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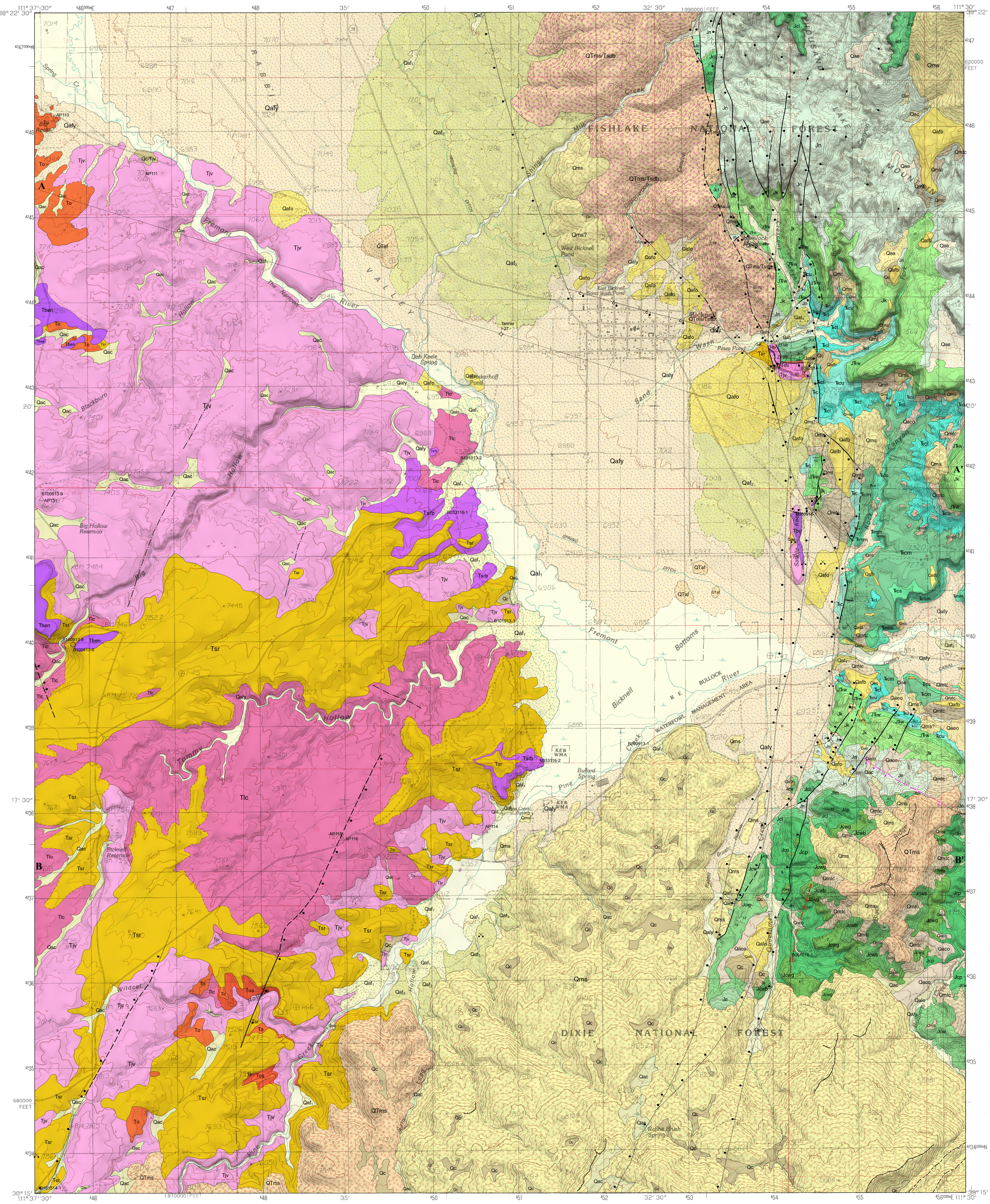
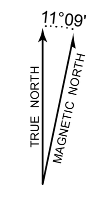
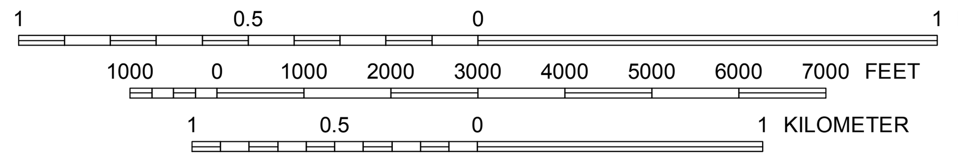


This geologic map was funded by the Utah Geological Survey and the U.S. Geological Survey, National Cooperative Geologic Mapping Program through USGS STATEMAP award number G15AC00249, 2015. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. This map and explanatory information is submitted for publication with the understanding that the United States Government is authorized to reproduce and distribute reprints for governmental use.



APPROXIMATE MEAN DECLINATION, 2016

SCALE 1:24,000



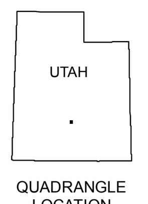
CONTOUR INTERVAL 40 FEET

INTERIM GEOLOGIC MAP OF THE BICKNELL QUADRANGLE, WAYNE COUNTY, UTAH

by

Robert F. Biek

2016



QUADRANGLE LOCATION

Base from USGS Bicknell 7.5’ Quadrangle (1985)
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1866

Project Manager: Grant C. Willis
GIS and Cartography: Basia Matyjasik

Utah Geological Survey
1594 West North Temple, Suite 3110
Salt Lake City, UT 84116
(801) 537-3300
geology.utah.gov

This map was created from geographic information system (GIS) data

1	2	3
4		5
6	7	8

1. Loa
2. Lyman
3. Flat Top
4. Moroni Peak
5. Torrey
6. Smooth Knoll
7. Government Point
8. Blind Lake

ADJOINING 7.5' QUADRANGLE NAMES

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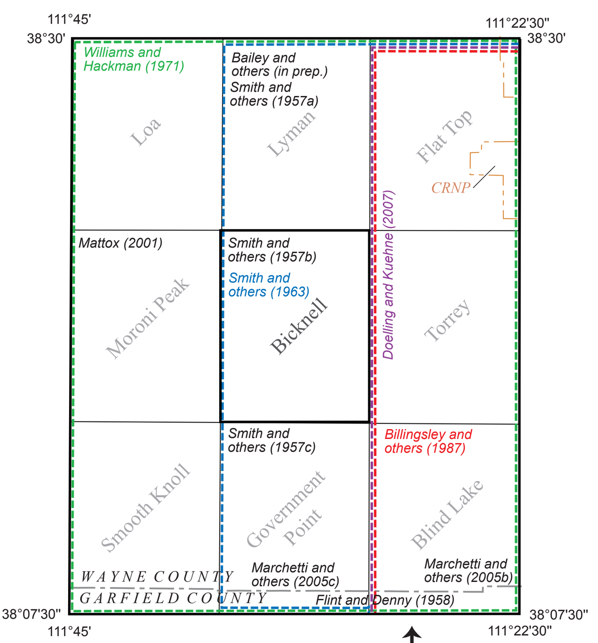
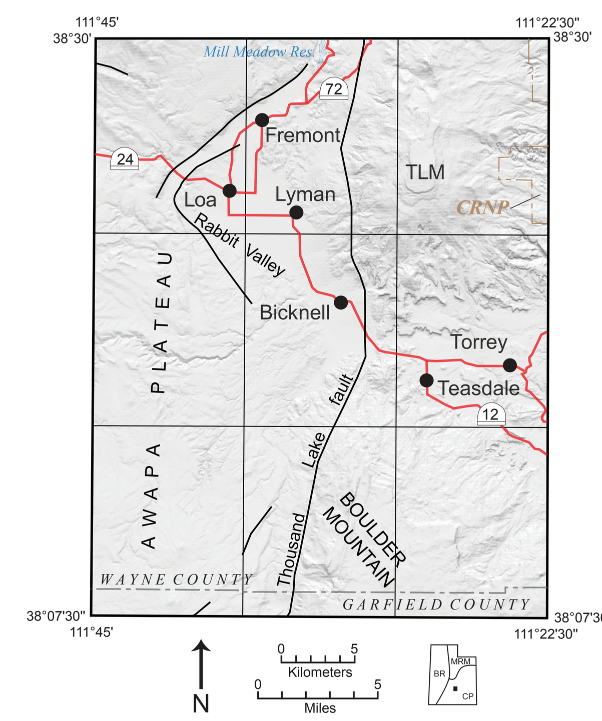


U. S. Geological Survey 7.5' quadrangles and principal sources of previous geologic mapping.
CRNP = Capitol Reef National Park



Shaded-relief image of the Loa 30'x60' quadrangle; TLM = Thousand Lake Mountain, CRNP = Capitol Reef National Park. Inset shows physiographic provinces: BR, Basin and Range; MRM, Middle Rocky Mountains; CP, Colorado Plateau.

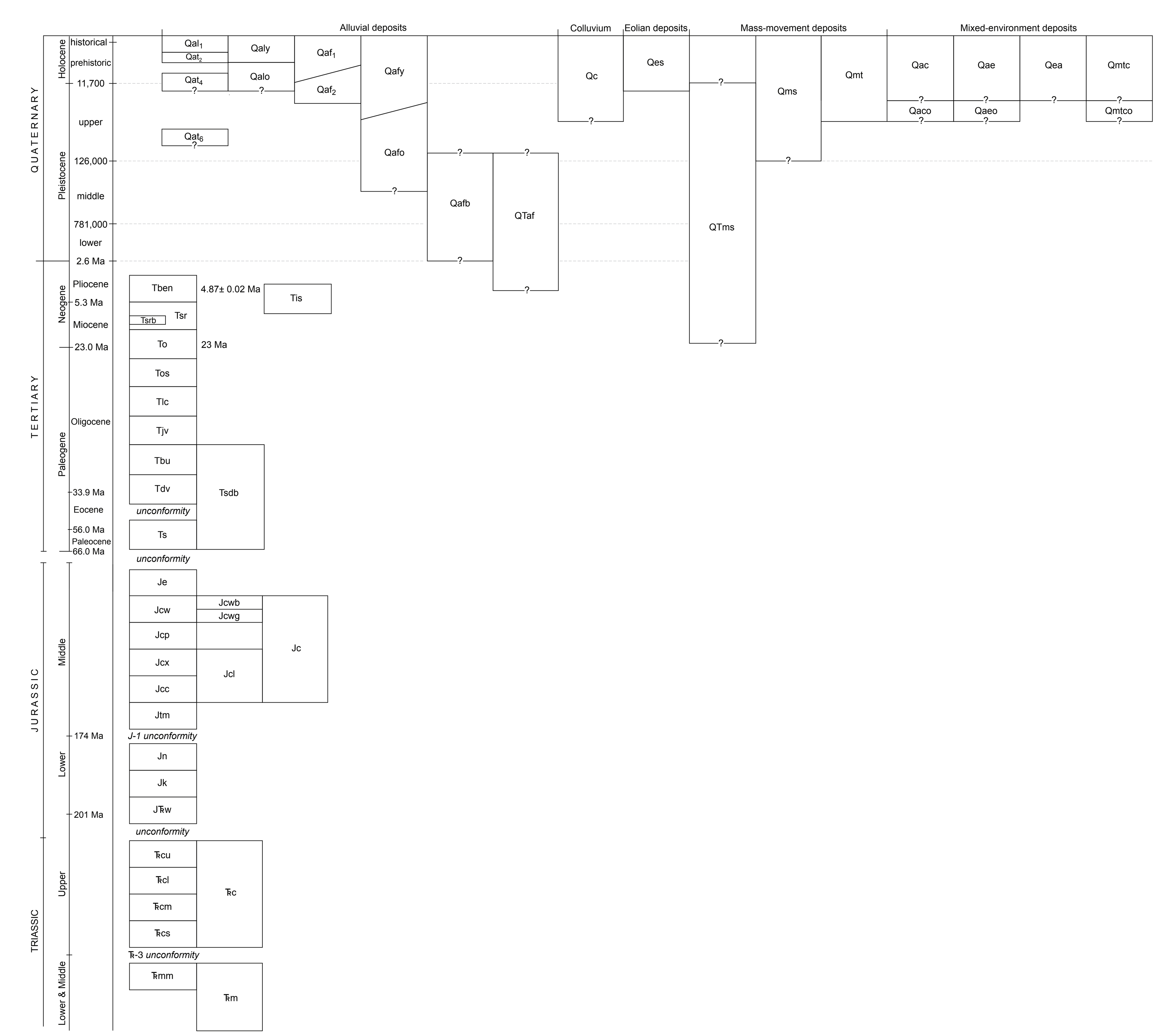
MAP SYMBOLS

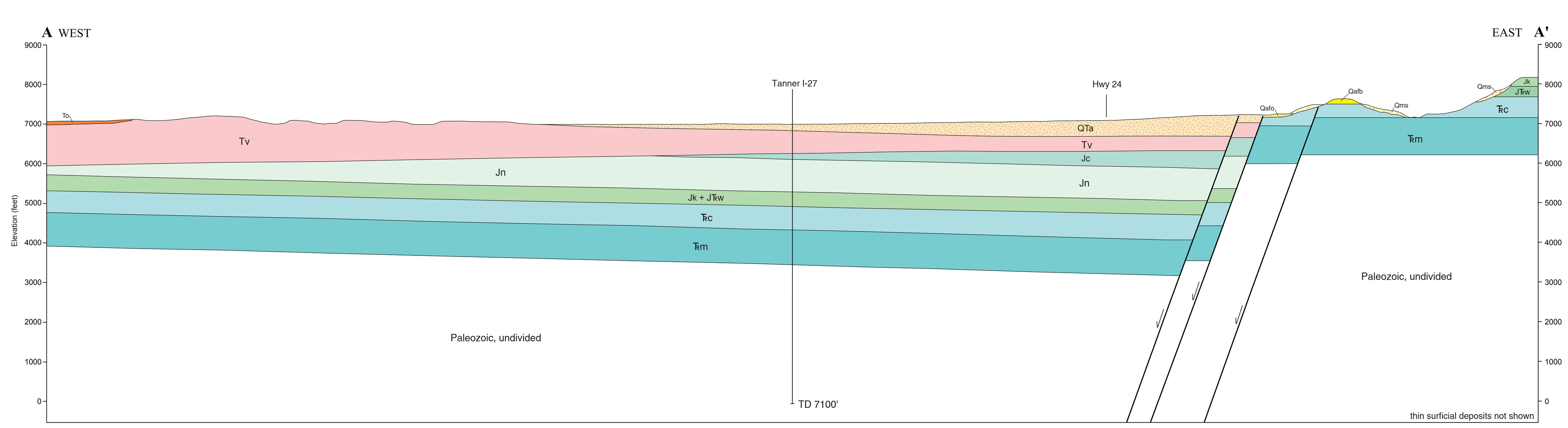
- Contact, dashed where approximately located
- Normal fault, dashed where approximately located, dotted where concealed; queried where uncertain; bar and ball on down-dropped side
- Reverse fault, dotted where concealed, teeth on upper plate
- Lineament
- Monocline fold axis, dashed where approximately located, dotted where concealed, arrows point to steeper limb
- Mafic dike
- Landslide scarp
- Strike and dip of bedding
- Approximate strike and dip of bedding
- Horizontal bedding
- Strike of vertical joint
- Sand and gravel pit
- Quarry
- Spring
- Sample location and number (B100913-9)

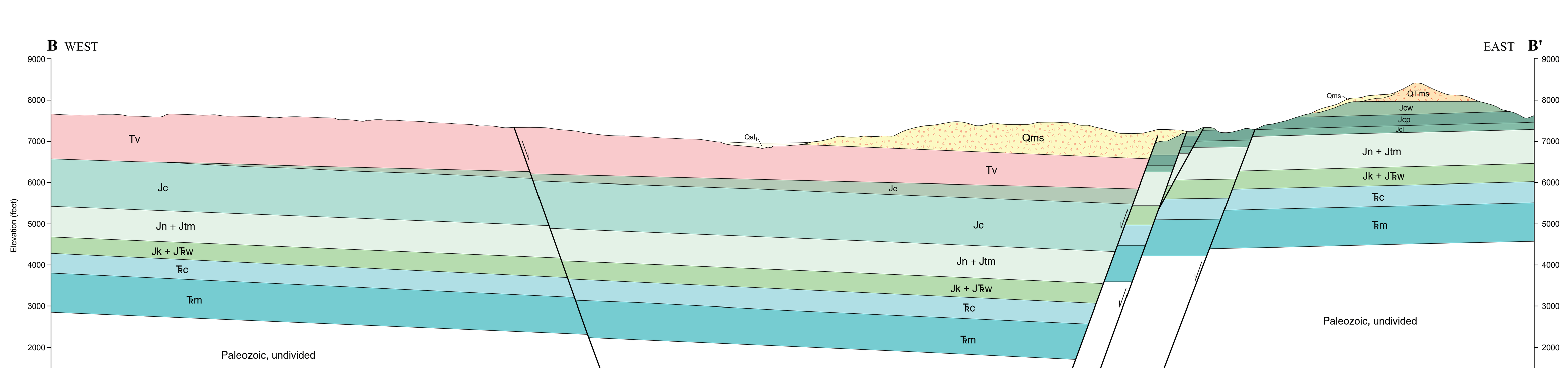
STRATIGRAPHIC COLUMN

Ma	System	Series	Map Unit	Map Symbol	Thickness feet (meters)	Plate Tectonic Setting	Depositional Environment	Dominant Rock Type and Weathering Profile	Notes
.012	QUATERNARY	Holocene	various surficial deposits see Correlation of Map Units		variable	Basin-range extension and bimodal (basalt and rhyolite) volcanism beginning about 17 Ma	alluvium and mass-wasting deposits in modern drainages and basins	unconsolidated sand, gravel, clay and silt	Typically maximum thickness reported and not all units present in any given area.
2.6		Pleistocene							
5.3	TERTIARY, Neogene	Pliocene	basaltic lava flows	Tben	20 (6)		Marysvale volcanic field and intermontaine basins; fluvial basin fill with volumetrically minor lava flows and air-fall tuff beds	lava flow	4.87±0.02 Ma
23.0		Miocene	Sevier River Formation	Tsr	150 (45)			sandstone, conglomerate, lava flows	
			basaltic lava flows	Tsrb	80 (24)				
	TERTIARY, Paleogene	Oligocene	Osiris Tuff	To	30 (9)	Calc-alkaline volcanism, development of clustered stratovolcanoes and calderas in southwest Utah from about 30-14 Ma	ash-flow tuff from Monroe Peak caldera	densely welded rhyodacite ash-flow tuffs	23.0 Ma
			sandstone associated with Osiris Tuff	Tos	50 (15)		fluvial	sandstone and conglomerate	
			trachyte of Lake Creek	Tlc	300+ (90+)		ash-flow tuffs from unknown vents	densely welded crystal-poor trachyte ash-flow tuff	25.13±0.02 Ma
			latite of Johnson Valley	Tjv	250-300+ (75-90+)			densely welded porphyritic latite ash-flow tuff	25-26 Ma
			Bullion Canyon Volcanics, undivided	Tbu (Tsdb)	150 (45)		volcanic mudflow	lahar	
33.9		Eocene	Dipping Vat Formation	Tdv (Tsdb)	150 (45)		local volcanic sediments deposited in low-relief river and lake basins	volcaniclastic sandstone, siltstone, mudstone, and conglomerate	forms large landslides mostly covered
		Paleocene	Tertiary sedimentary strata	Ts (Tsdb)	30 (9)	foreland basin	coastal plain	conglomerate, mudstone, limestone	unconformity
	JURASSIC	Middle	Entrada Sandstone	Je	245+ (75+)	Back-bulge basin; Sevier orogeny	tidal-flat, sabhka, coastal dune	sandstone and silty sandstone	
			Carmel Formation, Winsor Mbr., banded subunit	Jc, Jcw, Jcwb	1029+ (302+); 669+ (193+); 404+ (123+)		sandy mud flat	sandstone, siltstone, gypsum	
			Carmel Formation, Winsor Mbr., gypsiferous subunit	Jc, Jcw, Jcwg	229 (70)				
			Carmel Formation, Paria River Mbr.	Jc, Jcp	211 (64)		restricted shallow marine	micritic limestone, gypsum, shale	166 Ma
			Carmel Formation, Crystal Creek Mbr.	Jc, Jcl, Jcx	30 (9)		coastal sabkha and tidal flat	mudstone, siltstone	167 Ma
			Carmel Formation, Co-op Creek Limestone Mbr.	Jc, Jcl, Jcc	119 (36)		shallow marine	micritic limestone, sandstone, shale	169-170 Ma
174			Temple Cap Formation Manganese Wash Member	Jtm	43 (13)		tidal flat, fluvial	sandstone and siltstone	J-1 unconformity
		Lower	Navajo Sandstone	Jn	800 (245)	Low-relief continental interior of a back-arc basin	vast eolian dune field of arid west coast subtropical desert	sandstone	large cross-beds
			Kayenta Formation	Jk	200 (60)		fluvial, minor lake, eolian dune field	sandstone, siltstone, minor mudstone, limestone	
201			Wingate Sandstone	JŦw	250 (75)		eolian dune field	sandstone	large cross-beds
	TRIASSIC	Upper	Chinle Formation, upper slope former	Ŧc, Ŧcu	130 (40)		fluvial, floodplain, wetland, and lake	sandstone, siltstone, mudstone	forms landslides
			Chinle Formation, lower slope former	Ŧc, Ŧcl	210 (65)				
			Chinle Formation, Monitor Butte Member	Ŧc, Ŧcm	110 (33)				
237			Chinle Formation, Shinarump Member	Ŧc, Ŧcs	40 (12)		braided river	sandstone, conglomerate	Ŧ-3 unconformity
		Middle to Lower	Moenkopi Formation, Moody Canyon Member	Ŧm, Ŧmm	230+ (70+)	low-relief continental shelf	tidal flat	siltstone and sandstone	

CORRELATION OF MAP UNITS







Interim Geologic Map of the Bicknell Quadrangle, Wayne County, Utah

by

Robert F. Biek

Disclaimer

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UTAH DNR GEOLOGICAL SURVEY

OPEN-FILE REPORT 654
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with the
U.S. GEOLOGICAL SURVEY
2016

MAP UNIT DESCRIPTIONS

QUATERNARY

Alluvial deposits

Qal_1 **Modern stream alluvium** (Holocene) − Moderately sorted sand, silt, clay, and pebble to boulder gravel deposited in active, main-stem stream channels and floodplains of the Fremont River and Pine Creek; locally includes minor stream-terrace alluvium as much as about 10 feet (3 m) above current stream level; probably less than 20 feet (6 m) thick.

Qat_2, Qat_4, Qat_6

Stream-terrace alluvium (Holocene to upper? Pleistocene) − Moderately sorted sand, silt, and pebble to boulder gravel that forms gently sloping terraces above, and incised by, active streams and washes; deposited in a stream-channel environment, but locally includes colluvium and small alluvial fans; each terrace represents the elevation of stream base level prior to being incised; subscript denotes relative age and height above adjacent drainage; Qat_2 ranges from about 5 to 10 feet (2–3 m), Qat_4 ranges from about 30 to 50 feet (9-15 m), and Qat6 lies about 130 to 150 feet (40–45 m) above adjacent streams; alluvium of intervening terrace levels Qat_3 and Qat_5 is not present, but is mapped in the adjacent Lyman quadrangle (Biek and others, in preparation); as much as about 30 feet (9 m) thick.

Qaly **Young stream alluvium** (Holocene) − Combined stream alluvium (Qal_1) and the youngest (lowest elevation) part of stream-terrace alluvium (Qat_2), but undivided here due to limitations of map scale; mapped along upland drainages where it may include small alluvial-fan deposits from tributary drainages and colluvium from adjacent slopes; deposits commonly grade downslope into alluvial fans; locally includes historical debris-flow and debris-flood deposits derived from tributary drainages; typically less than 20 feet (6 m) thick.

Qalo O**ld stream alluvium** (Holocene to upper Pleistocene) – Similar to young stream alluvium (Qaly), but forms incised deposits along Bullberry Creek, in the southeast corner of the quadrangle; probably less than 20 feet (6 m) thick.

Qaf_1 **Young fan alluvium** (Holocene) − Poorly to moderately sorted, non-stratified, clay- to boulder-size sediment containing subangular to subrounded clasts deposited principally by debris flows and debris floods at the mouths of active drainages; equivalent to the upper part of young and middle fan alluvium (Qafy), but differentiated because Qaf_1 typically forms small, isolated fans; probably less than 30 feet (9 m) thick.

Qaf_2 **Middle fan alluvium** (Holocene to upper Pleistocene) − Similar in composition and morphology to young fan alluvium (Qaf_1), but forms mostly inactive surfaces incised by younger stream and fan deposits; equivalent to the older, lower part of young and middle fan alluvium (Qafy); larger deposits northwest and southeast of Bicknell are mostly uncultivated and characterized by large, black volcanic boulders derived from Thousand Lake Mountain; probably less than 30 feet (9 m) thick.

Qafy **Young and middle fan alluvium, undivided** (Holocene to upper Pleistocene) − Poorly to moderately sorted, non-stratified, boulder- to clay-size sediment containing subangular to subrounded clasts deposited at the mouths of streams and washes; forms both active depositional surfaces (Qaf_1 equivalent) and low-level inactive surfaces incised by small streams (Qaf_2 equivalent) that are undivided here; deposited principally as debris flows and debris floods, but colluvium locally constitutes a significant part adjacent to range fronts; small, isolated deposits are typically less than a few tens of feet thick, but large, coalesced deposits in Rabbit Valley are much thicker and form the upper part of basin-fill deposits; the Tanner 1-17 CO_2 test well immediately west of Bicknell encountered Carmel strata at a depth of 708 feet (216 m) (Doug Sprinkel, UGS, personal communication, May 14, 2015), above which is undifferentiated volcanic rocks and basin-fill alluvium, the upper part of which is this young and middle fan alluvium.

Qafo **Old fan alluvium** (upper to middle? Pleistocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment with moderately developed calcic soils (caliche); forms broad, gently sloping, deeply incised surfaces along the margins of Rabbit Valley; deposited principally as debris flows and debris floods; exposed thickness as much as several tens of feet.

Qafb **Oldest fan alluvium** (middle? to lower? Pleistocene) – Similar to old fan alluvium but much more deeply incised and preserved at higher levels on the flanks of Thousand Lake Mountain and Boulder Mountain; characterized by large, black volcanic boulders with a prominent iron-manganese patina, most of which are derived from the latite of Johnson Valley; locally, much of the finer-grained matrix is eroded away, leaving behind a lag of black boulders; deposited as debris flows and debris floods; exposed thickness as much as several tens of feet.

Colluvial deposits

Qc **Colluvium** (Holocene to upper Pleistocene) − Poorly to moderately sorted, angular to subrounded, clay- to boulder-size, locally derived sediment deposited by slope wash and soil creep on moderate slopes and in shallow depressions; locally grades downslope into deposits of mixed alluvial and colluvial origin; common on most slopes, but mapped only where it conceals contacts or mantles broad areas and shallow depressions; typically less than 20 feet (6 m) thick.

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 Wingate Sandstone and Kayenta Formation; forms small dunes partly stabilized by vegetation in a single deposit mapped south of Highway 24 near where the Fremont River cuts across the Thousand Lake fault zone; typically 0 to 20 feet (0–6 m) thick.

Mass-movement deposits

Qms **Landslides** (Historical? to upper? Pleistocene) − Very poorly sorted, locally derived material deposited by rotational and translational movement; composed of clay- to boulder-size debris as well as large, partly intact bedrock blocks; characterized by hummocky topography, numerous internal scarps, chaotic bedding attitudes, and common small ponds, marshy depressions, and meadows; query indicates areas of unusual morphology that may be due to landsliding; thickness highly variable, but map patterns suggest that larger deposits on the flanks of Boulder Mountain and Thousand Lake Mountain exceed several hundred feet thick; undivided as to inferred age because even landslides that have subdued morphology (suggesting that they are older, weathered, and have not experienced recent, large-scale movement) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003).

Vegetation and widespread colluvium may conceal unmapped landslides, and more detailed imaging techniques such as lidar may show that many slopes host surficial deposits that reveal evidence of creep or shallow landsliding. Understanding the location, age, and stability of landslides, and of slopes that may host as-yet unrecognized landslides, requires detailed geotechnical investigations.

Qmt **Talus** (Holocene to upper Pleistocene) − Poorly sorted, angular cobbles and boulders and finer-grained interstitial sediment deposited principally by rockfall on or at the base of steep slopes; talus that is part of large landslide complexes is not mapped separately; talus is common at the base of steep slopes across the map area, but is mapped only where it conceals contacts or forms broad aprons below cliffs of resistant bedrock units; commonly grades downslope into colluvium; typically less than 30 feet (9 m) thick.

Mixed-environment deposits

Qac **Alluvium and colluvium** (Holocene to upper Pleistocene) − Poorly to moderately sorted, generally poorly stratified, clay- to boulder-size, locally derived sediment deposited in swales and small drainages by fluvial, slope-wash, and creep processes; generally less than 20 feet (6 m) thick.

Qaco **Older alluvium and colluvium** (upper? Pleistocene) − Similar to mixed alluvium and colluvium (Qac), but forms incised, isolated remnants along the upper reaches of stream channels in the southeast corner of the quadrangle; probably about 20 to 30 feet (6–9 m) thick.

Qae **Alluvium and eolian sand** (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; mapped principally in shallow depressions on the Navajo Sandstone; 0 to about 20 feet (0–6 m) thick.

Qaeo **Older alluvium and eolian sand** (upper? Pleistocene) – Similar to younger alluvium and eolian sand deposits, but forms incised, inactive surfaces; mapped south of Highway 24 at the east edge of the quadrangle where it is as much as about 20 feet (6 m) thick.

Qea **Eolian sand and alluvium** (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; as much as about 20 feet (0–6 m) thick.

Qmtc **Talus and colluvium** (Holocene to upper? Pleistocene) – Poorly sorted, angular to subangular, cobble- to boulder-size and finer-grained interstitial sediment deposited principally by rockfall and slope wash on steep slopes throughout the quadrangle; includes minor alluvial sediment at the bottom of washes; talus and colluvium are common on steep slopes across the map area, but are mapped only where they conceal contacts or form broad aprons below cliffs of resistant bedrock units; commonly grades downslope into colluvium; generally less than 30 feet (9 m) thick.

Qmtco **Older talus and colluvium** (upper? Pleistocene) – Similar to talus and colluvium but forms incised surfaces, capped by resistant blocks of Wingate Sandstone, now isolated from nearby Wingate cliffs; generally less than 30 feet (9 m) thick.

Stacked-unit deposits

Stacked-unit deposits comprise a discontinuous veneer of Quaternary deposits that mostly conceal underlying bedrock units. Although most bedrock in the quadrangle is partly covered by colluvium or other surficial deposits, we use stacked units to indicate areas where bedrock is almost wholly obscured by thin surficial deposits that are derived from more than just residual weathering of underlying bedrock.

Qc/Tjv **Colluvium over latite of Johnson Valley** (Holocene to upper Pleistocene/upper Oligocene) – Mapped in the northwest corner of the quadrangle where a veneer of colluvium mostly conceals latite of Johnson Valley.

QTms/Jc

Older landslide deposits over Carmel Formation (Quaternary to Pliocene/Middle Jurassic) – Mapped along the Thousand Lake fault zone where Carmel strata are mostly concealed old mass-movement deposits and colluvium.

QTms/Tsdb

Older landslide deposits over Tertiary sedimentary strata, Dipping Vat Formation, and Three Creeks Tuff Member of the Bullion Canyon Volcanics (Quaternary to Pliocene/Oligocene to Eocene?) – Forms steep, rugged hills north of Bicknell, in the hanging wall of the Thousand Lake fault zone, that are mostly covered by volcanic boulders derived from the latite of Johnson Valley; limited exposures reveal fine- and coarse-grained volcaniclastic, and locally non-volcaniclastic, strata of widely varying attitudes, and it is unknown whether these exposures are fault-bounded bedrock blocks or rotated blocks that are part of a deeply eroded landslide; the distribution and thickness of individual units is highly variable, but map patterns suggest that the combined package is in excess of 900 feet (275 m) thick.

Fine-grained volcaniclastic facies, locally well exposed between Bicknell and Crescent Canyon, are mostly light-gray to white, thin- to medium-bedded, fine- to medium-grained, locally coarse-grained, sandstone, siltstone, and mudstone, here assigned to the Dipping Vat Formation of McGookey (1960) exposed on the northeastern flank of the Marysvale volcanic field. These beds yielded three teeth of *Saltirius utahensis* (stingray) only known from the coeval variegated unit of the Brian Head Formation exposed on the southeastern flank of the volcanic field (Jeff Eaton, personal communication, May 24, 2016). Coarse-grained volcanicastic facies consist of pebble-to boulder sandstone and conglomerate of possible Sevier River Formation affinity (or possibly of the older Bullion Canyon Volcanics).

North of Sand Wash, at the bedding attitude symbol showing a dip of 50 to 75 degrees north, reddish-brown mudstone, yellowish-brown sandy and micritic limestone, and quartzite- and chert-pebble conglomerate compose a block of non-volcaniclastic strata, collectively a few tens of feet thick, of uncertain age and correlation; these same beds (Ts) are poorly exposed south of Sand Wash. These non-volcaniclastic strata appear similar to strata in Lime Kill Hollow, north of Lyman in the adjacent Lyman quadrangle (Biek and others, in preparation), and to middle Eocene (Duchesnean Land Mammal Age, about 42–38 Ma) clastic strata of Flat Top (map unit Tc of Doelling and Kuehne, 2007). These non-volcaniclastic strata appear in a similar stratigraphic position as the Crazy Hollow Formation and the formation of Aurora (see Willis, 1988) on the northeastern flank of the Marysvale volcanic field, and as the informally named variegated unit of the Brian Head Formation and underlying conglomerate at Boat Mesa (see Biek and others, 2015a) on the southeastern flank of the volcanic field.

QUATERNARY and TERTIARY

QTaf **Fan alluvium** (Quaternary? to Pliocene?) – Similar to old fan alluvium (Qafo) but forms isolated, boulder-covered hills in Rabbit Valley; maximum exposed thickness about 30 feet (9 m).

QTms **Older landslides** (Quaternary? to Pliocene?) – Similar to modern landslides (Qms), but morphology and position in the landscape show that they are remnants now isolated from their source area; some now have such relief that they are the source of younger, modern landslides (as on Black Ridge); base of deposit in the southwest corner of the quadrangle typically includes as much as a few tens of feet of white, tuffaceous and fine-grained volcaniclastic strata likely of the Brian Head Formation (similar, largely coeval strata on the northeastern flank of the Marysvale volcanic field are known as the Dipping Vat Formation); thickness highly variable, but deposits on Black Ridge are in excess of 400 feet (120 m) thick.

The flanks of Boulder Mountain and Thousand Lake Mountain are nearly completely covered by rotational slumps, translational landslides, and earth flows of multiple ages. Previous reconnaissance-scale geologic maps and studies of the Quaternary geology of the region (Smith and others, 1957a, 1957b, 1957c, 1963; Flint and Denny, 1958; Billingsley and others, 1987; Doelling and Kuehne, 2007), and even the in-depth studies of Marchetti and others (2005a, 2007), typically show only the youngest such features, those with unambiguous landslide morphology. Intervening areas of subdued but still unusual topography were interpreted as colluvium-covered, faulted bedrock blocks (Smith, 1957a, 1957b, 1957c, 1963; Marchetti, 2007), Pleistocene boulder deposits (locally over the Flagstaff Formation, which was then defined to include what we now understand to be younger volcaniclastic deposits) (Smith, 1957a, 1957b, 1957c, 1963; Flint and Denny, 1958), or as volcanic boulder deposits in undifferentiated landslides, till, and colluvium (Doelling and Kuehne, 2007). Such areas of unusual topography are startling apparent when viewed in Google Earth imagery, and they contrast markedly from areas where this stratigraphic interval is obviously unaffected by mass-movement processes. Thus, much of the southeastern part of this quadrangle is here mapped as modern and older landslide deposits (Qms, QTms), whereas north of Bicknell, the range front is eroded from older landslide deposits that include or conceal Tertiary strata (QTms/Tsdb).

It is unclear what stratigraphic horizon serves as the principal slip surface for these large landslide complexes; likely more than one horizon is involved. Below their resistant volcanic caprocks, the uppermost 820 feet (245 m) or more of Boulder Mountain and the uppermost 300 feet (90 m) of Thousand Lake Mountain are concealed by mass movement and local glacial deposits. On the north flank of Boulder Mountain, the stratigraphically highest unit exposed is the Salt Wash Member of the Morrison Formation (Doelling and Kuehne, 2007). At the north end of Thousand Lake Mountain, the stratigraphically highest interval is sandstone, conglomerate, siltstone, marly siltstone, and mudstone of Eocene age, whereas the southern end reveals interbedded calcarenite, crystalline limestone, conglomeratic calcarenite, intraformational conglomerate, marl, and sandstone of undetermined Eocene to Paleocene age; regional correlation of both sections is uncertain (Doelling and Kuehne, 2007). The Brian Head Formation, notorious for its role in landslide generation in areas to the southwest (Biek and others, 2015a), is present at the base of older landslide deposits in the southwest corner of the Loa 30′ x 60′ quadrangle (Biek and others, 2015b), and its coeval twin the Dipping Vat Formation is present in fault blocks east of Bicknell, and I suspect that such beds may underlie the resistant caprock of both Thousand Lake and Boulder Mountains.

TERTIARY

Upper Tertiary basaltic lava flow

Tben **Basaltic lava flows of Elsies Nipple** (Pliocene) – Dark-gray, fine-grained basalt with small olivine phenocrysts (commonly altered to iddingsite) and abundant small plagioclase and clinopyroxene phenocrysts in a groundmass of plagioclase microlites, iron oxides, and glass; erupted from a vent at Elsies Nipple about 5 miles (8 km) southwest of Loa; Mattox (2001) reported a K-Ar age of 6.9 ± 0.3 Ma on a sample from Elsies Nipple, and our sample B100913-6 yielded an $^{40}Ar/^{39}Ar$ plateau age of 4.87 ± 0.02 Ma; flowed eastward down the dip slope of the Awapa Plateau, showing that the eastward tilt of the plateau was established by earliest Pliocene time; only the eastern end of the flow is preserved at the west margin of the quadrangle, where it is about 20 feet (6 m) thick.

In southwestern Utah, including within the Marysvale volcanic field, basaltic rocks are synchronous with basin-range extension—and thus with initial development of our modern topography that began in southwestern Utah between 23 and 17 million years ago—and are part of mostly small, bimodal (basalt and high-silica rhyolite) eruptive centers (Christiansen and Lipman, 1972; Rowley and Dixon, 2001). Basaltic magmas are partial melts derived from the compositionally heterogeneous lithospheric mantle (see, for example, Fitton and others, 1991). Rock names follow LeBas and others (1986) based on limited geochemistry. Major- and trace-element data for volcanic rocks in the western half of the Loa 30′ x 60′ quadrangle will be published separately at the end of this project.

Tis **Mafic dike** (Miocene) – Medium- to dark-gray mafic dike of probable basaltic composition; contains phenocrysts of olivine, altered to iddingsite, in a fine-grained groundmass; deeply weathered and mostly nonresistant; intrudes Carmel strata southwest of Black Ridge and is roughly parallel to the Thousand Lake fault zone; typically 1 to 6 feet (0.3–2 m) wide.

Tsr **Sevier River Formation** (Miocene) – Moderately to poorly consolidated, light-gray and grayish-brown volcaniclastic conglomerate, pebbly sandstone, sandstone, and minor siltstone; locally contains interbedded basaltic lava flows, remnants of which are mapped separately as Tsrb along the west side of Rabbit Valley; clasts are subrounded to rounded intermediate-composition volcanic rocks; locally contains thin, white, air-fall ash beds, some of which may belong to the Joe Lott Tuff Member of the Mount Belknap Volcanics (Rowley and others, 1986); forms poorly exposed, planar and gently sloping, sagebrush-covered surfaces on the Awapa Plateau where it unconformably overlies the Osiris Tuff, trachyte of Lake Creek, or latite of Johnson Valley; maximum thickness on the Awapa Plateau is about 400 feet (120 m), but in this quadrangle it is less than about 150 feet (45 m) thick on the Awapa Plateau; strata north of Bicknell, mapped as older landslide deposits over Tertiary strata (QTms/Tsdb), are in excess of 900 feet (275 m) thick, but it is unclear what part, if any, may belong to the Sevier River Formation.

The Sevier River Formation was named by Callaghan (1938) for partly consolidated basin-fill deposits near Sevier, Utah, on the north side of the Marysvale volcanic field. The name was formerly applied to all basin-fill deposits in and near Sevier and Grass Valleys, but, because most of its exposures are in adjacent ranges, it was later recognized to have been deposited in basins that formed generally prior to the main episode of basin-range extension, which created the present topography (Rowley and others, 1981, 1998, 2002; Rowley, 1998). In and near its type area near the town of Sevier, the Sevier River Formation contains air-fall tuffs and basaltic lava flows that have fission-track and K-Ar ages of 14 and 7 Ma and basaltic lava flows that have K-Ar ages of 9 and 5.6 Ma (Steven and others, 1979; Best and others, 1980; Rowley and others, 1994); Willis (1988) reported a fission-track age of 5.2 ± 0.4 Ma on a reworked ash bed in the upper part of the formation in the Aurora quadrangle to the north. The age of the Sevier River Formation is poorly constrained on the Awapa Plateau, but at the plateau's western margin it concordantly overlies the 23 Ma Osiris Tuff and is locally overlain by 5.0 to 6.5 Ma basaltic lava flows in the Antimony and upper Dry Wash areas. The Sevier River Formation thus spans much of the Miocene and was deposited in basins of different ages across this part of south-central Utah, basins that bear no relationship to the modern topography.

Tsrb **Basaltic lava flows in the Sevier River Formation** (Miocene) – Dark-gray, fine-grained basaltic lava flows interbedded in volcaniclastic gravels of the Sevier River Formation; contain small olivine phenocrysts (commonly altered to iddingsite) and common small plagioclase and clinopyroxene phenocrysts; as much as about 80 feet (24 m) thick southwest of Bicknell Bottoms, forming resistant ledges within non-resistant gravels.

To **Osiris Tuff** (lower Miocene to upper Oligocene) – Resistant, light-gray and grayish-brown, densely welded, moderately crystal-rich, trachyte ash-flow tuff (petrographically a rhyodacite); contains about 20 to 25% phenocrysts of plagioclase, subordinate sanidine and biotite, and minor pyroxene and Fe-Ti oxides (Anderson and Rowley, 1975; Mattox, 2001); forms a simple cooling unit, which typically includes an upper, light-gray vapor-phase zone and a basal black vitrophyre as much as 10 feet (3 m) thick; commonly weathers to large rounded boulders, as, for example, at Big Rocks in the northwest corner of the quadrangle; contains drawn-out pumice lenticles; the preferred age of the Osiris is about 23 Ma (Rowley and others, 1994); forms the uppermost widespread volcanic unit on the Awapa Plateau and is only locally overlain by volcaniclastic gravels of the Sevier River Formation and younger middle Miocene to Pliocene basaltic lava flows; about 30 feet thick in this quadrangle, but typically about 100 to 150 feet (30–45 m) thick on the Awapa Plateau to the west (Biek and others, 2015b).

The Osiris Tuff erupted from the Monroe Peak caldera, the largest caldera of the Marysvale volcanic field and the youngest of the calc-alkaline sequence (Steven and others, 1984; Rowley and others, 2002). The Osiris Tuff is one of the most widespread and distinctive ash-flow tuffs of the Marysvale volcanic field (Rowley and others, 1994) and has an estimated volume of 60 cubic miles (250 km^3) including its thick intracaldera fill (Cunningham and others, 2007). Fleck and others (1975) reported K-Ar ages for the Osiris Tuff (corrected according to Dalrymple, 1979) on biotite of 23.4 ± 0.4 Ma (sample R3) from the southern Sevier Plateau and 22.7 ± 0.4 Ma (sample R12) from the southern Tushar Mountains. Cunningham and others (2007) reported that the tuff erupted between 22.92 and 22.81 Ma based on preliminary unpublished $^{40}Ar/^{39}Ar$ ages by L.W. Snee, and Ball and others (2009) reported that several $^{40}Ar/^{39}Ar$ ages on sanidine average 23.03 ± 0.08 Ma.

Tos **Sandstone and conglomerate associated with the Osiris Tuff** (upper Oligocene) – Brownish-gray, fine- to coarse-grained volcaniclastic sandstone and conglomerate; clasts are subangular to subrounded pebbles and cobbles of intermediate volcanic rocks; weathers to poorly exposed slopes below resistant ledge of Osiris Tuff; as much as about 50 feet (15 m) thick.

Tlc **Trachyte tuff of Lake Creek** (upper Oligocene) (temporary name, see note below) – Gray, densely welded, phenocryst-poor trachyte ash-flow tuff with 5 to 15% phenocrysts of plagioclase, pyroxene, hornblende, and Fe-Ti oxides commonly in a glassy matrix; typically exhibits pronounced platy compaction foliation and lighter-colored "lenticules" interpreted to be flattened gas-rich zones; basal vitrophyre typically inconspicuous and poorly exposed; mapped southwest of Bicknell on the east flank of the Awapa Plateau; commonly weathers to poorly exposed, regolith-covered slopes that, from a distance, are difficult to distinguish from those developed on the volcanic rocks of Langdon Mountain or the Sevier River Formation; on the Awapa Plateau, Williams and Hackman (1971) called this unit a latite, but Mattox (1991, 2001), although he retained the name latite, correctly noted that it is a trachyte according to the classification scheme of LeBas and others (1986); includes "latite lava flows" of Mattox (2001), given their similar stratigraphic position, petrology, and chemistry; originally interpreted as lava flows (Williams and Hackman, 1971; Mattox, 1991, 2001) and subsequently identified as an ash-flow tuff (Ball and others, 2009); major- and trace-element discrimination diagrams (UGS unpublished data) show that samples identified as trachyte tuff of Lake Creek cluster remarkably tightly, further suggesting that these widely scattered samples support interpretation of the unit as an ash-flow tuff rather than multiple lava flows erupted from multiple sources as inferred by previous workers; on the northern Awapa Plateau and Fish Lake Plateau, map unit typically overlies the latite of Johnson Valley, but southward it overlies lahars of the volcanic rocks of Langdon Mountain; Mattox (1991) reported a K-Ar age of 23.1 ± 1.0 Ma for his sample AP119 in Wildcat Canyon on the east-central Awapa Plateau, considerably younger than the tuff of Albinus Canyon, which yielded a K-Ar age on plagioclase of 25.3 ± 1.3 Ma (Rowley and others, 1994); however, Bailey and Marchetti (in prep.; see also UGS and NIGL, 2012) reported $^{40}Ar/^{39}Ar$ ages of 25.68 ± 0.19 Ma (groundmass concentrate) and, our preferred age, 25.13 ± 0.02 Ma (sanidine) for their trachyte tuff of Lake Creek on the Fish Lake Plateau; as much as about 500 feet (150 m) thick on the Awapa Plateau, but only about 300 feet (90 m) of the unit is exposed in this quadrangle.

Rocks apparently equivalent to the trachyte tuff of Lake Creek are known by a variety of names on the Sevier Plateau and nearby areas. The stratigraphic position, age, petrography, and chemistry of the densely welded, phenocryst-poor trachyte tuff of Lake Creek is similar to that of the comparatively thin Kingston Canyon and Antimony Tuff Members of the Mount Dutton Formation (Anderson and Rowley, 1975), the tuff of Albinus Canyon (Steven and others, 1979; Cunningham and others, 1983), and the flows of Deer Spring Draw (Nelson, 1989). It is possible that the trachyte tuff of Lake Creek correlates with one or more of these units. Rowley and others (1994, p. 15) noted that

> "The tuff of Albinus Canyon is considered a proximal accumulation from a nearby source [possibly buried under southernmost Sevier Valley] that also erupted the Kingston Canyon and Antimony Tuff Members. The similarity in composition, appearance, and age of the tuff of Albinus Canyon and the Kingston Canyon and Antimony Tuff Members with the units of the Isom Formation and other units from sources in Nevada is a regional petrologic problem about which we and others currently are perplexed. Best, Christiansen, and others (1989) have discussed the Isom compositional type of tuff [densely welded, phenocryst-poor trachyte] and other compositional types and have suggested that they represent magmas in different areas that had similar origins and crystallization histories."

That the vent or vents of these densely welded rheomorphic ash-flow tuffs is not apparent may indicate that their magma source was deep in the crust and thus never expressed by typical collapse caldera (Ekren and others, 1984).

One difficulty with possible equivalency of these units is that the trachyte tuff of Lake Creek is the thickest among them, typically an order-of-magnitude thicker than the Kingston Canyon and Antimony Tuff Members even though it is far from the inferred source in southernmost Sevier Valley. Possibly this is due to accumulation on the flanks of the Marysvale volcanic complex; that is, these units are relatively thin on the volcanic pile itself, yet thicken eastward where they accumulated in paleovalleys that radiated away from the center of the pile. Ongoing research on regional correlation of these units may allow us to replace the temporary, informal name "trachyte tuff of Lake Creek" with earlier established nomenclature.

Tjv **Latite of Johnson Valley** (upper Oligocene) – Gray, weathering to brownish-gray, densely welded, porphyritic trachyandesite (latite) with 25 to 35% phenocrysts of plagioclase and pyroxene and minor olivine; plagioclase phenocrysts, commonly 0.4 inch (1 cm) in length, and slightly smaller pyroxene phenocrysts are typically present in subequal amounts, although some exposures show prominent plagioclase and smaller and fewer pyroxene phenocrysts; interpreted by Ball and others (2009) as an ash-flow tuff likely consisting of several cooling units, but they found no prominent vitrophyres, nor did Biek and others (2015b) in exposures on the Awapa Plateau; however, a vitrophyre is present at the base of what appears to be this same unit as shown by ongoing mapping of the western flank of the Fish Lake Plateau (Grant Willis, personal communication, June 22, 2016); Smith and others (1963) recognized three units at Boulder Mountain southeast of this map area; includes potassium-rich mafic lava flows of Mattox (2001) given their similar stratigraphic position, petrology, and chemistry; weathers to rough, dark-colored, bouldery outcrops that on aerial photographs look similar to younger, blocky lava flows; major- and trace-element discrimination diagrams (UGS unpublished data) show that samples identified as latite of Johnson Valley (Biek and others, 2015b) cluster remarkably tightly with few exceptions, notably the large-ion lithophile elements Ba and Sr, which are enriched in the northern Awapa Plateau as also noted by Mattox (1991); further, this similar geochemistry of widely scattered samples supports interpretation of the unit as an ash-flow tuff rather than having erupted as multiple lava flows, yet we remain uncertain whether the unit represents one or more ash-flow tuffs or lava flows; several $^{40}Ar/^{39}Ar$ ages for this unit are about 25 to 26 Ma (UGS and NMGRL, 2007, 2009; UGS and NIGL, 2012; UGS unpublished data), but because it clearly underlies the trachyte tuff of Lake Creek, our preferred age for the latite of Johnson Valley is 26 Ma; forms the cap of nearby Boulder Mountain and Thousand Lake Mountain east of the map area; incomplete section is about 250 to 300 feet (75–90 m) thick in this quadrangle, but is as much as 500 feet (150 m) thick at Big Hollow to the west (Mattox, 1991, 2001); incomplete exposures near Fish Lake may be 800 feet (245 m) thick (Bailey and Marchetti, in prep.) and Marchetti and others (2013) reported that the unit is locally in excess of 1000 feet (300 m) thick on the Fishlake Plateau, but these thicknesses are suspect due to widespread colluvial cover and possible duplication by normal faults; Smith and others (1963) reported this unit to be 475 feet (145 m) thick at Boulder Mountain.

Tsdb **Tertiary sedimentary strata, Dipping Vat Formation, and Three Creeks Tuff Member of the Bullion Canyon Volcanics, undivided** (Oligocene to Eocene?) – Used as a stacked unit involved in large landslide complexes north of Bicknell.

Tbu **Bullion Canyon Volcanics, undivided** (Oligocene) – Pale- to reddish-brown volcanic mudflow (lahar) with large blocks of dacitic tuff (possibly of the 27-Ma Three Creeks Tuff Member of the Bullion Canyon Volcanics); exposed east of Bicknell in a steeply west-dipping panel caught between splays of the Thousand Lake fault zone, where it is present below the latite of Johnson Valley, and also present immediately to the southeast; the nature of its upper contact is uncertain but likely of landslide origin; also mapped at Saddle Knoll south of Bicknell where it is a brecciated, light-gray, coarse-grained porphyry of unknown correlation, with plagioclase, quartz, and biotite phenocrysts in a coarse-grained groundmass, and immediately northeast of Saddle Knoll where this unknown porphyry and intensely brecciated blocks of volcaniclastic strata, Tertiary sedimentary strata, and Carmel Formation are juxtaposed in a fault sliver of the Thousand Lake fault zone; this latter exposure includes resistant, light-brownish-gray, silica-cemented, angular blocks possibly of the Shinarump Member of the Chinle Formation; as much as about 40 feet (12 m) thick near Bicknell and probably about 150 feet (45 m) thick at Saddle Knoll.

Tdv **Dipping Vat Formation** (lower Oligocene to upper Eocene) – Light-gray to white, thin- to medium-bedded, fine- to medium-grained, locally coarse-grained, sandstone, siltstone, and mudstone exposed along the Thousand Lake fault zone east of Bicknell; mudstone is typically smectitic with a conspicuous popcorn-like weathered surface, and coarser sandstone commonly contains conspicuous biotite; upper contact is not exposed due to faulting at entrance to Sand Wash, but immediately to southeast, map unit is overlain by quartzite pebble conglomerate (Ts) in what may be a structural (landslide) contact; Dipping Vat strata have not been reported on the mostly covered flanks of nearby Thousand Lake Mountain and Boulder Mountain (Doelling and Kuehne, 2007), yet its presence in the Thousand Lake Mountain fault zone suggests that the Dipping Vat Formation is indeed present, if concealed, and thus one of the principal zones of failure for large landslide complexes that blanket the flanks of these mountains; fine-grained volcaniclastic strata are locally exposed as chaotic blocks within landslide deposits on the flanks of Thousand Lake Mountain and Boulder Mountain (QTms/Tsdb); we tentatively assign these beds to the Dipping Vat Formation (defined from exposures on the northern flank of the Marysvale volcanic field [McGookey, 1960], but realize similar strata on the southern flank of the field are known as the Brian Head Formation); several fission-track and K-Ar ages from the Dipping Vat Formation in the Aurora quadrangle and nearby area show it to be about 36 to 29 Ma (Willis, 1988), whereas numerous isotopic ages on the Brian Head Formation show it to be 37 to 30 Ma (Biek and others, 2015a); east of Bicknell, these beds yielded three teeth of *Saltirius utahensis* (stingray) only known from the variegated unit of the Brian Head Formation (Jeff Eaton, personal communication, May 24, 2016); incomplete section about 150 feet (45 m) thick east of Bicknell; Dipping Vat strata are as much as about 600 feet (180 m) thick on the northern flank of the Marysvale volcanic field (Willis, 1986); Biek and others (2015b) reported that Brian Head strata at the southwestern margin of the Awapa Plateau are no more than about 1000 feet (300 m) thick in the upper reaches of Antimony Canyon, similar to its thickness on the southern Sevier Plateau southwest of this map area (Biek and others, 2015a).

Unconformity

Ts **Tertiary sedimentary strata** (middle Eocene? to Paleocene?) – Reddish-brown mudstone, yellowish-brown sandy and micritic limestone, and quartzite- and chert-pebble conglomerate; clasts are rounded, pebble- to small-cobble-size quartzite of tan, gray, and white hues; contains uncommon red quartzite and rare black chert and Paleozoic limestone pebbles; typically poorly cemented and non-resistant; conglomerate is present in a small fault sliver in Crescent Canyon and, southwest of Sunglow Campground where it is interpreted to be part of an old landslide mass, as a thin bed sandwiched between Dipping Vat Formation (Tdv) below and highly fractured Bullion Canyon Volcanics (Tbu) and latite of Johnson Valley (Tjv) above; similar pebbles are locally common as an unmapped lag along the length of the Thousand Lake fault zone, thus indicating the widespread presence of this unit on the covered slopes of Thousand Lake Mountain and Boulder Mountain; age and correlation uncertain, but may be related to middle Eocene (Duchesnean Land Mammal Stage, about 42–38 Ma) clastic strata of Flat Top (map unit Tc of Doelling and Kuehne, 2007), which yielded a lower jaw of *Telatoceras*, a small extinct rhinoceros (DeBlieux, 2006); as much as a few tens of feet thick.

Unconformity

JURASSIC

Je **Entrada Sandstone** (Middle Jurassic) – Pale- to light-brown, fine-grained sandstone and silty sandstone that weathers to steep slopes; indistinctly bedded but with local ripple cross-stratification; lower part contains minor secondary gypsum veins; exhibits local reduced zones and spots that are light gray; deposited in tidal-flat, sabkha, and coastal-dune environments (Peterson, 1988, 1994); incomplete section of a faulted-bounded block southwest of Black Ridge is about 245 feet (75 m) thick; Doelling and Kuehne (2007) reported that it is 650 to 800 feet (200–245 m) thick in the east half of the Loa 30′ x 60′.

Jc **Carmel Formation, undivided** (Middle Jurassic) – Undivided in a fault block along the Thousand Lake fault zone north of Bicknell, and also used on cross sections. The Bicknell quadrangle lies near the northern end of a region of extensive sand influx during the Middle Jurassic from north-central Arizona into south-central Utah, which created complex and intertonguing relations between shallow-marine, tidal-flat, and fluvial-eolian deposition of the Carmel Formation and Page Sandstone (Doelling and others, 2013). Carmel Formation nomenclature of Sprinkel and others (2011a) and Doelling and others (2013) is used in this map. The Carmel Formation was deposited in a back-bulge basin and, together with the underlying Temple Cap Formation, provides the first clear record of the effects of the Sevier orogeny in southwestern Utah (Sprinkel and others, 2011a; Phillips and Morris, 2013). Middle Jurassic age is from Imlay (1980), Sprinkel and others (2011a), and Doelling and others (2013). Thicknesses are from an unpublished measured section by Douglas Sprinkel and Hellmut Doelling (Utah Geological Survey, written communication, 2015). Pipiringos and O'Sullivan (1978) interpreted that Temple Cap and Carmel strata were separated by their J-2 unconformity, but new radiometric ages and palynomorph data suggest that the J-2 does not exist or is a very short hiatus in southern Utah (Sprinkel and others, 2011a; Doelling and others, 2013).

Jcw **Winsor Member** (Middle Jurassic, Callovian to Bathonian) – Undivided on cross section and in fault blocks along Thousand Lake fault zone, but along the northern half of the Waterpocket Fold it is divided into a lower gypsiferous subunit and a thicker upper banded subunit; deposited on a broad, sandy mud flat during the second major regression of the Middle Jurassic seaway (Imlay, 1980; Blakey and others, 1983).

Jcwb **Banded subunit** (Callovian to Bathonian) – Interbedded, mostly light-gray, yellowish-gray, greenish-gray, and minor reddish-brown siltstone, mudstone, and fine-grained sandstone, and numerous, thin (<3 feet [3 m] thick), white alabaster gypsum beds; thin, cross-cutting gypsum veins are common; mostly non-resistant and slope forming except for thin gypsum ledges; upper, conformable contact placed at the top of the highest thin gypsum ledge and at the base of massive weathering, pale- to light-brown, fine-grained sandstone of the Entrada Sandstone; incomplete section is 404 feet (123 m) thick on Black Ridge (Douglas Sprinkel, written communication, May 14, 2015), and Doelling and Kuehne (2007) reported that it thins eastward from 450 to 120 feet (137–37 m) thick in the east half of the Loa 30′ x 60′ quadrangle.

Jcwg **Gypsiferous subunit** (Bathonian) – Thick alabaster gypsum beds as much as several tens of feet thick and interbedded, thin- to medium-bedded, reddish-brown and light-gray siltstone, mudstone, fine-grained sandstone and, below the uppermost thick limestone bed, light-gray, laminated, aphanitic to finely crystalline silty limestone; forms ledgy slopes; upper contact is conformable and gradational and corresponds to the top of the highest thick (> 3 feet [1 m]) gypsum bed; incomplete section is 229 feet (70 m) thick on Black Ridge (Douglas Sprinkel, written communication, May 14, 2015), and Doelling and Kuehne (2007) reported that it thins eastward from 230 to 80 feet (70–24 m) thick in the east half of the Loa 30′ x 60′ quadrangle.

Jcp **Paria River Member** (Middle Jurassic, Bathonian) – Light-gray, greenish-gray, yellowish-gray, and minor reddish-brown, thin- to medium-bedded, fine-grained sandstone, siltstone, and mudstone, minor light-gray, aphanatic to finely crystalline, chippy-weathering limestone, and numerous thick white alabaster gypsum beds including a 31-foot-thick (10 m) bed at the base of the member; upper contact corresponds to the top of a bench-forming yellowish-gray sandy limestone or fine-grained calcareous sandstone; deposited in shallow-marine and coastal-sabkha environments during the second major transgression of the Middle Jurassic seaway (Imlay, 1980; Blakey and others, 1983); Sprinkel and others (2011a) reported an $^{40}Ar/^{39}Ar$ age on zircon from a volcanic ash of 165.9 ± 0.51 Ma on lower Paria River strata in south-central Utah; 211 feet (64 m) thick on Black Ridge (Douglas Sprinkel, written communication, May 14, 2015), and Doelling and Kuehne (2007) reported that it thins eastward from 220 to 100 feet (67-30 m) thick in the east half of the Loa 30′ x 60′ quadrangle.

As mapped southeast of Bicknell, near Sunglow Campground, the base of the member is tentatively placed at the base of a ridge-forming, light-gray, sandy limestone and calcareous mudstone capped by a 3- to 6-foot-thick (1–3 m), yellowish-brown, fine- to coarse-grained sandy limestone with subrounded, brown and gray chert grains 1 to 3 mm in diameter; this unusual, coarse sandstone interval is in turn overlain by a few tens of feet of light-gray to grayish-brown calcareous mudstone and fine- to medium-grained sandstone with local coarse grains of subrounded black chert; here, the remaining Carmel is apparently cut out by faulting.

Jcl **Crystal Creek and Co-op Creek Limestone Members, undivided** (Middle Jurassic, Bathonian to Bajocian) – Combined unit due to map scale limitations; members described separately below.

Jcx **Crystal Creek Member** (Middle Jurassic, Bathonian) – Non-resistant, thin- to medium-bedded, reddish-brown and yellowish-brown siltstone and fine-grained sandstone; upper contact typically corresponds to the base of a thick, white, nodular Paria River gypsum bed; as mapped southeast of Bicknell, near Sunglow Campground, the middle part of the member tentatively includes a channel-form, 10-foot-thick (3 m), light-gray to yellowish-brown intraformational pebble conglomerate with subrounded calcareous sandstone rip-up clasts as much as 3 inches (8 cm) in diameter; Kowallis and others (2001) reported two $^{40}Ar/^{39}Ar$ ages of 166 to 167 Ma for altered volcanic ash beds (that were likely derived from a magmatic arc in what is now southern California and western Nevada) within the member near Gunlock, and Doelling and others (2013) reported an average $^{40}Ar/^{39}Ar$ age on sanidine of 167.1 ± 0.70 Ma and an average U-Pb age on zircon of 165.7 ± 1.0 Ma for several ash beds in coeval Thousand Pockets Member in southcentral Utah; deposited in coastal-sabkha and tidal-flat environments during the first major regression of the Middle Jurassic seaway (Imlay, 1980; Blakey and others, 1983); 30 feet (9 m) thick on Black Ridge (Douglas Sprinkel, written communication, May 14, 2015).

Jcc **Co-op Creek Limestone Member** (Middle Jurassic, Bajocian) − Thin- to medium-bedded, light-gray, light-olive-gray, yellowish-brown, and minor reddish-brown micritic limestone, sandy limestone, calcareous, fine- to medium-grained sandstone, and calcareous shale; locally fossiliferous with *Isocrinus* sp. crinoid columnals, pelecypods, and gastropods, including a laterally persistant 1- to 2-foot-thick (0.1–0.2 m) coquina located about 10 feet (3 m) above the base of the member; upper contact corresponds to the top of a ledge-forming, brownish-gray sandy limestone with pelecypod fossil hash, above which lies slope-forming, reddish-brown siltstone; as mapped southeast of Bicknell, the middle part of the member includes a reddish-brown siltstone and fine-grained sandstone interval not present at Black Ridge; Kowallis and others (2001) reported several $^{40}Ar/^{39}Ar$ ages of 167 to 168 Ma for altered volcanic ash beds within the lower part of the member in southwest Utah that were likely derived from a magmatic arc in what is now southern California and western Nevada; Sprinkel and others (2011a) also reported $^{40}Ar/^{39}Ar$ ages of 169.2 ± 0.51 Ma and 169.9 ± 0.49 Ma on two ash beds in the lower part of the member in southwestern Utah; deposited in a shallow-marine environment during the first major transgression of the Middle Jurassic seaway (Imlay, 1980; Blakey and others, 1983); 119 feet (36 m) thick on Black Ridge, of which the upper 66 feet (20 m) is equivalent to the Rich Member of the Twin Creek Limestone and the lower 53 feet (16 m) is equivalent to the Slide Rock Member (Douglas Sprinkel, written communication, May 14, 2015).

Jtm **Temple Cap Formation, Manganese Wash Member** (Middle Jurassic) – Reddish-brown, yellowish-orange, yellowish-gray, and yellowish-brown, thin-bedded, fine- to medium-grained quartzose sandstone and minor siltstone; sandstone is typically coarser and more poorly sorted than that of the Navajo Sandstone and locally contains coarse grains; weathers to thin ledges and slopes; overall, lower half is yellowish brown and upper half is reddish brown; upper contact is at the base of a three-foot-thick (1 m) ledge of yellowish-brown, fine-grained sandy limestone; based on $^{40}Ar/^{39}Ar$ ages of sanidine and biotite, and UPb zircon ages, the preferred age of Temple Cap strata is 172.9 ± 0.6 to 170.2 ± 0.5 Ma (Sprinkel and others, 2011a); 43 feet (13 m) thick on Black Ridge (Douglas Sprinkel, written communication, May 14, 2015).

The Bicknell quadrangle lies along the east flank of an early Middle Jurassic paleohigh of the Navajo Sandstone, which likely formed during development of the regional J-1 unconformity (Doelling and others, 2013; Phillips and Morris, 2013). Temple Cap strata thin or are locally absent over this paleohigh, showing that erosional development of the J-1 unconformity later influenced sedimentation during Temple Cap time. Temple Cap strata are not present on much of the Waterpocket Fold, and they are also missing on the vertical, east limb of the large anticline exposed at the entrance to Antimony Canyon, possibly due to the area's location near the axis of this paleohigh or possibly due to attenuation associated with folding in the core of the anticline.

J-1 unconformity (Pipiringos and O'Sullivan, 1978) formed prior to 173 million years ago in southwest Utah (Sprinkel and others, 2011a).

Jn **Navajo Sandstone** (Lower Jurassic) − Massively cross-bedded, moderately well-cemented, pale-reddish-orange and light-gray to white sandstone that consists of well-rounded, fine- to medium-grained, frosted quartz sand; upper half is white on Black Ridge, whereas on the southwest flank of Thousand Lake Mountain only the middle part of the formation is white, in both areas due to alteration, remobilization, and bleaching of limonitic and hematitic (iron-bearing) cement, probably due to hydrocarbon migration (see, for example, Chan and others, 2000; Beitler and others, 2003; Potter and Chan, 2011); 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; ironstone bands and concretions are locally common; prominently jointed due to position on northwest-plunging nose of the Waterpocket Fold and proximity to the Thousand Lake Mountain fault zone, thus weathers to steep rounded knobs and slopes, unlike its typical sheer cliffs; upper, unconformable contact is the J-1 regional unconformity, corresponding to a prominent break in slope, with cross-bedded sandstone below in steep slopes and ledgy slopes of reddish-brown, thin-bedded, sandstone and siltstone of the Manganese Wash 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), part of one of the world's largest coastal and inland paleodune fields (Milligan, 2012); correlative in part 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; Sprinkel and others, 2011b); much of the sand may originally have been transported to areas north and northwest of Utah via a transcontinental river system that tapped Grenvillian-age (about 1.0 to 1.3 Ga) crust involved in Appalachian orogenesis of eastern North America (Dickinson and Gehrels, 2003, 2009a, 2009b; Rahl and others, 2003; Reiners and others, 2005); map patterns show that the Navajo is about 800 feet (245 m) thick on the southwest flank of Thousand Lake Mountain; Doelling and Kuehne (2007) reported that the formation is 800 to 1100 feet (240-330 m) thick in the adjacent east-half of the Loa 30′ x 60′ quadrangle.

Jk **Kayenta Formation** (Lower Jurassic) − Moderate- to dark-reddish-brown, thin- to thick-bedded, fine-grained sandstone and siltstone, and minor mudstone, thin algal-laminated limestone beds, and scattered lenses of intraformational conglomerate with mudstone and siltstone rip-up clasts; planar, low-angle, and ripple cross-stratification is common; upper part was mapped by Doelling and Kuehne (2007) as the "lower tongue" of the Navajo Sandstone, thus including an interval of mostly sandstone 110 to 150 feet (34–46 m) thick, but because this sandstone interval apparently thins westward and becomes less prominent, we prefer to place the upper contact at the stratigraphically highest siltstone interval; forms steep ledgy slope, and, near the top, a broad bench; upper contact is conformable and gradational and corresponds to the top of the highest thin siltstone and mudstone beds, above which is the massively cross-bedded Navajo Sandstone; deposited in river and minor lacustrine environments, although a thick eolian tongue of the Navajo Sandstone, east of the map area, is present in the upper part of the formation (Smith and others, 1963; Friz, 1980; Blakey, 1994; Peterson, 1994; Doelling and Kuehne, 2007); paleocurrent studies at Capitol Reef National Park show that Kayenta streams flowed towards the west in the lower and upper parts of the formation, but that the middle part of the formation is dominantly eolian with winds that blew from west to east (Friz, 1980); map patterns show that as defined here the Kayenta is about 200 feet (60 m) thick on the southwest flank of Thousand Lake Mountain; Doelling and Kuehne (2007) reported that the formation (not including their tongue of the Navajo Sandstone [Jnl]) is 150 to 220 feet (45–67 m) thick in the adjacent east-half of the Loa 30′ x 60′ quadrangle.

JURASSIC-TRIASSIC

JTRw **Wingate Sandstone** (Lower Jurassic to Upper Triassic) − Reddish-brown, light-brown, and pale-reddish-orange, massively cross-bedded, moderately well-cemented, fine-grained sandstone that consists of well-rounded, frosted quartz sand; prominently jointed due to position on northwest-plunging nose of the Waterpocket Fold and proximity to the Thousand Lake Mountain fault zone, thus weathers to steep rounded knobs and slopes, unlike its typical sheer cliffs; upper contact is gradational over several tens of feet and corresponds to the base of the lowest reddish-brown siltstone and mudstone interval; sand was deposited principally from winds out of the northwest (Stewart and others, 1959); basal Wingate strata are Triassic based on fossil trackways (Lockley and others, 2004; Lucas and others, 2005) and paleomagnetic data (Molina-Garza and others, 2003); map patterns show that the Wingate is about 250 feet (75 m) thick on the southwest flank of Thousand Lake Mountain; Doelling and Kuehne (2007) reported that the formation is 300 to 400 feet (90–120 m) thick in the adjacent east-half of the Loa 30′ x 60′ quadrangle, although Sorber and others (2007) reported a thickness of 260 to 310 feet (80–95 m) on the southwest flank of the Fruita anticline in the Twin Rocks quadrangle.

Unconformity

TRIASSIC

TRc **Chinle Formation, undivided** (Upper Triassic, Norian and Rhaetian) − Locally undivided in fault blocks along the Thousand Lake fault zone southeast of Bicknell, and also used on cross section. The Chinle Formation was deposited in a variety of fluvial, floodplain, palustrine, 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; resistant, locally conglomeratic sandstones, including the Shinarump Member, were deposited in braided and meandering streams that flowed north and northwest, whereas mudstone intervals were deposited in floodplains, lakes, and swamps (e.g., Stewart and others, 1972a; Blakey and Gubitosa, 1983, 1984; Lucas, 1993; Dubiel, 1994; Lucas and Tanner, 2007; Dubiel and Hasiotos, 2011). Chinle strata are among the most productive of fossilized continental plants and vertebrates in the world (Benton, 1995). Kirkland and others (2014) reported fossil conifers, giant horsetails, ferns, conchostrachans (clam shrimp), bivalves, and a variety of vertebrates including lungfish, metoposaurids (primitive amphibian), phytosaurs (crocodile-like reptiles), and aetosaurs (armored terrestrial animals) from nearby Capitol Reef National Park. Swelling, smectitic mudstone and claystone are common in the Chinle 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—these clay-rich beds weather to a "popcorn" surface and are responsible for numerous building foundation problems and landslides across its outcrop belt. The Chinle Formation represents a span of about 25 million years, from about 228 to 203 Ma, during the Late Triassic (Irmis and others, 2011; Ramezani and others, 2011, 2014). Kirkland and others (2014) provided a comprehensive summary of the formation at nearby Capitol Reef National Park where they recognized five members; from oldest to youngest these are the Shinarump, Monitor Butte, Moss Back, Petrified Forest, and Owl Rock Members (the Church Rock Member, commonly the uppermost member throughout the region, is not recognized in the Capitol Reef area). Collectively, Chinle strata thicken southward along the Waterpocket Fold, from 404 feet (123 m) near Chimney Rock to 528 feet (161 m) near Burr Trail (Kirkland and others, 2014).

TRcu **Chinle Formation, upper slope former (Owl Rock Member and upper part of the Petrified Forest Member)** (Upper Triassic) – Combined unit here due to map scale limitations and difficulty in placing member contact. The **Owl Rock Member** is reddish-brown, greenish-gray, and grayish-red, commonly mottled, fine- to medium-grained sandstone, siltstone, and mudstone that weathers to steep ledgy slopes mostly covered by talus derived from the Wingate Sandstone. The upper part of the **Petrified Forest Member** is similarly colored mudstone, siltstone, and fine-grained sandstone that weathers to slopes and is gradationally overlain by the Owl Rock Member. Upper, unconformable contact of combined unit is at the base of a thin, mottled, reddish-brown and greenish-gray, fine-grained pebbly sandstone with mudstone- rip-up clasts, above which is the massive, moderate-reddish-orange, eolian sandstone of the Wingate (Kirkland and others, 2014). In the east half of the Loa 30′ x 60′ quadrangle, this combined unit is 140 to 220 feet (43–67 m) thick (Doelling and Kuehne, 2007); Martz measured 26 feet (7.8 m) of upper Petrified Forest strata and 125 feet (38.2 m) of Owl Rock strata near Chimney Rock in Capitol Reef National Park (Kirkland and others, 2014); map patterns show that the upper slope-forming part of the Chinle as mapped here is about 130 feet (40 m) thick in the Rock Canyon area southeast of Bicknell.

TRcl **Chinle Formation, lower slope former (lower Petrified Forest Member and Mossback Member)** (Upper Triassic) – Combined unit here due to map scale limitations and difficulty in placing member contact. Lower part of the **Petrified Forest Member** is variably colored and commonly mottled, reddish-brown, yellowish-brown, grayish-red, and greenish-gray mudstone, siltstone, and minor fine-grained sandstone; includes numerous, thick, mottled paleosols with common greenish-gray carbonate nodules; weathers to rounded slopes below a thin sandstone ledge of the informally named Capitol Reef bed, a ledge-forming, fine- to coarse-grained sandstone and pebbly sandstone with mudstone rip-up clasts that is commonly fossiliferous and 15 to 23 feet (4.7–7 m) thick on the Waterpocket Fold (Kirkland and others, 2014). **Mossback Member** is reddish-brown to grayish-brown, thin- to medium-bedded, medium- to coarse-grained sandstone, locally with mudstone rip-up clasts and petrified wood; typically forms ledge and is gradationally overlain by the Petrified Forest Member. Upper contact as mapped here is placed at an abrupt change in slope at the top of the Capitol Reef bed. In the east half of the Loa 30′ x 60′ quadrangle, this combined unit is 90 to 190 feet (27–58 m) thick, but some of that variation may be due to the difficulty in placing the lower contact (Doelling and Kuehne, 2007); Martz measured 20 feet (6 m) of Mossback strata and 63 feet (19.2 m) of overlying Petrified Forest strata near Chimney Rock in Capitol Reef National Park (Kirkland and others, 2014); map patterns show that the lower slope-forming part of the Chinle as mapped here is about 210 feet (65 m) thick in the Rock Canyon area southeast of Bicknell.

TRcm **Chinle Formation, Monitor Butte Member** (Upper Triassic) – Mudstone and sandstone of predominantly gray and greenish-gray hues, with subordinate reddish-brown and yellowish-brown colors; commonly mottled and variegated; sandstone is typically fine to medium grained, rarely coarse grained, and is locally conglomeratic with mudstone rip-up clasts and local petrified wood; dark-yellowish-orange and grayish-orange carbonate nodules, indicative of paleosols, are abundant in the uppermost part of the member; forms rounded slopes; upper gradational contact corresponds to the base of reddish-brown, thin- to medium-bedded, fine- to coarse-grained sandstone and pebbly sandstone with mudstone rip-up clasts of the more resistant Mossback Member; in the east half of the Loa 30′ x 60′ quadrangle, the Monitor Butte Member is 110 to 190 feet (34-58 m) thick (Doelling and Kuehne, 2007); Martz measured 132.5 feet (40.4 m) of Monitor Butte strata near Chimney Rock in Capitol Reef National Park, although the lower part is deformed and thus of uncertain thickness, and noted that the member thickens southward on the Waterpocket Fold (Kirkland and others, 2014); map patterns show that Monitor Butte strata are about 110 feet (33 m) thick in the Rock Canyon area southeast of Bicknell.

TRcs **Chinle Formation, Shinarump Member** (Upper Triassic, lower Norian) – Yellowish-brown, fine- to coarse-grained sandstone and minor pebbly sandstone that forms a prominent cliff; clasts are subrounded quartz, quartzite, and chert; locally contains minor gray to greenish-gray siltstone and mudstone lenses; medium- to thick-bedded with both planar and low-angle cross-stratification and common scour and fill structures; locally contains petrified logs, especially in the upper part; important uranium host (Stewart and others, 1972a); regionally, upper contact is gradational and interfingering (Stewart and others, 1972a), but it is erosional on the Waterpocket Fold where Beer (2005) interpreted it as a sequence stratigraphic boundary (see also Kirkland and others, 2014); age from the likely correlative Mesa Redondo Member of northern Arizona (Ramezani and others, 2014); Kirkland and others (2014) reported that the thickness of

Shinarump strata vary considerably along the Waterpocket Fold due less to deposition in paleovalleys (as is typical elsewhere on the Colorado Plateau) than to pre-Monitor Butte Member erosion; in the east half of the Loa 30′ x 60′ quadrangle, the Shinarump Member is 0 to 145 feet (0–44 m) thick (Doelling and Kuehne, 2007); the Shinarump Member is about 40 feet (12 m) thick in the Rock Canyon area southeast of Bicknell.

TR-3 unconformity (Pipiringos and O'Sullivan, 1978), a widespread episode of erosion across the western U.S. that spans about 10 Ma during late Middle and early Late Triassic time (e.g., Kirkland and others, 2014).

TRm **Moenkopi Formation, undivided** (Lower to Middle Triassic) − Shown on cross section only; in the east half of the Loa 30′ x 60′ quadrangle, the Moenkopi Formation thickens westward from 625 to 990 feet (190-300 m) (Doelling and Kuehne, 2007).

TRmm **Moenkopi Formation, Moody Canyon Member** (lower Middle Triassic) − Reddish-brown, thin- to medium-bedded and laminated siltstone and fine-grained sandstone; commonly ripple laminated and siltstone is commonly micaceous; contains gypsum veinlets and thin beds; forms steep cliff and slope below the Shinarump Member; upper contact is a pronounced unconformity and corresponds to the base of yellowish-brown, medium- to coarse-grained sandstone and pebbly sandstone of the Shinarump Member; deposited in tidal flat environment on a low-relief continental shelf (Stewart and others, 1972b; Dubiel, 1994); probably Anisian (early Middle Triassic) on the Waterpocket Fold (Lucas and Schoch, 2002); in the east half of the Loa 30′ x 60′ quadrangle, the Moody Canyon Member of the Moenkopi Formation thickens westward from 260 to 425 feet (80–130 m) thick, whereas the entire Moenkopi Formation thickens westward from 625 to 990 feet (190–300 m) thick (Doelling and Kuehne, 2007); map patterns show that an incomplete section of the Moody Canyon Member is about 230 feet (70 m) thick near where the Fremont River exits the quadrangle.

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