and east part of the Clover Mountains 30′ x 60′ quadrangles, Washington and Iron Counties, Utah: Utah Geological Survey Map 242DM, 2 plates, 101 p., scale 1:100,000, GIS data (printed map published in 2009 as Map 242).

Billingsley, G.H., 1985, General stratigraphy of Petrified Forest National Park, Arizona: Museum of northern Arizona Bulletin 54, p. 3–8.

Birkeland, P.W., Machette, M.N., and Haller, K.M., 1991, Soils as a tool for applied Quaternary geology: Utah Geological and Mineral Survey Miscellaneous Publication 91-3, 63 p.

Blackett, R.E., and Wakefield, S.I., compilers, 2004, Geothermal resources of Utah, 2004—a digital atlas of Utah's geothermal resources: Utah Geological Survey Open-File Report 431, CD.

Blakey, R.C., 1994, Paleogeographic and tectonic controls on some Lower and Middle Jurassic erg deposits, Colorado Plateau, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 273–298.

Blakey, R.C., Bashem, E.L., and Cook, M.J., 1993, Early and Middle Triassic paleogeography, Colorado Plateau and vicinity, *in* Morales, M., editor, Aspects of Mesozoic geology and paleontology of the Colorado Plateau: Museum of Northern Arizona Bulletin 59, p. 13–26.

Blakey, R.C., and Gubitosa, R., 1983, Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona, *in* Reynolds, M.W., and Dolly, E.D., editors, Rocky Mountain Paleogeography Symposium 2: Rocky Mountain Section, Society of Paleontologists and Mineralogists, p. 39–45.

Budding, K.E., and Sommer, S.N., 1986, Low-temperature geothermal assessment of the Santa Clara and Virgin River valleys, Washington County, Utah: Utah Geological and Mineral Survey Special Studies 67, 34 p.

Chadwick, A.V., and Brand, L.R., 2013, Does the Moenkopi/Chinle contact represent a 10my depositional hiatus on the Colorado Plateau?: Geological Society of America Abstracts with Programs, v. 45, no. 7, p. 241.

Christenson, G.E., 1992, Geologic hazards of the St. George area, Washington County, Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 99–107.

Clemmensen, L.B., Olsen, H., and Blakey, R.C., 1989, Erg-margin deposits in the Lower Jurassic Moenave Formation and Wingate Sandstone, southern Utah: Geological Society of America Bulletin, v. 101, p. 759–773.

Clyde, C.G., 1987, Groundwater resources of the Virgin River basin in Utah: Logan, Utah State University, Utah Water Research Laboratory, 104 p.

Cordova, R.M., 1978, Ground-water conditions in the Navajo Sandstone in the central Virgin River basin, Utah: Utah Division of Water Rights Technical Publication 61, 66 p., map scale 1:250,000.

Cordova, R.M., Sandberg, G.W., and McConkie, W., 1972, Ground-water conditions in the central Virgin River basin, Utah: Utah Department of Natural Resources Technical Publication 40, 64 p.

Cornet, B., and Waanders, G., 2006, Palynomorphs indicate Hettangian (Early Jurassic) age for middle Whitmore Point Member of the Moenave Formation, Utah and Arizona, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Terrestrial Triassic-Jurassic transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 1–17.

Davis, G.H., 1999, Structural geology of the Colorado Plateau region of southern Utah with special emphasis on deformation bands: Geological Society of America Special Paper 342, 168 p.

DeCourten, F., 1998, Dinosaurs of Utah: Salt Lake City, University of Utah Press, 300 p.

Dickinson, W.R., Beard, S.L., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222–235.

Dickinson, W.R., and Gehrels, G.E., 2003, U-Pb ages of detrital zircons from Permian and Jurassic eolian sandstones of the Colorado Plateau, USA—paleogeographic implications: Sedimentary Geology, v. 163, issues 1-2, p. 29–66.

Dickinson, W.R., and Gehrels, G.E., 2009, U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau—evidence for transcontinental dispersal and intraregional recycling of sediment: Geological Society of America Bulletin, v. 121, nos. 3 and 4, p. 408–433.

Doelling, H.H., Sprinkel, D.A., Kowallis, B.J., and Kuehne, P.A., 2013, Temple Cap and Carmel Formations in the Henry Mountains Basin, Wayne and Garfield Counties, Utah, *in* Morris, T.H., and Ressetar, R., editors, The San Rafael Swell and Henry Mountains Basin—geologic centerpiece of Utah: Utah Geological Association Publication 42, p. 279–318.

Downing, R.F., 2000, Imaging the mantle in southwestern Utah using geochemistry and geographic information systems: Las Vegas, University of Nevada, M.S. thesis, 128 p.

Dubiel, R.F., 1994, Triassic deposystems, paleography and paleoclimate of the Western Interior, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, p. 132–168.

Embree, G.L., 1970, Lateral and vertical variations in a Quaternary basalt flow—petrography and chemistry of the Gunlock flow, southwestern Utah: Provo, Utah, Brigham Young University Geology Studies, v. 17, part 1, p. 67–115.

Eppinger, R.E., Winkler, G.R., Cookro, T.M., Shubat, M.A., Blank, H.R., Crowley, J.K., Kucks, R.P., and Jones, J.L., 1990, Preliminary assessment of the mineral resources of the Cedar City 1° x 2° quadrangle, Utah: U.S. Geological Survey Open-File Report 90-34, 146 p., map scale 1:250,000.

Fairbanks, R.G., Mortlock, R.A., Chiu, T-C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W., and Bloom, A.L., 2005, Radiocarbon calibration curve spanning 0 to 50,000 years B.P. based on paired $^{230}Th/^{234}U/^{238}U$ and ^{14}C dates on pristine corals: Quaternary Science Reviews, v. 24, p. 1781–1796.

Faust, M., 2005, Petrogenesis and geochemistry of Pleistocene and Pliocene basalt flows of the Pine Valley volcanic field, Utah, and their relationship to the tectonics of the Utah transition zone: Las Vegas, University of Nevada, M.S. thesis, 116 p.

Faust, M., and Smith, E., 2005, Volcanology of the Santa Clara and Diamond Valley lava flows, Snow Canyon

State Park, Utah: Geological Society of America Abstracts with Programs, v. 37, no. 4, p. 67.

Freethey, G.W., 1993, Maps showing recharge areas and quality of ground water for the Navajo aquifer, western Washington County, Utah: U.S. Geological Survey Water Resources Division Map WRIR 92-4160, scale approximately 1:250,000.

Gregory, H.E., 1950, Geology and geography of the Zion Park region, Utah and Arizona: U.S. Geological Survey Professional Paper 220, 200 p.

Hamblin, A.H., Lockley, M.G., and Milner, A.R.C., 2006, More reports of theropod dinosaur tracksites from the Kayenta Formation (Lower Jurassic), Washington County, Utah—implications for describing the Springdale Sandstone, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 276–281.

Hamblin, W.K., 1963, Late Cenozoic basalts of the St. George basin, Utah, *in* Heylmun, E.B., editor, Guidebook to the geology of southwestern Utah: Intermountain Association of Petroleum Geologists 12th Annual Field Conference, p. 84–89.

Hamblin, W.K., 1970a, Late Cenozoic basalt flows of the western Grand Canyon, *in* Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geological Society Guidebook to the Geology of Utah, no. 23, p. 21–38.

Hamblin, W.K., 1970b, Structure of the western Grand Canyon region, *in* Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geological Society Guidebook to the Geology of Utah, no. 23, p. 3–20.

Hamblin, W.K., 1987, Late Cenozoic volcanism in the St. George basin, Utah: Geological Society of America Centennial Field Guide—Rocky Mountain Section, p. 291–294.

Hamblin, W.K., and Best, M.G., 1970, Road log, *in* Hamblin, W.K., and Best, M.G., editors, The western Grand Canyon district: Utah Geology Society Guidebook to the Geology of Utah, no. 23, p. 93–154.

Hamblin, W.K., Damon, P.E., and Bull, W.B., 1981, Estimates of vertical crustal strain rates along the western margins of the Colorado Plateau: Geology, v. 9, p. 293–298.

Hamilton, W.L., 1984, The sculpturing of Zion: Springdale, Utah, Zion Natural History Association, 131 p.

Hammond, B.J., 1991, Geologic map of the Jarvis Peak quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 212, 63 p., scale 1:24,000.

Hayden, J.M., 2011a, Geologic map of the White Hills quadrangle, Washington County, Utah: Utah Geological Survey Map 250DM, 2 plates, scale 1:24,000.

Hayden, J.M., 2011b, Geologic road and trail guides to Snow Canyon State Park, Utah, *in* Anderson, P.B., and Sprinkel, D.A., editors, Geologic road, trail, and lake guides to Utah's parks and monuments: Utah Geological Association and Bryce Canyon Natural History Association, Utah Geological Association Publication 29 (third edition), 29 p., CD ROM.

Hayden, J.M., in press, Geologic map of the Veyo quadrangle, Washington County, Utah: Utah Geological Survey Map, 2 plates, scale 1:24,000.

Hayden, J.M., and Willis, G.C., 2011, Geologic map of the St. George 7.5′ quadrangle, Washington County, Utah: Utah Geological Survey Map 251DM, 2 plates, 20 p., GIS data.

Heckert, A.B., and Lucas, S.G., 2002, Revised Upper Triassic stratigraphy of the Petrified Forest National Park, Arizona, USA, *in* Heckert, A.B., and Lucas, S.G., editors, Upper Triassic stratigraphy and paleontology: New Mexico Museum of Natural History and Science Bulletin 21, p. 1–36.

Heilweil, V.M., Freethey, G.W., Stolp, B.J., Wilkowske, C.D., and Wilberg, D.E., 2000, Geohydrology and numerical simulation of ground-water flow in the central Virgin River basin of Iron and Washington Counties, Utah: Utah Department of Natural Resources Technical Publication 116, 139 p.

Heilweil, V.M., Watt, D.E., Solomon, D.K., and Goddard, K.E., 2002, The Navajo aquifer system of southwestern Utah, *in* Lund, W.R., editor, Field guide to geologic excursions in southwestern Utah and adjacent areas of Arizona and Nevada: U.S. Geological Survey Open-File Report 02-172, p. 105–130.

Hereford, R., Jacoby, G.C., and McCord, V.A.S., 1996, Late Holocene alluvial geomorphology of the Virgin River in the Zion National Park area, southwest Utah: Geological Society of America Special Paper 310, 41 p.

Hilburn, H., and Hunt, B., producers, 2006, The 2005 Santa Clara-Virgin River flood—images of loss and hope: St. George, Utah, Utah Flood Relief Committee, DVD video.

Hintze, L.F., 1986, Stratigraphy and structure of the Beaver Dam Mountains, southwestern Utah, *in* Griffen, D.T., and Phillips, W.R., editors, Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 1–36.

Hintze, L.F., and Hammond, B.J., 1994, Geologic map of the Shivwits quadrangle, Washington County, Utah: Utah Geological Survey Map 153, 21 p., scale 1:24,000.

Hintze, L.F., and Kowallis, B.J., 2009, Geologic history of Utah: Brigham Young University Geology Studies, Special Publication 9, 225 p.

Horrocks-Carollo Engineers, 1993, Culinary water resources study: St. George City Water and Power Department, June 1993, 128 p.

Hurlow, H.A., 1998, The geology of the central Virgin River basin, southwestern Utah, and its relation to ground-water conditions: Utah Geological Survey Water-Resources Bulletin 26, 53 p., 6 plates.

James, L.P., and Newman, E.W., 1986, Subsurface character of mineralization at Silver Reef, Utah, and a possible model for ore genesis, *in* Griffen, D.T., and Phillips, W.R., editors, Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 149–158.

Johnson, R.L., Smith, E.I., and Biek, R.F., 2010, Subalkaline volcanism in the Black Rock Desert and Markagunt Plateau volcanic fields of south-central Utah, *in* Carney, S.M., Tabet, D.E., and Johnson, C.L., editors, Geology and geologic resources of south-central Utah: Utah Geological Association Publication 39, p. 109–150.

Kirkland, J.I., and Milner, A.R.C., 2006, The Moenave Formation at the St. George Dinosaur Discovery Site at Johnson Farm, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 289–309.

Knudsen, T.R., and Lund, W.R., 2013, Geologic hazards of the State Route 9 corridor, La Verkin City to Town of Springdale, Washington County, Utah: Utah Geological Survey Special Study 148, 13 p., 9 plates, scale 1:24,000.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Zhang, C., and Everett, B.H., 2001, The record of Middle Jurassic volcanism in the Carmel and Temple Cap Formations of southwestern Utah: Geological Society of America Bulletin, v. 113, no. 3, p. 373–387.

Lambert, R.E., 1984, Shnabkaib Member of the Moenkopi Formation—depositional environment and stratigraphy near Virgin, Washington County, Utah: Brigham Young University Geology Studies, v. 31, pt. 1, p. 47–65.

LeBas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Leeman, W.P., 1974, Late Cenozoic alkali-rich basalt from the western Grand Canyon area, Utah and Arizona—isotopic composition of strontium: Geological Society of America Bulletin, v. 85, p. 1691–1696.

Lockley, M.G., and Milner, A.R.C., 2006, Tetrapod tracksites from the Shinarump Formation (Chinle Group, Upper Triassic) of southwestern Utah: New Mexico Museum of Natural History and Science Bulletin 37, p. 257–262.

Lowder, G.G., 1973, Late Cenozoic transitional alkali olivine tholeiitic basalt and andesite from the margin of the Great Basin, southwest Utah: Geological Society of America Bulletin, v. 84, no. 9, p. 2993–3012.

Lowe, M., 1992, The 1992 Truman Drive landslide, Santa Clara, Washington County, Utah *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 119–122.

Lucas, S.G., 1993, The Chinle Group—revised stratigraphy and biochronology of Upper Triassic nonmarine strata in the western United States, *in* Morales, M., editor, Aspects of Mesozoic geology and paleontology of the Colorado Plateau: Museum of Northern Arizona Bulletin 59, p. 27–50.

Lucas, S.G., and Heckert, A.B., 2001, Theropod dinosaurs and the Early Jurassic age of the Moenave Formation, Arizona-Utah, USA: Stuttgart, Germany, Neues Jahrbuch fuer Geologie und Paläeontologie Monatshefte, v. 7, p. 435–448.

Lucas, S.G., Lerner, A.J., Milner, A.R.C., and Lockley, M.G., 2006, Lower Jurassic invertebrate ichnofossils from a clastic lake margin, Johnson Farm, southwest Utah, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 128–136.

Lucas, S.G., and Milner, A.R.C., 2006, *Conchostraca* from the Lower Jurassic Whitmore Point Member of the Moenave Formation, Johnson Farm, southwestern Utah, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 421–423.

Lucas, S.G., and Tanner, L.H., 2006, The Springdale Member of the Kayenta Formation, Lower Jurassic of Utah-Arizona, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 71–76.

Lucas, S.G., and Tanner, L.H., 2007, Tetrapod biostratigraphy and biochronology of the Triassic-Jurassic transition on the southern Colorado Plateau, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 244, p. 242–256.

Lucas, S.G., Tanner, L.H., Donohoo-Hurley, L.L., Geissman, J.W., Kozur, H.W., Heckert, A.B., and Weems, R.E., 2011, Position of the Triassic-Jurassic boundary and timing of the end-Triassic extinctions on land—data from the Moenave Formation on the southern Colorado Plateau, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 302, p. 194–205.

Lucas, S.G., Tanner, L.H., and Heckert, A.B., 2005, Tetrapod biostratigraphy and biochronology across the Triassic-Jurassic boundary in northeastern Arizona, *in* Heckert, A.B., and Lucas, S.G., editors, Vertebrate paleontology in Arizona: New Mexico Museum of Natural History and Science Bulletin 29, p. 84–94.

Lund, W.R., Knudsen, T.R., and Sharrow, D.L., 2010, Geologic hazards of the Zion National Park geologic-hazards study area, Washington and Kane Counties, Utah: Utah Geological Survey Special Study 133, 95 p., 9 plates, DVD.

Lund, W.R., Knudsen, T.R., Vice, G.S., and Shaw, L.M., 2008, Geologic hazards and adverse construction conditions, St. George–Hurricane metropolitan area, Washington County, Utah: Utah Geological Survey Special Study 127, 105 p., 14 plates, DVD.

Lund, W.R., Sharrow, D.L., and Knudsen, T.R., 2007, Engineering geology in the Rocky Mountain west—effective geologic practice, *in* Lund, W.R., editor, Field guide to geologic excursions in southern Utah: Utah Geological Association Publication 35, 39 p.

Mabey D.R., and Budding, K.E., 1985, High-temperature geothermal resources of Utah: Utah Geological Survey Bulletin 123, 64 p.

Martz, J.W., and Parker, W.G., 2010, Revised lithostratigraphy of the Sonsela Member (Chinle Formation, Upper Triassic) in the southern part of Petrified Forest National Park, Arizona: PLoS ONE v. 5, issue 2, 26 p. (doi 10.1371/journal.pone.0009329).

Marzolf, J.E., 1994, Reconstruction of the early Mesozoic Cordilleran cratonal margin adjacent to the Colorado Plateau, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 181–216.

Milner, A.R.C., Birthisel, T.A., Kirkland, J.I., Breithaupt, B.H., Matthews, N.A., Lockley, M.G., Santucci, V.L., Gibson, S.Z., DeBlieux, D.D., Hurlbut, M., Harris, J.D., and Olsen, P.E., 2012, Tracking Early Jurassic dinosaurs across southwestern Utah and the Triassic-Jurassic transition, *in* Bonde, J.W., and Milner, A.R.C., editors, Field trip guidebook for the 71st annual meeting of the Society of Vertebrate Paleontology: Nevada State Museum Paleontological Papers, v.1, p. 1–107.

Milner, A.R.C., and Kirkland, J.I., 2006, Preliminary review of the Early Jurassic (Hettangian) freshwater Lake Dixie fish fauna in the Whitmore Point Member, Moenave Formation in southwest Utah, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 510–521.

Milner, A.R.C., and Kirkland, J.I., 2007, The case for fishing dinosaurs at the St. George Dinosaur Discovery Site at Johnson Farm: Utah Geological Survey, Survey Notes, v. 39, no. 3, p. 1–3.

Milner, A.R.C., Lockley, M.G., and Kirkland, J.I., 2006, A large collection of well-preserved theropod dinosaur swim tracks from the Lower Jurassic Moenave Formation, St. George, Utah, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 315–328.

Milner, A.R.C., and Spears, S.Z., 2007, Mesozoic and Cenozoic paleoichnology of southwestern Utah, *in* Lund, W.R., editor, Field guide to geologic excursions in southern Utah: Utah Geological Association Publication 35, p. 1–85.

Molina-Garza, R.S., Geissman, J.W., and Lucas, S.G., 2003, Paleomagnetism and magnetostratigraphy of the lower Glen Canyon and upper Chinle Groups, Jurassic-Triassic of northern Arizona and northeast Utah: Journal of Geophysical Research, v. 108, no. B4, 2181 (doi: 10.1029/2002JB001909).

Nelson, S.T., and Tingey, D.G., 1997, Time-transgressive and extension-related basaltic volcanism in southwest Utah and vicinity: Geological Society of America Bulletin, v. 109, no. 10, p. 1249–1265.

Nielsen, G.B., 2010, Geologic map and coloration facies of the Jurassic Navajo Sandstone, Snow Canyon State Park and areas of the Red Cliffs Desert Reserve, Washington County, Utah: Utah Geological Survey Open-File Report 561, 15 p., 2 plates.

Nielsen, G.B., and Chan, M.A., 2009, Mapping and correlation of diagenetic coloration facies, Jurassic Navajo Sandstone, Snow Canyon State Park, Utah, *in* Tripp, B.T., Krahulec, K., and Jordan, J.L., editors, Geology and geologic resources and issues of western Utah: Utah Geological Association Publication 38, p. 96–123.

Nusbaum, R.L., Unruh, D.M., and Millings, V.E., III, 1997, The role of lithosphere and asthenosphere in the genesis of late Cenozoic volcanism at Diamond Valley and Veyo volcano, southwest Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153-K, p. 229–239.

Paull, R.K., and Paull, R.A., 1994, Lower Triassic transgressive-regressive sequences in the Rocky Mountains, eastern Great Basin, and Colorado Plateau, USA, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, p. 169–180.

Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow seas—Jurassic paleogeography in the southern part of the Western Interior basin, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., editors, Mesozoic systems of the Rocky Mountain region, USA: Denver, Colorado, Rocky Mountain Section of the Society for Sedimentary Geology, p. 233–272.

Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—a preliminary survey: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Proctor, P.D., and Brimhall, W.H., 1986, Silver Reef mining district, revisited, Washington County, Utah, *in* Griffen, D.T., and Phillips, W.R., editors, Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 159–177.

Proctor, P.D., and Shirts, M.A., 1991, Silver, sinners and saints—a history of old Silver Reef, Utah: Provo, Utah, Paulmar, Inc., 224 p.

Rahl, J.M., Reiners, P.W., Campbell, I.H., Nicolescu, S., and Allen, C.M., 2003, Combined single-grain (U-Th)/He and U-Pb dating of detrital zircons from the Navajo Sandstone, Utah: Geology, v. 31, no. 9, p. 761–764.

Reiners, P.W., Campbell, I.H., Nicolescu, S., Allen, C.M., Hourigan, J.K., Garver, J.I., Mattinson, J.M., and Cowan, D.S., 2005, (U-Th)/(He-Pb) double-dating of detrital zircons: American Journal of Science, v. 305, p. 259–311.

Rowley, P.D., and Dixon, G.L., 2004, The role of geology in increasing Utah's ground-water resources from faulted terranes—lessons from the Navajo Sandstone, Utah, and the Death Valley flow system, Nevada-California, *in* Spangler, L.E., editor, Groundwater in Utah—source, protection, and remediation: Utah Geological Association Publication 31, p. 27–41.

Rowley, P.D., Dixon, G.L., D'Agnese, F.A., O'Brien, G.M., and Brickney, D.W., 2004, Geology and hydrology of the Sand Hollow Reservoir and well field area, Washington County, Utah: St. George, Utah, Washington County Water Conservancy District Report WCWCD-01, 14 p.

Sandburg, G.W., and Sultz, L.G., 1985, Reconnaissance of the quality of surface water in the upper Virgin River basin, Utah, Arizona, and Nevada, 1981–1982: Utah Division of Water Rights Technical Publication 83, 69 p.

Sansom, P.J., 1992, Sedimentology of the Navajo Sandstone, southern Utah, USA: Oxford, England, Department of Earth Sciences and Wolfson College, Ph.D. dissertation, 291 p.

Schudack, M.E., 2006, Basal Jurassic nonmarine ostracods from the Moenave Formation of St. George, Utah: New Mexico Museum of Natural History and Science Bulletin, v. 37, p. 427–431.

Smith, E.I., Sanchez, A., Walker, J.D., and Wang, K., 1999, Geochemistry of mafic magmas in the Hurricane volcanic field, Utah—implications for small- and large-scale chemical variability of the lithospheric mantle: The Journal of Geology, v. 107, p. 433–448.

Solomon, B.J., 1992a, Geology and the indoor-radon hazard in southwestern Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 164–172.

Solomon, B.J., 1992b, Environmental geophysical survey of radon-hazard areas in the southern St. George basin, Washington County, Utah, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 173–191.

Sprinkel, D.A., Kowallis, B.J., Waanders, G., Doelling, H.H., and Kuehne, P.A., 2009, The Middle Jurassic Temple Cap Formation, southern Utah—radiometric age, palynology, and correlation with the Gypsum Spring Member of the Twin Creek Limestone and the Harris Wash Member of the Page Sandstone [abs.]: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 690.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972a, Stratigraphy and origin of the Triassic Moenkopi Formation and related strata in the Colorado Plataeu region, with a section on sedimentary petrology by R.A. Cadigan: U.S. Geological Survey Professional Paper 691, 195 p., scale 1:2,500,000.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972b, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region, with a section on sedimentary petrology by R.A. Cadigan and on conglomerate studies by W. Thordarson, H.F. Albee, and J.H. Stewart: U.S. Geological Survey Professional Paper 690, 336 p.

Tidwell, W.D., and Ash, S.R., 2006, Preliminary report on the Early Jurassic flora from the St. George Dinosaur Discovery Site, Utah, *in* Harris, J.D., Lucas, S.G., Spielmann, J.A., Lockley, M.G., Milner, A.R.C., and Kirkland, J.I., editors, Tracking dinosaur origins—the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin 37, p. 414–420.

Tuesink, M.F., 1989, Depositional analysis of an eolian-fluvial environment—the intertonguing of the Kayenta Formation and Navajo Sandstone (Jurassic) in southwestern Utah: Flagstaff, Northern Arizona University, M.S. thesis, 189 p.

Utah Division of Water Resources, 1993, Municipal and industrial water diversions and depletions for the Virgin River and Kanab Creek drainage basins: Utah Division of Water Resources, unnumbered report, variously paginated.

Utah Geological Survey and New Mexico Geochronology Research Laboratory, 2008, $^{40}Ar/^{39}Ar$ geochronology results from the Veyo, Gunlock, Billies Mountain, The Flat Tops, Maple Ridge, Hebron, Enterprise, and Central West quadrangles, Utah: Utah Geological Survey Open-File Report 513, parts I and II, variously paginated.

Utah Geological Survey and U.S. Geological Survey, 2014, $^{40}Ar/^{39}Ar$ geochronology results from the Harrisburg

Junction, Hurricane, Little Creek Mountain, Santa Clara, Shivwits, Springdale West, St. George, The Divide, The Guardian Angels, Veyo, Virgin, Washington, and White Hills 7.5′ quadrangles, St. George 30′ x 60′ quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 629, 235 p. (variously paginated); http://ugspub.nr.utah.gov/publications/open_file_reports/OFR-629.pdf.

Utah Geological Survey and Utah State University Luminescence Laboratory, 2014, OSL geochronology results for the Washington Dome, Santa Clara, and Kanab 7.5′ quadrangles, Washington and Kane Counties, Utah: Utah Geological Survey Open-File Report 637, variously paginated, http://geology.utah.gov/online/ofr/ofr-637.pdf.

Wilkowske, C.D., Kenney, T.A., and McKinney, T.S., 2006, Flooding and streamflow in Utah during water year 2005: U.S. Geological Survey Fact Sheet 2006-3085, 6 p.

Willis, G.C., and Biek, R.F., 2001, Quaternary incision rates of the Colorado River and major tributaries in the Colorado Plateau, Utah, *in* Young, R.A., and Spamer, E.E., editors, Colorado River origin and evolution—proceedings of the symposium held at Grand Canyon National Park in June 2000: Grand Canyon Association Monograph 12, p. 119–123.

Willis, G.C., Biek, R.F., and Hayden, J.M., 2006, New age of the Santa Clara (Snow Canyon State Park) basalt flow: Utah Geological Survey, Survey Notes, v. 38, no. 3, p. 4–5.

Willis, G.C. and Hayden, J.M., in press, Geologic map of the Washington quadrangle, Washington County, Utah: Utah Geological Survey Map, 2 plates, scale 1:24,000.

Willis, G.C., and Higgins, J.M., 1996, Interim geologic map of the Santa Clara quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 339, 87 p., 2 plates, scale 1:24,000.

Woody, D.T., 2006, Revised stratigraphy of the lower Chinle Formation (Upper Triassic) of Petrified Forest National Park, Arizona, *in* Parker, W.G., Ash, S.R., and Irmis, R.B., editors, A century of research at Petrified Forest National Park—geology and paleontology: Museum of Northern Arizona Bulletin No. 62, p. 17–45.

APPENDIX A

Geochemical Analyses of Samples from Navajo Sandstone

Sample #	SiO_2	Fe_2O_3	MnO	Na_2O	MgO	Al_2O_3	K_2O	CaO	TiO_2	BaO	Total
SC0302	90.09	0.49	0.01	0.88	0.16	2.89	0.14	0.25	0.07	0.05	95.0
WA0305	63.86	21.10	5.28	0.36	0.19	1.51	0.25	0.86	0.02	0.59	94.0
WA0306	67.79	18.05	0.05	0.80	0.18	2.53	0.33	0.85	0.06	0.07	90.7
WA0307	77.10	1.69	0.08	4.83	0.18	5.25	0.15	0.15	0.35	0.23	90.0

Sample #	Quadrangle	Description	UTM 12 S mN (lat N)	UTM 12 S mE (long W)
SC0302 (map location A; table 1)	Santa Clara	White strongly bleached sandstone	4125779 N (37.2494°)	266983 E (113.6272°)
WA0305	Washington	Glossy very dark-brownish-black ironstone	4116385 N (37.1651°)	268031 E (113.6125°)
WA0306	Washington	Dull very dark-brownish-black ironstone	4116385 N (37.1651°)	268007 E (113.6128°)
WA0307	Washington	Typical moderate-reddish-brown sandstone	4112875 N (37.1337°)	269023 E (113.6003°)

ICP method; datum NAD 27
Samples represent the variability of secondary alteration of the Navajo Sandstone caused by migration of reducing (acidic water) and oxidizing (fresh water) through the rock; samples range from highly bleached sandstone (removal of hematitic cement) to dense ironstone (concentration of hematitic and goethitic cement).