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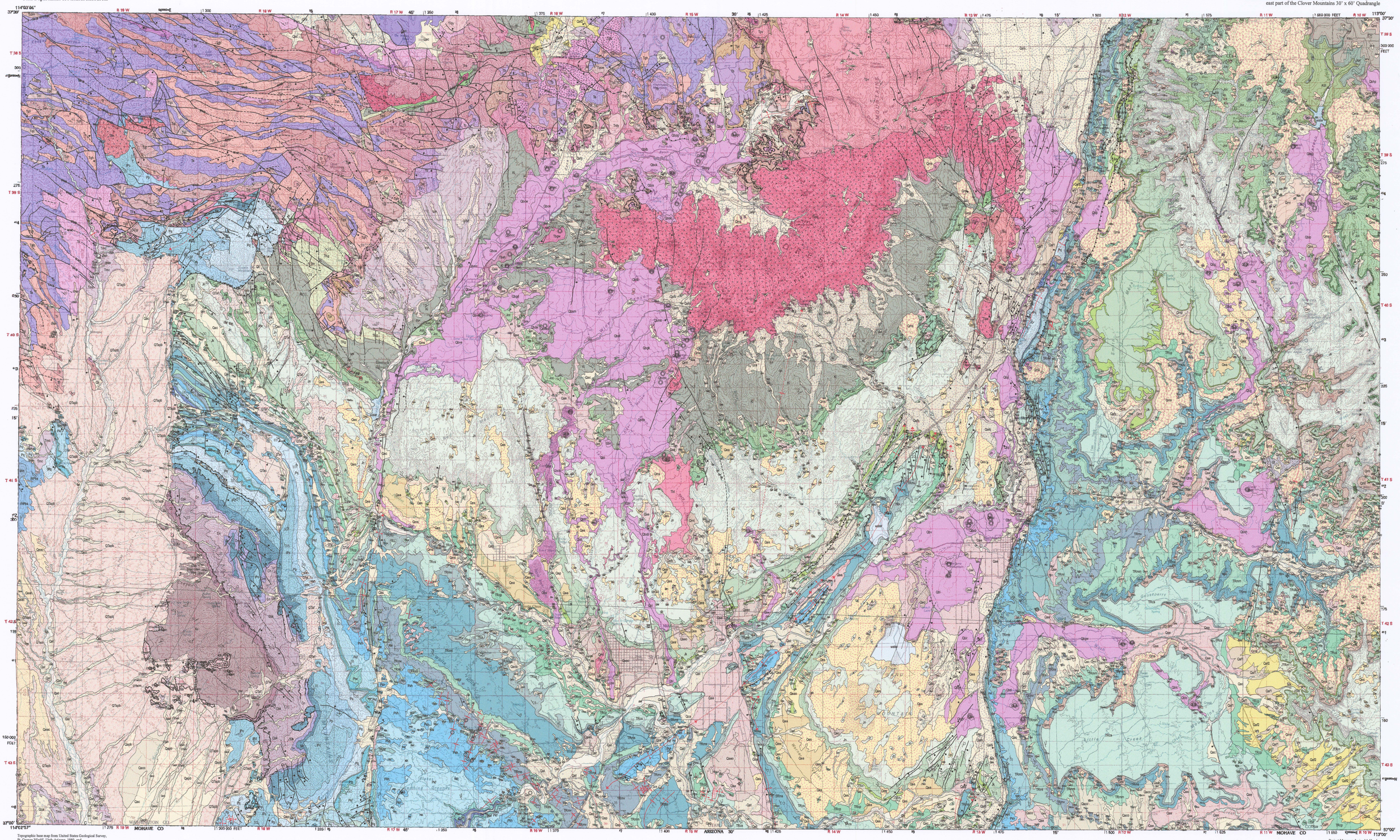

Topographic base map from United States Geological Survey,
St. George 30'x60', Utah-Arizona, 1980, and
Clover Mountains 30'x60', Nevada-Utah, 1978
Projection, UTM zone 12, NAD27

Project Manager: Janice M. Hayden
Cartography: Kent D. Brown

1:100,000

1 0.5 0 1 2 3 4 5 6 7 8 9 10 Miles

2 1 0 2 4 6 8 10 12 14 16 Kilometers

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ph. 801-537-3300; fax 801-537-3400; www.geology.utah.gov

14°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2006

Interim Geologic Map of the St. George 30' x 60' Quadrangle and east part of the Clover Mountains 30' x 60' Quadrangle, Washington and Iron Counties, Utah

by
Robert F. Biek[1], Peter D. Rowley[2], David B. Hacker[3], Janice M. Hayden[1], Grant C. Willis[1],
Lehi F. Hintze[4], R. Ernest Anderson[5], and Kent D. Brown[1]

2007

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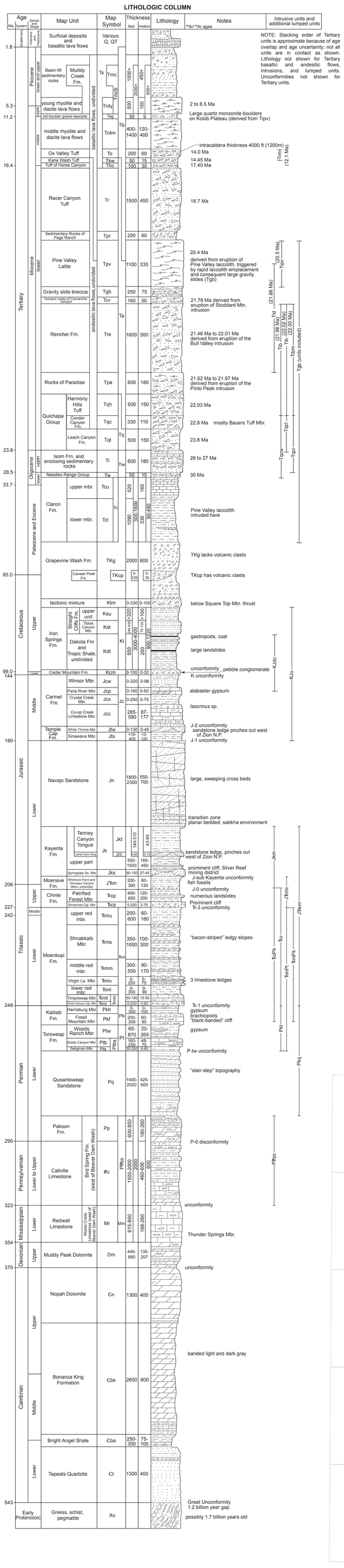
[3] Kent State University Trumbull Campus, Department of Geology, 4314 Mahoning Ave., N.W., Warren, OH 44483-1998;
[4] Brigham Young University, Department of Geology, S389 ESC, PO Box 24606, Provo, Utah 84602-4606, [5] USGS, retired

Map Location

UTAH DNR GEOLOGICAL SURVEY

StGeorge30x60_OFR_012907.mxd
January 29, 2007

LITHOLOGIC COLUMN



CORRELATION OF MAP UNITS

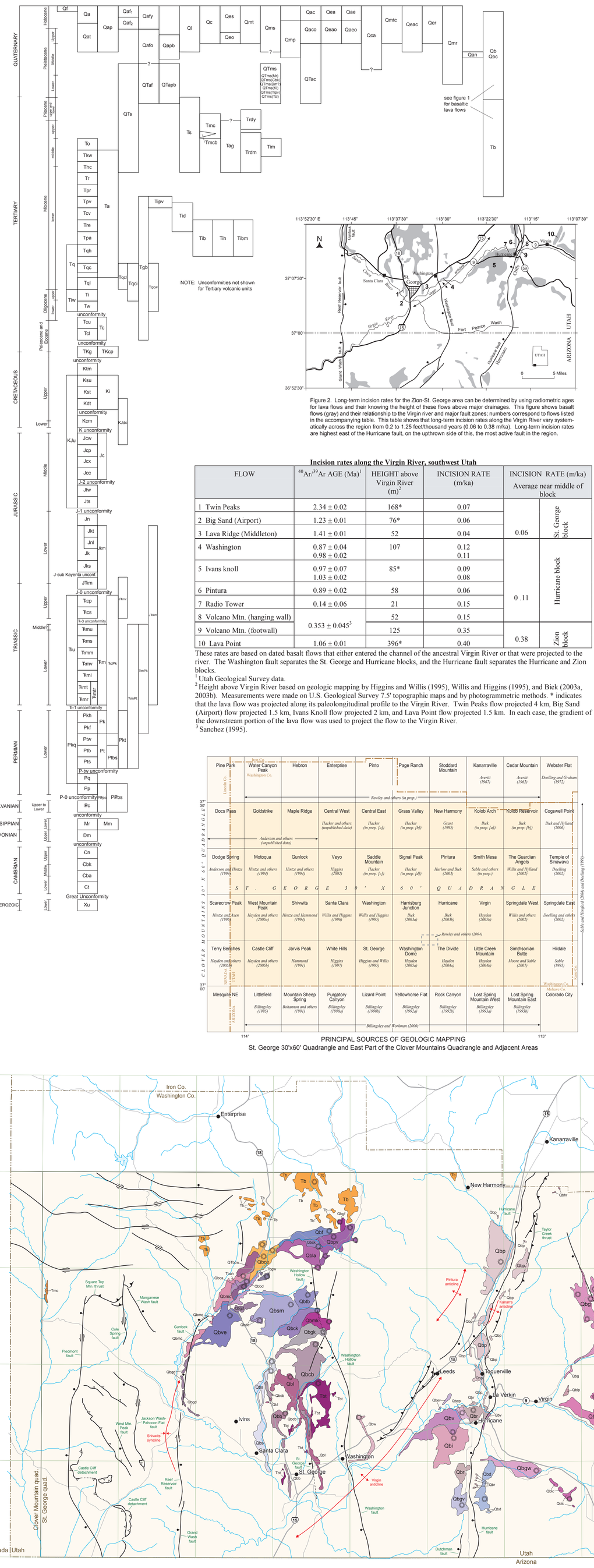


Figure 2. Long-term incision rates for the Zion-St. George area can be determined by using radiometric ages for lava flows and their knowing the height of these flows above major drainages. This figure shows basalt flows (gray) and their relationship to the Virgin river and major fault zones; numbers correspond to flows listed in the accompanying table. This table shows that long-term incision rates along the Virgin River vary systematically across the region from 0.2 to 1.25 feet/thousand years (0.06 to 0.38 m/ka). Long-term incision rates are highest east of the Hurricane fault, on the upthrown side of this, the most active fault in the region.

Incision rates along the Virgin River, southwest Utah

FLOW	$^{40}Ar/^{39}Ar$ AGE (Ma)[1]	HEIGHT above Virgin River (m)[2]	INCISION RATE (m/ka)	INCISION RATE (m/ka) Average near middle of block	
1 Twin Peaks	2.34 ± 0.02	168*	0.07	0.06	St. George block
2 Big Sand (Airport)	1.23 ± 0.01	76*	0.06		
3 Lava Ridge (Middleton)	1.41 ± 0.01	52	0.04		
4 Washington	0.87 ± 0.04 0.98 ± 0.02	107	0.12 0.11	0 .11	Hurricane block
5 Ivans knoll	0.97 ± 0.07 1.03 ± 0.02	85*	0.09 0.08		
6 Pintura	0.89 ± 0.02	58	0.06		
7 Radio Tower	0.14 ± 0.06	21	0.15		
8 Volcano Mtn. (hanging wall)	0.353 ± 0.045[3]	52	0.15	0.38	Zion block
9 Volcano Mtn. (footwall)		125	0.35		
10 Lava Point	1.06 ± 0.01	396*	0.40		

These rates are based on dated basalt flows that either entered the channel of the ancestral Virgin River or that were projected to the river. The Washington fault separates the St. George and Hurricane blocks, and the Hurricane fault separates the Hurricane and Zion blocks.

[1] Utah Geological Survey data.

[2] Height above Virgin River based on geologic mapping by Higgins and Willis (1995), Willis and Higgins (1995), and Biek (2003a, 2003b). Measurements were made on U.S. Geological Survey 7.5' topographic maps and by photogrammetric methods. * indicates that the lava flow was projected along its paleolongitudinal profile to the Virgin River. Twin Peaks flow projected 4 km, Big Sand (Airport) flow projected 1.5 km, Ivans Knoll flow projected 2 km, and Lava Point flow projected 1.5 km. In each case, the gradient of the downstream portion of the lava flow was used to project the flow to the Virgin River.

[3] Sanchez (1995).

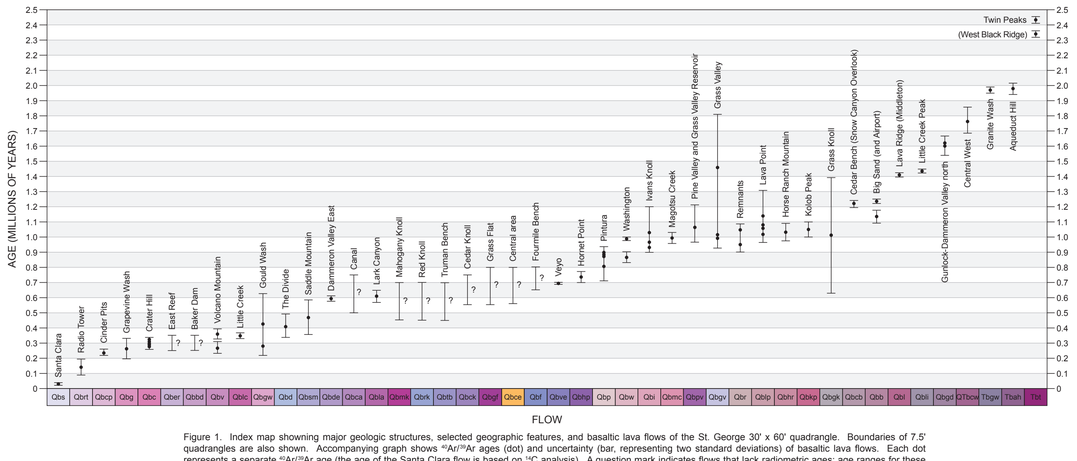
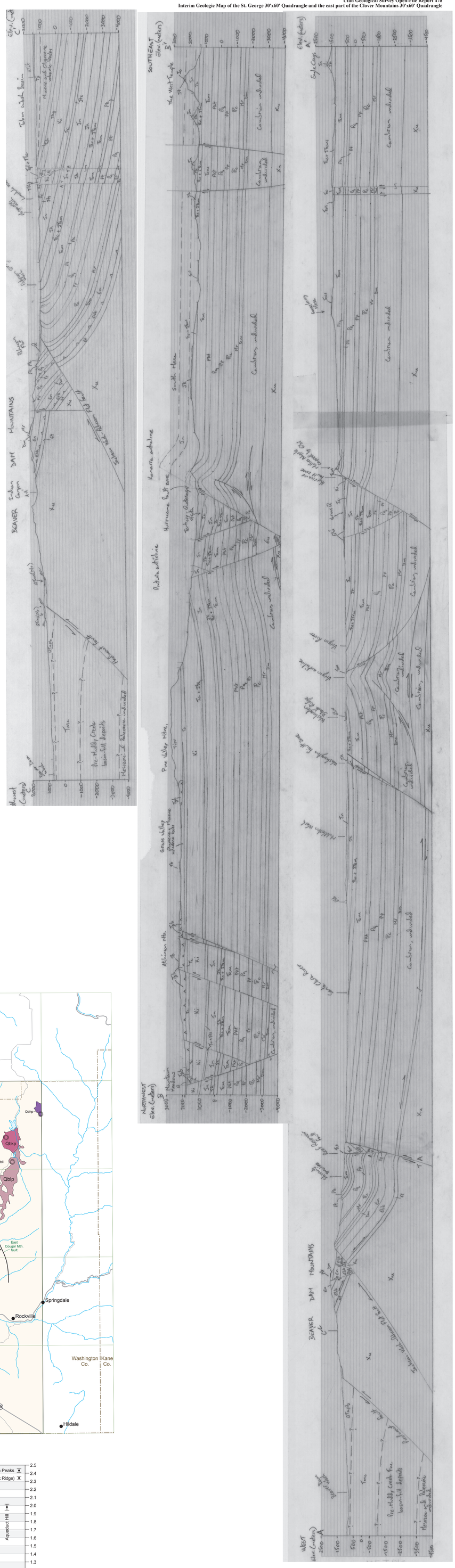


Figure 1. Index map showing major geologic structures, selected geographic features, and basaltic lava flows of the St. George 30' x 60' quadrangle. Boundaries of 7.5' quadrangles are also shown. Accompanying graph shows $^{40}Ar/^{39}Ar$ ages (dot) and uncertainty (bar, representing two standard deviations) of basaltic lava flows. Each dot represents a separate $^{40}Ar/^{39}Ar$ age (the age of the Santa Clara flow is based on ^{14}C analysis). A question mark indicates flows that lack radiometric ages; age ranges for these flows are estimated based on field relationships and regional incision rates. Undivided basaltic lava flows (Tb) and flows in the Muddy Creek Formation (Tmcb) are not shown on the graph.

GEOLOGIC SYMBOLS

- Contact - Dashed where location inferred
- Normal fault - Dashed where location inferred; dotted where concealed; bar and ball on downthrown side; arrows show relative movement on cross sections
- Strike-slip fault - Dashed where location inferred; dotted where concealed; arrows show relative movement on map; T (toward) and A (away) show relative movement on cross sections
- Oblique-slip fault - Dashed where location inferred; dotted where concealed; bar and ball on downthrown side and arrows show relative movement on map; arrows and T (toward) and A (away) show relative movement on cross sections
- Thrust fault - Dashed where location inferred; dotted where concealed; barbs on upper plate; arrows show relative movement on cross sections
- Low-angle normal fault - Dashed where location inferred; dotted where concealed; hachures on upper plate; arrows show relative movement on cross section
- Gravity-slide surface - Dashed where location inferred; dotted where concealed; barbs on upper plate; arrows show relative movement on cross section
- Fold axes - Dashed where location inferred; dotted where concealed; arrow on end of axes show plunge
- syncline
- anticline
- Caldera margin - Dashed where location inferred; dotted where concealed; hachures on downthrown side
- Strike and dip of bedding
- 30 inclined
- vertical
- 65 overturned
- horizontal
- Volcanic vent
- Deep petroleum exploration well
- oil well, plugged and abandoned
- dry hole
- Mine



INTERIM GEOLOGIC MAP OF THE ST. GEORGE 30'x60' QUADRANGLE AND THE EAST PART OF THE CLOVER MOUNTAINS 30'x60' QUADRANGLE, WASHINGTON AND IRON COUNTIES, UTAH

by

Robert F. Biek[1], Peter D. Rowley[2], David B. Hacker[3], Janice M. Hayden[1], Grant C. Willis[1], Lehi F. Hintze[4], R. Ernest Anderson[5], and Kent D. Brown[1]

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2007

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OPEN-FILE REPORT 478
UTAH GEOLOGICAL SURVEY
a division of
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2007

DESCRIPTION OF MAP UNITS

QUATERNARY

Artificial deposits

Qf **Artificial fill** (Historical) – Engineered fill used to create Quail Creek, Ash Creek, Sand Hollow, and Gunlock dams and other smaller flood-control and water-supply structures, as well as the Washington County landfill; fill placed for highways, building pads, and other uses not mapped.

Alluvial deposits

Qa **River and stream deposits** (Holocene) – Stratified, moderately to well-sorted gravel, sand, silt, and minor clay deposited in river and stream channels and flood plains; includes local small alluvial-fan and colluvial deposits, stream-terrace deposits less than about 10 feet (<3 m) above modern base level, and higher-level stream-terrace deposits too small to map separately; typically 10 to 25 feet (3-8 m) thick.

Qat **Old river and stream deposits** (Holocene to Middle Pleistocene) – Stratified, moderately to well-sorted alluvial gravel, sand, silt, and minor clay that forms level to gently sloping terraces above modern drainages; locally divisible into 6 or more distinct terrace levels based on elevation above modern drainages, but undivided here due to map scale; deposited in stream-channel and flood-plain environments and may include colluvial and alluvial-fan deposits too small to map separately; typically forms a sand-and-gravel veneer 10 to 30 feet (3-9 m) thick over an eroded bedrock surface.

Qap **Pediment deposits** (Holocene to Middle Pleistocene) – Poorly sorted, subangular to rounded, silt and sand to small-boulder gravel that forms a locally resistant cap over eroded bedrock surfaces; locally divisible into four or more distinct levels, as northwest of Santa Clara, but undivided here; deposited principally as debris flows, debris floods, and in ephemeral stream channels; 0 to about 80 feet (0-24 m) thick.

Qaf_1 **Level-1 alluvial-fan deposits** (Holocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment deposited at the mouths of active streams and washes; clast composition ranges widely and reflects rock types exposed in upstream drainage basins; deposited principally as debris flows and debris floods on active depositional surfaces; typically 10 to 30 feet (3-9 m) thick.

Qaf_2 **Level-2 alluvial-fan deposits** (Holocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment deposited at the mouths of active streams and washes; clast composition ranges widely and reflects rock types exposed in upstream drainage basins; deposited principally as debris flows and debris floods and typically forms inactive surfaces incised by active drainages; typically 10 to 50 feet (3-15 m) thick.

Qafy **Younger alluvial-fan deposits** (Holocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment deposited at the mouths of

active streams and washes; clast composition ranges widely and reflects rock types exposed in upstream drainage basins; forms both active depositional surfaces (Qaf_1 equivalent) and inactive surfaces incised by small streams (Qaf_2 equivalent) undivided here; deposited principally as debris flows and debris floods, but colluvium locally constitutes a significant part of the deposits; small, isolated alluvial fans are typically less than a few tens of feet thick, but large, coalesced fans, as in the New Harmony basin, are probably as much as 200 feet (60 m) thick.

Qafo **Older alluvial-fan deposits** (Upper to Middle[?] Pleistocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment with moderately developed calcic soils (caliche or hardpan); forms broad, gently sloping, deeply dissected surfaces on the flanks of the Pine Valley Mountains; deposits southeast of the Pine Valley Mountains are typically less than a few tens of feet thick, but deposits in the New Harmony basin likely exceed 200 feet (60 m) thick.

Qapb **Alluvial-pediment and basin-fill deposits** (Upper to Middle Pleistocene) – Silt, sand, gravel, and boulder conglomerate derived from Precambrian metamorphic and Paleozoic sedimentary rocks in the Beaver Dam Mountains and from a variety of mostly volcanic rocks exposed in the Bull Valley Mountains; form surfaces that slope toward Beaver Dam Wash and that have an intermediate level of incision, indicating that they are younger than Quaternary/Tertiary alluvial-pediment and basin-fill deposits (QTapb), but older than adjacent older alluvial and colluvial deposits (Qaco); deposited principally as debris flows and debris floods; as much as about 100 feet (30 m) thick.

Colluvial deposits

Qc **Colluvial deposits** (Holocene to Upper Pleistocene) – Poorly sorted, angular, clay- to boulder-size, locally derived sediment deposited principally by slope wash and soil creep; locally includes talus, alluvial, and eolian deposits too small to map separately; gradational with talus deposits; includes older colluvial deposits now incised by adjacent drainages; generally less than 20 feet (6 m) thick, although older colluvial deposits may be as much as 100 feet (30 m) thick on the Kolob Plateau.

Eolian deposits

Qes **Eolian sand deposits** (Holocene to Upper Pleistocene) – Well sorted, fine- to medium-grained, well-rounded, frosted quartz sand; sand is recycled principally from the Navajo Sandstone and Kayenta Formation; locally forms small dunes partly stabilized by vegetation; locally includes thick calcic soils (hardpan or caliche); typically 0 to 20 feet (0-6 m) thick.

Qeo **Older eolian sand deposits** (Upper Pleistocene) – Forms resistant, planar surfaces capped by calcic soils (hardpan or caliche) and lesser eolian sand; 0 to 20 feet (0-6 m) thick.

Lacustrine and basin-fill deposits

Ql **Lacustrine and basin-fill deposits** (Holocene to Middle Pleistocene) – Well-stratified sand, silt, and clay deposited in small lakes or basins created by landslides, rock falls, and basaltic lava flows; typically grades into colluvial, alluvial, and alluvial-fan deposits at basin margins and in stratigraphically upper part of deposits; sediments from 14 such lakes and ephemeral ponds are known in the Zion National Park area; see Hamilton (1978, 1979, undated, 1995), Doelling (2002), Willis and Hylland (2002), Willis and others (2002), Biek and others (2003), and Biek (in preparation[a, b]) for details on the many small lake deposits in this area.

Mass-movement deposits

Qmt **Talus deposits** (Holocene to Upper Pleistocene) – Poorly sorted, angular boulders and finer-grained interstitial sediment deposited principally by rock fall on and at the base of steep slopes; typically grades downslope into colluvial deposits and may include colluvial deposits where impractical to differentiate the two; also includes alluvial deposits in the bottom of washes, and, in the Smith Mesa quadrangle, locally includes landslide deposits along the outcrop belt of the Petrified Forest Member of the Chinle Formation; generally less than 30 feet (9 m) thick.

Qms **Landslide deposits** (Historical to Middle[?] Pleistocene) **–** Poorly sorted, clay- to boulder-size, locally derived material deposited by rotational and translational landslide movement; characterized by hummocky topography, numerous internal scarps, and chaotic bedding attitudes; basal slip surfaces most commonly form in the Shnabkaib Member of the Moenkopi Formation, Petrified Forest Member of the Chinle Formation, the Co-op Creek Limestone Member of the Carmel Formation, the Dakota Formation, and the upper unit of the Straight Cliffs Formation, and the slides incorporate these and overlying map units; the Petrified Forest Member and Dakota Formation especially form large, complex mass movements; undivided as to inferred age because new research shows that even landslides with subdued morphology (suggesting that they are older, weathered, and have not moved recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Francis Ashland, Utah Geological Survey, verbal communication, April 2006); typically several tens of feet thick, but some deposits may exceed 200 feet (60 m) thick.

Qmp **Older landslide, colluvial, and alluvial pediment-mantle deposits** (Holocene to Pleistocene) – Remnants of poorly sorted rock-fall, landslide, colluvial, and generally minor alluvial-fan debris that mantle and armor gently sloping, pediment-like benches cut across bedrock; consist of angular and subangular, house-sized boulders to fine-grained sand and lesser amounts of silt and clay derived from nearby cliffs and ledges; preserved as remnants that form inclined benches near steep bedrock slopes, high above modern drainages, in and near the southwest part of Zion National Park; as mapped, includes a talus slope above the bench-like deposits in the Smith Mesa quadrangle; these benches may be either remnants of much larger surfaces that were graded to the ancestral Virgin River, which, at the time of deposition, must have been as much as several hundred feet above its present position, or are the remnants of sloping erosional surfaces mantled and protected from erosion by the coarse deposits and were not graded to the river; as much

as 30 feet (9 m) thick; graded to several levels that project as much as 700 feet (210 m) above the modern river channel.

Mixed-environment deposits

Qac, Qaco

Alluvial and colluvial deposits (Holocene to Upper Pleistocene) – Poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment deposited principally in swales, small drainages, and the upper reaches of large streams by fluvial, slope-wash, and creep processes; gradational with both alluvial and colluvial deposits; older deposits (Qaco) include gypcrete (silt to small boulders cemented by gypsum) along the Moenkopi outcrop belt just west of St. George that is as much as 10 feet (3 m) thick; older deposits form incised, inactive surfaces commonly incised by younger (Qac) deposits; generally less than 30 feet (9 m) thick.

Qea, Qeao

Eolian and alluvial deposits (Holocene to Upper Pleistocene) – Well-sorted, fine- to medium-grained, reddish-brown eolian sand reworked by alluvial processes, and poorly to moderately sorted gravel, sand, and silt deposited in small channels; younger deposits (Qea) form active depositional surfaces, whereas older deposits (Qeao) typically form incised, inactive surfaces; 0 to about 20 feet (0-6 m) thick.

Qae, Qaeo

Alluvial and eolian deposits (Holocene to Upper Pleistocene) – Moderately sorted gravel, sand, and silt deposited in small channels and on alluvial flats, and well-sorted, fine- to medium-grained, reddish-brown eolian sand locally reworked by alluvial processes; younger deposits (Qae) form active depositional surfaces, whereas older deposits (Qaeo) typically form incised, inactive surfaces; 0 to about 20 feet (0-6 m) thick.

Qca **Colluvial and alluvial deposits** (Holocene to Middle[?] Pleistocene) – Poorly sorted, angular to subrounded, fine-grained to boulder-sized sediment deposited on moderate slopes by slope-wash, debris-flow, and alluvial processes; mapped along the base of the Pine Valley laccolith, where it includes alluvial-fan and talus deposits and includes both active and deeply dissected surfaces; also mapped near St. George, where it forms broad, low- to moderate-relief slopes that lack a well-defined drainage pattern, and near the Washington fault where it is moderately incised; and mapped west of Beaver Dam Wash, where it consists of gypsiferous, clay- to cobble-size sediment that forms deeply incised erosional remnants over the Muddy Creek Formation; typically 20 to 30 feet (6-9 m) thick, but deposits on the flanks of the Pine Valley Mountains may locally exceed 80 feet (25 m) thick.

Qmtc **Talus and colluvial deposits** (Holocene to Upper Pleistocene) – Poorly sorted, angular, boulders, gravel, sand, and silt deposited by rock-fall, slope-wash, debris-flow, and alluvial processes along scarps and hillsides; maximum thickness about 30 feet (9 m).

Qeac **Mixed eolian and alluvial deposits with well-developed calcic soils** (Holocene to Middle Pleistocene) – White, laminated calcic soil (caliche or hardpan) with crinkle bedding and pisolites (stage VI carbonate development of Birkeland and others, 1991); forms resistant cap on Quaternary/Tertiary alluvial-pediment and basin-fill deposits (QTapb) and the Muddy Creek Formation west of the Beaver Dam Mountains; typically 5 to 30 feet (2-9 m) thick.

Qer **Eolian and residual deposits** (Holocene to Upper Pleistocene) – Reddish-orange, fine- to medium-grained sand containing residual Navajo Sandstone pebbles, cobbles, and boulders; deposited in shallow topographic depressions and on gently sloping surfaces mostly on the Navajo Sandstone, from which it is derived; 0 to 20 feet (0-6 m) thick.

Qmr **Residual deposits of basaltic lava flows** (Holocene to Lower Pleistocene) – Residual lag of angular to subangular basaltic blocks derived from the Lava Point lava flow (northeast of Virgin) and the Little Creek Peak lava flow (south of Kolob Reservoir); probably as much as several tens of feet thick.

QUATERNARY/TERTIARY

Alluvial deposits

QTapb **Older alluvial-pediment and basin-fill deposits** (Pleistocene to Pliocene) – Silt, sand, gravel and boulder conglomerate derived from Precambrian metamorphic and Paleozoic sedimentary rocks in the Beaver Dam Mountains and from a variety of mostly volcanic rocks in the Bull Valley Mountains; surface locally has a well-developed calcic soil (caliche or hardpan) (stage VI, Birkeland and others, 1991); forms deeply dissected alluvial-fan surfaces in the northern Virgin River depression that slope toward Beaver Dam Wash; maximum exposed thickness, along Beaver Dam Wash, is about 300 feet (90 m).

QTaf **Oldest alluvial-fan deposits** (Pleistocene to Pliocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment typically capped by resistant, well-developed calcic soils (caliche or hardpan); clast composition ranges widely and reflects rock types exposed in upstream drainage basins; forms broad, gently sloping, deeply dissected surfaces generally grading into and correlative in time with alluvial-pediment and basin-fill deposits (QTapb); in the Gunlock and Motoqua quadrangles, forms erosional remnants of once-extensive pediment deposits shed off the southern Bull Valley Mountains; deposited principally as debris flows and debris floods; variable thickness as much as about 150 feet (45 m).

QTac **Oldest alluvial and colluvial deposits** (Pleistocene to Pliocene) – Poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment deposited in the Pakoon Flat area by fluvial, debris-flow, and slope-wash processes; may locally exceed 100 feet (30 m) thick.

QTs **Basin-fill sediments** (Pleistocene to Miocene) – Typically poorly consolidated, mostly tan, locally tuffaceous, alluvial sandstone, mudstone, siltstone, and conglomerate;

mapped in deeply dissected, poorly exposed fault blocks in the Beaver Dam Mountains; maximum thickness about 200 feet (60 m).

Mass-movement deposits

QTms(Mr), QTms(Cbk), QTms(Dm?), QTms(Ki), QTms(Tcl), QTms(Tipv), QTms

Oldest landslide deposits (Pleistocene to Pliocene) – Large blocks of highly brecciated Redwall Limestone, Bonanza King Formation, and Muddy Peak Dolomite(?) that rest on Quaternary/Tertiary alluvial-pediment and basin-fill deposits (QTapb) and Muddy Creek Formation (Tmc) at the west edge of the Beaver Dam Mountains; the blocks are typically 1000 feet (300 m) or more long and exposed parts are 10 to 200 feet (3-60 m) thick; some blocks, especially farther from the mountain front, appear as inselbergs partly buried by alluvial-pediment and basin-fill deposits; Cook (1960a) and Jones (1963) interpreted them as gravity slide blocks, derived from the east, and suggested that the comparatively unbrecciated block at Sheep Horn Knoll may be a remnant source of the slide blocks; Anders and others (1998; see also Anders and others, 2000) concluded that the blocks were emplaced by a single catastrophic event. Also includes large blocks of Iron Springs Formation, lower Claron Formation, and Pine Valley laccolith on the southeast flank of the Pine Valley Mountains, here reinterpreted from the original mapping of Hurlow and Biek (2003). QTms mapped in the northwest part of the White Hills is unsorted, clay- to boulder-size sediment that caps ridges in excess of 400 feet (120 m) above adjacent drainages; it includes large blocks of the Shinarump Conglomerate Member of the Chinle Formation that are more than 30 feet (9 m) long; these QTms deposits are about 20 to 80 feet (6-24 m) thick.

Basaltic lava flows

Basaltic lava flows in the St. George 30'x 60' quadrangle are part of the Western Grand Canyon basaltic field, which extends across the southwest part of the Colorado Plateau and adjacent transition zone in southwest Utah, northeast Arizona, and adjacent Nevada (Hamblin, 1963, 1970, 1987; Best and Brimhall, 1970, 1974; Best and others, 1980; Smith and others, 1999). This basaltic field contains hundreds of relatively small volume, widely scattered basaltic lava flows and cinder cones that range in age from late Miocene to Holocene. The St. George 30' x 60' quadrangle contains lava flows that range from a 17-million-year-old early Miocene basaltic flow widely exposed north of Pine Valley, and a 9-million-year-old late Miocene basaltic flow near the base of the Muddy Creek Formation along Beaver Dam Wash, to the newly dated 27,000-year-old Santa Clara lava flow at Snow Canyon State Park. Most lava flows in the quadrangle, however, are less than about one million years old; three temporal clusters occur between about 250,000 to 350,000, 550,000 to 700,000, and 950,000 and 1,050,000 years old (figure 1). $^{40}Ar/^{39}Ar$ raw data and major and trace-element geochemistry for these lava flows will soon be available on the Utah Geological Survey website http://geology.utah.gov/online/analytical_data.htm; see also NMGRL and UGS (2006). Rock names are after LeBas and others (1986).

Lava flows typically have a rubbly base, a dense, jointed middle part, and, if not eroded away, a vesicular upper part that has a blocky or rarely poorly developed pahoehoe surface. The flows commonly overlie stream-gravel and other surficial deposits, and are partly covered by eolian sand and calic soil (caliche) not shown on this map. Most lava flows are dark gray, fine

grained, and contain small olivine phenocrysts, and with few exceptions are difficult to differentiate by hand sample alone. They are differentiated only through detailed geologic mapping in concert with trace-element geochemistry and radiometric ages. Rarely, especially near vent areas, lava tubes are present, and in one locality, pillow basalts are present at the base of a flow where it blocked the ancestral Virgin River (Biek, 2003b).

Most lava flows are typically 10 to 40 feet (3-12 m) thick, but they are as much as several hundred feet thick where they fill ancient stream channels. Most also consist of multiple flow or cooling units that 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 weathering to occur. For example, the southern end of the Washington lava flow in the Harrisburg Junction quadrangle consists of three cooling units that together constitute the flow itself. Some lava flows, such as the Volcano Mountain and Veyo flows, have a longer, more complicated eruptive history and are themselves composed of several distinct flows.

Because each flow was emplaced in a "geological instant" (most basaltic volcanoes are monocyclic, meaning that each vent produces only one eruptive cycle that may last less than a year or as much as a few tens of years in duration), flowed several miles or more across the landscape and down ancient drainages, and because they are resistant to erosion, these lava flows provide a "snapshot" of the local landscape as it existed when the flow erupted. As the lava flows blocked drainages, the streams often briefly re-established themselves on top of the flow as evidenced by thin gravel deposits. However, the streams soon moved off to the side where they eroded softer sedimentary bedrock, ultimately leaving the resistant lava flows stranded as elevated, sinuous ridges called inverted valleys that mark the location of former channels. The greater St. George area is justly famous for these classic examples of inverted topography such as Washington and Middleton Black Ridges (as first described in detail by Hamblin (1963, 1970, 1987; Hamblin and others, 1981).

Long-term incision rates for the Zion-St. George area – calculated using radiometric ages for these lava flows and their height above major drainages – vary systematically across the region from 0.2 to 1.25 feet/thousand years (0.06 to 0.38 m/ka) (figure 2) (Willis and Biek, 2001). Our calculations reconfirm and expand on many of the findings of Hamblin and others (1981), who similarly documented incision rates in the St. George basin. Several of the lava flows crossed and are now offset by the Hurricane fault, providing important constraints on fault slip rates over the past one million years (Lund and others, 2001, 2002). Thus, in this area, we know that the amount and rate of long-term incision along the Virgin River is largely a function of base-level lowering along faults at and near the boundary of the Basin and Range. Long-term incision rates are highest east of the Hurricane fault, on the upthrown side of this, the most active fault in the region.

Importantly then, not taking the structural setting into account can lead to incorrect results when estimating relative ages of basalt flows based on degree of weathering and amount of "topographic inversion" ("stage" designations of Hamblin, 1963, 1970, 1987). For example, the lower reaches of Middleton and Washington Black Ridges, capped by the Lava Ridge and Washington lava flows, respectively, are classic inverted valleys both assigned to stage IIb by Hamblin (1987). The two flows are about 5 miles (8 km) apart and both flowed into a well-graded stretch of the ancestral Virgin River. The Washington flow stands about twice as high above the Virgin River as the Lava Ridge flow, yet $^{40}Ar/^{39}Ar$ ages now show that it is about 500,000 years younger than the Lava Ridge flow (figure 2), and thus, according to the stage

designations, should be lower. The greater topographic inversion on the younger flow is directly attributable to its position on the footwall (upthrown part) of a separate, relatively more elevated structural block. The old axiom that the older the lava flow the higher it now stands above adjacent drainages is generally only true when comparing flows on the same structural block.

Qb, Qbc

Basaltic lava flows and cinder deposits, undivided (Pleistocene) **–** Isolated basaltic lava flows (Qb) and cinder deposits (Qbc) of uncertain correlation along the Virgin River near Hurricane, and along the Santa Clara River near Veyo and Central.

Qbs, Qbsc

Santa Clara lava flow and cinder cones (Upper Pleistocene) **–** Dark-brownish-black to black subalkaline basalt (Qbs) that contains abundant small olivine phenocrysts in an aphanitic groundmass; has a jagged aa surface and is the youngest flow in the St. George basin; an iridescent sheen is locally present on protected surfaces; erupted from vents at two cinder cones (Qbsc) in Diamond Valley north of St. George; sample VY122001-1 yielded an unusable $^{40}Ar/^{39}Ar$ age of 0.05 $\pm$ 0.07 Ma and sample VR42-03, likely due to insufficient argon release, yielded unreliable $^{40}Ar/^{39}Ar$ ages of 0.120 $\pm$ 0.06 (plateau) and 0.089 $\pm$ 0.025 (isochron) Ma (UGS unpublished data); we obtained a new radiocarbon age of 27,270 $\pm$ 250 ^{14}C yr B.P. from charcoal discovered in loose sand just underneath the flow (Willis and others, 2006); lava flow is typically 10 to 30 feet (3-9 m) thick, but locally thicker where it fills paleotopography.

Qbrt, Qbrtc

Radio tower lava flow and cinder cones (Middle Pleistocene) **–** Medium- to dark-gray, fine-grained basalt to basanite (Qbr) with small olivine phenocrysts; erupted from vents at four overlapping cinder cones (Qbrc) west of Hurricane; yielded an $^{40}Ar/^{39}Ar$ plateau age of 0.14 $\pm$ 0.06 Ma (Biek, 2003b); lava flow is as much as 180 feet (55 m) thick where it fills the ancestral Virgin River channel.

Qbcp, Qbcpc

Cinder pits lava flow and cinder cones (Middle Pleistocene) **–** Medium- to dark-gray, fine-grained basalt (Qbcp) with small olivine phenocrysts; yielded an $^{40}Ar/^{39}Ar$ age of 0.24 $\pm$ 0.02 Ma (Biek, 2003b); erupted from vents at two overlapping cinder cones (Qbcpc) northwest of Hurricane; lava flow is as much as several tens of feet thick.

Qbg, Qbgc

Grapevine Wash lava flows and cinder cones (Middle Pleistocene) – Medium-gray, fine-grained basaltic trachyandesite lava flows (Qbg) with small olivine phenocrysts; erupted from a number of vents on the Lower Kolob Plateau, including the Firepit Knoll and Spendlove Knoll cinder cones (Qbgc); five $^{40}Ar/^{39}Ar$ ages on these flows range from 0.22 $\pm$ 0.03 Ma to 0.31 $\pm$ 0.02 Ma (Willis and Hylland, 2002); typically 20 to 40 feet (6-12 m) thick, but locally as much as 400 feet (120 m) thick where ponded in paleodrainages.

Qbc, Qbcc

Crater Hill lava flow and cinder cone (Middle Pleistocene) – Medium-gray basalt to trachybasalt (Qbc) with small olivine phenocrysts; erupted from a vent at a large cinder cone (Qbcc) east of Virgin; upper surface of flow has large arcuate flow ridges and one large rafted and tilted block once considered to be a separate cinder cone and vent (Nielson, 1977); this flow blocked the ancestral Virgin River, creating Lake Grafton, once the largest Pleistocene lake in the map area, which reached upstream into the lower part of Zion Canyon; yielded $^{40}Ar/^{39}Ar$ plateau ages of 0.310 $\pm$ 0.070 and 0.320 $\pm$ 0.130 Ma, and isochron ages of 0.228 $\pm$ 0.040, 0.294 $\pm$ 0.018, 0.298 $\pm$ 0.032, and 0.280 $\pm$ 0.080 Ma (UGS unpublished data); lava flow is typically 40 to 80 feet (12-24 m) thick, but locally as much as 400 feet (120 m) thick where it ponded in ancestral Virgin River and Coal Pits Wash channels.

Qber, Qberc

East Reef lava flow and cinder cones (Middle Pleistocene) – Medium-dark-gray, fine-grained basanite (Qber) with small olivine phenocrysts; erupted from vents at two overlapping cinder cones (Qberc) about 2 miles (3 km) southeast of Leeds; probably about 250,000 to 350,000 years old; lava flow is about 25 to 30 feet (7.5-9 m) thick.

Qbbd **Baker Dam lava flow** (Middle Pleistocene) – Dark-gray basaltic trachyandesite that contains abundant small olivine and some plagioclase phenocrysts in an aphanitic groundmass; likely erupted from a vent or vents in the Central area; probably about 250,000 to 350,000 years old; as much as about 50 feet (15 m) thick.

Qbv, Qbvc

Volcano Mountain lava flow and cinder cone (Middle Pleistocene) – Medium- to dark-gray to grayish-black, fine- to medium-grained alkali basalt (Qbv) with sparse olivine phenocrysts; erupted from a vent at Volcano Mountain (Qbvc) southwest of Hurricane; divisible into three separate flows (Biek, 2003a, b); youngest- and middle-level flows yielded $^{40}Ar/^{39}Ar$ ages of 0.258 $\pm$ 0.024 Ma and 0.353 $\pm$ 0.045 Ma, respectively (Sanchez, 1995); middle-level flow is displaced about 240 feet (73 m) by the Hurricane fault at Timpoweap Canyon and locally exhibits pillow basalts at its base; lava flows are generally 35 to 45 feet (11-14 m) thick and form rough, blocky surfaces, but the middle-level flow is as much as 170 feet (50 m) thick where it fills the ancestral Virgin River channel.

Qblc, Qblcc

Little Creek lava flow and cinder cone (Middle Pleistocene) – Medium-gray, fine-grained basalt to trachybasalt (Qblc) with sparse olivine phenocrysts; erupted from a vent at Gray Knoll cinder cone (Qblcc) and a series of northwest-trending vents marked by spatter cones on top of Little Creek Mountain; yielded an $^{40}Ar/^{39}Ar$ age of 0.345 $\pm$ 0.015 Ma (Downing, 2000); lava flow is generally 15 to 40 feet (5-12 m) thick.

Qbgw, Qbgwc

Gould Wash lava flow and cinder cones (Middle Pleistocene) – Dark-gray, fine-grained basalt (Qbgw) with abundant olivine phenocrysts; erupted from vents at two cinder cones (Qbgwc) about 6 miles (10 km) southeast of Hurricane; yielded an $^{40}Ar/^{39}Ar$ age of 0.278 $\pm$ 0.018 Ma (Downing, 2000), whereas our sample VR41-08 yielded $^{40}Ar/^{39}Ar$ ages of 0.420 $\pm$ 0.210 (plateau) and 0.420 $\pm$ 0.05 (isochron) Ma (UGS unpublished data); the flow exhibits a level of incision comparable to the adjacent 400,000-year-old Divide lava flow, and so is likely about 400,000 years old; lava flow is generally 20 to 30 feet (6-9 m) thick.

Qbd, Qbdc

Divide lava flow and cinder cones (Middle Pleistocene) – Dark-gray, fine-grained basalt to basanite (Qbd) with small olivine phenocrysts; forms lava cascade over Hurricane Cliffs south of Hurricane (T. 43 S., R. 13 W., section 3); erupted from vents at two cinder cones (Qbdc) and two north-trending dikes; yielded an $^{40}Ar/^{39}Ar$ age of 0.41 $\pm$ 0.08 Ma (Hayden, 2004a); lava flow is generally 15 to 40 feet (5-12 m) thick.

Qan **Andesite of Black Hills** (Middle Pleistocene) – Resistant, black andesite lava flows containing various percentages of phenocrysts as large as 0.2 inches (5 mm) of plagioclase and smaller pyroxene; mapped by Blank (1959, 1993) southwest of Enterprise, at the north edge of the map area; has an $^{40}Ar/^{39}Ar$ age of 0.42 $\pm$ 0.13 Ma (Peters, 2002; Rowley and others, 2006); thickness about 650 feet (200 m).

Qbsm, Qbsmc

Saddle Mountain lava flow and cinder cone (Middle Pleistocene) – Dark-gray, fine-grained lava flow (Qbsm) that ranges in composition from basalt to trachybasalt to basaltic trachyandesite; contains small olivine and plagioclase phenocrysts; erupted from a vent at a cinder cone (Qbsmc) about 6 miles (10 km) east of Veyo; yielded an $^{40}Ar/^{39}Ar$ isochron age of 0.47 $\pm$ 0.12 Ma (UGS unpublished data); lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbde, Qbdec

Dammeron Valley east lava flow and cinder cone (Middle Pleistocene) – Dark-gray trachybasalt (Qbde) with small olivine phenocrysts in an aphanitic groundmass; erupted from a vent at a cinder cone (Qbdec) about 2 miles (3 km) southeast of Veyo; yielded an $^{40}Ar/^{39}Ar$ age of 0.59 $\pm$ 0.02 Ma (UGS unpublished data); lava flow is generally 10 to 20 feet (3-6 m) thick.

Qbca, Qbcac

Canal lava flow and cinder cone (Middle[?] Pleistocene) – Brownish-gray basalt (Qbca) with sparse olivine and some plagioclase phenocrysts; erupted from a vent at a small cinder cone (Qbcac) about 2 miles (3 km) northeast of Veyo; appears to partially conceal the Aqueduct Hill, Magotsu Creek, and Subdivision Ridge lava flows; probably about 500,000 to 750,000 years old; lava flow is typically about 20 feet (6 m) thick.

Qbla, Qblac

Lark Canyon lava flow and cinder cone (Middle Pleistocene) – Dark-gray basalt (Qbla) with small olivine phenocrysts; erupted from a vent at a cinder cone (Qblac) about 2 miles (3 km) southwest of Pine Valley; yielded an $^{40}Ar/^{39}Ar$ plateau age of 0.61 $\pm$ 0.04 Ma (UGS unpublished data); lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbmk, Qbmkc

Mahogany Knoll lava flow and cinder cone (Middle[?] Pleistocene) – Dark-gray basalt (Qbmk) with small olivine phenocrysts; erupted from vents at cinder cones (Qbmkc) on the southwest flank of the Pine Valley Mountains; probably about 450,000 to 700,000 years old; lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbrk, Qbrkc

Red Knoll lava flow and cinder cone (Middle[?] Pleistocene) – Gray andesite (Qbrk) that erupted from a vent at a cinder cone (Qbrkc) on the southwest flank of the Pine Valley Mountains; yielded an $^{40}Ar/^{39}Ar$ integrated age of 0.45 $\pm$ 0.86 Ma (UGS unpublished data), but is probably about 450,000 to 700,000 years old; lava flow is generally 30 to 60 feet (9-18 m) thick.

Qbtb, Qbtbc

Truman Bench lava flow and cinder cone (Middle[?] Pleistocene) – Dark-gray basalt to trachybasalt (Qbtb) with small olivine phenocrysts; erupted from a vent at a cinder cone (Qbtbc) on the southwest flank of the Pine Valley Mountains; probably about 450,000 to 700,000 years old; lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbck, Qbckc

Cedar Knoll lava flow and cinder cone (Middle[?] Pleistocene) – Dark-gray basalt (Qbck) with small olivine phenocrysts; erupted from a vent at a cinder cone (Qbckc) about 2 miles (3 km) northwest of Pine Valley; probably about 550,000 to 750,000 years old; lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbgf, Qbgfc

Grass Flat lava flow and cinder cone (Middle to Lower Pleistocene) – Dark-gray basaltic trachyandesite (Qbgf) with small olivine phenocrysts; erupted from a vent at a cinder cone (Qbgfc) about 3 miles (5 km) north of Pine Valley; probably about 550,000 to 800,000 years old; lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbce, Qbcec

Central-area lava flow and cinder cone (Middle to Lower Pleistocene) – Dark-gray basaltic trachyandesite (Qbgf) with small olivine phenocrysts; erupted from four vents at cinder cones (Qbcec) just south of Central; probably about 550,000 to 800,000 years old; lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbf, Qbfc

Fourmile Bench lava flow and cinder cone (Middle to Lower Pleistocene) – Dark-gray basaltic trachyandesite (Qbf) with small olivine phenocrysts; erupted from a vent at a

cinder cone (Qbfc) about 2 miles (3 km) north of Pine Valley; probably about 650,000 to 800,000 years old; lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbve, Qbvec

Veyo lava flow and cinder cone (Middle Pleistocene) – Dark-gray, fine-grained basaltic trachyandesite (Qbve) with abundant olivine and sparse plagioclase phenocrysts; erupted from a vent at the Veyo Volcano cinder cone (Qbvec) just south of Veyo; divisible into five separate flows (Embree, 1970; Higgins, 2002); yielded $^{40}Ar/^{39}Ar$ age of 0.69 $\pm$ 0.04 Ma (UGS unpublished data); lava flow is generally 20 to 50 feet (6-15 m) thick.

Qbhp, Qbhpc

Hornet Point lava flow and cinder cone (Middle Pleistocene) – Medium- to dark-gray, medium- to coarse-grained basalt to trachybasalt (Qbhp) with small olivine and abundant pyroxene phenocrysts; locally deeply weathered to grus-like soils, and isolated boulders typically have concentric weathering rinds; erupted from a vent at a deeply eroded cinder cone (Qbhpc) at Hornet Point; yielded $^{40}Ar/^{39}Ar$ isochron age of 0.74 $\pm$ 0.05 Ma (Biek and Hylland, in preparation); lava flow is as much as 240 feet (73 m) thick.

Qbp, Qbpc

Pintura lava flow and cinder cones (Lower Pleistocene) – Medium- to dark-gray, fine- to medium-grained basaltic lava flows (Qbp) with small olivine phenocrysts; geochemically divisible into three groups: basalt, trachybasalt, and basaltic trachyandesite to basaltic andesite (Hatfield, 2001); locally contains abundant small plagioclase phenocrysts; erupted principally from the Pintura volcanic center (Qbpc), about 2.5 miles (4 km) north of Pintura, and from a smaller vent atop Black Ridge; displaced in excess of 1200 feet (365 m) by the Hurricane fault near Pintura; yielded five $^{40}Ar/^{39}Ar$ ages of 0.89 $\pm$ 0.02 Ma, 0.81 $\pm$ 0.10 Ma, 0.87 $\pm$ 0.04 Ma, 0.88 $\pm$ 0.05 Ma, and 0.84 $\pm$ 0.03 Ma (Lund and others, 2001, 2002; Biek, 2003b); lava flows are typically 20 to 40 feet (6-12 m) thick, but as much as 1140 feet (350 m) thick where they fill paleotopography on Black Ridge.

Qbw, Qbwc

Washington lava flow and cinder cone (Lower Pleistocene) – Medium- to dark-gray to dark-greenish-gray, fine-grained basanite to picrobasalt (Qbw) with abundant clinopyroxene and olivine phenocrysts; erupted from a vent at a cinder cone (Qbwc) about 3 miles (5 km) northeast of Washington; yielded $^{40}Ar/^{39}Ar$ ages of 0.87 $\pm$ 0.04 and 0.98 $\pm$ 0.02 Ma (Biek, 2003a), which fits well with regional incision rates (Willis and Biek, 2001), but Best and others (1980) reported an anomalously old K-Ar age of 1.7 $\pm$ 0.1 Ma for this flow; lava flow is 25 to 35 feet (8-11 m) thick except near its source, where it is as much as about 100 feet (30 m) thick.

Qbi, Qbic

Ivans Knoll lava flow and cinder cone (Lower Pleistocene) – Medium-gray, fine- to medium-grained basalt (Qbi) with small olivine phenocrysts; erupted from a vent marked by a deeply eroded cinder cone (Qbic) immediately south of Volcano Mountain,

southwest of Hurricane; remnant of flow caps Mollies Nipple at the top of the Hurricane Cliffs, showing about 1300 feet (400 m) of displacement along the Hurricane fault; yielded two $^{40}Ar/^{39}Ar$ ages of 0.97 ± 0.07 and 1.03 ± 0.02 Ma (Biek, 2003b), and sample VR41-06 yielded an $^{40}Ar/^{39}Ar$ age of 0.937 ± 0.06 (isochron) and 1.06 ± 0.16 (plateau) Ma (UGS unpublished data); this lava flow has a normal magnetic signature (Michael J. Hozik, The Richard Stockton College of New Jersey, verbal communication, 1998) and thus appears to have erupted during the Jamarillo normal event (see, for example, Glen, 1982), a short duration flip in the Earth's magnetic field that occurred about 0.99 to 1.07 million years ago during the Matuyama reversed polarity epoch (Biek, 2003b); lava flow is generally 20 to 30 feet (6-9 m) thick.

Qbmc, Qbmcc

Magotsu Creek lava flow and cinder cone (Lower Pleistocene) – Medium- to dark-gray, medium-grained trachybasalt to basaltic trachyandesite (Qbmc) with sparse plagioclase, sparse olivine, and rare quartz phenocrysts; erupted from a vent at a cinder cone (Qbmcc) about 2 miles (3 km) northeast of Veyo; yielded an $^{40}Ar/^{39}Ar$ age of 0.98 ± 0.03 Ma (Higgins, 2002); lava flow is generally 10 to 50 feet (3-15 m) thick.

Qbpv, Qbpvc

Pine Valley and Grass Valley Reservoir lava flows and cinder cones (Middle to Lower Pleistocene) – Dark-gray basaltic lava flows (Qbpv) with small olivine phenocrysts; erupted from a number of vents at cinder cones (Qbpvc) surrounding Pine Valley and Grass Valley; undivided pending further mapping; the Grass Valley flow yielded an $^{40}Ar/^{39}Ar$ plateau age of 1.08 ± 0.13 Ma (UGS unpublished data), and the Pine Valley flow, which erupted from vents that show a striking northeast alignment, may be about the same age; lava flows are generally 20 to 40 feet (6-12 m) thick.

Qbgv, Qbgvc

Grass Valley lava flow and cinder cone (Lower Pleistocene) – Dark gray, fine- to medium-grained trachybasalt to basalt (Qbgv) with small olivine phenocrysts; erupted from a vent at a deeply eroded cinder cone (Qbgvc) about 7 miles (11 km) south of Hurricane; yielded $^{40}Ar/^{39}Ar$ ages of 1.47 ± 0.34 (plateau), 1.09 ± 0.09 (plateau), and 0.96 ± 0.03 (isochron) Ma (UGS unpublished data); lava flow is several tens of feet thick.

Qbr **Remnants lava flow** (Lower Pleistocene) – Dark-brownish-black to dark-gray, medium-grained basanite with small olivine phenocrysts; erupted from a deeply eroded vent atop the Hurricane Cliffs near the "Three Brothers," about 5 miles (8 km) south of Hurricane; displaced by the Hurricane fault about 1450 feet (440 m); yielded $^{40}Ar/^{39}Ar$ ages of 1.06 ± 0.03 Ma and 0.94 ± 0.04 Ma (Hayden, 2004a); typically about 40 feet (12 m) thick.

Qblp, Qblpc

Lava Point lava flow and cinder cones (Lower Pleistocene) – Light- to medium-gray, fine- to medium-grained basaltic trachyandesite to basaltic andesite and trachybasalt (Qblp) with small olivine phenocrysts; erupted from vents at Home Valley Knoll, a group of three overlapping cinder cones (Qblpc) on the Kolob Terrace; yielded $^{40}Ar/^{39}Ar$

plateau ages of 1.02 ± 0.03 Ma, 1.06 ± 0.01 Ma, 1.08 ± 0.02 Ma, and 1.14 ± 0.16 Ma (Willis and Hylland, 2002; Biek, in prep.[b]), consistent with four published K-Ar ages (Best and others, 1980; Hamblin and others, 1981); lava flow is typically 20 to 40 feet (6-12 m) thick, but as much as 200 feet (60 m) thick where it fills paleodrainages.

Qbhr **Horse Ranch Mountain lava flow** (Lower Pleistocene) – Medium-gray, fine- to medium-grained basalt (Qbhr) with small olivine phenocrysts; caps Horse Ranch Mountain in the Kolob Canyons part of Zion National Park; yielded an $^{40}Ar/^{39}Ar$ plateau age of 1.03 ± 0.06 Ma (Biek, in prep.[b]); source of the lava flow is unknown, but likely to the northeast of the map area in the Cedar Mountain quadrangle; 30 to 125 feet (10-38 m) thick.

Qbkp, Qbkpc

Kolob Peak lava flow and cinder cone (Lower Pleistocene) – Medium- to light-gray, fine-grained basaltic trachyandesite (Qbkp) with small olivine phenocrysts; erupted from a vent at Kolob Peak, a cinder cone (Qbkpc) now eroded in half; yielded an $^{40}Ar/^{39}Ar$ plateau age of 1.05 ± 0.05 Ma (Biek, in prep.[b]); thickness of lava flow uncertain, but likely in excess of 100 feet (30 m) thick where it fills paleodrainages.

Qbgk, Qbgkc

Grass Knoll lava flow and cinder cone (Middle to Lower Pleistocene) – Dark-gray basalt to trachybasalt (Qbgk) with small olivine phenocrysts; erupted from a vent at the Grass Knoll cinder cone (Qbgkc) on the southwest flank of the Pine Valley Mountains; yielded an $^{40}Ar/^{39}Ar$ integrated age of 1.02 ± 0.36 Ma (UGS unpublished data); lava flow is generally 20 to 40 feet (6-12 m) thick.

Qbcb, Qbcbc

Cedar Bench lava flow and cinder cones (Lower Pleistocene) – Dark-greenish-gray to brownish-black trachybasalt (Qbcb) with small phenocrysts of clinopyroxene and olivine; based on similar geochemistry, includes the Snow Canyon Overlook lava flow of Willis and Higgins (1996), which yielded a K-Ar age of 1.2 ± 0.1 Ma (Best and others, 1980) and an $^{40}Ar/^{39}Ar$ plateau age of 1.23 ± 0.01 Ma (UGS unpublished data); erupted from vents at two overlapping cinder cones (Qbcbc) about 12 miles (20 km) north of St. George; lava flow is typically 10 to 30 feet (3-9 m) thick, but as much as about 100 feet (30 m) thick where it fills paleotopography.

Qbb, Qbbc

Big Sand and Airport lava flows and cinder cone (Lower Pleistocene) – Dark-reddish-gray to dark-brownish-gray basaltic trachyandesite (Qbb), locally with large quartz and plagioclase and small olivine phenocrysts; Big Sand phase erupted from a vent at a cinder cone (Qbbc) about 5 miles (8 km) north of St. George; although it lacks large quartz and plagioclase phenocrysts, the Airport lava flow of Higgins and Willis (1995) has similar geochemistry to the Big Sand lava flow, suggesting that the Big Sand vent may be the source of the Airport flow; the Airport flow yielded an $^{40}Ar/^{39}Ar$ plateau age of 1.23 ± 0.01 Ma (Higgins and Willis, 1995), somewhat older than the K-Ar age of 1.07 ± 0.04

Ma reported by Hamblin and others (1981); sample VR42-09 from the Big Sand flow yielded a slightly younger $^{40}Ar/^{39}Ar$ age of 1.13 $\pm$ 0.05 (plateau) and 1.11 $\pm$ 0.07 (isochron) Ma (UGS unpublished data); lava flow is generally 10 to 50 feet (3-15 m) thick.

Qbl, Qblc

Lava Ridge lava flow and cinder cone (Lower Pleistocene) – Moderate- to dark-gray to dark-brownish-gray basaltic trachyandesite (Qbl) with prominent euhedral plagioclase phenocrysts, common quartz and pyroxene phenocrysts, and small olivine phenocrysts; petrographic and limited geochemical data suggest that the Middleton lava flow of Higgins and Willis (1995), which forms the spectacular inverted valley of Middleton Black Ridge, is part of the Lava Ridge flow; erupted from a group of heavily weathered cinder cones (Qblc) on Lava Ridge, about 8 miles (13 km) north of St. George; the "Middleton" lava flow yielded a K-Ar age of 1.5 $\pm$ 0.1 Ma (Best and others, 1980) and an $^{40}Ar/^{39}Ar$ age of 1.41 $\pm$ 0.01 Ma (UGS unpublished data); lava flow is typically 20 to 30 feet (6-9 m) thick.

Qbli **Little Creek Peak lava flow** (Lower Pleistocene) – Medium-gray, fine- to medium-grained basalt with small plagioclase and olivine phenocrysts; source unknown; yielded $^{40}Ar/^{39}Ar$ plateau age of 1.44 $\pm$ 0.04 Ma (Willis and Hylland, 2002); typically 20 to 60 feet (6-18 m) thick.

Qbgd **Gunlock-Dammeron Valley north lava flow** (Lower Pleistocene) **–** Dark-gray basaltic trachyandesite to trachybasalt with common, small olivine phenocrysts; source unknown, but is at least 2 miles (3 km) east of Veyo, where it may be concealed by the younger Saddle Mountain lava flow; sample VY8301-9 from the Dammeron Valley north flow yielded an $^{40}Ar/^{39}Ar$ age of 1.62 $\pm$ 0.02 Ma (UGS unpublished data); 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 lower part of the Dammeron Valley north flow of Higgins (2002); the Gunlock lava flow yielded a K-Ar age of 1.6 $\pm$ 0.11 Ma (Best and others, 1980) and an $^{40}Ar/^{39}Ar$ age of 1.61 $\pm$ 0.07 Ma (UGS unpublished data); typically 20 to 50 feet (6-15 m) thick.

QTbcw

Central West andesitic porphyry lava flow (Lower Pleistocene to Pliocene) **–** Medium-gray to light-brownish-gray, coarse-grained lava flow with large plagioclase and slightly smaller quartz phenocrysts that ranges in composition from trachyandesite, andesite, dacite, and trachydacite; erupted from vent or vents just west of Baker Dam Reservoir; yielded an $^{40}Ar/^{39}Ar$ age of 1.77 $\pm$ 0.09 Ma (UGS unpublished data); forms hilly, rugged topography; locally in excess of 400 feet (120 m) thick.

Tbgw **Granite Wash lava flow** (Pliocene) **–** Dark-gray, fine-grained basalt to trachybasalt with small olivine phenocrysts; scattered cinder deposits suggest that this flow may have erupted from hill 5672 about 4 miles (6.5 km) northeast of Veyo; yielded an $^{40}Ar/^{39}Ar$

age of 1.97 ± 0.02 Ma (UGS unpublished data); generally about 20 to 100 feet (6-30 m) thick.

Tbah **Aqueduct Hill lava flow** (Pliocene) – Dark-gray basaltic andesite to trachyandesite with small olivine phenocrysts and distinctive aggregates of plagioclase; may have erupted from hill 5082 about 1.5 miles (2.5 km) northeast of Veyo; yielded an $^{40}Ar/^{39}Ar$ age of 1.98 ± 0.04 Ma (UGS unpublished data); generally about 20 to 50 feet (6-15 m) thick.

Tbt, Tbtc

Twin Peaks lava flow and cinder cones (Pliocene) – Dark-gray to dark-brownish-gray basaltic trachyandesite (Tbt) with large plagioclase and quartz, and small olivine and clinopyroxene phenocrysts; erupted from vents at extensively eroded cinder cones (Tbtc) at Twin Peaks, about 8 miles (13 km) north of St. George; limited geochemistry suggests that the West Black Ridge lava flow of Higgins and Willis (1995) and the older remnants (Tbo) of Willis and Higgins (1995) erupted from the Twin Peaks vents; yielded K-Ar ages of 2.3 ± 0.1 Ma (Best and others, 1980) and 2.24 ± 0.11 Ma (Hamblin and others, 1981), and an $^{40}Ar/^{39}Ar$ age of 2.43 ± 0.02 Ma (UGS unpublished data); the "West Black Ridge" part of the flow yielded K-Ar ages of 2.3 ± 0.1 Ma (Best and others, 1980) and 2.24 ± 0.11 Ma (Hamblin and others, 1981), and an $^{40}Ar/^{39}Ar$ age of 2.34 ± 0.02 Ma (UGS unpublished data); lava flow is generally about 20 to 80 feet (6-24 m) thick.

Tb **Basaltic lava flows, undivided** (Pliocene to Miocene) – Resistant, dark-gray and black, aphanitic to crystal-poor lava flows and local cinder cones of mostly olivine basalt that erupted in the north Bull Valley Mountains and Pine Valley area from about 20 Ma to about 2 Ma and that, along with Quaternary basaltic lava flows, are synchronous with basin-range extension (Christiansen and Lipman, 1972; Rowley and Dixon, 2001); Tertiary basalts (including trachybasalt, basaltic andesite, trachyandesite, and andesite) capping mesas and peaks north of the towns of Central and Pine Valley and extending as far as the north edge of the map area, have a wide range of ages, as suggested by the following $^{40}Ar/^{39}Ar$ ages: (1) 2.22 ± 0.05 Ma for a caprock about 1.5 miles (2.5 km) north of Central (Peters, 2002); (2) about 5.7 to 5.89 ± 0.11 Ma for the basalt of Gum Hill east-southeast of Enterprise and just north of the map area (by, respectively, Cornell and others, 2001, and Peters, 2006a); and (3) 17.39 ± 0.12 Ma for the basalt of Harrison Peak at the north edge of the map area (Peters, 2006b); includes basalts along Moody Wash about 6 miles (10 km) west of Central that both overlie and underlie Ox Valley Tuff (To) and that have K-Ar ages by Best and others (1980) of, respectively, 7.9 and 12.3 Ma; maximum thickness of lava flows about 300 feet (100 m).

TERTIARY

Ts **Basin-fill sedimentary rocks** (Pliocene to Miocene) – Poorly to moderately consolidated, tan, gray, and light-red, tuffaceous, alluvial sandstone and subordinate mudstone, siltstone, and conglomerate deposited in basins of various ages and origins; most basins are related to the basin-range episode of extension in the area; previously called the Muddy Creek Formation in some areas (Cook, 1957, 1960b; Hintze and others, 1994), but we prefer this generic label given the uncertain correlation to the principal

Muddy Creek basin of southeast Nevada; includes the volcaniclastic rocks of Enterprise Reservoir (Blank, 1993) in the northwest corner of the map area, Miocene sedimentary rocks in the Dodge Spring quadrangle (Anderson and Hintze, 1993), and sedimentary breccia of Miocene volcanic units near the Gunlock fault in the Gunlock quadrangle (Hintze and others, 1994); maximum thickness at least 1500 feet (450 m).

Tmc, Tmcb

Muddy Creek Formation (Pliocene to Miocene) – Fine- to coarse-grained, grayish-orange, pinkish-orange, and medium-reddish-brown calcareous sandstone, siltstone, mudstone, and poorly sorted, pebble- to cobble-conglomerate; commonly tuffaceous, with minor light-gray to white airfall and water-lain tuff beds less than 3 feet (1 m) thick, and local calcic soil (hardpan or calcrete) horizons as much as 3 to 6 feet (1-2 m) thick; grades from coarse, indistinctly bedded conglomeratic deposits near basin margins to finer grained, laminated to thick-bedded central-basin strata; typically poorly cemented, forming slopes; here restricted to the Virgin River depression (Mesquite Basin) due to uncertain correlation with other basins (Ts) in the northwest part of the mapped area; Hintze and others (1994) reported a 8.8 $\pm$ 0.3 Ma K-Ar age on basalt (Tmcb) at or near the base of the formation along Beaver Dam Wash in the Motoqua quadrangle; Bohannon (1984) noted that the Muddy Creek Formation is overlain by a 5.9 million-year-old basalt and overlies a 10.6 million-year-old sandstone near Lake Mead; ages for the entire formation range between about 11 to 5 million years old (Reynolds and Lindsay, 1999); deposited as basin-fill sediment in the Virgin River depression and other basins to the south and west as alluvial-fan deposits that grade laterally to fluvial and lacustrine deposits in the central parts of the basins, representing the youngest basin-fill sediment deposited prior to establishment of the through-going Colorado River system (Bohannon, 1984; Bohannon and others, 1993; Pederson, 1999; Langenheim and others, 2001); through study of sand grain provenance, Farrell and Pederson (2001) showed that the siliciclastic component of the Muddy Creek has a predominant volcanic source in the Caliente and Kane Creek Wash caldera complexes; where exposed in this quadrangle, unconformably overlies a variety of older, mostly Miocene and Oligocene volcanic units; unconformably overlain by high-level Quaternary-Tertiary alluvial deposits and locally capped by a 3- to 5-foot-thick (1-2 m), well-developed calcic soil (stage VI, Birkeland and others, 1991); Metcalf (1982) reported a regional thickness of over 2000 feet (600 m) in some of the deeper basins in southern Nevada, and Bohannon and others (1993) reported that it uniformly fills the upper 3000 to 6500 feet (1000-2000 m) of the Virgin River depression (Mesquite basin); this is one of the deepest (more than 21,000 feet [6400 m]) basins in the Basin and Range Province, on the basis of seismic and gravity data (Bohannon and others, 1993; Carpenter and Carpenter, 1994; Langenheim and others, 2001; Dixon and Katzer, 2002).

Tag **Old boulder gravel deposits of the Kolob Plateau** (Miocene?) – Poorly sorted, clay- to large-boulder-size sediment characterized by enormous quartz monzonite boulders; clasts also include large boulders of Cretaceous fossiliferous sandstone, cobbles and small boulders derived from the Carmel Formation, recycled rounded pebbles and small cobbles of Precambrian and Cambrian quartzite, and uncommon cobbles and boulders of

Claron limestone; most clasts are subangular to subrounded, but the quartz monzonite clasts are well rounded (likely due to exfoliation); quartz monzonite boulders as much as 24 feet (7.3 m) long, 22 feet (6.7 m) wide, and at least 8 feet (2.4 m) high are present near Kolob Reservoir, and subspherical quartz monzonite boulders 10 to 15 feet (3-5 m) long are common; most quartz monzonite clasts, however, are 1.5 to 3 feet (0.5-1 m) in diameter; forms a deeply eroded surface that drapes over pre-existing topography; probably deposited by debris flows or possibly a gravity slide originating in the ancestral Pine Valley Mountains; this hypothesis, however, requires a complete eastward-to-westward reversal of drainage across the Hurricane fault; Averitt (1962, 1964) first described similar deposits farther north, east and southeast of Cedar City, and Anderson and Mehnert (1979) interpreted those exposures as debris-flow deposits shed off the ancestral Pine Valley Mountains; Hacker (1998) and Hacker and others (2002) provided evidence that the Pine Valley Mountains stood very high and shed gravity slides, volcanic rocks, and debris flows about 20.5 million years ago, long before initiation of the Hurricane fault; blocks of the Pine Valley laccolith caught in the Hurricane fault zone (Biek, in preparation[a]) show that the laccolith once likely reached east of the Hurricane fault, thus providing a somewhat closer source for the large Pine Valley boulders; thickness uncertain, but probably less than 30 feet (9 m) thick.

Two basalt boulders clearly incorporated into the deposits at Kolob Reservoir have a chemical signature similar to the Horse Ranch Mountain lava flow, and one boulder yielded an $^{40}Ar/^{39}Ar$ age of 0.97 $\pm$ 0.18 Ma, analytically indistinguishable from the 1.03 $\pm$ 0.06 Ma Horse Ranch Mountain lava flow (Biek, in preparation[b]); how the basalt boulders came to be incorporated into these assumed Miocene-age deposits is not known.

Trdy **Young rhyolite and dacite lava flows** (Pliocene to Miocene) – Small centers of resistant, crystal-poor to crystal-rich, high-silica rhyolite and dacite volcanic domes and lava flows with isotopic ages of about 8.5 to 2 Ma; includes the Eight-Mile Dacite (Cook, 1957; Hacker, 1998) just northeast of the town of Central, which has an $^{40}Ar/^{39}Ar$ age of 2.03 $\pm$ 0.76 Ma (Peters, 2006b), the rhyolite of Shinbone Creek (Blank, 1959, 1993) at the north edge of the map area and northwest of Central (K-Ar ages of 5.0 $\pm$ 0.2 and 4.7 $\pm$ 0.02 Ma; McKee and others, 1997), and the rhyolite of Pilot Peak (Blank, 1959) at the north edge of the map area and northwest of Central ($^{40}Ar/^{39}Ar$ age of 6.05 $\pm$ 0.05 Ma; Peters, 2002); maximum thickness about 500 feet (150 m).

Trdm **Middle rhyolite and dacite lava flows** (Miocene) – Mostly resistant, generally light-gray and tan, crystal-poor, high-silica rhyolite and dacite volcanic domes and lava flows, locally with ash-flow tuff, tuff breccia, and airfall tuff that erupted from several centers in the west part of the map area; includes the rhyolite of Little Pine Creek (12.0 $\pm$ 0.4 Ma; Blank, 1959; McKee and others, 1997) and the rhyolite of Cow Hollow (15.3 $\pm$ 0.4 to 14.3 $\pm$ 0.4 Ma; Blank, 1959; McKee and others, 1997) at the north edge of the map northeast of Ox Valley; maximum thickness of each unit 400 to 1400 feet (120 to 400 m).

Tim **Mineral Mountain intrusion** (middle Miocene) – Resistant, gray and pink, high-silica granite porphyry stock made up of mostly fine-grained orthoclase but with distinctive

abundant large "eyes" of beta quartz and with minor ferromagnesian minerals; located in the southwest Bull Valley Mountains about 4 miles (6 km) northwest of the ghost town of Goldstrike (Cook, 1960b; Bullock, 1970; Eliopulos, 1974; Morris, 1980; Adair, 1986); considered to be the southern intrusion of the Iron Axis, a northeast-trending belt of intrusions partly structurally controlled by thrust faults and characterized by iron occurrences (Mackin, 1960; Tobey, 1976; Blank and others, 1992; Hacker, 1998; Hacker and others, 2002), including the large commercial deposits of the Iron Springs mining district north of the map area; however, this stock is compositionally much more silicic and much younger than the intrusions in other parts of the Iron Axis; it and small hypabyssal intrusions (Adair, 1986; Willden and Adair, 1986) may have been the heat source for hydrothermal (ground-water) solutions (Willden and Adair, 1986; Limbach and Pansze, 1987) that led to gold deposits at and northwest of Goldstrike; furthermore, unit appears to be the source of eruptions of Ox Valley Tuff (To), as an intracaldera (resurgent) intrusion that was emplaced into a caldera that now surrounds the intrusion; $^{40}Ar/^{39}Ar$ integrated age from a disturbed age spectrum is about 12.1 $\pm$ 1.9 Ma (Peters, 2006b).

To **Ox Valley Tuff** (middle Miocene) – Moderately resistant, gray and red, poorly to densely welded, crystal-poor (including distinctive "eyes" of beta quartz), high-silica rhyolite ash-flow tuff exposed as outflow and intracaldera tuff in the Bull Valley Mountains and Clover Mountains; derived from a caldera that is dismembered by faults and poorly exposed in an area centered about 1 mile (1.6 km) northwest of Greek Peak, in an area southwest of Greek Peak, and north of the community of Motoqua; suggested by Anderson and Hintze (1993) and Hintze and others (1994) to be intracaldera tuff because the thickness of the Ox Valley there was about 4000 feet (1200 m), but mapping has yet to determine if this area is partly underlain by a caldera; the age of the Ox Valley Tuff was formerly unclear and considered to be 12.6 to 12.3 Ma (Rowley and others, 1995), but the following new $^{40}Ar/^{39}Ar$ ages suggest that the age is 14.0 to 13.5 Ma (Snee and Rowley, 2000): (1) an age of 13.46 $\pm$ 0.05 Ma from a sample collected from the lowest of four cooling units exposed in the type area, at Ox Valley, 8 miles (13 km) northwest of Central (Rowley and others, 2006); (2) an age of 14.10 $\pm$ 0.03 Ma from a sample collected by R.E. Anderson just west of Beaver Dam State Park, Nevada, just northwest of the map area (Rowley and others, 2006); (3) an age of 12.19 $\pm$ 0.08 Ma from a rhyolite flow collected by R.E. Anderson that rests on Ox Valley Tuff at Docs Pass just west of the map area (Rowley and others, 2006); and (4) an unpublished age of 13.93 $\pm$ 0.08 Ma from a sample of Ox Valley Tuff collected about 3 miles (5 km) southwest of Enterprise, just north of the map area (Peters, 2006a); this reinterpretation of the age of the Ox Valley Tuff suggests, furthermore, that the Ox Valley Tuff may be correlative with the tuff of Etna, widely exposed as an outflow ash-flow sheet in the Caliente caldera complex, including south of Caliente, Nevada, that has similar compositions and mineralogy as the Ox Valley Tuff, and with an age interpreted to be 14.0 Ma based on ages of overlying and underlying rocks (Rowley and others, 1995); outflow thickness about 200 feet (60 m); intracaldera thickness about 4000 feet (1200 m).

Tkw **Kane Wash Tuff** (middle Miocene) – Resistant, tan and reddish-gray, densely welded, crystal-poor, high-silica rhyolitic and peralkaline ash-flow tuff, locally containing a brown and black basal vitrophyre; mapped west of Gunlock as "rhyolitic ash-flow tuff" by Anderson and Hintze (1993) and Hintze and others (1994) but suggested by them to be partly correlative with the Kane Wash Tuff; we agree and consider it to be the east finger edge of an outflow sheet derived from the Kane Springs Wash caldera complex of the Delamar and Meadow Valley Mountains of Nevada (Harding and others, 1995; Scott and others, 1995a, b); $^{40}Ar/^{39}Ar$ age of a sample collected from lower Moody Wash northwest of Veyo is 14.45 $\pm$ 0.06 Ma (Peters, 2002), suggesting that the unit is correlative with the upper and more voluminous (Gregerson Basin Member) of two members of the Kane Wash Tuff, which in turn has $^{40}Ar/^{39}Ar$ ages of 14.39 Ma from its upper cooling unit and of 14.55 Ma from its lower cooling unit (Scott and others, 1995a, b); maximum thickness about 50 feet (15 m).

Ta **Andesitic lava flows, flow breccia, and mudflow breccia** (middle to lower Miocene) – Soft to moderately resistant, red, brown, and green, mostly crystal-poor andesite to dacite lava flows, flow breccia, and mudflow breccia erupted from widely scattered stratovolcanoes or other local vents over a poorly known time span of 24(?) to 18(?) Ma; occurs at several stratigraphic positions in this age range, including (1) aphanitic lava flows and mudflow breccia that overlie Racer Canyon Tuff (Tr) in the northwest part of the map area; (2) the andesite of Maple Ridge (Blank, 1959, 1993), which underlies Racer Canyon Tuff (Tr) in the northwest part of the map area and contains abundant large phenocrysts of plagioclase, pyroxene, and biotite; (3) thin lava flows that locally underlie gravity slides (Tgb) that were shed during rapid emplacement of the intrusions of the Iron Axis, not including similar andesitic flows that erupted during emplacement of these intrusions but are mapped with those volcanic rocks (as Tcv and Tpa; see Hacker, 1998); and (4) andesitic flows and volcanic mudflow breccia at several stratigraphic positions within the Quichapa Group (Tq), both between the Harmony Hills Tuff (Tqh) and the Bauers Tuff Member of the Condor Canyon Formation (Tqc) (the andesite flows are called the andesite of Little Creek by Blank, 1993) and between the Bauers Member and the Leach Canyon Formation (Tql), that thickens southward from the north edge of the map area; the maximum thickness of individual sequences is about 600 feet (200 m), but west of the Greek Peak area, hydrothermally altered, poorly exposed andesite masses are probably well over 1000 feet (300 m) thick.

Thc **Tuff of Horse Canyon** (middle to lower Miocene) – Soft to moderately resistant, tan, light-yellow, and light-gray, unwelded to poorly welded, crystal-poor, high-silica rhyolite ash-flow tuff exposed as outflow tuffs in the upper Horse Canyon/Indian Draw/Wide Canyon area just north of the northwest corner of the map area (Rowley and others, 2006), where it was mapped as the upper member of the Racer Canyon Tuff by Siders (1991); includes intertongued, moderately resistant, tan tuffaceous sandstone; petrography indicates that the unit is correlative with rocks on North Flat Top Mountain, north of the map area, that were called the upper member of the Racer Canyon Tuff and the "Cove Mountain Formation" by Blank (1959); unit probably derived from a caldera in the Caliente caldera complex; $^{40}Ar/^{39}Ar$ age of 17.40 $\pm$ 0.06 Ma (Rowley and others,

2006), which shows some argon loss so its age could be slightly younger, was determined from a tuff just above the Racer Canyon Tuff that contains 5 percent quartz, 5 percent sanidine, and 2 percent plagioclase and was called the tuff of Dow Mountain by Snee and Rowley (2000) and considered to be derived from the north-central part of the Caliente caldera complex near Dow Mountain, Nevada, which is south of Panaca Summit; maximum thickness about 100 feet (30 m).

Tr **Racer Canyon Tuff** (lower Miocene) – Resistant, tan, gray, and pink, poorly to moderately welded, low-silica rhyolite ash-flow tuff; where exposed in the map area, is outflow tuff derived from a presumed buried east part of the Caliente caldera complex (Rowley and others, 1995); some outflow tuffs of the unit just north of the mapped area contain pumice blocks as large as 2 feet (0.6 m) and large abundant phenocrysts, suggestive of proximity to its source; exact age of the Racer Canyon Tuff is unclear (Rowley and others, 1995), but our best estimate is that it is about 18.7 Ma based on two ages for sample 89-314e (Rowley and others, 2006); in the Dodge Spring area, west of Motoqua, a unit correlated with Racer Canyon Tuff was mapped by Anderson and Hintze (1993) as Hiko Tuff, which is almost identical to Racer Canyon but slightly younger and clearly is derived from the west end of the Caliente caldera complex; about 12 outflow cooling units well exposed south of Upper Enterprise Reservoir, along the north edge of the map area, collectively total at least 1500 feet (450 m), but the unit thins abruptly southward.

Tpr **Sedimentary rocks of Page Ranch** (Miocene) – Mostly soft, tan conglomerate, sandstone, and mudflow breccia derived from erosion of rapidly intruded quartz monzonite plutons of the Iron Axis; unit mapped locally but may be correlative with lower parts of basin-fill sedimentary rocks (Ts), as just north of the northeast part of the map area; maximum thickness about 200 feet (60 m).

Tpv **Pine Valley Latite** (lower Miocene) – Resistant, gray, pink, and black, flow-foliated, crystal-rich, dacitic and trachydacitic lava flows erupted primarily from vent areas at Rencher Peak and Timber Mountain and derived from eruption of the Pine Valley laccolith (Tipv) (Cook, 1957; Hacker, 1998); Tpv has three $^{40}Ar/^{39}Ar$ ages of 20.44 to 20.42 Ma on two samples (Rowley and others, 2006), similar to the reported preferred age of 20.5 Ma for the Pine Valley laccolith (Hacker and others, 1996) on the basis of four $^{40}Ar/^{39}Ar$ ages given on two samples reported in Rowley and others (2006); maximum thickness in the mapped area about 1100 feet (335 m).

Tgb **Gravity-slide breccia** (lower Miocene) – Moderately resistant, mostly pink and gray, tectonic breccia resulting from gravity slides (huge landslides) of various ages, made up of sedimentary (Tc) and volcanic (Tpv, Tcv, Tre, Tpa, Tqh, Ta, Tqc, Tql, Ti, Tw) rocks shed off the roofs of rapidly rising quartz monzonite porphyry laccoliths and stocks (Tipv, Tib, Tih, Tibm, and several others outside the map area) of the Iron Axis (Cook, 1957; Mackin, 1960; Blank, 1959, 1993; Blank and Mackin, 1967; Blank and others, 1992; Hacker, 1998; Hacker and others, 1996, 2002); maximum thickness in the mapped area about 250 feet (75 m).

Tcv **Volcanic rocks of Comanche Canyon** (lower Miocene) – Moderately resistant, red and pink, crystal-rich dacitic lava flows and poorly to moderately welded ash-flow tuff derived from eruption of the Stoddard Mountain intrusion, located just north of the map area, and resting on gravity slides and fanglomerate also derived from the intrusion; the tuff issued from a small caldera about 1 mile (1.6 km) in diameter, along the east edge of the intrusion and north of the map area (Rowley and others, 2006); the tuff contains distinctive clasts of red Iron Springs Formation sandstone; unit has $^{40}Ar/^{39}Ar$ ages of 22.72 $\pm$ 0.07 and 21.78 $\pm$ 0.08 Ma on one sample (Rowley and others, 2006), the older of which is here rejected and the younger of which is consistent with ages of other Iron Axis plutons and that of the Stoddard Mountain intrusion; maximum thickness about 160 feet (50 m).

Tre **Rencher Formation** (lower Miocene) – Moderately resistant, white, tan, red, and purple, poorly to moderately welded, crystal-rich, dacite ash-flow tuff and tuff breccia; derived from eruption of the Bull Valley intrusion (Tib) (Blank, 1959; Hacker, 1998; Hacker and others, 2002); Tre locally rests on gravity-slide masses that partially unroofed the Bull Valley intrusion; Tre has K/Ar ages of 21.8 and 21.5 Ma (McKee and others, 1997) and $^{40}Ar/^{39}Ar$ ages of 21.65 $\pm$ 0.09 and 22.01 $\pm$ 0.08 Ma (Peters, 2002, and Peters, 2006a, respectively) from two samples collected 10 and 6 miles (16 and 10 km), respectively, west of Central, and 21.83 $\pm$ 0.17 and 21.46 $\pm$ 0.40 Ma from two samples collected from near the town of Pinto north of the map area (Cornell and others, 2001); thickness about 1600 feet (500 m).

Tpa **Rocks of Paradise** (lower Miocene) – Resistant to moderately resistant, gray, pink, and red, crystal-rich, dacitic lava flows and poorly to moderately welded ash-flow tuff derived from eruption of the Pinto Peak intrusion, located just north of the map area, and tilted westward by emplacement of the Stoddard Mountain intrusion, also just north of the map area (Hacker, 1998; Hacker and others, 2002); $^{40}Ar/^{39}Ar$ ages are 21.97 $\pm$ 0.09, 21.62 $\pm$ 0.08, and 21.75 $\pm$ 0.30 Ma on two samples (Rowley and others, 2006), in good agreement with the age of the Pinto Peak intrusion (21.96 $\pm$ 0.11 Ma; Peters, 2006b); maximum thickness about 600 feet (180 m).

Intrusions of quartz monzonite porphyry

Mostly resistant, gray and pink, crystal-rich, shallow (most emplaced within about 1.2 miles [2 km] of the surface), quartz monzonite laccoliths and concordant stocks that rose at about 22 to 20 Ma above the roof of an inferred large batholith (Blank and Mackin, 1967; Cook and Hardman, 1967; Rowley and others, 1998; Rowley, 1998) of the same material. The quartz monzonite plutons define the central part of a northeast-trending belt known as the Iron Axis, extending from the youngest Mineral Mountain intrusion (Tim) in the southwest Bull Valley Mountains to at least the Iron Peak laccolith (20.2 $\pm$ 0.05 Ma, second youngest in the Iron Axis; Fleck and others, 1975) in the Markagunt Plateau east of the town of Paragonah, northeast of the map area. Most of the central quartz monzonite plutons appear to be partly controlled by northeast-striking, southeast-verging Sevier-age (Late Cretaceous to early Tertiary) thrust faults, stratigraphically

located within Temple Cap and Carmel strata (Jct) or between Jct and Navajo Sandstone, that emplaced Jct over the Iron Springs Formation (Mackin and others, 1976; Van Kooten, 1988); the thrust faults provided access for the magma upward through the thick Navajo Sandstone. Some of the plutons of the Iron Axis produced hematite ore deposits, from replacement of the Homestake Limestone Member of the Carmel Formation and from magnetite veins; most of these deposits surround three plutons, which make up the Iron Springs mining district just north of the map area, the largest iron-producing district in the West (Mackin, 1947, 1954, 1960, 1968; Blank and Mackin, 1967; Bullock, 1970; Mackin and others, 1976; Mackin and Rowley, 1976; Rowley and Barker, 1978; Barker, 1995); the much smaller Bull Valley mining district, adjacent to the Bull Valley intrusion (Tib), shipped some ore (Wells, 1938; Bullock, 1970; Tobey, 1976). The quartz monzonite plutons are mapped individually because each differed slightly in age and evolved differently, although most are characterized by partial deroofing by gravity sliding, immediately followed by volcanic eruptions (Mackin, 1960; Blank and Mackin, 1967; Hacker, 1998; Hacker and others, 1996, 2002); relative ages of most plutons can be determined by mapping deformation of eruptive or gravity-slide products by younger plutons; most plutons in the central Iron Axis have several lithologic phases (thin outer peripheral-shell phase, selvage-joint phase, and interior phase) whose mapping elucidated that the iron solutions were derived from deuteric breakdown of ferromagnesian minerals in the selvage-joint phase (Mackin, 1947, 1954, 1960, 1968; Mackin and Ingerson, 1960; Mackin and others, 1976; Mackin and Rowley, 1976; Rowley and Barker, 1978; Barker, 1995).

Tipv **Pine Valley laccolith** (lower Miocene) – Perhaps the largest laccolith in the World (Cook, 1957, 1960b), it is 3000 feet (900 m) thick and is exposed over an area of 90 square miles (240 km^2), with well exposed concordant basal and flank intrusive contacts in the upper part of the Claron Formation (Tc), a much higher structural level than that of most of the other quartz monzonite intrusions, with which it is chemically similar; consists of locally flow layered, medium-gray quartz monzonite porphyry with medium- to coarse-grained phenocrysts of plagioclase, pyroxene, biotite, and sanidine; groundmass is fine-grained to microscopic plagioclase, quartz, and pyroxene; the northern flanks of the Pine Valley Mountains are covered by gravity slides, the largest with an area of at least 60 square miles (150 km^2) and more than 1800 feet (550 m) thick, made up of brecciated roof rocks, indicating that the laccolith was emplaced rapidly, then shed its roof and flanks by gravity sliding along relatively weak shale beds in Tc; removing its roof led to eruption of thick lava flows of the Pine Valley Latite (Tpv); because it was emplaced at such a shallow level (estimated at less than 600 feet [200 m]) below the former land surface, the rocks of both Tipv and Tpv may be distinguished from each other only with careful geologic mapping, and therefore early workers, the most recent of which was Mattison (1972), interpreted all the rocks as volcanic; we instead follow the interpretations of Cook (1957, 1960b), Hacker (1998), and Hacker and others (2002); K-Ar age on biotite is 20.9 $\pm$ 0.6 Ma (McKee and others, 1997), but we prefer $^{40}Ar/^{39}Ar$ ages of 20.47 $\pm$ 0.04 and 20.63 $\pm$ 0.12 Ma from a sample from the base of the laccolith, and 20.32 $\pm$ 0.08 and 20.46 $\pm$ 0.05 Ma from a sample collected 500 feet above the base (Rowley and others, 2006), in excellent agreement with the $^{40}Ar/^{39}Ar$ ages of Tpv.

Tid **The Dairy intrusion** (lower Miocene) – A small, apparent laccolith located about 3 miles (5 km) southeast of the small community of Pinto (Cook, 1957), it is interpreted by Hacker (1998) to be connected at depth with the much larger Stoddard Mountain intrusion, located just north of the map area; the Stoddard Mountain intrusion was emplaced into the Iron Springs Formation, at a lower structural level than the Pine Valley laccolith, but at a higher structural level than most of the other quartz monzonite plutons; the Stoddard Mountain intrusion produced gravity slides, then erupted to form the volcanic rocks of Comanche Canyon (Tcv); it has an $^{40}Ar/^{39}Ar$ age of 21.86 $\pm$ 0.09 Ma (Rowley and others, 2006), similar to the $^{40}Ar/^{39}Ar$ age of Tcv.

Tib **Bull Valley intrusion** (lower Miocene) – Exposed 6 miles (10 km) west-northwest of Central, the intrusion forms the southwest end of an intrusive arch that appears to connect with the Hardscrabble Hollow intrusion (Tih) farther northeast and with the Big Mountain intrusion (Tibm) at the northeast end (Blank, 1959, 1993; Blank and others, 1992; Hacker, 1998; Hacker and others, 2002); formed replacement hematite ore bodies within Temple Cap and Carmel strata, into which it intruded (Wells, 1938; Blank, 1959; Tobey, 1976); during rapid intrusion to form a mountain, the intrusive arch shed large gravity slides, followed by eruption of the Rencher Formation (Tre); it or other parts of the arch may have had an earlier episode of eruption, resulting in the significantly larger ash-flow tuff, Harmony Hills Tuff (Tqh) (Blank, 1959; Blank and others, 1992); unit has an $^{40}Ar/^{39}Ar$ age of 21.98 + 0.10 Ma (Peters, 2006a).

Tih **Hardscrabble Hollow intrusion** (lower Miocene) – Exposed 5 miles (8 km) northwest of Central, the intrusion is a small body that appears to be the central part of the same intrusive arch containing the Bull Valley and Big Mountain intrusions; has an $^{40}Ar/^{39}Ar$ age of 22.02 $\pm$ 0.11 Ma (Peters 2006a).

Tibm **Big Mountain intrusion** (lower Miocene) – Exposed as a mountain along the north edge of the map area, just west of Mountain Meadow, this is the north end of the intrusive arch that includes the Bull Valley and Hardscrabble Hollow intrusions and extends north of the map area (Blank, 1993); has an $^{40}Ar/^{39}Ar$ age of 22.00 $\pm$ 0.07 Ma (Peters, 2006a), almost identical to the ages of the other intrusions of the arch.

Quichapa Group

Tq **Quichapa Group, undivided** (lower Miocene) – Regional ash-flow sheets that are described in detail by Mackin (1960), Williams (1967), Anderson and Rowley (1975), and Rowley and others (1995); consist of the petrographically and chemically distinctive Harmony Hills Tuff, Condor Canyon Formation, and Leach Canyon Formation, here locally lumped where too thin to show separately.

Tqh **Harmony Hills Tuff** (lower Miocene) – Resistant, gray and tan, crystal-rich, moderately welded, dacitic ash-flow tuff; lithologically resembles the Rencher Formation (Tre) except that the Rencher has no quartz or sanidine; source of Harmony Hills Tuff unknown but isopachs are centered on Bull Valley (Williams, 1967), suggesting that it was derived from the east Bull Valley Mountains, probably from an early, much more

voluminous eruptive phase of the Bull Valley/Hardscrabble Hollow/Big Mountain intrusive arch, as suggested by Blank (1959), Williams (1967), and Rowley and others (1995); consistent with this interpretation is the fact that the $^{40}Ar/^{39}Ar$ plateau age of the Harmony Hills is 22.03 $\pm$ 0.15 Ma (Cornell and others, 2001), nearly identical to that of Tib, Tih, and Tibm; maximum thickness about 500 feet (150 m).

Tqci **Bauers Tuff Member of the Condor Canyon Formation, Leach Canyon Formation, and Isom Formation, undivided**.

Tqcl **Bauers Tuff Member of the Condor Canyon Formation and Leach Canyon Formation, undivided**.

Tqcw **Condor Canyon Formation, Leach Canyon Formation, Isom Formation, and Wah Wah Springs Formation, undivided**.

Tqc **Condor Canyon Formation** (lower Miocene) – Consists of two members, here not mapped separately; the upper one, the **Bauers Tuff Member**, is a resistant, brown, gray, and purple, crystal-poor, densely welded, dacitic to trachydacitic ash-flow tuff, commonly with a black basal vitrophyre, derived from the northwest part (Clover Creek caldera) of the Caliente caldera complex (Rowley and others, 1995); $^{40}Ar/^{39}Ar$ age of the Bauers Tuff Member is about 22.8 Ma (Best and others, 1989a), which is also the $^{40}Ar/^{39}Ar$ age of its intracaldera intrusion exposed just north of Caliente (Rowley and others, 1994b); the underlying member, the **Swett Tuff Member**, is a resistant, brown, crystal-poor, densely welded, dacitic ash-flow tuff, probably derived from the Caliente caldera complex; $^{40}Ar/^{39}Ar$ age is 23.87 $\pm$ 0.04 Ma (Rowley and others, 2006), but this age may be too old because it is slightly older than the $^{40}Ar/^{39}Ar$ age of the underlying Leach Canyon Formation (Tql); maximum thickness of the Bauers is about 300 feet (100 m), whereas the Swett is only exposed in the north part of the map area, where its maximum thickness is about 30 feet (10 m).

Tql **Leach Canyon Formation** (lower Miocene) – Moderately resistant, tan and gray, crystal-poor, poorly welded, low-silica rhyolite ash-flow tuff containing abundant cognate pumice and red lithic fragments; source is unknown but probably is the Caliente caldera complex because isopachs show that it thickens toward the complex (Williams, 1967); the $^{40}Ar/^{39}Ar$ age of the formation is about 23.8 Ma (Best and others, 1993; Rowley and others, 1995); maximum thickness about 500 feet (150 m).

Tiw **Isom Formation and Wah Wah Springs Formation of the Needles Range Group (Mackin, 1960; Anderson and Rowley, 1975), undivided**.

Ti **Isom Formation and enclosing sedimentary rocks, undivided** (upper Oligocene) – Consists of two members, here not mapped separately, the upper **Hole-in-the-Wall Tuff Member** and the lower **Bald Hills Tuff Member,** both resistant, brown and reddish-brown, crystal-poor, densely welded, trachydacitic ash-flow tuffs derived perhaps from the Indian Peak caldera complex (Best and others, 1989a, b) north of the map area; the

Bald Hills Tuff Member consists of several cooling units, some with black basal vitrophyres; the Hole-in-the-Wall Tuff Member is a single cooling unit, commonly with a black basal vitrophyre, exposed only in the north part of the map area; tuffs of the Isom Formation are interbedded with lacustrine limestone and fluvial tuffaceous sandstone that thicken southwestward into the Bull Valley Mountains (Blank, 1959; Hintze and others, 1994; Hacker, 1998); age of the Isom appears to be about 27 to 26 Ma, on the basis of many $^{40}Ar/^{39}Ar$ and K-Ar ages (Best and others, 1989b; Rowley and others, 1994a); maximum thickness of sedimentary rocks above the tuffs is as much as 250 feet (80 m), of the Hole-in-the-Wall Tuff Member is as much as 30 feet (10 m), of the Bald Hills Tuff Member is as much as 120 feet (40 m), and of the sedimentary rocks below the tuffs is as much as 200 feet (60 m).

Tw **Wah Wah Springs Formation of the Needles Range Group** (lower Oligocene) – Soft to resistant, light-greenish-gray, tan, grayish-pink, and light-purple, crystal-rich, moderately welded, dacite ash-flow tuff; derived from the Indian Peak caldera complex (Best and others, 1989a, b); in the Gunlock-Motoqua area, map unit is correlated with the Wah Wah Springs Formation (Hintze and others, 1994), and probably is Wah Wah Springs elsewhere in the map area (the Wah Wah Springs Formation is the upper formation of the Needles Range Group in most areas); preferred age, based on many K-Ar and $^{40}Ar/^{39}Ar$ age determinations, about 30 Ma (Best and others, 1989a, b); maximum thickness about 50 feet (15 m).

unconformity

Claron Formation (lower Oligocene to upper Paleocene)

Tc **Claron Formation, undivided** – Upper and lower members combined in the Bull Valley Mountains and along the flanks of the Pine Valley Mountains; may locally include pre-Isom lacustrine strata of Hintze and others (1994) in the Bull Valley Mountains; age from Goldstrand (1994), but is poorly constrained, and the formation was probably deposited during several restricted time intervals; the entire formation in the St. George quadrangle ranges from about 300 to 1600 feet (90-490 m) thick; the maximum thickness in the northern Bull Valley Mountains is about 1000 feet (300 m), but it thins southward to about 300 to 500 feet (90-150 m) thick on the south margin of the range.

Tcu **Upper member** – White to light-gray, resistant limestone interbedded with mottled pale-gray, pinkish-gray, and maroon mudstone; limestone is medium to thick bedded and includes unfossiliferous micrite, fine-grained bioclastic calcarenite, pelletal calcarenite, and local laminated algal structures; deposited in fluvial and lacustrine environments extensively modified by post-depositional bioturbation and pedogenic processes (Mullett and others, 1988a, 1988b; Mullett, 1989; Taylor, 1993); unconformably overlain by a variety of Miocene and Oligocene volcanic and sedimentary rocks; about 520 feet (160 m) thick in the Pintura area (Hurlow and Biek, 2003).

Tcl **Lower member** – Interbedded mudstone, siltstone, sandstone, conglomerate, and limestone; mudstone is orangish red to reddish brown; sandstone is light-brown, medium-

to coarse-grained, cross-bedded to structureless litharenite; sandstone grades into, or is locally incised by thick-bedded pebble conglomerate with limestone, quartzite, and chert clasts; lower to middle part of the lower member contains resistant, thick-bedded micrite that is stained orange, pink, tan, lavender, and yellow and that contains sparse bivalve and gastropod shell fragments; upper part of the lower member contains medium-gray, thin- to medium-bedded, resistant micrite to calcarenite with locally common bivalve fragments, oncolites, and calcite-filled veins and vugs; in the Pintura area, upper contact corresponds to a pronounced color change from brightly colored reddish-orange mudstone below to gray to pinkish-gray mudstone above; about 1090 feet (330 m) thick in the Pintura area (Hurlow and Biek, 2003).

unconformity

TERTIARY-CRETACEOUS

TKg **Grapevine Wash Formation** (Lower Tertiary to Upper Cretaceous) – Present only in the Gunlock and Square Top Mountain area where it is divisible into three units (Wiley, 1963; Hintze and others, 1994); in descending order, but undivided here (unit descriptions summarized from Hintze [1986] and Hintze and others [1994]): **Upper conglomerate unit** – Poorly sorted, subangular to subrounded pebble to cobble conglomerate, but with some boulders as much as 6 feet (2 m) in diameter; most clasts derived from the Queantoweap Sandstone and Callville Limestone; forms white to pale-yellowish-gray ledges and cliffs; about 330 to 430 feet (100-130 m) thick. **Middle sandstone and conglomerate unit** – Contains more sandstone and siltstone and forms less resistant, less vegetated slopes than enclosing units; about 60% of the clasts are limestone derived from the Callville, Toroweap, and Kaibab Formations, with the remainder derived from the Queantoweap Sandstone; about 1300 feet (400 m) thick. **Lower conglomerate unit** – Resistant, pebble to cobble conglomerate and minor cross-bedded gritstone, sandstone, and siltstone; clast composition similar to that of the middle unit, but includes well-rounded pebbles and cobbles of gray quartzite; forms reddish-brown cliffs; about 360 to 500 feet (110-150 m) thick. Represents alluvial and alluvial-fan deposits derived principally from the Square Top Mountain thrust plate (Wiley, 1963; Hintze, 1986); unconformably overlain by the Claron Formation or Oligocene and Miocene volcanic and sedimentary rocks with an angular discordance of 5 to 10 degrees; as mapped, may locally include Claron Formation; the entire formation is as much as about 2000 feet (600 m) thick.

unconformity

TKcp **Canaan Peak Formation** (Lower Tertiary to Upper Cretaceous) – Conglomerate with minor interbedded sandstone and mudstone; clast-supported conglomerate is reddish brown, contains pebble- to cobble-sized, rounded clasts of tan, purple, gray, rusty brown, and black, structureless to cross-bedded quartzite, welded dacitic to andesitic ash-flow tuff, chert, and pale-gray to brownish-gray, fine- to medium-grained sandstone; welded tuff clasts contain altered feldspar and quartz phenocrysts in a gray, pale-green, orange-tan, or purple-brown, devitrified groundmass; Goldstrand (1992) correlated the tuff clasts

with Jurassic volcanic rocks in southeast California; sandstone is reddish-brown, medium- to coarse-grained, structureless to weakly laminated litharenite in 0.5- to 1-foot-thick (0.2-0.3 m) beds; mudstone is present near the base and top of the formation, and is reddish brown and finely laminated; preserved in paleochannels on the Navajo Sandstone (Goldstrand, 1992) along a structural culmination interpreted to be the hinge zone of the Pintura anticline (Hurlow and Biek, 2003); palynomorphs collected from the Canaan Peak Formation on the Table Cliff Plateau in south-central Utah indicate a late Campanian to early Paleocene age (Goldstrand, 1994); 0 to 120 feet (0-35 m) thick (Hurlow and Biek, 2003).

unconformity

CRETACEOUS AND JURASSIC

KJu **Iron Springs, Carmel, and Temple Cap Formations, undivided** – Steeply dipping, faulted strata of the uppermost Iron Springs Formation, Co-op Creek Limestone Member of the Carmel Formation, and the Sinawava Member of the Temple Cap Formation exposed in the Virgin River canyon just west of Utah Highway 9.

CRETACEOUS

East of the Hurricane fault, where they have been extensively studied, Upper Cretaceous strata in the St. George 30’ x 60’ quadrangle are divided into, in ascending order, the Dakota Formation, Tropic Shale, and Straight Cliffs Formation; west of the fault they remain undivided as the Iron Springs Formation.

Ktm **Tectonic mixture** (Upper Cretaceous) – Unconsolidated, unbedded, reddish-brown silty matrix that contains scattered angular blocks of red sandstone, light-gray limestone, and conglomerate as much as 2 feet (0.5 m) in diameter; clasts derived from the Moenkopi Formation, Shinarump Conglomerate Member of the Chinle Formation, and Kayenta Formation; description from Hintze and others (1994), who interpreted it to be a chaos of material caught under the Square Top Mountain thrust as it moved eastward over Triassic and Jurassic strata.

Ki **Iron Springs Formation** (Upper Cretaceous, Santonian or lower Campanian to Cenomanian) – Interbedded, ledge-forming, calcareous, cross-bedded, fine- to medium-grained sandstone and less resistant, poorly exposed sandstone, siltstone, and mudstone; contains a few thin sandy coquina beds, minor carbonaceous shale, and uncommon pebbly sandstone; lower part contains numerous light-gray to reddish-brown smectitic mudstone intervals; the formation is variously colored grayish orange, pale yellowish orange, dark yellowish orange, white, pale reddish brown, and greenish gray and is locally stained by iron-manganese oxides; Liesegang banding is locally common in the sandstone beds; sandstone beds range from quartz arenite to litharenite (Fillmore, 1991; Goldstrand, 1992); deposited principally in braided-stream and flood-plain environments (Johnson, 1984; Fillmore, 1991), but Eaton and others (1997) noted that brackish water molluscan faunas collected about 1000 feet (300 m) above the base of the formation in the Pine Valley Mountains probably indicate the maximum transgression of the Cretaceous Seaway; tentatively correlated to the Dakota Formation (as used here), Tropic

Shale, and Straight Cliffs Formation of the Markagunt Plateau (Eaton, 1999); age from Goldstrand (1994); about 3500 to 4000 feet (1070-1220 m) thick in the Pine Valley Mountains (Cook, 1960b) and about 3000 feet (900 m) thick near Gunlock (Hintze, 1986).

Straight Cliffs Formation

Ksu **Upper unit** (Upper Cretaceous, Santonian[?] to Turonian) – Slope-forming, grayish-orange to yellowish-brown, thin- to thick-bedded, fine-grained subarkosic sandstone and gray mudstone and shale; contains a few thin coal beds, common carbonaceous shale, and several thin coquina beds; forms broad, rounded hills typically mantled with colluvium; believed to be equivalent to the Smoky Hollow Member and possibly John Henry Member of the Straight Cliffs Formation of the Kaiparowits Plateau (see, for example, Eaton and others, 2001); deposited in fluvial, flood-plain, and lagoonal environments of a coastal plain (Eaton and others, 2001); incomplete thickness as much as 320 feet (100 m) in the Kolob Reservoir quadrangle (Biek, in prep.[b]), but upper part not preserved.

Kst **Tibbet Canyon Member** (Upper Cretaceous, Turonian) – Grayish-orange to yellowish-brown, generally medium- to thick-bedded, planar-bedded, fine- to medium-grained quartzose sandstone and lesser interbedded, grayish-orange to gray mudstone and siltstone; locally contains pelecypods, gastropods, and thin to thick beds of oyster coquina; typically forms cliffs, but here more commonly weathers to steep, vegetated slopes; upper contact corresponds to a break in slope and is placed at the top of a coquinoid oyster bed that caps the member; deposited in shoreface, lagoonal, estuarine, and flood-plain environments of a coastal plain (Laurin and Sageman, 2001; Tibert and others, 2003); thickens eastward across the Kolob Reservoir quadrangle from about 240 to 450 feet (75-135 m) thick (Biek, in prep.[b]).

KJdc **Dakota Formation, Cedar Mountain Formation, and Winsor Member of the Carmel Formation, undivided** (Upper Cretaceous to Middle Jurassic) – Mapped on the Upper Kolob Plateau near Little Creek Peak where access to private land was denied; the Dakota Formation is present over most of this area, Cedar Mountain strata may be present, and Winsor strata are likely present at the lowest elevations.

Kdt **Dakota Formation and Tropic Shale, undivided** (Upper Cretaceous, Cenomanian) – Interbedded, slope- and ledge-forming sandstone, siltstone, mudstone, claystone, carbonaceous shale, coal, and marl; sandstone is yellowish brown or locally white, thin to thick bedded, fine to medium grained; includes two prominent cliff-forming sandstone beds, each several tens of feet thick, in the upper part of the formation; mudstone and claystone are gray to yellowish brown and commonly smectitic; oyster coquina beds, clams, and gastropods, including large *Craginia* sp., are common, especially in the upper part of the section; uppermost marl beds above the uppermost sandstone cliff contain distinctive gastropods with a beaded edge (*Admetopsis* n. sp. indicative of a latest Cenomanian brackish environment [Eaton and others, 2001]); Dakota strata are typically poorly exposed and involved in large landslides; includes the overlying Tropic Shale, which is restricted to the east part of the Kolob Reservoir quadrangle where it is silty and

sandy and no more than a few feet thick (Biek, in prep.[b]), representing the farthest west encroachment of offshore-marine environments of the Cretaceous seaway in this part of Utah (see, for example, Eaton and others, 2001); upper contact placed at the top of a slope-forming, coaly and marly mudstone sequence and at the base of the typically cliff-forming sandstone of the Tibbet Canyon Member of the Straight Cliffs Formation; deposited in flood-plain, estuarine, lagoonal, and swamp environments (Gustason, 1989; Laurin and Sageman, 2001; Tibert and others, 2003); invertebrate and palynomorph fossil assemblages indicate shallow-marine, brackish, and fresh-water deposits of Cenomanian age (Nichols, 1995); about 850 feet (260 m) thick (Biek, in prep.[b]).

unconformity

Kcm **Cedar Mountain Formation, undivided** (Cretaceous, Cenomanian to Albian) – Consists of two units, not mapped separately, in southwest Utah (Hylland, 2000; Biek and Hylland, in preparation) in ascending order: **Conglomerate unit** – Thick-bedded, yellowish-brown, channel-form conglomerate, pebbly sandstone, and pebbly gritstone; clasts are subrounded to rounded, pebble- to small-cobble-size quartzite, chert, and limestone; locally stained reddish brown to dark yellowish brown; best developed on the Upper Kolob Plateau, east flank of the Pine Valley Mountains, and in the Gunlock-Veyo area, where it is 30 to 100 feet (10-30 m) thick, but nearly everywhere present as a thin, commonly less than one-foot-thick (0.3 m) pebbly conglomerate deposited on paleotopography developed on top of the various members of the Carmel Formation. **Mudstone unit** – Gray to variegated smectitic mudstone with minor light-gray to yellowish-gray fine-grained sandstone that weathers to poorly exposed slopes; near the base of this predominantly mudstone interval on the Kolob Plateau there is a distinctive, 1- to 4-foot-thick (0.3-1.2 m), locally ledge-forming, pale-olive to greenish-gray, thin- to medium-bedded, fine- to medium-grained sandstone containing subangular, reddish-brown chert granules; upper contact is poorly exposed and corresponds to a color and lithologic change, from comparatively brightly colored smectitic mudstone below to gray and light-yellowish-brown mudstone and fine-grained sandstone above.

Unconformably overlain by the Dakota Formation east of the Hurricane fault (see, for example, Kirkland and others, 1997) and by the Iron Springs Formation west of the fault; deposited in river-channel and floodplain environments on a broad, coastal plain (Tschudy and others, 1984; Kirkland and others, 1997); Biek and Hylland (in preparation) reported a single-crystal $^{40}Ar/^{39}Ar$ age of 97.9 $\pm$ 0.5 Ma on sanidine from a volcanic ash in Cedar Mountain mudstone immediately above this conglomerate bed in the Straight Canyon quadrangle east of Zion National Park; Dyman and others (2002) obtained an $^{40}Ar/^{39}Ar$ age of 101.7 $\pm$ 0.42 Ma on sanidine from a stratigraphically similar mudstone near Gunlock, the same 20-foot-thick (6 m), moderate-red bentonitic bed near the Gunlock Reservoir for which Hintze and others (1994) reported an anomalously young fission-track age of 80 $\pm$ 10 Ma; pollen analyses indicate an Albian or older age for these beds (Doelling and Davis, 1989; Hylland, 2000); conglomeratic member previously mapped as the lower part of the Dakota Formation, and the mudstone unit (in the Gunlock area) as an Upper Cretaceous bentonite, but the lithology, age, and stratigraphic position of these beds suggest correlation to the Cedar Mountain Formation;

where conglomerate is thickest, likely represents deposits of the main Cedar Mountain river channel, whereas thin conglomerate deposits may represent terrace remnants of this river system or possibly younger gravels that were reworked in the early Late Cretaceous; 0 to about 100 feet (0-30 m) thick.

K unconformity (Pipiringos and O'Sullivan, 1978)

JURASSIC

Carmel Formation

Nomenclature follows that of Doelling and Davis (1989); deposited in a shallow inland sea of a back-bulge basin, the first clear record of the effects of the Sevier orogeny in southwestern Utah; forms an eastward-thickening wedge preserved beneath the basal Cretaceous unconformity; age from Imlay (1980).

Jc **Carmel Formation** (Middle Jurassic, Callovian to Bajocian) – Mapped on the nose of the Pintura anticline.

Jcw **Winsor Member** (Middle Jurassic, Callovian to Bathonian) – Light-reddish-brown, fine- to medium-grained sandstone and siltstone; poorly cemented and weathers to densely vegetated slopes; preserved only northeast of Leeds Creek, under the basal Cretaceous unconformity; typically overlain by the conglomerate unit of the Cedar Mountain Formation, but locally overlain by the Dakota Formation where the conglomerate appears to be missing; deposited on a broad, sandy mudflat (Imlay, 1980; Blakey and others, 1983); thins westward due to truncation under the K unconformity, from 0 to 320 feet (0-98 m) thick.

Jcp **Paria River Member** (Middle Jurassic, Bathonian) – Laminated to thin-bedded, yellowish-gray to light-olive-gray argillaceous limestone and micritic limestone that locally overlies a thick, white, alabaster gypsum bed in the basal part of the Paria River Member; limestone weathers to small chips and plates and contains rare, small pelecypod fossils; forms steep, ledgy slopes; upper contact is sharp and planar on the Kolob Plateau, but is unconformably overlain by the Cedar Mountain Formation in western exposures; deposited in shallow-marine and coastal-sabkha environments (Imlay, 1980; Blakey and others, 1983); thins westward due to truncation under the K unconformity, from 0 to 160 feet (50 m) thick.

Jcx **Crystal Creek Member** (Middle Jurassic, Bathonian) – Thin- to medium-bedded, pale- to moderate-reddish-brown gypsiferous siltstone, mudstone, fine- to medium-grained sandstone, and gypsum; typically friable and weakly cemented with gypsum; contains local thin interbeds of yellowish-gray to light-olive-gray mudstone with abundant fine- to coarse-sand-size biotite flakes; moderate-reddish-brown blebs of jasper are common in the lower part of the member; uppermost part on the southeast flank of the Pine Valley Mountains consists of white, grayish-orange-pink, light-brown, and dark-yellowish-orange, fine- to medium-grained sandstone and minor mudstone and siltstone; forms vegetated, poorly exposed slopes; in the Zion National Park area, upper contact is sharp and broadly wavy and corresponds to the base of a thick Paria River gypsum bed or

argillaceous limestone, but in western exposures the upper part is truncated under the basal Cretaceous unconformity; Kowallis and others (2001) reported two $^{40}Ar/^{39}Ar$ ages of 167 to 166 million years old for altered volcanic ash beds within the member near Gunlock, likely derived from a magmatic arc in what is now southern California and western Nevada; deposited in coastal-sabkha and tidal-flat environments (Imlay, 1980; Blakey and others, 1983); thins westward due to truncation under the K unconformity, from 0 to 250 feet (0-75 m) thick.

Jcc **Co-op Creek Limestone Member** (Middle Jurassic, Bajocian) – Divisible into two informal unmapped units: **Upper unit** – Thin- to medium-bedded, light-gray, yellowish-gray, or yellowish-brown micritic limestone and, especially in the upper part, oolitic and sandy limestone; forms sparsely vegetated, ledgy slopes and cliffs; locally contains abundant *Isocrinus* sp. columnals, pelecypods, and gastropods. **Lower unit** – Mostly thinly laminated to thin-bedded, light-gray micritic limestone, calcareous shale, platy limestone, and, near the base, lesser gypsum and fine-grained sandstone; forms steep, vegetated slopes; contact with upper unit is gradational and corresponds to a subtle break in slope and vegetation patterns. Contact with Crystal Creek Member is sharp and planar and corresponds to a prominent color change from yellowish- and brownish-gray to reddish-brown, with fossiliferous sandy limestone and micritic limestone giving way to gypsiferous mudstone and siltstone; locally, moderate-reddish-brown blebs of jasper and an oyster coquina are present in uppermost mudstones of the Co-op Creek; in the west half of the map area, locally unconformablly overlain by the conglomerate unit of the Cedar Mountain Formation; Kowallis and others (2001) reported several $^{40}Ar/^{39}Ar$ ages of 168 to 167 million years old for altered volcanic ash beds, likely derived from a magmatic arc in what is now southern California and western Nevada, within the lower unit in southwest Utah; deposited in a shallow-marine environment (Imlay, 1980; Blakey and others, 1983); generally thins to the west, but ranges from about 285 to 580 feet (87-177 m) thick.

J-2 unconformity (Pipiringos and O'Sullivan, 1978), formed about 169 to 168 million years ago in southwest Utah (Kowallis and others, 2001)

Temple Cap Formation

Jtw **White Throne Member** (Middle Jurassic, Bajocian) – Very thick bedded, yellowish-gray to pale-orange, well-sorted, fine-grained quartz sandstone with high-angle, tabular-planar, and wedge-planar cross-beds in sets as much as 20 feet (6 m) thick, similar to the Navajo Sandstone; forms prominent cliff in the south part of Zion National Park, but pinches out westward under the Upper Kolob Plateau, likely due to truncation beneath the J-2 unconformity; deposited in a coastal dune field (Blakey, 1994; Peterson, 1994); 0 to 130 feet (0-40 m) thick.

Jts **Sinawava Member** (Middle Jurassic, Bajocian) – Slope-forming, moderate-reddish-brown mudstone, siltstone, and fine-grained silty sandstone; west of the Hurricane Cliffs, contains several white, gray, and pink alabaster gypsum beds as much as 10 feet (3 m) thick and several thin intervals containing white and pinkish-gray chert nodules that may

be silicified bentonite; western exposures also contain numerous, thin, greenish-gray mudstone (altered volcanic ash) beds with common biotite; a ledge-forming, pinkish-gray to light-greenish-gray, calcareous, medium- to coarse-grained, locally pebbly sandstone is present about one-third the way up the section in the Harrisburg Junction quadrangle (Biek, 2003a); forms narrow, but prominent, deep-reddish-brown, vegetated slope at the top of the Navajo Sandstone in the Zion National Park area; elsewhere forms conspicuous bright-red and gray slopes that weather to soft, gypsiferous soils; upper contact is gradational and interfingering with the White Throne Member in the Zion National Park area, but unconformable with light-gray calcareous shale and micritic limestone of the Co-op Creek Limestone Member to the west; deposited in coastal-sabkha and tidal-flat environments (Blakey, 1994; Peterson, 1994); member mapped as a colored line where too thin to show separately; Kowallis and others (2001) reported several $^{40}Ar/^{39}Ar$ ages of 170 to 169 million years old for altered volcanic ash beds, likely derived from a magmatic arc in what is now southern California and western Nevada, within the formation in southwest Utah; thins abruptly over the crest of the Pintura anticline; thickens west and south from less than 10 feet (< 3 m) thick in the Kolob Canyons part of Zion National Park to about 400 feet (120 m) thick near Gunlock.

J-1 unconformity (Pipiringos and O'Sullivan, 1978), formed prior to about 170.5 million years ago in southwest Utah (Kowallis and others, 2001)

Jn **Navajo Sandstone** (Lower Jurassic) – Pale-reddish-orange, reddish-brown, or white, cliff-forming, cross-bedded, quartz sandstone; forms spectacular sheer cliffs, deep canyons, and impressive spires, promontories, and monoliths; consists of well-sorted, well-rounded, fine- to medium-grained, frosted quartz sand; bedding consists of high-angle, large-scale cross-bedding in tabular-planar, wedge-planar, and trough-shaped sets 10 to 45 feet or more (3-14+ m) thick; contains sparse planar interdune deposits and locally common ironstone bands and concretions; locally prominently jointed (see, for example, Rogers and Engelder, 2004; Rogers and others, 2004); lower part forms transition zone characterized by planar bedded, fine-grained sandstone and silty sandstone with thin siltstone interbeds with wavy bedding, flaser-like laminae, and soft-sediment deformation and bioturbation features, and less common but resistant cross-stratified sandstone; divided into three informal non-stratigraphic units of variable but roughly equal thickness based on color and weathering habit in the south part of Zion National Park: (1) "white Navajo," which forms the upper part of the Navajo Sandstone and is pale-gray, yellowish-gray, orangish-gray, and white because of alteration, remobilization, and bleaching of limonitic and hematitic (iron-bearing) cement, probably due to hydrocarbon migration (see, for example, Beitler and others, 2003); (2) "pink Navajo," which forms the middle part of the Navajo Sandstone, is generally less resistant than the "white Navajo" above and "brown Navajo" below, and is pale-reddish-orange due to more uniformly dispersed hematitic cement; and (3) "brown Navajo," which is streaked medium to dark reddish brown due to iron oxide remobilization caused by ground-water or hydrocarbon migration, and which forms the lower massive cliff of the Navajo Sandstone and is correlative in part with the lower transitional beds of the Navajo; the upper, unconformable contact of the Navajo is sharp and planar and

corresponds to a prominent break in slope, with cliff-forming, cross-bedded sandstone below and reddish-brown mudstone of the Sinawava Member of the Temple Cap Formation above; deposited in a vast coastal and inland dune field with prevailing winds principally from the north (Blakey, 1994, Peterson, 1994); correlative with the Nugget Sandstone of northern Utah and Wyoming and the Aztec Sandstone of southern Nevada and adjacent areas (see, for example, Kocurek and Dott, 1983; Riggs and others, 1993); the lower transition interval, which reaches its maximum thickness of about 300 feet (100 m) in the Red Cliffs area northeast of St. George, represents deposition in a sand-dominated sabkha environment (Tuesink, 1989; Sansom, 1992); much of the sand may originally have come 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 (Dickinson and Gehrels, 2003; Rahl and others, 2003); forms the principal aquifer throughout much of the quadrangle (Clyde, 1987; Hurlow, 1998; Heilweil and others, 2000; Heilweil and others, 2002; Rowley and Dixon, 2004; Rowley and others, 2004); about 1800 to 2300 feet (550-700 m) thick.

Jkm **Kayenta and Moenave Formations, undivided** (Lower Jurassic to Upper Triassic) – Mapped in the Kolob Canyons area where it is undivided due to structural complications.

Kayenta Formation

Marzolf (1994) and Blakey (1994) presented evidence to restrict the Moenave Formation to the Dinosaur Canyon and Whitmore Point Members, with a major regional unconformity at the base of the Springdale Sandstone. Further work supports this evidence, indicating that the Springdale Sandstone is more closely related to the Kayenta Formation and should be made its basal member (see, for example, Lucas and Heckert, 2001; Molina-Garza and others, 2003; Steiner, 2005). We anticipate that this change will be formalized (Lucas and Tanner, in preparation), and so here informally reassign the Springdale Sandstone as the basal member of the Kayenta Formation.

Jk **Kayenta Formation (entire upper part above the Springdale Sandstone Member west of Zion National Park; lower part [main body] in and near Zion National Park where Lamb Point and Tenney Canyon Tongues are mapped separately; and entire formation on cross section)** (Lower Jurassic) – Moderate- to dark-reddish-brown, thin- to thick-bedded siltstone, fine-grained sandstone, and mudstone with planar, low-angle, and ripple cross-stratification; contains several thin, light-olive-gray-weathering, light-gray dolomite beds; forms steep ledgy slope grading up to ledgy cliffs at top; upper contact is conformable and gradational and corresponds to the top of the highest thin siltstone and mudstone beds, above which are the towering cliffs of Navajo Sandstone; deposited in distal river, playa, and minor lacustrine environments (Tuesink, 1989; Sansom, 1992; Blakey, 1994; Peterson, 1994); entire upper part thickens westward from about 550 to 700 feet (165-210 m) thick in the south part of Zion National Park, to 900 to 1200 feet (275-365 m) thick in the greater St. George area, to about 1500 feet (460 m) thick in the northern Beaver Dam Mountains; lower part below the Lamb Point Tongue is about 290 to 400 feet (88-120 m) thick.

Jkt **Tenney Canyon Tongue of Kayenta Formation** (Lower Jurassic) – Forms the upper part of the Kayenta Formation in the Zion National Park area, above the Lamb Point Tongue; consists of lenticular beds of pale-reddish-brown to moderate-reddish-orange siltstone and fine-grained sandstone, and minor claystone and limestone; forms a steep slope grading up to ledgy cliffs at top; pinches out to the east near the Paunsaugunt fault; thickens westward from about 140 to 315 feet (43-95 m).

Jnl **Lamb Point Tongue of Navajo Sandstone** (Lower Jurassic) – Mostly reddish-brown, fine-grained, well-sorted, strongly cross-bedded, quartzose sandstone; contains scattered thin lenses of flat-bedded, pale-reddish-brown siltstone and claystone similar to Kayenta Formation beds; forms a vertical ledge in the upper one-third of the Kayenta Formation in the Zion National Park area; upper contact placed at top of a thick, laterally continuous ledge-forming sandstone; locally contains a 1-foot-thick (30 cm) bed of limestone near the top; deposited in a coastal dune field and sabkha environment; thins westward and pinches out near Right Fork North Creek; mapped as a colored line where thin; 0 to 60 feet (0-18 m) thick.

Jks **Springdale Sandstone Member** (Lower Jurassic) – Medium- to thick-bedded, fine- to medium-grained sandstone with planar and low-angle cross-stratification, and minor, thin, discontinuous lenses of intraformational conglomerate and thin interbeds of moderate-reddish-brown or greenish-gray mudstone and siltstone; contains locally abundant petrified and carbonized fossil plants; forms conspicuous cliffs and mesas and is host to the ore deposits of the Silver Reef mining district (Proctor and Shirts, 1991; Biek and Rohrer, 2006); upper contact is conformable and corresponds to the first appearance of laterally continuous, thin-bedded, reddish-brown, fine-grained silty sandstone that overlies the Springdale cliff; deposited in braided-stream and minor flood-plain environments of a northward-flowing river system (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998); about 90 to 150 feet (27-45 m) thick.

J-sub Kayenta unconformity (Blakey, 1994)

JURASSIC AND TRIASSIC

JTRmc **Moenave and Chinle Formations, undivided** (Lower Jurassic to Upper Triassic) – May include parts of all members of these formations where mapped along the Hurricane fault.

JTRm **Moenave Formation** (Lower Jurassic to Upper Triassic) – **Whitmore Point Member** (Lower Jurassic): pale-red-purple, greenish-gray, and blackish-red mudstone and claystone, lesser moderate-reddish-brown, fine-grained sandstone and siltstone, and uncommon dark-yellowish-orange micaceous siltstone; contains several 3- to 18-inch-thick (8-120 mm), bioturbated, cherty, dolomitic limestone beds with algal structures, small reddish-brown chert blebs, and fossil fish scales of *Semionotus kanabensis* (Hesse, 1935; Schaeffer and Dunkle, 1950); the dolomitic limestones are light greenish gray, light gray, and yellowish gray, and they weather to mottled colors of pale yellowish orange, white, yellowish gray, and pinkish gray, commonly with green iron or copper-carbonate stains; upper part locally includes fine-grained, channel-like sandstone beds, and lower

part locally contains brown sandstone beds similar to those of the Dinosaur Canyon Member; weathers to poorly exposed, locally brightly colored slopes; upper contact corresponds to a major regional unconformity (Blakey, 1994; Marzolf, 1994); deposited in flood-plain and lacustrine environments (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998); lacustrine deposits are best developed in the St. George-Washington area (Kirkland and Milner, in preparation), becoming thinner and less well developed to the northeast and northwest; ranges from about 50 to 140 feet (15-40 m) thick. **Dinosaur Canyon Member** (Lower Jurassic to Upper Triassic): generally thin-bedded, moderate-reddish-brown and moderate-reddish-orange, fine-grained sandstone, fine-grained silty sandstone, and lesser siltstone and mudstone with planar, low-angle, and ripple cross-stratification; basal part typically includes a single bed of reddish-brown, fine-grained silty sandstone several tens of feet thick; a thin chert-pebble conglomerate marks the base of the member; forms ledgy slopes; upper contact is conformable and gradational and corresponds to the base of a light-gray, bioturbated, dolomitic limestone with algal structures and reddish-brown chert blebs; lower part may be equivalent to the Rock Point (= Church Rock) Member of the Chinle Formation (Kirkland and Milner, in preparation); deposited in river-channel and flood-plain environments of a northward-flowing river system (Clemmensen and others, 1989; Blakey, 1994; Peterson, 1994; DeCourten, 1998); age from Molina-Garza and others (2003) and Lucas and others (2005); ranges from about 150 to 250 feet (45-75 m) thick.

J-0 unconformity (Pipiringos and O'Sullivan, 1978). The Jurassic-Triassic boundary is now widely believed to lie within the Dinosaur Canyon Member of the Moenave Formation (Molina-Garza and others, 2003; Lucas and others, 2005; Kirkland and Milner, in preparation).

TRIASSIC

TRu **Chinle and Moenkopi Formations, undivided** (Upper to Lower Triassic) – May include Petrified Forest, and lower, middle, or upper red strata caught in the Hurricane fault near Toquerville Springs; may include parts of all members of these formations where mapped along the Reef Reservoir fault and in the northern Beaver Dam Mountains.

Chinle Formation

TRcp **Petrified Forest Member** (Upper Triassic) – Varicolored, typically gray to purple mudstone, claystone, and siltstone, lesser white to yellow-brown sandstone and pebbly sandstone, and minor chert and nodular limestone; regionally divisible into three parts, in ascending order: (1) the bentonitic Blue Mesa, (2) the pebbly sandstone of the Mossback or Sonsela (depending on clast provenance), and (3) the bentonitic Painted Desert (Lucas, 1993; Woody [2006], however, suggested restricting the Petrified Forest to strata above the Sonsela, that is, to Lucas' Painted Desert unit); the Owl Rock Member of the Chinle Formation may be present at the top of the unit as mapped here (Spencer Lucas, New Mexico Museum of Natural History and Science, verbal communication, August 2005), and the lowermost part of the Petrified Forest Member as mapped here locally contains light-gray, fine- to medium-grained sandstone, with abundant petrified wood and cobble- to small boulder-size, "cannonball" sandstone concretions, that may represent a distal, unmapped facies of the Monitor Butte Formation; the middle part of member is marked

by a distinctive, thick-bedded, white to yellow-brown sandstone and pebbly sandstone with well rounded chert and quartzite clasts likely correlative with the Sonsela; swelling, bentonitic mudstone and claystone are common throughout the member and although typically poorly exposed, their bright purple, grayish-red, dark-reddish-brown, light-greenish-gray, brownish-gray, olive-gray, and similar hues locally show through to the surface – they weather to a "popcorn" surface and and are responsible for numerous building foundation problems in the region; typically poorly exposed and commonly forms landslides; contains petrified wood, especially in sandstone beds; upper, unconformable contact is at the top of brightly colored swelling mudstones with nodular limestone, above which is a thin chert-pebble conglomerate and overlying reddish-brown, non-bentonitic siltstone and fine-grained sandstone; deposited in a variety of fluvial, flood-plain, and lacustrine environments of a back-arc basin formed inland of a magmatic arc associated with a subduction zone along the west coast of North America (Stewart and others, 1972a; Dickinson and others, 1983; Lucas, 1993; Dubiel, 1994; DeCourten, 1998); about 400 to 650 feet (120-200 m) thick.

TRcs **Shinarump Conglomerate Member** (Upper Triassic) – Medium- to coarse-grained sandstone, pebbly sandstone, and lesser pebbly conglomerate, locally with silty sandstone, claystone, and smectitic claystone interbeds, that forms prominent cliffs, hogbacks, and mesas; clasts are subrounded chert, quartzite, and quartz; mostly thick bedded with both planar and low-angle cross-stratification, although thin, platy beds with ripple cross-stratification occur locally; predominantly pale- to dark-yellowish-orange, but pale-red, grayish-red, pale-orange, and pale-yellow-brown hues are common; commonly stained by iron-manganese oxides, locally forming "picture stone"; contains poorly preserved petrified wood and plant debris, commonly replaced in part by iron-manganese oxides; upper contact typically corresponds to the first appearance of varicolored, swelling mudstone; deposited in braided streams that flowed north and northwest (Stewart and others, 1972a; Dubiel, 1994; DeCourten, 1998); typically about 100 feet (30 m) thick, but ranges from 5 to 250 feet (2-75 m) thick due to deposition over paleotopography developed on the TR-3 unconformity.

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

Moenkopi Formation

TRm **Moenkopi Formation** (Middle[?] and Lower Triassic) – West-dipping, fault-bounded blocks of mostly lower, middle, or upper red strata along the Hurricane fault; at Washington Dome, includes strata of the lower red and Virgin Limestone Members; along the north side of Bloomington Dome, includes strata of the lower red and Timpoweap Members; along the Reef Reservoir and Gunlock faults, it may include parts of all the members of the formation; may not include strata of Middle Triassic age in southwest Utah (Spencer Lucas, New Mexico Museum of Natural History and Science, verbal communication, August 2005).

TRmu **Upper red member** (Middle[?] and Lower Triassic) – Moderate-reddish-orange to moderate-reddish-brown, mostly thin- to medium-bedded siltstone, mudstone, and fine-

grained sandstone with planar, low-angle, and ripple cross-stratification; locally contains thin gypsum beds and abundant discordant gypsum stringers and typically forms ledgy slopes; locally includes a prominent, cliff-forming, medium- to thick-bedded, 100-foot-thick (30 m), fine-grained sandstone near the base of the member (locally known as the pale-yellowish-orange Purgatory sandstone where it is bleached in the core of the Virgin anticline); upper, unconformable contact is at the base of the first coarse-grained, thick-bedded, pale-yellowish-brown pebbly sandstone of the Shinarump Conglomerate; deposited in tidal-flat and coastal-plain environments (Stewart and others, 1972b; Dubiel, 1994); may not include strata of Middle Triassic age in southwest Utah (Spencer Lucas, New Mexico Museum of Natural History and Science, verbal communication, August 2005); generally thins to the northeast from about 400 to 600 feet (120-180 m) thick west of St. George to 200 to 280 feet (60-85 m) thick in the Zion National Park area.

TRms **Shnabkaib Member** (Lower Triassic) – Forms "bacon-striped," ledgy slopes of laminated to thin-bedded, gypsiferous, pale-red to moderate-reddish-brown mudstone and siltstone, resistant, white to greenish-gray gypsum, and minor thin, laminated, light-gray dolomite beds; gypsum is present as laterally continuous structureless beds, finely laminated commonly silty or muddy beds, nodular intervals as much as about 10 feet (3 m) thick, and as secondary cavity fillings and cross-cutting veins; in the Beaver Dam Mountains, the member contains numerous limestone beds as much as about 10 feet (3 m) thick, and far fewer red beds; typically weathers to soft, gypsiferous soils; upper conformable and gradational contact corresponds to the top of the highest thick gypsum bed; deposited in a variety of supratidal, intertidal, and subtidal environments on a broad, coastal shelf of low relief (Stewart and others, 1972b; Lambert, 1984); generally thickens westward from about 350 to 500 feet (105-150 m) east of the Hurricane Cliffs to about 800 to 1000 feet (245-300 m) west of St. George and in the Beaver Dam Mountains.

TRmm **Middle red member** (Lower Triassic) – Interbedded, slope-forming, laminated to thin-bedded, moderate-reddish-brown to moderate-reddish-orange siltstone, mudstone, and fine-grained sandstone with thin interbeds and veinlets of greenish-gray to white gypsum; lower part includes several thick gypsum beds; upper, conformable and gradational contact corresponds to the base of the first thick gypsum bed; deposited in a tidal-flat environment (Stewart and others, 1972b; Dubiel, 1994); generally thins westward from about 450 to 550 feet (140-170 m) thick east of the Hurricane Cliffs to about 300 to 400 feet (90-120 m) thick west of St. George.

TRmv **Virgin Limestone Member** (Lower Triassic) – Light-gray, light-olive-gray, and yellowish-brown limestone and silty limestone that typically forms three thin, resistant ledges at the base, middle, and top of the member, but in the Virgin River Gorge and White Hills contains five such limestone ledges; locally fossiliferous with circular and five-sided crinoid columnals, gastropods, and brachiopods; intervening slopes account for about 80% of the member and are mudstone and siltstone that have variable gray, yellowish-gray, and grayish-purple hues; upper, conformable contact corresponds to the top of the uppermost Virgin limestone bed; deposited in a variety of shallow-marine environments (Stewart and others, 1972b; Dubiel, 1994); generally thickens westward,

but ranges from 0 to about 250 feet (0-75 m) thick due to deposition over paleotopography developed on the Permian-Triassic unconformity.

TRml **Lower red member** (Lower Triassic) – Interbedded, slope-forming, laminated to thin-bedded, moderate-reddish-brown mudstone, siltstone, and fine-grained sandstone with local, thin, laminated, light-olive-gray gypsum beds and veinlets; upper contact corresponds to the base of the first Virgin limestone bed; deposited in a tidal-flat environment (Stewart and others, 1972b; Dubiel, 1994); generally thickens eastward, but ranges from 0 to about 300 feet (0-90 m) thick due to deposition over paleotopography developed on the Permian-Triassic unconformity.

TRmtr **Timpoweap and Rock Canyon Conglomerate Members, undivided** (Lower Triassic) – **Timpoweap Member:** lower part consists of light-brown-weathering, light-gray to grayish-orange, thin- to thick-bedded limestone and cherty limestone; chert occurs as small disseminated blebs, thus giving weathered surfaces a rough texture; upper part consists of grayish-orange, thin- to thick-bedded, slightly calcareous, fine-grained sandstone, siltstone, and mudstone; both parts form low cliffs and ledges and form a gently undulating surface on top of the Permian-Triassic unconformity; upper contact with the lower red member is conformable and gradational and corresponds to a change from yellowish-brown, fine-grained sandstone, siltstone, and minor limestone below to reddish-brown siltstone and mudstone above; deposited in a shallow-marine environment (Nielson and Johnson, 1979; Dubiel, 1994); ranges from 50 to 180 feet (15-55 m) thick (Nielson, 1981). **Rock Canyon Conglomerate Member:** consists of two main rock types: (1) a pebble to cobble, clast-supported conglomerate, with rounded chert and minor limestone clasts derived from the Harrisburg Member of the Kaibab Formation, which was deposited in paleovalleys and is typically 0 to several tens of feet thick, but locally as much as about 200 feet (60 m) thick; and (2) a widespread but thin breccia about 3 to 10 feet (1-3 m) thick, which probably formed as a regolith deposit on Harrisburg strata (Nielson, 1991); conformably and gradationally overlain by limestone of the Timpoweap Member.

TRmt **Timpoweap Member** (Lower Triassic) – As described above, but mapped separately in the White Hills, Jarvis Peak, and Scarecrow Peak quadrangles, and locally along the Hurricane Cliffs.

TRmr **Rock Canyon Conglomerate Member** (Lower Triassic) – As described above, but mapped separately in the White Hills, Jarvis Peak, and Scarecrow Peak quadrangles, and locally along the Hurricane Cliffs.

TR-1 unconformity (Pipiringos and O'Sullivan, 1978)

TRIASSIC AND PERMIAN

TRcPk **Chinle, Moenkopi, and Kaibab Formations, undivided** (Upper Triassic to Lower Permian) – Fault-bounded, highly fractured blocks containing various members of the Chinle, Moenkopi, and Kaibab Formations along the Hurricane fault.

TRmPk

Moenkopi and Kaibab Formations, undivided (Lower Triassic to Lower Permian) – Fault-bounded, highly fractured blocks containing various members of the Moenkopi and Kaibab Formations along the Hurricane fault.

TRmPt

Moenkopi, Kaibab, and Toroweap Formations, undivided (Lower Triassic to Lower Permian) – Fault-bounded, highly fractured blocks containing various members of the Moenkopi, Kaibab, and Toroweap Formations along the Grand Wash fault.

PERMIAN

Pkq **Kaibab Formation, Toroweap Formation, and Queantoweap Sandstone, undivided** (Lower Permian, Leonardian to Wolfcampanian) – Fault-bounded, highly fractured blocks of Kaibab, Toroweap, and Queantoweap strata along the Hurricane fault.

Pkt **Kaibab and Toroweap Formations, undivided** (Lower Permian, Leonardian) – Fault-bounded, highly fractured blocks of Kaibab and Toroweap strata along the Hurricane fault.

Kaibab Formation

Pk **Kaibab Formation** (Lower Permian, Leonardian) – Fault-bounded, highly fractured blocks of the Harrisburg and Fossil Mountain Members along the Hurricane fault.

Pkh **Harrisburg Member** (Lower Permian, Leonardian) – Thin- to thick-bedded limestone and cherty limestone, and medium- to thick-bedded, laminated gypsum and gypsiferous mudstone; gypsum abundance increases markedly westward from the Hurricane Cliffs, where it is uncommon, to the Beaver Dam Mountains, where it makes up about one-half of the member; characterized by wavy, irregular bedding likely due to gypsum dissolution; forms ledgy slopes that enclose a resistant, cliff- and ledge-forming medial white chert and limestone interval; Late Permian to Early Triassic subaerial erosion created significant paleotopography on the Kaibab Formation, with channels commonly several tens of feet deep but locally several hundred feet deep; unconformably overlain by river-channel and breccia deposits of the Rock Canyon Conglomerate at the deepest levels of incision, and locally by the Timpoweap, lower red, or Virgin Limestone Members in former paleotopographic high areas; deposited in shallow-marine and sabkha environments (McKee, 1938; Nielson, 1981, 1986; Sorauf and Billingsley, 1991); the contact of the Harrisburg Member and basal Moenkopi Formation is locally difficult to identify (Biek, 2003b) and the uppermost Harrisburg Member as mapped by Billingsley and Workman (2000) apparently contains strata we assign to the Rock Canyon and Timpoweap Members of the Moenkopi Formation; ranges from 0 to 350 feet (100 m) thick due to erosion associated with the Permian-Triassic unconformity (Nielson, 1981).

Pkf **Fossil Mountain Member** (Lower Permian, Leonardian) – Lithologically uniform, light-gray, thick-bedded, fossiliferous limestone and cherty limestone; fossils are whole

brachiopods, broken bryozoans, and disarticulated crinoids; “black-banded” due to abundant reddish-brown, brown, and black ribbon chert and irregular chert nodules that locally make up 20 to 40 percent of the rock; forms a prominent cliff in the Hurricane Cliffs and Beaver Dam Mountains; upper conformable contact with Harrisburg strata corresponds to a sharp break in slope with gypsiferous mudstone above and limestone cliff below; deposited in a shallow-marine environment (McKee, 1938; Nielson, 1981, 1986; Sorauf and Billingsley, 1991); maintains a fairly uniform thickness of about 200 to 300 feet (60-90 m) (Nielson, 1981).

P-k unconformity (Blakey, 1996)

Toroweap Formation

Pt **Toroweap Formation** (Lower Permian, Leonardian) – Fault-bounded, highly fractured blocks of the Woods Ranch, Brady Canyon, and Seligman Members in the Beaver Dam Mountains and along the Hurricane fault in the Kolob Canyons area.

Ptw **Woods Ranch Member** (Lower Permian, Leonardian) – Laterally variable, interbedded, yellowish-gray to light-gray, laminated to thin-bedded dolomite and similarly bedded black chert, massive gypsum, yellowish-orange gypsiferous mudstone and siltstone, and limestone; forms slopes and strike valleys and so is typically poorly exposed, but contains three principal gypsum beds in the Virgin River Gorge, each 20 to 50 feet (6-15 m) thick (Hintze, 1986); contains local intraformational conglomerate and collapse breccia in Hurricane Cliff exposures; eastern exposures in the Hurricane Cliffs contain significantly more carbonate and lesser gypsum compared to exposures in the Beaver Dam Mountains and Virgin River Gorge; Nielson (1986) noted that much of the gypsum in the Beaver Dam Mountains is replaced by aragonite and calcite; upper contact with Fossil Mountain strata corresponds to a sharp break in slope with slope-forming, gypsiferous siltstone and thin limestone beds below and cliff-forming cherty limestone above – Billingsley and Workman (2000) described an unconformity with about 15 feet (4.5 m) of relief on this contact to the south; deposited in a complex sequence of shallow-marine and sabkha environments (McKee, 1938; Rawson and Turner-Peterson, 1979, 1980; Nielson, 1981, 1986); gypsum dissolution and structural complications account for a variable thickness of 65 to 870 feet (20-265 m) in the Beaver Dam Mountains (Hintze and Hammond, 1994; Hayden and others, 2005a) and about 120 to 320 feet (35-98 m) in the Hurricane Cliffs (Nielson, 1981).

Ptbs **Brady Canyon and Seligman Members, undivided** (Lower Permian, Leonardian) – **Brady Canyon Member**: lithologically uniform, light- to medium-gray, medium- to coarse-grained, thick-bedded, fossiliferous limestone and cherty limestone; fossils are broken brachiopods, bryozoans, and crinoids; ribbon chert and irregular chert nodules locally make up 30 to 40 percent of the rock; forms a prominent gray cliff, similar to that developed in Fossil Mountain strata, in the lower part of the Hurricane Cliffs and in the Beaver Dam Mountains; the base of the member is dolomitic in the Beaver Dam Mountains; upper contact with Woods Ranch strata corresponds to a sharp break in slope, with cliff-forming cherty limestone below and slope-forming, gypsiferous siltstone and

thin limestone beds above; deposited in a shallow-marine environment (McKee, 1938; Rawson and Turner-Peterson, 1979, 1980; Nielson, 1981, 1986); typically about 250 feet (75 m) thick in the Beaver Dam Mountains and about 160 to 250 feet (48-75 m) thick in the Hurricane Cliffs (Nielson, 1981). **Seligman Member**: forms slopes of yellowish-brown to grayish-orange, thin-bedded, planar-bedded, fine- to medium-grained sandstone and minor siltstone with brown-weathering nodular chert; contains gypsiferous siltstone and minor gypsum in the Beaver Dam Mountains and Virgin River Gorge, but Nielson (1986) noted that much of the gypsum is replaced by aragonite and calcite; upper contact with the Brady Canyon Member corresponds to a sharp break in slope, with slope-forming, thin-bedded sandstone below and cliff-forming cherty limestone above; deposited in shallow-marine and beach environments (McKee, 1938; Rawson and Turner-Peterson, 1979, 1980; Nielson, 1981, 1986); thickens westward from about 30 feet (9 m) in the Hurricane Cliffs to about 100 to 200 feet (30-60 m) in the Beaver Dam Mountains (Nielson, 1981).

Ptb **Brady Canyon Member** (Lower Permian, Leonardian) – As described above, but mapped separately in the Beaver Dam Mountains where outcrop pattern allows.

Pts **Seligman Member** (Lower Permian, Leonardian) – As described above, but mapped separately in the Beaver Dam Mountains where outcrop pattern allows.

P-tw unconformity (Blakey, 1996)

Pq **Queantoweap Sandstone** (Lower Permian, Leonardian to Wolfcampanian) – Yellowish-brown, pale-orange, and grayish-orange, thick-bedded, cross-bedded, fine- to medium-grained sandstone that weathers to a conspicuous stair-step topography; forms the bulk of the Hurricane Cliffs near Pintura, where it is typically noncalcareous quartz arenite, and it is also exposed in the Beaver Dam Mountains, Virgin River Gorge, and Square Top Mountain where it has a calcareous cement; in the Hurricane Cliffs near Pintura, lower 120 feet (37 m) is slope-forming, brown-weathering, brownish-gray, thin- to medium-bedded, fine-grained sandy dolomite, calcareous sandstone, and silty sandstone that is locally vuggy-weathering; upper half stratigraphically equivalent to the Hermit Formation of northwest Arizona and southeast Nevada and the lower half is stratigraphically equivalent to the Esplanade Sandstone of northwest Arizona (Blakey, 1996; Billingsley, 1997); upper contact with the Seligman Member corresponds to a subtle break in slope, with ledge- and cliff-forming cross-bedded sandstone below and slope- and ledge-forming, planar-bedded sandstone and gypsiferous, sandy siltstone above; deposited in shallow-marine, beach, and dune environments (Nielson, 1981; Johansen, 1988); age from Blakey (1996); about 1400 to 2000 feet (425-600 m) thick in the Beaver Dam Mountains (Hintze and Hammond, 1994; Hintze and others, 1994), and about 1400 to 1700 feet (425-520 m) thick in the Hurricane Cliffs just south of Pintura (Hurlow and Biek, 2003).

Pp **Pakoon Formation** (Lower Permian, Wolfcampanian) – Light- to medium-gray, thin- to thick-bedded dolomite, dolomitic limestone, and minor limestone, all with yellowish-

brown-weathering, light-gray to white, irregularly shaped chert nodules; in the Beaver Dam Mountains, the upper 60 feet (18 m) is mostly gypsum with minor limestone and sandstone; contains sparse macrofossils, including bryozoans, fusilinids, and crinoid columnals, especially in thin limestone beds in the upper part; weathers to low ledges and slopes; stratigraphically equivalent to the lower Esplanade Sandstone of northwest Arizona (Blakey, 1996; Billingsley, 1997) and to the upper part of the Bird Spring Formation of southeast Nevada (Hintze and Axen, 1995); in the Beaver Dam Mountains, upper contact is gradational and corresponds to the top of the gypsiferous interval above which is yellowish-brown, cross-bedded sandstone, whereas at Black Ridge, this same contact appears sharp and corresponds to the first appearance of thin-bedded, yellowish-brown-weathering sandy dolomite; deposited in a shallow-marine environment (McNair, 1951); 600 to 850 feet (180-260 m) thick in the Beaver Dam and southern Bull Valley Mountains (Hintze and Hammond, 1994; Hintze and others, 1994).

P-0 disconformity (Blakey, 1996)

PERMIAN and PENNSYLVANIAN

PIPpc **Pakoon and Callville Formations, undivided** (Lower Permian to Lower Pennsylvanian) – Locally undivided near Beaver Dam Wash in the Beaver Dam Mountains.

PIPbs **Bird Spring Formation** (Lower Permian to Pennsylvanian) – Mapped only west of Beaver Dam Wash, where strata equivalent to the Pakoon and Callville Formations are collectively known as the Bird Spring Formation; unit description after Hintze and Axen (1995); cyclically interbedded limestone and cherty limestone, dolomite, and sandstone; fossils include brachiopods, corals, and bryozoan and crinoid debris; formation is mostly limestone in its lower part and becomes more dolomitic in its upper part; forms distinctive ledge-slope topography; upper contact is gradational and placed at the top of the uppermost carbonate bed; deposited in a shallow-marine environment (Rich, 1963); estimated thickness of 2000 feet (600 m) may be high due to unmapped faults that repeat parts of the formation.

PENNSYLVANIAN

IPc **Callville Limestone** (Upper to Lower Pennsylvanian, Virgilian to Morrowan) – Medium-gray, fine- to medium-grained, medium- to thick-bedded limestone with cyclic interbeds of moderate-orange-pink calcareous siltstone, sandstone, and light-gray dolomite increasing in the upper third; commonly cherty and fossiliferous; *Chaetetes* coral is common in the upper part, whereas brachiopods and bryozoans are common in limestone beds throughout (Hintze, 1986); forms ledge-slope topography in the Beaver Dam Mountains and at Square Top Mountain, similar to the overlying Pakoon Dolomite; stratigraphically equivalent to the lower part of the Bird Spring Formation of southeast Nevada (Hintze and Axen, 1995); upper contact is placed at the base of the lighter-colored, non-fossiliferous dolomite beds of the Pakoon Dolomite; represents shallow-marine deposits (Welsh and Bissell, 1979); age from Welsh and Bissell (1979); about 1500 to 2000 feet (460-600 m) thick in the Beaver Dam and southern Bull Valley Mountains (Hammond, 1991; Hintze and Hammond, 1994; Hintze and others, 1994).

unconformity

MISSISSIPPIAN

Mr **Redwall Limestone** (Lower Mississippian) – Divided into four members in the Grand Canyon by McKee (1963; see also McGee and Gutschick, 1969), in descending order the Horseshoe Mesa, Mooney Falls, Thunder Springs, and the Whitmore Wash Members, which Steed (1980) described but did not map in the Virgin River Gorge, and that remains undivided in the Beaver Dam Mountains (Hintze, 1986); known as the Monte Cristo Limestone in the Basin and Range (Hewitt, 1931), with its Yellowpine and Arrowhead Members (Horseshoe Mesa lithologic equivalent), Bullion Member (Mooney Falls lithologic equivalent), Anchor Member (Thunder Springs lithologic equivalent), and Dawn Member (Whitmore Wash lithologic equivalent); typically forms a single uniform cliff of medium- to dark-gray, thick-bedded, locally cherty and fossiliferous limestone; in the Beaver Dam Mountains, the basal 60 feet (18 m) is coarse-grained and dolomitic, above which is an 80-foot-thick (25 m), dark-yellowish-brown weathering, thin-bedded, cherty, bioclastic limestone – likely the Thunder Springs Member – that forms a prominent marker horizon; upper 460 feet (140 m) is bioclastic and fossiliferous, containing horn corals, colonial corals, and brachiopods (Hintze, 1985a; Hayden and others, 2005a); upper contact corresponds to a prominent break in slope, with massive Redwall Limestone cliffs below and cyclic, ledgy slopes above; forms many of the gravity slide blocks west of the Beaver Dam Mountains; deposited on a gently sloping shallow-marine shelf as two transgressive (Whitmore Wash and Mooney Falls Members) and two regressive (Thunder Springs and Horseshoe Mesa Members) sequences (McKee and Gutschick, 1969); ranges between 615 feet (188 m) thick in the Virgin River Gorge (Steed, 1980) to about 850 feet (260 m) thick at Horse Canyon in the West Mountain Peak quadrangle (Hintze, 1986).

Mm **Monte Cristo Limestone** (Lower Mississippian) – Mapped only west of Beaver Dam Wash, where strata equivalent to the Redwall Limestone are known as the Monte Cristo Limestone (Hintze and Axen, 1995); thick-bedded, light-gray limestone and cherty limestone; about 1000 feet (300 m) thick.

DEVONIAN

Dm **Muddy Peak Dolomite** (Upper Devonian) – Consists of two informal units (Hintze, 1985b; 1986) not mapped separately: (1) upper, “pinnacle” unit is light- to medium-gray, medium- to coarse-grained, thick-bedded dolomite with sandy laminae and scattered chert nodules that weathers to form light-gray pinnacles below the massive Redwall Limestone cliffs; (2) lower, “slope” unit, is light-olive-gray to pale-yellowish-gray, fine-grained, thin- to medium-bedded, silty dolomite with ledge-forming sandstone beds near the top, which weathers to a ledgy-slope between more resistant Nopah and pinnacle dolomites; “slope” unit includes small, silicified, stromatoporoid-like structures as well as rare biohermal mounds that include crinoid debris and scattered coral, gastropod, and brachiopod fragments (Hintze, 1985b); collectively equivalent to the Temple Butte Formation as exposed in the Virgin Mountains (Beus, 1980; Billingsley and Workman,

2000); deposited in a shallow-marine environment (Beus, 1980); “pinnacle” unit is 140 to 190 feet (45-55 m) thick, whereas “slope” unit is 300 to 450 feet (90-135 m) thick (Hayden and others, 2005a); Hammond (1991) reported a thickness of 680 feet (207 m) for the entire formation in the Shivwits quadrangle.

unconformity

CAMBRIAN

Cn **Nopah Dolomite** (Upper Cambrian) – Light-gray to brownish-gray, fine- to medium-grained, generally thick-bedded dolomite; contains algal stromatolites in upper part, small tubular trace fossils (twiggy bodies), and mottled zones that suggest bioturbation during deposition in a warm shallow-marine environment (Hintze, 1986); thin, slope-forming, orangish- to greenish-gray, glauconitic silty dolomite or limestone unit at the base of the Nopah may correspond to the Dunderberg Shale of southern Nevada (Hintze, 1986); similar to Bonanza King Formation, but except for lowest part is more massive and forms steeper ledges and cliffs; upper contact is a major regional unconformity and corresponds to the base of the more gentle slope of the “slope” unit of the Devonian Muddy Peak Dolomite; about 1300 feet (400 m) thick (Hintze, 1985b, 1986; Hayden and others, 2005a).

Cbk **Bonanza King Formation** (Upper and Middle Cambrian) – Medium- to light-brownish-gray, fine- to medium-grained, medium- to thick-bedded dolomite with some bluish-gray silty limestone beds in the lower part (Hintze, 1986); upper half consists of numerous thin beds of light-gray, fine-grained boundstone (Hintze, 1985b; Hammond, 1991); commonly mottled light and medium gray, and typically forms banded light- and dark-gray ledges and cliffs; commonly pervasively brecciated; olive-gray, slope-forming argillaceous limestone near base may be equivalent to the Chisholm Shale of the Pioche, Nevada, area (Hintze, 1985b; 1986); upper contact with the more massive, ledge- and cliff-forming Nopah Dolomite is marked by a thin slope-forming interval; equivalent to the Mauv Limestone of the Grand Canyon region and so mapped on the adjacent Littlefield 30’ x 60’ quadrangle (Billingsley and Workman, 2000), but similarity to equivalent strata in southern Nevada led Hintze (1986) to use the miogeoclinal nomenclature of Bonanza King; 2600 feet (800 m) thick (Hintze and Hammond, 1994; Hayden and others, 2005a) along the north side of Horse Canyon in the West Mountain Peak quadrangle, but the base may not be exposed due to attenuation faulting.

Cba **Bright Angel Shale** (Middle to Lower Cambrian) – Olive-green, slope-forming, micaceous shale, siltstone, and fine-grained quartzose sandstone; contains a ledge-forming, pale-brown-weathering, 10-foot-thick (3 m) dolomite about 125 feet (38 m) above the base and a 6-inch-thick (15 cm) limestone bed about 50 feet (15 m) below the top; weathers to strike valleys, and commonly thinned or absent due to attenuation faulting; upper contact is gradational and drawn at the base of the limestone ledges of the Bonanza King Formation; stratigraphically equivalent to the Pioche Shale, Lyndon Limestone, and Chisolm Shale of the Pioche, Nevada, area (Page and others, 2005);

deposited in shallow-marine environment (Stewart, 1970); 250 to 350 feet (75-100 m) thick (Hayden and others, 2005a).

Ct **Tapeats Quartzite** (Lower Cambrian) – Dark-reddish-orange to pale-reddish-brown, thin- to thick-bedded, medium- to coarse-grained orthoquartzite with a few thin beds of gritstone and quartz-pebble conglomerate; forms ledges; upper contact is gradational where the quartzite gives way to the shale and siltstone of the Bright Angel Shale; deposited in sandy intertidal and nearshore environments as the coarse-grained facies of the transgressing Cambrian sea (McKee, 1945; Hereford, 1977); 1300 feet (400 m) thick in the northern and eastern Beaver Dam Mountains (Hammond, 1991; Hintze and Hammond, 1994), but, due to attenuation faulting, only about 600 feet (180 m) thick south and west of West Mountain Peak.

Great Unconformity

PRECAMBRIAN

Xu **Gneiss, schist, and pegmatite** (Early Proterozoic) – Dark-gray dioritic gneiss and lesser schist cut by pegmatite sills and dikes; these rocks are also exposed in the Virgin Mountains of northwest Arizona where Moore (1972) reported a complex assemblage of garnet-biotite gneiss, garnet-sillimanite-biotite schist, granite gneiss, granodiorite gneiss, and amphibolite; forms the exposed core of the Beaver Dam Mountains of Utah, with dioritic gneiss the most resistant and most extensively exposed rock type (Hintze, 1985a, b; 1986; Hayden and others, 2005b); granitic pegmatites are common and intrude both gneiss and schist, principally parallel to foliation; less common, white pegmatites composed principally of orthoclase and quartz with minor muscovite mica, plagioclase, and garnet commonly exhibit graphic granite texture (Hintze, 1986); upper contact is an unconformity of approximately 1.2 billion years, referred to in the Grand Canyon region as the "Great Unconformity"; age not determined, but King (1976) compared these rocks to the Vishnu and Brahma schists of the Grand Canyon, which are Middle Proterozoic in age; a pegmatite in similar Precambrian rocks in the nearby East Mormon Mountains, Nevada, yielded a 1.7 billion-year K-Ar age (Olmore, 1971); Karlstrom and Bowring (1993) and Karlstrom and others (2005) considered these rocks Early Proterozoic in age and part of the Mojave Province; Quigley and others (2002) considered similar rocks in the North Virgin Mountains as Early Proterozoic.

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REFERENCES

Adair, D.H., 1986, Structural setting of the Goldstrike district, 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. 129-135.

Anders, M.H., Aharonov, Einat, and Walsh, J.J., 2000, Stratified granular media beneath large slide blocks – implications for mode of emplacement: Geology, v. 28, no. 11, p. 971-974.

Anders, M.H., Walsh, J.J., and Christie-Blick, Nicholas, 1998, Fluidization events in detachment zones – evidence for catastrophic emplacement of large slide blocks: Geological Society of America Abstracts with Programs, v. 30, no. 5, p. 3.

Anderson, J.J., and Rowley, P.D., 1975, Cenozoic stratigraphy of the southwestern High Plateaus of Utah, *in* Anderson, J.J., Rowley, P.D., Fleck, R.J., and Nairn, A.E.M., Cenozoic geology of southwestern High Plateaus of Utah: Geological Society of America Special Paper 160, p. 1-52.

Anderson, R.E., and Hintze, L.F., 1993, Geologic map of the Dodge Spring quadrangle, Washington County, Utah, and Lincoln County, Nevada: U.S. Geological Survey Geological Quadrangle Map GQ-1721, 2 plates, scale 1:24,000.

Anderson, R.E., and Mehnert, H.H., 1979, Reinterpretation of the history of the Hurricane fault in Utah, *in* Newman, G.W., and Goode, H.D., editors, 1979 Basin and Range Symposium: Rocky Mountain Association of Geologists and Utah Geological Association, p. 145-165.

Averitt, Paul, 1962, Geology and coal resources of the Cedar Mountain quadrangle, Iron County, Utah: U.S. Geological Survey Professional Paper 389, 71 p., 3 plates, scale 1:24,000.

—1964, Table of post-Cretaceous geologic events along the Hurricane fault near Cedar City, Iron County, Utah: Geological Society of America Bulletin, v. 75, p. 901-908.

—1967, Geologic map of the Kanarraville quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-694, 1 plate, scale 1:24,000.

Barker, D.S., 1995, Crystallization and alteration of quartz monzonite, Iron Springs mining district, Utah—relation to associated iron deposits: Economic Geology, v. 90, p. 2197-2217.

Beitler, Brenda, Chan, M.A., and Parry, W.T., 2003, Bleaching of Jurassic Navajo Sandstone on Colorado Plateau Laramide highs – evidence of exhumed hydrocarbon supergiants?: Geology, v. 31, no. 12, p. 1041-1044.

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 Geological Society Guidebook to the Geology of Utah no. 23, p. 57-74.

—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., Christiansen, E.H., and Blank, R.H., Jr., 1989a, Oligocene caldera complex and calc-alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and Utah: Geological Society of America Bulletin, v. 101, p. 1076-1090.

Best, M.G., Christiansen, E.H., Deino, A.L., Gromme, C.S., McKee, E.H., and Noble, D.C., 1989b, Excursion 3A—Eocene through Miocene volcanism in the Great Basin of the western United States: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 91-133.

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.

Best, M.G., Scott, R.B., Rowley, P.D., Swadley, W.C., Anderson, R.E., Gromme, C.S., Harding, A.E., Deino, A.L., Christiansen, E.H., Tingey, D.G., and Sullivan, K.R., 1993,

Oligocene-Miocene caldera complexes, ash-flow sheets, and tectonism in the central and southeastern Great Basin, *in* Lahren, M.M., Trexler, J.H., Jr., and Spinosa, Claude, editors, Crustal evolution of the Great Basin and Sierra Nevada: Field trip guide, Geological Society of America, Cordilleran and Rocky Mountain Sections Meeting, p. 285-311.

Beus, S.S., 1980, Late Devonian (Frasnian) paleogeography and paleoenvironments in northern Arizona, *in* Fouch, T.D., and Magathan, E.R., editors, Paleozoic paleogeography of the west-central United States, Rocky Mountain Symposium 1: Denver, Colorado, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 55-69.

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

—2003b, Geologic map of the Hurricane quadrangle, Washington County, Utah: Utah Geological Survey Map 187, 61 p., 2 plates, scale 1:24,000.

—in preparation(a), Geologic map of the Kolob Arch quadrangle, Washington and Iron Counties, Utah: Utah Geological Survey Map 225, 3 plates, scale 1:24,000.

—in preparation(b), Geologic map of the Kolob Reservoir quadrangle, Washington and Iron Counties, Utah: Utah Geological Survey Map 220, 2 plates, scale 1:24,000.

Biek, R.F., and Hylland, M.D., in preparation, Geologic map of the Cogswell Point quadrangle, Washington, Kane, and Iron Counties, Utah: Utah Geological Survey Map 221, 2 plates, scale 1:24,000.

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., Willis, G.C., Hylland, M.D., and Doelling, H.H., 2003, Geology of Zion National Park, Utah, *in* Sprinkel, D.A., Chidsey, T.C., and Anderson, P.B., editors, Geology of Utah's parks and monuments: Utah Geological Association and Bryce Canyon Natural History Association, Utah Geological Association Publication 28, Second Edition, p. 107-137.

Billingsley, G.H., 1990a, Geologic map of the Purgatory Canyon quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 90-540, scale 1:24,000.

—1990b, Geologic map of the Lizard Point quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 90-643, scale 1:24,000.

—1992a, Geologic map of the Yellowhorse Flat quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 92-442, 17 p., scale 1:24,000.

—1992b, Geologic map of the Rock Canyon quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 92-449, 17 p., scale 1:24,000.

—1993a, Geologic map of the Lost Spring Mountain West quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 93-566, 11 p., scale 1:24,000.

—1993b, Geologic map of the Lost Spring Mountain East quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 93-565, 9 p., scale 1:24,000.

—1995, Geologic map of the Littlefield quadrangle, northern Mohave County, Arizona: U.S. Geological Survey Open-File Report 95-559, 15 p., scale 1:24,000.

—1997, The Permian clastic sedimentary rocks of northwestern Arizona: U.S. Geological Survey Bulletin 2153-F, p. 108-124.

Billingsley, G.H., and Workman, J.B., 2000, Geologic map of the Littlefield 30' x 60' quadrangle, Mohave County, northwestern Arizona: U.S. Geological Survey Geologic Investigations Series Map I-2628, Version 1.0, 25 p., 2 plates, scale 1:100,000.

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.

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.

—1996, Permian eolian deposits, sequences, and sequence boundaries, Colorado Plateau, *in* Longman, M.W., and Sonnenfeld, M.D., editors, Paleozoic systems of the Rocky Mountain region: Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 405-426.

Blakey, R.C., Peterson, Fred, Caputo, M.V., Geesman, R.C., and Voorhees, B.J., 1983, Paleogeography of Middle Jurassic continental, shoreline, and shallow marine sedimentation, southern Utah, *in* Reynolds, M.W., and Dolley, E.D., editors, Mesozoic paleogeography of west-central United States: Denver, Colorado, Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, p. 77-100.

Blank, H.R., Jr., 1959, Geology of the Bull Valley district, Washington County, Utah: Seattle, Washington, University of Washington, unpublished Ph.D. dissertation, 177 p.

—1993, Preliminary geologic map of the Enterprise quadrangle, Washington and Iron Counties, Utah: U.S. Geological Survey Open-File Report 93-203, scale 1:24,000.

Blank, H.R., Jr., and Mackin, J.H., 1967, Geologic interpretation of an aeromagnetic survey of the Iron Springs district, Utah: U.S. Geological Survey Professional Paper 516-B, 14 p.

Blank, H.R., Rowley, P.D, and Hacker, D.B., 1992, Miocene monzonite intrusions and associated megabreccias of the Iron Axis region, southwestern Utah, *in* Wilson, J.R., editor, Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Geological Society of America, Rocky Mountain section meeting: Utah Geological Survey Miscellaneous Publication 92-3, p. 399-420.

Bohannon, R.G., 1984, Nonmarine sedimentary rocks of Tertiary age in the Lake Mead region, southeastern Nevada and northwestern Arizona: U.S. Geological Survey Professional Paper 1259, 1 plate, 72 p.

Bohannon, R.G., Grow, J.A., Miller, J.J., and Blank, R.H., Jr., 1993, Seismic stratigraphy and tectonic development of Virgin River depression and associated basins, southeastern Nevada and northwestern Arizona: Geological Society of America Bulletin, v. 105, p. 501-520.

Bohannon, R.G., Lucchitta, Ivo, and Anderson, R.E., 1991, Geologic map of the Mountain Sheep Spring quadrangle, Mohave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-2265, scale 1:24,000.

Bullock, K.C., 1970, Iron deposits of Utah: Utah Geological and Mineralogical Survey Bulletin 88, 101 p.

Carpenter, J.A., and Carpenter, D.G., 1994, Analysis of Basin-Range and Fold-Thrust structure, and reinterpretation of the Mormon Peak detachment and similar features as gravity slide systems, southern Nevada, southwest Utah and northwest Arizona, *in* Dobbs, S.W., and Taylor, W.J., editors, Structural and stratigraphic investigations and petroleum potential of Nevada, with special emphasis south of the Railroad Valley producing trend: Nevada Petroleum Society Conference Volume II, p. 15-52.

Christiansen, R.L., and Lipman, P.W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States—II. Late Cenozoic: Royal Society of London Philosophical Transactions (A), v. 271, p. 249-284.

Clemmensen, L.B., Olsen, Henrik, 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 Resource Laboratory, unnumbered, 104 p.

Cook, E.F., 1957, Geology of the Pine Valley Mountains, Utah: Utah Geological and Mineralogical Survey Bulletin 58, 111 p.

—1960a, Breccia blocks (Mississippian) of the Welcome Spring area, southwestern Utah: Geological Society of America Bulletin, v. 71, p. 1709-1712.

—1960b, Geologic atlas of Utah, Washington County: Utah Geological and Mineralogical Survey Bulletin 70, 119 p., scale 1:125,000.

Cook, K.L., and Hardman, Elwood, 1967, Regional gravity survey of the Hurricane fault area and Iron Springs district, Utah: Geological Society of America Bulletin, v. 78, p. 1063-1076.

Cornell, D., Butler, T., Holm, D., Hacker, D., and Spell, T., 2001, Stratigraphy and Ar/Ar ages of volcanic rocks of the Pinto quadrangle, Colorado Plateau transition zone, SW Utah (abs.), *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 420-421.

DeCourten, Frank, 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.

Dixon, G.L., and Katzer, Terry, 2002, Geology and hydrology of the lower Virgin River Valley in Nevada, Arizona, and Utah: Mesquite, Nevada, Virgin Valley Water District, Report VVWD-01, 126 p.

Doelling, H.H., 1999, Interim geologic map of the Kanab 30x60 quadrangle, Kane and Washington Counties, Utah, and Coconino and Mohave Counties, Arizona: Utah Geological Survey Open-File Report, 366, 11 p., 1 plate, scale 1:100,000.

—2002, Interim geologic map of the Temple of Sinawava quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 396, 15 p., scale 1:24,000.

Doelling, H.H., and Davis, F.D., 1989, The geology of Kane County, Utah – geology, mineral resources, geologic hazards: Utah Geological and Mineral Survey Bulletin 124, 192 p., 10 plates, scale 1:100,000.

Doelling, H.H., and Graham, R.L., 1972, Southwestern Utah coal fields – Alton, Kaiparowits Plateau, and Kolob-Harmony: Utah Geological and Mineral Survey Monograph Series 1, 333 p.

Doelling, H.H., Willis, G.C., Solomon, B.J., Sable, E.G., Hamilton, W.L., and Naylor, L.P., II, 2002, Interim geologic map of the Springdale East quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 393, 20 p., scale 1:24,000.

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, paleogeography, 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: Denver, Colorado, Rocky Mountain Section of Society of Economic Paleontologists and Mineralogists, p. 133-168.

Dyman, T.S., Cobban, W.A., Titus, Alan, Obradovich, J.D., Davis, L.E., Eves, R.L., Pollock, G.L., Takahashi, K.I., and Hester, T.C., 2002, New biostratigraphic and radiometric ages for Albian-Turonian Dakota Formation and Tropic Shale at Grand Staircase-Escalante National Monument and Iron Springs Formation near Cedar City, Parowan, and Gunlock, Utah: Geological Society of America Abstracts with Programs, v. , p. A-13.

Eaton, J.G., 1999, Vertebrate paleontology of the Iron Springs Formation, Upper Cretaceous, southwestern Utah, *in* Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 339-343.

Eaton, J.G., Kirkland, J.I., Hutchinson, J.H., Denton, Robert, O'Neill, R.C., and Parrish, J.M., 1997, Nonmarine extinction across the Cenomanian-Turonian (C-T) boundary, southwestern Utah, with a comparison to the Cretaceous-Tertiary extinction event: Geological Society of America Bulletin, v. 109, p. 560-567.

Eaton, J.G., Laurin, Jiri, Kirkland, J.I., Tibert, N.E., Leckie, R.M., Sageman, B.B., Goldstrand, P.M., Moore, D.W., Straub, A.W., Cobban, W.A., and Dalebout, J.D., 2001, Cretaceous and early Tertiary geology of Cedar and Parowan Canyons, western Markagunt Plateau, Utah, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 337-363.

Eliopulos, G.J., 1974, A geological evaluation of mineralization at Mineral Mountain, Washington County, Utah: Tucson, University of Arizona, M.S. thesis, 81 p.

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.

Farrell, J.M., and Pederson, J.L., 2001, Finding the pre-Grand Canyon Colorado River – petrology of the Muddy Creek Formation north of Lake Mead: Geological Society of America Abstracts with Programs, v. 33, no. 5, p. 13.

Fillmore, R.P., 1991, Tectonic influence on sedimentation in the southern Sevier foreland, Iron Springs Formation (Upper Cretaceous), southwestern Utah, *in* Nations, J.D., and Eaton, J.G., editors, Stratigraphy, depositional environments, and sedimentary tectonics of the western margin, Cretaceous Western Interior seaway: Geological Society of America Special Paper 260, p. 9-25.

Fleck, R.J., Anderson, J.J., and Rowley, P.D., 1975, Chronology of mid-Tertiary volcanism in High Plateaus region of Utah, *in* Anderson, J.J., Rowley, P.D., Fleck, R.J., and Nairn, A.E.M., editors, Cenozoic geology of southwestern High Plateaus of Utah: Geological Society of America Special Paper 160, p. 53-62.

Glen, William, 1982, The road to Jamarillo – critical years of the revolution in earth science: Stanford, California, Stanford University Press, 459 p.

Goldstrand, P.M., 1992, Evolution of Late Cretaceous and early Tertiary basins of southwest Utah based on clastic petrology: Journal of Sedimentary Petrology, v. 62, no. 3, p. 495-507.

—1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, p. 145-154.

Grant, S.K., 1995, Geologic map of the New Harmony quadrangle, Washington County, Utah: Utah Geological Survey Miscellaneous Publication 95-2, 14 p., 2 plates, scale 1:24,000.

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

Gustason, E.R., 1989, Stratigraphy and sedimentology of the middle Cretaceous (Albian-Cenomanian) Dakota Formation, southwestern Utah: Boulder, Colorado, University of Colorado, Ph.D. dissertation, 376 p.

Hacker, D.B., 1998, Catastrophic gravity sliding and volcanism associated with the growth of laccoliths – examples from early Miocene hypabyssal intrusions of the Iron Axis

magmatic province, Pine Valley Mountains, southwestern Utah: Kent, Ohio, Kent State University, Ph.D. dissertation, 5 plates, 258 p.

Hacker, D.B., Holm, D.K., Rowley, P.D., and Blank, H.R., 2002, Associated Miocene laccoliths, gravity slides, and volcanic rocks, Pine Valley Mountains and Iron Axis region, 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 OF 02-0172, p. 235-283.

Hacker, D.B., Rowley, P.D., Blank, H.R., and Snee, L.W., 1996, Deformational structures related to the emplacement and growth of the Pine Valley laccolith, southern Iron Axis region, Washington County, Utah [abs.]: Eos Transactions, American Geophysical Union, v. 76, no. 46, p. 625.

Hacker, D.B., in preparation(a), Geologic map of the Central East quadrangle, Washington County, Utah: Utah Geological Survey Map, scale 1:24,000.

—in preparation(b), Geologic map of the Grass valley quadrangle, Washington County, Utah: Utah Geological Survey Map, scale 1:24,000.

—in preparation(c), Geologic map of the Saddle Mountain quadrangle, Washington County, Utah: Utah Geological Survey Map, scale 1:24,000.

—in preparation(d), Geologic map of the Signal Peak quadrangle, Washington County, Utah: Utah Geological Survey Map, scale 1:24,000.

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 – Transition between the Basin-Range and Colorado Plateau provinces: Salt Lake City, Intermountain Association of Petroleum Geologists 12th Annual Field Conference, p. 84-89.

—1970, 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.

—1987, Late Cenozoic volcanism in the St. George basin, Utah, *in* Beus, S.S., editor, Geological Society of America Centennial Field Guide – Volume 2, Rocky Mountain Section: Geological Society of America, p. 291-294.

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., 1978 (revised 1987), Geological map of Zion National Park, Utah: Zion Natural History Association, scale 1:31,680.

—1979, Holocene and Pleistocene lakes in Zion National Park, Utah, *in* Linn, R.M., editor, Proceedings of the First Conference on Scientific Research in the National Parks, 1977 New Orleans Conference: NPS-AIBS, DOI-NPS Transactions and Proceedings, ser. 5., p. 835-844.

—undated, Quaternary ponds and lakes in Zion National Park, Utah: unpublished 42-page report on file at the Zion National Park library.

—1995, The sculpturing of Zion: Springdale, Utah, Zion Natural History Association, 132 p.

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

Harding, A.E., Scott, R.B., Mehnert, H.H., and Snee, L.W., 1995, Evidence of the Kane Springs Wash caldera in the Meadow Valley Mountains, southeastern Nevada, *in* Scott, R.B., and Swadley, W C, editors, Geologic studies in the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 135-179.

Hatfield, S.C., 2001, Appendix B – geochemistry and petrology, *in* Lund, W.R., Pearthree, P.A., Amoroso, Lee, Hozik, M.J., and Hatfield, S.C., Paleoseismic investigation of earthquake hazard and long-term movement history of the Hurricane fault, southwestern Utah and northwestern Arizona – final technical report: National Earthquake Hazards Reduction Program, External Research, Program Element I, Panel NI, Award No. 99HQGR0026, p. B1-B13.

Hayden, J.M., 2004a, Geologic map of The Divide quadrangle, Washington County, Utah: Utah Geological Survey Map 197, 32 p., 2 plates, scale 1:24,000.

—2004b, Geologic map of Little Creek Mountain quadrangle, Washington County, Utah: Utah Geological Survey Map 204, 2 plates, scale 1:24,000.

—2005a, Geologic map of Washington Dome quadrangle, Washington County, Utah: Utah Geological Survey Map 209, 29 p., 2 plates, scale 1:24,000.

—2005b, Interim geologic map of the Virgin quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 442, 2 plates, scale 1:24,000.

Hayden, J.M., Hintze, L.F., and Ehler, J.B., 2005a, Interim geologic map of the West Mountain Peak quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 454, 1 plate, 20 p., scale 1:24,000.

Hayden, J.M., Hintze, L.F., and Ehler, J.B., 2005b, Interim geologic maps of the Castle Cliff and the east half of the Terry Benches quadrangles, Washington County, Utah: Utah Geological Survey Open-File Report 457 and 464, 2 plates, 16 p., scale 1:24,000.

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, Richard, 1977, Deposition of the Tapeats Sandstone (Cambrian) in central Arizona: Geological Society of America Bulletin, v. 88, p. 199-211.

Hesse, C.J., 1935, *Semionotus* cf *gigas* from the Triassic of Zion Park, Utah: American Journal of Science, 5th series, v. 29, p. 526-531.

Hewitt, D.F., 1931, Geology and ore deposits of the Goodsprings quadrangle, Nevada: U.S. Geological Survey Professional Paper, 162, 172 p.

Higgins, J.M., 1997, Interim geologic map of the White Hills quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 352, 94 p., 2 plates, scale 1:24,000.

—2002, Interim geologic map of the Veyo quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 401, 17 p., 1 plate, scale 1:24,000.

Higgins, J.M., and Willis, G.C., 1995, Interim geologic map of the St. George quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 323, 108 p., 2 pl., 1:24,000.

Hintze, L.F., 1985a, Geologic map of the Castle Cliffs and Jarvis Peak quadrangles, Washington County, Utah: U.S. Geological Survey Open-File Report 85-120, 19 p., scale 1:24,000.

—1985b, Geologic map of the Shivwits and West Mountain Peak quadrangles, Washington County, Utah: U.S. Geological Survey Open-File Report 85-119, 19 p., scale 1:24,000.

—1986, Stratigraphy and structure of the Beaver Dam Mountains, southwestern Utah, *in* Griffin, 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., Anderson, R.E., and Embree, G.F., 1994, Geologic map of the Motoqua and Gunlock quadrangles, Washington County, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2427, 7 p., scale 1:24,000.

Hintze, L.F., and Axen, G.J., 1995, Geologic map of the Scarecrow Peak quadrangle, Washington County, Utah, and Lincoln County, Nevada: U.S. Geological Survey Geological Quadrangle Map GQ-1759, 2 plates, scale 1:24,000.

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.

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, various scales.

Hurlow, H.A., and Biek, R.F., 2003, Geologic map of the Pintura quadrangle, Washington County, Utah: Utah Geological Survey Map 196, 20 p., 2 plates, scale 1:24,000.

Hylland, M.D., 2000, Interim geologic map of the Clear Creek Mountain quadrangle, Kane County, Utah: Utah Geological Survey Open-File Report 371, 12 p., 2 plates, scale 1:24,000.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.

Johansen, S.J., 1988, Origins of upper Paleozoic quartzose sandstones, American southwest: Sedimentary Geology, v. 56, p. 153-166.

Johnson, B.T., 1984, Depositional environments of the Iron Springs Formation, Gunlock, Utah: Brigham Young University Geology Studies, v. 31, pt. 1, p. 29-46.

Jones, R.W., 1963, Gravity structures in the Beaver Dam Mountains, southwestern Utah, *in* Heylmun, E.B., editor, Guidebook to the geology of southwestern Utah, transition between Basin-Range and Colorado Plateau Provinces: International Association of Petroleum Geologists Guidebook 12, p. 90-95.

Karlstrom, K.E., and Bowring, S.A., 1993, Proterozoic orogenic history of Arizona, *in* Reed, J.C., Jr., and others, editors, Precambrian – conterminous U.S.: Geological Society of America, The Geology of North America, v. C-2, p. 188-211.

Karlstrom, K.E., Whitmeyer, S.J., Dueker, Ken, Williams, M.L., Bowring, S.A., Levander, Alan, Humphreys, E.D., Keller, G.R., and the CD-ROM Working Group, 2005, Synthesis of results from the CD-ROM experiment – 4-D image of the lithosphere beneath the Rocky Mountains and implications for understanding the evolution of continental lithosphere, *in* Karlstrom, K.E., and Keller, G.R., editors, The Rocky Mountain region – an evolving lithosphere: Washington D.C., American Geophysical Union, Geophysical Monograph 154, p. 421-441.

King, P.B., 1976, Precambrian geology of the United States: as explanatory text to accompany the Geologic Map of the United States: U.S. Geological Survey Professional Paper 902, 85 p.

Kirkland, J.I., Britt, Brooks, Burge, D.L., Carpenter, Ken, Cifelli, Richard, Decourten, Frank, Eaton, Jeffrey, Hasiotis, Steve, and Lawton, Tim, 1997, Lower to middle Cretaceous dinosaur faunas of the central Colorado Plateau – a key to understanding 35 million years of tectonics, sedimentology, evolution and biogeography, *in* Link, P.K., and Kowallis, B.J., editors, Mesozoic to recent geology of Utah: Brigham Young University Geology Studies, v. 42, part 2, p. 69-103.

Kirkland, J.I., and Milner, A.R.C., in preparation, The Moenave Formation at the St. George Dinosaur Discovery Site at Johnson Farm, *in* Harris, J.D., editor, Tracking dinosaur origins – the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin.

Kocurek, G., and Dott, R.H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountains region, *in* Reynolds, M.W., and Dolley, E.D., editors, Mesozoic paleogeography of the west-central United States: Denver, Rocky Mountain Section Society of Economic Paleontologists and Mineralogists, p. 101-116.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Zhang, Chengning, and Everitt, 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.

Langenheim, V.E., Bohannon, R.G., Glen, J.M., Jachens, R.C., Grow, J.A., Miller, J.J., Dixon, G.L., and Katzer, T.C., 2001, Basin configuration of the Virgin River depression, Nevada, Utah, and Arizona – a geophysical view of deformation along the Colorado Plateau-Basin and Range transition, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin – a symposium and field guide: Utah Geological Association Publication 30 and Pacific Section American Association of Petroleum Geologists Publication GB78, p. 205-225.

Laurin, Jiri, and Sageman, B.B., 2001, Tectono–sedimentary evolution of the western margin of the Colorado Plateau during the latest Cenomanian and early Turonian, *in* Erskine, M.C., editor and Faulds, J.E., Bartley, J.M., and Rowley, P.D., co-editors, The geologic transition, High Plateaus to Great Basin – a symposium and field guide, The Mackin Volume: Utah Geological Association Publication 30 and Pacific Section American Association of Petroleum Geologists Publication GB 78, p. 57-74.

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.

Limbach, F.W., and Pansze, A.J., 1987, Volcanic geology and mineralization, western Bull Valley Mountains, Utah, *in* Kopp, R.S., Cohenour, R.E., editors, Cenozoic geology of western Utah—Sites for precious metal and hydrocarbon accumulations: Utah Geological Association Publication 16, p. 471-477.

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: Neues Jahrbuch fur Geologie und Paläontologie Mh., Stuttgart, Germany, v. 7, p. 435-448.

Lucas, S.G., Tanner, L.H., Heckert, A.B., and Hunt, A.P., 2005, Tetrapod biostratigraphy across the Triassic-Jurassic boundary on the southern Colorado Plateau, USA, *in* Tracking dinosaur origins, the Triassic/Jurassic terrestrial transition, abstracts volume, a conference held at Dixie State College, St. George, Utah, March 14-16, 2005, p. 16.

Lucas, S.G., and Tanner, L.H., in preparation, The Springdale Sandstone Member of the Kayenta Formation, Lower Jurassic of Utah-Arizona, *in* Harris, J.D., editor, Tracking dinosaur origins – the Triassic/Jurassic terrestrial transition: New Mexico Museum of Natural History and Science Bulletin.

Lund, W.R., Pearthree, P.A., Amoroso, Lee, Hozik, M.J., and Hatfield, S.C., 2001, Paleoseismic investigation of earthquake hazard and long-term movement history of the Hurricane fault, southwestern Utah and northwestern Arizona – final technical report: National Earthquake Hazards Reduction Program, External Research, Program Element I, Panel NI, Award No. 99HQGR0026, 120 p.

Lund, W.R., Taylor, W.J., Pearthree, P.A., Stenner, H.D., Amoroso, Lee, Hurlow, H.A., 2002, Structural development and paleoseismology of the Hurricane fault, southwestern Utah and northwestern Arizona, *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. 1-84.

Mackin, J.H., 1947, Some structural features of the intrusions in the Iron Springs district: Utah Geological Society Guidebook 2, 62 p.

—1954, Geology and iron deposits of the Granite Mountain area, Iron County, Utah: U.S. Geological Survey Mineral Investigations Field Studies Map MF-14, scale 1:12,000.

—1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: American Journal of Science, v. 258, no. 2, p. 81-131.

—1968, Iron ore deposits of the Iron Springs district, southwestern Utah, *in* Ridge, J.D., editor, Ore deposits of the United States, 1933-1967 (Graton-Sales volume): New York, American Institute of Mining and Metallurgical Petroleum Engineers, v. 2, p. 992-1019.

Mackin, J.H., and Ingerson, F.E., 1960, An hypothesis for the origin of ore-forming fluid: U.S. Geological Survey Professional Paper 400-B, p. B1-B2.

Mackin, J.H., Nelson, W.H., and Rowley, P.D., 1976, Geologic map of the Cedar City NW quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1295, scale 1:24,000.

Mackin, J.H., and Rowley, P.D., 1976, Geologic map of The Three Peaks quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1297, scale 1:24,000.

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.

Mattison, G.D., 1972, The chemistry, mineralogy, and petrography of the Pine Valley Mountains, southwestern Utah: College Station, Pennsylvania, The Pennsylvania State University, Ph.D. dissertation, 141 p.

McKee, E.D., 1938, The environment and history of the Toroweap and Kaibab Formations of northern Arizona and southern Utah: Carnegie Institute of Washington Publication 492, 268 p.

—1945, Stratigraphy and ecology of the Grand Canyon Cambrian, part 1 of Cambrian history of the Grand Canyon region: Carnegie Institution Washington Publication 563, p. 3-168.

—1963, Nomenclature for lithologic subdivisions of the Mississippian Redwall Limestone, Arizona: U.S. Geological Survey Professional Paper 475-C, p. C21-C22.

McKee, E.H., Blank, H.R., and Rowley, P.D., 1997, Potassium-argon ages of Tertiary igneous rocks in the eastern Bull Valley Mountains and Pine Valley Mountains, southwestern Utah, *in* Maldonado, Florian, and Nealey, L.D., editors, Geologic studies in the Basin and Range-Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 243-252.

McKee, E.D., and Gutsckick, R.C., 1969, History of the Redwall Limestone of northern Arizona, with chapters on paleontology of the Redwall Limestone by Betty Skipp, W.J. Sando, Helen Duncan, E.L. Yochelson, W.M. Furnish, D.B. Macurda, Jr., and J.C. Brower: Geological Society of America Memoir 114, 726 p.

McNair, A.H., 1951, Paleozoic stratigraphy of part of northwestern Arizona: American Association of Petroleum Geologists Bulletin, v. 35, no. 3, p. 503-541.

Metcalf, L.A., 1982, Tephrostratigraphy and potassium-argon age determinations of seven volcanic ash layers in the Muddy Creek Formation of southern Nevada [M.S. thesis]: Reno, University of Nevada, 187 p.

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.

Moore, D.W., and Sable, E.G., 2001, Geologic map of the Smithsonian Butte quadrangle, Washington County, Utah and Mohave County, Arizona: Utah Geological Survey Miscellaneous Publication MP-01-01, 30 p., 2 plates, scale 1:24,000.

Moore, R.T., 1972, Geology of the Virgin and Beaver Dam Mountains, Arizona: Arizona Bureau of Mines Bulletin, 65 p.

Morris, S.K., 1980, Geology and ore deposits of Mineral Mountain, Washington County, Utah: Brigham Young University Studies in Geology, v. 27, pt. 2, p. 85-102.

Mullett, D.J., 1989, Interpreting the early Tertiary Claron Formation of southern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 120.

Mullett, D.J., Wells, N.A., and Anderson, J.J., 1988a, Early Cenozoic deposition in the Cedar-Bryce depocenter – certainities, uncertainities, and comparisons with other Flagstaff-Green River basins [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 3, p. 217.

—1988b, Unusually intense pedogenic modification of the Paleocene-Eocene Claron Formation of southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 5, p. 382.

New Mexico Geochronology Research Laboratory and Utah Geological Survey, 2006, $^{40}Ar/^{39}Ar$ geochronology results from Zion National Park (Cogswell Point, Kolob Arch, and Kolob Reservoir quadrangles), Utah: Utah Geological Survey Open-File Report 474, variously paginated.

Nichols, D.J., 1995, Palynology and ages of some Upper Cretaceous formations in the Markagunt and northwestern Kaiparowits Plateaus, southwestern Utah, *in* Maldonado, Florian, 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-E, p. 81-95.

Nielson, R.L., 1977, The geomorphic evolution of the Crater Hill volcanic field of Zion National Park: Brigham Young University Geology Studies, v. 24, part 1, 1 plate, scale 1:47,000, p. 55-70.

—1981, Depositional environment of the Toroweap and Kaibab Formations of southwestern Utah: Salt Lake City, University of Utah, Ph.D. dissertation, 495 p.

—1986, The Toroweap and Kaibab Formations, 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. 37-53.

—1991, Petrology, sedimentology and stratigraphic implications of the Rock Canyon Conglomerate, southwestern Utah: Utah Geological Survey Miscellaneous Publication 91-7, 65 p.

Nielson, R.L., and Johnson, J.L., 1979, The Timpoweap Member of the Moenkopi Formation, Timpoweap Canyon, Utah: Utah Geology, v. 6, no. 1, p. 17-27.

Olmore, S.D., 1971, Style an evolution of thrusts in the region of the Mormon Mountains, Nevada: Salt Lake City, University of Utah, Ph.D. dissertation, 7 plates, scale 1:24,000, 213 p.

Page, W.R., Lundstrom, S.C., Harris, A.G., Langenheim, V.E., Workman, J.B., Mahan, S.A., Paces, J.B., Rowley, P.D., Dixon, G.L., Burchfiel, B.C., Bell, J.W., and Smith, E.I., 2005, Geologic and geophysical maps of the Las Vegas 30’ x 60’ quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations Map 2814, scale 1:100,000.

Pederson, J.L., 1999, A long-term record of climate-controlled hillslope sedimentation: Albquerque, University of New Mexico Ph.D. dissertation, 235 p.

Peters, Lisa, 2002, $^{40}Ar/^{39}Ar$ geochronology results from the Veyo quadrangle and the Bull Valley Mountains: New Mexico Geochronology Research Laboratory internal report NMGRL-IR-284, 7 p., on file with the Utah Geological Survey.

—2006a, $^{40}Ar/^{39}Ar$ geochronology results: New Mexico Geochronology Research Laboratory internal report NMGRL-IR-470, 6 p., on file with the Utah Geological Survey.

—2006b, $^{40}Ar/^{39}Ar$ geochronology results from the Pine Valley Mountains: New Mexico Geochronology Research Laboratory internal report NMGRL-IR-482, 8 p., on file with the Utah Geological Survey.

Peterson, Fred, 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 Shirts, M.A., 1991, Silver, sinners and saints – a history of old Silver Reef, Utah: Provo, Utah, Paulmar, Inc., 224 p.

Quigley, M.C., Karlstrom, K.E., Beard, Sue, and Bohannon, Bob, 2002, Influence of Proterozoic and Laramide structures on the Miocene extensional strain field, North Virgin Mountains, Nevada/Arizona, *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. 86-104.

Rahl, J.M., Reiners, P.W., Campbell, I.H., Nicolescu, Stefan, 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.

Rawson, R.R., and Turner-Peterson, C.E., 1979, Marine-carbonate, sabkha, and eolian facies transitions within the Permian Toroweap Formation, northern Arizona, *in* Baars, D.L., editor, Permianland: Four Corners Geological Society Guidebook, 9th Field Conference, p. 87-99.

—1980, Paleogeography of northern Arizona during the deposition of the Permian Toroweap Formation, *in* Fouch, T.D., and Magathan, E.R., editors, Paleozoic paleogeography of the west-central United States, Rocky Mountain Symposium 1: Denver, Colorado, Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 341-352.

Reynolds, R.E., and Lindsay, E.H., 1999, Late Tertiary basins and vertebrate faunas along the Nevada-Utah border, *in* Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 469-478.

Rich, Mark, 1963, Petrographic analysis of Bird Spring Group (Carboniferous-Permian) near Lee Canyon, Clark County, Nevada: American Association of Petroleum Geologists Bulletin, v. 47, no. 9, p. 1657-1681.

Riggs, N.R., Mattinson, J.M., and Busby, C.J., 1993, Correlation of Jurassic eolian strata between the magmatic arc and the Colorado Plateau – new U-Pb geochronologic data from southern Arizona: Geological Society of America Bulletin, v. 105, p. 1231-1246.

Rogers, C.M., and Engelder, Terry, 2004, The feedback between joint-zone development and downward erosion of regularly spaced canyons in the Navajo Sandstone, Zion National Park, Utah, *in* Cosgrove, J.W., and Engelder, Terry, editors, The initiation, propagation, and arrest of joints and other fractures: Geological Society, London, Special Publications 231, p. 49-71.

Rogers, C.M., Meyers, D.A., and Engelder, Terry, 2004, Kinematic implications of joint zones and isolated joints in the Navajo Sandstone at Zion National Park, Utah – evidence for Cordilleran relaxation: Tectonics, TC1007, v. 23, p. 1-16, doi:1029/2001TC001329.

Rowley, P.D., 1998, Cenozoic transverse zones and igneous belts in the Great Basin, western United States – their tectonic and economic implications, *in* Faulds, J.E., and Stewart, J.H., editors, Accommodation zones and transfer zones--the regional segmentation of the Basin and Range province: Geological Society of America Special Paper 323, p. 195-228.

Rowley, P.D., and Barker, D.S., 1978, Geology of the Iron Springs mining district, Utah: Geological Association of Utah Publication 7, Guidebook to mineral deposits of southwestern Utah, p. 49-58.

Rowley, P.D., Cunningham, C.G., Steven, T.A., Mehnert, H.H., and Naeser, C.W., 1998, Cenozoic igneous and tectonic setting of the Marysvale volcanic field, and its relation to other igneous centers in Utah and Nevada, *in* Friedman, J.D., and Huffman, A.C., Jr., coordinators, Laccolith complexes of southeastern Utah—time of emplacement and tectonic setting—workshop proceedings: U.S. Geological Survey Bulletin 2158, p. 167-202.

Rowley, P.D., and Dixon, G.L., 2001, The Cenozoic evolution of the Great Basin area, U.S.A.—New interpretations based on regional geologic mapping, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin – A symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists: Utah Geological Association Publication 30, p. 169-188.

—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, Ground water 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.

Rowley, P.D., Mehnert, H.H., Naeser, C.W., Snee, L.W., Cunningham, C.G., Steven, T.A., Anderson, J.J., Sable, E.G., and Anderson, R.E., 1994a, Isotopic ages and stratigraphy of Cenozoic rocks of the Marysvale volcanic field and adjacent areas, west-central Utah: U.S. Geological Survey Bulletin 2071, 35 p.

Rowley, P.D., Shroba, R.R., Simonds, F.W., Burke, K.J., Axen, G.J., and Olmore, S.D., 1994b, Geologic map of the Chief Mountain quadrangle, Lincoln County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-1731, scale 1:24,000.

Rowley, P.D., Nealey, L.D., Unruh, D.M., Snee, L.W., Mehnert, H.H., Anderson, R.E., and Gromme, C.S., 1995, Stratigraphy of Miocene ash-flow tuffs in and near the Caliente caldera complex, southeastern Nevada and southwestern Utah, *in* Scott, R.B., and Swadley, W C, editors, Geologic studies in the Basin and Range – Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 43-88.

Rowley, P.D., Williams, V.S., Vice, G.S., Maxwell, D.J., Hacker, D.B., Snee, L.W., and Mackin, J.H., 2006, Interim geologic map of the Cedar City 30' x 60' quadrangle, Iron and Washington Counties, Utah: Utah Geological Survey Open-File Report 476DM, scale 1:100,000.

Sable, E.G., 1995, Geologic map of the Hildale quadrangle, Washington and Kane Counties, Utah and Mohave County, Arizona: Utah Geological Survey Map 167, 14 p., 2 plates, scale 1:24,000.

Sable, E.G., and Hereford, Richard, 2004, Geologic map of the Kanab 30' x 60' quadrangle, Utah and Arizona: U.S. Geological Survey Investigations Series I-2655, scale 1:100,000.

Sable, E.G., Biek, R.F., and Willis, G.C., in preparation, Interim geologic map of the Smith Mesa quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report, 2 plates, scale 1:24,000.

Sanchez, Alexander, 1995, Mafic volcanism in the Colorado Plateau/Basin-and-Range transition zone, Hurricane, Utah: Las Vegas, University of Nevada, M.S. thesis, 92 p., scale 1:52,000.

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.

Schaeffer, B., and Dunkle, D.H., 1950, A semionotid fish from the Chinle Formation, with consideration of its relationships: American Museum Novitates, no. 1457, p. 1-29.

Scott, R.B., Gromme, C.S., Best, M.G., Rosenbaum, J.G., and Hudson, M.R., 1995a, Stratigraphic relationships of Tertiary volcanic rocks in central Lincoln County, southeastern Nevada, *in* Scott, R.B., and Swadley, W C, editors, Geologic studies in the Basin and Range—Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992: U.S. Geological Survey Bulletin 2056, p. 7-41.

Scott, R.B., Unruh, D.M., Snee, L.W., Harding, A.E., Nealey, L.D., Blank, H.R., Jr., Budahn, J.R., and Mehnert, H.H., 1995b, Relation of peralkaline magmatism to heterogeneous extension during the middle Miocene, southeastern Nevada: Journal of Geophysical Research, v. 100, no. B6, p. 10,381-10,401.

Siders, M.A., 1991, Geologic map of the Mount Escalante quadrangle, Iron County, Utah: Utah Geological and Mineral Survey Map 122, 9 p., scale 1:24,000.

Smith, E.I., Sanchez, Alexander, Walker, J.D., and Wang, Kefa, 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.

Snee, L.W., and Rowley, P.D., 2000, New $^{40}Ar/^{39}Ar$ dates from the Caliente caldera complex, Nevada-Utah – At least 10 million years of Tertiary volcanism in one of the World's largest caldera complexes [abs.]: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A461.

Sorauf, J.E., and Billingsley, G.H., 1991, Members of the Toroweap and Kaibab Formations, Lower Permian, northern Arizona and southwestern Utah: The Mountain Geologist, v. 28, no. 1, p. 9-24.

Steed, D.A., 1980, Geology of the Virgin River Gorge, northwest Arizona: Provo, Utah, Brigham Young University Geology Studies, v. 27, part 3, 1 plate, scale 1:24,000, p. 97-115.

Steiner, M.B., 2005, Correlation of Triassic/Jurassic boundary strata of North America through paleomagnetic characteristics, *in* Tracking dinosaur origins, the Triassic/Jurassic terrestrial transition, abstracts volume, a conference held at Dixie State College, St. George, Utah, March 14-16, 2005, p. 24.

Stewart, J.H., 1970, Upper Precambrian and Lower Cambrian strata in the southern Great Basin, California and Nevada: U.S. Geological Survey Professional Paper 620, 206 p.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972a, 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 William Thordarson, H.F. Albee, and J.H. Stewart: U.S. Geological Survey Professional Paper 690, 336 p.

—1972b, 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.

Taylor, W.J., 1993, Stratigraphic and lithologic analysis of the Claron Formation in southwestern Utah: Utah Geological Survey Miscellaneous Publication 93-1, 52 p.

Tibert, N.E., Leckie, R.M., Eaton, J.G., Kirkland, J.I., Colin, Jean-Paul, Leithold, E.L., and McCormic, M.E., 2003, Recognition of relative sea-level change in Upper Cretaceous coal-bearing strata – a paleoecological approach using agglutinated foraminifera and ostracods to detect key stratigraphic surfaces, *in* Olsen, H.C., and Leckie, R.M., editors, Micropaleontologic proxies for sea-level change and stratigraphic discontinuities: Society for Sedimentary Geology Special Publication no. 75, p. 263-299.

Tobey, E.F., 1976, Geology of the Bull Valley intrusive-extrusive complex and genesis of the associated iron deposits: Eugene, Oregon, University of Oregon, Ph.D. dissertation, Ann Arbor, Michigan, Xerox University Microfilms 77-13,216, 244 p.

Tschudy, R.H., Tschudy, B.D., and Craig, L.C., 1984, Palynological evaluation of Cedar Mountain and Burro Canyon Formations, Colorado Plateau: U.S. Geological Survey Professional Paper 1281, 24 p., 9 plates.

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.

Van Kooten, G.K., 1988, Structure and hydrocarbon potential beneath the Iron Springs laccolith, southwestern Utah: Geological Society of America Bulletin, v. 100, p. 1533-1540.

Wells, F.G., 1938, The origin of the iron ore deposits in the Bull Valley and Iron Springs districts, Utah: Economic Geology, v. 33,p. 477-507.

Welsh, J.E., and Bissell, H.J., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States – Utah: U.S. Geological Survey Professional Paper 1110-Y, p. Y1 to Y35.

Wiley, M.S., 1963, Structure and stratigraphy of the Jackson Mountain-Tobin Wash area, southwest Utah: Austin, University of Texas, M.S. thesis, 103 p.

Willden, Ronald, and Adair, D.H., 1986, Gold deposits at Goldstrike, 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. 137-147.

Williams, P.L., 1967, Stratigraphy and petrography of the Quichapa Group, southwestern Utah and southeastern Nevada: Seattle, University of Washington, unpublished Ph.D. dissertation, 182 p.

Willis, G.C., and Biek, R.F., 2001, Quaternary incision rates of the Colorado Plateau 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., Doelling, H.H., Solomon, B.J., and Sable, E.G., 2002, Interim geologic map of the Springdale West quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 394, 19 p., scale 1:24,000.

Willis, G.C., and Higgins, J.M., 1995, Interim geologic map of the Washington quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 324, 108 p., 2 plates, scale 1:24,000.

—1996, Interim geologic map of the Santa Clara quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 339, 87 p., scale 1:24,000.

Willis, G.C., and Hylland, M.D., 2002, Interim geologic map of The Guardian Angels quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 395, 27 p., 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.