UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

INTERIM GEOLOGIC MAP OF THE WEST PART OF THE PANGUITCH 30' X 60' QUADRANGLE, GARFIELD, IRON, AND KANE COUNTIES, UTAH – YEAR 2 PROGRESS REPORT

by
Robert F. Biek[1], Florian Maldonado[2], David W. Moore[3], John J. Anderson[4], Peter D. Rowley[5], Van S. Williams[3], David Nealey[3], and Edward G. Sable[3]

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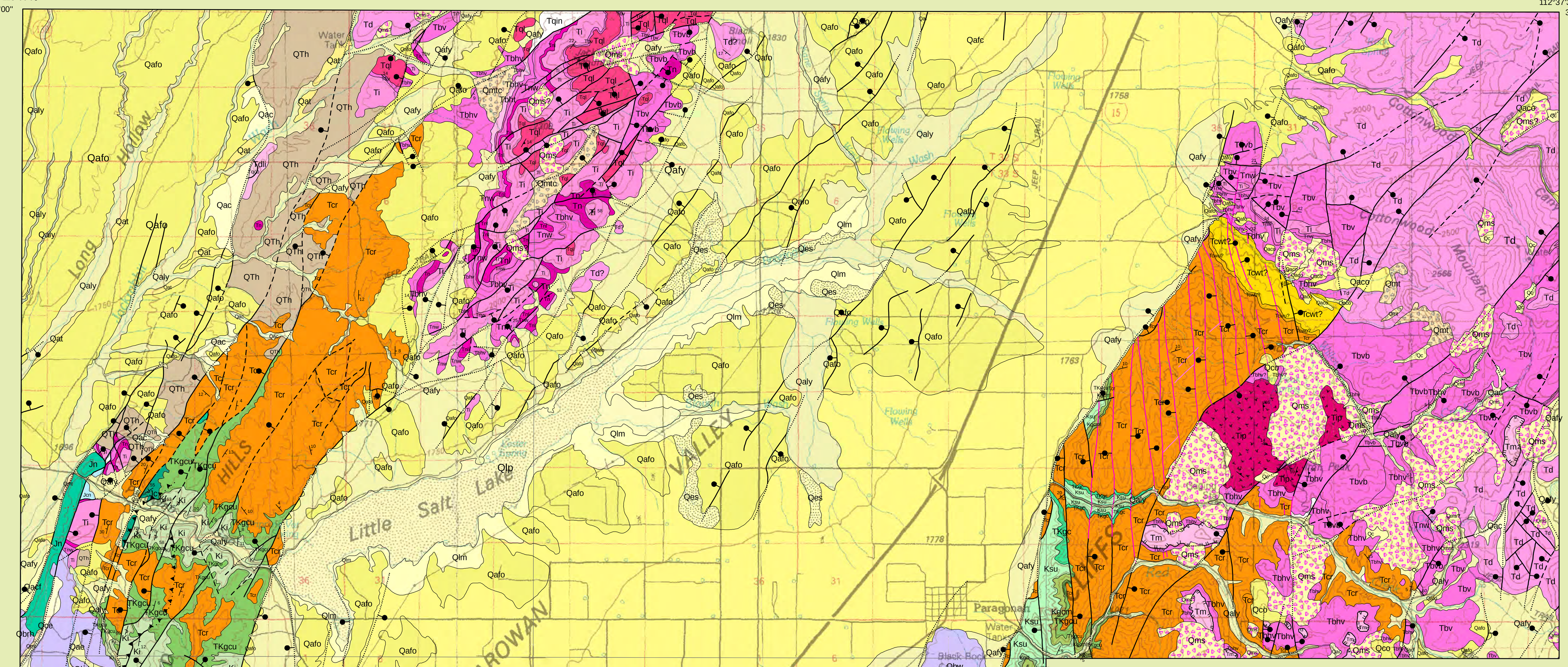
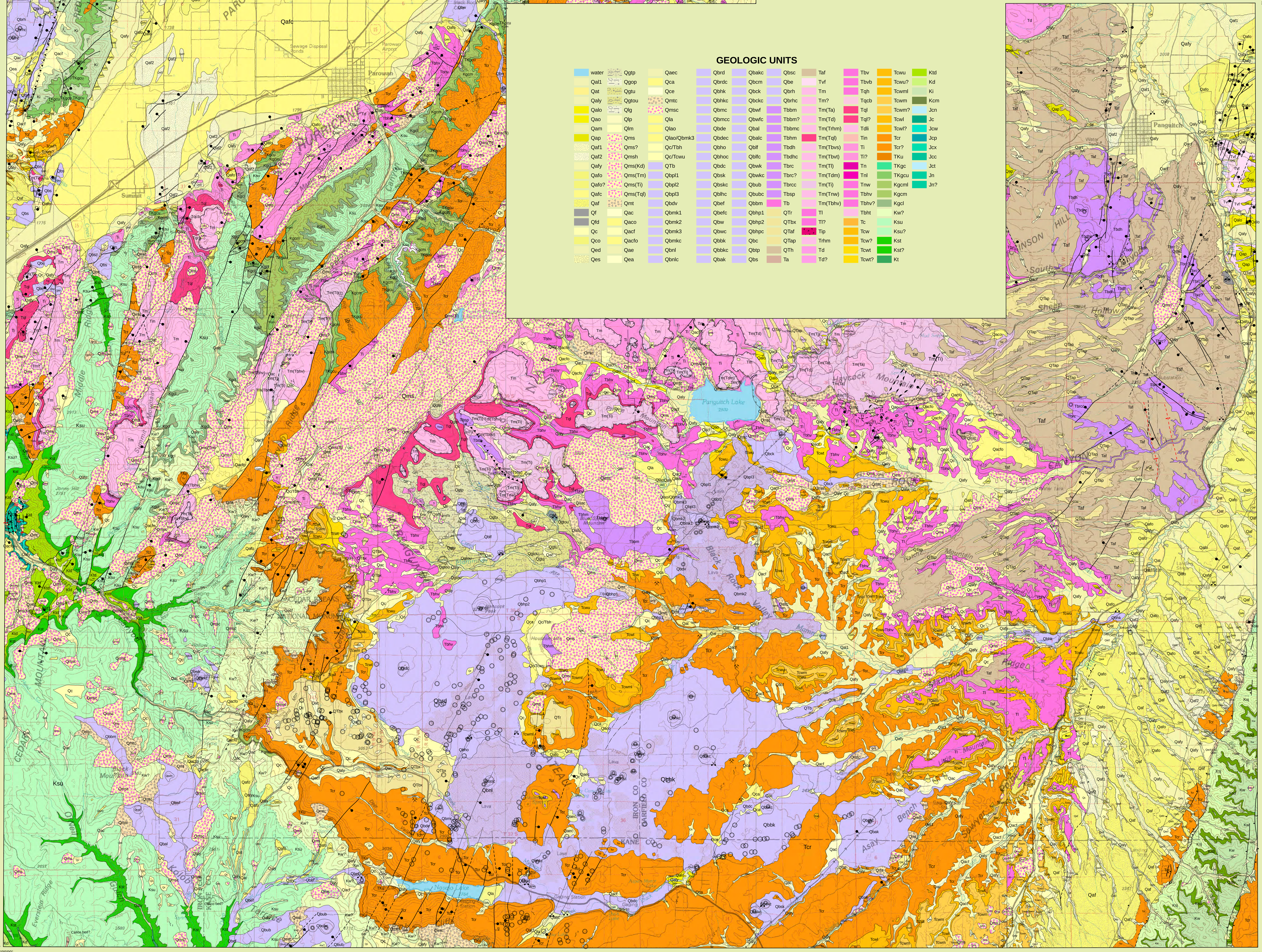
113°00'00"
38°00'00"
112°37'30"
38°00'00"



112°22'30"
37°52'30"



GEOLOGIC UNITS

water	Qgtp	Qaec	Qbrd	Qbakc	Qbsc	Taf	Tbv	Tcwu	Ktd
Qal1	Qgop	Qca	Qbrdc	Qbcm	Qbe	Tvf	Tbvb	Tcwu?	Kd
Qat	Qgtu	Qce	Qbhk	Qbck	Qbrh	Tm	Tqh	Tcwml	Ki
Qaly	Qgtou	Qmtc	Qbhkc	Qbckc	Qbrhc	Tm?	Tqcb	Tcwm	Kcm
Qalo	Qlg	Qmsc	Qbmc	Qbwf	Tbbm	Tm(Ta)	Tql	Tcwm?	Jcn
Qao	Qlp	Qla	Qbmcc	Qbwfc	Tbbm?	Tm(Td)	Tql?	Tcwl	Jc
Qam	Qlm	Qlao	Qbde	Qbal	Tbbmc	Tm(Trhm)	Tdli	Tcwl?	Jcw
Qap	Qms	Qlao/Qbmk3	Qbdec	Qbalc	Tbhm	Tm(Tql)	Tin	Tcr	Jcp
Qaf1	Qms?	Qc/Tbh	Qbho	Qblf	Tbdh	Tm(Tbvs)	Ti	Tcr?	Jcx
Qaf2	Qmsh	Qc/Tcwu	Qbhoc	Qblfc	Tbdhc	Tm(Tbvt)	Ti?	TKu	Jcc
Qafy	Qms(Kd)	QTb	Qbdc	Qbwk	Tbrc	Tm(Tl)	Tn	TKgc	Jct
Qafo	Qms(Tm)	Qbpl1	Qbsk	Qbwkc	Tbrc?	Tm(Tdm)	Tnl	TKgcu	Jn
Qafo?	Qms(Ti)	Qbpl2	Qbskc	Qbub	Tbrcc	Tm(Ti)	Tnw	Kgcml	Jn?
Qafc	Qms(Tql)	Qbpl3	Qblhc	Qbubc	Tbsp	Tm(Tnw)	Tbhv	Kgcm	
Qaf	Qmt	Qbdv	Qbef	Qbbm	Tb	Tm(Tbhv)	Tbhv?	Kgcl	
Qf	Qac	Qbmk1	Qbefc	Qbhp1	QTr	Tl	Tbht	Kw?	
Qfd	Qaco	Qbmk2	Qbw	Qbhp2	QTbx	Tl?	Tc	Ksu	
Qc	Qacf	Qbmk3	Qbwc	Qbhpc	QTaf	Tip	Tcw	Ksu?	
Qco	Qacfo	Qbmkc	Qbbk	Qbc	QTap	Trhm	Tcw?	Kst	
Qed	Qae	Qbnl	Qbbkc	Qbtp	QTh	Td	Tcwt	Kst?	
Qes	Qea	Qbnlc	Qbak	Qbs	Ta	Td?	Tcwt?	Kt	

37°30'00"
113°00'00"
37°30'00"
112°22'30"

Base from USGS Panguitch 30 x 60 Quadrangle (1980)
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1886

Project Manager: Douglas A. Sprinkel
GIS and Cartography: Basia Matyjasik
Lori Douglas
Jay Hill

CONTOUR INTERVAL 50 METERS

SCALE 1:65,000

10000 0 10000 20000 30000 40000 50000 Feet
2 0 2 4 6 8 10 Miles
4 0 4 8 12 Kilometers

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W E
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Utah Department of Natural Resources
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2011

MAP UNIT DESCRIPTIONS

QUATERNARY

Alluvial deposits

Qal_1 **Stream alluvium** (Holocene) − Moderately sorted sand, silt, clay, and pebble to boulder gravel deposited in active stream channels and floodplains of the Sevier River and major tributaries; locally includes minor stream-terrace alluvium as much as about 10 feet (3 m) above current base level; probably less than 30 feet (<9 m) thick.

Qat **Stream-terrace alluvium** (Holocene to middle? Pleistocene) − Moderately sorted sand, silt, and pebble to boulder gravel that forms incised gently sloping terraces above principal streams in the mapped area; deposited in stream-channel environment, but locally includes colluvium and small alluvial fans; terraces are at elevations of 10 to 120 feet (3-35 m) above adjacent streams, but are not subdivided here due to limitations of map scale; typically less than 20 feet (<6 m) thick.

Qaly **Younger stream alluvium** (Holocene) − Similar to stream alluvium (Qal_1) and lower elevation stream-terrace alluvium (Qat), but undivided here due to limitations of map scale; includes small alluvial-fan deposits from tributary drainages; locally includes historical debris-flow and debris-flood deposits derived from tributary drainages, as, for example, the deposits of the 1995 Black Mountain debris flow that entered the upper reaches of Coal Creek in Cedar Canyon (Giraud and Lund, 2006); typically less than 20 feet (<6 m) thick, but deposits of major stream valleys may locally exceed 30 feet (9 m) thick.

Qalo **Older stream alluvium** (Holocene and upper Pleistocene) – Similar to lower- to middle-elevation stream-terrace alluvium (Qat), but mapped in upland drainages not well graded to the Sevier River; typically less than 20 feet (<6 m) thick.

Qao **Oldest stream alluvium** (Pleistocene) – Moderately sorted sand, silt, and pebble to boulder gravel that forms topographically inverted channel deposits at the mouth of Clear Creek and on the south side of Panguitch Lake, both in the Panguitch Lake 7.5' quadrangle; the latter deposits were well exposed near Panguitch Lake in excavations associated with a new housing development that revealed interbedded sand and pebbly to cobbly, locally iron-stained gravel containing clasts mostly of the Isom Formation (Ti; typically grussy weathering) and subordinate chalcedony and quartzite, but apparently lacking basalt; unit also includes deposits that underlie the nearby Cooper Knoll lava flow and that consist of subrounded to rounded pebbles to boulders of the Isom Formation, mafic volcanic rocks, chalcedony, and, especially near the base of the deposits, quartzite pebbles and cobbles; the source of the quartzite pebbles and cobbles is unknown, but they may be recycled from the Grand Castle Formation now exposed in grabens below the western rim of the Markagunt Plateau; deposits near Panguitch

Lake are 40 to 60 feet (12-18 m) thick, and those underlying the Cooper Knoll lava flow are as much as 120 feet (35 m) thick.

Qam **Marsh alluvium** (Holocene and upper Pleistocene) − Dark-yellowish-brown clay, silt, sand, and minor gravel lenses deposited in closed depressions on landslides and glacial moraines in the Lowder Creek area east of Brian Head peak; forms small marshy areas characterized by cattails and other hydrophilic vegetation; typically less than 10 feet (3 m) thick, but marsh alluvium of Lowder Creek bog is at least 21 feet (7 m) thick (Mulvey and others, 1984).

Qap **Pediment alluvium** (Holocene and Pleistocene) **–** Poorly sorted, subangular to rounded sand and gravel that forms a locally resistant cap that overlies eroded bedrock surfaces or locally overlies old fan alluvium (Taf, Qafo) in the Sevier Valley near Panguitch; deposited principally as debris flows, debris floods, and in ephemeral stream channels; probably less than 20 feet (<6 m) thick.

Qaf_1 **Level 1 fan alluvium** (Holocene) − Poorly to moderately sorted, non-stratified, subangular to subrounded, clay- to boulder-size sediment deposited principally by debris flows and debris floods at the mouths of active drainages; equivalent to the upper part of younger fan alluvium (Qafy), but differentiated because Qaf_1 typically forms smaller, isolated fans; probably less than 30 feet (<9 m) thick.

Qaf_2 **Level 2 fan alluvium** (Holocene and upper Pleistocene) − Similar to level 1 fan alluvium (Qaf_1), but forms inactive, incised surfaces cut by younger stream and fan deposits; equivalent to the older, lower part of younger fan alluvium (Qafy); these deposits preserve previously unreported fault scarps east and north of Summit in southern Parowan Valley that appear to be the southwest continuation of the Parowan Valley faults that Black and Hecker (1999) inferred to be latest Pleistocene to early Holocene in age; probably less than 30 feet (<9 m) thick.

Qafy **Younger fan alluvium** (Holocene and upper Pleistocene) − Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment 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; small, isolated deposits are typically less than a few tens of feet thick, but large, coalesced deposits in Sevier and Parowan Valleys are much thicker and form the upper part of Sevier Valley basin-fill deposits.

Qafo **Older fan alluvium** (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, incised surfaces in Sevier and Parowan Valleys; fault scarps locally prominent on these deposits; deposited principally as debris flows and debris floods; exposed thickness as much as several tens of feet.

Qafc **Coalesced fan alluvium of Parowan Valley** (Holocene and Pleistocene) – Similar to younger fan alluvium but forms large, coalesced fans of Parowan Valley; typically exhibits a lower overall slope than younger fan alluvium (Qafy), which we mapped as smaller fans close to the range front; forms unfaulted, active surfaces deposited principally as debris flows and debris floods; thin planar beds with small snails exposed in arroyo walls immediately east of Winn Gap (at the south end of the Red Hills) may represent deposits of a shallow lake or playa (Biek, Maldonado and Sable, in preparation), but it is unclear what may have blocked the outlet at Winn Gap (alternatively, these deposits may simply be distal fan alluvium); thickness uncertain, but Hurlow (2002) showed that Quaternary and Neogene basin fill is in excess of 2000 feet (600 m) thick in southern Parowan Valley west of Parowan and that this basin fill thickens to the northeast; only the uppermost part of this basin-fill is included in map unit Qafc, which we assume to be in excess of several tens of feet thick.

Qaf **Oldest fan alluvium** (Pleistocene) – Similar to older fan alluvium, but forms deeply dissected surfaces with little or no remaining fan morphology; preserved in the footwall of inferred faults in southern Sevier Valley; also used for deposits that enclose the 1.0 Ma Summit lava flow and overlie the 1.3 Ma Red Hills lava flow at the south end of the Red Hills; maximum exposed thickness is about 150 feet (45 m).

Artificial deposits

Qf **Artificial fill** (Historical) − Engineered fill used to construct the dam at Navajo Lake; fill of variable thickness and composition should be anticipated in all developed or disturbed areas; typically less than 20 feet (6 m) thick.

Qfd **Disturbed land** (Historical) − Area in Castle Valley (about 5 miles [9 km] southwest of Panguitch Lake) mapped because it obscures extent of glacial deposits and landforms; also used for large sand and gravel operation southeast of Panguitch.

Colluvial deposits

Qc **Colluvium** (Holocene and upper Pleistocene) − Poorly to moderately sorted, angular, 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; mapped only where it conceals contacts or fills broad depressions; the Claron and Brian Head Formations and Upper Cretaceous strata shed enormous amounts of colluvium, such that an apron of heavily vegetated colluvium (unmapped because it forms a veneer having poor geomorphic expression) typically envelops at least the lower part of steep slopes along their outcrop belt; typically less than 20 feet (6 m) thick.

Eolian deposits

Qed **Eolian dune sand** (Holocene) − Grayish-pink to pale-red, well-sorted silt and fine-grained sand largely stabilized by vegetation; most of the sand consists of tiny clay pellets eroded from the Claron Formation and carried eastward by strong winds and updrafts where it was deposited in the lee of the Cedar Breaks escarpment; typically less than 15 feet (5 m) thick.

Qes **Eolian sand** (Holocene) − Yellowish-brown to reddish-brown, moderately well sorted sand and silt derived from deflation of Little Salt Lake playa deposits located to the south and west; forms thin sheets and poorly developed dunes partly covered by sparse vegetation; generally more saline than underlying alluvium and so allows greasewood to flourish at the expense of sagebrush; description modified from Maldonado and Williams (1993b); typically less than 6 feet (2 m) thick.

Glacial deposits

Glacial till and outwash are present east of Brian Head peak in the Castle Creek and Lowder Creek drainages and in the greater Castle Valley area. These deposits are of the Pinedale alpine glacial advance and an older glaciation of unknown Quaternary age (possibly the Bull Lake alpine glacial advance). Pinedale deposits in their type area in the Wind River Range of Wyoming are about 12 to 24 ka (Imbrie and others, 1984) (with glacial maxima about 16 to 23 ka based on cosmogenic ^{26}Al and ^{10}Be dating; Gosse and others, 1995), and are roughly coeval with the late Wisconsin glaciation, Last Glacial Maximum (LGM), and marine oxygen isotope stage 2 (MIS 2). Early Wisconsin glacial moraines (MIS 4, about 59 to 71 ka; Imbrie and others, 1984) are not known in Utah (Laabs and Carson, 2005). Deposits of the Bull Lake alpine glacial advance in their type area in the Wind River Range of Wyoming are about 128 to 186 ka (Imbrie and others, 1984) (with glacial maxima about 140 to 160 ka; Gosse and Phillips, 2001; Sharp and others, 2003), and are roughly coeval with the Illinoian glaciation or MIS 6.

Qgtp **Glacial till of Pinedale age** (upper Pleistocene) **–** Non-stratified, poorly sorted, sandy pebble to boulder gravel in a matrix of sand, silt, and minor clay; clasts are matrix supported, subangular to subrounded, and were derived from the Leach Canyon, Isom, and Brian Head Formations and the Markagunt megabreccia exposed in the headwaters of the Castle Creek and Lowder Creek drainage basins; terminal moraine at the west end of Castle Valley is at an elevation of about 9750 feet (2973 m), whereas the terminal moraine of the smaller Lowder Creek basin is at Long Flat at an elevation of about 10,100 feet (3080 m); recessional and lateral moraines and hummocky, stagnant ice topography are locally well developed, but sculpted bedrock is absent or inconspicuous, probably owing to the relatively small size and suspected short duration of the glaciers (Mulvey and others, 1984); well-developed terminal and recessional moraines are as much as 120 feet (37 m) thick, but till is much thinner elsewhere and locally consists only of scattered boulders or a veneer of meltout till on bedrock.

The Brian Head-Sidney Peaks area marks the southernmost occurrence of late Pleistocene glaciation in Utah (Mulvey and others, 1984), which was first briefly described by Gregory (1950); Agenbroad and others (1996) interpreted glacial deposits and features that they attributed to their “Mammoth Summit glacier” at the southwest side of Brian Head peak and northern edge of Cedar Breaks National Monument, but that we interpret as landslide deposits and in-place Brian Head Formation, the latter partly covered by a lag of large blocks of the Isom Formation.

Till is Pinedale age based on distinct, well-preserved morainal morphology and relatively unweathered clasts, and minimum limiting age of 14,400 ± 850 ^{14}C yr B.P. from marsh deposits of the Lowder Creek bog that overlies the till (Mulvey and others, 1984; Currey and others, 1986; see also Anderson and others, 1999); Madsen and others (2002) identified the 14,300 ^{14}C yr B.P. Wilson Creek #3 ash (erupted from Mono Craters in California) in the Lowder Creek bog; Marchetti and others (2005, 2007) reported ^{3}He cosmogenic ages of 20.0 ± 1.4 to 23.1 ± 1.3 ka on basaltic andesite boulders on moraines of the main Pinedale advance on Boulder Mountain approximately 80 miles (130 km) to the northeast; Weaver and others (2006) reported ^{3}He cosmogenic ages of 21.1 ± 2.1 to 23.2 ± 3.7 ka on andesite boulders on moraines of the main Pinedale advance on the Fish Lake Plateau just northwest of Boulder Mountain; these ages coincide with the global LGM (21 ± 2 ka) and thus likely are the age of the main Pinedale moraines on the Markagunt Plateau; Marchetti and others (2005) also reported a smaller advance at 15.2 ± 0.5 to 16.8 ± 0.5 ka in the Fish Creek drainage on Boulder Mountain.

Qgop **Glacial outwash of Pinedale age** (upper Pleistocene) **–** Moderately to well-sorted, generally subrounded, clast-supported, pebble to boulder sand and gravel; clasts are typically little weathered and of the same provenance as glacial till (Qgtp); mapped on the east side of Castle Valley where the deposits likely represent the waning stages of Pinedale glaciation; probably about 20 to 30 feet (6-9 m) thick.

Qgtu **Older glacial till of uncertain pre-Pinedale age** (middle? Pleistocene) **–** Similar to glacial till of Pinedale age, but glacial landforms are poorly preserved or absent; forms a low-relief, rubble-covered, locally hummocky surface both northeast and southwest of the Long Flat cinder cone (peak 10,392, the southernmost map unit Qblfc); the northeast flank of the cinder cone is conspicuously truncated, perhaps by this glacial advance; also forms low hills south of Castle Valley, in the southwest part of the Panguitch Lake 7.5’ quadrangle, that are composed almost entirely of large blocks of Leach Canyon Formation, with minor blocks of Isom Formation and chalcedony, that we infer to be deeply eroded remains of a medial or recessional moraine; Mulvey and others (1984) and Currey and others (1986) first suggested that glacial till older than Pinedale age may be present in the Brian Head quadrangle, west of Castle Valley; we sampled a sandy till exposed in a bluff northwest of the confluence of Mammoth and Crystal Creeks (map unit Qgtou) that yielded an Optically Stimulated Luminescence (OSL) age of 48.95 ± 19.24 ka, suggesting that the deposits may correspond to the MIS 3-4 advance; however, given the widespread extent and degree of incision of Qgtou deposits, we interpret these glacial deposits to be older, more likely of Bull Lake age; probably about 10 to 30 feet (3-10 m) thick.

Qgtou **Older glacial till and outwash, undivided** (upper to middle? Pleistocene) – Similar to older glacial till of uncertain pre-Pinedale age, but forms broad, open, boulder-strewn and sage-brush-covered, eastward-sloping surfaces of the Castle Creek and Mammoth Creek areas; exposures just north of the junction of Crystal Creek and Mammoth Creek suggest that most of this surface is underlain by till now deeply incised at its eastern end; glacial outwash deposits, especially those graded to the Pinedale terminal moraines, are presumed to be present locally on this till plain, but are not readily differentiated at this map scale; Mulvey and others (1984) and Currey and others (1986) briefly reported on possible ice wedge polygons as evidence for periglacial features on the southwest side of Castle Valley; glacial till is as much as 60 feet (18 m) thick where exposed near the confluence of Castle and Mammoth Creeks.

Lacustrine and playa deposits

Qlg **Coarse-grained lacustrine sediment** (Holocene and upper Pleistocene) – Sand and gravel deposited at the east end of Navajo Lake, which formed behind a lava dam created by the Henrie Knolls lava flows; probably 10 to 15 feet (3-5 m) thick.

Qlp **Little Salt Lake playa deposits** (Holocene) – Calcareous, saline, and gypsiferous gray clay, silt, and fine-grained sand deposited on the flat playa floor of Little Salt Lake in the southwest part of Parowan Valley; locally includes small dunes of eolian silt; playa formed in response to relative uplift of the Red Hills structural block (Threet, 1952; Maldonado and Williams, 1993a, b); the playa reflects ponded drainage and represents the latest stage in the history of antecedent drainage through Parowan Gap; description modified from Maldonado and Williams (1993b); we infer that a playa has occupied this area intermittently throughout the Pleistocene, but near-surface deposits are doubtless Holocene in age; at least 25 feet (8 m) thick.

Qlm **Little Salt Lake playa-margin deposits** (Holocene and upper Pleistocene) – Calcareous, saline, and gypsiferous gray clay, silt, sand, and local volcanic and quartzite pebbles, deposited on gentle slopes around the margin of Little Salt Lake playa; periodically flooded during high lake levels; includes small alluvial fans, eolian sand and silt, and alluvium; less than 12 feet (4 m) thick.

Mass-movement deposits

Qms, Qmsh, Qms?, Qms(Kd), Qms(Ti), Qms(Tql)

Landslides (Historical? and 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; the largest landslide complexes involve tuffaceous strata of the Brian Head

(Tbhv) and Dakota (Kd and Ktd) Formations, and to a lesser extent the Limerock Canyon Formation (Tl), and are several square miles in size; undivided as to inferred age because new research shows that even landslides having 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); Lund and others (2009) reported on a rock fall associated with the large landslide in Cedar Canyon where State Highway 14 crosses the upper part of the Dakota Formation; Qmsh denotes landslides known to be active in historical time, but any landslide deposit may have been historically active even if not so identified; large rotational slump blocks of Isom Formation (Qms[Ti]) and Leach Canyon Formation (Qms[Tql]) are mapped in the Yankee Meadows graben and in the lower part of the Lowder Creek basin, and slump blocks of Dakota Formation (Qms[Kd]) are mapped in Cedar Canyon; query indicates areas of unusual morphology that may be due to landsliding; thickness highly variable, but typically several tens of feet or more thick and the largest landslides, for example at Yankee Meadows graben, may be as much as 600 feet (200 m) thick (Maldonado and others, 1997).

Dense forests and widespread colluvium may conceal unmapped landslides, and more detailed imaging techniques such as LiDAR may show that many slopes, particularly those developed on the Brian Head (Tbhv), Bear Valley (Tbv), and Limekiln Knoll (Tl) Formations and on Upper Cretaceous strata 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 and upper Pleistocene) − Poorly sorted, angular cobbles and boulders and finer-grained interstitial sediment deposited principally by rock fall 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 only mapped where it conceals contacts or forms broad aprons below cliffs of resistant bedrock units; typically less than 30 feet (9 m) thick.

Mixed-environment deposits

Qac **Alluvium and colluvium** (Holocene and 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, typically in the upper reaches of streams that drain the map area; probably about 20 to 30 feet (6-9 m) thick.

Qacf **Colluvium and fan alluvium** (Holocene and upper Pleistocene?) − Poorly to moderately sorted, non-stratified, clay- to boulder-size sediment deposited principally by debris flows, debris floods, and slope wash at the mouths of active drainages and the base of steep slopes; locally reworked by small, ephemeral streams; forms coalescing apron of fan alluvium and colluvium that cannot be mapped separately at this scale; typically 10 to 40 feet (3-12 m) thick.

Qacfo **Older colluvium and fan alluvium** (Pleistocene) − Mapped below the west edge of the Markagunt Plateau, where it consists of poorly sorted, boulder- to clay-size sediment mostly derived from the Claron, Brian Head, and Isom Formations; deposited principally by debris flows, debris floods, and slope wash; typically forms a resistant cap on isolated hill tops and ridges underlain by Upper Cretaceous strata, remnants of a once larger apron of sediment shed off the plateau and now preserved as deeply dissected inverted valleys; also forms broad bench, preserved in the Iron Peak graben, west of the town of Brian Head, where it is locally exposed in the main scarp of a large landslide complex southeast of Sugarloaf Mountain (T. 36 S., R. 9 W., SE1/4SW1/4 section 8); also forms incised, isolated remnants south of Haycock Mountain, in the upper reaches of the Clear Creek drainage, and a single deposit southeast of Brian Head peak; typically about 20 to 30 feet (6-9 m) thick but larger deposits may locally exceed 50 feet (15 m) thick.

Qae **Alluvium and eolian sand** (Holocene and upper Pleistocene) − Moderately to well sorted, mostly light-reddish-brown silt and sand deposited by sheetwash and ephemeral streams in small drainages and swales on the Henrie Knolls lava flow in the west-central part of the Henrie Knolls quadrangle; probably less than 10 feet (3 m) thick.

Qea **Eolian sand and alluvium** (Holocene and upper Pleistocene) − Moderately to well sorted, yellowish-brown sand deposited by wind and locally reworked by ephemeral streams; includes sand, silt, clay, and pebble to boulder gravel of stream channels; mapped in the southern Red Hills; probably less than 20 feet (6 m) thick.

Qaec **Alluvium, eolian sand, and colluvium** (Holocene and upper Pleistocene) − Moderately sorted, light-reddish-brown and moderate- to dark-yellowish-brown silt and sand and locally gravelly lenses deposited in swales and small drainages on and adjacent to the Henrie Knolls lava flow (Qbhk); the margins of the deposits include significant colluvium derived from adjacent hillslopes developed on the Claron Formation and basaltic lava flows; soils developed on this unit have an argillic horizon 1 to 1.5 feet (0.3-0.5 m) thick of moderate-reddish-brown sandy clay and clayey fine-grained sand; typically less than 10 feet (3 m) thick, although deposits in the Cow Lake area, south of the Henrie Knolls flows, are likely as much as 20 feet (6 m) thick.

Qca **Colluvium and alluvium** (Holocene to middle Pleistocene) − Poorly to moderately sorted, angular, clay- to pebble-size, locally derived sediment deposited principally by slope wash and locally reworked by alluvial processes;

typically mapped where lava flows dammed local washes causing ponding of mixed colluvial and alluvial sediment; distal, finer-grained parts form broad, open meadows; thickness uncertain, but likely less than about 20 feet (6 m) thick.

Qce **Colluvium and eolian sand** (Holocene to upper Pleistocene) − Poorly to moderately sorted, angular, clay- to boulder-size, locally derived sediment **—** partly covered by a veneer of eolian sand **—** deposited by slope wash on moderate slopes and in shallow depressions in the Red Hills graben south of Parowan Gap; colluvial debris is derived from the Red Hills lava flow and underlying Navajo Sandstone; probably less than 20 feet (6 m) thick.

Qmtc **Talus and colluvium** (Holocene and upper Pleistocene) **–** Poorly sorted, angular to subangular, cobble- to boulder-size and finer-grained interstitial sediment deposited principally by rock fall and slope wash on steep slopes throughout the quadrangle; includes minor alluvial sediment at the bottom of washes; generally less than 30 feet (9 m) thick.

Qmsc **Landslides and colluvium** (Holocene and upper Pleistocene) **–** Landslides and colluvium impractical to differentiate at this scale; typically mapped below the west rim of the Markagunt Plateau, where Upper Cretaceous strata, locally covered by basalt talus and colluvium, reveal evidence of slumping and soil creep; as much as several tens of feet thick.

Qla **Lacustrine sediment and alluvium** (Holocene) − Not exposed, but forms the meadow of Blue Spring Valley about 2 miles (3 km) southwest of Panguitch Lake, which we interpret to be moderately to well-sorted, thinly bedded, light-gray and light-brown, fine-grained sand, silt, and clay derived principally from Brian Head strata in the Bunker and Deer Creek drainages; upper surface is marked by numerous small stream channels and meander cutoffs; also mapped near the east end of Navajo Lake, where it consists of fine-grained sediment eroded from the red member of the Claron Formation.

Blue Spring Valley was flooded to form a shallow reservoir following completion of the Blue Spring Valley dam in the late 1800s or early 1900s; the small dam was breached by 1917 (Ipson and Ipson, 2008). The valley is now drained at its north end by Spring Creek, which may have formed in response to the Miller Knoll lava flows that blocked the original outlet at the southeast end of the valley possibly as late as middle Holocene time. Lacustrine sediment and alluvium is likely several tens of feet thick in Blue Spring Valley, and may overlie stream deposits of ancestral Bunker Creek, which may have exited the southeast side of the valley prior to being blocked by the Miller Knoll lava flows.

Qlao **Older lacustrine sediment and alluvium** (Holocene and upper Pleistocene) − Similar to lacustrine sediment and alluvium (Qla), but forms incised surfaces 5 to 10 feet (2-3 m) above the meadows of Blue Spring Valley; likely several tens of feet thick.

Stacked unit deposits

Stacked unit deposits are used to indicate 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 those areas where bedrock is almost wholly obscured by surficial deposits that are derived from more than just residual weathering of underlying bedrock.

Qlao/Qbmk$_3$

Older lacustrine sediment and alluvium over the Miller Knoll lava flow (Holocene and upper Pleistocene/Holocene to upper Pleistocene) − Mapped along the southeast edge of Blue Spring Valley (about 2 miles [3 km] southwest of Panguitch Lake) where the oldest Miller Knoll lava flow (Qbmk$_3$) is partly concealed by a veneer of sediment interpreted to be a mixture of lacustrine and alluvial, and possibly eolian, sand and silt; Blue Spring Valley likely drained through Black Rock Valley prior to being blocked by the Miller Knoll lava flows, with lacustrine and alluvial sediment accumulating in the basin upstream of the flows; surficial cover is likely less than 6 feet (2 m) thick.

Qc/Tbh

Colluvium over the Brian Head Formation (Holocene to Pleistocene/Oligocene to Eocene) – Mapped on the west flank of Houston Mountain (6 miles [10 km] east of Cedar Breaks National Monument) and south of the town of Brian Head, where colluvium, residual deposits, and possibly landslide deposits conceal the underlying Brian Head Formation; at Houston Mountain, colluvium includes large blocks of the Houston Mountain lava flow enclosed in a matrix of colluvium derived from weathered, tuffaceous Brian Head strata; surficial cover may exceed 20 feet (6 m) thick.

Qc/Tcwu

Colluvium over the upper limestone unit of the white member of the Claron Formation (Holocene and upper Pleistocene/Eocene) – Mapped on the southwest side of Houston Mountain (6 miles [10 km] east of Cedar Breaks National Monument) where colluvium conceals the underlying upper limestone unit of the white member of the Claron Formation; colluvium includes large blocks of the Houston Mountain lava flow enclosed in a matrix of colluvium derived from weathered, tuffaceous Brian Head strata and the upper limestone unit of the white member of the Claron Formation; surficial cover may exceed 10 feet (3 m) thick.

QUATERNARY-TERTIARY

Holocene(?) to Late Tertiary lava flows

Basaltic and andesitic lava flows in the Panguitch 30’ x 60’ quadrangle are at the northern edge of the Western Grand Canyon basaltic field, which extends across the southwest part of the Colorado Plateau and adjacent transition zone with the Basin and Range Province 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; Johnson and others, 2010). This volcanic field contains hundreds of relatively small-volume, widely scattered, mostly basaltic lava flows and cinder cones that range in age from Miocene to Holocene. In southwestern Utah, basalts are synchronous with basin-range deformation and are part of mostly small, bimodal (basalt and high-silica rhyolite) eruptive centers (Christiansen and Lipman, 1972; Rowley and Dixon, 2001). The oldest basalts in southwestern Utah are about 17 Ma (basalt of Harrison Peak; Biek and others, 2009). The youngest dated lava flow in southwest Utah is the 32,000-year-old Santa Clara basaltic lava flow (Willis and others, 2006; Biek and others, 2009), but the Miller Knoll, Dry Valley, and Panguitch Lake lava flows south of Panguitch Lake may be younger still. Red-hot lava flows, an integral part of the Southern Paiute legend "How the whistler [bird] and badger got their homes," may relate to the Panguitch Lake-area lava flows (Palmer, 1957; Southern Paiutes lived in southwest Utah beginning about A.D. 1100 [Canaday, 2001]). Schulman (1956) briefly reported on 850- to 950-year-old juniper (*Juniperus scopulorum*) trees growing on young lava flows, thus showing that the lava flows are at least that old but still could be many thousands of years old; these lava flows are apparently near Panguitch Lake although definitive sample locations are unavailable (samples BRY 2104 and BRY 2110, table "Overage drought conifers," p. 32). Apart from the mafic block and ash flow that is apparently part of the 20 Ma Markagunt megabreccia, the oldest basaltic lava flows in the map area are the Houston Mountain flow (Tbhm), for which we report a new $^{40}Ar/^{39}Ar$ plateau age of 5.27 ± 0.14 Ma, and the 5.3 Ma Dickinson Hill and Rock Canyon flows; Stowell (2006) reported an $^{40}Ar/^{39}Ar$ plateau age of 2.78 ± 0.16 Ma for what is likely the Blue Spring Mountain lava flow, and an $^{40}Ar/^{39}Ar$ maximum isochron age of 0.60 ± 0.25 Ma for what is likely the Long Flat lava flow.

Lava flows in the map area typically have a rubbly base, a dense, jointed middle part, and – if not eroded away – a vesicular upper part that has a rough aa (a Hawaiian term for a blocky, jagged flow) or, rarely, a poorly developed pahoehoe (a Hawaiian term for a smooth or ropy flow) surface. Several lava flows, including the Duck Creek and Bowers Knoll lava flows, contain open lava tubes; the best known is Mammoth Cave (6 miles [10 km] northeast of Duck Creek Village). The flows commonly overlie stream-gravel and other surficial deposits. Older lava flows are partly covered by eolian sand and calcic soil (caliche) not shown on this map. Most lava flows are dark gray and fine grained, and contain small olivine phenocrysts and common crystal clusters of olivine, plagioclase, and clinopyroxene. With few exceptions, these lava flows are difficult to distinguish by hand sample alone. They are distinguished for this geologic map by detailed geologic mapping, trace-element geochemistry, and radiometric ages.

The lava flows in the map area provide a "snapshot" of the local landscape as it existed when the flow erupted. Each flow was emplaced in a "geological instant" (most small basaltic volcano vents produce 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 across the landscape, and is resistant to erosion. Because lava flows blocked drainages, streams were shunted to the side where they preferentially eroded adjacent, less resistant sedimentary strata, ultimately leaving the resistant lava flows stranded as elevated, sinuous ridges (called inverted valleys) that mark the location of former channels. Southwest Utah is famous for its classic examples of inverted topography, such as Washington and Middleton Black Ridges near St. George, as first described in detail by Hamblin (1963, 1970, 1987) and Hamblin and others (1981). Classic, if lesser known, inverted valleys are present on the east-tilted Markagunt Plateau as well, as at the distal ends of the Asay Knoll (Qbak), Bowers Knoll (Qbbk), and Coopers Knoll (Qbck) lava flows.

Several lava flows cross and are cut by range-bounding normal faults, including the Water Canyon (Qbw), Summit (Qbs), and Red Hills (Qbrh) flows. For example, the 0.44 Ma Water Canyon flow crosses a relay ramp between two en echelon sections of the Parowan-Paragonah fault zone; at the mouth of Water Canyon, the flow reveals about 250 feet (75 m) of displacement, yielding a long-term slip rate of about 0.17 mm/yr (about 0.007 in/yr or 550 feet/Ma) for the eastern fault strand.

Basaltic magmas are partial melts derived from the compositionally heterogeneous lithospheric mantle, and this, coupled with fractional crystallization, may account for most of the geochemical variability between individual lava flows (Lowder, 1973; Best and Brimhall, 1974; Leeman, 1974; Nealey and others, 1995, 1997; Nelson and Tingey, 1997; Nusbaum and others, 1997; Smith and others, 1999; Downing, 2000; Johnson and others, 2010). Nb/La ratios for virtually all samples of basaltic and andesitic lava flows from the map area are less than 1.0, thus suggesting a lithospheric mantle source (Fritton and others, 1991). Rock names are from LeBas and others (1986).

QTb **Basaltic lava flow, undivided** (Pleistocene? to Miocene?) – Medium- to dark-gray basalt lava flow that caps a ridge north of Wilson Creek, a southern tributary of Mammoth Creek, in the Asay Bench quadrangle; correlation is uncertain, but major- and trace-element geochemistry shows affinities to the 5.3 Ma Houston Mountain lava flow, although its degree of topographic inversion suggests that it is not that old; about 20 to 30 feet (6-9 m) thick.

$Qbpl_1$, $Qbpl_2$, $Qbpl_3$

Panguitch Lake lava flows (middle Holocene to upper Pleistocene) – Mapped as three separate lava flows, with $Qbpl_1$ being the youngest; all three flows are mostly unvegetated, blocky, and exhibit steep flow fronts 100 to 200 feet (30-60 m) high: $Qbpl_1$ is dark-gray to black latite (potassium-rich trachyandesite) containing small (1 mm), stubby plagioclase phenocrysts in a glassy to aphanatic groundmass; $Qbpl_2$ and $Qbpl_3$ are dark-gray latite containing small stubby plagioclase and abundant acicular hornblende phenocrysts in a fine-grained groundmass; the $Qbpl_1$ lava flow lacks collapsed lava tubes and exhibits blocky flow lines similar to those of the Dry Valley lava flow (Qbdv); the smaller $Qbpl_2$ lava flow has collapsed lava tubes and partly buries the $Qbpl_3$ lava flow; the $Qbpl_3$ flow, which has abundant collapsed lava tubes and branching distributary lobes, erupted from a vent apparently now concealed by the younger vents of the $Qbpl_1$ and $Qbpl_2$ lava flows (immediately northeast of Miller Knoll, the large cinder cone about 3 miles [5 km] south of Panguitch Lake) and flowed northward about 3 miles (5 km) nearly to Panguitch Lake; this is the “northern Panguitch flow” of Stowell (2006); age uncertain, but may be as young as middle Holocene; individual lava flows are typically about 200 feet (60 m) thick.

Qbdv **Dry Valley lava flow** (middle Holocene to upper Pleistocene) – Dark-gray latite (potassium-rich trachyandesite) that contains olivine and abundant hornblende phenocrysts in an aphanatic to fine-grained groundmass; forms a thick, blocky, laterally restricted flow west of Black Rock Valley that exhibits high, steep flow fronts (except at Dry Valley, immediately west of the vent, where a slightly older more fluid phase is present); upper surface shows prominent arcuate ridges that reveal flow directions, but vent area lacks scoria or cinders and there is no "tuff ring" as stated by Stowell (2006); northern flank of flow is partly vegetated, but upper surface and south-facing slopes are not vegetated; age uncertain, but overlies and is younger than the Miller Knoll lava flow (Qbmk$_2$ – the "arcuate andesite flow" of Stowell, 2006); lava flow is typically 100 to 120 feet (30-35 m) thick.

Qbmk$_1$, Qbmk$_2$, Qbmk$_3$, Qbmkc

Miller Knoll lava flows and cinder cone (middle Holocene to upper Pleistocene) – Mapped as three separate lava flows in the Black Rock Valley area south of Panguitch Lake, with Qbmk$_1$ being the youngest flow: Qbmk$_1$ is dark-gray to black andesite that contains small (1 mm), stubby plagioclase phenocrysts in a glassy to aphanatic groundmass; Qbmk$_2$ and Qbmk$_3$ are dark- to medium-gray basaltic trachyandesite containing clusters of olivine, plagioclase, and clinopyroxene phenocrysts in an aphanatic to fine-grained groundmass and includes both sodium-rich (mugearite) and potassium-rich (shoshonite) rock types, locally containing small, thin plagioclase phenocrysts; the Qbmk$_1$ lava flow erupted from a vent near the top of the Miller Knoll cinder cone (Qbmkc, at the northwest end of Black Rock Valley) and forms a blocky, mostly unvegetated flow that looks morphologically similar to, and may be chemically transitional with, latite of the Panguitch Lake lava flows (Qbpl); the much larger Qbmk$_2$ lava flow erupted from vents on the south side of the Miller Knoll cinder cone and flowed about 4 miles (6 km) southeast through Black Rock Valley to Mammoth Creek, forming a young-looking, blocky, poorly vegetated flow that has abundant collapsed lava tubes and branching distributary lobes; the Qbmk$_3$ lava flow erupted from a vent now concealed by the Miller Knoll cinder cone; the Qbmk$_3$ lava flow is mostly well vegetated and was the first flow to block Blue Spring Valley – the western part of this flow is partly covered by old mixed lacustrine and alluvial deposits (Qlao) that we interpret as having accumulated upstream of the lava-flow dam; the southern extent of the Qbmk$_2$ lava flow (in the northwest corner of the Asay Bench quadrangle) was clearly limited by pre-existing topography of the red member of the Claron Formation, but the flow now lies at the modern base level of Mammoth Creek, suggesting that the lava flow blocked Mammoth Creek, which has since eroded the adjacent, less-resistant Claron strata (lacustrine sediments are absent upstream of the lava flow along Mammoth Creek, but stream terraces there may record partial infilling and subsequent exhumation of the valley); this is the "southern Panguitch flow" of Stowell (2006); the Qbmk$_2$ lava flow yielded preliminary cosmogenic exposure ages of about 37,000 years (Dave Marchetti, Western State College of Colorado, written communication, August 4, 2009) – the Qbmk$_2$ and Qbmk$_3$ flows are thus likely late Pleistocene in age; the Qbmk$_1$ flow unit may be as young as middle Holocene; lava flows are typically 30 to 100 feet (10-30 m) thick, but may be thicker where they fill paleotopography.

Qbnl, Qbnlc

Navajo Lake lava flows and cinder cone (upper? Pleistocene) **–** Medium- to dark-gray mugearite (sodium-rich basaltic trachyandesite) containing clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; some lava flows contain common small plagioclase phenocrysts; lava flows (Qbnl) erupted from vents at a cinder cone (Qbnlc) about 3 miles (5 km) north of Navajo Lake (Moore and others, 2004) and coalesced into flow complexes not mapped separately; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3-9 m) high; cinder cone is well vegetated; lava flows are locally well vegetated, but more commonly barren and characterized by a rough, blocky surface; vegetated areas collect wind-blown sediment that forms a sparse soil cover on parts of the flow; age unknown, but likely late Pleistocene based on degree of incision and weathering, although Moore and others (2004) considered the lava flow as probably Holocene; lava flows are typically several tens of feet thick, but thicker where they fill paleotopography.

Qbrd, Qbrdc

Red Desert lava flows and cinder cone (upper? Pleistocene) **–** Medium- to dark-gray basalt and basaltic andesite that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; some lava flows contain common small plagioclase phenocrysts; lava flows (Qbrd) erupted from vents at a cinder cone (Qbrdc) north of Navajo Lake quadrangle (Moore and others, 2004), and from a small vent in the adjacent Henrie Knolls quadrangle, and coalesced into flow complexes not mapped separately; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3-9 m) high; cinder cone is well vegetated; lava flows are locally well vegetated, but more commonly are barren and have a rough, blocky surface; vegetated areas collect wind-blown sediment that forms a sparse soil on parts of the flow; age unknown, but lava flows are likely late Pleistocene based on degree of incision and weathering, although Moore and others (2004) considered the lava flow as probably Holocene; lava flows are typically several tens of feet thick, but thicker where they fill paleotopography.

Qbhk, Qbhkc

Henrie Knolls lava flows and cinder cones (upper Pleistocene) **–** Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; some lava flows, particularly those between Duck Creek Sinks and Dry Camp Valley Spring, also contain common plagioclase phenocrysts and have a slightly coarser groundmass; lava flows that erupted from the northeasternmost group of cinder cones tend to be of basaltic andesite composition; forms coalescing lava flows (Qbhk) that erupted from at least 20 separate vents marked by cinder cones (Qbhkc), including the largest two cones at Henrie Knolls, in the northeast part of the Henrie Knolls quadrangle; the wide chemical variation reflects the fact that these flows erupted from multiple vents and coalesced into flow complexes not mapped separately; cinder cones are strikingly aligned along a northeast trend, subparallel to mapped normal faults in the quadrangle; no fault that postdates eruption of the Henrie Knolls lava flows has been identified along this trend, but a concealed fault likely controls the alignment of vents; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3-9 m) high; cinder cones are well vegetated; lava flows are locally well vegetated but more commonly barren, exhibiting a rough, blocky surface; the southernmost of the Henrie Knolls lava flows blocked the Navajo Lake and Dry Valley drainages, forming Navajo Lake and intermittent Cow Lake; age unknown, but probably late Pleistocene because the north end of flow complex is incised by Tommy Creek and capped by level 4 stream-terrace deposits (Biek and others, 2007, here mapped as Qat) assumed to be of late Pleistocene age; sample HK092106-1 near Henrie Knolls yielded a low-precision $^{40}Ar/^{39}Ar$ age of 0.058 ± 0.035 Ma (UGS and NMGRL, 2009); vegetated areas collect wind-blown sediment that forms a sparse soil cover on parts of the flow; lava flows are typically several tens of feet thick, but likely exceed 200 feet (60 m) thick where they fill paleotopography.

Qbmc, Qbmcc

Midway Creek lava flow and cinder cones (Pleistocene) **–** Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flow (Qbmc) erupted from a vent at a cinder cone (Qbmcc) and is partly covered by the Navajo Lake lava flow (Qbnl) (Moore and others, 2004); this cinder cone may be the source of the Duck Creek lava flow (Qbdc); lava flow is typically several tens of feet thick, but thicker where it fills paleotopography.

Qbde, Qbdec

Deer Valley lava flow and cinder cone (Pleistocene) **–** Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; small lava flow (Qbde) erupted from a vent at a cinder cone (Qbdec) 1.5 miles (2.5 km) north of Navajo Lake; lava flow is typically several tens of feet thick, but thicker where it fills paleotopography.

Qbho, Qbhoc

Horse Pasture lava flow and cinder cone (Pleistocene) **–** Medium- to dark-gray basalt and hawaiite (sodium-rich trachybasalt) containing clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flow (Qbho) erupted from a vent at a cinder cone (Qbhoc) 4 miles (6 km) north of Navajo Lake; this cinder cone may be the source of the Duck Creek lava flow (Qbdc); lava flow is typically several tens of feet thick, but thicker where it fills paleotopography.

Qbdc **Duck Creek lava flow** (Pleistocene) **–** Medium-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts and abundant small plagioclase phenocrysts in a fine-grained groundmass; location of vent unknown, but it may be concealed by the Henrie Knolls (Qbhk) or Navajo Lake (Qbnl) lava flows; alternatively, geochemical data suggest that the Duck Creek lava flow may be the distal part of either the Midway Creek or Horse Pasture lava flows; the lava flowed from west to east down the ancestral Duck Creek drainage and continued northeastward to at least the Bowers Flat area at the west edge of the Asay Bench quadrangle; contains a long, open lava tube near Aspen Mirror Lake, just west of Duck Creek village (U.S. Forest Service restricts access); lava flow is typically partly concealed by a veneer of unmapped surficial deposits of alluvial, colluvial, and eolian origin; age unknown, but it locally covers the Bowers Knoll lava flow (Qbbk) and in turn is locally covered by the Henrie Knolls lava flow (Qbhk), thus is probably late to middle Pleistocene; however, Johnson and others (2010) suggested that the distal end of the Bowers Knoll flow as mapped here, including the part that contains Mammoth Cave, may be the Duck Creek flow—if so, incision there suggests that the Duck Creek flow is about 500,000 years old, far older than the degree of incision suggests along the upstream part of the flow; maximum exposed thickness is about 15 feet (5 m) near Aspen Mirror Lake, but likely several tens of feet thick where it fills paleotopography in the Duck Creek drainage.

Qbsk, Qbskc

Strawberry Knolls lava flows and cinder cones (Pleistocene) – Medium- to dark-gray potassic trachybasalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flows (Qbsk) erupted from Strawberry Knolls (Qbskc), two cinder cones located about 2 miles (3 km) east of Duck Creek village, and flowed mostly northeast along Strawberry Creek to Uinta Flat; age unknown, but cinder cones are well vegetated and flow is incised by Strawberry Creek as much as 40 feet (12 m) at its downstream end and so is probably middle Pleistocene; lava flows are typically 20 to 30 feet (6-9 m) thick, but doubtless many tens of feet thick near vent areas.

Qblhc **Lake Hollow cinder cone** (Pleistocene) – Forms a small, partly eroded cinder cone about 1.5 miles (3 km) north of Mammoth Creek and east of Black Rock Valley, with a small lava flow (not differentiated on this map) at the base of the cone of medium- to dark-gray hawaiite (sodium-rich trachybasalt) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; vent is on-trend with the Henrie Knolls lava flows, to which it may be related; age unknown, but likely late to middle Pleistocene based on position in landscape; lava flow is less than about 20 feet (6 m) thick.

Qbef, Qbefc

East Fork Deep Creek lava flow and cinder cone (Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt lava flow (Qbef) west of Navajo Lake; cinder cone (Qbefc) is deeply eroded due to its location just below the western escarpment of the Markagunt Plateau, just west of Navajo Lake; the distal southern end of this flow was called the Three Creeks lava flow by Biek and Hylland (2007), which they estimated to be less than 300,000 years old based on degree of incision and comparison with nearby dated lava flows; lava flow is probably 20 to 40 feet (6-12 m) thick.

Qbw, Qbwc

Water Canyon lava flow and cinder cone (middle Pleistocene) – Dark-gray potassic trachybasalt and shoshonite (potassium-rich basaltic trachyandesite) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; quartz xenocrysts common; lava flow (Qbw) erupted from cinder cone (Qbwc) in Water Canyon about 3 miles (5 km) southeast of Paragonah (Maldonado and Moore, 1995); Fleck and others (1975) reported a K-Ar age of 0.44 ± 0.04 Ma for this flow; lava flow is as much as 200 feet (60 m) thick where it partly fills Water Canyon.

Qbbk, Qbbkc

Bowers Knoll lava flow and cinder cones (middle Pleistocene) – Medium-gray mugearite (sodium-rich basaltic trachyandesite) containing abundant clusters of olivine, plagioclase, and clinopyroxene phenocrysts in a fine-grained groundmass; lava flow erupted from Bowers Knoll, a cinder cone (Qbbkc) about 3 miles (5 km) northeast of Duck Creek village; forms rugged, heavily vegetated, blocky surface having steep flow fronts 40 feet (12 m) or more high; as mapped, contains Mammoth and Bower caves, large open lava tubes, but this part of the flow may belong to the Duck Creek flow (Johnson and others, 2010); age unknown, but locally underlies the Duck Creek lava flow (Qbdc), so is probably middle Pleistocene; Best and others (1980) reported a K-Ar age of 0.52 ± 0.05 Ma for the nearby Asay Knoll lava flow (Qbak), which exhibits a similar degree of incision and weathering; typically 40 feet (12 m) or more thick near flow margins, but may exceed 100 feet (30 m) thick near the central part of the flow.

Qbak, Qbakc

Asay Knoll lava flow and cinder cone (middle Pleistocene) – Medium- to dark-gray potassic trachybasalt and shoshonite (potassium-rich basaltic trachyandesite) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flow (Qbak) erupted from Asay Knoll cinder cone (Qbakc) and covers Asay Bench; Best and others (1980) reported a K-Ar age of 0.52 ± 0.05 Ma for this flow; lava flow is typically 20 to 30 feet (6-9 m) thick, but is doubtless many tens of feet thick near vent area.

Qbck, Qbckc

Cooper Knoll lava flow and cinder cone (middle Pleistocene) – Medium-gray basalt that contains clusters of olivine, plagioclase, and clinopyroxene phenocrysts in a fine-grained groundmass; lava flow (Qbck) erupted from a vent at a cinder cone (Qbckc) on the south flank of Cooper Knoll, about 1 mile (1.6 km) southeast of Panguitch Lake; overlies stream gravels containing rounded pebbles and cobbles of the Isom Formation, mafic and intermediate volcanic rocks of the Mount Dutton Formation, chalcedony, and minor quartzite; age uncertain, but may be about 500,000 years old based on comparison with the similarly incised Asay Bench lava flow (Qbak) for which Best and others (1980) reported a K-Ar age of 0.52 ± 0.05 Ma; lava flow is about 20 to 40 feet (6-12 m) thick.

Qbwf, Qbwfc

Webster Flat lava flow and cinder cone (middle Pleistocene) – Medium-gray, fine-grained olivine basalt with small plagioclase phenocrysts; lava flow (Qbwf) erupted from vent at cinder cone (Qbwfc) about 1 mile (1.6 km) east of Black Mountain in the Webster Flat quadrangle and flowed mostly south down the Kolob Terrace; age uncertain, but probably about 500,000 years old based on comparison with nearby dated flows and its position in the landscape; lava flow is typically several tens of feet thick.

Qbal, Qbalc

Aspen Lake lava flow and cinder cone (middle Pleistocene) – Medium-gray, fine-grained olivine basalt with small plagioclase phenocrysts; lava flow (Qbal) erupted from vent at cinder cone (Qbalc) about 1 mile (1.6 km) south of Black Mountain in the Webster Flat quadrangle and flowed mostly south down the Kolob Terrace; age uncertain, but probably about 500,000 years old based on comparison with nearby dated flows and its position in the landscape; lava flow is typically several tens of feet thick.

Qblf, Qblfc

Long Flat lava flow (middle Pleistocene) – Medium-gray basalt to hawaiite (sodium-rich trachybasalt) that contains clusters of olivine and clinopyroxene phenocrysts; lava flow (Qblf) erupted from hills 10,392 and 10,352 (Brian Head 7.5' topographic map), two cinder cones (Qblfc) near Long Flat about 3 miles (5 km) east of Brian Head peak; Stowell (2006) reported an $^{40}Ar/^{39}Ar$ maximum isochron age of 0.60 ± 0.25 Ma for sample LEA71SS2, which is likely from the Long Flat lava flow, but minor- and trace-element signatures of the Long Flat and nearby Hancock Peak flows are similar and Stowell's sample location lacks precision to be properly located, thus age is uncertain; parts of the lava flow are covered by Pinedale-age glacial till and glacial outwash, and the cinder cones appear to be more heavily eroded than the nearby Hancock Peak cinder cone (Qbhpc); the northeast flank of hill 10,392 is conspicuously truncated and it may have been eroded by an earlier glacial advance (if so, likely the Bull Lake [Illinoian or MIS 6] advance); lava flow is several tens of feet thick.

Qbwk, Qbwkc

Wood Knoll lava flow and cinder cone (middle Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt; lava flow (Qbwk) erupted from vent at Wood Knoll, a cinder cone (Qbwkc) about 2 miles (3 km) southwest of Cedar Breaks National Monument and flowed northwest into Long Hollow; a remnant of the flow, perched 1100 feet (335 m) above the junction of Ashdown Creek and Coal Creek yielded an $^{40}Ar/^{39}Ar$ age of 0.63 ± 0.10 Ma and a long-term down cutting rate of 0.53 mm/yr (about 21 inches per thousand years or 1700 ft/Ma), inferred to be a minimum rate of relative uplift on the Hurricane fault to the west (Lund and others, 2007); lava flow is typically several tens of feet thick, but is as much as about 300 feet (90 m) thick where it fills the ancestral Coal Creek channel.

Qbub, Qbubc

Upper Bear Springs lava flows and cinder cones (middle to lower Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt; lava flows (Qbub) erupted from vents at cinder cones (Qbubc) about 2 miles (3 km) southwest of Navajo Lake and flowed mostly south onto the Kolob Terrace; probably about 750,000 years old because they appear to be the same lava flows as those at Horse Knoll (Sable and Hereford, 2004; Doelling, 2008), which yielded a K-Ar age of 0.81 ± 0.05 Ma and an $^{40}Ar/^{39}Ar$ age of 0.73 ± 0.02 Ma (Biek and Hylland, 2007; UGS and NMGRL, 2008); lava flows are several tens of feet thick.

Qbbm **Black Mountain lava flow** (middle to lower Pleistocene) – Medium-gray, fine-grained olivine basalt with small plagioclase and pyroxene phenocrysts; lava flow caps the northwest sloping surface of Black Mountain in the Webster Flat quadrangle; vent unknown but may be concealed by nearby younger lava flows or surficial deposits to the southeast; yielded K-Ar ages of 0.80 ± 0.24 and 0.87 ± 0.24 Ma (Anderson and Mehnert, 1979; Best and others, 1980); lava flow is typically several tens of feet thick.

$Qbhp_1$, $Qbhp_2$, Qbhpc

Hancock Peak lava flows and cinder cone (middle to lower Pleistocene) – Medium-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; based on chemistry and morphology the map unit is divided into two flows, both of which are well vegetated; erupted from Hancock Peak, a large, well-preserved cinder cone (Qbhpc) southeast of Brian Head peak; $Qbhp_1$ appears to overlie $Qbhp_2$ and extends farther downstream where it caps an inverted valley about 600 feet (180 m) above Mammoth Creek just north of the community of Mammoth Creek; age unknown, but estimated to be middle to early Pleistocene based on comparison with the 600,000-year-old Long Flat lava flow (Qblf) and the 2.8 Ma Blue Spring Mountain lava flow (Tbbm); lava flows are typically several tens of feet thick, but likely exceed 100 feet (30 m) thick where they fill paleotopography.

Qbc **First Left Hand Canyon vent area** (middle to lower Pleistocene?) – Lower part contains abundant angular blocks of Claron Formation and mafic volcanic rocks and minor rounded quartzite pebbles and cobbles; the whole is cut by several basaltic dikes; some blocks are as large as 12 feet (4 m) in size, but most are pebble to small cobble size; unbedded; appears to be a volcanic mudflow deposit. Upper part is mostly basaltic blocks and lesser Claron blocks, welded into scoriaceous matrix. Unconformably overlies the lower conglomerate and middle sandstone members of the Grand Castle Formation on the northwest side of Henderson Hill in First Left Hand Canyon; forms deeply eroded vent area about 600 feet (180 m) above modern drainage, and may be associated with adjacent basaltic dikes; about 400 feet (120 m) thick.

Qbtp **The Pass lava flow** (Pleistocene?) – Medium- to dark-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; caps small knob just south of The Pass east of Panguitch Lake that Wagner (1984) interpreted as a small gabbroic intrusion, but that appears to be a flow remnant partly involved in a landslide; chemically similar to the 5.3 Ma Houston Mountain lava flow (Tbhm), but source is uncertain; lava flow may be about 50 feet (15 m) thick.

Qbs, Qbsc

Summit lava flow and cinder cone (lower Pleistocene) – Medium- to dark-gray, fine-grained olivine basalt that Maldonado and others (1997) referred to as the Cinder Hill cone and flow; lava flow (Qbs) erupted from vent at cinder cone (Qbsc) at the base of the Hurricane Cliffs, about 2 miles (3 km) southwest of Summit; lava flow also crops out at the southeast margin of the Red Hills and is presumed to underlie the southern part of the Parowan Valley graben, where it is displaced by graben-bounding faults; yielded K-Ar ages of 1.00 ± 0.16 Ma and 0.94 ± 0.14 Ma (Anderson and Mehnert, 1979); lava flow is typically several tens of feet thick.

Qbe **Elliker Basin lava flow** (lower Pleistocene) – Medium- to dark-gray, fine-grained olivine basaltic trachyandesite; vent area unknown, but minor scoria and blocky flow breccia is present on the north rim of Elliker Basin, suggesting that the vent could underlie the basin, which is southwest of Summit; yielded K-Ar ages of 1.00 ± 0.16 Ma and 1.11 ± 0.11 Ma (Anderson and Mehnert, 1979); lava flow is typically several tens of feet thick.

Qbrh, Qbrhc

Red Hills lava flows and cinder cones (lower Pleistocene) – Medium- to dark-gray, fine-grained basaltic andesite with small olivine and plagioclase phenocrysts; lava flows (Qbrh) erupted from vents at three cinder cones (Qbrhc) in the northwest corner of the Summit quadrangle and adjacent Enoch quadrangle (Rowley and Threet, 1976); lava flows are mostly covered by eolian sand and silt, and locally by small areas of fan alluvium, but only larger such areas are mapped due to map scale; lava flow is cut by faults associated with the Red Hills horst and graben; yielded K-Ar ages of 1.28 ± 0.4 Ma (Anderson and Mehnert, 1979) and 1.30 ± 0.3 Ma (Best and others, 1980); lava flow is typically several tens of feet thick.

Tbbm, Tbbmc

Blue Spring Mountain lava flow and cinder cone (Pliocene) – Medium-gray hawaiite and mugearite (sodium-rich trachybasalt and basaltic trachyandesite, respectively) lava flow (Tbbm) that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; erupted from vents at a cinder cone (Tbbmc) on Blue Spring Mountain and flowed east and south, mostly toward the ancestral Mammoth Creek drainage; an erosional outlier caps

Mahogany Hill, about 500 feet (150 m) above Mammoth Creek east of its intersection with Black Rock Valley; the cinder cone is heavily eroded and the lava flow is well vegetated; between Blue Spring Mountain and Blue Spring Valley, the flow is involved in a large landslide complex, which slid on the underlying Brian Head Formation; Stowell (2006) reported an $^{40}Ar/^{39}Ar$ plateau age of 2.78 ± 0.16 Ma for what is likely the Blue Spring Mountain lava flow, but Stowell's sample location lacks precision to be properly located, thus age is uncertain; based on their similar chemistry, the map unit includes a northeast-trending dike at the north end of Blue Spring Valley and a small flow remnant a few tens of feet above Blue Spring Creek (Biek and Sable, in preparation); if the Blue Spring Creek remnant is indeed part of the 2.8-million-year-old Blue Spring Mountain lava flow, it means that the Blue Spring Valley area has been a topographic low for nearly the past 3 million years, an unlikely scenario; lava flow is typically several tens of feet thick, but is doubtless thicker near the vent area and where it fills paleotopographic lows.

Tbhm **Houston Mountain lava flow** (lower Pliocene to upper Miocene) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; unconformably overlies the Brian Head Formation (Tbhv) and Leach Canyon Formation (Tql) along the west edge of Blue Spring Mountain; an erosional outlier on the south side of Clear Creek contains abundant 1- to 2-mm-long plagioclase phenocrysts, but is otherwise chemically similar to the Houston Mountain flow; also caps Houston Mountain (about 6 miles [10 km] east of Cedar Breaks National Monument) and other hills of lower elevation to the south (about 3 miles [5 km] northeast of Navajo Lake), where it is typically platy weathering; source vent unknown and margins of lava flow are entirely eroded away, but elevation of remnants suggests flow was derived from the west in the Brian Head quadrangle, likely at a vent now eroded and concealed by younger deposits; sample HK092006-3 yielded an $^{40}Ar/^{39}Ar$ age of 5.27 ± 0.14 Ma (UGS and NMGRL, 2009); maximum thickness is about 140 feet (43 m) at Houston Mountain.

Tbdh, Tbdhc

Dickinson Hill lava flows and cinder cones (lower Pliocene to upper Miocene) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; interbedded with upper Tertiary fan alluvium (Taf); lava flows (Tbdh) erupted from vents at mostly eroded cinder cones (Tbdhc) southwest of Panguitch; Anderson and Christenson (1989) reported a K-Ar age of 5.3 ± 0.5 Ma for one of these lava flows; major- and trace-element chemistry and age are similar to that of the nearby Rock Canyon lava flow, making differentiation of the two lava flows uncertain in the DD Hollow and Graveyard Hollow area; exposed thickness of lava flows is as much as 65 feet (20 m), and cinder deposits are 3 to 10 feet (1-3 m) thick.

Tbrc, Tbrcc

Rock Canyon lava flow and cinder cone (lower Pliocene to upper Miocene) – Medium-gray potassic trachybasalt that contains clusters of olivine and clinopyroxene and small plagioclase phenocrysts in a fine-grained groundmass; lava flow (Tbrc) is interbedded with upper Tertiary fan alluvium (Taf); erupted from a cinder cone (Tbrcc) about 4 miles (6 km) northwest of Hatch; apparent age, and major- and trace-element chemistry, is similar to the nearby 5.3 Ma Dickinson Hill lava flow (Tbdh); query indicates our uncertainty in correlating these two flows in their area of possible overlap; maximum exposed thickness is about 100 feet (30 m).

Based on limited geochemistry, the Rock Canyon lava flow may be the same lava flow exposed in the footwall and hanging wall of the Sevier fault just south of State Route 12 and Red Canyon; Lund and others (2008) reported $^{40}Ar/^{39}Ar$ ages on the Red Canyon flow of 4.94 ± 0.03 (footwall outcrop) and 4.98 ± 0.03 (hanging wall outcrop). If this correlation is correct, it implies that Sevier Valley and the footwall of the Sevier fault zone did not exist as topographic barriers to eastward movement of the Rock Canyon lava flow in early Pliocene time, about 5 million years ago; it further implies that the Rock Canyon lava flow underlies parts of Sevier Valley.

Tbsp **Sidney Peaks lava flow** (lower Pliocene to upper Miocene) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts as much as ¼ inch (5 mm) in diameter in a fine-grained groundmass; forms deeply dissected flow and flow breccia that unconformably overlies the Markagunt megabreccia; deposit just northeast of Sidney Peaks, which unconformably overlies the Leach Canyon Formation, consists of lava blocks in a cinder matrix, is locally cut by basaltic dikes, and may be a deeply eroded vent area; as much as 80 feet (25 m) thick.

QUATERNARY-TERTIARY

QTr **Residuum** (Holocene to Pliocene) − Mapped about 4 miles (7 km) northeast of Navajo Lake where blocky remnants of the Houston Mountain lava flow (Tbhm) have been let down by erosion of underlying beds; angular to subangular blocks of the lava flow, typically 3 feet (1 m) or less in diameter but locally as large as about 12 feet (4 m), tend to accumulate in swales, on ridge crests, and at and near the base of steep slopes; locally, the blocks form a basaltic pavement on the white member of the Claron Formation, but typically they are widely scattered; other than uncommon small fragments of chalcedony (itself likely the remains of the Brian Head Formation that was once buried by the Houston Mountain lava flow), no other exotic rock types are present; probably formed as former basalt-capped hilltops succumbed to chemical weathering of carbonate beds in the underlying Claron Formation and concomitant hillslope erosion, undermining the lava flow and scattering resistant basalt blocks over the bedrock; unmapped colluvium derived from this unit blankets much of the nearby Claron Formation; typically less than a few feet thick. Also mapped on the south side of Blue Spring Mountain (about 5 miles [8 km] southwest of Panguitch Lake) where the deposit is of likely Quaternary age and consists of blocks of the Blue Spring Mountain lava flow (Tbbm) that conceal the upper part of the white member of the Claron Formation and possibly the lower part of the Brian Head Formation.

QTbx **Regolithic breccia deposits** (Holocene to Pliocene?) **–** Mapped south of the outcrop belt of the Markagunt megabreccia (Tm), from the west rim of the Markagunt Plateau eastward to the Haycock Mountain area; typically consists mostly of rubble of the Isom Formation, locally with minor blocks of chalcedony from the Brian Head Formation; near the north end of Cedar Breaks National Monument, consists of large blocks of Isom Formation as much as several hundred feet in extent that rest on lowermost Brian Head strata; many of the large Isom blocks are internally brecciated on a fine scale, then rehealed by silicification, presumably by devitrification of the ash flow itself (the brecciation is a direct result of formation of the Markagunt megabreccia, discussed below); deposits are unconsolidated and blocks are subangular and commonly as much as 10 feet (3 m) or more in size, but deposits near the north end of Cedar Breaks contain rafted Isom blocks that are at least as large as a city block; as described below, and like the interpretations of Moore (1992) and Sable and Maldonado (1997a), lead-author Biek interprets these deposits to be a remobilized product of the Miocene Markagunt megabreccia, emplaced after the megabreccia in later Tertiary through modern time; maximum thickness about 120 feet (40 m) at Blowhard Mountain immediately south of Cedar Breaks National Monument, but most deposits are 5 to 30 feet (2-9 m) thick.

Between Blowhard Mountain and Long Valley Creek, these deposits form an extensive, hummocky surface draped over the Claron Formation that lead-author Biek interprets as landslide debris, residuum, and colluvium derived from the Markagunt megabreccia following Moore (1992), not as Brian Head strata as did Moore and others (2004); Moore and Nealey (1993) considered the unit to be an unconsolidated mantle of Pleistocene to late Tertiary age but were uncertain of its origin, whereas Hatfield and others (2003) interpreted the unit to be Markagunt megabreccia, as discussed below. These deposits are exposed only on the west side of Blowhard Mountain, revealing large fractured blocks of Brian Head tuffaceous mudstone, sandstone, micritic limestone, and chalcedony; some blocks are as large as 100 feet (30 m) across. The base of this deposit overlies alluvial boulder gravel that consists mostly of subrounded Isom Formation clasts and minor quartzite clasts, but much of the west side of this outcrop belt at Blowhard Mountain is involved in landslides, many with historical movement, and so it is uncertain if the gravel is part of the megabreccia residuum or part of an underlying channel. Elsewhere, the deposit at Blowhard Mountain and areas to the east and south is characterized by abundant large, angular Isom boulders that litter the surface. The hummocky surface is due to dissolution and collapse of underlying Claron limestone, which created numerous sinkholes in this area (Hatfield and others, 2003; Moore and others, 2004; Spangler, in preparation), but is also likely due to ongoing slumping and slope creep that results from admixed tuffaceous Brian Head strata (Moore, 1992).

The large blocks of Isom near the north end of Cedar Breaks National Monument rest unconformably on Brian Head and Claron strata, whereas not far to the north, the main mass of the Markagunt megabreccia rests on Leach Canyon Formation. Because the southern margin of the megabreccia (and underlying regional ash-flow tuffs) is erosional in nature, we do not know their southern depositional limit. However, because debris from the Leach Canyon Formation is missing in areas mapped as QTbx in the northern part of Cedar Breaks National Monument and at and near Blowhard Mountain, it seems likely that the Leach Canyon did not extend much further south than its present-day outcrop. Because there is no evidence for a post-Leach Canyon (but pre-Markagunt megabreccia) unconformity that cuts out strata southward across the west edge of the Markagunt Plateau, lead-author Biek interprets these large Isom blocks to be landslide remnants that are at a lower structural level than the main mass of the Markagunt megabreccia, inferring that the blocks reflect late Tertiary and Quaternary northward retreat of the erosional escarpment that stretches from Brian Head peak eastward to Haycock Mountain. Thus in this view, similar to that suggested by Moore (1992) and Sable and Maldonado (1997a), the blocks are remobilized parts of the Markagunt megabreccia, the southern extent of which was emplaced on a paleohigh of Brian Head strata that served to constrain the southern limit of the Isom and Leach regional ash-flow tuffs; the megabreccia has since been let down to its present position principally by landsliding in late Tertiary and Quaternary time, with smectitic clays of the Brian Head Formation providing the weak shear surface for downslope movement of the blocks. Hatfield and others (2003), Moore and others (2004), and Rowley and others (in preparation), however, interpreted the blocks as a bona fide part of the Miocene Markagunt megabreccia, which thus must have been emplaced as far south as Blowhard Mountain over a significant Miocene unconformity; subsequent weathering and sapping of the megabreccia and underlying Claron Formation then spread debris southward to the area beyond State Route 14. Our differences in interpretation reflect this uncertainty.

QTaf **High-level fan alluvium** (Pleistocene and Pliocene?) **–** Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment; mapped in the Sevier Valley southeast of Panguitch, where it forms deeply dissected surfaces; deposited principally as debris flows and debris floods; exposed thickness is about 100 feet (30 m).

QTap **High-level pediment alluvium** (Pleistocene and Pliocene?) **–** Moderately sorted, subrounded to rounded pebble to boulder gravel and sand that forms a gently east-dipping, locally resistant cap over the Limerock Canyon Formation (Tl) and upper Tertiary fan alluvium (Taf) near the east margin of the Markagunt Plateau; surface of deposit typically covered by veneer of pebble and cobble residuum; divisible into two different levels (Moore and Straub, 1995), but undivided here due to map scale; deposited principally as debris flows, debris floods, and in ephemeral stream channels; probably less than 20 feet (<6 m) thick.

QTh **Basin-fill deposits of Long Hill** (Pleistocene and Pliocene?) **–** Poorly sorted, poorly stratified, subangular to subrounded, boulder- to clay-size sediment preserved in down-dropped blocks on the west side of the Red Hills; northern exposures consist predominantly of volcanic clasts, some as much as 3 feet (1 m) in diameter; southern exposures contain abundant quartzite cobbles in a reddish-brown calcareous matrix; original depositional form is not preserved; interpreted to represent deeply eroded basin-fill deposits deposited principally as debris flows and debris floods on large alluvial fans; Maldonado and Williams (1993a) mapped kilometer-scale blocks of Oligocene and Miocene ash flow tuffs within this basin-fill unit that they interpreted to be gravity-slide blocks of Pliocene or Pleistocene age; lead author Biek reinterprets these blocks simply as autochthonous normal-fault-bounded blocks partly covered by basin-fill deposits; exposed thickness as much as about 300 feet (90 m).

TERTIARY

Taf **Upper Tertiary fan alluvium** (Pliocene to Miocene) – Moderately to poorly consolidated, brown and grayish-brown sandstone, siltstone, pebbly sandstone, and conglomerate that forms incised, east-tilted surface of low, rounded hills along the west side of Sevier Valley; clasts are of various volcanic rocks (95%) and about 5% quartzite and sandstone (Kurlich and Anderson, 1997); clasts were derived from the west and north from the Mount Dutton Formation and regional ash-flow tuffs and deposited as agrading alluvial fans in a structurally closed basin later incised by through-going drainage of the Sevier River (Moore and Straub, 1995; Kurlich and Anderson, 1997); includes uncommon, thin, ash-fall tuff beds; interbedded with upper Tertiary basaltic lava flows (including the Rock Canyon lava flows [Tbrc] and the 5.3 Ma Dickinson Hill lava flows [Tbdh]) and uncommon, thin, lenticular beds of lacustrine limestone; east part of the outcrop belt locally includes upper Tertiary stream alluvium representing an axial valley stream; unconformably overlies Claron, Brian Head, Isom, and Limekiln Knoll strata and locally capped by pediment deposits (QTap); as much as 760 feet (230 m) thick in the Hatch quadrangle (Kurlich and Anderson, 1997) and at least 1000 feet (300 m) thick in the Panguitch quadrangle (Moore and Straub, 1995).

Previously referred to as the Sevier River Formation, which was named by Callaghan (1938) for partly consolidated basin-fill deposits near Sevier, Utah, on the north side of the Marysvale volcanic complex (see, for example, Anderson and Rowley, 1975; Anderson and others, 1990a; Moore and others, 1994; Rowley and others, 1994a), a name that formerly had value in reconnaissance-scale studies in the High Plateaus. In later, more detailed mapping in the High Plateaus, the name Sevier River Formation was restricted to its type area for older basin-fill sediments deposited in post-20 Ma basins that preceded development of the present topography (Rowley and others, 2002) (later basin-fill deposits of the main phase of basin-range deformation in the northern Marysvale area were referred to as "sedimentary basin-fill deposits [QTs]"; Rowley and others, 2002). J.J. Anderson (verbal communication, November 16, 2004) referred to these deposits as the Panguitch gravels. Rowley and others (1981) used K-Ar ages of mapped volcanic rocks in the Sevier Plateau to the north to constrain the main phase of basin-range faulting to between 8 and 5 Ma, during which time the

Sevier Plateau was uplifted along the Sevier fault zone at least 6000 feet (2000 m). Anderson (1987) provided evidence that basin-fill deposits once filled the ancestral Sevier Valley to a depth at least 1000 feet (300 m) above the modern river where it cuts through Circleville Canyon, immediately north of the map area, showing that Circleville Canyon was cut by superposition of the Sevier River across the resistant Spry intrusion and vent-facies rocks of the Mount Dutton Formation.

Tvf **Upper Tertiary fine-grained basin fill** (Miocene) – Light-brown, pinkish-gray, and white tuffaceous mudstone, siltstone, fine-grained sandstone, and local diatomite; moderately to poorly consolidated; laminated to thick beds, locally with small gastropods; contains few thin beds of peloidal micritic limestone; exposed along Sevier Valley southeast of Panguitch; likely deposited in small lake basins and floodplains (Moore and Straub, 1995); exposed thickness about 100 feet (30 m).

unconformity

Markagunt megabreccia (lower Miocene) – Structurally chaotic assemblage of Miocene and Oligocene regional ash-flow tuff, local volcanic rock, and lesser sedimentary strata that covers much of the central and northern Markagunt Plateau; mapping and stratigraphic studies during the 1970s to 1990s show how understanding of this complex unit has evolved and continues to be controversial, as summarized by Maldonado and others (1992), Anderson (1993), Moore and Nealey (1993), Sable and Maldonado (1997a), Hatfield and others (2003, 2004), Moore and others (2004), and Rowley and others (in preparation). Sable and Maldonado (1997a) noted that four separate rock units have been termed the megabreccia, including (1) primary volcanic mudflow deposits, (2) megabreccia that resulted from collapse of high-angle fault scarps, (3) megabreccia associated with the Red Hills shear zone (Maldonado and others, 1989, 1992; Maldonado, 1995), and (4) the principal mass of the Markagunt megabreccia that covers much of the central and northern Markagunt Plateau; to this we add a fifth unit, namely unconsolidated megabreccia rubble. Sable and Maldonado (1997a) restricted the term to unit (4), with which we concur, noting that unit 1 consists of primary volcano-sedimentary breccia, likely the alluvial facies of the 22-32 Ma Mount Dutton Formation; that unit 2 is now known to be a large, modern landslide complex below Black Ledge (Maldonado and others, 1997; Rowley and others, in preparation); and that unit 3 is geographically separate from, but may be a dismembered part of, the main mass of the Markagunt megabreccia. We interpret the unconsolidated rubble breccia (the fifth unit), located south of the main mass of the Markagunt megabreccia, to be simply the weathering product of the Markagunt megabreccia – residuum, colluvium, landslide and collapse material, and alluvium, here collectively mapped as QTbx – that is commonly present at a lower structural level along its distal southern margin (such rubble is also present on the main mass of megabreccia, but it is not practical to differentiate such late Tertiary and Quaternary weathering products where they overlie the rubble of the Miocene megabreccia itself). Hatfield and others (2003, 2004), Moore and others (2004), and Rowley and others (in preparation) mapped or called this rubble (here mapped as QTbx) "Markagunt megabreccia," although they noted its unconsolidated nature.

Most reports describe the megabreccia as consisting of house-size to city-block-size blocks, or even blocks that are as much as one square mile (2.5 km^2) in size, but in this map area (which covers only the southern part of the megabreccia outcrop belt), we see the megabreccia principally as a large sheet, tens of square miles in extent, of mostly intact Isom Formation and comparatively minor amounts of thin underlying Wah Wah Springs and Brian Head Formations and overlying mafic block and ash-flow tuff, Bear Valley Formation, and Mount Dutton Formation that has moved more or less as a coherent mass and remained in proper stratigraphic order. Exposures of the megabreccia are limited so it is difficult to ascertain attitudes of individual units, but outcrop patterns suggest that most of the strata within the megabreccia, and the megabreccia as a whole, dips gently east following the regional dip of the plateau. Only in a few locations in the map area, as northwest of Castle Valley and north of Bunker Creek in the SW1/4 section 35, T. 35 S., R. 8 W., are strata seen to dip moderately 20° to 25° northeast. Clearly there must be faults within the megabreccia that bound isolated tilted blocks such as these, but they are not readily discernable on aerial photographs and are thus impractical to map at 1:100,000 scale.

The basal slip surface of the Markagunt megabreccia generally dips gently east (mimicking the regional dip of the plateau because it was tilted with underlying strata following its emplacement) and south (because the inferred source of the megabreccia was to the north; Sable and Maldonado, 1997a; Anderson, 2001), but at Haycock Mountain the basal slip surface dips north. The northward-dipping Isom Formation (cap rock of Haycock Mountain) was interpreted by Anderson (1993) and Sable and Maldonado (1997a) as autochthonous, and they also interpreted autochthonous Isom Formation at the type area of the megabreccia along Highway 143 east of Panguitch Lake. However, we identified a previously unreported basal conglomerate and associated clastic dikes exposed at the base of the megabreccia on the south side of Haycock Mountain (figures 1a, 1b; 2a, 2b, and 2c). These exposures show that the entire Isom section is likely part of the gravity slide. If true, the northward dip likely reflects thrusting and folding in the toe of the gravity slide, not post-megabreccia tilting and folding. Moderately northeast-dipping blocks near Castle Valley and Bunker Creek, described above, may also reflect thrusting and folding in the toe area of the Markagunt megabreccia gravity slide. Just south of Panguitch Lake, Claron and Brian Head strata dip moderately to the northwest, and this may reflect folding above a structurally deeper level of the gravity slide. Several previous workers reported slickenlines on the basal slip surface of the megabreccia, as well as roche-moutonnée-like features and tilted beds, that collectively suggest southward transport. Slickenlines at the base of the megabreccia exposed on the south side of Haycock Mountain, as well as clastic dikes, also demonstrate south-southeast transport, as well as catastrophic emplacement by gravity sliding.

Among the authors of this map, there remains disagreement as to the age of emplacement of the Markagunt megabreccia; Anderson (2001) described the key points of this disagreement, and an additional complication is described below. The resolution of this problem involves, among other issues, the Haycock Mountain Tuff in the type area of the Markagunt megabreccia, first described in detail by Anderson (1993). He reasoned that the Haycock Mountain Tuff (22.75 ± 0.12 Ma, Ed Sable, U.S. Geological Survey, unpublished data, 1996) and underlying alluvial gravels are unconformable on and thus postdate the Markagunt megabreccia. Sable and Maldonado (1997a) interpreted the Haycock Mountain Tuff to be part of the upper plate of the Markagunt megabreccia, as a distal facies of the Leach Canyon Formation. Mapping in the Panguitch Lake quadrangle, described below (see description of the Leach Canyon Formation), however, now confirms that the 23.8 Ma Leach Canyon Formation and 22.8 Ma Haycock Mountain Tuff are different units of slightly different age. Thus, the interpretation of Anderson (1993, 2001) that the Haycock Mountain Tuff represents a post-Markagunt-megabreccia tuff that partly filled a stream channel eroded into the megabreccia appears eminently reasonable. The fact that the Haycock Mountain Tuff at its type location is undeformed was used by Anderson (1993) as evidence that it postdates emplacement of the megabreccia. However, it should be noted that the caprock of Haycock Mountain, although composed of resistant Isom Formation that is part of the megabreccia, also appears undeformed as little as 30 feet (10 m) above the basal gravity-slide plane. Furthermore, on the south side of Haycock Mountain, the basal slip surface of the megabreccia is in strata we tentatively identify as the 20 to 21 Ma Limerock Canyon Formation (it is possible that these beds are in the pre-30 Ma Brian Head Formation, or in the 24 Ma Bear Valley Formation, or that the Limerock Canyon has a wider age range than we can now demonstrate; this awaits further geochemical and radiometric age control). One final complication involves exposures in Parowan Canyon that were interpreted by Maldonado and Moore (1995) as Harmony Hills Tuff in normal fault contact against Isom Formation, but that lead-author Biek reinterprets as Isom Formation that is part of the Markagunt megabreccia that unconformably overlies the 22.03 Ma Harmony Hills Tuff (i.e., the two units are separated by a gently southeast-dipping gravity-slide fault, not a steeply west-dipping normal fault). If this interpretation is correct, it suggests that the Markagunt megabreccia was emplaced sometime after 22.03 Ma. To summarize, all workers agree that catastrophic emplacement of the Markagunt megabreccia postdates the 23.8 Ma Leach Canyon Formation; most of us now agree that it also postdates the 22.8 Ma Haycock Mountain Tuff. Lead-author Biek tentatively interprets the megabreccia as post-dating the 22.03 Ma Harmony Hills Tuff, suggesting that it may be somewhat younger than most workers previously envisioned; ongoing mapping and pending $^{40}Ar/^{39}Ar$ age analyses may resolve timing of Markagunt megabreccia emplacement.

The Markagunt megabreccia was interpreted by Maldonado (1995) and Sable and Maldonado (1997a) to have formed by either gravity sliding off the Iron Peak laccolith and associated large shallow intrusive bodies or by low-angle, thinned-skinned thrusting away from the intrusions about 20 to 22 million years ago. Anderson (2001), however, noted that the 20 to 21 Ma Iron Peak laccolith may be too young and too small to produce a dome large enough to produce the megabreccia. Rather, Anderson (2001) suggested that the megabreccia originated from southward failure off the backslope of west-northwest-striking Miocene fault blocks.

Interestingly, on-trend with the south margin of the Markagunt megabreccia in the Bryce Canyon area, south-vergent thrust faults involving Upper Cretaceous and Paleocene-Eocene Claron Formation strata are well documented. These thrust faults have been interpreted to represent gravitational loading and collapse of the Marysvale volcanic field (or possibly coeval batholithic emplacement) (Davis and Krantz, 1986; Lundin, 1989; Davis and Rowley, 1993; Merle and others, 1993; Davis, 1999). In the "two-tiered" model of Davis (1999), the Markagunt megabreccia is but one – a surficial part – of a second, deeper series of Tertiary thrusts directed outward from the Marysvale volcanic field, which spread and collapsed under its own weight, resulting in southward-directed thrust faults rooted in gypsiferous strata of the Middle Jurassic Carmel Formation.

Figure 1a. Base of Markagunt megabreccia (exposed just south of Haycock Mountain on the southwest side of hill 8652, NW1/4SE1/4 section 5, T. 36 S., R. 6 W.). Note planar slip surface (strike N. 10° W., dip 6° NE.) and underlying thin basal conglomerate, which in turn unconformably overlies similarly dipping volcaniclastic pebbly sandstone, tentatively assigned to the Limerock Canyon Formation (Tl). Basal conglomerate is light-reddish-brown and consists of both angular (Isom) and rounded (intermediate volcanics and quartzite) clasts floating in a well-cemented sandy matrix; the conglomerate is texturally similar to concrete and is inferred to have been derived from pulverized Isom and underlying strata immediately above and below the detachment surface. This conglomerate is injected as dikes into the basal part of the megabreccia, which here consists of pulverized and recemented Isom Formation (Tm[Ti]). Pulverized Isom Formation forms a cliff 15 to 30 feet (5-10 m) high and grades abruptly upward into fractured but otherwise undisturbed Isom Formation.

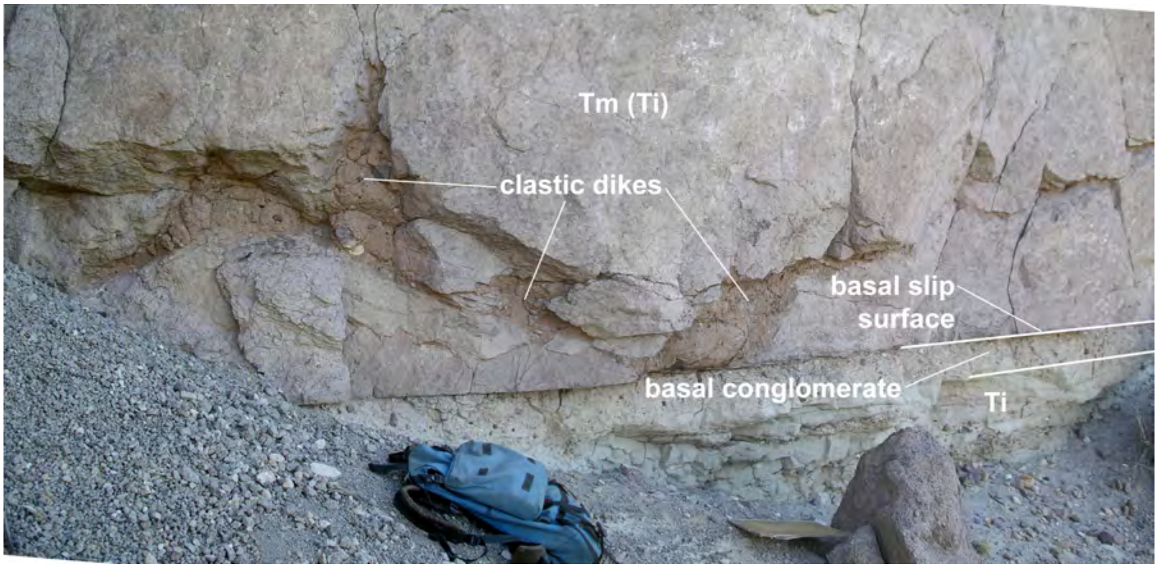

Figure 1b. Close-up of area near pack in figure 1a. Note clastic dikes injected into base of megabreccia.

Figure 2a. Base of Markagunt megabreccia (exposed just south of Haycock Mountain on the southeast side of an unnamed hill at the head of Little Coal Wash, NE1/4 section 6, T. 36 S., R. 6 W.). The basal part of the megabreccia consists of about 30 feet (10 m) of brecciated, pulverized, and resilicified Isom Formation (Tm[Ti]), which grades abruptly upward into fractured but otherwise undisturbed Isom Formation. Basal conglomerate is

hidden by shadow; we tentatively assign underlying volcaniclastc sandstone to the Limerock Canyon Formation (Tl).

Figure 2b. Close-up of brecciated and pulverized Isom Formation shown in figure 2a; Brunton compass for scale.

Figure 2c. Close-up of slickenlines exposed at the west side of figure 2a. Slickenlines trend 20° NW. and plunge 30° on the base of the megabreccia, which forms a planar surface that strikes N. 50° W. and dips 15° NE. Note basal conglomerate at base of megabreccia.

Tm **Markagunt megabreccia, undivided –** The Markagunt megabreccia (restricted usage following Sable and Maldonado, 1997a) is undivided where exposures are insufficient to delineate bedrock units, and in the remote northwest part of the Flanigan Arch quadrangle; most areas mapped as Tm consist predominantly of the Isom Formation (which is typically pervasively and finely fractured so that it weathers to grussy soils and rounded hills), but locally includes Wah Wah Springs and Brian Head strata, and, north of Panguitch Lake, large amounts of mafic block and ash-flow tuff, volcaniclastic sandstone, and pebbly conglomerate; on top of the Markagunt Plateau, north of the latitude of Panguitch Lake, Tm is unconformable on the resistant, planar, gently east-dipping surface of the Isom Formation, but between Brian Head peak and Clear Creek, it unconformably overlies the Leach Canyon Formation; at the west edge of the plateau, south of Iron Peak, it unconformably overlies Brian Head strata; maximum thickness exceeds 500 feet (150 m).

Tm(Ta) **Markagunt megabreccia – middle Tertiary alluvium component –** Volcaniclastic conglomerate and pebbly sandstone on the north flank of Haycock Mountain that may be a coarse alluvial facies of the Mount Dutton Formation; contains quartzite cobbles and small boulders in the basal part of the deposits; typically forms cobble-covered hillsides, but is locally well-consolidated in exposures on the southwest side of Haycock Mountain; this middle Tertiary alluvium that locally caps Haycock Mountain is likely older than similar alluvium under the Haycock Mountain Tuff described by Anderson (1993); as mapped here, the alluvium (Tm[Ta]) at Haycock Mountain overlies and is in turn locally overlain by Isom Formation (Tm[Ti]), all interpreted to be part of the upper plate of the Markagunt megabreccia; additionally, this alluvium is as much as 800 feet (250 m) above Panguitch Creek and the type section of Haycock Mountain Tuff (thus to have postdated emplacement of the megabreccia, the alluvium we map as [Tm(Ta)]would have had to completely fill the ancestral Panguitch Creek drainage and then been exhumed, but we see no compelling evidence for this interpretation); maximum thickness in this area is probably about 100 feet (30 m).

Tm(Td) **Markagunt megabreccia – Mount Dutton Formation component –** Massive block and ash-flow tuff of mafic and intermediate composition, volcaniclastic pebble to boulder conglomerate, and minor tuffaceous sandstone; characterized by brown or locally reddish-brown hues; mapped northwest of Haycock Mountain; tentatively interpreted to be part of the Markagunt megabreccia, but may contain strata that postdate emplacement of megabreccia (ongoing mapping in areas to the north may resolve this uncertainty); maximum thickness in this area is probably about 300 feet (100 m).

Tm(Thm) **Markagunt megabreccia – Haycock Mountain Tuff component –** Consists of two cooling units: lower unit is white to very light pink, unwelded, crystal-poor rhyolite tuff that is overlain by light-pink, poorly welded, moderately resistant crystal-poor rhyolite tuff; both contain common pumice fragments and lithic fragments of black, aphanatic, mafic volcanic rock; forms gently east-dipping ledge that at its type section overlies apparently undeformed volcaniclastic conglomerate and elsewhere overlies deformed Bear Valley Formation sandstone; petrographically and chemically similar to the Leach Canyon Formation (see the Leach Canyon Formation unit description for details); yielded $^{40}Ar/^{39}Ar$ age of 22.75 ± 0.12 Ma (Ed Sable, U.S. Geological Survey, unpublished data, 1996); Anderson (1993) interpreted the Haycock Mountain Tuff to postdate emplacement of the Markagunt megabreccia, but lead-author Biek tentatively interprets the tuff as riding largely undisturbed in the upper plate of the megabreccia; mapped north of Haycock Mountain; about 35 feet (11 m) thick.

Tm(Tbvs) **Markagunt megabreccia – Bear Valley volcaniclastic strata component –** White to light-gray, moderately to well-sorted, fine- to medium-grained volcaniclastic sandstone having high-angle cross-beds, and similarly colored tuffaceous mudstone and siltstone; typically pervasively deformed by faults and folds indicative of deformation as part of the Markagunt megabreccia; mapped north of Haycock Mountain; exposed thickness as much as 120 feet (35 m).

Tm(Tbvt) **Markagunt megabreccia – Bear Valley ash-flow tuff component –** White, unwelded, massive, likely rhyolitic ash-flow tuff that contains common pebble-size lithic fragments of intermediate volcanic rocks and rounded quartzite pebbles; mapped north of Haycock Mountain; exposed thickness as much as 100 feet (30 m).

Tm(Tl) **Markagunt megabreccia – Limerock Canyon Formation component –** White and light-gray, locally tuffaceous, volcaniclastic sandstone, pebbly sandstone, mudstone, minor tuffaceous limestone, and local multi-hued chalcedony; mapped on the southeast side of Haycock Mountain, where it is faulted and folded, indicative of deformation as part of the Markagunt megabreccia; we are uncertain of the identification of the Limerock Canyon Formation at Haycock Mountain (it is possible that these beds are in the pre-30 Ma Brian Head Formation, or are part of the 24 Ma Bear Valley Formation, or that the Limerock Canyon has a wider age range than the 20 to 21 Ma age we can now demonstrate), and this awaits further geochemical and radiometric age control; exposed thickness as much as 150 feet (45 m).

Tm(Tdm) **Markagunt megabreccia – Mafic block and ash-flow tuff of the Mount Dutton Formation component –** Dark-gray, vesicular, basaltic andesite and basalt present as angular cobble- to boulder-size blocks floating in a light-gray sandy matrix of the same composition; monolithic; minor basaltic scoria, likely a rafted block, is present north of Bunker Creek in the NE1/4NE1/4 section 12, T. 36 S., R. 8 W.; mapped between Panguitch Lake and Sidney Peaks where it unconformably overlies 24 Ma Leach Canyon Formation (Tql); in the Bunker Creek drainage west of Panguitch Lake, the map unit is overlain by Isom

Formation or locally by Wah Wah Springs Formation, each as part of the Markagunt megabreccia; exposures north of Bunker Creek (in the north-central part of section 12, T. 36 S., R. 8 W.) show 30 feet (9 m) of paleotopography cut into the upper surface of the Leach Canyon, with blocks of the rhyolite tuff incorporated into the base of the overlying mafic block and ash flow; similar mafic block and ash-flow tuff is present north of Panguitch Lake, where it is clearly part of the Markagunt megabreccia and so mapped as Tm(Tdm) and lumped as Tm in hill 8980 to the north; it is unclear if the deposits between Panguitch Lake and Sidney Peaks partly underlie or are everywhere part of the megabreccia; maximum thickness is about 80 feet (24 m).

Tm(Ti) **Markagunt megabreccia – Isom Formation component –** Medium-gray, crystal-poor, densely welded, trachydacitic ash-flow tuff; small (1-3 mm) euhedral crystals constitute 15 to 20 % of the rock and are mostly plagioclase (90%) and minor pyroxene, magnetite, and quartz set in a devitrified glassy groundmass; most outcrops and blocks weather to grussy soils and rounded hills; except at Haycock Mountain, rarely forms cliffs as is typical of the autochthonous Isom Formation; although generally poorly exposed, constitutes the great bulk of the megabreccia mapped between Panguitch Lake and Brian Head; may locally include areas of Brian Head Formation, Wah Wah Springs Formation, and mafic block and ash-flow tuff that are difficult to delineate given extensive forest cover and inconspicuous outcrop habit; generally unconformably overlies the Leach Canyon Formation west of Panguitch Lake (but also locally overlies Wah Wah Springs Formation and Brian Head Formation in this area), whereas east of Panguitch Lake, unconformably overlies what we tentatively map as Limerock Canyon Formation; maximum thickness as much as about 400 feet (120 m).

Tm(Tnw) **Markagunt megabreccia – Wah Wah Springs Formation component –** Pale-red, grayish-orange-pink, and pale-red-purple, crystal-rich, moderately welded, dacitic ash-flow tuff; phenocrysts of plagioclase, hornblende, biotite, and quartz (with minor Fe-Ti oxides and sanidine) comprise about 40% of the rock; forms a single cooling unit; mapped northeast of Castle Valley, where it rests on displaced Brian Head strata (Tm[Tbhv]) and in the upper reaches of Bunker Creek, where it rests on displaced Isom Formation (Tm[Ti]) or displaced mafic block and ash-flow tuff (Tm[Tdm]); about 40 feet (12 m) thick.

Tm(Tbhv)**Markagunt megabreccia – Brian Head Formation component –** Poorly exposed, but distinctive white to light-gray volcaniclastic mudstone, pebbly sandstone, micritic limestone, and chalcedony are present as colluvium, thus betraying the formation's presence northeast of Castle Valley where it rests out-of-sequence on the Leach Canyon Formation; on the ridge at the common border of sections 9 and 16, T. 36 S., R. 8 W., pebbly volcaniclastic sandstone of the Brian Head Formation, well exposed at the head of a landslide, dips about 25° northeast and is overlain by similarly dipping Wah Wah Springs Formation; on the hill to the south, however, Brian Head strata appear to be subhorizontal;

thickness uncertain but outcrop patterns suggest that displaced Brian Head strata likely exceed 100 feet (30 m) thick.

Tl **Limerock Canyon Formation** (lower Miocene) – White, light-gray, and pale- to olive-green, locally tuffaceous, volcaniclastic sandstone, pebbly sandstone, gritstone, pebbly conglomerate, mudstone, and minor tuffaceous limestone; may contain minor multi-hued chalcedony in areas north and west of the type section near Hatch, but as described below, we are as yet uncertain in differentiating Brian Head strata (which contain abundant chalcedony), Bear Valley Formation, and Limerock Canyon Formation; includes at least 10 thin beds of ash-fall tuff; commonly bioturbated; clasts are about 90% volcanic but include as much as 10% quartzite and sandstone; Kurlich and Anderson (1997) stated that the formation lacks Needles Range, Isom, Bear Valley, and Mount Dutton clasts, but most clasts appear to lead-author Biek to be Isom; mapped on the east part of the Markagunt Plateau north and west of Hatch, where it appears to cut out much of the Brian Head Formation, although this interpretation is uncertain as described below; unconformably overlain by upper Tertiary unconsolidated fan alluvium (Taf); query indicates uncertain identification; deposited in fluvial and minor lacustrine environments; two ash-fall tuff beds, about 100 feet (30 m) and 200 feet (60 m) above the base of the formation at the type section west of Hatch, respectively, yielded K-Ar ages of 21.5 ± 0.6 Ma (biotite) and 21.0 ± 1.0 Ma (sanidine), and 20.2 ± 1.4 Ma (biotite) and 19.8 ± 0.8 Ma (sanidine) (Sable and Maldonado, 1997b); Sable and Maldonado (1997b) also reported an $^{40}Ar/^{39}Ar$ age of 20.48 ± 0.8 Ma (biotite) and 21.0 ± 1.0 Ma (sanidine); as much as 290 feet (88 m) thick in a composite type section west of Hatch (Kurlich, 1990; Kurlich and Anderson, 1997).

Sable and Maldonado (1997b) described the difficulty of differentiating similar volcaniclastic strata of the Limerock Canyon, Bear Valley, and Brian Head Formations. The type section of the Limerock Canyon Formation (west of Hatch) contains a few tens of feet of strata that we tentatively reassign to the Brian Head Formation, and we interpret that the limestone that Kurlich and Anderson (1997) assigned to the Brian Head Formation at the base of this type section is in fact the upper white member of the Claron Formation as originally described by Kurlich (1990). Relationships of strata that we assign to the Brian Head and Limerock Canyon Formations are much clearer in the southeast corner of the Haycock Mountain quadrangle, 1 to 2 miles (1.5-3 km) west of the type section. There, and along the flanks of Hatch Mountain and Haycock Mountain, we place the contact between the two formations at the top of a massive multihued chalcedony bed that is typically 3 to 6 feet (1-2 m) thick. Strata underlying this chalcedony are typical of Brian Head strata as they are exposed at Brian Head peak; overlying strata are typically sandier and locally, as on the south flank of Hatch Mountain, contain significant pebble conglomerate.

Tip **Iron Peak laccolith** (early Miocene) – Medium-gray gabbro-diorite porphyry composed almost entirely of augite and plagioclase (calcic labradorite) and about 8% opaque oxide minerals, mostly magnetite, with diorite the dominant phase

(Anderson, 1965; Spurney (1984); magnetite veins are present throughout the intrusion and are as much as 10 feet (3 m) in width, but most are less than one inch (2.5 cm) wide (Spurney, 1984); base of laccolith is well exposed in the north canyon wall of Little Creek, which has incised through the laccolith to reveal numerous feeder dikes; originally referred to as the Iron Point laccolith by Anderson (1965) and Anderson and Rowley (1975), as the namesake peak was then known, but the peak was renamed and is now referred to as Iron Peak; intruded at the stratigraphic level of Brian Head Formation and is preserved in a graben at the west edge of the Markagunt Plateau, about 5 miles (8 km) northeast of Paragonah; roof rocks are not preserved; yielded K-Ar whole-rock age of 19.7 ± 0.5 Ma (Fleck and others, 1975); exposed thickness is as much as about 800 feet (240 m).

Forms the easternmost laccolith of the Iron Axis, a northeast-trending belt of early Miocene calc-alkaline 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, 1998; Rowley and others, 1998); Iron Peak is the second youngest and most mafic of the Iron Axis intrusions; most of the central quartz monzonite plutons appear to be partly controlled by northeast-striking, southeast-verging Sevier-age thrust faults and were emplaced at shallow depths, mostly within about 1.2 miles (2 km) of the surface (Mackin and others, 1976; Van Kooten, 1988; Hacker and others, 2002, 2007; Rowley and others, 2006), but the Iron Peak laccolith exhibits no such structural control; like the other laccoliths in the belt, the Iron Peak laccolith probably formed rapidly following a two-stage emplacement process – injection of a sill immediately followed by inflation – at shallow crustal depth of less than 4000 feet (1.2 km) based on stratigraphic reconstructions (Spurney, 1984; see also Hacker and others, 2002, 2007; Willis, 2002); rapid inflation of the laccoliths commonly led to partial unroofing by gravity sliding, immediately followed by volcanic eruptions (Mackin, 1960; Blank and Mackin, 1967; Hacker and others, 1996, 2002, 2007; Hacker, 1998; Willis, 2002), although it is unclear if the Iron Peak laccolith experienced a similar history; Spurney (1984) interpreted exposures immediately east of the Iron Peak laccolith as a peripheral breccia complex and described volcanic rocks of similar composition to the south in the adjacent Red Creek Reservoir quadrangle that suggest that the intrusion erupted and produced lava flows or block and ash flow breccias; Maldonado and others (in preparation), however, interpreted the eastern exposures as older Bear Valley breccia; ongoing mapping in the Red Creek Reservoir and Cottonwood Mountain quadrangles may further elucidate the emplacement history of the Iron Peak laccolith.

Emplacement of the Iron Peak laccolith was suggested as one possible source of the Markagunt megabreccia (Sable and Maldonado, 1997a), but Anderson (1993, 2001) suggested that the intrusion was too small to have produced such a large gravity slide; however, because the laccolith is only exposed in a graben, we do not know its original extent, particularly how far west it may hhave once reached; we mapped megabreccia deposits (here lumped with the Markagunt megabreccia for lack of suitable criteria for differentiation) on the divide between Red Creek and Little Creek canyons, and these deposits may be a result of local gravity sliding off the south flank of the laccolith.

Spurney (1982, 1984) suggested that magnetite veins formed late in the laccolith's emplacement, a result of alteration of augite phenocrysts; while magnetite veins are common, they are apparently of insufficient number to have been of economic importance, unlike the nearby Iron Springs mining district west of Cedar City, the largest iron-producing district in the western U.S. (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; Rowley and others, 2006).

Tipd **Feeder dikes of Iron Peak laccolith** (lower Miocene) **–** Mafic dikes exposed in the north canyon wall of Little Creek, immediately south of the Iron Peak laccolith; of the same composition as the adjacent laccolith, and so are interpreted to be its feeder dikes (Anderson, 1965; Spurney, 1984; Hacker and others, 2007); dikes intrude altered Brian Head Formation, which early workers then called the upper part of the Claron Formation, and are resistant and so stand as tall fins; most dikes trend northeast, dip moderately to steeply west, and most are about 6 feet (2 m) wide but range from about 0.8 to 25 feet (0.25-8 m) wide.

Timd **Mafic dikes at the west edge of the Markagunt Plateau** (lower Miocene) **–** Highly altered, greenish-gray to brownish-gray, aphanitic to fine-grained mafic dikes that trend both north-northwest and northeast in the Cottonwood Mountain quadrangle; some dikes contain small plagioclase phenocrysts; typically deeply weathered and so poorly exposed, but most dikes fill joints and small-displacement faults, which are especially well developed in a horst of gently northwest-tilted Claron strata at the west edge of the plateau, west of Iron Peak; Maldonado and others (1997a; in preparation) suggested that the dikes may be related to an older phase of the Iron Peak intrusion or to dikes of Mount Dutton; a sample from one of the northwest-trending dikes west of the Iron Peak laccolith yielded a K-Ar age of about 20 Ma (H.H. Mehnert and R.E. Anderson, written communication to F. Maldonado, 1988); dikes range from about 1 to 20 feet (0.3-6 m) wide.

Td **Mount Dutton Formation, alluvial facies** (lower Miocene to Oligocene) **–** Light- to dark-gray and brown, andesitic to dacitic volcanic mudflow breccia and lesser interbedded volcaniclastic conglomerate and tuffaceous sandstone; also contains subordinate lava flows, flow breccia, and minor felsic tuff; Anderson and Rowley (1975) defined the Mount Dutton Formation as consisting of most of the rocks exposed on the south flank of the Marysvale volcanic pile, and divided it into complexly interfingering and cross-cutting vent and alluvial facies derived from clustered stratovolcanoes and dikes that form most of the southern Marysvale volcanic field; most of the formation consists of intermediate-composition volcanic rocks of the alluvial facies, with comparatively thin, intercalated formally named members; on the northern Markagunt Plateau, the formation overlies the Bear Valley Formation; makes up the youngest (in the

Panguitch quadrangle) of several voluminous calc-alkaline, subduction-related volcanic centers and underlying source plutons that characterized the West from Oligocene to Miocene time at this latitude (Lipman and others, 1972; Rowley and Dixon, 2001); Fleck and others (1975) and Rowley and others (1994a) reported several K-Ar ages of 21 to 30 Ma on rocks of the coeval vent facies; at least 1000 feet (300 m) thick in the map area in the northern Markagunt Plateau (Anderson and Rowley, 1987) (and at least 6000 feet [2000 m] thick farther north; Rowley and others, 2005), but pinches out radially from an east-trending string of stratovolcanoes along the southern part of the Marysvale volcanic pile.

Tbv **Bear Valley Formation, undivided** (lower Miocene to upper Oligocene) – White to light-gray, yellowish-gray, and olive-gray, moderately to well-sorted, fine- to medium-grained volcaniclastic sandstone; sand is about 60% quartz, and the remainder is feldspar, biotite, hornblende, augite, and relict pumice replaced by zeolite; cement is mostly zeolite (clinoptilolite) (Anderson, 1971); sandstone is characterized by high-angle cross-beds indicative of eolian deposition; thick eolian sand was derived from the south and west and accumulated in a low-relief basin bounded on the north by an east-trending fault scarp possibly associated with the 25 Ma Spry intrusion (Anderson, 1971; Anderson and others, 1990a); also contains lesser interbedded lava flows, volcanic mudflow breccia, conglomerate, and ash-fall and ash-flow tuff beds, especially in the upper part of the formation; where mapped as part of the Markagunt megabreccia, sandstone facies (Tbvs) and ash-flow tuff facies (Tbvt) are mapped separately; Fleck and others (1975) reported two K-Ar ages of 24.0 ± 0.4 Ma and 23.9 ± 0.5 Ma from the upper part of the formation; an incomplete section of Bear Valley strata is only 100 feet (30 m) thick in the Panguitch quadrangle (Moore and Straub, 1995) and about 400 feet (120 m) thick in the Cottonwood Mountain quadrangle, but the formation is in excess of 1000 feet (300 m) thick on the northern Markagunt Plateau (Anderson, 1971); the unit is as much as about 260 feet (80 m) thick in the Red Hills (Maldonado and Williams, 1993b).

Tbvb **Bear Valley Formation mudflow breccia** (lower Miocene to upper Oligocene) – Pale-yellowish-brown breccia composed of pebble- to cobble-size clasts, mostly of intermediate composition volcanic rocks and lesser amounts of tuff and tuffaceous sandstone; as much as about 800 feet (245 m) thick in the Cottonwood Mountain quadrangle.

Quichapa Group (lower Miocene to upper Oligocene) – Regionally consists of three distinctive ash-flow tuffs: in ascending order, the Leach Canyon Formation, Condor Canyon Formation, and Harmony Hills Tuff (Mackin, 1960; Williams, 1967; Anderson and Rowley, 1975; Rowley and others, 1995); the lower two formations erupted from the Caliente caldera complex, but the Harmony Hills Tuff likely erupted from the eastern Bull Valley Mountains (Rowley and others, 1995).

Tqh **Harmony Hills Tuff** (lower Miocene) – Resistant, pale-pink to grayish-orange-pink, crystal-rich, moderately welded, dacitic ash-flow tuff; contains about 50% phenocrysts of plagioclase (63%), biotite (16%), horneblende (9%), quartz (7%), pyroxene (5%), and sanidine (trace) (Williams, 1967); exposed in Parowan Canyon where it overlies the Bauers Tuff Member of Condor Canyon Formation and reinterpreted by lead-author Biek to underlie the Isom Formation that is part of the Markagunt megabreccia; 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 ± 0.15 Ma (Cornell and others, 2001), nearly identical to that of those intrusions; as much as 50 feet (15 m) thick.

Tqcb **Bauers Tuff Member of Condor Canyon Formation** (lower Miocene) – Resistant, light-brownish-gray to pinkish-gray, densely welded, rhyolitic ash-flow tuff; contains about 10 to 20% phenocrysts of plagioclase (40-70%), sanidine (25-50%), biotite (2-10%), Fe-Ti oxides (1-8%), and pyroxene (<3%) (Rowley and others, 1995); bronze-colored biotite and light-gray flattened lenticules are conspicuous; exposed in Parowan Canyon where it is as much as 50 feet (15 m) thick and overlies volcaniclastic sandstone and mudflow breccia, here ascribed to the Mount Dutton Formation but mapped by Maldonado and Moore(1995) as Oligocene mudflow and lava-flow breccia and tuffaceous sandstone; also exposed in a fault block in the Red Hills, where it is as much as about 100 feet (30 m) thick (Maldonado and Williams, 1993a); derived from the northwest part (Clover Creek caldera) of the Caliente caldera complex and at the time of its eruption, covered an area of at least 8900 square miles (23,000 km^2) (Best and others, 1989b; Rowley and others, 1995); the prefered $^{40}Ar/^{39}Ar$ age of the Bauers Tuff Member is 22.7 Ma (Best and others, 1989a) or 22.8 Ma (Rowley and others, 1995), which is also the $^{40}Ar/^{39}Ar$ age of its intracaldera intrusion exposed just north of Caliente (Rowley and others, 1994b); Fleck and others (1975) reported K-Ar ages of 22.1 ± 0.6 Ma (plagioclase) and 20.7 ± 0.5 Ma (whole rock) for Bauers Tuff that is east of Fivemile Ridge and south of Horse Valley, respectively.

Tql **Leach Canyon Formation** (lower Miocene to upper Oligocene) – Grayish-orange-pink to pinkish-gray, unwelded to moderately welded, crystal-rich rhyolite tuff that contains abundant white or light-pink collapsed pumice fragments and several percent lithic clasts, many of which are reddish brown; contains 25 to 35% phenocrysts of quartz, feldspar, and biotite; forms the resistant caprock of Brian Head peak and the southern part of Black Ledge, and is also exposed eastward nearly to the Panguitch Lake area, as described below; source is unknown, but it is probably the Caliente caldera complex because isopachs show that it thickens toward the complex (Williams, 1967; Rowley and others, 1995); typically about 100 feet (30 m) thick in the map area.

At Brian Head peak, the Leach Canyon Formation, which unconformably overlies the Isom Formation, consists of four parts, the lower three of which are rarely exposed elsewhere. At the base is nonresistant, 6- to 10-foot-thick (2-3 m), unwelded, white, rhyolite tuff that is overlain by a 10-foot-thick (3 m) moderate-orange-pink rhyolite tuff that has sparse reddish-brown lithic clasts, which becomes slightly more indurated in the upper part of the unit. This is overlain by a massive, 12-foot-thick (4 m) black vitrophyre, which is in turn overlain by a 25-foot-thick (8 m) resistant, pale-red, moderately welded rhyolite tuff that contains pale-lavender flattened pumice lenticules and as much as 1% distinctive, small, reddish-brown lithic clasts of flow rock torn from the vent walls; this resistant upper unit forms the cap rock of Black Ledge northward to beyond the Sidney Peaks area.

To the east, west of Panguitch Lake, the Leach Canyon Formation unconformably overlies the Brian Head Formation or locally stream gravel containing clasts of Isom Formation welded tuff (for example, on the southeast side of Prince Mountain at sample location PL061708-3); pumice makes up about 10% of the tuff and is typically less than 0.5 inch (1 cm) in length, but somewhat larger near the top of the cooling unit; a nonresistant, moderate-orange-pink ash-fall tuff identical to that at Brian Head peak is present at the base of the unit; the main part of the cooling unit contains only rare, small, reddish-brown lithic fragments.

Previously, there was considerable confusion over the distribution of the petrographically and chemically similar Leach Canyon Formation and the Haycock Mountain Tuff in the map area (the two units are not reliably distinguishable based on their major- and trace-element chemistry, but the Haycock Mountain Tuff is typically less welded than the Leach Canyon and contains conspicuous black lithic fragments, unlike the reddish-brown lithic fragments of the Leach Canyon). Detailed mapping of the Panguitch Lake quadrangle (Biek and Sable, in preparation) has resolved this problem. The Leach Canyon Formation can be traced in continuous outcrop from Brian Head peak northward to the head of Bunker Creek and then east to the east end of Prince Mountain just west of Panguitch Lake; it is unconformably overlain by the Markagunt megabreccia, which consists mostly of the Isom Formation. Samples from the south side of Prince Mountain yielded K-Ar ages of 22.8 ± 1.1 Ma (biotite) and 24.8 ± 1.0 Ma (sanidine) (Rowley and others, 1994a, sample 89USa-1a) and a duplicate K-Ar age of 24.3 ± 1.0 Ma (sanidine) as well as an $^{40}Ar/^{39}Ar$ age of 23.86 ± 0.26 Ma (biotite) (Sable and Maldonado, 1997a, on the same sample 89USa-1a). The Leach Canyon Formation is widely agreed to be about 23.8 Ma (Best and others, 1993; Rowley and others, 1995). However, both Rowley and others (1994a) and Sable and Maldonado (1997a) interpreted this tuff to be the Haycock Mountain Tuff, which yielded a slightly younger $^{40}Ar/^{39}Ar$ age of 22.75 ± 0.12 Ma (sanidine) at its type section one mile (1.6 km) northeast of Panguitch Lake (Sable, unpublished data, 1996). The facts that the tuff at Prince Mountain yielded an age analytically indistinguishable from the Leach Canyon Formation, that it can be traced continuously to outcrops at Brian Head peak, and that it is unconformably overlain by the Markagunt megabreccia, are irrefutable evidence that it is the Leach Canyon Formation and not the Haycock Mountain Tuff.

The Leach Canyon Formation unconformably overlies the Isom Formation at Brian Head peak and the southern part of Black Ledge. North of Castle Valley and at Prince Mountain, however, the Leach Canyon unconformably overlies Brian Head strata. This distribution suggests that the Prince Mountain-Castle Valley area was a paleohigh of Brian Head strata during Isom time, and that, once the resistant Isom was in place, this paleohigh was preferentially eroded to form a broad, east-trending stream valley in which the Leach Canyon accumulated; the Leach Canyon is not present north of Clear Creek in the map area. We speculate that northwest-trending Clear Creek may conceal a pre-Isom down-to-the-north normal fault that helped control distribution of the Isom Formation.

unconformity

Ti **Isom Formation** (upper Oligocene) – Medium-gray, crystal-poor, densely welded, trachydacitic ash-flow tuff, locally having distinctive rheomorphic features including flow folds, elongated vesicles, and flow breccia; small (1-3 mm) euhedral crystals constitute 10 to 15% or less of the rock and are mostly plagioclase (90%) and minor pyroxene and Fe-Ti oxides set in a devitrified-glass groundmass; exhibits pronounced platy outcrop habit and is thus accompanied by extensive talus deposits; rarely, a black basal vitrophyre is exposed, and locally fracture surfaces and elongated vesicles (lenticules, described below) are dark reddish brown to dusky red; query indicates uncertain correlation in the upper reaches of the Clear Creek drainage

The best and most extensive exposures of the Isom Formation are at Brian Head peak and to the northeast along Black Ledge where at least three cooling units are locally present; at Brian Head peak, the lower part of the formation is classic tufflava about 80 feet (24 m) thick, whereas the upper part is a flow breccia 60 to 90 feet (18-27 m) thick; along Black Ledge, about 7 miles (11 km) northeast of Brian Head peak, the flow breccia is absent and the Isom there appears to consist of a single cooling unit about 350 feet (100 m) thick; the Isom also forms prominent cliffs north of Clear Creek and Panguitch Lake.

Regionally, many outcrops of all cooling units in the Isom Formation reveal secondary flow characteristics, including flow breccias, contorted flow layering, and linear vesicles such that the unit was considered a lava flow until Mackin (1960) mapped its widespread distribution (300 cubic miles [1300 km^3] today spread over an area of 9500 square miles [25,000 km^2]; Best and others, 1989a) and found evidence of glass shards, thus showing its true ash-flow tuff nature; for that reason it is commonly referred to as a tufflava, and is also called a rheomorphic ignimbrite, an ash-flow tuff that was sufficiently hot to move with laminar flow as a coherent ductile mass – see, for example, Anderson and Rowley (1975) and Andrews and Branney (2005); exhibits pronounced subhorizontal lamination or platiness, which Mackin (1960) called "lenticules"; Fryman (1986, 1987), Anderson and others (1990b), and Anderson (2002) described the light-gray, pancake-shaped lenticules, which are typically spaced 4 to 8 inches (10-20 cm) apart and that may extend for 30 feet (10 m) or more, and which are locally contorted, suggesting turbulence in the flow as it moved over uneven topography;

Fryman (1986, 1987) also described fumaroles in the Isom of the northern Markagunt Plateau, a result of degassing of the flow as it came to a rest.

The source is unknown, but isopach maps and pumice distribution suggest that the Isom Formation was derived from late-stage eruptions of the 27-32 Ma Indian Peak caldera complex that straddles the Utah-Nevada border, possibly in an area now concealed by the western Escalante Desert (Rowley and others, 1979; Best and others, 1989a, 1989b); estimated crystallization temperature and pressure of phenocrysts of the Isom is 950°C and < 2 kbar (Best and others, 1993), and this relatively high temperature is supported by its degree of welding and secondary flow features; at its type area in the Iron Springs district southwest of the map area, Mackin (1960) defined three members, a lower unnamed member, the Baldhills Tuff Member, and the upper Hole-in-the-Wall Tuff Member; Rowley and others (1975) redefined the Baldhills Tuff Member to include Mackin's lower unnamed member, and noted that the Baldhills consists of at least six cooling units; Maldonado and Williams (1993a, b) described nine apparent cooling units in the northern Red Hills at the west edge of the map area; in the northern Markagunt Plateau, Anderson and Rowley (1975) defined the Blue Meadows Tuff Member, which underlies the Baldhills Tuff Member, but it is possible that the Blue Meadows Tuff is part of the Mount Dutton Formation, and thus a local tuff of the Marysvale volcanic field (Rowley and others, 1994a); in some places in the Panguitch 30' x 60' quadrangle, autochthonous Isom Formation may include the Baldhills Tuff Member, but this member was not recognized in the southern part of its outcrop belt in the map area; the Isom Formation is about 26 to 27 Ma on the basis of many $^{40}Ar/^{39}Ar$ and K-Ar ages (Best and others, 1989b; Rowley and others, 1994 a); maximum exposed thickness is about 350 feet (110 m) at Black Ledge and about 250 feet (75 m) along Ipson Creek.

Mapped as the Blue Meadows Tuff Member of the Isom Formation at the east edge of the Cottonwood Mountain quadrangle (Maldonado and others, in preparation), but refered to simply as Isom Formation undivided here pending ongoing mapping in areas to the east.

Tn **Needles Range Group, undivided** (lower Oligocene) **–** Lund Formation and Wah Wah Springs Formation undivided in the Red Hills due to map scale.

Tnl **Lund Formation** (lower Oligocene) **–** Grayish-orange-pink, moderately welded, crystal-rich, dacitic ash-flow tuff exposed in the Red Hills; similar to underlying Wah Wah Springs Formation, but with generally smaller mafic phenocrysts and a lighter-colored matrix; locally contains spheroidal masses of tuff as large as 1 foot (0.3 m) in diameter near the top of the unit; base of the formation includes about 12 feet (4 m) of pale-greenish-yellow tuffaceous sandstone and lesser pebbly volcaniclastic conglomerate; exhibits normal magnetic polarity (Best and Grant, 1987); derived from the White Rock caldera, the southwest part of the older Indian Peak caldera, and is of similar volume to the underlying Wah Wah Springs Formation (Best and Grant, 1987; Best and others, 1989a, b); preferred age is 27.9

Ma (Best and others, 1989a); as much as about 200 feet (60 m) thick; unit description modified from Maldonado and Williams (1993a).

unconformity

Tnw **Wah Wah Springs Formation** (lower Oligocene) – Pale-red to grayish-orange-pink, moderately welded, crystal-rich, dacitic ash-flow tuff that rests on Brian Head strata and is overlain by the Isom Formation; phenocrysts of plagioclase, hornblende, biotite, and quartz (plus minor Fe-Ti oxides and sanidine) constitute about 40% of the rock; elongate collapsed pumice is common; exposed west of Cottonwood Mountain and west of Bear Valley in the Cottonwood Mountain quadrangle, at the head of Bunker Creek in the Brian Head quadrangle, and in the Red Hills; exhibits reversed magnetic polarity (Best and Grant, 1987); derived from the 27-32 Ma Indian Peak caldera complex that straddles the Utah-Nevada border (Best and others, 1989a, 1989b); today, Wah Wah Springs covers at least 8500 square miles (22,000 km^2) with an estimated volume as much as about 720 cubic miles (3000 km^3) (Best and others, 1989a); about 30 Ma based on many K-Ar and $^{40}Ar/^{39}Ar$ age determinations (Best and Grant, 1987; Best and others, 1989a, b; Rowley and others, 1994a); about 40 feet (12 m) thick near the west edge of the Markagunt Plateau, but as much as 400 feet (120 m) thick in the Red Hills (Maldonado and Williams, 1993a, b).

A small exposure on Lowder Creek (east of Brian Head peak) is deeply weathered, nonresistant, white, crystal-rich ash-flow tuff about 6 feet (2 m) thick; phenocrysts of plagioclase, hornblende, biotite, and quartz (plus minor Fe-Ti oxides and sanidine) make up about 30 to 40% of the rock; color and degree of welding contrast sharply with typical Wah Wah Springs, leading Rowley and others (in preparation) to suggest that the tuff at Lowder Creek was deposited in a lake; the Lowder Creek exposure is overlain by 3 to 6 feet (1-2 m) of volcanic mudflow breccia, which is in turn overlain by 10 to 15 feet (3-5 m) of deeply weathered, nonresistant, crystal-poor ash-flow tuff(?) of uncertain provenance, which is itself overlain by autochthonous Isom Formation.

unconformity

Brian Head Formation (lower Oligocene to uppermost Eocene) – The Brian Head Formation is the oldest widespread Tertiary volcaniclastic unit in the region; it disconformably overlies the uppermost mudstone, siltstone, and sandstone interval (Tcwt) and the upper white limestone interval (Tcwu) of the white member of the Claron Formation on the Markagunt Plateau (in the northern Markagunt Plateau and Red Hills, where the white member appears to be missing, Brian Head strata overlie the red member of the Claron Formation). Sable and Maldonado (1997b) divided the Brian Head Formation into three informal units, ascending: (1) nontuffaceous sandstone and conglomerate, (2) a volcaniclastic unit that has minor but conspicuous limestone and chalcedony, and (3) a volcanic unit, locally present, characterized by volcanic mudflow breccia, mafic lava flows, volcaniclastic sandstone and conglomerate, and ash-flow tuff; we include the basal nontuffaceous sandstone and conglomerate as a new uppermost part of the Claron Formation (Tcwt), so that only their middle volcaniclastic unit is present in the map area; in the map area, Brian Head strata are unconformably overlain by the 30 Ma Wah Wah Springs Formation (Tnw), or locally by the 26 to 27 Ma Isom Formation (Ti), and so is early Oligocene to latest Eocene (Sable and Maldonado, 1997b). Maldonado and Moore (1995) reported $^{40}Ar/^{39}Ar$ ages of 33.00 ± 0.13 Ma (plagioclase) and 33.70 ± 0.14 Ma (biotite) on an ash-flow tuff in the northern Red Hills that lies in the upper part of the formation. We obtained a U-Pb age on zircon from an airfall tuff at the base of the formation at Cedar Breaks National Monument of 35.77 ± 0.28 Ma.

Tbhv **Middle volcaniclastic unit –** White to light-gray volcaniclastic mudstone, siltstone, silty sandstone, sandstone, conglomerate, volcanic ash, micritic limestone, and multi-hued chalcedony; near Mineral Canyon and northwest of Little Salt Lake (hill 7292), conglomerate consists of pebble- to boulder-size, rounded clasts of intermediate volcanic rocks of unknown affinity and quartzite pebbles and cobbles; Maldonado and Williams (1993a) reported clasts of ash-flow tuff that resemble some *overlying* rocks (for example the Bauers Tuff), and additional work is underway to investigate this possibility; sandstone is commonly bioturbated with pencil-size root or burrow casts that weather out in relief; soft-sediment slump features are locally common; chalcedony is various shades of white, gray, yellow, red, black, and brown, typically has a white weathering rind, is commonly highly brecciated and resilicified, typically occurs in beds 1 to 3 feet (0.3-1 m) thick but locally as much as 8 feet (2.5 m) thick, is locally stained by manganese oxides, and may have resulted from silicification of limestone beds (Maldonado, 1995; Sable and Maldonado, 1997b) or possibly volcanic ash beds (Bakewell, 2001); chalcedony is almost always highly fractured, but some is useful for lapidary purposes (Strong, 1984); the formation is typically nonresistant, poorly exposed, and extensively covered by colluvium, but locally well exposed near Panguitch Lake and on the southwest side of Brian Head peak; because of abundant bentonitic clay derived from weathered volcanic ash, this unit weathers to strongly swelling soils (unlike underlying Claron Formation) and forms large landslide complexes; deposited in low-relief fluvial, floodplain, and lacustrine environments in which large amounts of volcanic ash accumulated; thickness uncertain, but maximum exposed thickness, at Brian Head peak, is about 500 feet (150 m).

Tbht **Rhyolitic tuff of middle volcaniclastic unit –** Pinkish-brown, unwelded rhyolite tuff in the upper part of the formation in the northern Red Hills, on the west flank of Jackrabbit Mountain; yielded K-Ar ages of 34.2 ± 2.1 Ma (plagioclase) and 36.3 ± 1.3 Ma (biotite), and $^{40}Ar/^{39}Ar$ ages of 33.00 ± 0.13 Ma (plagioclase) and 33.70 ± 0.14 Ma (biotite) (Maldonado and Williams, 1993b); as much as about 200 feet (60 m) thick.

unconformity

Claron Formation (Eocene to Paleocene) **–** Mapped as five informal lithostratigraphic units described below: an upper white member (which is itself divided into an uppermost mudstone interval, an upper limestone interval, a middle mudstone and sandstone interval, and a lower limestone interval) and the lower red member. This map is the first publication with the several lithologic facies of the white member of the Claron mapped separately, which has proven useful to better understand faulting at the west edge of the Markagunt Plateau, the distribution of overlying volcaniclastic units of the Brian Head and Limerock Canyon Formations, and the southern depositional limit of the Markagunt megabreccia and location of inferred toe thrusts. The Claron Formation consists of mudstone, siltstone, sandstone, limestone, and minor conglomerate deposited in fluvial, floodplain, and lacustrine environments of an intermontaine basin bounded by Laramide uplifts (Schneider, 1967; Goldstrand, 1990, 1991, 1992; Taylor, 1993; Ott, 1999). Much of the red member, and clastic parts of the white member, were greatly modified by bioturbation and pedogenic processes, creating a stacked series of paleosols (Mullett and others, 1988a, b; Mullett, 1989; Mullett and Wells, 1990; see also Bown and others, 1997). The Claron Formation is typically forested and covered by colluvium, but it forms the Pink Cliffs, the uppermost riser of the Grand Staircase, and is spectacularly exposed at Cedar Breaks National Monument and Bryce Canyon National Park. It is mostly nonfossiliferous and its age is poorly constrained as Eocene to Paleocene (Goldstrand, 1994; Feist and others, 1997).

Tcw **White member, undivided** (Eocene) – Used for areas south of Blue Spring Mountain and west of the Brian Head resort where incomplete and isolated exposures preclude subdivision; query indicates uncertain correlation in the northwest corner of the Brian Head quadrangle. The entire white member is about 340 feet (100 m) thick in Rock Canyon; Hatfield and others (2003) reported that it is 360 feet (110 m) thick at Cedar Breaks National Monument, but if the lower sandstone and conglomerate unit of Sable and Maldonado (1997b) is included as part of the white member, as suggested here, the thickness is 440 feet (135 m) (regardless, the white member is truncated south of Cedar Breaks National Monument by late Tertiary and Quaternary erosion associated with development of the Markagunt Plateau); Moore and others (1994) reported significant facies changes in the white member in the Asay Bench quadrangle, but there, in aggregate, it is 448 feet (137 m) thick. Sinkholes are common in the white member in the central Markagunt Plateau (Hatfield and others, 2003; Moore and others, 2004; Biek and others, 2007; Rowley and others, in preparation); large sinkholes visible on 1:20,000-scale aerial photographs are plotted on the geologic map, and doubtless many smaller sinkholes are present; these sinkholes capture local runoff and serve to shunt shallow ground water rapidly down dip where it emerges as springs, including the large Mammoth and Asay Springs (Wilson and Thomas, 1964; Spangler, in preparation).

Tcwt **Uppermost mudstone, siltstone, and sandstone interval of white member** (upper and middle Eocene) – Varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, dark-yellowish-orange, grayish-pink, and similarly hued calcareous mudstone and siltstone, locally with minor fine-grained silty sandstone and micritic limestone; indistinguishable in lithology and color from the middle white (Tcwm) and red members (Tcr) of the Claron Formation; forms a brightly colored slope on top of the upper white member of the Claron Formation in the northern part of Cedar Breaks National Monument (figure 3); best exposed near the North View overlook, where it is 109 feet (33 m) (Schneider, 1967) of mudstone and siltstone capped by a thin calcareous sandstone and pebbly conglomerate; this capping bed is 1 to 10 feet (0.3-3 m) thick and has chert, quartzite, and Claron limestone clasts but apparently no volcanic clasts; the sandstone and pebbly conglomerate are overlain by gray bentonitic mudstone of the Brian Head Formation (Tbhv); also exposed immediately south of Panguitch Lake, where it is about 50 feet (15 m) thick, and in the upper reaches of Rock Canyon, but is apparently absent elsewhere on the Markagunt Plateau; queried near Winn Gap at the south end of the Red Hills, where, based on similar four-part limestone-clastic-limestone-clastic section above the red member, we infer that the white member may be present; also queried near Mineral Canyon northeast of Paragonah, where as much as a few hundred feet of Claron redbeds lie above what may be the upper limestone interval.

Schneider (1967) reported biotite in some of these beds, and while some beds exhibit slightly expansive soils, we found no biotite – even so, it is the apparent presence of biotite-bearing strata, and possible correlation to variegated strata on the southern Sevier Plateau (see Feist and others, 1997), that led Sable and Maldonado (1997b) to provisionally include these strata as part of their Brian Head Formation. However, these same exposures strongly suggest to us that the nontuffaceous sandstone and conglomerate as defined by Sable and Maldonado (1997b) is simply the uppermost facies of the Claron Formation; they reasoned that because Brian Head volcaniclastic strata overlie different parts of the Claron Formation on the Markagunt Plateau, a disconformity separates the two formations; although we agree that an unconformity exists, we place the unconformity at the base of the thin sandstone and conglomerate (not at the top of the limestone ledge of the white member), thereby including the Claron-like red beds as a new upper unit of the white member. Sable and Maldonado (1997b) and Feist and others (1997) reported on sparse late to middle Eocene vertebrate fossils and charophytes in strata on the southern Sevier Plateau that may be equivalent to this map unit.

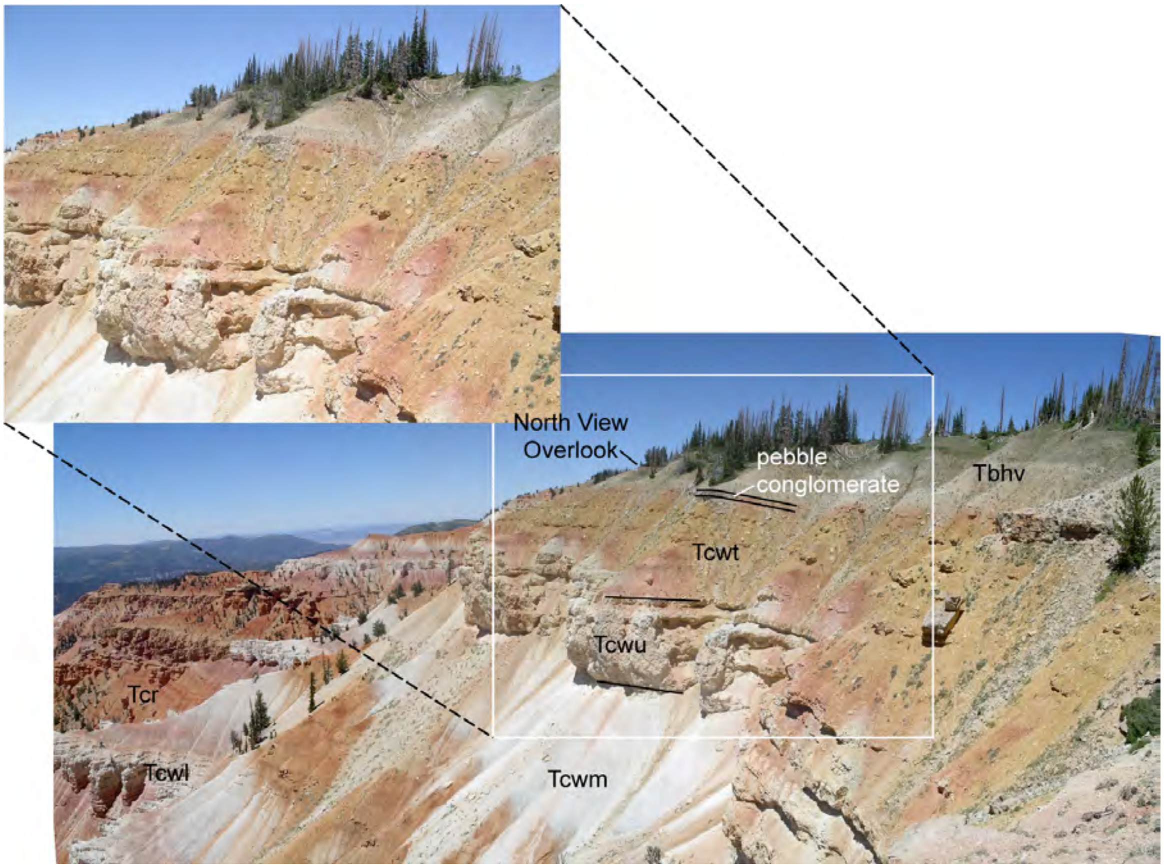

Figure 3. View northwest to North View overlook at Cedar Breaks National Monument showing contact between Claron and Brian Head strata (the North Overlook is on basal strata of the gray volcaniclastic unit of the Brian Head Formation, Tbhv). Sable and Maldonado (1997b) assigned variegated, nontuffaceous mudstone, siltstone, and minor sandstone and pebble conglomerate (here labeled Tcwt, 109 feet [33 m] thick) to their lower Brian Head Formation. However, these strata appear identical to strata of the middle white unit (Tcwm); they are nontuffaceous and appear simply to be an uppermost facies of the white member of the Claron Formation, to which we assign them. The top of the Claron, as defined here, is marked by a thin, calcareous, pebbly sandstone that has rounded clasts of chert, quartzite, and Claron limestone but apparently no volcanic clasts.

Tcwu **Upper limestone interval of white member** (Eocene) – White, pale-yellowish-gray, pinkish-gray, and very pale orange micritic limestone and uncommon pelmicritic limestone, locally containing intraformational rip-up clasts; locally contains sparse charophytes and planispiraled snails; typically poorly bedded and knobby weathering; locally vuggy with calcite spar and commonly cut by calcite veinlets; resistant and so forms prominent ledge and flat ridge tops; upper conformable contact with Tcwt corresponds to a pronounced color change from white to very pale orange micritic limestone below to brightly colored reddish-orange mudstone and siltstone above; queried at the south end of the Red Hills, and near Mineral Canyon northeast of Paragonah; thins to the west from 80 to 100 feet (24-30 m) thick in the southwest quarter of the Haycock Mountain quadrangle, 80 to 165 feet (24-50 m) thick in the Asay Bench quadrangle (Moore and others, 1994), about 150 to 180 feet (45-55 m) thick in the Henrie Knolls quadrangle (Biek and others, 2007), but only 45 to 60 feet (14-18 m) thick at Cedar Breaks (Schneider, 1967; Moore and others, 2004; Rowley and others, in preparation) and about 30 feet (10 m) thick in the southern Red Hills (Threet, 1952).

Tcwml **Lower limestone interval and middle mudstone, siltstone, and sandstone interval of white member, undivided** (Eocene) – Locally undivided at Cedar Breaks National Monument due to map scale, and in the northwest part of the Henrie Knolls quadrangle due to poor exposure; as mapped, less than about 250 feet (75 m) thick.

Tcwm **Middle mudstone, siltstone, and sandstone interval of white member** (Eocene) **–** Varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, yellowish-gray, dark-yellowish-orange, and grayish-pink calcareous mudstone and siltstone, and minor fine-grained calcareous sandstone and chert-pebble conglomerate that weathers to a poorly exposed slope; upper conformable contact corresponds to a pronounced color change from brightly colored reddish-orange mudstone and siltstone below to white to very pale orange micritic limestone above; queried at the south end of the Red Hills, and near Willow Creek northeast of Paragonah; about 120 feet (36 m) thick near Cameron Troughs south of Panguitch Lake, but appears to thin abruptly to about 50 feet (15 m) thick about one mile (1 km) to the north; at Cedar Breaks National Monument, Schneider (1967) measured 227 feet (69 m) of strata we assign to Tcwm, but Rowley and others (in preparation) reported that this interval is 310 feet (94 m) thick in this same area; Moore and others (1994) reported that their middle sandy unit is 175 to at least 220 feet (54-67 m) thick in the Asay Bench quadrangle.

Tcwl **Lower limestone interval of white member** (Eocene) **–** Micritic limestone similar to the upper white limestone interval (Tcwu); forms cliff or steep, ledgy, white slope above more colorful but typically subdued slopes of the red member (Tcr); contains sparse charophytes; upper conformable contact corresponds to a pronounced color change from white to very pale orange micritic limestone below to brightly colored reddish-orange mudstone and siltstone above; query indicates uncertain identification on Navajo Ridge, at the south end of the Red Hills, and near Willow Creek northeast of Paragonah; about 100 to 120 feet (30-35 m) thick in the upper reaches of Rock Canyon; Moore and others (1994) reported that their lower white limestone is generally 85 to 120 feet (26-36 m) thick, but as much as 180 feet (55 m) thick, in the Asay Bench quadrangle; only about 47 feet (14 m) thick at Cedar Breaks National Monument, where it is informally called the “lower white limestone” (Schneider, 1967; Rowley and others, in preparation), and about 30 feet (10 m) thick in the southern Red Hills (Threet, 1952).

Tcr **Red member** (Eocene and Paleocene) − Alternating beds of varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, dark-yellowish-orange, grayish-pink, and similarly hued sandy and micritic limestone, calcite-cemented sandstone, calcareous mudstone, and minor pebbly conglomerate that weathers to colluvium-covered slopes. **Limestone** is poorly bedded, microcrystalline, generally sandy with 2 to 20% fine-grained quartz sand, and is locally argillaceous; contains common calcite veinlets, calcite spar-filled vugs, calcite spar- and micrite-filled burrows, and stylolites; also contains sparse small bivalves and planispiral gastropods; many of these limestone beds may be calcic paleosols (Mullett and others, 1988a, b; Mullett, 1989; Mullett and Wells, 1990). **Sandstone** is thick-bedded, fine- to coarse-grained, calcareous, locally cross-bedded quartz arenite that typically weathers to sculpted or fluted ledges that pinch out laterally; sandstone locally contains pebble stringers. **Mudstone** is generally moderate reddish orange, silty, calcareous, contains calcareous nodules, and weathers to earthy, steep slopes between ledges of sandstone and limestone. **Pebbly conglomerate** forms lenticular beds 5 to 15 feet (2-5 m) thick with rounded quartzite, limestone, and chert pebbles, cobbles, and, locally, small boulders; conglomerate is uncommon on the Markagunt Plateau south of Parowan Canyon, but lower red member strata are abundantly conglomeratic in the Red Hills and at the northwest edge of the Markagunt Plateau north of Parowan; at Sugarloaf Mountain west of Brian Head, several tens of feet of conglomerate (or several thinner beds within this interval) overlie the basal Claron limestone. Upper, conformable contact corresponds to a pronounced color and lithologic change from brightly colored reddish-orange mudstone and siltstone below to a white to very pale orange micritic limestone above; mostly nonfossiliferous and its age is poorly constrained as Eocene to Paleocene(?) (Goldstrand, 1994), but Nichols (1997) reported Late Cretaceous (Santonian?) pollen from gradationally underlying strata here mapped as TKu south and west of Blowhard Mountain, thus suggesting that the Claron Formation may be older than previously thought; measurements from the map suggest that the red member is about 1000 feet (300 m) thick at Cedar Breaks National Monument, similar to the measured thickness of Schneider (1967), who reported that the red member there was 993 feet (303 m) thick (the lower 56 feet [17 m] of his section includes beds we assign to TKu, thus the red member there is 937 feet [286 m] thick), considerably less than the 1300 feet (400 m) reported in Sable and Maldonado (1997b); strata that we include in the red member are likely of similar thickness in more structurally complicated outcrops of the Red Hills (Threet, 1952, 1963).

TERTIARY-CRETACEOUS

TKu **Tertiary-Cretaceous strata, undivided** (Paleocene? to Upper Cretaceous?) **–** Yellowish-brown, commonly stained dark-reddish-brown, fine-grained sandstone and lesser interbedded, similarly colored mudstone and siltstone; bedding is thin to very thick and appears tabular from a distance; weathers to ledgy slope or cliff; outcrop habit and surficial color make it look like the red member of the Claron Formation from a distance (figure 4); not yet mapped in Parowan Canyon and areas to the north, where basal Claron strata are conglomeratic and identification of this interval, if present, is problematic; upper contact placed at the base of the first sandy limestone bed (calcic paleosol) of the red member of the Claron

Formation, following Moore and Straub (2001); appears to represent fluvial and floodplain environments gradationally overlain by the Claron Formation; like Moore and Straub (2001), we recognize no significant erosion beneath the Claron Formation at the west edge of the Markagunt Plateau, leading to uncertainty as to the age of this interval and the age of basal Claron strata; Nichols (1997) reported Late Cretaceous (Santonian?) pollen from strata we map as TKu south and west of Blowhard Mountain, but the apparently gradationally overlying red member of the Claron Formation is widely believed to be Paleocene(?) to Eocene (Goldstrand, 1994) and Goldstrand (1991) reported late Paleocene palynomorphs from basal Claron strata in the Pine Valley Mountains; about 200 feet (60 m) thick near State Highway 14 at the west edge of the Markagunt Plateau, but apparently thins to the north where it may be about 60 feet (20 m) thick in Parowan Canyon.

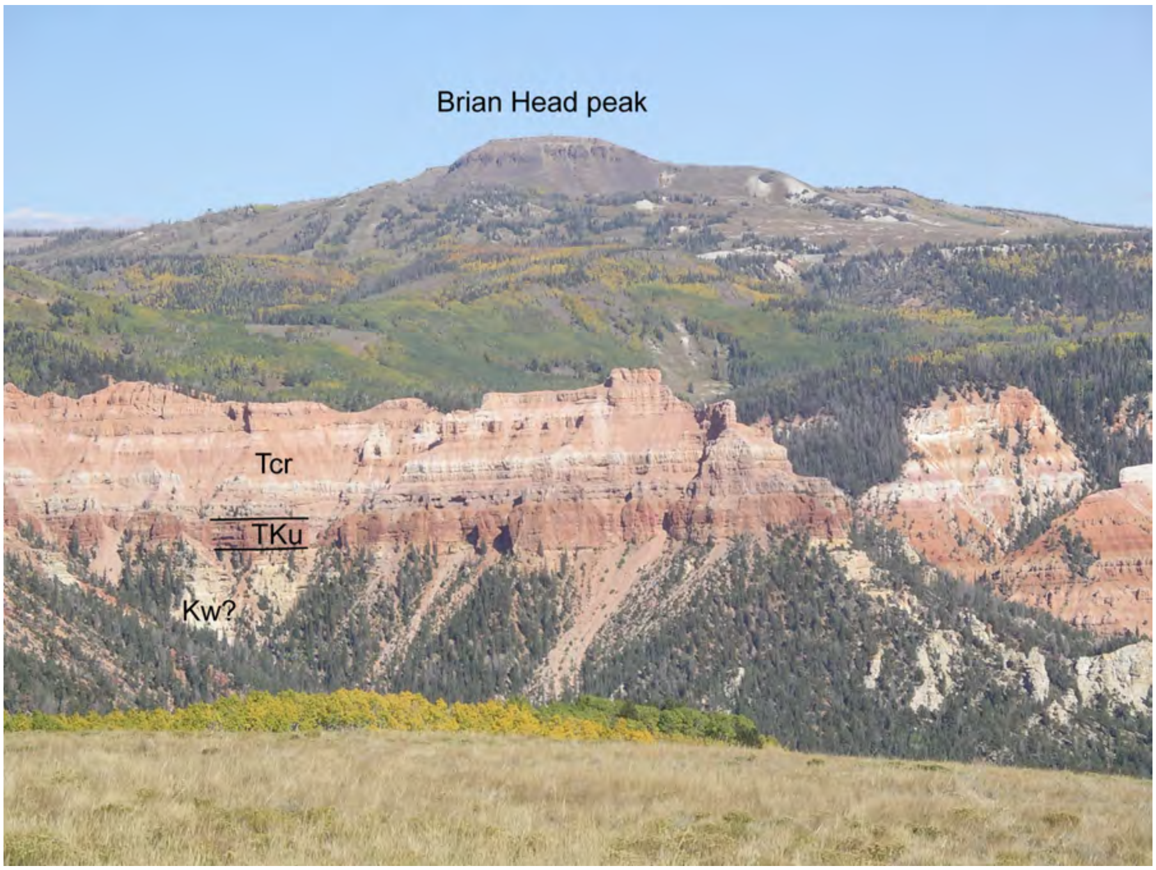

Figure 4. View east to Brian Head peak from High Mountain. Note sandstone cliff (TKu), stained dark-reddish-brown from runoff from overlying red member of the Claron Formation (Tcr). In most areas south of Parowan Canyon, the base of TKu corresponds to the top of a thin conglomerate with rounded quartzite and limestone clasts (TKgcu), although in some areas, as here, the conglomerate appears to be missing. Underlying yellowish-brown mudstone, siltstone, and sandstone are tentatively assigned to the Wahweap Formation (Kw?). The base of the Claron Formation corresponds to the base of the first limestone bed, likely a calcic paleosol.

TKgc **Grand Castle Formation, undivided** (Paleocene? to Upper Cretaceous) – In its type area of Parowan Canyon, divided into an upper light-gray and light-red, massive, cliff-forming conglomerate, a middle light-gray to white slope-forming sandstone, and a lower, cliff-forming, light-gray conglomerate that weathers to form hoodoos (commonly shaped like old-fashioned beehives [bee skeps]); undivided along the northwest flank of the Markagunt Plateau between Red Creek and Little Creek where the three members are too thin to map separately at this scale; about 200 feet (60 m) thick.

TKgcu **Upper conglomerate of the Grand Castle Formation** (Paleocene? to Upper Cretaceous) – Light-gray and light-red, massive, cliff-forming conglomerate; clasts are well-rounded, pebble- to boulder-size quartzite, limestone, sandstone, and chert; like the lower conglomerate member (Kgcl), locally weathers to form hoodoos (commonly shaped like old-fashioned beehives [bee skeps]); upper contact with strata here mapped as TKu on the Markagunt Plateau, and as basal red member of the Claron Formation in the Red Hills and northwestern Markagunt Plateau, appears gradational; on the Markagunt Plateau south of Parowan, the upper contact corresponds to the base of ledge- and cliff-forming, tabular bedded sandstone stained dark-reddish-brown from overlying Claron strata (figure 4); elsewhere, upper contact generally corresponds to the top of the cliff-forming conglomerate, above which is interbedded reddish-brown siltstone, sandstone, mudstone, and sandy limestone of the Claron Formation; deposited in a braided fluvial environment with paleoflow direction principally to the east to south-southeast, suggesting source areas in the Wah Wah, Blue Mountain, and Iron Springs thrust sheets of southwest Utah (Goldstrand and Mullett, 1997); as much as about 200 feet (60 m) (Threet, 1952, 1963) to 300 feet (90 m) (Maldonado and Williams, 1993a) thick near Parowan Gap; on the Markagunt Plateau, thins abruptly to the south from 183 feet (56 m) thick at the type area in First Left Hand Canyon southeast of Parowan (Goldstrand and Mullet, 1997) and the conglomerate may locally be absent south of Navajo Ridge (where it was not recognized in the measured sections of Goldstrand, 1991), but this interval is typically mantled in talus and colluvium that may obscure its presence; however, based on mapping of Upper Cretaceous strata between Parowan and Cedar Canyons, we believe it is present at Sugarloaf Mountain, in the upper reaches of Spring Creek Canyon, west of Blowhard Mountain, and west of Navajo Lake where it is no more than a few feet thick, and in Last Chance Canyon where it is about 25 feet (8 m) thick; mapped as the conglomerate of Parowan Gap by Maldonado and Williams (1993a) but, following Goldstrand and Mullet (1997) inferred to be the upper conglomerate of the Grand Castle Formation because it is gradationally overlain by the red member of the Claron Formation and the underlying middle Grand Castle sandstone is absent; a debris-flow deposit within the upper part of the unit in its type section yielded Late Cretaceous (Santonian?) pollen that Goldstrand and Mullett (1997) interpreted as recycled from older strata; however, Nichols (1997) reported Late Cretaceous (Santonian?) pollen from beds here mapped as TKu west and south of Blowhard Mountain, suggesting that the entire Grand Castle Formation is Late Cretaceous; Goldstrand and Mullett (1997) inferred a Paleocene age for the entire Grand Castle Formation based on distant correlations with Canaan Peak and Pine Hollow Formations on the Table Cliff Plateau, but we found evidence that the lower two members are Late Cretaceous (described below) and that the upper conglomerate may be Late Cretaceous or early Paleocene.

Anderson and Dinter (2010) reported a 10- to 15-foot-thick (3-5 m) poorly sorted, matrix supported conglomerate at the base of the Grand Castle that they informally called the conglomerate of Parowan Gap. They described this unit, which is restricted to the hanging wall of the Iron Springs thrust, as distinct from overlying Grand Castle conglomerate, but lead-author Biek found mostly clast-supported conglomerate identical to the Grand Castle conglomerate at this horizon in his remapping of the Parowan Gap area. The basal few feet of Grand Castle Conglomerate are locally iron stained throughout the Parowan Gap area, likely a result of a strong permeability contrast between underlying Upper Cretaceous strata and the overlying Grand Castle conglomerate.

CRETACEOUS

Kgcml **Middle sandstone and lower conglomerate of the Grand Castle Formation, undivided** (Upper Cretaceous) – Mapped north of Red Creek where the lower two members are too thin to map separately at this scale.

Kgcm **Middle sandstone of the Grand Castle Formation** (Upper Cretaceous) – Light-gray to white, fine- to medium-grained sandstone composed of well rounded and commonly frosted quartz grains (apparently recycled from the Navajo Sandstone); thin to medium bedded, cross stratified or horizontally stratified, and locally contains carbonized or petrified plant debris, small mudstone rip-up clasts, iron concretions, and soft-sediment deformation features; locally contains thin mudstone intervals, especially in the lower part of the member; typically forms poorly exposed slope, but well exposed about 2 miles (km) southwest of Parowan, at the mouth of Summit Creek canyon, at the type area in First Left Hand Canyon, and in a State Highway 14 road cut west of Blowhard Mountain; deposited in a braided fluvial environment with a paleoflow direction principally to the east to south-southeast, suggesting source areas in Navajo Sandstone exposed in the upper plate of the Iron Springs thrust, now exposed in the Red Hills (Goldstrand and Mullett, 1997; Lawton and others, 2003); appears to interfinger southward with strata tentatively assigned to the Wahweap Formation (Kw?), and, except at the southwest edge of Blowhard Mountain, we include it as the upper part of that formation south of the Summit and Parowan quadrangles where exposures are typically inadequate to map at this scale; our mapping confirms the finding of Goldstrand and Mullet (1997), who first correlated the sandstone at the Websters Flat turnoff with the middle sandstone member of the Grand Castle Formation, and this interval may be equivalent to the capping sandstone member of the Wahweap Formation as suggested by Lawton and others (2003); detrital zircon analyses are planned that may help constrain age and provenance of this interval; we discovered Campanian to Santonian palynomorphs and a theropod dinosaur track (the latter found by Eric Roberts, formerly with Southern Utah University and now at James Cook University, Australia) in the lower part of the interval in an unnamed canyon about 2 miles (3 km) southwest of Parowan, confirming our suspicion of a Late Cretaceous age for this member; 277 feet (85 m) thick at its type section in First Left Hand Canyon southeast of Parowan, about 100 feet (30 m) thick in last Chance Canyon, and about 200 feet (60 m) thick at the southwest side of Blowhard Mountain; collectively, the middle sandstone and queried Wahweap Formation thickens southward from 277 feet (85 m) in Parowan Canyon (where only the middle sandstone is present) to about 900 feet (275 m) in Cedar Canyon where both units are present.

Kgcl **Lower conglomerate of the Grand Castle Formation** (Upper Cretaceous) **–** Similar to the upper Grand Castle Conglomerate; locally weathers to form hoodoos (commonly shaped like old-fashioned beehives [bee skeps]), but forms resistant ledge in the upper reaches of Summit Creek canyon and the upper reaches of Pickering Creek canyon; 135 feet (41 m) thick at the type section in First Left Hand Canyon southeast of Parowan (Goldstrand and Mullet, 1997), and of similar thickness southward to Sugarloaf Mountain; south of this area, however, the lower conglomerate thins irregularly southward, ranging from a few feet thick to nearly 100 feet (30 m) thick, and locally appears as two conglomerate intervals separated by a few feet to a few tens of feet of yellowish-brown, fine-grained sandstone or variegated mudstone; pebbly sandstone and conglomerate at the top of the "S" curve switchback on the north side of State Highway 14 is among the thinnest exposures of this conglomerate, but it is several tens of feet thick immediately south of the highway and is nearly 100 feet (30 m) thick on the north side of Black Mountain; suggested by Eaton and others (2001), Moore and Straub (2001), Lawton and others (2003), and Eaton (2006) to possibly be equivalent to the Drip Tank Member of the Straight Cliffs Formation, which is late Santonian or early Campanian at its type section on the Kaiparowits Plateau, possibly somewhat younger than the conglomerate here; typically overlies stacked or amalgamated sandstone beds (as at the State Highway 14 and Black Mountain exposures) but locally overlies variegated mudstone (as at Ashdown Creek); inferred by Goldstrand and Mullett (1997) to be Paleocene, but as described above is Late Cretaceous (Campanian or Santonian).

Upper Cretaceous strata undergo significant west-to-east and north-to-south facies changes on the Markagunt Plateau, thus presenting significant challenges to correlation and mapping as described by Eaton and others (2001), Moore and Straub (2001), Moore and others (2004), and Rowley and others (in preparation). These strata consist of coastal plain, marginal marine, and a westward-thinning wedge of marine strata deposited in a foreland basin east of the Sevier orogenic belt. Collectively, this sedimentary package, represented by the Dakota, Tropic, and Straight Cliffs Formations, was deposited during the Greenhorn Marine Cycle, a large-scale sea-level rise and fall recognized world-wide and that here corresponds to the maximum transgression of the Western Interior Seaway (figure 5). They are overlain by river and floodplain strata that we tentatively assign to the Wahweap Formation, but that may be an exceptionally thick section of the underlying

John Henry Member of the Straight Cliffs Formation. Ongoing stratigraphic studies at the west edge of the Markagunt Plateau may further elucidate relationships among these foredeep basin strata.

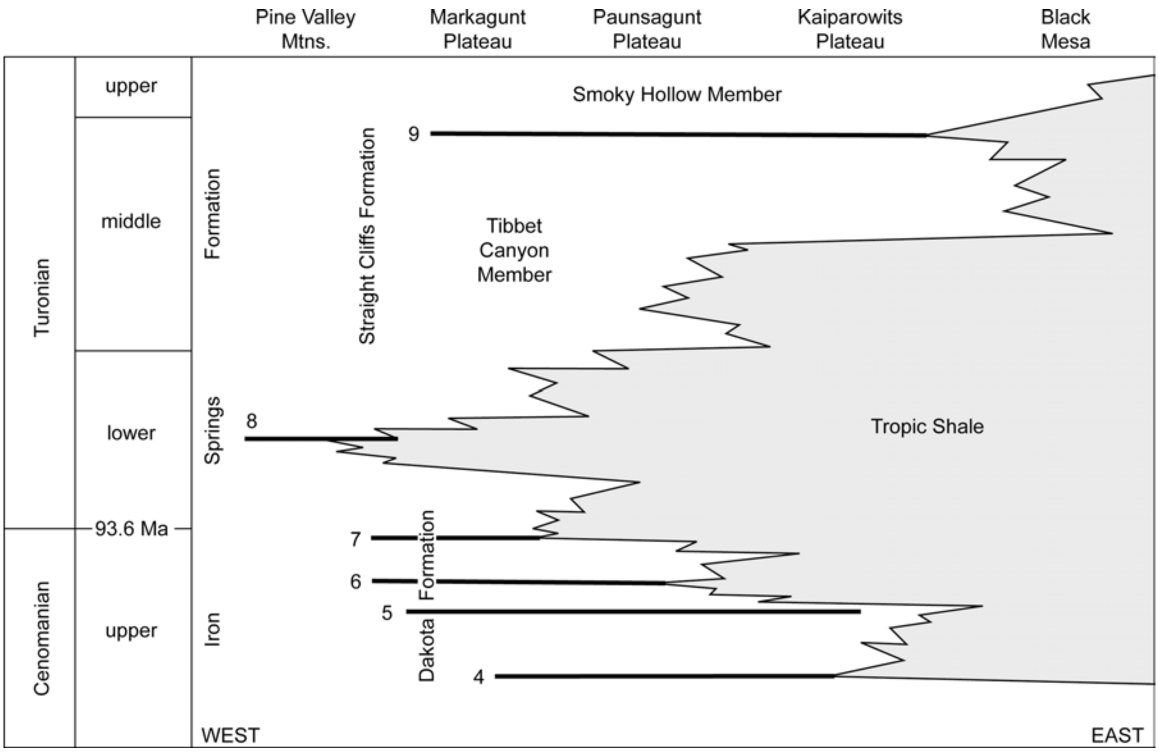

Figure 5. Strata of the Greenhorn Cycle, showing maximum flooding surface represented by the open-marine strata of the Tropic Shale and intermediate flooding surfaces represented by coal zones (4 to 9) that accumulated in brackish, estuarine environments near the margin of the Western Interior Sea. Note numerous smaller cycles superimposed on the larger Greenhorn Cycle, which are due to changes in subsidence, compaction, and climate. Note also the diachronous nature of the strata, meaning that the same facies differ in age from place to place. The upper Dakota Formation is equivalent in age to the lower part of the Tropic Shale exposed farther east — that is, they are the time-correlative coastal-plain and estuarine facies of the deeper water, offshore mud deposits of the Tropic Shale. Similarly, the Tibbet Canyon Member of the Straight Cliffs Formation is older in western exposures; it respresents eastward prograding shoreline deposits that also are time-correlative with offshore Tropic muds. The Iron Springs Formation was deposited principally in braided-stream and floodplain environments of a coastal plain and is considered correlative with the Straight Cliffs Formation, Tropic Shale, and Dakota Formation. Simplified from Tibert and others (2003).

Kw? **Wahweap Formation(?)** (Upper Cretaceous, Campanian? or Santonian?) – Varicolored and mottled mudstone of brown, gray, reddish-brown, and pinkish hues, and lesser interbedded yellowish-brown fine-grained sandstone and silty sandstone; upper part of formation contains more sandstone than mudstone, also noted by Moore and Straub (2001) and Moore and others (2004); deposited in braided river and floodplain environments of a coastal plain by northeast-flowing rivers longitudinal to the foreland basin that tapped sources in the Cordilleran magmatic arc and Mogollon Highlands (Pollock, 1999; Lawton and others, 2003; Eaton, 2006); Eaton and others (1999a) and Eaton (2006) reported enigmatic fossil mammals from near the base and top of the formation in Cedar Canyon that may be Campanian, and Lawton and others (2003) reported middle Campanian pollen from the upper part of the formation near Webster Flat (we also recovered Santonian to Campanian pollen near Webster Flat); Jinnah and others (2009) and Larsen and others (2010) reported an $^{40}Ar/^{39}Ar$ age of 80.6 ± 0.3 Ma (Campanian) on lower Wahweap strata on the Kaiparowits Plateau; measurements from the map show that the Wahweap(?) Formation is about 800 feet (245 m) thick below Cedar Breaks National Monument and south of Blowhard Mountain; Moore and Straub (2001) measured 760 feet (230 m) of strata in Cedar Canyon that we assign to Wahweap(?). If the lower conglomerate of the Grand Castle Formation is not equivalent to the Drip Tank Member of the Straight Cliffs Formation, strata here mapped as Wahweap(?) may simply be the upper part of the Straight Cliffs Formation (John Henry Member equivalent); ongoing stratigraphic studies may help assess the validity of our tentative correlation to early to middle Campanian Wahweap strata on the Kaiparowits Plateau, a correlation initially proposed by Eaton and others (1999a) and Moore and Straub (2001).

Ksu **Straight Cliffs Formation, upper unit** (Upper Cretaceous, Santonian[?] to Turonian) – Consists of strata widely interpreted as equivalent to the Smoky Hollow and John Henry Members of the Straight Cliffs Formation on the Kaiparowits Plateau, which form an overall regressive sequence following the last marine incursion of the Western Interior Seaway (see, for example, Eaton and others, 2001; Moore and Straub, 2001; Tibert and others, 2003). Lower, Smoky Hollow-equivalent strata are slope-forming, brown and gray mudstone, shale, and interbedded yellowish-brown fine-grained sandstone; lower part contains a few thin coal beds, common carbonaceous shale, and several thin oyster coquina beds; on the Kaiparowits Plateau, upper contact corresponds to the top of the Calico bed, which Moore and Straub (2001, their subunit 4 of interval A) suggested may be present in Cedar Canyon about 285 feet (87 m) above the base of the formation; this sandstone is about 30 feet (9 m) thick and is not distinctive – it lacks pebbles and we were unable to use this bed as a marker horizon; however, we did locally map a thin pebble conglomerate about 330 feet (100 m) above the base of the formation in the southern part of the Webster Flat quadrangle, which may be the Calico bed; Smoky Hollow strata are middle to upper Turonian based on a diverse assemblage of mollusks, benthic foraminifera, and ostracods from Cedar Canyon exposures (Eaton and others, 2001; Tiebert and others, 2003); Eaton and others (2001) measured 364 feet (110 m) of strata that likely belong to the Smoky Hollow Member, the lower 167 feet (54 m) of which are brackish and an order of magnitude thicker than equivalent brackish strata on the Kaiparowits Plateau, reflecting greater subsidence rates in the western part of the foredeep basin; Moore and Straub (2001) assigned 313 feet (95 m) of strata in Cedar Canyon as likely equivalent to the Smoky Hollow Member.

Upper, John Henry-equivalent strata are slope-forming, variegated, gray, brown, and reddish-brown mudstone and thin- to thick-bedded, grayish-orange to yellowish-brown, fine-grained subarkosic sandstone; stacked or amalgamated sandstone beds make up most of the upper part of the unit; upper contact corresponds to the base of the lower conglomerate of the Grand Castle Formation (which may be the Drip Tank Member of the Straight Cliffs Formation as described above); deposited in fluvial and floodplain environments of a coastal plain (Eaton and others, 2001); biotite from an ash bed about 800 feet (245 m) above the base of the upper unit in Cedar Canyon yielded an $^{40}Ar/^{39}Ar$ age of 86.72 ± 0.58 Ma (early Coniacian) (Eaton, 1999; Eaton and others, 1999b); probably about 900 to 1000 feet (275-300 m) thick in Cedar Canyon (Moore and Straub, 2001).

We tentatively assign strata previously mapped as the Iron Springs Formation in Parowan Canyon and in the Summit quadrangle to the Straight Cliffs Formation; these strata consist of ledge-forming, calcareous, cross-bedded, fine- to medium-grained sandstone and less-resistant, slope-forming mudstone; the formation here 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; thin coal seams and oyster coquinas are present in the lower part of the section in both areas, suggesting correlation to the brackish deposits of the Smoky Hollow Member; incomplete section is about 1100 feet (335 m) thick in Parowan Canyon (Maldonado and Moore, 1995).

The striking difference in facies and outcrop habit of correlative strata between Cedar and Parowan Canyons has long been noted (see, for example, Eaton and others, 2001). However, only about the upper 1000 feet (300 m) of strata previously assigned to the Iron Springs Formation is exposed in Parowan Canyon, where it is characterized by repetitive ledge-forming tabular sandstone beds and interbedded, slope-forming mudstone. Equivalent strata to the south in Cedar Canyon, widely correlated to the John Henry Member of the Straight Cliffs Formation, are characterized by generally poorly exposed, typically slope-forming, stacked or amalgamated sandstone and relatively little mudstone; mudstone, however, dominates the lower part of the John Henry in Cedar Canyon.

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 minor interbedded, grayish-orange to gray mudstone and siltstone; locally contains pelecypods, gastropods, and thin to thick beds of oyster coquina; forms bold cliffs in Cedar Canyon and in the West and East Forks of Braffits Creek south of Summit; upper contact corresponds to a pronounced break in slope and is placed at the top of a coquinoid oyster bed and base of overlying thin coal and carbonaceous shale interval that caps the member; forms the riser of the Gray Cliffs part of the Grand Staircase; represents initial progradational (overall regressive) strata of the Greenhorn Cycle deposited in shoreface, beach, lagoonal, and estuarine environments adjacent to a coastal plain (Laurin and Sageman, 2001; Tibert and others, 2003); about 650 to 800 feet (200-245 m) thick.

Kt **Tropic Shale** (Upper Cretaceous, Turonian to Cenomanian) **–** Dark-gray and yellowish-brown sandy mudstone, silty fine-grained sandstone, and minor shale; best developed at the south edge of the Kolob Terrace in the Webster Flat quadrangle, where the basal mudstone is locally characterized by a lag of septarian nodules; locally contains *Inoceramus* sp. fossils indicative of open shallow-marine environment (see, for example, Eaton and others, 2001); very poorly exposed, but forms subtle, vegetated slope at the base of the Straight Cliffs Formation and above the prominent "sugarledge sandstone" (Cashion, 1961) at the top of the Dakota Formation; upper contact placed at the base of the cliff-forming, planar beds of the Straight Cliffs Formation (figure 6); deposited in shallow-marine environment dominated by fine-grained clastic sediment (Tibert and others, 2003); thins north westward across the map area, from about 40 feet (12 m) thick in the southwest part of the Webster Flat quadrangle to a few feet thick in Cedar Canyon.

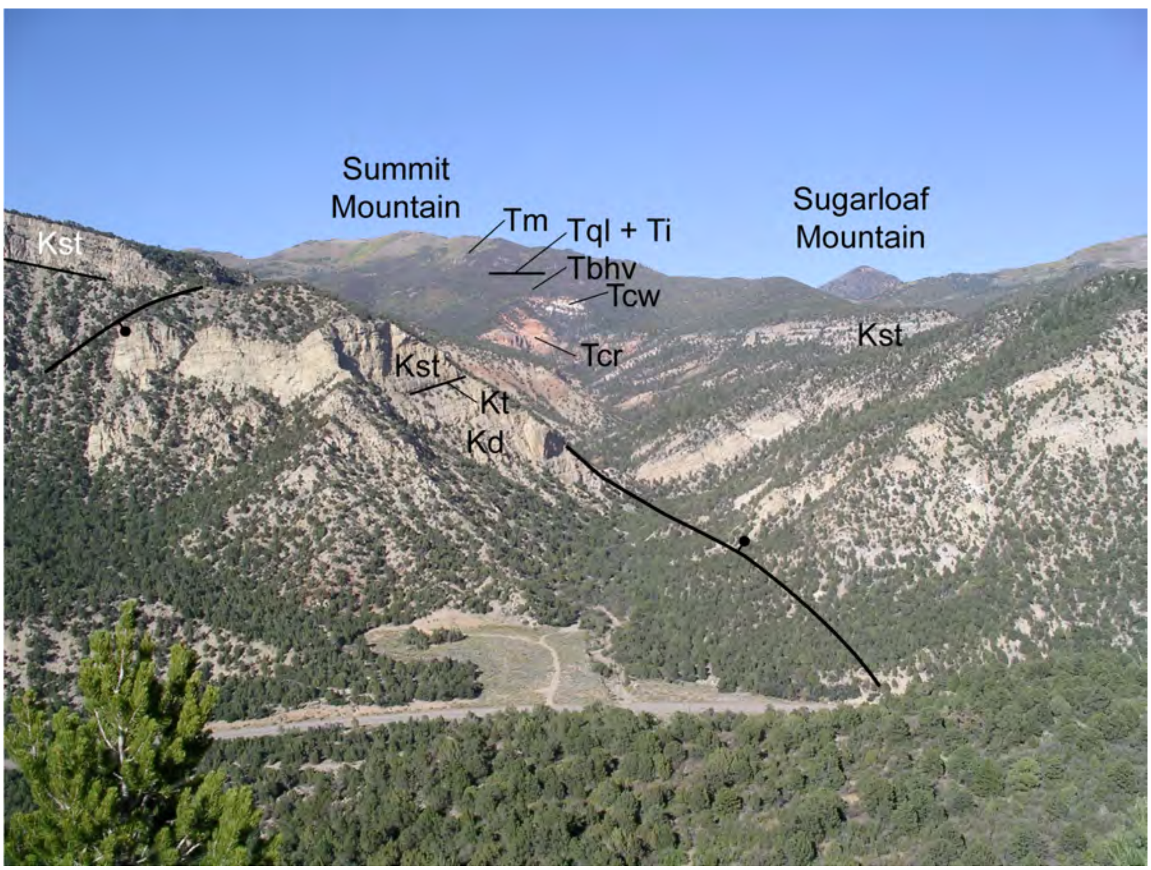

Figure 6. View north into Maple Canyon, tributary to Cedar Canyon at the west edge of the Markagunt Plateau; State Highway 14 is in the foreground. The Tropic Shale is represented by a thin, dark-gray mudstone and siltstone that forms a slope between ledge and cliff-forming sandstone of the Dakota Formation (Kd) and the Tibbet Canyon

Member of the Straight Cliffs Formation (Kst). The thin slope of Tropic represents the maximum incursion of the Western Interior Seaway in Late Cretaceous (early Turonian) time. Underlying Dakota strata – deposited as an overall regressive unit of floodplain, estuarine, lagoonal, and swamp environments of a coastal plain – record the encroachment of that seaway, whereas overlying Tibbet Canyon strata were deposited in an overall progradational sequence of marginal-marine and beach environments following retreat of the Western Interior Sea.

Several normal faults cut strata of Maple Canyon, which partly follows the south end of the Summit Mountain graben. Tcr (red member) and Tcw (white member) of the Claron Formation; regional ash-flow tuffs of the Leach Canyon Formation (Tql) and Isom Formation (Ti), which overlie the vegetated Brian Head Formation (Tbhv), are unconformably overlain by the Markagunt megabreccia (Tm).

Ktd **Tropic Shale and Dakota Formation, undivided** (Upper Cretaceous, Turonian to Cenomanian) **–** Undivided in Cedar Canyon where the Tropic Shale is a few feet to at most a few tens of feet thick.

Kd **Dakota Formation** (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 very thick bedded, fine to medium grained; includes several prominent cliff-forming sandstone beds each several tens of feet thick in the upper part of the formation, the upper one of which may correspond to the "sugarledge sandstone" of Cashion (1961); 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; thin marl beds above the "sugarledge sandstone" locally contain small, distinctive gastropods with 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 in the Cedar Canyon area; most workers divide the Dakota Formation into three members, the lower one of which we re-assign to the Cedar Mountain Formation and the upper two of which we combine given the difficulty of mapping their mutual contact; upper contact placed at the top of the thin marl beds overlying the "sugarledge sandstone;" represents an overall regressive sequence, the lower part of which was deposited in floodplain and river environments, whereas the upper part represents estuarine, lagoonal, and swamp environments of a coastal plain (Gustason, 1989; Eaton and others, 2001; Laurin and Sageman, 2001; Tibert and others, 2003); Gustavson (1989), based in part on study of Cedar Canyon exposures, was the first to correlate fluvial packages of the Dakota with orbital cycles of marine sedimentation of the deeper parts of the Western Interior Sea; Laurin and Sageman (2001) expanded on that work, constructing a high resolution temporal and stratigraphic framework of middle Cretaceous marginal-marine deposits – they documented changes in shoreline position and also linked these changes to rhythmic, Milankovitch-driven deposition of marine limestone of the Western Interior Seaway; invertebrate and palynomorph fossil assemblages indicate shallow-marine, brackish, and freshwater deposits of Cenomanian age (Nichols, 1997); based on map measurements, about 1300 to 1400 feet (400-425 m) thick at the south end of Jones Hill west of Maple Canyon.

Ki **Iron Springs Formation, undivided** (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 present in the Red Hills at the west edge of the map area; 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 common in the sandstone beds; sandstone beds range from quartz arenite to litharenite (Fillmore, 1991; Goldstrand, 1992); the entire formation weathers to repetitive, thick tabular sandstone beds and thinner interbedded mudstone; lower part (in the upper plate of the Iron Springs thrust) contains numerous oyster coquina beds commonly 1 to 3 feet (0.3-1 m) thick; upper contact with the upper conglomerate of the Grand Castle Formation is difficult to map on the east and south sides of the Red Hills due to abundant TKgcu-derived colluvium and faults; deposited principally in braided-stream and floodplain environments of a coastal plain (Johnson, 1984; Fillmore, 1991; Eaton and others, 2001; Milner and others, 2006); mapped in the Red Hills where it is correlated to the Dakota Formation, Tropic Shale, and Straight Cliffs Formation (Eaton, 1999; Eaton and others, 2001); age from Goldstrand (1994) and an ash that is 712 feet (217 m) below the top of the formation in Parowan Canyon (here reassigned to the upper part of the Straight Cliffs Formation), which yielded an $^{40}Ar/^{39}Ar$ age of 83.0 ± 1.1 Ma (Eaton and others, 1999b); lower Iron Springs strata (in the upper plate of the Iron Springs thrust) may be associated with the maximum transgression of the Greenhorn Sea of late Cenomanian or early Turonian age (Eaton and others, 1997; Eaton, 1999); Milner and others (2006) reported on dinosaur tracks in upper Iron Springs strata near Parowan Gap, and also noted a diverse assemblage of plant fossils, bivalves, gastropods, turtles, fish, and trace fossils suggestive of upper Santonian to early Campanian age (Milner and Spears [2007] mistakenly reported an early Turonian age for these same beds); incomplete sections are about 2500 feet (750 m) thick in the Red Hills (Maldonado and Williams, 1993a) and about 1100 feet (335 m) thick in Parowan Canyon (Maldonado and Moore, 1995), but the entire formation is about 3500 to 4000 feet (1070-1220 m) thick in the Pine Valley Mountains (Cook, 1960).

Kcm **Cedar Mountain Formation** (Cretaceous, Cenomanian to Albian) **–** Consists of a basal pebble conglomerate overlain by brightly colored variegated mudstone in Cedar Canyon. Mudstone is variegated gray, purplish-red, and reddish-brown, distinctly different from the gray and yellowish-brown hues of overlying Dakota strata; clay is smectitic and weathers to “popcorn-like” soils; includes minor light-gray to dark-yellowish-brown, fine- to medium-grained channel sandstone. Basal conglomerate is grayish brown and typically poorly cemented and non-resistant; clasts are subrounded to rounded, pebble- to small-cobble-size quartzite, chert, and limestone; red quartzite clasts are common; ranges from less than one foot (0.3 m) to about 10 feet (3 m) thick.

Except for thin conglomerate ledge at base, weathers to generally poorly exposed slopes covered with debris from the overlying Dakota Formation; 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 (figures 7 and 8); regionally, the Cedar Mountain Formation is unconformably overlain by the Dakota Formation (see, for example, Kirkland and others, 1997); volcanic ash from correlative strata on the Kolob Plateau yielded a single-crystal $^{40}Ar/^{39}Ar$ age of 97.9 $\pm$ 0.5 Ma on sanidine (Biek and Hylland, 2007), and pollen analyses indicate an Albian or older age (Doelling and Davis, 1989; Hylland, 2010); Dyman and others (2002) obtained an $^{40}Ar/^{39}Ar$ age of 101.7 $\pm$ 0.42 Ma (latest Albian) on equivalent strata near Gunlock; additionally, palynomorphs from a thin mudstone interval, including rare occurrences of *Trilobosporites humilis* and possibly *Pseudoceratium regium*, collected immediately to the west in the Cedar City quadrangle (NW1/4 NW1/4 SE1/4 section 17, T. 36 S., R. 10 W.) suggest a late Albian age for this horizon (Michael D. Hylland, unpublished data, November 9, 2001); deposited in floodplain environment of a broad coastal plain (Tschudy and others, 1984; Kirkland and others, 1997; Cifelli and others 1997; Kirkland and Madsen, 2007); previously mapped as the lower part of the Dakota Formation, but the lithology, age, and stratigraphic position of these beds suggest correlation to the Cedar Mountain Formation (Biek and others, 2009); specifically, the mudstone interval appears to be time-correlative with the Mussentuchit Member of the Cedar Mountain Formation of central and eastern Utah; ongoing detrital zircon studies may help resolve the provenance and correlation of the underlying conglomeratic unit; about 60 feet (18 m) thick in Cedar Canyon.

Figure 7. Cedar Mountain Formation exposed in Cedar Canyon near the west edge of the map area. Base of Cedar Mountain Formation (Kcm) is marked by a thin pebble conglomerate and overlying dark-gray bentonitic ash; note thin, lenticular channel sandstone near base of Cedar Mountain strata and bleached upper part of Winsor Member of the Carmel Formation (Jcw). Coop Creek Limestone Member of the Carmel Formation (Jcc) is exposed at road level; Crystal Creek strata are hidden from view; Paria River Member (Jcp). View west down Cedar Canyon; outcrop is in the SW1/4NE1/4NW1/4 section 21, T. 36 S., R. 10 W.

Figure 8. View north to the Cedar Mountain Formation (Kcm) in the SW1/4SE1/4SW1/4 section 16, T. 36 S., R. 10 W. Swelling mudstone of light-gray, reddish-brown, and purplish hues contrast sharply with yellowish-brown and olive-gray mudstone of overlying Dakota Formation (Kd). About 40 feet (12 m) above the base of the Dakota Formation there is a ledge-forming 20-foot-thick (6 m) pebbly sandstone and conglomerate with rounded quartzite and black chert clasts, and it is this bed that may have been mistaken in the past for the basal Cretaceous unconformity. Jcw = Winsor Member of Carmel Formation.

unconformity (K) No rocks of late Middle Jurassic to middle Early Cretaceous age are preserved in southwest Utah. This is because during this time, the back-bulge basin that developed in front of the Sevier orogenic belt had migrated eastward, and much of Utah was a forebulge high, a broad, gentle uplift that was high enough to undergo a prolonged period of modest erosion (see, for example, Willis, 1999). In this area, this 60-million-year-long gap in the rock record is marked by a bleached zone at the top of the Winsor Member of the Carmel Formation (figure 7). The Cretaceous unconformity cuts down section to the west, where, on the south flank of the Pine Valley Mountains, first Winsor, then Paria River, and finally Crystal Creek strata are completely eroded away, so that at Gunlock the Cedar Mountain Formation rests upon the Co-op Creek Limestone, the lower member of the Carmel Formation (Biek and others, 2009).

JURASSIC

Carmel Formation (Middle Jurassic)

Nomenclature follows that of Doelling and Davis (1989); deposited in a shallow inland sea of a back-bulge basin, together with the underlying Temple Cap Formation, the first clear record of the effects of the Sevier orogeny in southwestern Utah; age from Imlay (1980); measured thicknesses in Cedar Canyon are from Doug Sprinkel, Utah Geological Survey, written communication, June 22, 2010).

Jcw **Winsor Member** (Middle Jurassic, Callovian to Bathonian) – Light-reddish-brown, fine- to medium-grained sandstone and siltstone; uppermost beds typically bleached white under the Cretaceous unconformity; poorly cemented and so weathers to vegetated slopes, or, locally, badland topography; upper contact is at the base of a pebble conglomerate, which marks the Cretaceous unconformity; deposited on a broad, sandy mudflat (Imlay, 1980; Blakey and others, 1983); 250 feet (75 m) thick in Cedar Canyon.

Jcp **Paria River Member** (Middle Jurassic, Bathonian) – Consists of three parts not mapped separately: (1) upper part is about 50 feet (15 m) of cliff-forming, olive-gray, micritic and argillaceous limestone and calcareous mudstone; laminated in very thick beds; locally contains small pelecypod fossils; (2) middle part is about 20 feet (6 m) of reddish-brown and greenish-gray shale that forms slope; and (3) lower part is gypsum and minor interbedded shale as much as 80 feet (25 m) thick in nodular, highly fractured and contorted beds and as thin, laminated beds. Upper contact is sharp and planar; deposited in shallow-marine and coastal-sabkha environments (Imlay, 1980; Blakey and others, 1983); 173 feet (53 m) thick in Cedar Canyon.

Jcx **Crystal Creek Member** (Middle Jurassic, Bathonian) – Thin- to medium-bedded, reddish-brown siltstone, mudstone, and fine to medium-grained sandstone; commonly gypsiferous and contains local contorted pods of gypsum; forms vegetated, poorly exposed slopes; upper contact is sharp and broadly wavy and corresponds to the base of the thick Paria River gypsum bed; 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 that were 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); 294 feet (90 m) thick in Cedar Canyon.

Jcc **Co-op Creek Limestone Member** (Middle Jurassic, Bajocian) **–** Thin- to medium-bedded, light-gray micritic limestone and calcareous shale; locally contains *Isocrinus* sp. columnals, pelecypods, and gastropods; forms sparsely vegetated, ledgy slopes and cliffs; Kowallis and others (2001) reported several $^{40}Ar/^{39}Ar$ ages of 168 to 167 million years old 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; deposited in a shallow-marine environment (Imlay, 1980; Blakey and others, 1983); probably about 400 feet (120 m) thick, but may be about 300 feet (90 m) thick if the lower gypsiferous part is the Temple Cap Formation; the member is as much as about 350 feet (105 m) thick on the Kolob Terrace north of Zion National Park (Biek and Hylland, 2007).

unconformity (J-2?) (Pipiringos and O'Sullivan, 1978); formed about 169 to 168 million years ago in southwest Utah (Kowallis and others, 2001). New research suggests that the Temple Cap Formation, lower part of the Page Sandstone (Harris Wash Tongue of south-central Utah), and Gypsum Springs Member of the Twin Creek Limestone (of central and northern Utah) are time equivalent (Dickinson and Gehrels, 2009a, b; Dickinson and others, 2009; Sprinkel and others, 2009). Thus, whereas the J-2 unconformity locally marks a significant change in depositional environments, recording encroachment of a shallow inland sea, it may not represent a significant gap in the rock record as envisioned by Pipiringos and O'Sullivan (1978).

Jct **Carmel and Temple Cap Formations, undivided** (Middle Jurassic, Bajocian to Aalenian) **–** Poorly exposed in fault blocks near Parowan Gap where it consists of light-gray micritic limestone and calcareous shale (Co-op Creek Limestone Member of the Carmel Formation) and reddish-brown mudstone and siltstone (Temple Cap Formation); Sprinkel and others (2009) reported that the Temple Cap Formation is 177.8 to 171.4 ± 1.5 Ma based on several $^{40}Ar/^{39}Ar$ and U-Pb zircon ages; deposited in coastal-sabkha and tidal-flat environments (Blakey, 1994; Peterson, 1994); incomplete section about 30 feet (10 m) thick near Parowan Gap (Maldonado and Williams, 1993a).

Reddish-brown mudstone and siltstone, and gypsum, of the Temple Cap Formation may be exposed immediately west of the map area in Cedar Canyon (Doug Sprinkel, Utah Geological Survey, verbal communication, December 7, 2009), although it is unclear if these beds belong to the Sinawava Member or newly recognized red beds previously included at the base of the Co-op Creek Limestone Member of the Carmel Formation.

unconformity (J-1)

Jn **Navajo Sandstone** (Lower Jurassic) **–** Massively cross-bedded, poorly to moderately well-cemented, light-gray or white sandstone that consists of well-rounded, fine- to medium-grained, frosted quartz; upper, unconformable contact is sharp and planar and regionally corresponds to a prominent break in slope, with cliff-forming, cross-bedded sandstone below and reddish-brown mudstone above; deposited in a vast coastal and inland dune field with prevailing winds principally from the north (Blakey, 1994, Peterson, 1994); 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, 2009); much of the sand may originally have been transported to areas north and northwest of Utah via a transcontinental river system that tapped Grenvillian-age (about 1.0 to 1.3 billion-year-old) crust involved in Appalachian orogenesis of eastern North America (Dickinson and Gehrels, 2003; Rahl and others, 2003; Reiners and others, 2005); incomplete thickness exposed at Parowan Gap may be as much as 1300 feet (400 m) thick; the entire formation is about 2100 to 2200 feet (640-670 m) thick in the Zion area (Biek and others, 2009).

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MAP SYMBOLS

Contact, dashed where approximately located

Normal fault, dashed where approximatley located, dotted where concealed; queried where uncertain; bar and ball on down-dropped side; arrow and number show dip of fault

Thrust fault, dashed where approximately located, dotted where concealed; teeth on upper plate

Gravity-slide fault, dashed where approximatley located, dotted where concealed; barbs on upper plate

High-angle fault within upper plate of gravity-slide block; ornamentation on down-dropped side

Strike and dip of inclined bedding

Approximate strike and dip of inclined bedding

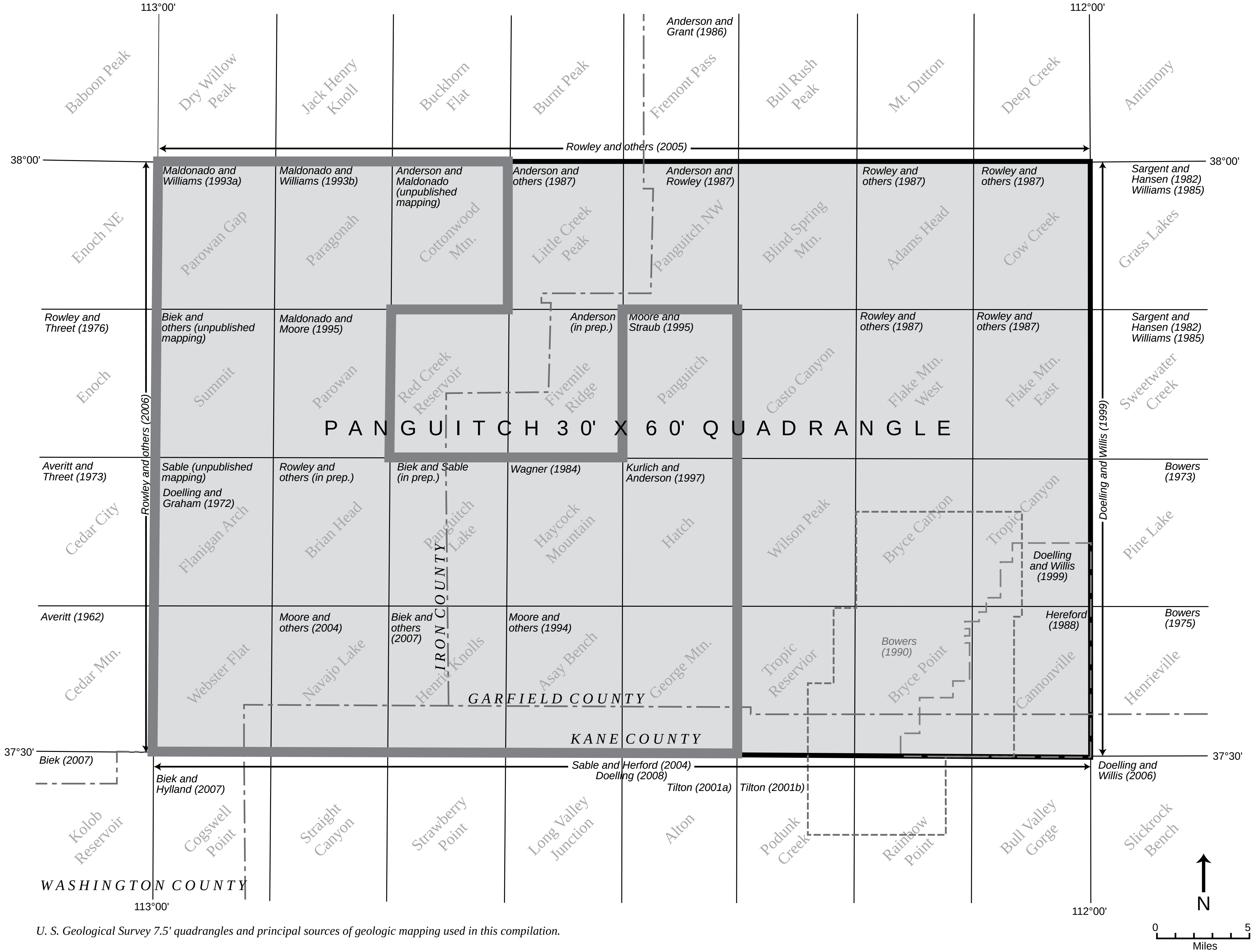
Sand and gravel pit or cinder pit

Quarry (crushed rock)

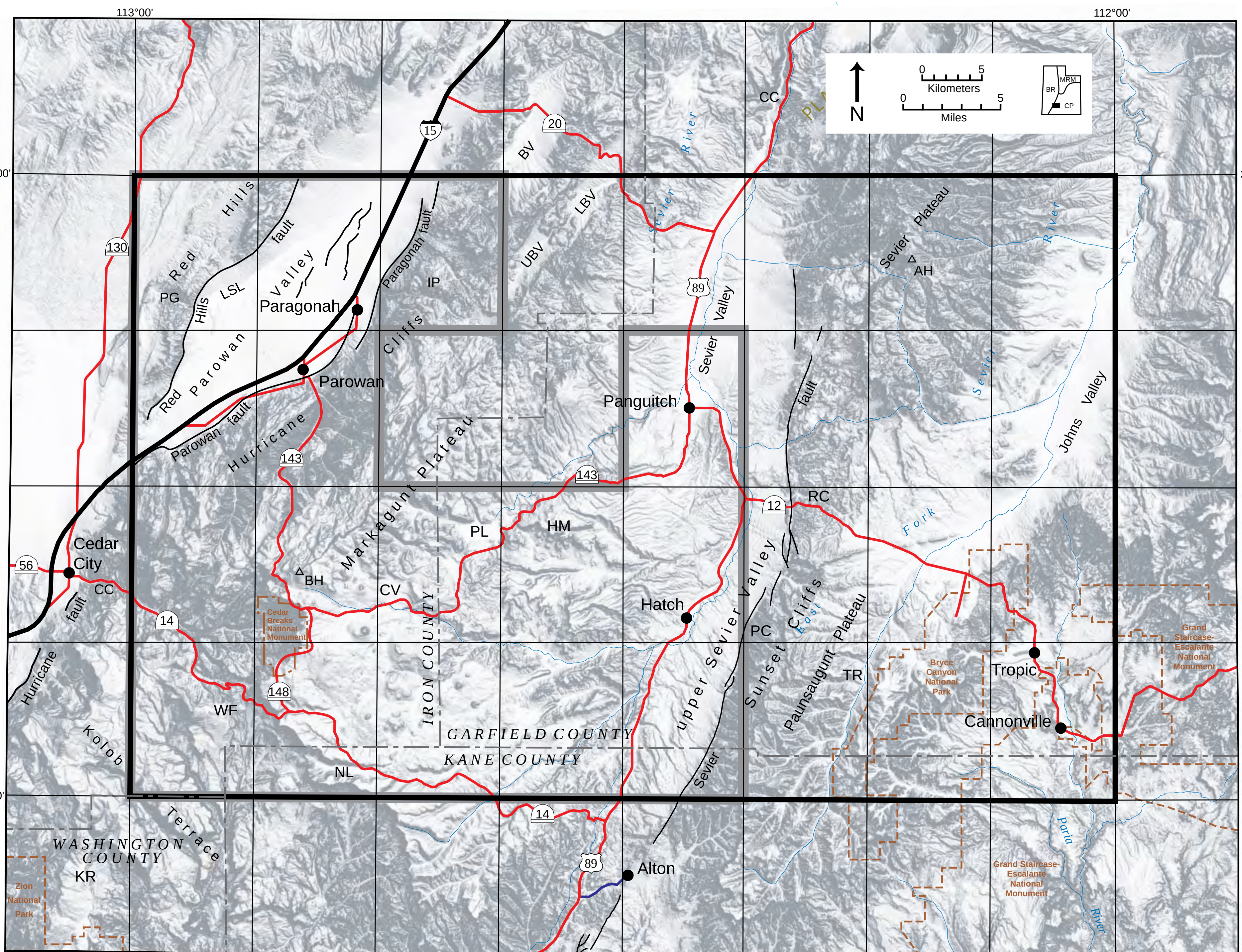
Volcanic vent

Sinkhole

Marker beds

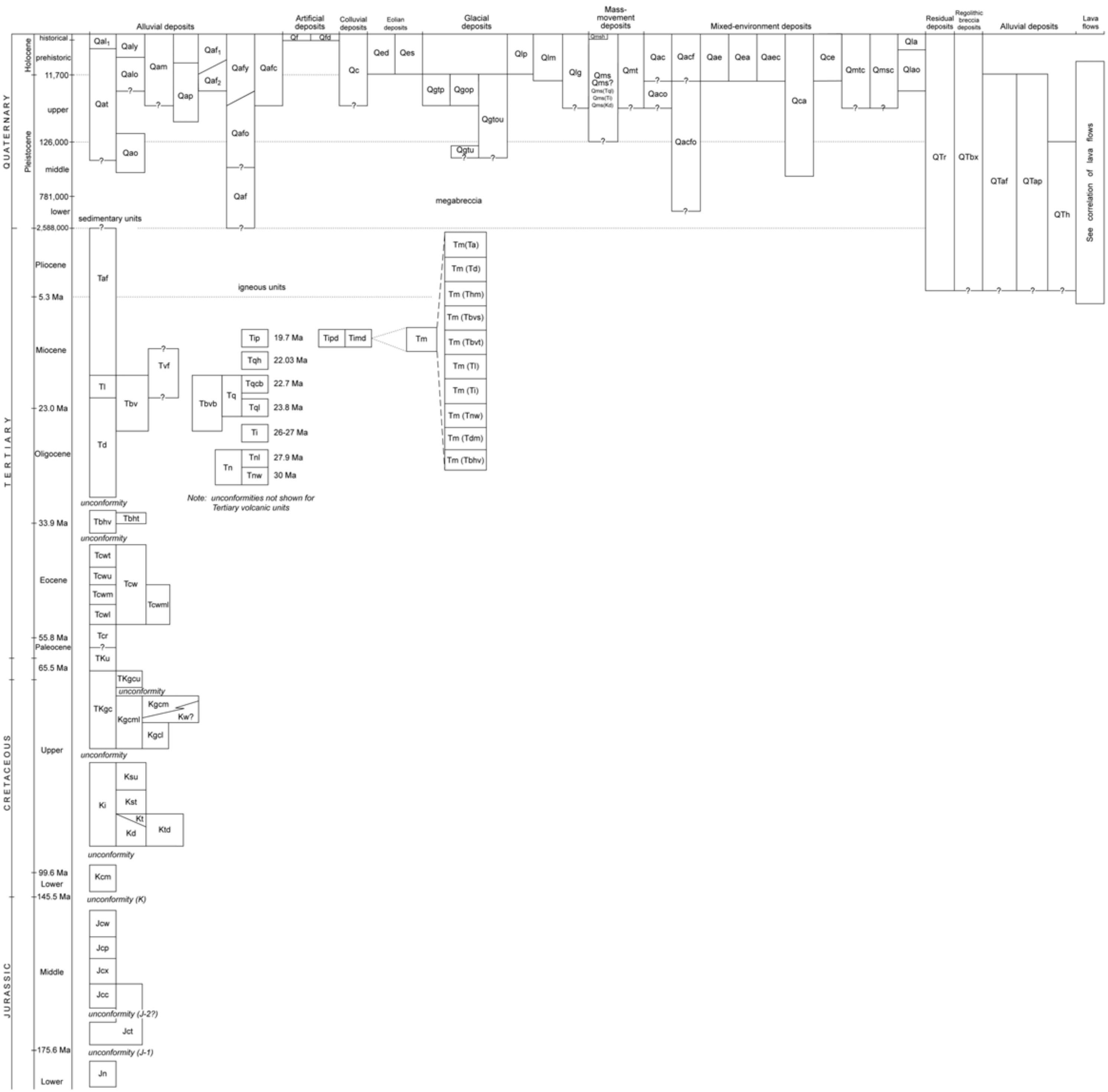


U. S. Geological Survey 7.5' quadrangles and principal sources of geologic mapping used in this compilation.

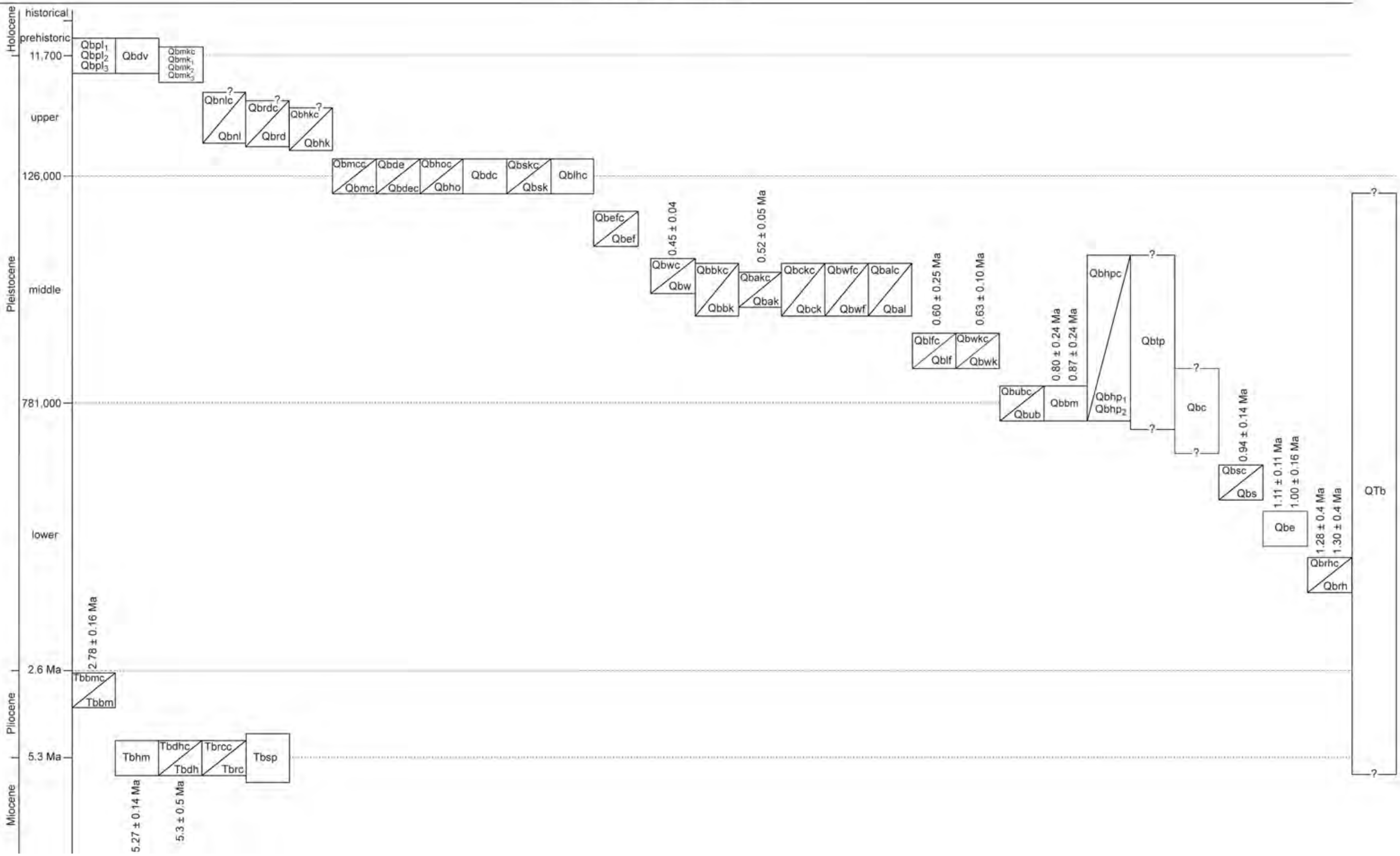


Index map showing major geographic features in the Panguitch 30´ x 60´ quadrangle. AH, Adams Head; BH, Brian Head peak; BV, Buckskin Valley; CC (near Cedar City), Cedar Canyon; CC (on Sevier River), Circleville Canyon; CV, Castle Valley; HM, Haycock Mountain; IP, Iron Peak; KR, Kolob Reservoir; LBV, Lower Bear Valley; LSL, Little Salt Lake; NL, Navajo Lake; PC, Paunsaugunt Cliffs; PG, Parowan Gap; PL, Panguitch Lake; RC, Red Canyon; TR, Tropic Reservoir; UBV, Upper Bear Valley; WF, Webster Flat.

CORRELATION OF MAP UNITS



CORRELATION OF LAVA FLOWS



STRATIGRAPHIC COLUMN