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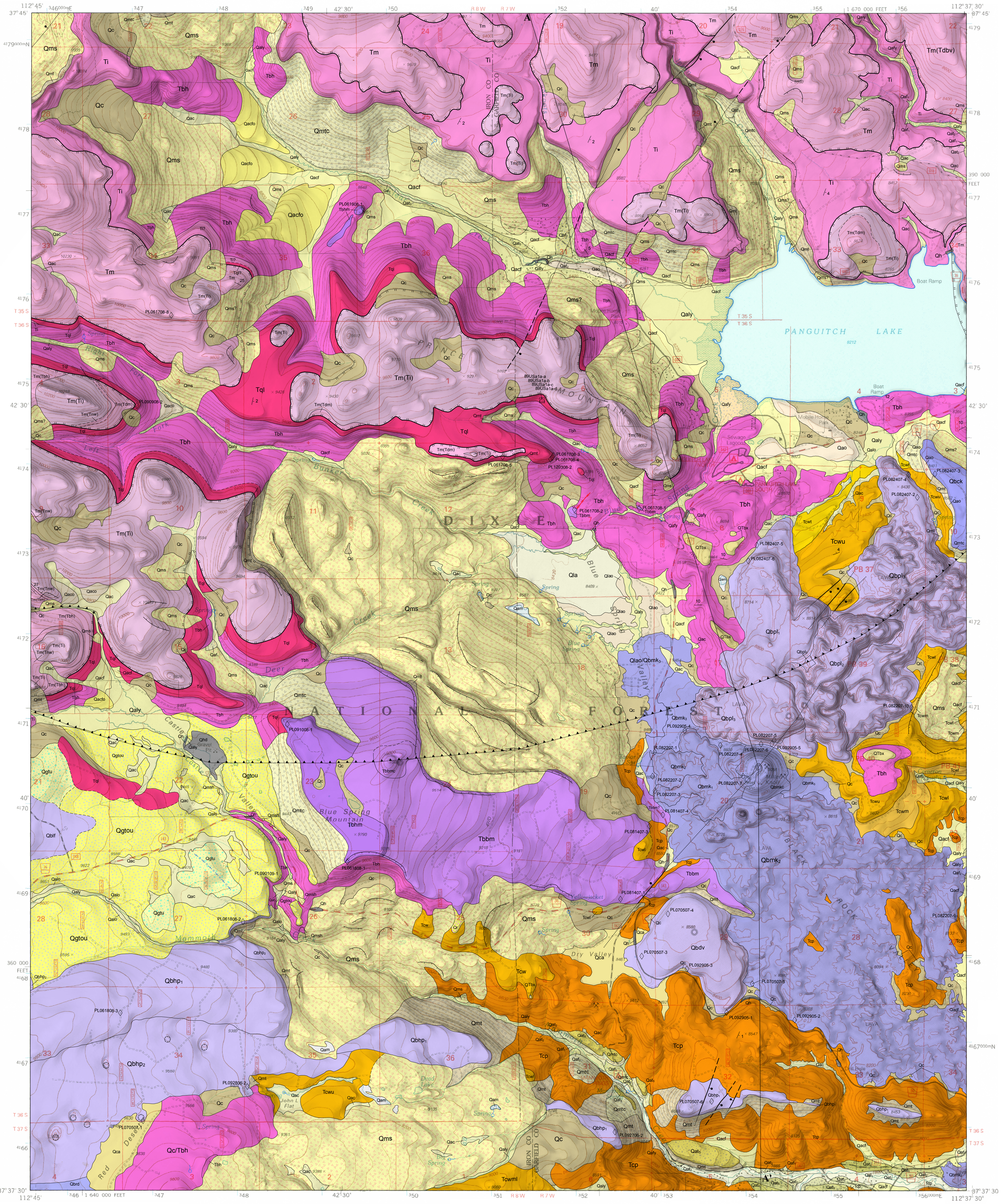

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SCALE 1:24,000

1 0.5 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 0.5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET

MAP LOCATION

APPROXIMATE MEAN DECLINATION, 2014

GEOLOGIC MAP OF THE PANGUITCH LAKE QUADRANGLE, GARFIELD AND IRON COUNTIES, UTAH

by

Robert F. Biek[1], John J. Anderson[2], Edward G. Sable[3], and Peter D. Rowley[4]

2014

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Base from USFS Panguitch Lake 7.5' Quadrangle (2002)
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1866

Project Manager: Douglas A. Sprinkel
GIS and Cartography: Jay C. Hill

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1	2	3
4	·	5
6	7	8

1. Parowan
2. Red Creek Reservoir
3. Fivemile Ridge
4. Brian Head
5. Haycock Mountain
6. Navajo Lake
7. Henrie Knolls
8. Asay Bench

ADJOINING 7.5' QUADRANGLE NAMES

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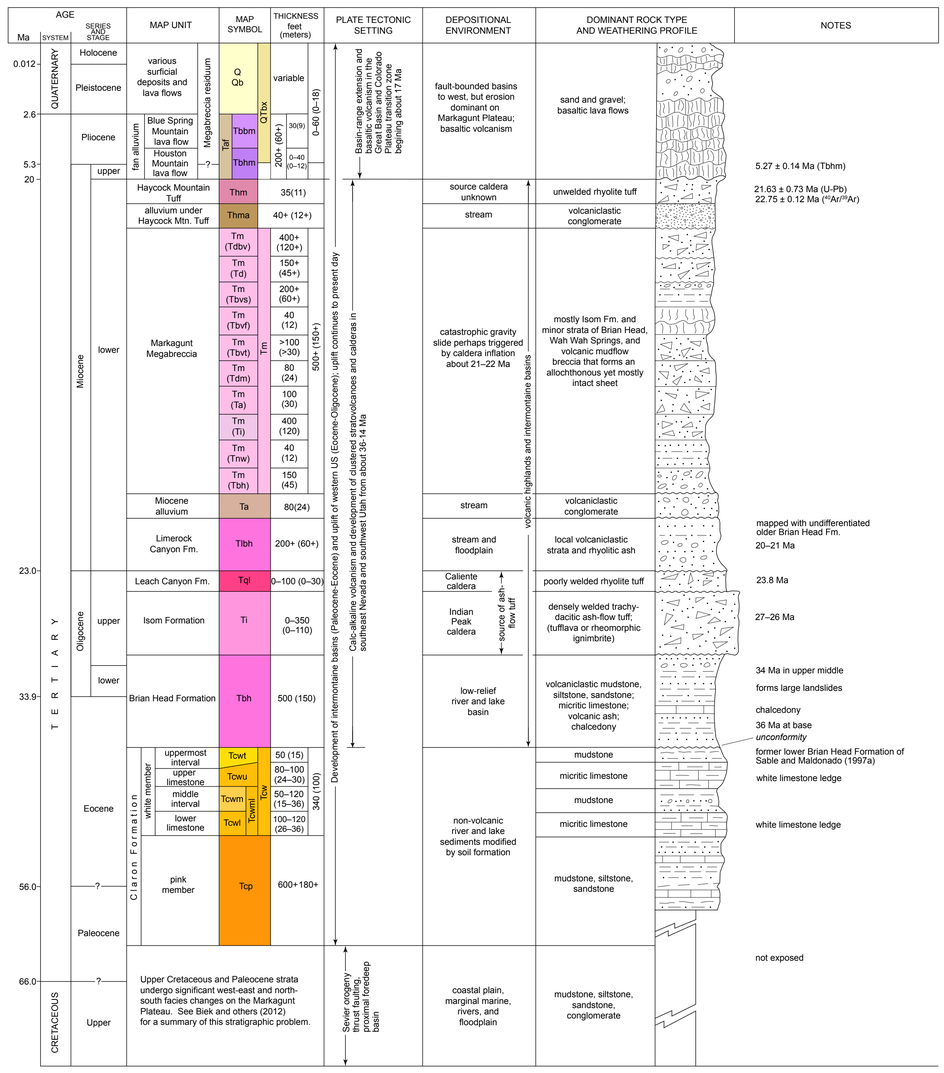
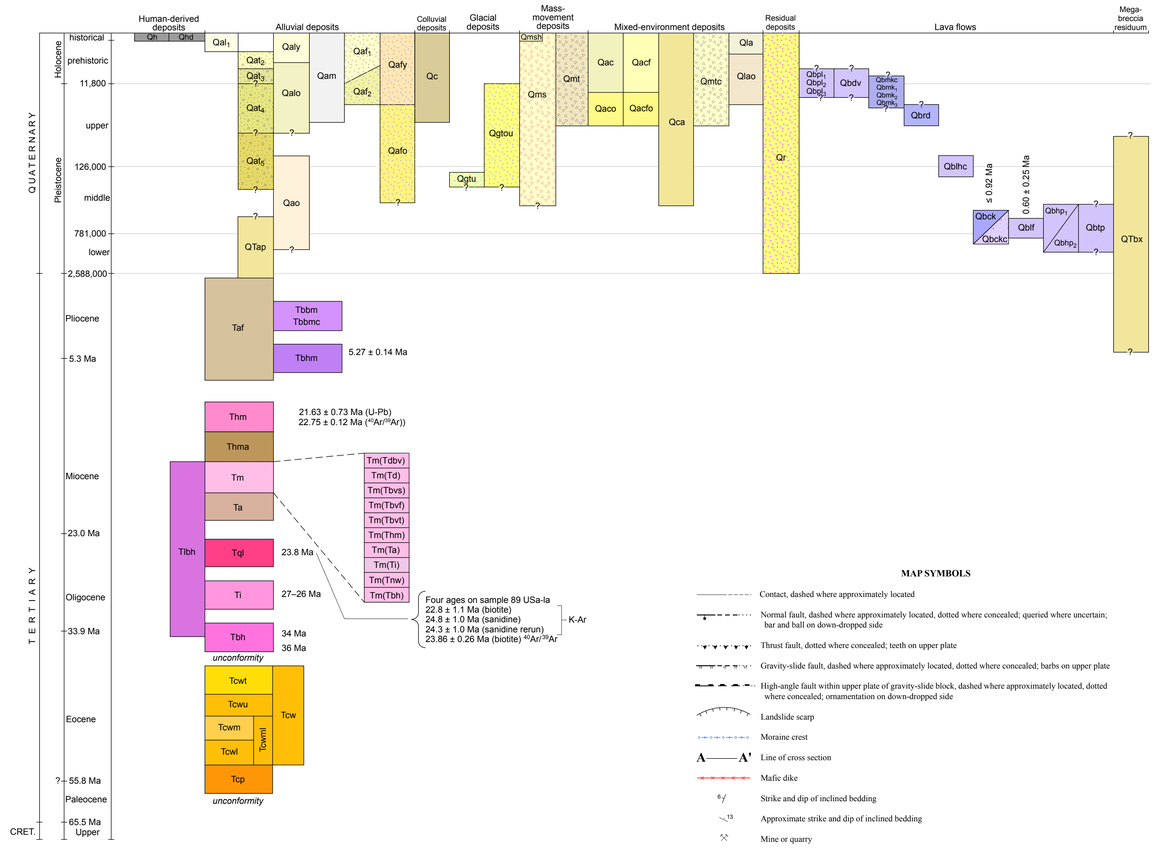
LITHOLOGIC COLUMN

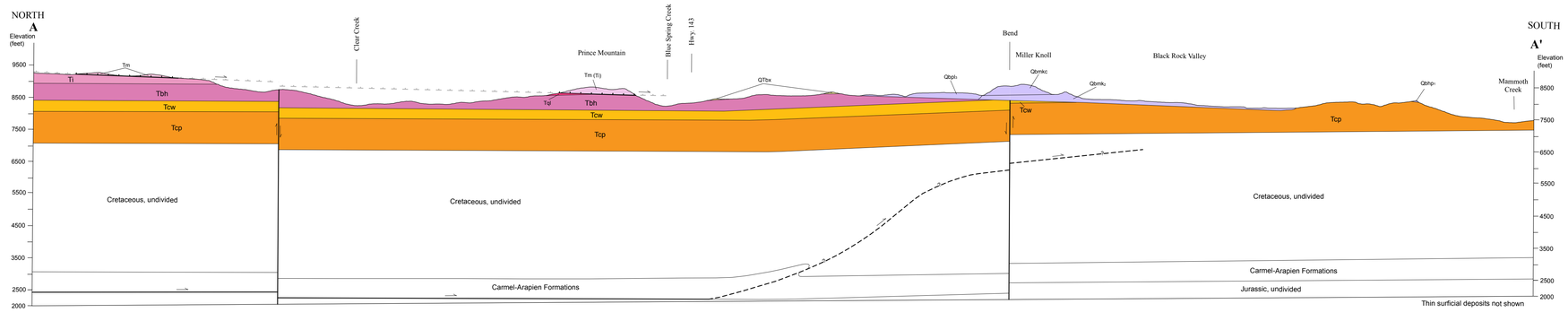


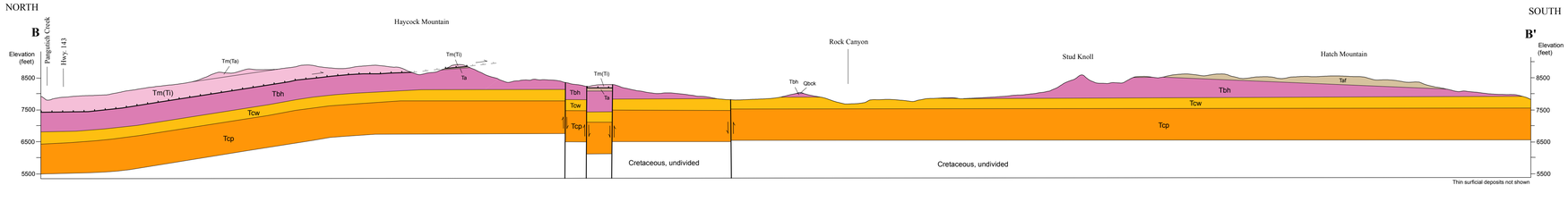
CORRELATION OF MAP UNITS



MAP SYMBOLS

- Contact, dashed where approximately located
- Normal fault, dashed where approximately located, dotted where concealed; queried where uncertain; bar and ball on down-dropped side
- Thrust fault, dotted where concealed; teeth on upper plate
- Gravity-slide fault, dashed where approximately located, dotted where concealed; barbs on upper plate
- High-angle fault within upper plate of gravity-slide block, dashed where approximately located, dotted where concealed; ornamentation on down-dropped side
- Landslide scarp
- Moraine crest
- A——A' Line of cross section
- Mafic dike
- Strike and dip of inclined bedding
- Approximate strike and dip of inclined bedding
- Mine or quarry
- Sand and gravel pit or cinder pit
- Volcanic vent
- Sinkhole
- Chalcedony marker bed in Brian Head Fm., dashed where approximately located
- Spring
- Radiometric age sample (see http://geology.utah.gov/online/analytical_data.htm)
- Geochemical sample (see http://geology.utah.gov/online/analytical_data.htm)
- Optically Stimulated Luminescence sample (see http://geology.utah.gov/online/analytical_data.htm)





GEOLOGIC MAPS OF THE PANGUITCH LAKE AND HAYCOCK MOUNTAIN QUADRANGLES, GARFIELD AND IRON COUNTIES, UTAH

by Robert F. Biek, John J. Anderson, Edward G. Sable, and Peter D. Rowley

MAP 268DM & MAP 269DM
UTAH GEOLOGICAL SURVEY
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2014

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SCALE: 1:24,000

Note: This booklet is intended for two quadrangle geologic maps, published and purchased separately.

Cover photo: *(top) View northwest to a 34 Ma rhyolitic ash-fall tuff in the Brian Head Formation; hill in the distance is capped by Isom Formation as part of the Markagunt Megabreccia. (bottom) The rugged Miller Knoll and Panguitch Lake lava flows, about 2 miles (3 km) south of Panguitch Lake.*

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MAP 268DM & MAP 269DM
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2014

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MAP UNIT DESCRIPTIONS

NOTE: This description of map units is intended for both the Haycock Mountain and Panguitch Lake quadrangle geologic maps. Not all map units are present in each quadrangle.

QUATERNARY

Human-derived deposits

Qh **Artificial fill** (Historical) – Engineered fill and general borrow material used mostly for major roads and small dams; fill of variable thickness and composition should be anticipated in all developed or disturbed areas; typically less than 20 feet (6 m) thick.

Qhd **Disturbed land** (Historical) – Disturbed area in Castle Valley (about 5 miles [9 km] southwest of Panguitch Lake) mapped because it obscures extent of glacial deposits and landforms.

Alluvial deposits

Qal_1 **Stream alluvium** (Holocene) – Moderately sorted sand, silt, clay, and pebble to boulder gravel deposited along Mammoth Creek; locally includes minor stream-terrace alluvium as much as about 10 feet (3 m) above current base level, and locally includes historical debris-flow and debris-flood deposits; probably less than 30 feet (<9 m) thick.

Qat_2, Qat_3, Qat_4, Qat_5
Stream-terrace deposits (Holocene to middle? Pleistocene) – Moderately sorted sand, silt, and pebble to boulder gravel that forms incised gently sloping surfaces above major streams, including Mammoth, Clear, Panguitch, and Haycock Creeks; deposited in stream-channel environment, but locally includes small alluvial-fan and colluvial deposits; each terrace represents the elevation of the stream base level prior to being incised; subscript denotes relative age (younger to older) and height above adjacent drainage; Qat_2 ranges from about 5 to 10 feet (2–3 m), Qat_3 ranges from about 10 to 20 feet (3–6 m), Qat_4 ranges from about 40 to 60 feet (12–18 m), and Qat_5 ranges from about 80 to 120 feet (25–35 m) above adjacent streams; typically less than 20 feet (<6 m) thick.

Qaly **Young stream alluvium** (Holocene) – Combined stream alluvium (Qal_1) and the youngest (lowest elevation) stream-terrace alluvium (Qat_{2-3}), but undivided here due to limitations of map scale; this lumped unit is commonly mapped in upland drainages not well graded to the Sevier River and may include small alluvial-fan deposits from tributary drainages and colluvium from adjacent slopes; commonly grades downslope into alluvial fans; locally includes historical debris-flow and debris-flood deposits; typically less than 20 feet (<6 m) thick, but deposits of major stream valleys may locally exceed 30 feet (9 m) thick.

Qalo **Old stream alluvium** (Holocene and upper Pleistocene) – Similar to lower- to middle-elevation parts of stream-terrace alluvium (Qat_{3-4}), but these dissected deposits are largely restricted to smaller 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, which drains eastward into Panguitch Lake, and on the south side of the lake itself; during mapping, the Panguitch Lake deposits were well exposed in excavations associated with a new housing development, revealing interbedded sand and pebbly to cobbly, locally iron-stained gravel containing clasts mostly of grussy-weathering Isom Formation (Ti) and resistant, subordinate chalcedony and quartzite, but apparently lacking basalt; map unit includes deposits that underlie the nearby Cooper Knoll lava flow (Qbck, just southeast of Panguitch Lake) 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 cob-

bles is unknown, but they were ultimately recycled from the Grand Castle Formation (redefined) or Drip Tank Member of the Straight Cliffs Formation now exposed in grabens below the western topographic rim of the Markagunt Plateau; Qao deposits record an early phase in the development of the Clear Creek drainage and the related Rock Canyon drainage, which also drains eastward across the central Haycock Mountain quadrangle and the lower part of which is now drained by its markedly underfit northern tributary, Pass Creek; in other words, ancestral Clear Creek apparently used to drain southeast into Rock Canyon, thus giving the canyon a much larger drainage basin before Clear Creek was diverted by the Panguitch Lake lava flows; 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 south of Mammoth Creek in the southwest corner of the Panguitch Lake quadrangle; forms small marshy areas characterized by cattails and other hydrophilic vegetation; typically less than 10 feet (3 m) thick.

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

Qaf_2 **Middle fan alluvium** (Holocene and upper Pleistocene) – Similar in composition and morphology to young fan alluvium (Qaf_1), but forms inactive surfaces incised by younger stream and fan deposits; equivalent to the older, lower part of young and middle fan alluvium (Qafy) and mixed alluvium, colluvium, and fan alluvium (Qacf); probably less than 30 feet (<9 m) thick.

Qafy **Young and middle fan alluvium, undivided** (Holocene and upper Pleistocene) – Poorly to moderately sorted, non-stratified, boulder- to clay-size sediment containing subangular to subrounded clasts deposited at the mouths of streams and washes; forms both active depositional surfaces (Qaf_1 equivalent) and low-level inactive surfaces incised by small streams (Qaf_2 equivalent) that are undivided here; deposited principally as debris flows and debris floods, but colluvium locally constitutes a significant part; larger deposits are probably several tens of feet thick.

Qafo **Older fan alluvium** (upper and middle? Pleistocene) – Poorly to moderately sorted, non-stratified, subangular to subrounded, boulder- to clay-size sediment with moderately developed calcic soils (caliche); forms deeply dissected, gently sloping surfaces above major drainages in the map areas; deposited principally as debris flows and debris floods; exposed thickness as much as several tens of feet.

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 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.

Glacial deposits

On the Markagunt Plateau, glacial till and outwash are present only east of Brian Head peak in the Castle Creek and Lowder Creek drainages (in the adjacent Brian Head quadrangle) and in the greater Castle Valley area (in the west-central part of the Panguitch Lake quadrangle). These deposits mark the southernmost occurrence of late Pleistocene glaciation in Utah (Mulvey and others, 1984), as first briefly described by Gregory (1950). The deposits are of the Pinedale alpine glacial advance and an older glaciation of uncertain Quaternary age. 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 3-4, about 59 to 71 ka; Imbrie and others, 1984) were not previously known in Utah (Laabs and Carson, 2005); however, Biek and others (2012; see also UGS and USULL, 2013) reported a new optically stimulated luminescence age of 49 ka for pre-Pinedale till exposed on the southeast margin of Castle Valley (sample PL090109-1), and it may be that the MIS 3-4 advance is more widespread in the west than originally thought (Tammy Rittenour, Utah State University, written communication, August 3, 2010). 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.

Pinedale-age glacial till is not present in the Panguitch Lake quadrangle, but is present as a terminal moraine a few tens of feet west of the map boundary along Castle Creek. This till is 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 drainage basin (Rowley and others, 2013). This terminal moraine at the west end of Castle Valley is at an elevation of about 9750 feet (2973 m), whereas another terminal moraine farther west, in the smaller Lowder Creek basin, is at Long Flat at an elevation of about 10,100 feet (3080 m) (Biek and others, 2012; Rowley and others, 2013). Recessional and lateral moraines and hummocky, stagnant-ice topography are locally well developed in these basins, 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).

The till is Pinedale age based on distinct, well-preserved morainal morphology and relatively unweathered clasts, and a 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, 2011) and Weaver and others (2006) reported boulder exposure ages from four different moraines that indicate a local LGM of about 21.1 ka for the main Pinedale advance on Boulder Mountain approximately 80 miles (130 km) to the northeast. Their 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, 2011) also reported a smaller advance at about 16 ka on Boulder Mountain.

Qgtu **Glacial till of uncertain pre-Pinedale age** (middle? Pleistocene) – Similar to glacial till of Pinedale age described above (and present in the adjacent Brian Head quadrangle [Rowley and others, 2013]), but glacial landforms are poorly preserved or absent; forms a low-relief, rubble-covered, locally hummocky surface west and south of Castle Valley; low hills south of Castle Valley are composed almost entirely of large blocks of Leach Canyon Formation, with minor blocks of Isom Formation and chalcedony, that we infer to be the deeply eroded remains of a medial moraine; thickness uncertain, but probably about 10 to 30 feet (3–10 m) thick.

Mulvey and others (1984) and Currey and others (1986) first suggested that glacial till older than Pinedale age may be present in this area. We sampled a sandy till exposed in a bluff northwest of the confluence of Mammoth and Castle Creeks (map unit Qgtou) that yielded an optically stimulated luminescence age of 48.95 ± 19.24 ka, suggesting that the deposits may correspond to the MIS 3-4 advance, but we remain uncertain how to interpret this age (UGS and USULL, 2013). Given the widespread extent and degree of incision of Qgtou deposits, we interpret these glacial deposits to be older than 50 ka, more likely of Bull Lake age.

Qgtou **Glacial till and outwash of Pinedale and uncertain pre-Pinedale age, undivided** (upper to middle? Pleistocene) – Similar to 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 Castle 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 due to poor topographic expression; 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; as much as 60 feet (18 m) thick where exposed near the confluence of Castle and Mammoth Creeks.

Mass-movement deposits

Qms, Qmsh

Landslides (Historical to middle? 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 (Tbh) Formation, and to a lesser extent the Limerock Canyon Formation (Tl), and are several square miles in size; Qmsh denotes landslides, mostly along State Highway 143 east of Castle Valley, known to be active in historical time, but any landslide deposit may have been historically active even if not so identified; 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 may exceed 150 feet (45 m) thick.

Undivided as to inferred age because 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).

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 (Tbh), Bear Valley (Tbv), and Limerock Canyon (Tl) Formations, 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 areas, but is only mapped where it conceals contacts or forms broad aprons below cliffs of resistant bedrock units; commonly grades downslope into colluvium; typically less than 30 feet (9 m) thick.

Mixed-environment deposits

Qac **Alluvium and colluvium** (Holocene 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; probably about 20 to 30 feet (6–9 m) thick.

Qacf **Alluvium, 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 coalesced apron of fan alluvium and colluvium impractical to map separately at this scale; typically 10 to 40 feet (3–12 m) thick.

Qacfo **Older alluvium, colluvium, and fan alluvium** (Pleistocene) – Similar to mixed alluvium, colluvium, and fan alluvium (Qacf), but forms incised, isolated remnants southeast of Haycock Mountain, in the upper reaches of the Clear Creek drainage, and at the west end of Castle Valley; typically about 20 to 30 feet (6–9 m).

Qca **Colluvium and alluvium** (Holocene to middle Pleistocene) – Poorly to moderately sorted, 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, as at Dry Valley; distal, finer-grained parts form broad, open meadows; thickness uncertain, but likely less than about 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.

Qla **Lacustrine sediment and alluvium** (Holocene) – Forms the meadow of Blue Spring Valley (figure 1) about 2 miles (3 km) southwest of Panguitch Lake, which we interpret to be a lake deposit made up mostly of 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.

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 Blue Spring Creek, which may have formed in response to the Miller Knoll lava flows that blocked the original Bunker Creek outlet at the southeast end of the valley possibly as recently as early Holocene time. Lacustrine sediment and alluvium is likely several tens of feet thick in Blue Spring Valley.

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

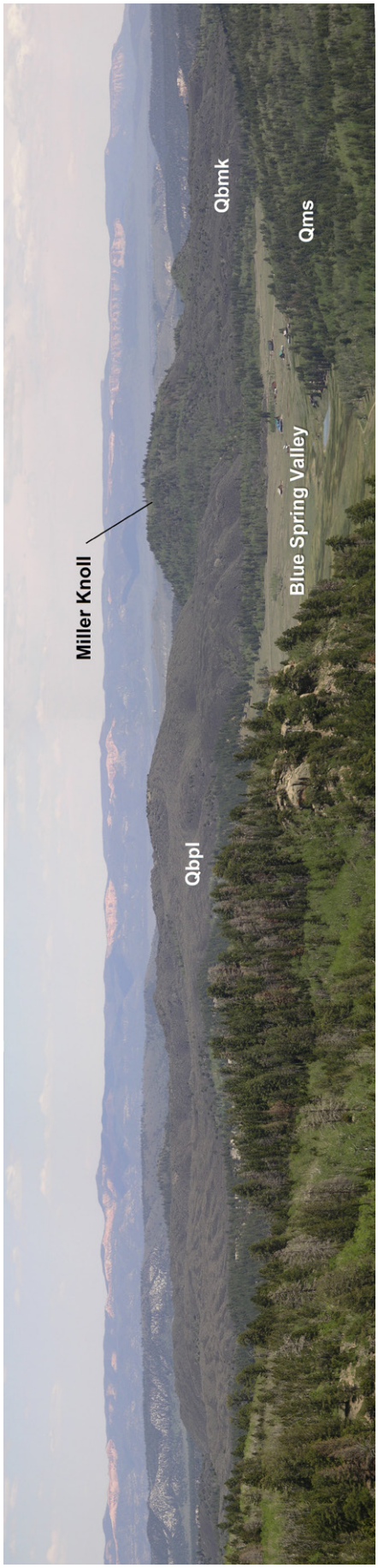

Figure 1. *View southeast of Blue Spring Valley. Ancestral Bunker Creek (at lower right) is thought to have originally flowed through the Blue Spring Valley into Black Rock Valley prior to being diverted by the Miller Knoll (Qbmk) lava flows. Miller Knoll cinder cone and Panguitch Lake (Qbpl) lava flows are east of the valley, whereas a large landslide complex (Qms) developed on Brian Head Formation bounds its west side.*

Residual deposits

Qr **Relict Blue Spring Mountain lava flow** (Holocene to Pleistocene) – Mapped on the south side of Blue Spring Mountain where blocks of the Blue Spring Mountain lava flow (Tbbm) conceal the upper part of the white member of the Claron Formation and possibly the lower part of the Brian Head Formation.

Stacked unit deposits

Stacked unit deposits comprise a discontinuous veneer of Quaternary deposits that mostly conceal underlying bedrock units. Although most bedrock in the quadrangle is partly covered by colluvium or other surficial deposits, we use stacked units to indicate 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 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 upper Pleistocene/Oligocene to Eocene) – Mapped on the north flank of Houston Mountain in the southwest corner of the Panguitch Lake quadrangle where colluvium, residual deposits, and possibly landslide deposits conceal the underlying Brian Head Formation; 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.

QUATERNARY-TERTIARY

Holocene(?) to upper Tertiary lava flows

Basaltic lava flows in the Panguitch Lake and Haycock Mountain quadrangles are at the northern edge of the Western Grand Canyon basaltic field, which extends across the southwest part of the Colorado Plateau Province and the adjacent High Plateaus transition zone into the Basin and Range Province in southwest Utah, northwest 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 late 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 oldest basaltic lava flow in this two-quadrangle area is the 5.3 Ma Houston Mountain flow (Tbhm). 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 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," were suggested to relate to the Panguitch Lake-area lava flows (Palmer, 1957; Southern Paiutes lived in southwest Utah beginning about A.D. 1100 [Canaday, 2001]), but it is unlikely the flows are this young. 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 older (the lava flows Schulman sampled are apparently near Panguitch Lake although definitive sample locations are unavailable [his samples BRY 2104 and BRY 2110, table "Overage drought conifers," p. 32]).

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 and major- and trace-element geochemistry. Lava flows 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. Basaltic lava flows commonly contain lava tubes, but even though the Panguitch Lake and Miller knoll lava flows contain prominent collapsed lava tubes, we know of no large open tubes in the quadrangles. The flows commonly overlie stream-gravel and other surficial deposits. Older lava flows are partly covered by eolian sand and silt and calcic soil (caliche) not shown on this map.

The lava flows in the Haycock Mountain and Panguitch Lake quadrangles 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) (see also Biek and others, 2009). Classic, if lesser known, inverted valleys are also present on the east-tilted Markagunt Plateau, including those on Blue Spring Mountain, Hancock Peak, and Coopers Knoll, each of which once must have looked much like the middle Miller Knoll flow ($Qbmk_2$), which now blocks Black Rock Valley and is only beginning to be incised.

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). Major- and trace-element data for volcanic rocks in these map areas are available at http://geology.utah.gov/online/ofr/ofr-623.pdf. Nb/La ratios for virtually all samples of basaltic lava flows from this area are less than 1.0, thus suggesting a lithospheric mantle source (Fritton and others, 1991). Rock names are from LeBas and others (1986).

$Qbpl_1$, $Qbpl_2$, $Qbpl_3$

Panguitch Lake lava flows (Holocene? to upper Pleistocene?) – Mapped as three separate lava flows, with $Qbpl_1$ being the youngest, all three of which are mostly unvegetated and blocky, and exhibit steep flow fronts 100 to 200 feet (30–60 m) high (figures 2, 3, and 4): $Qbpl_1$ is dark-gray to black latite (potassium-rich trachyandesite) containing small (1 mm), stubby plagioclase phenocrysts in a glassy to aphanitic groundmass; $Qbpl_2$ and $Qbpl_3$ are dark-gray latite containing small stubby plagioclase and abundant acicular hornblende phenocrysts in a fine-grained groundmass; age uncertain, but all are likely closely related in age and all may be as young as late Holocene; we are currently attempting to date the $Qbpl_3$ flow; individual lava flows are typically about 200 feet (60 m) thick.

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 $Qbpl_3$ lava 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 north-

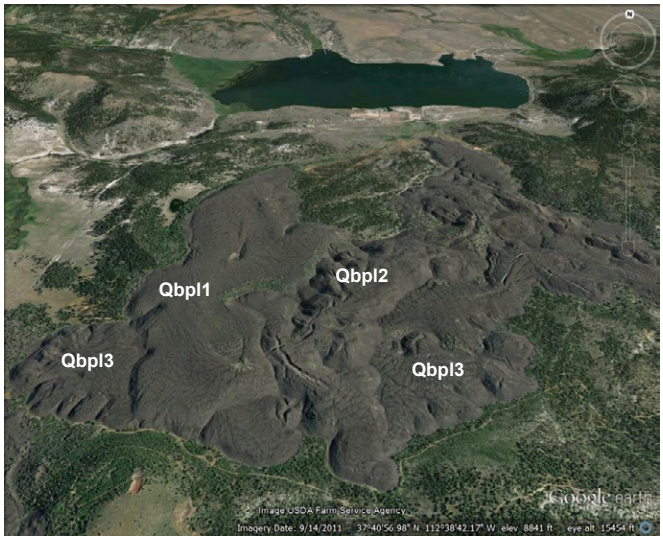

Figure 2. *Oblique aerial view to the north of the Panguitch Lake lava flows (Qbpl$_1$, Qbpl$_2$, and Qbpl$_3$), just south of Panguitch Lake. Miller Knoll, with a cinder pit at its summit, is in the foreground. From 2011 Google Earth imagery.*

east of Miller Knoll, the large cinder cone [Qbmkc] 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).

Qbdv **Dry Valley lava flow** (Holocene? to upper Pleistocene?) – Dark-gray latite (potassium-rich trachyandesite) that contains olivine and abundant hornblende phenocrysts in an aphanitic to fine-grained groundmass; forms a thick, blocky, laterally restricted flow west of Black Rock Valley and north of Mammoth Creek that exhibits high, steep flow fronts (except at Dry Valley, immediately west of the vent, where a slightly older more fluid phase erupted); upper surface shows prominent arcuate ridges that reveal flow directions (figure 5), 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$_2$); this is the "arcuate andesite flow" of Stowell (2006); typically 100 to 120 feet (30–35 m) thick.

Qbmk$_1$, Qbmk$_2$, Qbmk$_3$, Qbmkc
Miller Knoll lava flows and cinder cone (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 aphanitic groundmass; Qbmk$_2$ and Qbmk$_3$ are dark- to medium-gray basaltic trachyandesite containing clusters of olivine, plagioclase,

Figure 3. *View south across Panguitch Lake showing the mostly unvegetated Panguitch Lake (Qbpl$_3$) lava flow.*

Figure 4. View east-northeast of the Miller Knoll (Qbmk$_1$, at right) and Panguitch Lake (Qbpl$_3$, at left) lava flows just northwest of the Miller Knoll cinder cone. Note blocky, steep flow fronts of these latitic lava flows.

Figure 5. Oblique aerial view northwest of the Dry Valley latite lava flow (Qbdv) showing arcuate ridges that record flow direction. The less silica-rich and thus more fluid Miller Knoll basaltic trachyandesite lava flow (Qbmk$_2$) exhibits abundant branching distributary lobes and collapsed lava tubes. From 2011 Google Earth imagery.

and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass and include both sodium-rich (mugearite) and potassium-rich (shoshonite) rock types, locally containing small, thin plagioclase phenocrysts; the Qbmk$_2$ lava flow, the "southern Panguitch flow" of Stowell (2006), yielded cosmogenic exposure ages of about 37,000 years (Dave Marchetti, Western State Colorado University, Gunnison, 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 late Holocene; lava flows are typically 30 to 100 feet (10–30 m) thick, but may be thicker where they fill paleotopography.

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 (figure 6). The Qbmk$_3$ lava flow erupted from a vent now concealed by the Miller Knoll cinder cone; the 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 along Mammoth Creek was clearly limited by pre-existing topography of the pink member of the Claron Formation, but the flow now lies at the modern base level of Mammoth Creek. The lava flow once 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.

Qbrd **Red Desert lava flow** (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; present only in the extreme southwest corner of the Panguitch Lake quadrangle; erupted from vents at a cinder cone 4 miles (6.5 km) west-southwest of the quadrangle (Moore and others, 2004); age uncertain, but lava flows are likely late Pleistocene based on degree of incision and weathering (Biek and others, 2012), although Moore and others (2004) considered the lava flow as probably Holocene; lava flow is several tens of feet thick.

Qbck, Qbckc
Cooper Knoll lava flow and cinder cone (middle to lower Pleistocene) – Medium-gray basalt that con-

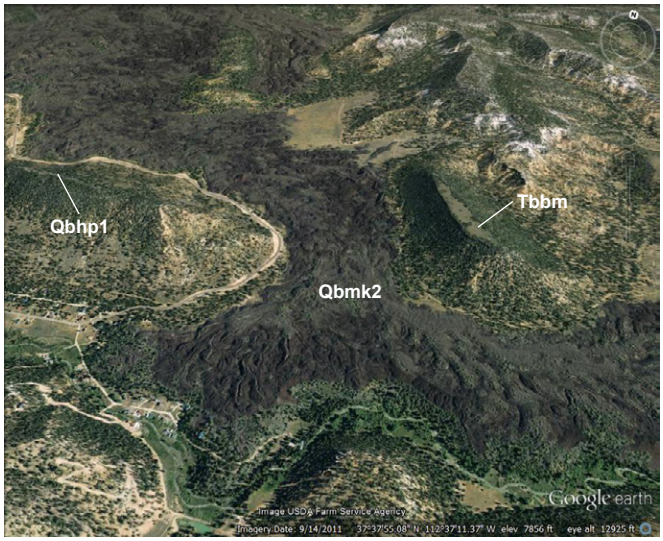

Figure 6. *Oblique aerial view north to the Miller Knoll lava flow (Qbmk$_2$) showing branching distributary lobes and collapsed lava tubes. A remnant of the Hancock Peak lava flow (Qbhp$_1$) caps an inverted valley north of the small community of Mammoth at the west edge of the photo, whereas a remnant of the Blue Spring Mountain lava flow (Tbbm) caps the ridge to the east. Both of these lava flows once looked like the much younger Miller Knoll flow, and now record the topographic inversion of former stream valleys. Mammoth Creek flows from left to right across the bottom of the image. From 2011 Google Earth imagery.*

tains 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; lava flow forms a classic inverted valley on the north side of Rock Canyon, and overlies stream gravels (Qao) containing rounded pebbles and cobbles of the Isom Formation, mafic and intermediate volcanic rocks of the Mount Dutton Formation, chalcedony, and minor quartzite; sample HM101408-1 yielded a discordant age spectrum showing that the flow is less than or equal to 0.92 Ma (UGS and NIGL, 2013); more likely, it may be about 500,000 years old on the basis of comparison with the similarly incised Asay Bench lava flow (Biek and others, 2012) 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.

Qblf **Long Flat lava flow** (middle to lower Pleistocene) – Medium-gray basalt to hawaiite (sodium-rich trachybasalt) that contains clusters of olivine and clinopyroxene phenocrysts; present only at the west edge of the Panguitch Lake quadrangle, west of Castle Valley; lava flow erupted mostly from hills 10,392 and 10,352 (Brian Head 7.5′ topographic quadrangle map), which are two cinder cones (Qblfc) near Long Flat 1 to 2 miles (1.5–3 km) west of the quadrangle (Rowley and others, 2013); 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 the age of the Long Flat flow 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); lava flow is several tens of feet thick.

Qbhp$_1$, Qbhp$_2$ **Hancock Peak lava flows** (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 1.5 miles (2.5 km) west of the Panguitch Lake quadrangle (figure 7); 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 apparently 60,000-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.

Qblhc **Lake Hollow cinder cone** (upper to middle Pleistocene) – Forms a small, partly eroded cinder cone about 1.5 miles (3 km) north of Mammoth Creek in the southwest part of the Haycock Mountain quadrangle, 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 its degree of erosion; lava flow is less than about 20 feet (6 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 a small knob just south of The Pass, about 1 mile (1.6 km) east of Panguitch Lake; Wagner (1984) interpreted the unit to be a small gabbroic intrusion, but it 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; probably about 50 feet (15 m) thick.

Tbbm, Tbbmc

Blue Spring Mountain lava flow and cinder cone (upper 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 (figure 6); 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; lava flow is typically 30 feet (9 m) thick, but is doubtless thicker near the vent area and where it fills paleotopographic lows.

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 similar chemistry, the map unit includes a northeast-trending dike at the north end of Blue Spring Valley and a small flow remnant southwest of the dike and a few tens of feet above Blue Spring Creek. If the Blue Spring Creek remnant is indeed part of the 2.8 Ma 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. Alternately, this remnant may be a small basaltic sill.

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 (Tbh) and Leach Canyon Formation (Tql) along the west edge of Blue Spring Mountain; an erosional outlier on the south side of Clear Creek, about 3 miles (5 km) west-northwest of Panguitch Lake, contains abundant 1- to 2-mm-long plagioclase phenocrysts, but is otherwise chemically similar to the Houston Mountain flow; unit also caps Houston Mountain just south of the southwest corner of the Panguitch Lake quadrangle; source vent unknown and margins of lava flow are entirely eroded away, but elevation of remnants suggests flow was derived from the west of its current exposures, probably in the Brian Head quadrangle, likely at a vent now eroded and concealed by younger deposits (Biek and others, 2012); yielded an $^{40}Ar/^{39}Ar$ whole-rock age of 5.27 ± 0.14 Ma (UGS and NMGRL, 2009; see also Biek and others, 2012); about 40 feet (12 m) thick at Blue Spring Mountain.

Figure 7. *View southwest of the cinder cone of Hancock Peak, vent area for the Hancock Peak lava flows.*

QUATERNARY and TERTIARY

QTbx **Markagunt Megabreccia residuum** (Pleistocene to Pliocene) – Consists of an unconsolidated mix of Isom blocks and minor Brian Head debris that caps hills between Panguitch Lake and Blue Spring Valley, and south of the lake between Miller Knoll and Birch Spring Knoll; Isom blocks are subangular and locally as much as 6 feet (2 m) in size and are commonly internally brecciated on a fine scale, then rehealed by silicification to become a resistant rock (Hatfield and others, 2010), presumably by redeposition of silica from ash shards and fine breccia fragments of the Isom ash-flow tuff itself (the brecciation is a direct result of formation of the Markagunt Megabreccia, described below); interpreted by Biek and others (2012) to be derived from mass wasting and erosion of the southern margin of the Markagunt Megabreccia, similar to much more extensive deposits in and south of Cedar Breaks National Monument (Moore and others, 2004; Hatfield and others, 2010; Biek and others, 2012); as much as about 60 feet (18 m) thick.

QTap **High-level pediment alluvium** (Pleistocene and Pliocene?) – Moderately sorted, subrounded to rounded pebble to boulder gravel and sand that form a gently east-dipping, locally resistant cap on upper Tertiary fan alluvium (Taf) along the east margin of the Haycock Mountain quadrangle; surface of deposit typically covered by veneer of pebble and cobble residuum; deposited principally as debris flows and debris floods, and in ephemeral stream

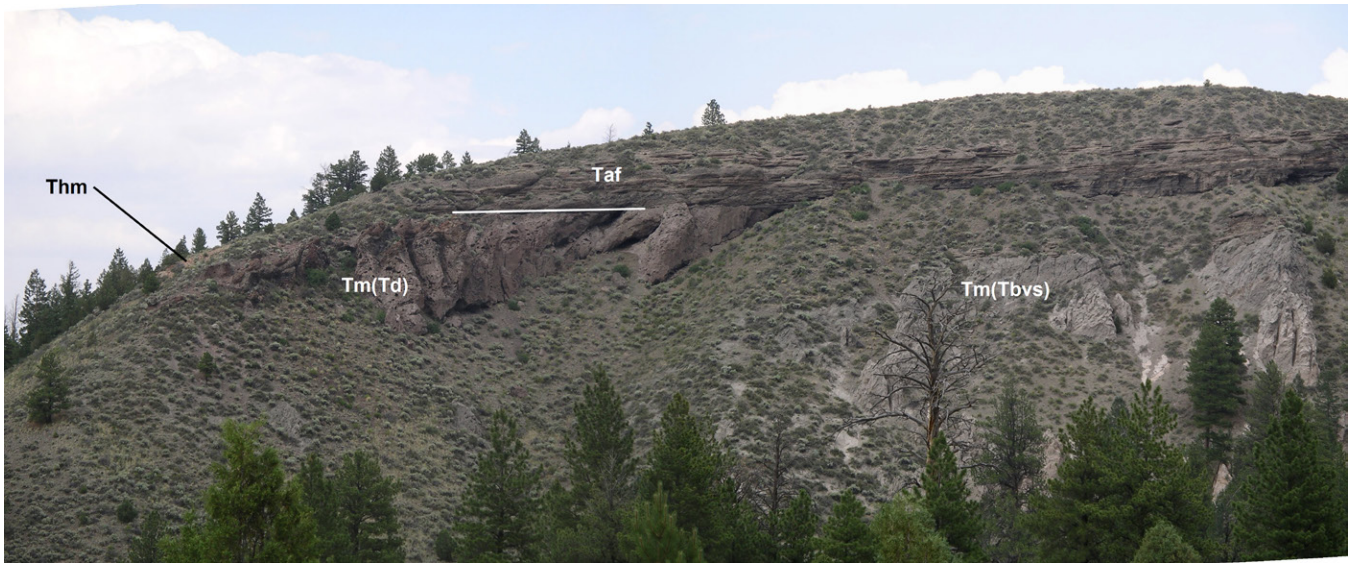

Figure 8. *View northeast of angular unconformity between subhorizontal late Tertiary fan alluvium (Taf) and underlying, moderately northwest-dipping Bear Valley sandstone (Tm[Tbvs]), Mount Dutton Formation (Tm[Td])—both part of the Markagunt Megabreccia—and Haycock Mountain Tuff (Thm). This exposure is east of Panguitch Creek near the center of section 25, T. 35 S., R. 7 W.*

channels; probably less than 20 feet (<6 m) thick.

TERTIARY

Taf **Upper Tertiary fan alluvium** (Pliocene to Miocene) – Moderately to poorly consolidated, brown and grayish-brown sandstone, siltstone, pebbly sandstone, and conglomerate that form an incised, east-tilted alluvial-fan surface of low, rounded hills along the east flank of the Markagunt Plateau; 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 erosion of the Mount Dutton Formation, regional ash-flow tuffs, and the Markagunt Megabreccia and deposited as aggrading alluvial fans, possibly 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; east and north of the Haycock Mountain quadrangle, this fan alluvium is interbedded with upper Tertiary basaltic lava flows (including the 5.0 Ma Rock Canyon lava flow and the 5.3 Ma Dickinson Hill lava flow of Biek and others [2012]) and uncommon, thin, lenticular beds of lacustrine limestone; unconformably overlies Claron, Brian Head, Markagunt Megabreccia, and Limerock Canyon strata and locally capped by pediment alluvium (QTap) (figure 8); as much as about 200 feet (60 m) thick in the Haycock Mountain quadrangle, but entire deposits are at least 1000 feet (300 m) thick in the Panguitch 7.5′ quadrangle (Moore and Straub, 1995).

The deposits were 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 field (see, for example, Anderson and Rowley, 1975; Anderson and others, 1990a; Moore and others, 1994; Rowley and others, 1994). The name Sevier River Formation formerly had value in reconnaissance-scale studies in the High Plateaus; in and near its type area near the town of Sevier, the formation contains air-fall tuffs that have fission-track and K-Ar ages of 14 and 7 Ma and basaltic lava flows that have K-Ar ages of 9 and 7 Ma (Steven and others, 1979; Best and others, 1980; Rowley and others, 2002). 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, but 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).

The Sevier River Formation and other late Tertiary basin-fill deposits provide control on structural development of the High Plateaus area. 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). This timing is supported by $^{40}Ar/^{39}Ar$ ages

of about 7 Ma for the formation of alunite and natrojarosite at Big Rock Candy Mountain, in Marysvale Canyon 35 miles (55 km) north of the map areas, due to oxidation (supergene alteration) as a result of downcutting by the Sevier River to expose altered rocks in the mountain (Cunningham and others, 2005).

Pediment deposits preserved atop the Spry intrusion, about 400 feet (120 m) above Circleville Canyon (Anderson and others, 1990a), which is about 28 miles (45 km) northeast of Panguitch Lake, led Anderson (1987) to suggest that basin-fill deposits once filled the ancestral valley of the Sevier River to a similar depth above the modern river. Some support for this interpretation is a similar pediment capped by Sevier River Formation over 1000 feet (300 m) above the Sevier River in northern Marysvale Canyon about 40 miles (64 km) north of the map areas (Eardley and Beutner, 1934; Rowley and others 1988a, 1988b). This interpretation may be correct, although senior author Biek sees no evidence for such exhumation of late Tertiary fan alluvium. Rather, he suggests that the structural high of the Spry intrusion and its capping pediment deposits may be due to an inferred fault segment boundary of the Sevier fault zone; that is, the long-term displacement rate or total displacement there may be lower than that in the basins to the south and to the north. Thus, Biek interprets the capping pediment deposits simply to be remnants stranded by continued downcutting of the Sevier River as a result of differential slip on the Sevier fault, not due to a superposed Sevier River and exhumation of Sevier valley and Circleville Valley basin-fill deposits.

unconformity

Thm **Haycock Mountain Tuff** (lower Miocene) – Consists of two cooling units at its type section along Panguitch Creek about one mile (1.6 km) northeast of Panguitch Lake: lower unit is white to very light pink, unwelded, crystal-poor rhyolite tuff that is overlain by light-pink, unwelded, moderately resistant crystal-poor rhyolite tuff; both contain common pumice fragments and lithic fragments of black, aphanitic, mafic volcanic rock; typically forms moderately resistant ledge over volcaniclastic conglomerate (Thma) and elsewhere overlies locally deformed Bear Valley Formation [Tm(Tbv)] and Mount Dutton Formation [Tm(Td)]; mapped north of Haycock Mountain where it is about 35 feet (11 m) thick.

The Haycock Mountain Tuff is petrographically and chemically similar to the Leach Canyon Formation, but lacks red lithic fragments that characterize the Leach Canyon Formation (see the Leach Canyon Formation unit description for details). As noted by Hatfield and others (2010), the Haycock Mountain Tuff yielded an $^{40}Ar/^{39}Ar$ age of 22.75 ± 0.12 Ma (Ed Sable, U.S. Geological Survey, unpublished data, 1996). On the basis of the undeformed nature of the Haycock Mountain Tuff and its underlying conglomerate (Thma), Anderson (1993), Rowley and others (1994), and Hatfield and others (2010) interpreted the Haycock Mountain Tuff to postdate emplacement of the Markagunt Megabreccia.

However, the 22.75 Ma age of the undeformed Haycock Mountain Tuff is at odds with the fact that the Markagunt gravity slide overlies the 22.03 Ma Harmony Hills Tuff in Parowan Canyon (sections 14 and 15, T. 35 S., R. 9 W.). Here, exposures interpreted by Maldonado and Moore (1995) as Harmony Hills Tuff in normal fault contact against autochthonous Isom Formation, were reinterpreted by Biek and others (2012) to consist of Isom within the Markagunt gravity slide that slid over the Harmony Hills Tuff; in other words, the normal fault of Maldonado and Moore (1995) is in fact a gently southeast-dipping gravity-slide plane, not a west-dipping normal fault. This interpretation is consistent with similar exposures of the Harmony Hills Tuff in Summit Canyon to the west. Therefore, the Markagunt gravity slide must be younger than about 22 million years old. We resampled the Haycock Mountain Tuff and report a new U-Pb age on zircon of 21.63 ±0.73 Ma (UGS and AtoZ, 2013). The Haycock Mountain Tuff does indeed represent a post-Markagunt gravity slide ash-flow tuff that partly filled a stream channel and adjacent lowlands eroded into the gravity slide.

Thma **Alluvium underlying Haycock Mountain Tuff** (lower Miocene) – Moderately sorted, moderately consolidated, pebble to boulder volcaniclastic gravel underlying undisturbed Haycock Mountain Tuff at its type section about one mile (1.6 km) northeast of Panguitch Lake; maximum exposed thickness about 40 feet (12 m).

unconformity

Markagunt Megabreccia (lower Miocene) – With an apparent aerial extent of at least 1300 mi^2 (3400 km^2), larger than the state of Rhode Island, the Markagunt gravity slide is among the largest subaerial gravity slides on earth; it rivals and may surpass in size the famous Heart Mountain detachment in northwestern Wyoming (see, for example, Malone and Craddock, 2008; Beutner and Hauge, 2009; Craddock and others, 2009). At its simplest, the gravity slide is a great sheet of volcanic rock that slid many miles southward and at its distal southern end overrode the earth's surface to place older rock on younger rock. The ramp, north of the map ar-

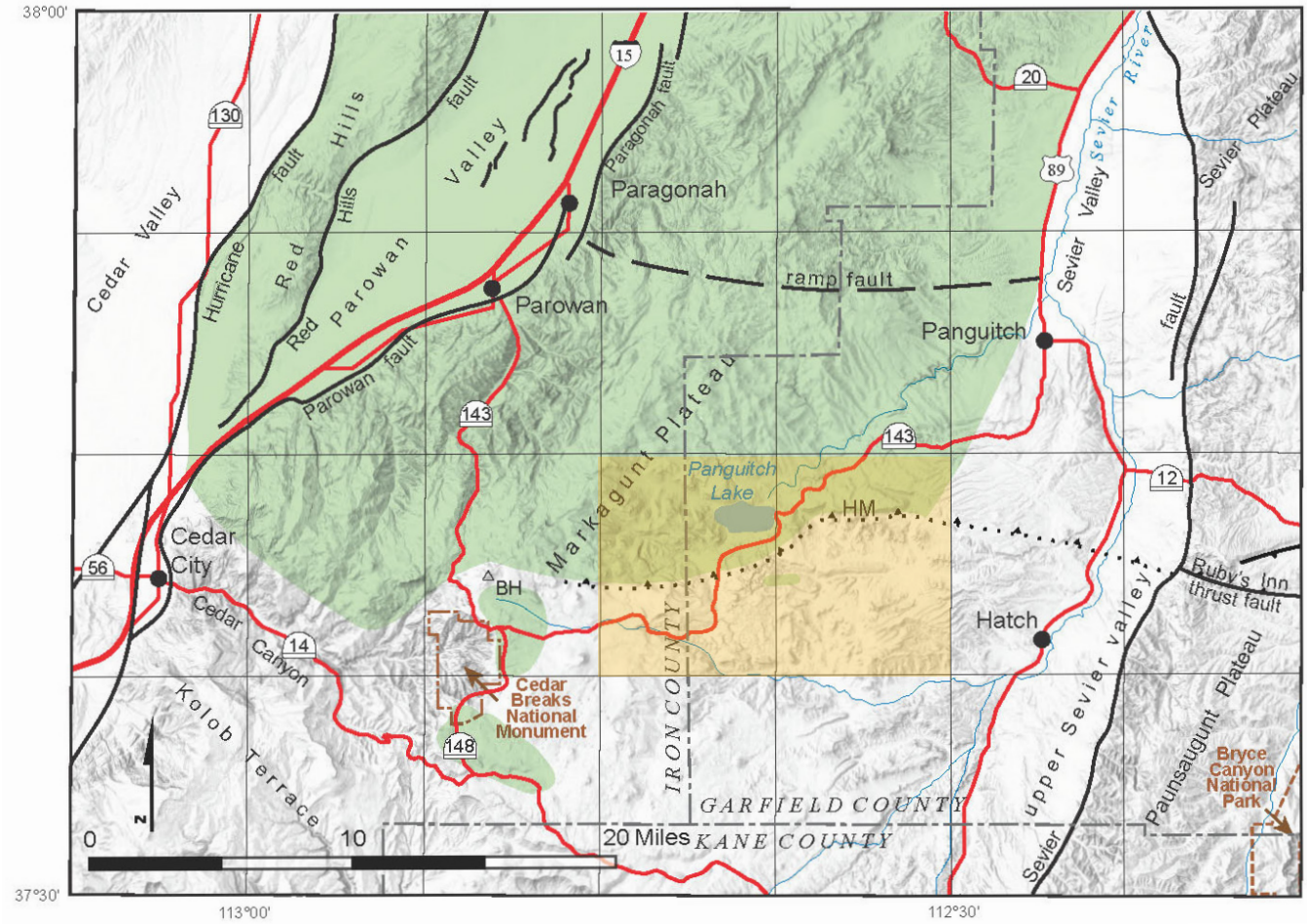

Figure 9. *Index map showing extent of Markagunt Megabreccia (green) in the Panguitch 30' x 60' quadrangle; ongoing mapping suggests that the northern extent is near the latitude of Beaver, some 50 miles (80 km) north of Panguitch Lake. BH, Brian Head peak; HM, Haycock Mountain. Grid shows location of 7.5' quadrangles; Panguitch Lake and Haycock Mountain quadrangles are highlighted. Modified from Biek (2013).*

eas, is where the gravity slide plane came to the surface. The slide mass, known as the Markagunt Megabreccia, consists of large blocks of Miocene and Oligocene regional ash-flow tuffs (most originally erupted from calderas along the Utah-Nevada border) and local volcanic and volcaniclastic rocks (derived from the Marysvale volcanic field), and blankets the entire central and northern Markagunt Plateau (figure 9). See Biek (2013) and Biek and others (in preparation) for a fuller description of the Markagunt Megabreccia, including the history of its discovery and still unresolved questions about its origin.

We use the term Markagunt Megabreccia to refer to the eroded remains of the Markagunt gravity slide as to better tie its deposits to its structural origin. Also, the deposits were so named early after their discovery, when it was realized that they represented the product of a gravity slide but when knowledge of the extent and source of the slide was based on incomplete and preliminary mapping of areas for which we now have a much fuller understanding. The Markagunt Megabreccia (map unit Tm) is used for those parts of the gravity slide where individual rock units are not mapped separately; map symbols with a unit name, for example Tm(Tnw) for Wah Wah Springs Formation, are used where the map unit is mapped separately as part of the upper plate of the gravity slide. Typically, we map only the basal shear as a gravity slide fault; boundaries between the many units that compose its upper plate are mapped as contacts for simplicity and to avoid map clutter, though we recognize that many such contacts are indeed slip surfaces that accommodated variable amounts of extension and thinning of upper plate strata.

Grooves, striations, Riedel shears, pseudotachylyte, crushed and rehealed clasts, basal cataclastic breccia, and clastic dikes demonstrate catastrophic emplacement of the Markagunt Megabreccia from the north. The uniformity of directional indicators, the sequence of volcanic rocks that make up upper plate strata, and the overall geometry of the gravity slide show that it was emplaced during a single event and is not composed of multiple, smaller gravity slides derived from multiple sources. The gravity slide was emplaced on rocks as young as the 22 Ma Harmony Hills Tuff. The gravity slide is overlain by, and thereby apparently predates, undeformed

Haycock Mountain Tuff, which yielded an $^{40}Ar/^{39}Ar$ age of 22.75 ± 0.12 Ma (Ed Sable, U.S. Geological Survey, unpublished data, 1996), but for which we report a new U-Pb zircon age of 21.63 ± 0.73 Ma (UGS and AtoZ, 2013). Thus, it is our current interpretation that the Markagunt gravity slide was emplaced about 21 to 22 million years ago.

The Markagunt Megabreccia exhibits the full range of structural features commonly seen in modern landslides, including compression and resultant folding and thrust faulting in the landslide's toe area, simple translational movement across the main body of the landslide, and extensional faulting in the upper parts of the landslide. Figure 10 shows a block diagram illustrating major components of such gravity-slide deposits, which are a special class of extremely large landslides.

South of the ramp fault, which strikes east at the latitude of Parowan (north of the map areas), most of the Markagunt Megabreccia was emplaced on resistant Isom Formation on the former Miocene land surface. Near its southern extent, part of which is in the Haycock Mountain and Panguitch Lake quadrangles, the gravity slide was also emplaced on Leach Canyon Formation and Miocene alluvial gravels eroded into the Brian Head Formation; west of the map areas, it was also emplaced on the 22.7 Ma Bauers Tuff Member and the 22.03 Ma Harmony Hills Tuff.

Throughout much of its extent, formations within the gravity slide appear to be subparallel to the basal shear plane, but locally upper plate strata are chaotically jumbled, as at its type section along State Highway 143, primarily in sections 25 and 26, T. 35 S., R. 7 W., northeast of Panguitch Lake (Anderson, 1993) and along Caddy and Butler Creeks north of Haycock Mountain. Elsewhere, upper plate strata are locally tilted north as exceptionally large panels, especially along the south margin of the gravity slide, as, for example, northeast of Castle Valley. For the most part, except in especially structurally complex areas, units within the Megabreccia are in their proper stratigraphic order.

The basal slip surface of the Markagunt gravity slide generally dips gently east (mimicking the regional dip of the plateau that was subsequently tilted in the late Tertiary) and south (because the source of the gravity slide is to the north; Sable and Maldonado, 1997a; Anderson, 2001), but near the toe at Haycock Mountain the basal slip surface dips north. The northward-dipping Isom Formation (caprock of Haycock Mountain) was reasonably 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 previously unreported basal breccias, shear zones, and associated clastic dikes exposed at the base of the Megabreccia on the south side of Haycock Mountain (figures 11, 12a, 12b, and 12c). These exposures show that the entire Isom Formation in this area is part of the gravity slide and collectively demonstrate catastrophic emplacement by gravity sliding. Furthermore, slickenlines at the base of the Megabreccia, as well as clastic dikes and Riedel shears (see, for example, Angelier and others, 1985; Petit, 1987), demonstrate north-to-south transport. Sable and Maldonado (1997a) 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. Because moderately northwest-dipping Claron and Brian Head strata are present just south of Panguitch Lake, the northward dipping Isom on Haycock Mountain (collectively with the sedimentary units) likely reflects tilting due to a blind thrust fault in underlying strata. This must be the westward equivalent of the Miocene Paunsaugunt thrust fault zone of Lundin and Davis (1987), Lundin (1989), Nickelson and others (1992), Merle and others (1993), and Davis (1999). At the west end of Haycock Mountain near The Pass, the Isom Formation appears undisturbed, including its basal vitrophyre; we infer that the basal slip surface is concealed by talus and colluvium in underlying Brian Head strata.

With our new mapping, we are able to further constrain the emplacement age of the Markagunt gravity slide. At the premature close of the USGS BARCO project in the mid 1990s, disagreement remained as to the age and extent of the Markagunt Megabreccia, as described by Anderson (2001). The resolution of the age and extent of the gravity slide involves, among other issues, the Haycock Mountain Tuff in the type area of the Markagunt Megabreccia, first described in detail by Anderson (1993). Because it is undeformed, he reasoned that the Haycock Mountain Tuff ($^{40}Ar/^{39}Ar$ sanidine age of 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 gravity slide, as did Rowley and others (1994) and Hatfield and others (2010). However, Sable and Maldonado (1997a) interpreted the Haycock Mountain Tuff to be a distal facies of the Leach Canyon Formation and part of the upper plate of the Markagunt gravity slide. Mapping in the Panguitch Lake 7.5′ quadrangle, described below (see description of the Leach Canyon Formation), however, now reconfirms that the 23.8 Ma Leach Canyon Formation and 22.8 Ma Haycock Mountain Tuff are different units of slightly different ages, as first suggested by Anderson (1993). Thus, the interpretation of Anderson (1993, 2001), and of Rowley and others (1994) and Hatfield and others (2010), that the Haycock Mountain Tuff represents a post-Markagunt gravity slide tuff that partly filled a stream channel eroded into the gravity slide appeared eminently reasonable.

However, the 22.75 Ma age of the undeformed Haycock Mountain Tuff is at odds with the fact that the Markagunt gravity slide overlies 22.03 Ma Harmony Hills Tuff. Exposures in Parowan Canyon (sections 14 and 15, T. 35 S., R. 9 W.) were interpreted by Maldonado and Moore (1995) as Harmony Hills Tuff in normal fault contact against autochthonous Isom Formation, but we reinterpret this Isom to be part

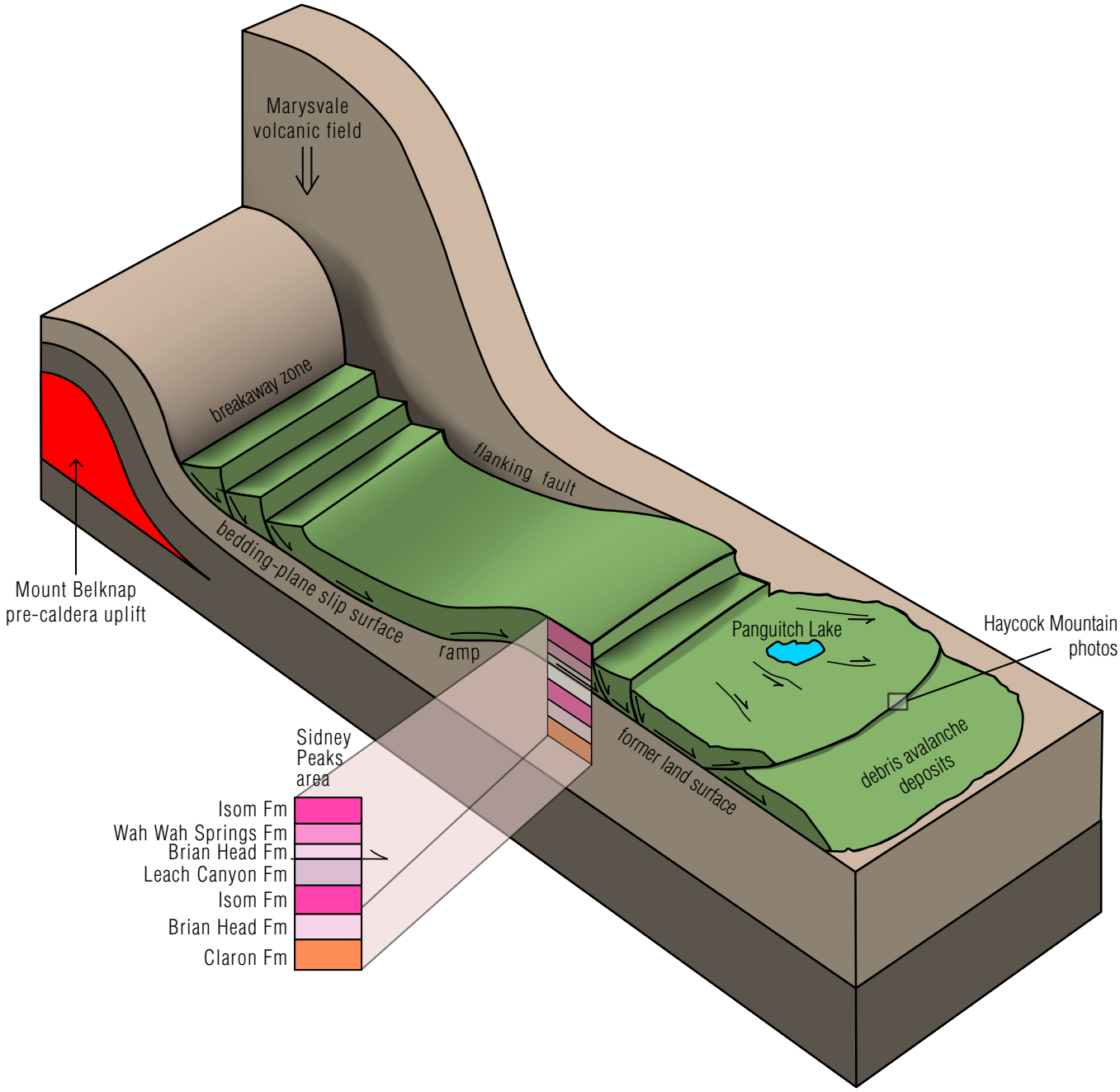

Figure 10. *Block diagram of the idealized Markagunt gravity slide. Note the four main bounding surfaces: the bedding-plane slip surface in mechanically weak clay-rich rocks of the Brian Head Formation; the ramp, where the slide mass breaks upward to the surface; the former land surface, now covered by the medial part and the toe of the slide mass; and the flanking failure, in essence a strike-slip fault that bounds the margin of the slide. The basal slip surface resembles shallow low-angle faults, complete with slickensided and striated surfaces, cataclastic zones, local pseudotachylyte, and brittle microfabrics. Extensional deformation characterizes the upper part of the slide, whereas compressional deformation characterizes the toe area. The main part of the gravity slide, above the bedding plane slip surface, remains mostly intact with individual blocks as much as many square miles in size, preserving a stratigraphy inherited from the source area. At and near the ramp (which strikes roughly east at the latitude of Parowan), upper-plate rocks exhibit intense compressional deformation, with numerous thrust splays creating older on younger structural relationships. Southward, on the former Miocene land surface, upper-plate rocks are commonly pervasively fractured and locally back-tilted into the slide plane, but commonly they too form large, mostly intact blocks many square miles in size. Distal portions of the slide mass disaggregate into debris avalanche deposits. Because gravity is the driver of such large landslides, the dip of the slip surface must be sufficient to overcome the shear strength of the detachment layer. Once moving, however, the slides can travel many miles over former land surfaces. Here, the inferred trigger is pre-caldera inflation of the Mount Belknap area, causing arching of overlying strata and consequent failure on over-steepened slopes.*

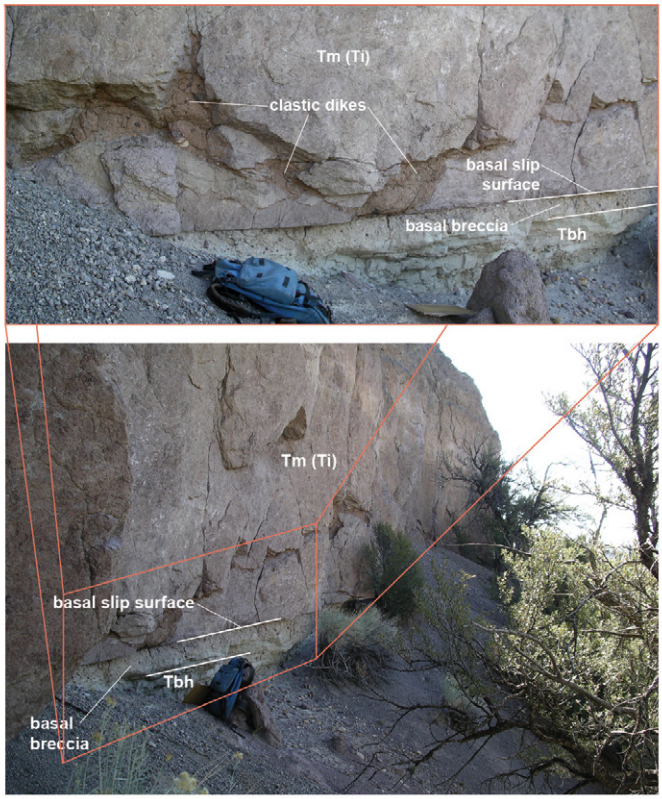

Figure 11. *Base of Markagunt Megabreccia (exposed just south of Haycock Mountain on the southwest side of hill 8652, NW1/4SE1/4 section 5, T. 36 S., R. 6 W.; UTM NAD83 coordinates are Easting 363449, Northing 4174754). Note planar slip surface (strike N. 10° W., dip 6° NE.) and underlying thin basal breccia, which in turn unconformably overlies similarly dipping volcaniclastic pebbly sandstone of the Brian Head Formation (Tbh). Basal breccia 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 breccia is texturally similar to concrete or glacial till and is inferred to have been derived from pulverized Isom and underlying strata immediately above and below the detachment surface. This breccia is injected as dikes into the basal part of the Megabreccia, which here consists of cataclastic Isom Formation (Tm[Ti]). Cataclastic Isom Formation forms a cliff 15 to 30 feet (5–10 m) high and grades abruptly upward into fractured but otherwise undisturbed Isom Formation. Close-up shows clastic dikes injected into base of Megabreccia.*

Figure 12a. *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.; UTM NAD83 coordinates are Easting 361510, Northing 4175032). The basal part of the Megabreccia consists of about 30 feet (10 m) of cataclastic Isom Formation (Tm[Ti]), which grades abruptly upward into fractured but otherwise undisturbed Isom Formation. Basal breccia, in shadow, unconformably overlies Miocene stream gravels (Ta) eroded into the Brian Head Formation. These gravels contain rounded clasts of 2–27 Ma Isom Formation and so are younger than the Isom Formation, thus creating an older-on-younger relationship and showing that the entire Isom caprock of Haycock Mountain is part of the Markagunt gravity slide. Geologists Pete Rowley (right, Geologic Mapping, Inc.), David Hacker, (center, Kent State University), and Tyler Knudsen (UGS) discuss significance of gravels.*

of the Markagunt gravity slide that slid over the Harmony Hills Tuff; this fault is a gently southeast-dipping gravity-slide plane, not a west-dipping normal fault. This interpretation is consistent with similar exposures of the Harmony Hills Tuff in Summit Canyon to the west. The Markagunt gravity slide must thus be younger than about 22 million years old. We resampled the Haycock Mountain Tuff and report a new U-Pb age on zircon of 21.63 ± 0.73 Ma (UGS and AtoZ, 2013). We now interpret the Haycock Mountain Tuff as representing a post-Markagunt gravity slide ash-flow tuff that partly filled a stream channel eroded into the gravity slide.

To summarize, catastrophic emplacement of the Markagunt gravity slide postdates the 22.03 Harmony Hills Tuff. The gravity slide is overlain by undeformed Haycock Mountain Tuff for which we report a new U-Pb age on zircon of about 21.6 Ma. We are currently attempting to date pseudotachylyte, which may yield a more tightly constrained emplacement age. We are also dating a basaltic dike that cuts the gravity slide near Cottonwood Mountain. Currently, we interpret that the gravity slide was emplaced between about 21 and 22 million years ago, near the end of peak calk-alkaline volcanic activity in the Marysvale volcanic field.

The Markagunt Megabreccia was interpreted by Maldonado (1995) and Sable and Maldonado (1997a) to have formed by either gravity sliding off the 20 Ma Iron Peak laccolith and associated large shallow intrusive bodies or by low-angle, thin-skinned thrusting away from the intrusions about 20 to 22 million years ago. Exposures at Haycock Mountain described above, and others described by Biek and others (in preparation), clearly show emplacement by catastrophic gravity sliding, but the trigger for the slide remains elusive. Anderson (2001) noted that the Iron Peak laccolith may be too small to have produced a dome large enough to produce the Markagunt Megabreccia, and so suggested that the Megabreccia originated from southward failure off the backslope of inferred west-northwest-striking Miocene fault blocks.

Even if the Iron Peak laccolith was once much larger—part of a much larger intrusive complex that underlies the Red Hills, northern Parowan Valley, northern Markagunt Plateau,

Figure 12b. *Close-up of clastic Isom Formation shown in figure 11a; Brunton compass for scale.*

Figure 12c. *Close-up of slickenlines exposed at the west side of figure 11a. Slickenlines trend 20° NW and plunge about 15°. The base of the Markagunt Megabreccia forms a planar surface that strikes N. 50° W. and dips 15° NE. Note basal breccia at base of Megabreccia.*

and most of Panguitch valley as suggested by aeromagnetic anomaly and well data (Blank and Crowley, 1990; Blank and others, 1992, 1998; and Rowley and others, 1994)—we now know that Iron Peak is located too far south and west to possibly have been a trigger of the gravity slide. We are attempting to redate the Iron Peak laccolith, but now interpret the laccolith as postdating emplacement of the Markagunt gravity slide. In the past, the Iron Peak laccolith was originally thought to be a prime candidate as the trigger of the Markagunt gravity slide because it was about the correct age and because in this larger intrusive complex, most if not all intrusions are laccoliths (Anderson, 1965; Anderson and Rowley, 1975; Anderson and others, 1990a, 1990b). It was thought that inflation of this larger complex, or several individual laccoliths within it, may have triggered catastrophic emplacement of the gravity slide. Mapping in the Iron Springs mining district and along the Iron Axis west and southwest of Cedar City, where a complex of laccoliths produced many gravity slides similar to but much smaller than the Markagunt gravity slide (Hacker, 1998; Hacker and others, 2002, 2007; Rowley and others, 2008; Knudsen and Biek, 2014), demonstrate laccolith emplacement as a trigger for catastrophic gravity slides.

Based on our new mapping that extends the Markagunt gravity slide north of the Iron Peak laccolith, our preferred trigger is thus farther north and is the subject of ongoing mapping. At present, we suggest that it may be due to pre-caldera inflation of the Mount Belknap area, some 50 miles (80 km) north of Panguitch Lake.

Interestingly, as noted by Sable and Maldonado (1997a) and by Davis (1997a, 1997b), the south margin of the Markagunt Megabreccia is on trend with well documented, east-trending, south-vergent thrust faults, including the Rubys Inn thrust fault, involving Upper Cretaceous strata and the Eocene-Paleocene Claron Formation on the Paunsaugunt Plateau. These thrust faults are interpreted to represent gravitational loading and collapse of the southern part 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 (1997a, 1997b, 1999), the Markagunt Megabreccia is but one structure–an upper-level part–of a second, deeper series of Tertiary thrusts directed outward from the southern Marysvale volcanic field, which spread and collapsed under its own weight, resulting in southward-directed thrust faults rooted in evaporite strata of the Middle Jurassic Carmel Formation. On the Markagunt Plateau, gently northwest-dipping

Claron and Brian Head strata south of Panguitch Lake, and gently north-dipping Isom Formation at Haycock Mountain, may reflect folding in the upper plate of an east-trending, south-vergent, blind thrust fault, the westward continuation of the Rubys Inn thrust fault.

Tm **Markagunt Megabreccia, undivided** – The Markagunt Megabreccia is undivided where exposures are insufficient to delineate bedrock units at the map scale and in more remote areas due to time constraints. 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 volcanic mudflow brecia, volcaniclastic sandstone, and minor pebbly conglomerate of the Bear Valley and Mount Dutton Formations. North of Panguitch Lake, Tm was emplaced on the resistant, planar surface of the Isom Formation, but south of the lake it was emplaced on the Leach Canyon Formation. The Markagunt Megabreccia is as much as 500 feet (150 m) thick in the Haycock Mountain and Panguitch Lake quadrangles.

Tm(Tdbv) **Markagunt Megabreccia, Mount Dutton and Bear Valley components, undivided** – Mapped north of Panguitch Lake where exposures are inadequate to readily differentiate these formations; exceeds 400 feet (120 m) thick.

Tm(Td) **Markagunt Megabreccia, Mount Dutton Formation, alluvial facies component** – Brown or locally reddish-brown volcanic mudflow breccia of mostly andesitic composition, volcaniclastic pebble to boulder conglomerate, and minor tuffaceous sandstone; interpreted to be part of the Markagunt Megabreccia; maximum thickness in the map areas is probably at least 150 feet (45 m).

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 field, and divided it into complexly interfingering and cross-cutting vent and alluvial facies derived from clustered stratovolcanoes and dikes; only those rocks associated with the alluvial facies are present in the map areas, where they are part of the Markagunt Megabreccia.

The Marysvale volcanic field is one of several voluminous calc-alkaline, subduction-related volcanic centers and underlying source batholiths that characterized the western U.S. from Oligocene to Miocene time at this latitude (Lipman and others, 1972; Rowley and Dixon, 2001). Fleck and others (1975) and Rowley and others (1994) reported several K-Ar ages of 23 to 30 Ma on rocks of the coeval vent facies. The alluvial facies is at least 1000 feet (300 m) thick in the northern Markagunt Plateau (Anderson and Rowley, 1987) and is at least 6000 feet (2000 m) thick farther north (Anderson and others, 1990a, 1990b; Rowley and others, 2005). It pinches out radially from individual stratovolcanoes that lie along the southern part of the Marysvale volcanic field.

Tm(Tbvs) **Markagunt Megabreccia, Bear Valley Formation, sandstone component** – White to light-gray, moderately to well sorted, fine- to medium-grained volcaniclastic sandstone having high-angle cross-beds; includes minor similarly colored tuffaceous mudstone and siltstone; typically pervasively deformed along shears and by small folds; sand in the Bear Valley Formation 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 26 Ma Spry intrusion (Anderson, 1971, 2001; Anderson and others, 1990a, 1990b); as much as several hundred feet thick.

Tm(Tbvf) **Markagunt Megabreccia, Bear Valley Formation, lava flow component** – Dark-gray to brownish-gray, mafic to intermediate composition lava flows, commonly with conspicuous pyroxene phenocrysts; includes volcanic mudflow breccia of similar composition; about 40 feet (12 m) thick.

Tm(Tbvt) **Markagunt Megabreccia, Bear Valley Formation, tuff component** – White to pinkish-gray, unwelded, massive rhyolitic ash-flow tuff with small phenocrysts of quartz, feldspar, and biotite, and with common pebble-size lithic fragments of intermediate volcanic rocks and rounded quartzite pebbles; Anderson (1993) reported that the tuff is found over an area of about 150 square miles (375 km^2) in the north-central Markagunt Plateau; locally exceeds 100 feet (30 m) thick.

Rowley and others (1994) reported a K-Ar age on plagioclase of 22.3 ± 1.1 Ma (their sample 89USa2a) for what they then interpreted to be the basal vitrophyre of Haycock Mountain Tuff at the southwest side of Haycock Mountain. However, this sampled tuff appears to be part

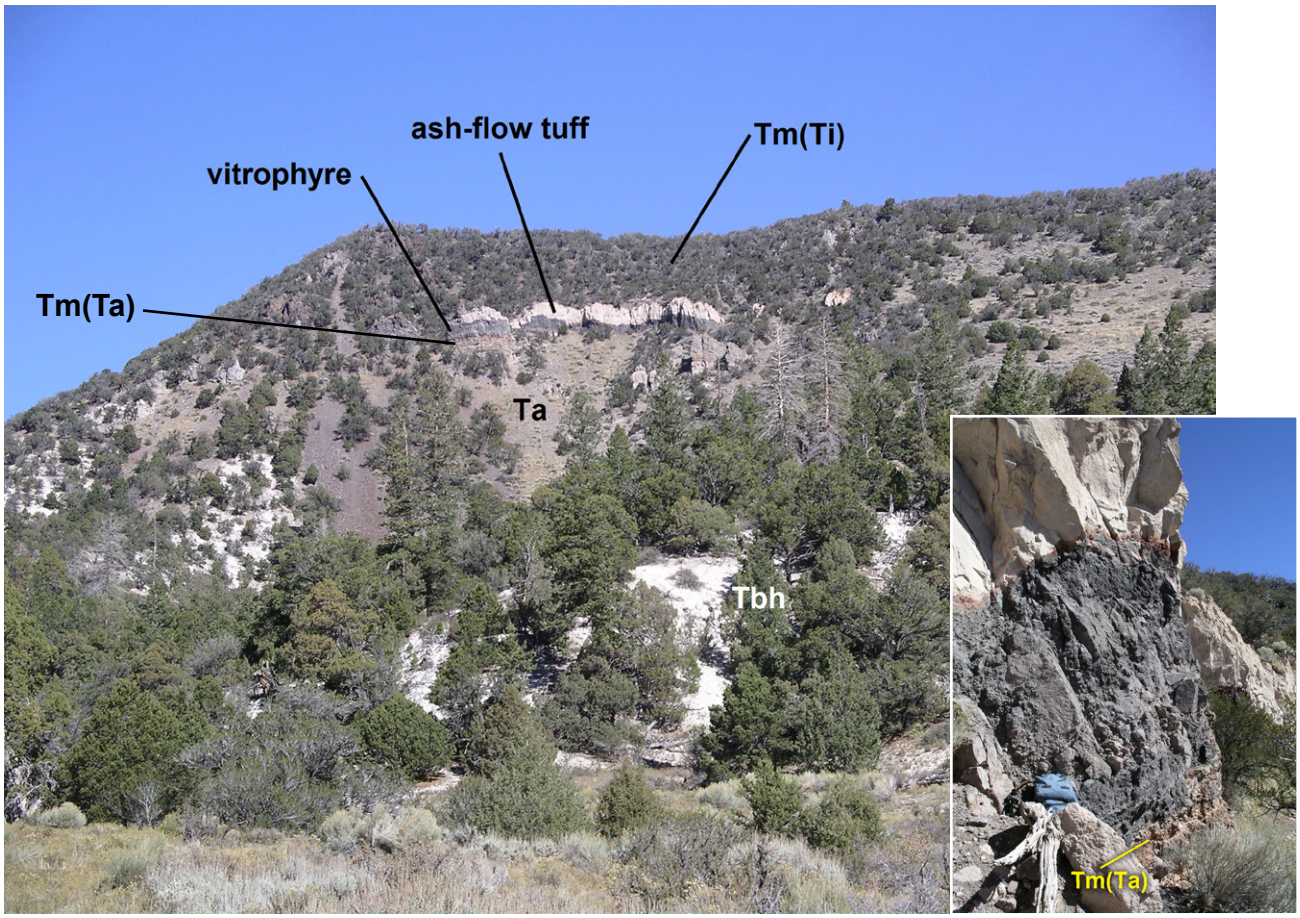

Figure 13. *View northwest to the southwest part of Haycock Mountain. Note light-colored ash-flow tuff and its underlying basal vitrophyre near the top of the mountain, shown in more detail in inset. Volcaniclastic strata of the Brian Head Formation (Tbh) are in the foreground, overlain by several tens of feet of Miocene alluvial gravel (Ta) and Miocene alluvial gravel (Tm[Ta]) that appears to be part of the upper plate of the Markagunt gravity slide; exact location of basal slip surface that separates Ta from Tm(Ta) is uncertain."Caprock" of Haycock Mountain, above the ash-flow tuff, is the Isom Formation as part of the Markagunt gravity slide (Tm[Ti]).*

Inset shows ash-flow tuff and its basal vitrophyre; note underlying reddish-brown conglomerate (Tm[Ta]), which consists of rounded, pebble- to boulder-size clasts of intermediate volcanic rocks and quartzite—importantly, including clasts of Isom Formation. Discontinuous exposures suggest that the gravel is about 100 feet (30 m) thick, its upper part locally sheared and faulted as part of the Markagunt Megabreccia (Tm[Ta]) and its lower part apparently undeformed (Ta). Thus, here, we suggest that the basal slip surface of the Markagunt gravity slide lies within Miocene gravels. The vitrophyre is about 20 feet (6 m) thick and is marked by a thin brick-red devitrified band at its top. It is overlain by a similar thickness of unwelded light-brown ash-flow tuff; chemically, both the unwelded tuff and its vitrophyre are trachydacite. This vitrophyre yielded a K-Ar age on plagioclase of 22.3 ± 1.1 Ma (Rowley and others, 1994; their sample 89USa2a) and an $^{40}Ar/^{39}Ar$ plagioclase age of 24.23 ± 0.17 Ma on the same sample (Sable and Maldonado, 1997a). Rowley (in Hatfield and others, 2010) re-interpreted it to be an older Bear Valley tuff, with which we concur. Its presence again demonstrates that the entire caprock of Haycock Mountain is allochthonous.

of the Markagunt Megabreccia, is chemically a trachydacite (although apparently weathered with a large LOI on analysis), and yielded an $^{40}Ar/^{39}Ar$ plagioclase age of 24.23 ± 0.17 Ma (Sable and Maldonado, 1997a). The upper few inches of the vitrophyre are weathered to a brick-red color, above which is the unwelded, light-brownish-gray tuff, also chemically a trachydacite (figure 13). Rowley (in Hatfield and others, 2010) re-interpreted it to be an older Bear Valley tuff, with which we concur, noting that it too is part of the Markagunt gravity slide.

Tm(Tdm) **Markagunt Megabreccia, Mount Dutton Formation, mafic alluvial facies component** – Dark-gray, vesicular, basaltic andesite and basalt present as angular cobble- to boulder-size blocks floating in a light-gray sandy and muddy matrix of the same composition; monolithic; interpreted to be a volcanic mudflow breccia that is part of the Markagunt gravity slide; a small area of basaltic scoria, possibly a primary rafted block, is present north of Bunker Creek in the NE1/4NE1/4 section 12, T. 36 S., R. 8 W., about 3 miles (5 km) west of

Panguitch Lake; maximum thickness in this map areas is about 80 feet (24 m).

Mapped west of Panguitch Lake, where it apparently structurally overlies 23.8 Ma Leach Canyon Formation (Tql), and north of the lake, where it was emplaced over the Isom Formation that is part of the Megabreccia (Tm[Ti]). 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.

Tm(Ta) **Markagunt Megabreccia, middle Tertiary alluvium component –** Volcaniclastic conglomerate and pebbly sandstone on Haycock Mountain and areas to the north in the Fivemile Ridge quadrangle; 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; mostly overlies the Isom Formation component [Tm(Ti)], but also underlies upper plate Isom on the south side of Haycock Mountain; maximum thickness in this area is probably about 100 feet (30 m).

Anderson (1993) suggested that this alluvium postdated emplacement and tilting of the gravity slide and that remnant alluvium at Haycock Mountain, some as much as 800 feet (250 m) above Panguitch Creek, is simply what remained after exhumation of the ancestral Panguitch Creek drainage. However, new mapping now suggests that there are multiple intervals of Miocene gravels that both predate (Ta) and postdate (Thma) the gravity slide. Importantly, the gravels atop Haycock Mountain are tilted northward, concordantly with underlying Isom Formation, and we thus interpret them to have ridden largely undisturbed on the Isom during emplacement of the gravity slide. Thus we now envision these gravels as a relatively thin sheet that blanketed the landscape prior to emplacement of the Megabreccia, not as the exhumed remains of post-gravity slide basin fill.

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 rare quartz set in a devitrified glassy groundmass; most outcrops and blocks weather to grussy soils and rounded hills; except locally along the south edge of Haycock Mountain, rarely forms cliffs as is typical of the autochthonous Isom Formation; maximum thickness about 400 feet (120 m).

Although generally poorly exposed, Isom constitutes the great bulk of the Megabreccia along its southern margin. This map unit locally includes areas of Brian Head Formation, Wah Wah Springs Formation, and volcanic mudflow breccia that are difficult to delineate given extensive forest cover and inconspicuous outcrop habit. It generally has slid over the Leach Canyon Formation west of Panguitch Lake, over Isom Formation north of Panguitch Lake, and over thin lower Miocene conglomerate that unconformably overlies the Brian Head Formation on the south flank of Haycock Mountain.

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; the abundance of hornblende over biotite is unique among Great Basin ash-flow tuffs; elongate collapsed pumice is common; mapped at the northwest edge of Castle Valley, where it rests on displaced Brian Head strata [Tm(Tbh)], and in the upper reaches of Bunker Creek, where it rests on displaced volcanic mudflow breccia (Tm[Tdm]); about 40 feet (12 m) thick.

Erupted from the Indian Peak caldera of the 27 to 32 Ma Indian Peak caldera complex that straddles the Utah-Nevada border (Best and others, 1989a, 1989b). Today, the 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). The age of the Wah Wah Springs Formation is about 30 Ma based on many K-Ar and $^{40}Ar/^{39}Ar$ age determinations (Best and Grant, 1987; Best and others, 1989a, 1989b; Rowley and others, 1994).

Tm(Tbh) **Markagunt Megabreccia, Brian Head Formation component** – Poorly exposed, but distinctive white to light-gray volcaniclastic mudstone, pebbly sandstone, micritic limestone, and chalcedony are present in colluvium, thus betraying the formation's presence northwest of Castle Valley where it rests out-of-sequence on autochthonous Leach Canyon Formation; at the west edge of the Panguitch Lake quadrangle, 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 is well exposed at the head of a small landslide, dips 27° 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; we thus infer a small thrust fault in the upper plate separating these two dip domains; thickness uncertain, but outcrop patterns suggest that displaced Brian Head strata west of Panguitch Lake likely exceeds 100 feet (30 m) thick.

Unit on the southeast side of Haycock Mountain is characterized by white and light-gray, locally tuffaceous, volcaniclastic sandstone, pebbly sandstone, mudstone, minor tuffaceous limestone, and local multi-hued chalcedony that are faulted and folded, indicative of deformation as part of the Markagunt Megabreccia (alternatively, deformation may be due to south-vergent thrust faulting associated with the westward extension of the Rubys Inn thrust); exposed thickness at Haycock Mountain as much as 150 feet (45 m).

Ta **Miocene alluvium** (lower Miocene) – Moderately sorted, moderately consolidated, pebble to boulder gravel mapped on the south side of Haycock Mountain; contains well rounded volcanic clasts and lesser quartzite and Claron Formation limestone clasts; importantly, also contains clasts derived from the 27 to 26 Ma Isom Formation and so unit is at least as young as 26–27 Ma; regardless, the Markagunt gravity slide is emplaced onto the map unit at Haycock Mountain; maximum exposed thickness about 80 feet (25 m).

Tlbh **Limerock Canyon and Brian Head Formations, undivided** (lower Miocene and lower Oligocene to middle Eocene) – Sable and Maldonado (1997b) and Biek and others (2012) described the difficulty of differentiating similar volcaniclastic strata of the Limerock Canyon, Bear Valley, and Brian Head Formations. We remain uncertain how to distinguish apparently similar strata of the Brian Head and Limerock Canyon Formations at Hatch Mountain in the southeast part of the Haycock Mountain quadrangle. Limerock Canyon strata are described separately below, based principally on better exposures in the adjacent Hatch quadrangle, and Brian Head strata are also described separately.

Limerock Canyon Formation (lower Miocene) – White, light-gray, and pale- to olive-green, tuffaceous, volcaniclastic sandstone, pebbly sandstone, gritstone, pebbly conglomerate, mudstone, and minor tuffaceous limestone; commonly bioturbated; includes at least 10 thin beds of ash-fall tuff; 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 apparent 27- to 26-Ma Isom clasts are indeed abundant and many of the mafic volcanic clasts that they reported could be derived from the Mount Dutton Formation; conglomerate, however, forms lenticular beds and is not present in all sections, making differentiation of Brian Head and Limerock Canyon strata problematic; unconformably overlain by unconsolidated upper Tertiary fan alluvium (Taf); as much as 290 feet (88 m) thick in a composite type section west of Hatch, immediately east of the Haycock Mountain quadrangle (Kurlich, 1990; Kurlich and Anderson, 1997).

The Limerock Canyon Formation was deposited in fluvial, floodplain, and minor lacustrine environments (Kurlich and Anderson, 1997). It is present only on the east part of the Markagunt Plateau near Hatch, south of the Markagunt Megabreccia, where it appears to be eroded into the Brian Head Formation. We suggest that it is preserved in a subtle basin in front of an inferred blind west-trending thrust fault, the inferred westward continuation of the Rubys Inn thrust fault. 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 of 20.2 ± 1.4 Ma (biotite) and 19.8 ± 0.8 Ma (sanidine) (Sable and Maldonado, 1997b); Sable and Maldonado (1997b) also reported $^{40}Ar/^{39}Ar$ ages of 20.48 ± 0.8 Ma (biotite) and 21.0 ± 1.0 Ma (sanidine), and we obtained a U-Pb age on zircon from an air-fall tuff near the middle of the formation of 20.52 ± 0.49 Ma (UGS and AtoZ, 2013).

Quichapa Group (lower Miocene to upper Oligocene) – Consists of three regionally 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). Only the Leach Canyon Formation is present in the Panguitch Lake quadrangle.

Tql **Leach Canyon Formation** (upper Oligocene) – Grayish-orange-pink, pinkish-gray, and white, poorly 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 red-

dish brown; contains 25 to 35% phenocrysts of plagioclase, slightly less but subequal amounts of quartz and sanidine, and minor biotite, hornblende, Fe-Ti oxides, and a trace of pyroxene; 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 Panguitch Lake quadrangle, but is locally missing over inferred paleotopographic high areas.

West of Panguitch Lake, the Leach Canyon Formation unconformably overlies the Brian Head Formation or, locally, stream gravel too thin to map that contains clasts of Isom Formation (for example, on the southeast side of Prince Mountain at sample location PL061708-3). A nonresistant, moderate-orange-pink ash-fall tuff identical to that at Brian Head peak (Rowley and others, 2013) is present at the base of the unit on the southeast side of Prince Mountain.

The Leach Canyon Formation and the Haycock Mountain Tuff are petrographically and chemically similar, which led Sable and Maldonado (1997a) to suggest that the latter is a distal facies of Leach Canyon. While it is true that the two formations are not reliably distinguishable based on their major- and trace-element chemistry, 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, facts previously noted by Anderson (1993), Rowley and others (1994), and Hatfield and others (2010). Our mapping of the Panguitch Lake and Haycock Mountain quadrangles reconfirms that these are indeed two different units (see also Biek and others, 2012). 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, 1994, sample 89USa-1a, which they mistakenly called Haycock Mountain Tuff) 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 thus widely agreed to be about 23.8 Ma (Best and others, 1993; Rowley and others, 1995). As noted by Hatfield and others (2010), both Rowley and others (1994) and Sable and Maldonado (1997a) misinterpreted 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; see also Hatfield and others, 2010). The facts that the tuff at Prince Mountain yielded an age analytically indistinguishable from the Leach Canyon Formation, and that it can be traced continuously to classic Leach Canyon outcrops at Brian Head peak, 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 the west edge of the Markagunt Plateau (Rowley and others, 2013). 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. Except for outcrops in Bear Valley north of Utah Highway 20, Leach Canyon is not present on the Markagunt Plateau north of Clear Creek, a west- northwest-trending tributary to Panguitch Lake.

Ti **Isom Formation** (upper Oligocene) – Medium-gray, crystal-poor, densely welded, trachydacitic ash-flow tuff, typically having distinctive rheomorphic features including flow folds, elongated vesicles, and flow breccias and thus commonly known as a tufflava (Mackin, 1960; Cook, 1965, 1966; Anderson and Rowley, 1975, 2002); 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; fracture surfaces and elongated vesicles (lenticules, described below) are locally dark reddish brown to dusky red; forms prominent cliffs north of Clear Creek and Panguitch Lake; query indicates uncertain correlation in the upper reaches of the Clear Creek drainage northwest of Panguitch Lake; the Isom Formation is about 27 to 26 Ma on the basis of many $^{40}Ar/^{39}Ar$ and K-Ar ages (Best and others, 1989b; Rowley and others, 1994), and because it is locally interbedded with the 26 Ma Buckskin Breccia (Anderson and others, 1987); maximum exposed thickness is about 350 feet (110 m) at Black Ledge and about 250 feet (75 m) along Ipson Creek, but it is locally absent over inferred paleotopographic high areas west of Panguitch Lake.

Because of its secondary flow characteristics 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 in its basal vitrophyre, thus showing its true ash-flow tuff nature. Such an ash-flow tuff is also called a tufflava or rheomorphic ignimbrite, one that was sufficiently hot to move with laminar flow as a coherent ductile mass–see, for example, Cook (1966), Anderson and Rowley (1975, 2002), Ekren and others (1984), Andrews and Branney (2005), and Geissman and others (2010). It exhibits pronounced subhorizontal lamination or platiness, which Mackin (1960) called "lenticules." Fryman (1986, 1987), Anderson and others (1990c), and Anderson and Rowley (2002) also described the light-gray, pancake-shaped lenticules, which are typically spaced 4 to 8 inches (10–20 cm) apart and 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 of the Isom is unknown, but isopach maps and pumice distribution suggest that it 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 to the west, 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, 1993b) described nine apparent cooling units in the northern Red Hills northwest of Parowan. 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, 1994).

unconformity

Brian Head Formation (lower Oligocene to middle Eocene) – The Brian Head Formation is the oldest widespread Tertiary volcaniclastic unit in the region. On the Markagunt Plateau, it disconformably overlies the uppermost mudstone, siltstone, and sandstone interval (Tcwt) of the white member of the Claron Formation (Biek and others, 2012). Sable and Maldonado (1997b) designated a type section at Brian Head peak, just west of the Panguitch Lake quadrangle, and 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 in the northern Markagunt Plateau but not at the type section, characterized by volcanic mudflow breccia, mafic lava flows, volcaniclastic sandstone and conglomerate, and ash-flow tuff. Following Biek and others (2012), we include their basal nontuffaceous sandstone and conglomerate as a new uppermost part of the Claron Formation (Tcwt), thus further restricting the Brian Head Formation to a widespread volcaniclastic unit (Tbh) and a local volcanic unit present only in the northern Markagunt Plateau. In the Panguitch Lake quadrangle, Brian Head strata are unconformably overlain by the 27 to 26 Ma Isom Formation (Ti) or the 23.8 Ma Leach Canyon Formation. Regionally, Brian Head strata overlie the 38 Ma conglomerate at Boat Mesa, but that relatively thin, distinctive, pebbly conglomerate (which lacks volcanic clasts) is apparently missing in the Haycock Mountain and Panguitch Lake quadrangles.

Davis and others (2009) reported U-Pb (SHRIMP-RG) ages of 35.2 ± 0.8 Ma and 34.7 ± 0.6 Ma from the Brian Head Formation at Brian Head peak. Biek and others (2012) obtained U-Pb ages on zircon from air-fall tuffs at the base of the formation at Cedar Breaks National Monument of 35.77 ± 0.28 Ma, from about 80 feet (25 m) above the base of the formation on the southwest flank of the Sevier Plateau of 36.51 ± 1.69 Ma, and from the upper part of the formation near Haycock Mountain of 34.95 ± 0.83 Ma and 33.55 ± 0.80 Ma; the two Haycock Mountain samples also yielded $^{40}Ar/^{39}Ar$ ages on sanidine of 35.04 ± 0.23 Ma and 33.80 ± 0.05 Ma (UGS and NIGL, 2013). 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 near the top of the formation. Eaton and others (1999) and Korth and Eaton (2004) reported on Duchesnean (middle Eocene) vertebrate fossils in the lower Brian Head Formation on the Sevier Plateau. The Brian Head Formation is thus early Oligocene to latest middle Eocene. Golder and Wizevich (2009) and Golder and others (2009) described trace fossils, including possible crayfish burrows and root traces, in the Brian Head Formation on the Sevier Plateau.

Tbh **Middle volcaniclastic unit** – White to light-gray volcaniclastic mudstone, siltstone, silty sandstone, sandstone, conglomerate, volcanic ash, micritic limestone, and multi-hued chalcedony; 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, and is locally stained by manganese oxides; chalcedony beds probably reflect silicification of limestone beds (Maldonado, 1995; Sable and Maldonado, 1997b; Schinkel, 2012) as silica is leached from the glass shards in volcanic ash beds; Bakewell (2001) suggested that the chalcedony may have resulted from silicification of the tuff beds themselves; chalcedony is almost always highly fractured, but some is useful for lapidary purposes (Strong, 1984); we mapped a particulary prominent chalcedony bed as a marker bed in the Haycock and Hatch Mountain areas; map unit is about 500 feet (150 m) thick at Brian Head peak, just west of the Panguitch Lake quadrangle.

The Brian Head Formation is typically nonresistant, poorly exposed, and extensively covered by colluvium. Because of abundant smectitic clay derived from weathered volcanic ash, this unit weathers to strongly swelling soils (unlike the underlying Claron Formation) and forms large landslide complexes; it was the principal detachment surface for the Markagunt Megabreccia. The Brian Head Formation was deposited in low-relief fluvial, floodplain, and lacustrine environments in which large amounts of volcanic ash accumulated (Sable and Maldonado, 1997b).

unconformity

Claron Formation (Eocene to Paleocene) – Claron Formation strata are among the most visually arresting rocks in southwestern Utah, but because the formation lacks a type section and was named for incomplete, fault-bounded exposures in the Iron Springs mining district, the nomenclatural history of these rocks is complicated. Mackin (1947) first applied the name Claron Formation to strata of the Markagunt Plateau, noting the similarity with rocks in the Iron Springs mining district to which Leith and Harder (1908) first applied the name. Bowers (1972) subdivided the Claron Formation into three informal members on the Table Cliff Plateau (northeast of Tropic, Utah): ascending, the lower pink, white limestone, and variegated sandstone members. We suspect that Bowers' variegated member is a thicker equivalent to what Biek and others (2012) mapped as the conglomerate at Boat Mesa and overlying non-volcaniclastic Brian Head strata on the south flank of the Sevier Plateau. Anderson and Rowley (1975) provide the best review of this nomenclatural history, although since then, additional mapping and stratigraphic work has enabled the upper part of their Claron Formation to be split off as the conglomerate at Boat Mesa and the Brian Head Formation. Anderson and Rowley (1975) considered the formation to have two informal members, a lower red member and an upper white member, but, based on precedence and a long informal usage of the term "pink" when referring to the uppermost part of the Grand Staircase and its strata, we retain Bowers' informal name pink member for the lower Claron. We further subdivide the white member and restrict it to nonvolcaniclastic strata unconformably overlain by the conglomerate at Boat Mesa, or, where that unit is missing, the Brian Head Formation, and note that the pink member has long been known informally as the red member on the Markagunt Plateau.

We thus map the Claron Formation as two members made up of five informal lithostratigraphic units described below: the upper white member (which is divided into an uppermost mudstone unit, an upper limestone unit, a middle mudstone and sandstone unit, and a lower limestone unit) and the lower pink member.

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; the pink member is almost wholly fluviatile and the white member is both lacustrine and fluviatile (Goldstrand, 1990, 1991, 1992, 1994; Bown and others, 1997). Ott (1999) recognized a 130-foot-thick (40 m) interval of mostly medium-bedded bioclastic limestone and thin-bedded micritic limestone with gastropods, ostracods, charophytes, and algal filaments in the lower part of the pink member in Bryce Canyon National Park; this lacustrine interval does not appear to be present in western exposures on the Markagunt Plateau, suggesting that lacustrine strata are better developed in the central part of the basin. Much of the pink 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, 1988b; Mullett, 1989; Mullett and Wells, 1990; see also Bown and oth-

ers, 1997). Ott (1999) reported cyclicity within the Claron Formation at Bryce Canyon National Park, with multiple regressive cycles, each with increasing pedogenesis toward their tops, stacked one upon the other. Bown and others (1995a, 1995b, 1997) reported on trace fossils of ants, wasps, and bees in the upper part of the pink member and lower part of the white member, recording nest activity during paleosol formation. Hasiotis and Bown (1997) reported on crayfish burrows in Claron strata of the Markagunt Plateau that record relatively deep and highly fluctuating water tables in the pink member, and relatively shallow water tables in alluvial parts of the white member. Davis and others (2009) used isotopic and elemental records preserved in authigenic calcite from samples in the Claron, Flagstaff, and Uinta lake basins to better understand Paleogene landscape evolution of Utah, showing an along-strike migration of a high-elevation landscape from north to south over time and, in southwest Utah, a transition from a closed to open basin beginning with deposition of the white member; Ott (1999) also showed that the pink member was deposited in a hydrologically closed basin. Detrital zircon studies of the Claron Formation from the Escalante Mountains show that the formation there was largely derived from erosion of lower Paleozoic sandstones exposed in surrounding Laramide uplifts (Link and others, 2007; Larsen and others, 2010). 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.

On the Paunsaugunt Plateau, south-vergent thrust faults place Upper Cretaceous strata on the pink member of the Claron Formation. Davis (1990, 1991, 1997b, 1999; see also Biek and others, 2012) described this interesting story of the rediscovery of faults originally identified by Chevron Corporation geologists 30 years earlier. These thrust faults are part of the Rubys Inn thrust fault zone, which forms an arcuate belt around the southeast margin of the Marysvale volcanic field. Following the "two-tiered" model of Davis (1997a, 1997b, 1999; see also Nickelsen and others, 1992, Davis and Rowley, 1993, and Merle and others, 1993), we envision the thrusts as directed outward from the Marysvale volcanic field, which spread and collapsed under its own weight, resulting in southward-directed thrust faults rooted in evaporite strata of the Middle Jurassic Carmel Formation. Biek and others (2012) reported that the age of thrust faulting can only be definitively constrained as postdating the 37 to 31 Ma Brian Head Formation and predating basin-fill deposits of poorly constrained Miocene age. If gravitational loading by the Marysvale volcanic pile caused the thrusting as we suspect, then it is reasonable to conclude the faults were coincident with late-phase development of the approximately 30 to 20 Ma volcanic center.

On the Markagunt Plateau, we find no evidence of large-scale older-on-younger relationships (disregarding the Markagunt Megabreccia) indicative of thrust faulting. However, along trend with the Rubys Inn thrust fault, tilted Claron and Brian Head strata near Panguitch Lake, and tilted Isom Formation at Haycock Mountain, suggest having been folded above a blind thrust that, at Haycock Mountain, ramped up and soled into the Brian Head Formation; a deeper thrust would be required to fold Claron and Brian Head strata near Panguitch Lake. The 21 to 20 Ma Limerock Canyon Formation, present only at Hatch Mountain and nearby areas to the south, may be preserved in a subtle basin south of this inferred blind thrust, implying that thrust faulting took place near the end of major calc-alkaline volcanic activity in the southern part of the Marysvale volcanic field. Alternatively, the folding may reflect the location of these strata on the southeast limb of a poorly expressed syncline that clearly folds the Pliocene(?) Fivemile Ridge lava flow northeast of Panguitch Lake, a fold possibly related to an inferred segment boundary on the Sevier fault zone (Biek and others, 2012).

The age of the white member is well constrained as late middle Eocene (Duchesnean Land Mammal Age) based on sparse vertebrate fossils from this unit on the eastern Markagunt Plateau (Eaton and others, 2011); by limiting ages of 35.77 ± 0.28 Ma and 36.51 ± 1.69 Ma for overlying basal Brian Head Formation on the Markagunt and Sevier Plateaus, respectively (Biek and others, 2012); and by a U-Pb detrital zircon age of 37.97 +1.78–2.70 Ma from the conglomerate at Boat Mesa on the southwestern Sevier Plateau (Biek and others, 2012). Middle Eocene vertebrate fossils and charophytes are also known in basal Brian Head strata on the southwestern Sevier Plateau (Eaton and others, 1999; Feist and others, 1997).

The maximum age of the mostly nonfossilferous pink member, however, is poorly constrained as Eocene to Paleocene(?) (Goldstrand, 1994). Goldstrand (1990) reported unspecified late Paleocene palynomorphs from lower Claron strata on the east side of the Pine Valley Mountains, and noted the Paleocene to Eocene gastropods *Viviparus trochiformis*, *Physa* sp., and *Goniobasis* sp. from the pink member. Goldstrand (1992, 1994) suggested that the pink member may be time transgressive,

being older in western exposures and possibly no older than middle Eocene on the Table Cliff Plateau. This idea, however, was based on fission-track analysis of a single sample from the underlying Pine Hollow Formation, which we consider suspect. For one, such a young age seems at odds with the time required to accummulate such a thick stack of mature paleosols. Larsen and others (2010) suggested a late Paleocene to early Eocene age for the underlying Pine Hollow Formation on the Table Cliff Plateau, although they noted a complete lack of fossils, datable ash layers, or age-constraining detrital zircons on which to support that assumption. Bowers (1972) also noted a complete lack of datable materials in the Pine Hollow, and although he preferred a Paleocene(?) age for the formation, he correctly noted that a latest Cretaceous age cannot be ruled out, as did Anderson and Rowley (1975) and Rowley and others (1979). Given our current understanding of the lower Claron Formation and its paucity of datable materials, we consider it possible that basal beds of the pink member are latest Cretaceous in age. Anderson and Dinter (2010) showed that lower Claron strata are cut by and gently folded above a large, east-vergent, Sevier-age thrust fault near Parowan Gap, showing that the last stages of thrust faulting in southwest Utah continued into lower Claron time. Biek and others (2012, in preparation) also showed that significant Sevier-age compressional deformation is present east of the "frontal" Iron Springs thrust fault as evidenced by two faults at the west edge of the Markagunt Plateau that reveal an earlier history of thrust displacement, and by the Paunsaugunt fault, which exhibits an earlier history of pre-Claron, east-directed movement. Previously, Claron and underlying Grand Castle strata were thought to postdate Sevier thrust faulting in southwest Utah.

Tcw **White member, undivided** (Eocene) – Lithologies are described below for individual units. Used for areas south and east of Blue Spring Mountain where incomplete and isolated exposures preclude subdivision; also used on cross sections.

In aggregate, the white member maintains a relatively uniform thickness of about 350 to 450 feet (105–135 m) on the Markagunt Plateau. However, the member thickens to the east where it is dominated by white micritic limestone and is about 550 feet (170 m) thick on the Table Cliff Plateau (Bowers, 1973). The entire white member is about 340 feet (100 m) thick in Rock Canyon southeast of Panguitch Lake. Hatfield and others (2010) reported that it is 360 feet (110 m) thick at Cedar Breaks National Monument, but when the lower sandstone and conglomerate unit of Sable and Maldonado (1997b) is included as part of the white member the thickness is 440 feet (135 m). Moore and others (1994) reported significant facies changes in the white member near Asay Bench (south of the Haycock Mountain quadrangle), but there, in aggregate, it is 448 feet (137 m) thick.

Tcwt **Uppermost mudstone, siltstone, and sandstone unit of white member** (upper and middle Eocene) – Varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, dark-yellowish-orange, and grayish-pink 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 pink members (Tcp) of the Claron Formation; forms a brightly colored slope at the top of the upper white member of the Claron Formation immediately south of Panguitch Lake and in the upper reaches of Rock Canyon where it is about 50 feet (15 m) thick, but this unit appears to be missing across the southern part of the quadrangles.

Tcwu **Upper limestone unit 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.

The upper limestone unit of the white member thickens irregularly to the east and ranges from about 30 to 180 feet (10–55 m) thick on the Markagunt Plateau, but some of this variation may be due to difficulties in placing the locally gradational contacts (Biek and others, 2012). The unit is 45 to 60 feet (14–18 m) thick at Cedar Breaks (Schneider, 1967; Moore and others, 2004; Rowley and others, 2013).

It is about 80 to 100 feet (24–30 m) thick in Black Rock Valley south-southeast of Panguitch Lake, 80 to 165 feet (24–50 m) thick southwest of Hatch in the Asay Bench quadrangle (Moore and others, 1994), and about 150 to 180 feet (45–55 m) thick near Houston Mountain north-northeast of Navajo Lake (Biek and others, 2011).

Tcwm **Middle mudstone, siltstone, and sandstone unit of white member** (upper middle 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 rare 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.

Eaton and others (2011) reported the first sparse late middle Eocene (Duchesnean Land Mammal Age) vertebrate fossils and ostracods of *Cypris* sp. from this unit on the eastern Markagunt Plateau. The unit is 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 (1.6 km) to the east. At Cedar Breaks National Monument, Rowley and others (2013) reported that this interval is 310 feet (94 m) thick. 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 southwest of Hatch.

Tcwl **Lower limestone unit 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 pink member (Tcp); 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.

The lower limestone unit is about 100 to 120 feet (30–35 m) thick in the upper reaches of Rock Canyon, southeast of Panguitch Lake. 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 adjacent Asay Bench quadrangle to the south. This unit is 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, 2013).

Tcp **Pink member** (Eocene and Paleocene) – Alternating beds of varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, dark-yellowish-orange, and grayish-pink sandy and micritic limestone, calcite-cemented sandstone, calcareous mudstone, and minor pebbly conglomerate that weather to colluvium-covered ledgy 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 are calcic paleosols (Mullett and others, 1988a, 1988b; 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 and that locally contain 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 typically 5 to 15 feet (2–5 m) thick containing rounded quartzite, limestone, and chert pebbles, cobbles, and, locally, small boulders, but conglomerate is uncommon on the Markagunt Plateau south of Parowan Canyon (Biek and others, 2012). Upper, conformable contact corresponds to a pronounced color and lithologic change from brightly colored reddish-orange mudstone and siltstone below to white to very pale orange micritic limestone above.

Sinkholes are common in the pink member in the central Markagunt Plateau (Moore and others, 2004; Biek and others, 2011; Hatfield and others, 2010; Rowley and others, 2013). 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, 2010).

The pink member is mostly nonfossiliferous and its age is poorly constrained as Eocene to Paleocene(?) (Goldstrand, 1994) as described above. An incomplete section of the member is about 600 feet (180 m) thick in the Haycock Mountain and Panguitch Lake quadrangles. A complete section of the pink member is about 1000 feet (300 m) thick at Cedar Breaks National Monument (Biek and others, 2012), similar to the measured thickness of Schneider (1967), who reported that the pink member there was 993 feet (303 m) thick (the lower 56 feet [17 m] of his section includes beds we assign to Km, thus the pink member there is 937 feet [286 m] thick), but considerably less than the 1300 feet (400 m) reported in Sable and Maldonado (1997b).

CRETACEOUS

Challenges of correlating Upper Cretaceous strata

Although not exposed in the Haycock Mountain or Panguitch Lake quadrangles, Upper Cretaceous strata undergo significant west-to-east and north-to-south facies changes on the Markagunt and Paunsaugunt Plateaus, thus presenting significant challenges to correlation and mapping, as described by Tilton (1991), Eaton and others (2001), Moore and Straub (2001), Moore and others (2004), Biek and others (2012), and Rowley and others (2013). The lower part of this Upper Cretaceous section consists 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 (see, for example, McGookey, 1972; Kauffman, 1984). This package of rock is overlain by Upper Cretaceous river and floodplain strata of the Straight Cliffs and Wahweap Formations, the upper conglomerate member of the redefined and restricted Grand Castle Formation, and as much as about 200 feet (60 m) of Upper Cretaceous strata of unknown correlation (Biek and others, 2012). Biek and others (2012) showed that mapping coarse alluvial strata associated with major sequence boundaries has been the key to working out these lithostratigraphic correlations.

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