GEOLOGIC MAP OF THE BRIAN HEAD QUADRANGLE, IRON COUNTY, UTAH

by Peter D. Rowley, Robert F. Biek, Edward G. Sable,
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UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
in cooperation with the U.S. Geological Survey
and the National Park Service
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Cover photo: *View southwest to the Hancock Peak cinder cone, vent area of the middle to early Pleistocene Hancock Peak lava flows.*

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INTRODUCTION

Brian Head, at an elevation of 11,307 feet (3446 m), is the highest mountain in southwestern Utah and surmounts the highest part of the west-facing range front of the Markagunt Plateau. The peak (figure 1) is the center point of an area of great natural beauty and of recreational uses of many types. Cedar Breaks National Monument (figure 2) is about 1 mile (1.6 km) to the south, Ashdown Gorge Wilderness Area is about 1.5 miles (3 km) to the west-southwest, Brian Head Resort is on the northwestern flank of the peak, and the resort town of Brian Head is about 1 mile (1.6 km) to the northwest. Campgrounds at Yankee Meadows Reservoir, Panguitch Lake, and Navajo Lake are respectively 5.5 miles (9 km) to the north-northeast, 10 miles (16 km) to the east-northeast, and 11 miles (18 km) to the south-southeast. Most of the map area is within Dixie National Forest, and hiking, horseback-riding, and bicycling trails abound. As abundant as the scenic qualities are, the geologic qualities are no less as significant: the Brian Head quadrangle contains an extraordinary variety of spectacular geologic features, as described below.

The Markagunt Plateau lies in the High Plateaus subprovince of the Colorado Plateau, a physiographic and structural transition zone between the stable, main part of

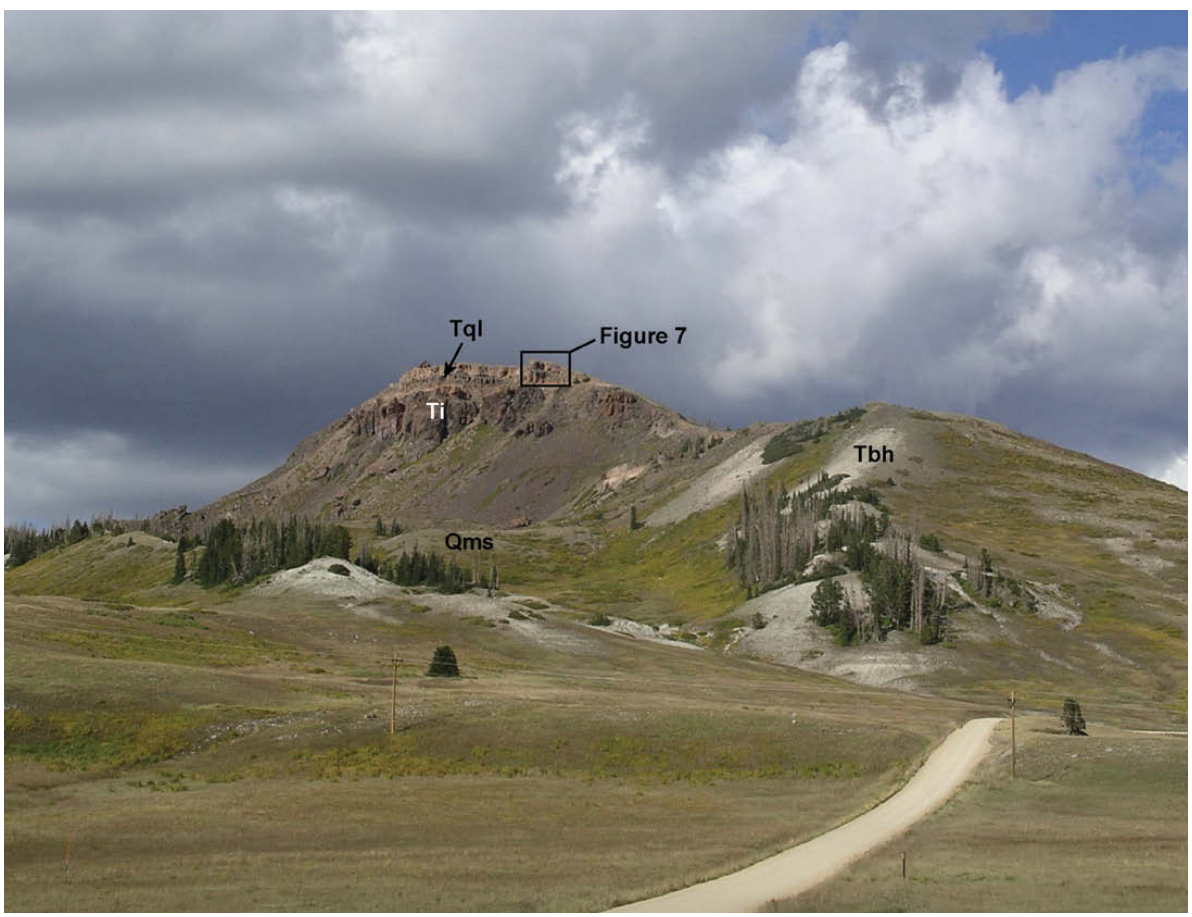

***Figure 1**. View north-northeast to Brian Head peak. The type section of the Brian Head Formation (Tbh) is on the ridge just right of center. Brian Head peak is capped by the Leach Canyon Formation (Tql; see also figure 7), which overlies the Isom Formation (Ti). A large landslide complex (Qms) is west and south of the peak.*

the Colorado Plateau province to the east and the heavily faulted Great Basin subprovince of the Basin and Range Province to the west (Fenneman, 1931; Anderson and Rowley, 1975). The western scarp of the Markagunt Plateau is called the Hurricane Cliffs. In the Cedar City area, about 10 miles (16 km) west of the map area, the boundary between the Colorado Plateau and the Great Basin is the north-trending Hurricane fault zone, which passes through the eastern edge of Cedar City, at the base of the Hurricane Cliffs. The Markagunt Plateau has been partly uplifted relative to the topographically and structurally lower Great Basin along the Hurricane fault zone (Lund and others, 2007). About 5 miles (8 km) north of Cedar City, the Hurricane fault zone continues north but the Hurricane Cliffs veer northeast away from the fault zone to and beyond Parowan, Utah, 5 miles (8 km) north of the map area and similarly on the Colorado Plateau–Great Basin boundary. Where the Hurricane Cliffs trend northeast, they are uplifted along an array of en echelon, north-northeast-trending faults, including the Parowan-Paragonah fault zone (Biek and others, 2012).

From the top of Brian Head, views to the west show the Great Basin to be characterized by alternating, mostly north-trending basins (valleys) and ranges. As in the High Plateaus, these basins and ranges were formed by mostly northerly-trending basin-range faults, known as normal faults, along which relative movement on either side of the fault is mostly vertical. Many faults have large displacements, and rocks are locally tilted to high angles. The faulting is known as basin-range deformation, which began about 20 million years ago (middle Miocene), although most of the faulting occurred in the past 10 million years (Mackin, 1960; Rowley and others, 1979; Rowley and Dixon, 2001; Hintze, 2005; Hintze and Kowallis, 2009). Thus the ranges are high and the landscapes are youthful. Most exposed rocks in the Great Basin are volcanic, derived from vents and calderas in the roofs of igneous intrusions, some of which formed metallic mineral deposits that are abundant in the Great Basin, leading to early economic development.

The main part of the Colorado Plateau, in contrast to the High Plateaus, consists mostly of plateaus and mesas formed by long erosion of mostly flat-lying sedimentary rocks, with far fewer and smaller faults. Some older faults, resulting from Laramide deformation of early Tertiary age and typically concealed at depth, folded rocks into sharp

Figure 2. *View southeast to the North View Overlook area at Cedar Breaks National Monument. This area provides the best exposures of the contact between the Claron and Brian Head Formations on the Markagunt Plateau. Here, the Claron is divided into two informal members: (1) an upper white member, which is itself divided into an uppermost mudstone unit [Tcwt], an upper limestone unit (Tcwu), a middle mudstone and sandstone unit [Tcwm], and a lower limestone unit [Tcwl]), and (2) the lower pink member (Tcp). The location of sample BH062310-1, from a thin rhyolitic ash-fall tuff at the base of the Brian Head Formation that yielded a U-Pb age on zircon of 35.77 ± 0.28 Ma, is also shown.*

monoclines, and several clusters of Tertiary laccolith intrusions also occur on the Plateau, but these interruptions of the flat-lying sedimentary rock expanses are uncommon (Hintze, 2005; Hintze and Kowallis, 2009).

The Markagunt Plateau, like most other plateaus of the High Plateau subprovince, is actually a cuesta (a tilted plateau), uplifted on its western side along the Hurricane-Parowan-Paragonah fault zones and tilted several degrees to the east. Uplift with respect to the same rocks beneath Cedar Valley west of Cedar City is probably about 10,000 feet (3000 m) (Anderson and Rowley, 1975; Anderson and Mehnert, 1979; Hurlow, 2002; Rowley and others, 2006; Lund and others, 2007). The rocks in the Brian Head quadrangle, from youngest to oldest, consist of the following:

1. Holocene and Pleistocene surficial deposits, including glacial deposits of limited extent and extensive landslide deposits.
2. Pleistocene and Pliocene basaltic lava flows and cinder cones that formed during and since the latest basin-range faulting in the area.
3. The Miocene Markagunt Megabreccia, which is made up of older, pre-basin-range middle Tertiary volcanic rocks and early Tertiary sedimentary rocks that were catastrophically displaced southward along low-angle gravity slide planes.
4. The same Miocene and Oligocene volcanic rocks, mostly derived from calderas at and west of the Utah-Nevada state line, that are not part of the Markagunt Megabreccia.
5. A soft, early Oligocene to late Eocene sedimentary unit, the Brian Head Formation, that contains volcanic ash from initial phases of the early volcanism and which has weathered into smectitic clays that facilitate landslides wherever the Brian Head is exposed by erosion or faulting.
6. The Eocene and Paleocene Claron Formation, made up of stream- and lake-deposited sedimentary rocks that weather into spectacularly beautiful amphitheaters of red and white hoodoos, the colorful reason for establishing Bryce Canyon National Park 30 miles (50 km) to the east and Cedar Breaks National Monument (figure 2) in this quadrangle.
7. Upper Cretaceous sedimentary rocks of coastal alluvial-plain origins, the westward equivalent of better exposed and better studied dinosaur-bearing strata of the Kaiparowits Basin to the east.

The geology of the Brian Head quadrangle is far more complicated than one would imagine by looking at the serene beauty of the gently east-dipping beds of Cedar Breaks National Monument. The forested plateau preserves evidence of many fascinating and spectacular geologic events, as perhaps one might hope for in an area that has been largely set aside as a national monument and national forest.

NOTES ON SELECTED GEOLOGIC FEATURES

Landslides

About a quarter of the area of the Brian Head quadrangle is underlain by landslides of all sizes and of several origins and causes. The largest landslides resulted from ground failure along the scarp of the Black Ledge fault, which was first mapped by Gregory (1950) and is the easternmost of several large, northeast-trending normal faults that break apart the western margin of the Markagunt Plateau. The scarp (named the Black Ledge by Gregory, 1950) is capped by resistant Isom and Leach Canyon Formations, which overlie weak, landslide-prone Brian Head Formation (figure 3). Together with the Rattlesnake Canyon fault, these two main faults form the Yankee Meadows graben (cross section A–A′), one of several grabens and intervening horsts at the west edge of the plateau. The town of Brian Head and Brian Head Resort are nestled in the Yankee Meadows graben, which is mostly filled with landslide deposits and cut by concealed subsidiary faults (figure 4).

Most landslides moved northwest off the highest part of the Black Ledge scarp and passed over other, lower fault scarps, resulting in deposits that probably are less than 100 feet (30 m) thick in most places. The faults are shown on the map as concealed (dotted) because they underlie the landslides; no faults are known to cut (postdate) the landslides in the map area. Even though concealed, the faults can be inferred at the base of several abrupt topographic scarps on the basis of observations of aerial photographs and satellite imagery. Data from several water wells helped in the interpretation of the faults beneath the large landslides. For example, the 700-foot-deep (200 m) Brian Head Town Hall well, located in southern Bear Flat, drilled the Isom Formation between 130 and 630 feet (40–192 m), then the Brian Head Formation to the well's total depth; this requires a down-to-the-west fault east of Bear Flat and a down-to-the-east fault west of Bear Flat.

Some blocks brought down by the slides are larger than houses, if not city blocks, and they contain coherent rock, but such displaced blocks are mapped as landslide deposits. However, locally within the large landslide masses, we map bedrock units, but this is done only where senior author Rowley interprets these coherent rocks as undisplaced bedrock (bounded by concealed high-angle normal faults) that underlies the landslide deposits. Alternatively, some of these masses of coherent rocks may have moved downslope as coherent, back-tilted blocks; if so, the landslide deposits in the graben may exceed several hundred feet thick. The 1:62,500-scale map of Biek and others (2012) shows this alternate interpretation.

Boswell and others (2008) mapped the landslides in a 12-square-mile (31 km^2) area centered on the town of Brian Head. Based on the morphology of the features, they broke the overall slide mass into three groups of apparent ages. In the large landslides located highest on the Black Ledge scarp, modern landslide scars are abundant, and lakes typical of landslide terrain are locally present within closed depressions. They also noted landslide deposits of subdued morphology, suggesting that they may be older and less active. However, because detailed slope stability studies have not been undertaken, we do not divide landslide deposits as to inferred age and group all of them into a single Quaternary map unit. 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). Inasmuch as the Black Ledge fault and most of the other basin-range faults in the map area probably have been active as long ago as late Miocene, landslides of Miocene and Pliocene age probably were triggered along these faults. However, no such old landslides were identified, so we assume that such old deposits were removed by erosion or incorporated within Quaternary slides.

Northwest of Bear Flat and the town of Brian Head, landslides are largely developed on the Brian Head Formation. These slides moved primarily down the low slopes of Navajo Ridge, primarily toward the southeast (figure 4). As befitting their low slope, the associated landslide scars and other features are subdued, and thus cumulative movement of each point on the slide surface is inferred to be much less than in the large slide masses off the Black Ledge. Nonetheless, the landslides on Navajo Ridge are moving in places, especially where remobilized by construction activities. Here and adjacent to Bear Flat, homes, buildings, and roads are abundant, and landslide movement is demonstrated by visible cracks and displacement in some concrete foundations, sidewalks, roads, driveways, and ski lifts.

In addition to these large slides, many smaller landslides are present throughout the map area. The common theme of nearly all the landslides is that they moved in part or in total because they are underlain by the Brian Head Formation (Tbh). Brian Head deposits formed as volcanic ash was deposited in lake and stream environments as recurring columns of ash drifted eastward and southward across southwestern Utah. The volcanic ash weathered into bentonite and other clays, which swell when wet, and which provide a weak shear surface for landslide movement on slopes of even low gradients; movement continues until an increase in shear strength (for example, by lowering the

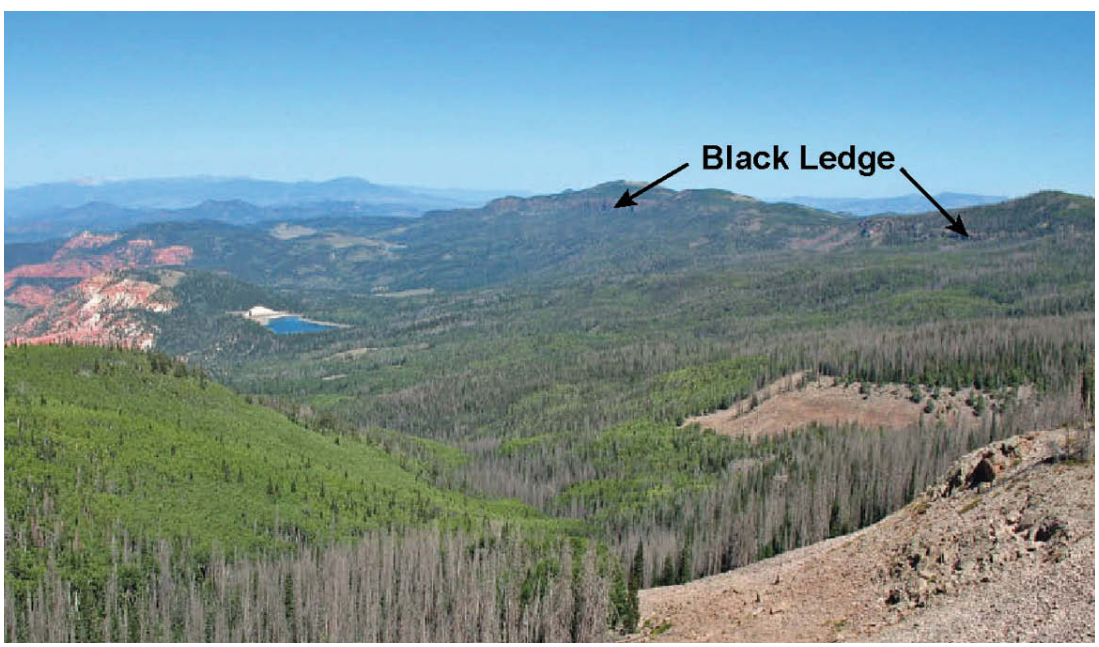

***Figure 3**. View northward of the northern Markagunt Plateau, taken from a fault block of the Leach Canyon Formation (bare ledges and slopes in the foreground) located 0.5 mile (0.8 km) northwest of Sidney Peaks. The fault block is downthrown along the Black Ledge fault, to the right of the photographer. Another down-to-the-west basin-range fault runs down the valley left of the Leach Canyon outcrops. The Black Ledge makes up the highest ridges that continue south off the image to the right of the photographer. Yankee Meadow Reservoir is near the center of the image, just left (west) of which is a prominent, linear, down-to-the-east fault that displaces pink Claron Formation on the west from dark volcanic rocks at the reservoir. The hummocky timbered slopes between the Black Ledge and Yankee Meadow Reservoir consist of landslides off the Black Ledge. The farthest-left pink cliffs of Claron Formation make up the Hurricane Cliffs, to the west of which is Parowan Valley.*

gradient of the shear plane, reducing the moisture content of the landslide mass, buttressing the toe area of the landslide, or some other mechanism) is obtained, in which case the landslide temporarily stabilizes. So virtually everywhere the Brian Head Formation is exposed on a slope by erosion or faulting, it ultimately undergoes landslide movement. This may be seen on a small scale, far too fine to show on this map, in nearly all roadcuts that expose the Brian Head Formation, notably along State Highway 143 from Parowan Canyon to Panguitch Lake, as well as in bulldozer cuts for foundations, utility lines, and driveways.

Most homes, buildings, ski lifts, and roads in the Brian Head area are built on landslides. The effects of landslide damage become progressively more obvious with time: cracks in foundations, roads, driveways, and retaining walls eventually widen downhill, and parts of yards, septic systems, buildings, and other infrastructure may be damaged as movement continues in active slides. Even in apparently stable older landslides, construction activities, especially those that disturb or destroy the toe (the downslope end of the deposits) or introduce water into the slopes, may reactivate slides. The possibility of reactivation becomes greater with more precipitation and steeper slopes.

Professional realtors in Utah are under no obligation to inform prospective buyers about the dangers to persons, buildings, or bank accounts of buying raw land or homes that are underlain by landslides or are in other geologic hazard zones. Buyers are responsible for recognizing any potential hazards before buying or building. The Utah Geological Survey has an active program of informing the public on how to recognize and mitigate landslide hazards, and it offers many forms of information and advice (see http://geology.utah.gov/utahgeo/hazards/landslide/index.htm). In addition, geological engineering firms in southwestern Utah are available to provide advice for a fee. With proper engineering, many adverse potential effects caused by landsliding can be prevented. This map can help in identifying and locating areas of greatest landslide potential (mapped landslides) and areas having a high potential for sliding (many steep slopes and all rocks mapped as Brian Head Formation, as well as surficial deposits derived from Brian Head strata). The reader should remember, however, that at the map scale (1:24,000), our map-unit contacts are too coarse and generalized for lot-sized property evaluations and that many small landslides cannot be shown at this scale. Furthermore, many contacts are approximate and could be hundreds of feet on either side of where they are shown, and some contacts may be in error because they are based on interpretation of only surface morphology. Site-specific studies are necessary to adequately characterize landslide hazards.

Figure 4. *View north at Bear Flat and most of the town of Brian Head, most of which is underlain by landslide deposits. Several beginner ski slopes are on Navajo Ridge left (west) of southern Bear Flat. In the far middle ground, the pink Hurricane Cliffs mark the western edge of the High Plateaus, with Parowan Valley, the northern Red Hills, and the Black Mountains of the Great Basin in the distance. Photo taken from cliffs of the Isom Formation on hill 10,395 southeast of Bear Flat.*

Glacial Deposits

Gregory (1950, p. 71) was the first to identify and briefly describe glacial deposits in the map area, in Sidney Valley and along Castle Creek. Mulvey and others (1984) noted that these were deposited by the southernmost late Pleistocene glaciers in Utah, and they provided more detailed descriptions of these deposits, as well as those in the adjacent Lowder Creek drainage. Glacial deposits of both Pinedale age and an older glacial advance are known in these basins (Biek and others, 2012). Based on morphology and inferred age, the deposits are assigned to several map units. Most ice flowed east-southeast and, just past the terminal moraine along Castle Creek and off the map boundary in this direction, ice-wedge polygons were also recognized by Mulvey and others (1984). They also interpreted that a small glacier flowed north off Black Ledge just northeast of Sidney Peaks. The evidence for this small glacier is an apparent cirque and morainal deposits, as well as glacial striae in volcanic rock at the top of the scarp. The striae suggest that some contribution to this glacier came from ice in upper Castle Creek that flowed north as well as southeast. Based on glacial erratics and projections of inferred ice thicknesses, the former levels of glacier surfaces were as much as 200 feet (60 m) higher than the deposits shown (Mulvey and others, 1984). Agenbroad and others (1996) suggested that another glacier flowed east-southeast in Mammoth Creek, and that its western part may have also flowed west over the scarp of Cedar Breaks, but we disagree with this interpretation, in part because it was based on blocks that they considered glacial erratics but instead are simply debris from erosion of the Markagunt Megabreccia (Tm). Mulvey and others (1984) noted that the glaciers in this area resulted in only minor sculpting of the bedrock landscape, for the glaciers were too thin and small and probably short-lived to have much erosive effect. Nonetheless, the apparent cirque northeast of Sidney Peaks and a subdued cirque on the east side of hill 10,794 southwest of southern Sidney Valley attest to moderate glacial erosion in those areas, as do the morainal deposits themselves in the Lowder Creek, Castle Creek, and Sidney Valley areas.

Young Basalt Lava Flows and Cinder Cones

Basaltic lava flows underlie much of the southeastern part of the quadrangle and some areas east of Sidney Peaks, where they are mostly vegetated but in a few places are not. Three cinder cones, including the spectacular one that rises 600 feet (200 m) to form Hancock Peak (altitude 10,598 feet) (figure 5), are present in the quadrangle. The basalts in the Brian Head quadrangle form the northwestern part of the western Grand Canyon basaltic field, which extends across the southwestern part of the Colorado Pla-

***Figure 5**. View southwest to the Hancock Peak cinder cone, vent area of the middle to early Pleistocene Hancock Peak lava flows.*

teau and adjacent High Plateaus transition zone with the Basin and Range Province in southwestern Utah, northeastern Arizona, and adjacent Nevada (Hamblin, 1963, 1970, 1987; Best and Brimhall, 1970, 1974; Best and others, 1980; Smith and others, 1999; Johnson and others, 2010). This volcanic field contains hundreds of relatively small-volume, widely scattered, mostly basaltic lava flows and cinder cones that range in age from Miocene to Holocene. Along Utah State Highway 14 about 3.5 miles (5 km) south of the map area, many unvegetated, blocky basalt flows suggestive of latest Pleistocene or perhaps early Holocene age are well exposed. Here also the older, late Pleistocene Henrie Knolls lava flow created a lava dam, behind which ancestral Navajo Lake formed just south of the highway (Moore and others, 2004; Biek and others, 2011). Although there is no geologic evidence in the map area that any flows postdate glaciations and are Holocene (indeed, the southeastern Long Flat cinder cone reveals evidence of having its northeast margin sculpted by glacial ice), Native American legends refer to "smoking hills" in the Panguitch Lake area to the east (Hatfield and others, 2000b, 2010).

Volcanic rock types that are at opposite ends of the compositional spectrum, namely basaltic rocks and high-silica rhyolite rocks, form a bimodal sequence in the West. For 20 million years (and continuing locally today), bimodal volcanism has been coincident with regional extension (basin-range faulting) in the Great Basin (Christiansen and Lipman, 1972). The rhyolite part of the sequence is not present in the map area, although rhyolitic flows and tuffs of Miocene and Pliocene age are abundant farther north and west, across western Utah. The Long Flat lava flow yielded a poorly constrained age of 0.60 ± 0.25 Ma, and the Hancock Peak flow is likely of similar age based on comparison with nearby dated flows. The Sidney Peaks lava flow lacks a cinder cone and its relative degree of erosion suggests that it is at least several million years old, probably Pliocene in age. However, elsewhere in southwestern Utah not far from the map area, the rhyolites and basalts span the complete 20-Myr age range, with the older rocks being progressively more faulted (Best and others, 1980; Rowley and others, 2006; Biek and others, 2009).

Basin-Range Faults

Basin-range deformation (Mackin, 1960), which began about 20 million years ago and continues today, results from regional extension that is pulling apart of the upper crust in a general east-west direction. North-striking, primarily high-angle normal faults formed in this stress field, and relatively small volumes of bimodal volcanism accompanied the faulting and were in turn displaced by the younger faults. Most faulting took place after about 10 million years ago, producing the present topography. The normal faults define alternating series of north-trending basins (grabens and half-grabens) and ranges (horsts) that characterize the Great Basin and the High Plateaus. As the grabens dropped relative to the horsts, they were filled with basin-fill sediments derived from erosion of the horsts. These basin-fill sediments are in places thousands of feet thick, as beneath Cedar Valley west of Cedar City.

No large faults like the Hurricane, Parowan, or Paragonah faults, located respectively west and north of the map area, are present in the Brian Head quadrangle. Some of the northeast-trending faults in the western half of the map area, however, exhibit about 1000 feet (300 m) of vertical displacement, as shown on cross section A–A′, and the peak of Brian Head is about 1500 feet (500 m) higher than the elevation of the town of Brian Head due to cumulative movement on several northeast-striking faults. The distribution of faults in the map area can be described by dividing the map by a line from the northeast corner to the southwest corner. Northwest of this line are many large and continuous northeast-trending basin-range faults that collectively form a number of horsts and grabens, including the Yankee Meadows graben (figure 3). The grabens preserve younger volcanic rocks and are largely covered by landslide deposits, whereas the horsts expose older sedimentary rocks of Upper Cretaceous strata and the early Tertiary Claron Formation.

To the southeast of the line, the faults strike east-southeast, at almost 90 degrees to the ones to the northwest. They are relatively small and discontinuous and the subject of debate. This southeast area is the volcanic cap of the Markagunt Plateau, beneath which lies the incompetent Brian Head Formation. Therefore, some of the east-southeast-trending faults may partly represent piecemeal lateral (eastward) movement of the caprock down the cuesta dipslope on the underlying incompetent Brian Head Formation. One of the faults in the southeast area, in fact, is well exposed as downthrown, steeply dipping, and fault-brecciated beds of the Brian Head Formation to the north displaced against gently dipping Claron Formation to the south, as seen along the northern side of State Highway 143 nearly 0.5 mile (0.8 km) north of Mammoth Summit; this fault continues east-southeast as an obsequent fault-line scarp.

Alternatively, co-author Biek believes the existence of east-trending faults as penetrative tectonic features is speculative. Although the top of the Markagunt Plateau is densely vegetated and strata are typically poorly exposed, he found no evidence of such faults that cut and displace well-exposed Isom and Leach Canyon Formations at the Black Ledge escarpment, and thus reasoned that the faults are fewer in number and restricted to the upper plate of the Markagunt Megabreccia. Their anomalous easterly trend and location at the southern margin of the megabreccia suggested to him that some of these faults are south-vergent thrust faults that accommodated compressional deformation near the toe of this gravity slide. Biek also found no evidence for Rowley's down-to-the-north

and down-to-the-south Mammoth Creek faults, the former of which Rowley interpreted as an obsequent fault-line scarp. Biek interprets these features as the toe and main scarp of landslides, for they exhibit classic landslide morphology, are formed in landslide-prone Brian Head strata, the inferred faults do not offset Claron strata to the west, and the strike of the faults is at odds with the regional pattern of northeast-striking faults (itself one of the critical indicators of the confusion between structures generated by landsliding and those generated by tectonic faults [Hart and others, 2012]).

Markagunt Megabreccia

The Markagunt Megabreccia is a mostly poorly exposed, erosional remnant of an early Miocene, displaced, structurally chaotic assemblage of angular clasts and broken masses of older Tertiary rock units spread over the northern and central Markagunt Plateau (Sable and Anderson, 1985; Anderson, 1993; Maldonado and others, 1997; Sable and Maldonado, 1997b; Biek and others, 2012). The older Tertiary rocks are volcanic and sedimentary units, including the Brian Head, Wah Wah Springs, and Isom Formations, that range from house-sized to larger than 1 square-mile (2.5 km^2) blocks in a matrix of breccia and sheared rock. In this map area, the Megabreccia rests on undeformed bedrock of the white member of the Claron Formation, the Brian Head Formation, the Isom Formation, the Leach Canyon Formation, and volcanic mudflow breccia of the Mount Dutton Formation. North and east of the map area, the Megabreccia contains, and overlies, these same map units as well as other upper Oligocene and lower Miocene units not present in the map area, including conglomerate, sandstone, and tuff at least as young as 22 Ma (Anderson, 1993; Biek and others, 2012) and lava flows of the Bear Valley Formation (Anderson, 1971).

The Markagunt Megabreccia was first recognized in thesis mapping by Judy (1974), although it would take years of additional mapping by students, their advisor (J.J. Anderson), and colleagues before its large extent and likely origin were realized. Most information on the Markagunt Megabreccia comes from exposures north and east of the mapped area. As each worker mapped part of the Markagunt Megabreccia, that person provided new or additional data and interpretations. Interpretations on the age and source of the Megabreccia especially differed from person to person. Maldonado and others (1990, 1992) and Anderson (1993) discussed its regional importance, and Anderson (1993) described a 500-foot-thick (150 m) reference section 5 miles (8 km) east of the map area along Utah State Route143. Maldonado and others (1997) and Sable and Maldonado (1997b) summarized what was known at the time from their mapping on the Markagunt Plateau. Moore (1992), Moore and Nealey (1993), and Moore and others (2004) described the unit in the Navajo Lake quadrangle (directly south of the map area), and Hatfield and others (2000a, 2000b, 2000c, 2004, 2010) described it in Cedar Breaks National Monument. All workers interpreted the Markagunt Megabreccia as a gravity-slide mass that moved on subhorizontal surfaces (shown on the map as "gravity-slide faults") mostly in incompetent sedimentary rocks of the Brian Head Formation. With compilation of what appeared at the time to be the entire extent of the Megabreccia, Biek and others (2012) assembled and analyzed in detail all the disparate main observations and conclusions about the Markagunt Megabreccia, resulting in a comprehensive picture that most of the authors of that and this report agree on entirely, and for the other coauthors, in all important aspects.

Remnants of the Markagunt Megabreccia in the map area have three distinct and separate physical types, from north to south: (1) In northern exposures (Brian Head plateau crest, east-southeast of the Black Ledge and notably at, south, and east of Sidney Peaks) the Megabreccia consists of coherent masses, semi-coherent masses, and breccias of mostly volcanic rocks that rest mostly on the Leach Canyon Formation and locally on the Isom Formation or patches of the Mount Dutton Formation that overlie the Leach Canyon Formation. (2) Farther south in the quadrangle and in the Navajo Lake quadrangle (Moore and others, 2004), due southward of the depositional pinchout of the Leach Canyon and Isom Formations against presumed valley sides cut in the Brian Head Formation, the Megabreccia rests on the Brian Head or Claron Formations. Where it overlies the Brian Head and Claron Formations, the Megabreccia forms poorly coherent (mostly unconsolidated) masses, as in and near Cedar Breaks National Monument in the Brian Head and Navajo Lake quadrangles and on Blowhard Mountain southwest of the Monument in the Navajo Lake quadrangle. (3) Still farther south of the resistant plateau-capping Leach Canyon Formation and continuing southward to Utah State Highway 14 where it follows Midway Creek about 4 miles (6 km) south of the map area, all that remains of the Megabreccia are isolated blocks of Isom Formation and subordinate agatized limestone of the Brian Head Formation. These blocks, which cannot be mapped separately, rest on a rounded erosional surface of poorly exposed Brian Head or Claron Formation covered with thin residual deposits from chemical weathering or a thin colluvium. Interestingly, such large blocks of the Isom Formation were "mined" from the Brian Head or Navajo Lake quadrangles by a landscape designer and used as decorative rocks placed around the campus of Southern Utah University in Cedar City.

All parts of the Markagunt Megabreccia in all three physical types, including about 80 to 90 percent of the blocks of the third type, are dominated by a distinctive, resistant, massive, reddish-brown, fairly crystal-rich (15–20 percent phenocrysts), densely welded, ash-flow tuff cooling unit from the Bald Hills Tuff Member of the Isom Formation. This tuff is the same unit seen in the type Isom area in

the northern Iron Springs mining district (Mackin, 1960; Anderson and Rowley, 1975; Mackin and Rowley, 1976), but it is also exposed in the northern Markagunt Plateau north of the study area, from where it was picked up in the gravity slide. It is important to note, however, that this cooling unit is not present where the Isom is in place in the map area, such as below the Leach Canyon Formation on the Brian Head plateau; instead, in-place Isom Formation here consists of other cooling units that are characterized by linear vesicles and fewer (mostly 5 to 15 percent) phenocrysts. The isolated Bald Hills blocks, which resemble glacial erratics, are commonly large, as much as 16 feet (5 m) long (figure 6 of Hatfield and others, 2000b, 2010). These blocks cannot be glacial erratics because no evidence for former glacial ice exists in the upper Mammoth Creek basin of the map area and the upper Midway Creek basin to the south. Furthermore, about 10 percent of them are internally brecciated, then relithified by devitrification and silicification so that they ring to the hammer (figure 6; see also figure 7 of Hatfield and others, 2000b, 2010). Brecciation identifies them as a product of the Markagunt Megabreccia emplacement, and similar clasts make up a similar percentage of the deposits of the Markagunt Megabreccia.

The interpretation of the origin of the second and third physical types in the map area differs between the first and second authors of the map. The senior author interprets the masses of blocks (the second physical type) in the map area and continuing southward to the radio towers on Blowhard Mountain 2.3 miles (3.7 km) south of the map area (see Moore and others, 2004) as being let down through soft sediment of the Brian Head Formation. This was done by sapping and erosion of this soft underlying rock and by solution—with lateral joining and expansion of sinkholes under moist periglacial conditions—of underlying limestone beds in the Claron and Brian Head Formations. In other words, these masses that extend to Blowhard Mountain represent the southern edge of the Markagunt Megabreccia and are mapped as such. The scattered individual blocks of mostly Isom Formation (the third physical type), on the other hand, represent scattered blocks of the Megabreccia that were either moved by snowmelt and/or stream processes or are the remains after the rest of the Megabreccia mass was removed by the same processes. The second author (Biek), as also discussed in the map of Biek and others (2012), however, intrepreted the masses and individual blocks as landslide or erosional products derived from the southern margin of the Markagunt Megabreccia, which he interpreted to have retreated northward over time as a result of erosion of the southern margin of the Megabreccia. As evidence, Biek and others (2012) noted that the masses and blocks are at a structurally significantly lower elevation than the main

Figure 6. *Typical block of the Isom Formation, brecciated by movement along the gravity-slide plane that transported the Markagunt Megabreccia in the map area. Includes a 2-foot-long (0.7 m) angular fragment at the pick end of the hammer and smaller angular fragments below the hammer.*

mass of the Megabreccia, as well as the apparent paucity of sinkholes in this area. The senior author counters that a mapped east-striking, down-to-the-south fault just south of the plateau (just north of Mammoth Creek), or sliding of the let-down masses along the Brian Head Formation, could have shifted the masses to their present position.

The slide plane on which the Megabreccia moved is exposed in few places. Northeast of the map area, northerly-striking slickensides on low-angle shear surfaces are present locally (Anderson, 1993; Sable and Maldonado, 1997b). In the northeastern part of the map area, the slide plane is exposed just east of the road to Yankee Meadows Reservoir, where the road drops off the Black Ledge west of hill 10,632. Here the slide plane rests on the Leach Canyon Formation and a thin wedge of volcanic mudflow breccia of the Mount Dutton Formation that rests on the Leach Canyon. The overlying Markagunt Megabreccia consists of a basal part about 50 feet (15 m) thick of deformed, brecciated, and sheared claystone and sandstone of the Brian Head Formation, and overlying deformed and brecciated blocks and masses of Isom Formation (mapped within the Brian Head Formation), above which is a 10-foot-thick (3 m) ledge of Wah Wah Springs Formation, then a 50-foot (15 m) cliff of Isom Formation.

The age of the Markagunt Megabreccia is younger than the youngest rocks on which the gravity-slide mass rests and older than the oldest undeformed rocks that rest on the Megabreccia. In the map area, the youngest unit on which the gravity-slide plane rests is several thin (about 10 feet [3 m] thick) wedges of volcanic mudflow breccia of the Mount Dutton Formation; this unit is poorly dated as Oligocene and Miocene where thick north of the map area (Anderson and Rowley, 1975), but must be Miocene here. Northeast of Brian Head peak, the Megabreccia rests mostly on 23.8 Ma Leach Canyon Formation, which underlies the Mount Dutton Formation. However, 0.5 mile (0.8 km) north of the map area, along State Highway 143 in Parowan Canyon, the Megabreccia rests on 22 Ma Harmony Hills Tuff (Biek and others, 2012). Furthermore, on the southern flank of Haycock Mountain 9 miles (14 km) east of the map area, the Megabreccia overlies conglomerate that contains well-rounded boulders, cobbles, and pebbles of volcanic rocks as young as the Harmony Hills Tuff (Biek and others, 2012).

Rock units that unconformably overlie the Markagunt Megabreccia provide little help in constraining the most recent time of movement of the gravity slide that produced the Megabreccia. In the map area, the oldest such unit consists of deeply eroded basalt lava flows of the Sidney Peaks lava flow, but this unit has not been isotopically dated and is assigned only a general age of late Miocene or early Pliocene. Several other undated basalt units of similar age overlie the Markagunt Megabreccia to the east (Biek and others, 2012). Before Biek and others (2012) completed mapping of the Haycock Mountain area to the east, this broad plateau of mostly undeformed Isom Formation and younger undeformed units that overlie the Isom was considered autochthonous. The younger units above the Isom in the Haycock Mountain area were, in fact, considered to postdate emplacement of the Markagunt Megabreccia. These younger units are poorly to moderately consolidated, gray and tan, stream-deposited conglomerate and sandstone between 15 and 100 feet (5–30 m) thick and an overlying local, tan, poorly welded, rhyolite ash-flow tuff, the Haycock Mountain Tuff, that has a maximum thickness of 50 feet (15 m) (Anderson, 1993). This tuff petrographically and superficially in the field resembles the Leach Canyon Formation but, unlike the Leach Canyon, the Haycock Mountain Tuff contains black, basaltic, lithic fragments instead of dense red rhyolite flow-rock fragments characteristic of the Leach Canyon. Our best estimate of the age of the Haycock Mountain Tuff is 22.75 Ma (Anderson, 1993; Rowley and others, 1994a; Hatfield and others, 2000b, 2010). Therefore, the time of emplacement of the Markagunt Megabreccia was formerly considered to predate this tuff (Anderson, 1993; Hatfield and others, 2000b, 2010). However, once mapping by Biek and others (2012) outside the present map area found that the Markagunt Megabreccia not only postdates the 22-Ma Harmony Hills Tuff, but also postdates a conglomerate containing clasts of the Harmony Hills, we agree that the age of the Megabreccia is less than 22 Ma. We cannot tell how much younger than this it is, owing to the poor constraints provided by the basalts or other rocks, but interpretations on the ultimate source of gravity sliding provide hints.

The ultimate source of the Markagunt Megabreccia slide mass is poorly known. Anderson (1993) was equivocal: in general he preferred northward movement of the gravity slide, but this left him with no mechanism as to why any broad uplift would form south of the distribution of the Markagunt Megabreccia. So he also suggested, as an alternative, southward movement along dip slopes off a series of large, west-northwest-striking, down-to-the-north faults between 5 and 10 miles (8–16 km) north of Panguitch Reservoir (5 miles [8 km] east of the map area). The latter hypothesis, with considerably more details, is discussed by Anderson (2001). Sable and Maldonado (1997b) suggested that the slide came from the north, off the southern side of a structural dome resulting from emplacement of the 20-Ma Iron Peak laccolith northeast of Paragonah. The Iron Peak laccolith (Anderson and Rowley, 1975; Spurney, 1984) may be part of a large batholith (Blank and Kucks, 1989; Blank and others, 1998), above which other laccolith cupulas rose, notably the Spry intrusion north of the map area (Anderson and Rowley, 1975; Anderson and others, 1990). But the Spry laccolith is 26 Ma, clearly too old to provide a dome off which the Megabreccia slid. Sable and Maldonado (1997b) cited slickensides on the gravity-slide plane that converged toward the Iron Peak laccolith. Some of those slickensides, however, also point to the fault

tilt blocks of Anderson (1993, 2001). However, recently discovered exposures of the Markagunt Megabreccia on the northern Markagunt Plateau show that the Iron Peak laccolith is located too far south and west to possibly have been a trigger for catastrophic emplacement of the Megabreccia. Thus our preferred trigger is farther north and may be linked to the 18 to 20 Ma (Cunningham and others, 1998; Rowley and others, 2002, 2005) Mount Belknap caldera 40 miles (65 km) north of the map area. We continue to work on further constraining the extent, age, and emplacement mechanism of the Markagunt Megabreccia.

In a more regional perspective, Davis (1999) proposed a "two tiered" model of the Markagunt Megabreccia and other structures linked to the Megabreccia. He proposed that the gravity-slide mass of the Markagunt Megabreccia is but one—a surficial part—of a second deeper series of Tertiary thrusts directed outward from the Marysvale volcanic field (e.g., Rowley and others, 1998; Cunningham and others, 2007), which spread and collapsed under its own weight (Davis and Rowley, 1993; Davis, 1999), resulting in southward-directed thrust faults that sole into Middle Jurassic evaporite beds and which are exposed at the surface locally, such as north of Bryce Canyon National Park (Davis and Krantz, 1986; Lundin, 1989; Bowers, 1990; Nickelsen and Merle, 1991; Nickelsen and others, 1992; Merle and others, 1993; Davis, 1999; Biek and others, 2012), and perhaps south of Haycock Mountain (Biek and others, 2012).

Oligocene and Miocene Ash-Flow Tuffs

Regional ash-flow tuff sheets derived from the west underlie Brian Head and parts of the northern Markagunt Plateau (Anderson and Rowley, 1975; Biek and others, 2012). From top to base in the map area, the tuffs consist of the Bauers Tuff Member of the Condor Canyon Formation and the Leach Canyon Formation, both of the Quichapa Group; the Isom Formation; and the Wah Wah Springs Formation of the Needles Range Group, all first recognized and named by Mackin (1960) from exposures in the Iron Springs mining district. Some of these tuffs, namely the Bauers Tuff Member and the Isom Formation, are densely welded and were considered lava flows until Mackin (1960), Williams (1960, 1967), and Cook (1965) traced them over large parts of southwestern Utah and eastern Nevada. All these tuffs are resistant. They range in composition from low-silica rhyolite to dacite and belong to the Eocene to Miocene, calc-alkaline sequence of volcanic rocks, largely ash-flow tuffs, but in places they include thick sequences of lava flows and volcanic mudflows, all of which are voluminous throughout the Great Basin and High Plateaus (Lipman and others, 1972; Best and others, 1989b, 1993). These rocks represent subduction processes, as Pacific tectonic plates to the west were overridden by westward-moving North America (Atwater, 1970; Hamilton, 1989, 1995; Severinghaus and Atwater, 1990). Subduction at this latitude ended at about 20 Ma, when basin-range deformation began. The landscape in the Great Basin at the time of subduction appears to have been made up of east- to east-northeast-trending igneous belts, consisting largely of eruptive centers (Stewart and others, 1977; Rowley, 1998; Rowley and Dixon, 2001), especially calderas and stratovolcanoes, that combined to form mountain ranges. The valleys between the belts were filled with outflow tuffs, and the overall landscape may have been subdued by burial by the voluminous volcanic rocks. As befits other areas above subduction zones, the regime was mildly extensional, with pulling apart generally directed east-west (Hamilton, 1989, 1995).

The map area is near the eastern depositional extent of Great Basin ash-flow tuffs, which pinch out to the east, perhaps against a highland that may represent an early phase of uplift of the Colorado Plateau (Rowley and others, 1978). The map area also contains the southern depositional extent of most of these ash-flow tuffs, on and against rocks of the older Brian Head Formation, which in turn represents the southern and eastern edge of a shallow river or lake basin that included interbedded ash-fall tuffs.

Of the regional, calc-alkaline ash-flow tuffs, the youngest in the area, the Bauers Tuff Member, is exposed only in the northwestern corner of the map area. Being resistant, it should be present on the Brian Head–Sidney Peaks escarpment if deposited that far south, so we infer that it pinched out against higher paleotopography to the south of where it is now, probably restricted to an east-northeast-trending paleovalley. The Bauers Tuff was derived from the Clover Creek caldera of the northern Caliente caldera complex in Nevada-Utah, about 85 miles (140 km) to the west (Rowley and others, 1995). The source of the underlying Leach Canyon Formation has not been found but, based on isopachs (thickness) of the tuff, Williams (1967) concluded that it was also derived from the Caliente caldera complex. If so, correlative intracaldera tuffs or intrusions have not yet been found there (Rowley and others, 1995). The source of the Isom Formation has not been found either, but based on large thicknesses present in the southern part of the Indian Peak caldera complex that straddles the Utah-Nevada border, Best and others (1989a, 1989b) concluded that it came from that area. The extremely voluminous Wah Wah Springs Formation was derived from the Indian Peak caldera of the Indian Peak caldera complex (Best and others, 1989a), one of the world's largest, about 50 miles (80 km) west of the map area.

STRATIGRAPHIC PROBLEMS IN THE PALEOCENE TO UPPER CRETACEOUS

Along the western scarp of the Markagunt Plateau in the Brian Head and Navajo Lake quadrangles, a thick sequence of poorly exposed Upper Cretaceous rocks below the

Claron Formation has been correlated with various other units in the region and has been assigned various ages. It required the effort of many workers to elucidate the problem of correlating these strata with better exposed and better known coeval strata of the Kaiparowits basin to the east, and that correlation has only now been satisfactorily resolved with the regional-scale mapping of Biek and others (2012). We outline the problem here not only for its historical interest, but also to recognize the collective effort that went into resolving the correlation of Upper Cretaceous and Paleocene strata along what was once the western margin of the Western Interior Seaway. We discuss the rocks from top to bottom; see the correlation of Upper Cretaceous strata diagram as an aid to help follow this discussion.

Upper Cretaceous Strata in Cedar Canyon

Just below the ledges of pink Claron Formation in the Brian Head and Navajo Lake quadrangles is a thick section of mostly nonresistant, poorly exposed, light-gray and light-yellow sandstone, siltstone, and mudstone. Moore and Nealey (1993) described the upper part of the section in the adjacent Navajo Lake quadrangle as consisting of 33 to 59 feet (10–18 m) of chiefly cherty, argillaceous, yellowish "dirty salt-and-pepper" sandstone that contains 8 to 15 percent black chert grains; 20 to 25 percent light-gray, white, and tan angular chert grains; and 10 to 30 percent varicolored, silty, and clayey microcrystalline calcite (micrite) and siltstone sand grains, with accessory weathered feldspar grains (volumetrically as much as 20 percent locally) and traces of greenish-gray mica. This "dirty" sandstone also contains calcite spar-filled vugs, pelecypod shells (heart-shaped and as large as 3.5 inches [9 cm]), fossil wood, vertebrate bone, and common limonitic replacement of organic fibrous material (bone or plant material?). Nichols (1997) reported Late Cretaceous (Santonian?) pollen from these strata, and Biek and others (2012) recovered late Campanian to Maastrichtian pollen from this same interval, which Biek and others mapped as “Cretaceous strata on the Markagunt Plateau” (Km). The dirty sandstone is underlain by as much as 142 feet (43 m) of predominately "clean" light-gray, friable, well-sorted, fine- to medium-grained, locally cross-bedded, quartz sandstone containing subordinate interbeds of mudstone and conglomeratic sandstone. The clean sandstone is especially prominent along Utah State Highway 14 at the intersection with the Webster Flat–Kolob Reservoir road, about 1000 feet (300 m) west of the border of the Navajo Lake quadrangle. Moore and Nealey (1993) called the combined dirty and clean sandstone units the Kaiparowits(?) Formation of Late Cretaceous age, with a total thickness of about 200 feet (60 m). Subsequent work by Goldstrand and Mullett (1997) showed that the friable white quartz sandstone is the same interval as what they called the middle sandstone member of the Grand Castle Formation; this correlation was subsequently reconfirmed by Biek and others (2012), although they and we reassigned the member to the capping sandstone member of the Wahweap Formation (Kwcs).

The Grand Castle Connection

In stratigraphic studies north, northwest, and northeast of the map area, Goldstrand (1991, 1992, 1994) recognized a thick light-gray (the upper part has a wash of light-red pigment from overlying rocks) conglomerate and sandstone that previous workers had mapped as the basal conglomerate of the Claron Formation until it was broken out as the “beehive unit” in subsequent theses (Moore, 1982; Hilton, 1984). On the basis of similar lithology, Goldstrand tentatively correlated the conglomerate and sandstone with at least the upper part of the Canaan Peak Formation (Bowers, 1972) in the Table Cliff Plateau 44 miles (70 km) east of the map area. Goldstrand considered that a new name was required because in the Table Cliff Plateau, the Canaan Peak is separated from the Claron by the Pine Hollow Formation (Bowers, 1972). Goldstrand and Mullett (1997) formalized the name of the conglomerate and sandstone as the Grand Castle Formation, with a type section only 3 miles (5 km) north of the Brian Head map area (Maldonado and Moore, 1995). At the type section, the Grand Castle contains resistant thick conglomerate beds at its top and base, but an even thicker series of nonresistant sandstone beds (our Kwcs) lies between them, resulting in a total formation thickness of 596 feet (181 m). In measured sections southward along the Markagunt scarp, Goldstrand and Mullett (1997) thought that the conglomerates pinched out southward, leaving only the poorly exposed intervening sandstone remaining south of Cedar Breaks, which in turn thins southward. They correlated the light-gray, friable, clean sandstone and overlying dirty sandstone, respectively at and north of the intersection of Utah State Highway 14 and the Webster Flat–Kolob Reservoir road, with their Grand Castle Formation, and they concluded, incorrectly as we shall see below, that the Grand Castle pinched out south of Utah State Highway 14.

Goldstrand and Mullett (1997) considered the Grand Castle to be Paleocene on the basis of Paleocene palynomorphs (spores and pollen) from the Pine Hollow and Canaan Peak Formations in the Table Cliff Plateau, but in the Markagunt Plateau the only diagnostic fossils (palynomorphs) collected from the formation were of Late Cretaceous age (“possibly” of the Santonian stage), based on a 1991 analysis that they cited as written communication from D.J. Nichols (U.S. Geological Survey). Goldstrand and Mullett (1997) interpreted this Late Cretaceous age assignment to be erroneous, suggesting instead that the sample represented reworked fossils recycled from erosion of underlying rocks. Nichols (1997, p. 93–94) provided more information on this sample, in a report in the same volume as that of Goldstrand and Mullett: the sample was collected 525 feet (160 m) above the base of the

Grand Castle Formation at the type section (in the upper part of their upper conglomerate member) and it is "probably" Santonian.

Initial Correlation to Kaiparowits Basin Strata

As noted above, Nichols (1997) reported on palynomorphs from other parts of the unit called Kaiparowits(?) Formation by Moore and Nealey (1993), not only south of where Goldstrand and Mullett (1997) showed Grand Castle to pinch out in the Navajo Lake quadrangle, but also from rocks correlated with the Grand Castle by Goldstrand and Mullett at the intersection of Utah State Highway 14 and the Webster Flat–Kolob Reservoir road. All had similar fossil pollen and spores. Nichols (1997) concluded that their "Kaiparowits?" Formation is probably Santonian, thus somewhat older than the type Upper Cretaceous Kaiparowits Formation on the Kaiparowits Plateau to the east, which is late Campanian (Titus and others [2005] noted that the Kaiparowits Formation in the type area of the Kaiparowits Plateau contains ash-fall tuffs that have been dated by $^{40}Ar/^{39}Ar$ methods at 76 to 74 Ma, late Campanian). Nichols (1997) suggested that the rock unit in the Markagunt Plateau might better be called "Wahweap?" Formation. Such a designation apparently has merit because the varied lithology of these rocks is like that of the Wahweap, and also because Moore and Nealey (1993) mapped 870 to 1050 feet (265–320 m) of poorly exposed rocks below their "Kaiparowits?" and above the upper Straight Cliffs Formation in the Navajo Lake quadrangle as Wahweap Formation. The Wahweap unit of Moore and Nealey (1993) is chiefly brownish-gray, light-olive-brown, and reddish-brown mudstone that contains 30 to 40 percent silty to fine-grained quartz sand and sparse pure clay, and includes interbedded grayish-orange to dark-yellowish-orange, soft to friable, lenticular beds of cross-bedded clayey sandstone that are 3 to 8 feet (1–2.5 m) thick and contain leaf impressions. The upper third of their Wahweap contains more sandstone than the lower two-thirds. Biek and others (2012) assigned the Wahweap unit of Moore and Nealey (1993) to Eaton's (1991) lower, middle, and upper members, undivided, of the Wahweap Formation (Kw), and they assigned beds overlying the capping sandstone member (Kwcs) to an informal unit "Upper Cretaceous strata on the Markagunt Plateau (Km)." Like Moore and Straub (2001), Biek and others (2012) recognized no significant erosion beneath the Claron Formation at the west edge of the Markagunt Plateau that would suggest a significant hiatus, leading to uncertainty as to the age of the Km interval and the age of basal Claron strata.

A More Detailed Look at the Upper Cretaceous in Cedar Canyon

Moore and Straub (2001) compiled measured sections and undertook sedimentary petrography of Upper Cretaceous rocks across southwestern Utah, including one 2800-foot-thick (850 m) section along Utah State Highway 14, up to the base of the Claron Formation near the intersection with the Webster Flat–Kolob Reservoir road. Even though they found that the rocks they formerly called Wahweap in the Navajo Lake quadrangle do not resemble the type Kaiparowits or Wahweap in gross appearance and petrology, they preferred the name Wahweap, whereas the overlying 142-foot-thick (43 m) clean sandstone they considered Grand Castle Formation except that palynologic data indicated a Late Cretaceous age. Thus they concluded that "further study is needed."

Eaton and others (2001) made a useful summary of the stratigraphic problems but, lacking definitive stratigraphic or fossil evidence, referred to the lower unit (Wahweap of Moore and Nealey [1993] and Moore and Straub [2001]) as the "Wahweap(?) Formation" and the upper unit as "white sandstone" (the clean sandstone at the road intersection), which they interpreted to most likely be the middle sandstone member of the Grand Castle Formation of Goldstrand and Mullett (1997). The uncertainty indicated by Eaton and others (2001) in their use of "Wahweap?" was also because Nichols (1997) found Santonian palynomorphs in the "Kaiparowits?" in the Navajo Lake quadrangle, which overlies the Wahweap of Moore and Nealey (1993) and Moore and Straub (2001), unlike the Campanian type Wahweap and Kaiparowits. Therefore, referring to their "Wahweap?," Eaton and others (2001, p. 343) stated that " it is possible that . . . the entire upper sequence is equivalent to the John Henry Member [of the Straight Cliffs Formation]." Inasmuch as all except the lower part of the Straight Cliffs Formation is Santonian (Eaton and others, 2001; Titus and others, 2005), this interpretation appeared reasonable. However, during the field trip of Eaton and others (2001), J.G. Eaton (verbal communication with P.D. Rowley, 2001) noted that fossils that he recovered from the overall interval should be able to resolve the possible correlation and that, until he studies the fossils in detail, perhaps it is best to call the whole interval by an informal name such as "formation of Cedar Canyon" of Late Cretaceous and Paleocene age (it turned out that these fossils were not age-diagnostic).

Compounding the problem is the fact that at the time, the exact location of the base of the formation of Cedar Canyon and the upper member of the Straight Cliffs was not conclusive because these rocks are poorly exposed and contain no diagnostic beds; both units were deposited largely in floodplains and meandering river channels so rock types are similar. In the Navajo Lake map area, Moore and Nealey (1993) placed the top of the Straight Cliffs Formation at the top of a non-resistant, light-yellowish-brown, quartzite-pebble conglomerate and gray quartzose sandstone that they thought may be equivalent to the Drip Tank Member, the upper member of the Straight Cliffs Formation as defined by Peterson (1969). But similar sandstone beds are present in the lower part of their Wahweap For-

mation that also could be Drip Tank Member, or possibly none of them are Drip Tank Member. Eaton and others (2001) also equivocated and showed this conglomerate and sandstone as "Drip Tank(?) Conglomerate." With all these facts in consideration, Moore and others (2004) took Eaton's advice and named the interval between the Claron and the upper unit of the Straight Cliffs Formation in the Navajo Lake quadrangle as the formation of Cedar Canyon, which they considered a temporary informal name; in the Navajo Lake quadrangle, it has a total thickness of 1070 to 1250 feet (325–380 m) (Moore and others, 2004).

Regional-Scale Mapping

Regional-scale mapping in conjunction with the stratigraphic studies outlined above helped resolve these uncertainties in correlation. It turns out that mapping coarse alluvial strata associated with major sequence boundaries has been the key to working out these correlations. Strata that Goldstrand and Mullett (1997) assigned to their three-part Grand Castle Formation are indeed present along the entire west flank of the Markagunt Plateau, but they thin dramatically southward from the type section. Furthermore, and this is what so confused previous workers, the thin Wahweap-like mudstone interval at the base of their middle sandstone member at the type section thickens dramatically southward. We now know that Goldstrand and Mullett's (1997) middle sandstone member is Late Cretaceous in age based on new pollen samples and the discovery of dinosaur tracks (Hunt and others, 2011; Biek and others, 2012). It also has a detrital zircon signature identical to that of the capping sandstone member of the Wahweap Formation (Johnson and others, 2011). So, as originally suggested by Pollock (1999) and Lawton and others (2003), we can with confidence reassign the middle sandstone member of the originally defined Grand Castle Formation to the capping sandstone member of the Wahweap Formation (Kwcs), which, having been named earlier, has nomenclatural precedence. Mapping of Biek and others (2012) also showed that the lower conglomerate member of the original Grand Castle Formation is in fact the Drip Tank Member of the Straight Cliffs Formation (as originally suggested by Eaton and others, 2001; Moore and Straub, 2001; Lawton and others, 2003; and Eaton, 2006).

The Iron Springs Formation

One additional stratigraphic problem that previous workers faced was whether to call the oldest rocks in the Brian Head and Navajo Lake quadrangles the Iron Springs Formation or the Straight Cliffs Formation. In Cedar Canyon and the Navajo Lake quadrangle, these rocks are interpreted to be Straight Cliffs because they consist of a soft, light-gray, poorly exposed, river-floodplain-derived upper member; an underlying transitional, gray, coal-bearing, brackish-water sequence; and a resistant, light-gray, marginal-marine (pelecypod-bearing) lower member. These three units were interpreted by Eaton and others (2001) to correlate with, respectively, the John Henry, Smoky Hollow, and Tibbet Canyon Members of the type Straight Cliffs Formation on the Kaiparowits Plateau. That division is obvious along Utah State Highway 14, and it is documented by the measured section of Moore and Straub (2001) and the paleontology of Eaton and others (2001) and Eaton (2006).

However, in the northern Brian Head quadrangle and the Parowan quadrangle to the north (Maldonado and Moore, 1995), that division is much less obvious. In that area, all the rocks below what was known as the lower conglomerate member of the original Grand Castle Formation are light-yellow, resistant sandstone beds and subordinate mudstone, shale, siltstone, and conglomerate. They were correlated by Maldonado and Moore with the Iron Springs Formation to the west in the Red Hills and Iron Springs mining district. The Iron Springs Formation is a lumped unit, the westward equivalent to the Kaiparowits, Wahweap, Straight Cliffs, Tropic, and Dakota Formations, and is used where these formations are not readily differentiated. Eaton and others (2001, p. 344) noted, "This remarkable lateral change in depositional style (between Cedar and Parowan Canyons) is puzzling." They suggested that two depositional units may have existed side by side: (1) the Iron Springs Formation along the northern side of the map area, which to the west trended southwesterly to include the present Iron Springs district, Pine Valley Mountains, and eastern Bull Valley Mountains; and (2) an area of multiple formations just south of the map area, which continued south and east. Eaton and others (2001, p. 344) suggested that a basin existed whose western and northwestern side was overwhelmed by abundant sediment supplied from the thrusted highlands to the west, whereas to the south the Cedar Canyon section was represented by a marine embayment. If so, the margin of the bay did not shift significantly laterally to the east or southeast due to this sediment influx. The location of their inferred lithofacies change between the Iron Springs Formation and the lower (Tibbet Canyon) member of the Straight Cliffs Formation is north of Ashdown Creek, which drains Cedar Breaks National Monument. Biek and others (2012), however, found no such significant lithofacies change between the two canyons. It turns out that only the upper John Henry Member is exposed in Parowan Canyon (the entire three-part Straight Cliffs Formation is exposed to the west near Summit Canyon), and that the apparent difference in outcrop habit between Cedar and Parowan Canyons is due largely to increased vegetative and colluvial cover in Cedar Canyon.

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DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Qal **Alluvium** (Holocene)—Youngest alluvium in channels, floodplains, and adjacent low terraces of major streams; interbedded gravel, sand, silt, and clay; grades laterally into alluvium and colluvium (Qac) and alluvial-fan deposits (Qafy, Qacf); maximum thickness about 20 feet (6 m).

$Qat_{2,4}$ **Stream-terrace deposits** (Holocene and upper Pleistocene)—Sand, gravel, silt, and clay that form dissected stream-terrace surfaces above the level of adjacent modern streams in the Ashdown Creek drainage basin; maximum thickness about 20 feet (6 m). Subscript denotes relative height above adjacent stream: level-2 terraces are typically 10 to 30 feet (3–9 m) above modern streams; level-3 terraces are not mapped in this quadrangle; and level-4 terraces are typically 100 to 120 feet (30–35 m) above modern streams.

Qafy **Fan alluvium** (Holocene)—Poorly to moderately sorted silt, sand, and gravel deposited by streams, sheetwash, debris flows, and flash floods on alluvial fans; includes alluvium and colluvium in upper stream courses; surface is modern and generally undissected; maximum thickness at least 30 feet (10 m).

Qc **Colluvium** (Holocene and upper Pleistocene)—Poorly to moderately sorted, clay- to pebble-size, locally derived sediment deposited principally by slope wash and locally reworked by alluvial processes; locally includes Isom Formation boulders derived from weathering of the Markagunt Megebreccia; maximum thickness about 15 feet (5 m).

Qc/Tbh **Colluvium over the Brian Head Formation** (Holocene and upper Pleistocene/Oligocene to Eocene)—Mapped where colluvium conceals the underlying Brian Head Formation; maximum thickness of surficial deposits is about 15 feet (5 m).

Qac **Alluvium and colluvium** (Holocene and upper Pleistocene)—Alluvium in channels, floodplains, and adjacent low terraces of small streams, and laterally gradational colluvium from weathering of adjacent bedrock hills; interbedded gravel, sand, silt, and clay; locally includes Isom Formation boulders derived from weathering of the Markagunt Megebreccia; maximum thickness about 15 feet (5 m).

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; typically 10 to 40 feet (3–12 m) thick.

Qacfo **Older alluvium, colluvium, and fan alluvium** (Pleistocene)—Mapped along the western edge of the map area and in the Mammoth Creek drainage where it forms dissected, coalesced, higher

benches of reworked debris; consists of poorly to moderately sorted, non-stratified, clay- to boulder-size sediment deposited principally by debris flows, debris floods, and slope wash; maximum thickness about 50 feet (15 m).

Qmt **Talus** (Holocene and upper Pleistocene)—Loose, angular rock fragments deposited on steeply sloping surfaces by rock falls; fragments range from silt size to blocks 3 to 15 feet (1-5 m) across; downslope, unit includes colluvium and slope wash; along the Black Ledge fault scarp west and northwest of Sidney Peaks, talus locally exhibits a rumpled surface suggestive of relic rock glaciers; thickness about 6 to 30 feet (2–10 m).

Qms, Qmsh, Qms(Ti)

Landslide deposits (Historical to Pleistocene)—Unsorted, mostly angular, unstratified rock debris moved by gravity from nearby slopes and cliffs; contains youthful, including historical, landslide topography; locally includes talus and colluvium; the reason for most slides in the map area is the combination of high relief and the presence of Brian Head Formation, which contains tuffaceous material that weathers into smectitic clay, which in turn facilitates landsliding when wet or on steep slopes; Qmsh denotes landslides known to be active in historical time, but any landslide deposit may have been historically active even if not so identified; Qms(Ti) denotes a slide made up almost exclusively of the Isom Formation; mostly undivided as to inferred age because 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); thickness variable and uncertain but may locally exceed 200 feet (60 m) thick north and northeast of Brian Head.

Qes **Wind-blown sand** (Holocene and upper Pleistocene)—Well-sorted silt (loess), quartz sand, and clay pellets in vegetated sheets and subdued dunes on the rim of Cedar Breaks National Monument; deposited by winds that ascended the west-facing cliffs; maximum thickness 15 feet (5 m).

Qam **Marsh alluvium** (Holocene and upper Pleistocene)—Dark-yellowish-brown and brownish-black clay, silt, sand, and minor gravel lenses deposited in closed depressions on glacial moraines in the Lowder Creek area east of Brian Head peak; forms marshy areas; includes water-saturated, partly decomposed plant material and minor clay and silt, with a spongy, soft surface; includes peat, as a dense organic mat of grass roots, moss, and herbaceous annuals; locally contains scarce, light-gray chitinous bivalve shells 0.1 to 0.2 in (3–5 mm) across; mapped only at Lowder Creek bog, but unit forms smaller bogs on landslides and on glacial deposits at and near the top of the Markagunt Plateau that have been consistently saturated with water; pollen fossils and tephra that erupted from the Mono Craters of California demonstrate that the peat bogs of the high Markagunt Plateau are at least 17,000 years old (Canaday and others, 2001); thickness 2 to at least 21 feet (0.5–6+ m) (Mulvey and others, 1984).

Glacial Deposits

Glacial till and outwash are present east of Brian Head peak in the Castle Creek and Lowder Creek drainages and, immediately east of the map area, in the lower Castle Creek area. These 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). 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.

Biek and others (2012) reported a new optically stimulated luminescence (OSL) age of 49 ka for pre-Pinedale till exposed on the southeast margin of lower Castle Creek, but were uncertain how to interpret this age. Laabs and Carson (2005) reported that early Wisconsin glacial moraines (MIS 3-4, about 59 to 71 ka; Imbrie and others, 1984) are not known in Utah. However, 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).

Qgtp **Glacial till of Pinedale age** (upper Pleistocene)—Non-stratified, poorly sorted, sandy pebble- to boulder-sized clasts in a matrix of sand, silt, and minor clay; includes scattered subangular bedrock blocks, probably deposited as ground moraine; 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 headwa-

ters of the Castle Creek and Lowder Creek drainage basins; terminal moraine (shown by map symbol) just south of where Castle Creek crosses the eastern map boundary is at an elevation of about 9750 feet (2973 m), whereas the terminal moraine of the smaller Lowder Creek basin is at Long Flat at an elevation of about 10,100 feet (3080 m); recessional and lateral moraines (shown by map symbol) and hummocky, stagnant ice topography (for example, ponds, kettles, and bogs) are locally well developed and little dissected, but sculpted bedrock is absent or inconspicuous, probably owing to the relatively small size and suspected short duration of the glaciers (Mulvey and others, 1984); well-developed terminal and recessional moraines are as much as 120 feet (37 m) thick, but till is much thinner elsewhere and locally consists only of scattered boulders or a veneer of meltout till on bedrock.

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 last glacial maximum 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.

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

Qgtu **Older glacial till of uncertain pre-Pinedale age** (Pleistocene)—Similar to glacial till of Pinedale age, but glacial landforms are poorly preserved or absent; forms a low-relief, rubble-covered, locally hummocky surface both northeast and southwest of the Long Flat cinder cone (peak 10,392, the southernmost map unit Qblfc); the northeast flank of the cinder cone is conspicuously truncated, perhaps by this glacial advance; also forms low hills south of Castle Valley, in the southwestern part of the Panguitch Lake 7.5′ quadrangle, that are composed almost entirely of large blocks of Leach Canyon Formation, with minor blocks of Isom Formation and chalcedony, that we infer to be deeply eroded remains of a medial or recessional moraine (Biek and others, 2012); probably about 10 to 30 feet (3–9 m) thick.

Mulvey and others (1984) and Currey and others (1986) first suggested that glacial till older than Pinedale age may be present in the Brian Head quadrangle, west of Castle Valley. Biek and others (2012) sampled a sandy till exposed in a bluff northwest of the confluence of Mammoth and Crystal Creeks (map unit Qgtou), in the Panguitch Lake quadrangle, that yielded an OSL age of 48.95 ± 19.24 ka, but we are uncertain how to interpret this age as described above. Given the widespread extent and degree of incision of Qgtou deposits, we interpret these glacial deposits to be older, more likely of Bull Lake age.

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

Holocene(?) to Upper Tertiary Basaltic Lava Flows and Cinder Cones

Parts of four basaltic lava flows are present in the eastern part of the map area. The youngest of these is the Red Desert lava flow of latest Pleistocene or possibly early Holocene age, which erupted from a vent to the south in the adjacent Navajo Lake quadrangle. The oldest lava flow, of probable Pliocene age, is the Sidney Peaks flow, so named

for a deeply eroded vent area just northeast of Sidney Peaks. The remaining two lava flows, the Long Flat and Hancock Peak flows, are each probably of middle to early Pleistocene age. The petrology and geochemistry of each flow was described in detail by Moore and others (2004) and Biek and others (2011, 2012), who noted that the rocks have conspicuous olivine+plagioclase+clinopyroxene phenocrysts and glomerocrysts (aggregates of crystals) set in a matrix of olivine, plagioclase, clinopyroxene, Fe-Ti oxides, and glass. Major- and trace-element geochemistry of the flows is available in Biek (2013). Moore and others (1994), Stowell and Smith (2003), and Stowell (2006) also described the petrology and geochemistry of the rocks, and Nealey and others (1994, 1997) and Stowell (2006) discussed the petrogenesis. Sinkholes, many of which are mapped within basalt flows in the southeastern part of the map area, have worked their way upward by solution collapse from the limestone beds in the underlying Claron Formation; south of the map area, such sinkholes locally follow north-northeast trends, which doubtless reflect underlying fractures and small-displacement normal faults (Moore and others, 2004; Biek and others, 2011). The thickness of individual flows is commonly less than 15 feet (5 m) but aggregate thickness, especially in paleovalleys, is much greater and in vent areas the flows and cinders accumulated to at least 600 feet (200 m) thick.

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; lava flow erupted from a vent at a cinder cone about 2 miles (3 km) south of the map boundary; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3–9 m) high, and the lava flow is mostly unvegetated with a rough, blocky surface; age uncertain, but likely late Pleistocene based on morphology and degree of weathering, although Moore and others (2004) considered the lava flow as probably Holocene.

Qblf, Qblfc

Long Flat lava flow and cinder cones (middle Pleistocene)—Medium-gray basalt to hawaiite (sodium-rich trachybasalt) that contains clusters of olivine and clinopyroxene phenocrysts; lava flow (Qblf) erupted from hills having elevations of 10,392 and 10,352 feet, two cinder cones (Qblfc) near Long Flat about 3 miles (5 km) east of Brian Head peak, and another probable vent farther southeast along Utah State Highway 143, now the site of a borrow pit; parts of the lava flow are covered by Pinedale-age glacial till and glacial outwash, and the cinder cones appear to be more heavily eroded than the nearby Hancock Peak cinder cone (Qbhpc); the northeast flank of hill 10,392 is conspicuously truncated and it may have been eroded by a pre-Pindale glacial advance (if so, likely the Bull Lake [Illinoian or MIS 6] advance); 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 its age is uncertain.

$Qbhp_1$, $Qbhp_2$, Qbhpc

Hancock Peak lava flows and cinder cone (middle to lower Pleistocene)—Medium-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; based on chemistry and morphology the map unit is divided into two flows, both of which are well vegetated; erupted from Hancock Peak, a large, well-preserved cinder cone (Qbhpc) in the southeastern corner of the map area; $Qbhp_1$ 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 (Biek and others, 2012); age unknown, but estimated to be middle to early Pleistocene based on comparison with the Long Flat lava flow (Qblf) to the north and the 2.8 Ma Blue Spring Mountain lava flow east of the map area (Biek and others, 2012).

Tbsp **Sidney Peaks lava flow** (lower Pliocene to upper Miocene)—Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts as much as ¼ inch (5 mm) in diameter in a fine-grained groundmass; forms deeply dissected flow and flow breccia remnants that unconformably overlie the Markagunt Megabreccia; deposit just northeast of Sidney Peaks, where it unconformably overlies the Leach Canyon Formation and the Markagunt Megabreccia, consists of lava blocks in a cinder matrix, is locally cut by basaltic dikes, and may be a deeply eroded vent area; age uncertain, but probably early Pliocene or late Miocene based on comparison with dated flows elsewhere on the Markagunt Plateau; about 40 feet (12 m) thick.

BEDROCK UNITS

Tm, Tm(Tqcb), Tm(Ti), Tm(Tnw), Tm(Tbh)

Markagunt Megabreccia (Miocene)—Poorly exposed, structurally chaotic assemblage of angular clasts and sheared, brecciated, and broken mass-

es of older rock units spread by a large gravity slide over what is now the northern and central Markagunt Plateau (Sable and Anderson, 1985; Anderson, 1993; Sable and Maldonado, 1997b; Biek and others, 2012). Slide rocks in the map area are dominated by the Isom Formation (Ti; see discussion below), a resistant, regional ash-flow tuff (Mackin, 1960; Fleck and others, 1975; Best and others, 1989a), but older rocks of the resistant Wah Wah Springs Formation (Tnw) and the soft Brian Head Formation (Tbh) are also exposed in the upper plate of the Markagunt Megabreccia. Where they are part of the gravity slide mass, both the Isom and Wah Wah Springs Formations are lithologically different from nearby in-place outcrops in the map area, as discussed below, indicating distant transport. The upper plate rocks were variably emplaced on the Mount Dutton Formation (Td), Leach Canyon Formation (Tql), and Isom Formation (Ti) in the northern and central part of the map area, and on the Brian Head and Claron Formations in the southern part of the map area. In the central and eastern parts of the map area, the Markagunt Megabreccia is locally well exposed and mapped by its individual components Tm(Tqcb, Ti, Tnw, Tbh), but where poorly exposed or where it consists of brecciated rocks of more than one unit, it is mapped as Markagunt Megabreccia (Tm).

In the southern part of the map area and in the Navajo Lake quadrangle, the unit consists of poorly exposed hills of breccia, mapped as Markagunt Megabreccia (Tm and Tm[Ti]) sitting on Brian Head or Claron Formation. South of Mammoth Creek, the Markagunt Megabreccia consists locally only of scattered, isolated, angular blocks of Isom Formation and minor agatized limestone of the Brian Head Formation unconformably on the Brian Head and Claron Formations. Being thin and scattered, these latter deposits are not mapped or are included within alluvium and colluvium deposits (Qac) or colluvium deposits (Qc). In the Navajo Lake quadrangle, they are similarly not mapped or are included in volcanic gravel colluvium (Qcv) or gravelly decomposition residuum and colluvium (QTrg). The isolated, angular blocks overwhelmingly consist of the Isom Formation and are as large as 16 feet (5 m) long (Hatfield and others, 2000b, 2010, figure 6), resembling glacial erratics. Many blocks of the Isom Formation are autobrecciated, that is internally brecciated (figure 6; see also Hatfield and others, 2000b, 2010, figure 7), then "healed" into hammer-ringing resistant rock presumably by devitrification and silicification of the tuff. Where appearing as unconsolidated rubbly outcrops or isolated blocks, Hatfield and others (2000b, 2000c, 2010) and Moore and others (2004) attributed it to being let down from a higher-level surface by sapping and dissolution of the underlying limestone in the Brian Head and Claron Formations, which formed abundant sinkholes in and south of the map area. Maximum thickness in the map area is about 450 feet (140 m); in the places where they are components of the slide mass, the Isom Formation is as much as 300 feet (90 m) thick, the Wah Wah Springs Formation is as much as 40 feet (12 m) thick, and the Brian Head Formation is as much as 150 feet (45 m) thick.

Quichapa Group (Miocene and Oligocene)—Three distinctive regional ash-flow tuffs that form a recognizable package spread over large parts of southwestern Utah. Their widespread distribution allowed their recognition as tuffs rather than lava flows (Mackin, 1960). From top to base, the Quichapa Group comprises the Harmony Hills Tuff, Condor Canyon Formation, and Leach Canyon Formation (Williams, 1967; Anderson and Rowley, 1975); the Harmony Hills Tuff is not present in the map area.

Tqcb **Bauers Tuff Member of the Condor Canyon Formation** (lower Miocene)—Resistant, medium-brown, densely welded, crystal-poor (15 to 20 percent phenocrysts), dacitic to trachydacitic ash-flow tuff; forms a single cooling unit present only near White Hill in the northwestern corner of the map area where it is part of the Markagunt Megabreccia; derived from the northwestern part (Clover Creek caldera) of the Caliente caldera complex of Nevada and Utah (Rowley and others, 1995); $^{40}Ar/^{39}Ar$ age of both its outflow tuff (Best and others, 1989b) and its intracaldera intrusion is 22.8 Ma (Rowley and others, 1994b); probably about 50 feet (15 m) thick.

Tql **Leach Canyon Formation** (upper Oligocene)—Resistant, tan, poorly welded, crystal-poor (15 to 20 percent phenocrysts), low-silica rhyolite ash-flow tuff; single cooling unit whose lower part consists of a resistant, platy, dark-brown and black basal vitrophyre as much as 20 feet (7 m) thick that is locally underlain by a non-resistant, pale-orange, unwelded ash-fall tuff as much as 15 feet (5 m) thick (figure 7); characterized by as much as 1 percent bright-red and gray lithic clasts (rock fragments) of flow rock torn from the magma chamber or vent, and common, little-collapsed, cognate pumice fragments, each as much as 0.5 inch (1.5 cm) long; probably derived from the Caliente caldera complex based on isopachs that show the Leach Canyon Formation thickening toward the complex (Williams, 1967; Rowley and others, 1995); $^{40}Ar/^{39}Ar$ age is about 23.8 Ma (Best and others, 1993; Rowley and others,

1995); 55 to 100 feet (17–30 m) thick.

Td **Mount Dutton Formation** (Miocene)—Moderately resistant, light- to medium-gray, volcanic mudflow breccia made up of dark-gray and black, matrix-supported, angular and subangular clasts of crystal-poor dacitic and andesitic flow rock in a fine-grained matrix (former mud) (Anderson and Rowley, 1975); mapped northeast of Sidney Peaks, where it forms small patches that post-date the Leach Canyon Formation (Tql) and pre-date emplacement of the Markagunt Megabreccia (Tm); maximum thickness about 10 feet (3 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. The Marysvale volcanic field is one of several voluminous calc-alkaline, subduction-related volcanic centers and underlying source plutons that characterized the West from Oligocene to Miocene time at this latitude (Lipman and others, 1972; Rowley and Dixon, 2001). Fleck and others (1975) and Rowley and others (1994a) reported several K-Ar ages of 23 to 30 Ma on rocks of the coeval vent facies, but only the youngest part of the formation is present in the map area. The alluvial facies is at least 1000 feet (300 m) thick in the map area 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 an east-trending string of stratovolcanoes along the southern part of the Marysvale volcanic field.

Ti **Isom Formation** (Oligocene)—Resistant, medium- to dark-brown, black, reddish-brown, brick-red, and greenish-brown, crystal-poor, densely welded, trachydacitic ash-flow tuff; comprises at least three cooling units in the map area, some of which have black basal vitrophyres and local flow-breccia bases; below Brian Head peak, the top of

Figure 7. *View north to Leach Canyon Formation on the south side of Brian Head peak (see figure 1), the most complete section of this formation exposed on the Markagunt Plateau. Here, the classic three-part section of an ash-flow tuff is exposed, including an unwelded basal ash-fall tuff, a thick vitrophyre, and moderately welded ash-flow tuff which caps Brian Head peak. A flow breccia of the Isom Formation (Ti) is present in the lower left corner of the photograph; its contact with the Leach Canyon is concealed by talus.*

the Isom is at least 40 feet (13 m) of breccia, interpreted to be flow breccia. Together with the Leach Canyon Formation, the Isom Formation (figures 8 and 9) forms the prominent cliff of Black Ledge that trends northeast from Brian Head peak. All Isom cooling units are densely welded and show evidence of rheomorphic flow (flowed during the last several dozens of feet of emplacement), as indicated by steep flow folds common west of the map area, by basal flow breccias, and by linear vesicles (figure 10); thus the map unit was considered to be a lava flow until Mackin (1960) and Williams (1960) traced it widely over western Utah and eastern Nevada and found petrographic evidence in the basal glass that the matrix consists of welded glass shards. Where in place in the map area, cooling units contain distinctive linear vesicles 0.08 inch (2 mm) to 0.3 inch (1 cm) in diameter and drawn out laterally 1 to 2 inches (3–6 cm) during flow, and the tuffs contain only 5 to 15 percent phenocrysts. In contrast, however, where included in the Markagunt Megabreccia, the Isom Formation consists of several cooling units with linear vesicles and an upper distinctive cooling unit that is recognizable as the main cooling unit of the Baldhills Tuff Member in the formation's type area in the Iron Springs mining district west of Cedar City (Mackin, 1960; Anderson and Rowley, 1975). In that area, the Baldhills Tuff Member is a massive, more crystal-rich (15 to 25 percent phenocrysts) tuff that lacks linear vesicles but contains lighter colored, vesicular, planar lenticules as much as 1.5 feet (0.5 m) long in the plane of bedding and 1 inch (2 cm) thick. The closest this cooling unit is recognized in place is several miles north of the map area, the likely source of the slide mass of the Markagunt Megabreccia (Sable and Maldonado, 1997b). The Isom Formation is probably derived from the Indian Peak caldera complex (Best and others, 1989a, 1989b); the age appears to be about 26–27 Ma on the basis of many $^{40}Ar/^{39}Ar$ and K-Ar ages (Best and others, 1989b; Rowley and others, 1994a). The maximum thickness where in place is about 350 feet (107 m) along Black Ledge; its maximum thickness within the Markagunt Megabreccia

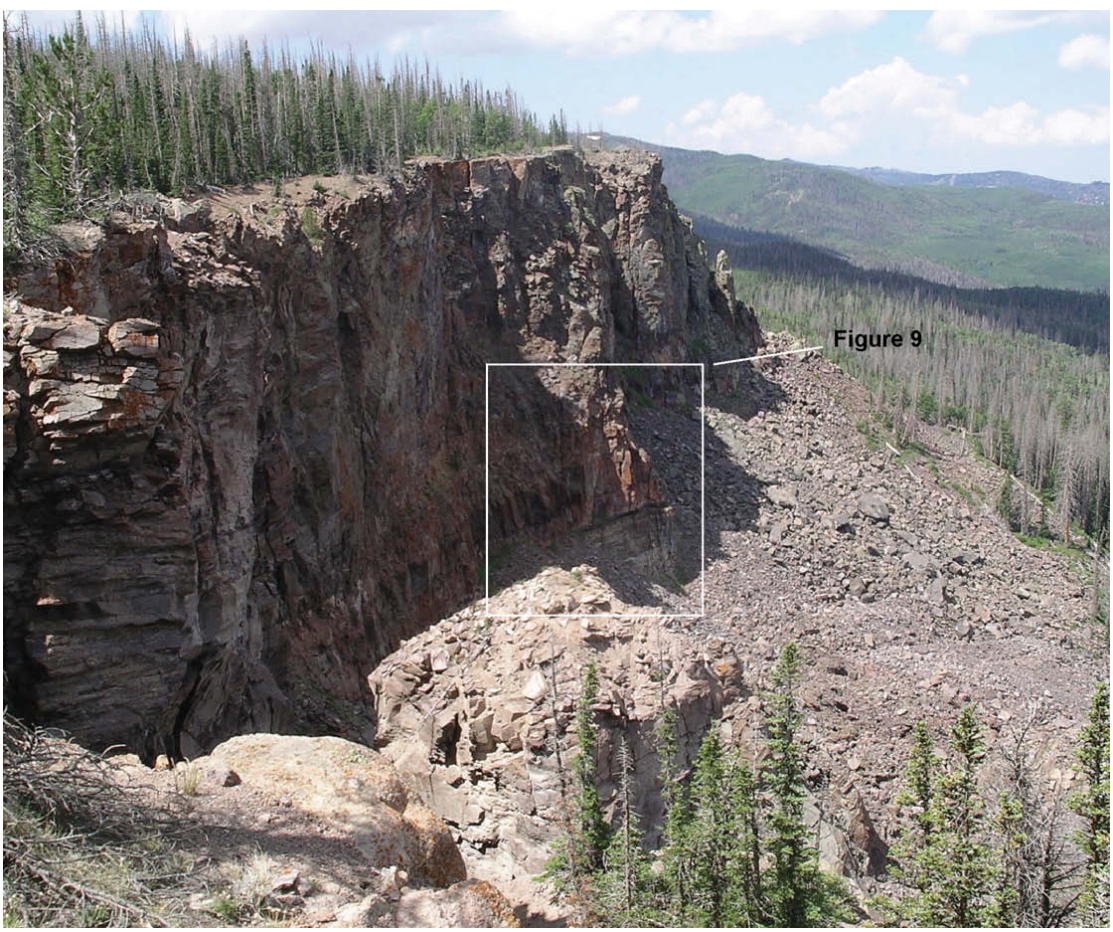

Figure 8. *View southwest to Black Ledge near Yankee Datum (elevation 10,172) in the northeast corner of the map area. Here, Black Ledge appears to consist of a single cooling unit of the Isom Formation, in addition to an unusual underlying pebbly sandstone and breccia phase (see figure 9).*

about 300 feet (100 m).

Tnw **Wah Wah Springs Formation of the Needles Range Group** (Oligocene)—Resistant to non-resistant, light-red, medium-gray, and pink, crystal-rich (30 to 40 percent phenocrysts), moderately welded, dacite ash-flow tuff that contains sparse lithic clasts and partly collapsed, cognate pumice fragments. Where in place, it is exposed only along the upper part of Lowder Creek, where it is non-resistant and overlain by about 10 feet (3 m) of tuffaceous sandstone mapped with Wah Wah Springs, but identical to sandstone of the Brian Head Formation below it; the poorly welded nature of the ash-flow tuff and its stratigraphic position here suggests that it was emplaced into a lake. The Wah Wah Springs Formation is present in the Markagunt Megabreccia only in the eastern part of the map area, where it is resistant and moderately welded and was derived from areas to the north (Sable and Maldonado, 1997b; Biek and others, 2012) by gravity sliding. It erupted from the Indian Peak caldera complex (Best and others, 1989a, 1989b) along the Utah-Nevada border; Best and others (1989a) considered it to have an age of 29.5 Ma, and Rowley and others (1994a) reported four K-Ar ages of 29 to 32 Ma from biotite-hornblende pairs from two samples collected from Lowder Creek. Its thickness where in place along Lowder Creek is 3 to 8 feet (1–3 m), and maximum thickness in the Markagunt Megabreccia is as much as 40 feet (12 m).

Tbh **Brian Head Formation** (Oligocene and Eocene)—Mostly poorly resistant, pink and light-gray, tuffaceous, fluvial sandstone, siltstone, shale, and minor conglomerate and locally resistant 2- to 6-foot-thick (1–2 m) ledges of white lacustrine micritic limestone that has characteristically been partly to mostly replaced by tan, light-gray, orange, yellow, green, red, and brown agate (chalcedony); formation rests unconformably upon the Claron Formation, which is not tuffaceous. The Brian Head Formation was first defined by Gregory (1944) to describe a thick package of sedimentary and volcanic rocks that included at its base the white member of the Claron Formation; the name was abandoned by Anderson and Rowley (1975) because of confusion over its use, especially the improper inclusion of basal volcanic rocks of the Marysvale volcanic field in areas to the north. Based on mapping in the Red Hills

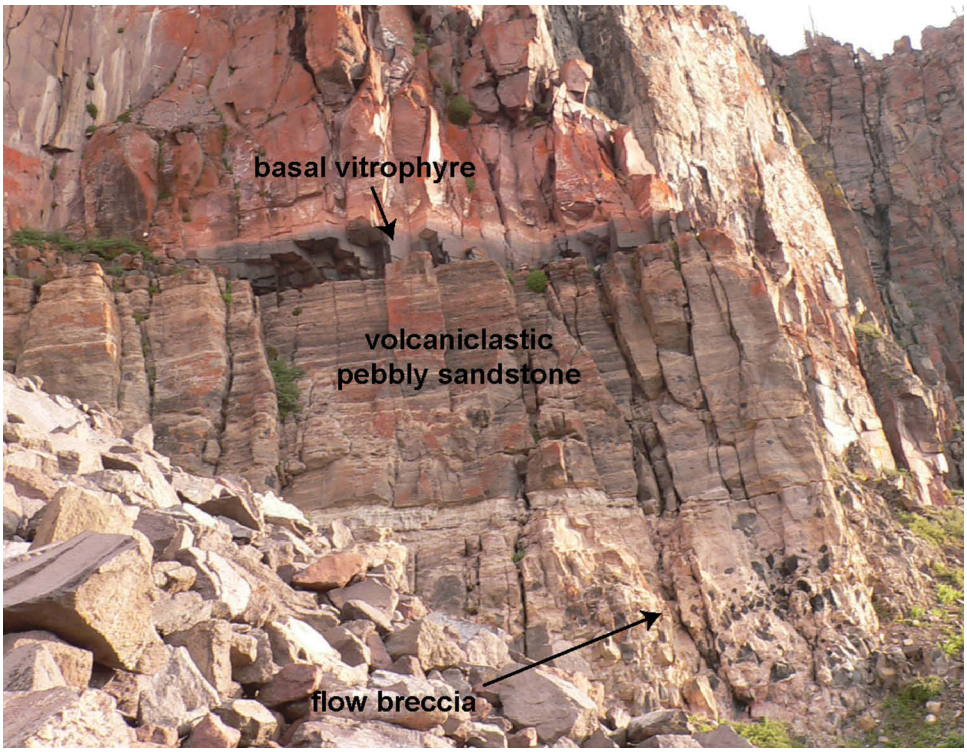

Figure 9. *The lower part of the Isom Formation, just east of Yankee Meadows Reservoir, contains two unusual components that we have not observed elsewhere. Here, a 3-foot-thick (1 m) vitrophyre marks the base of densely welded Isom that is reddish-brown in its lower part and that grades upward into typical dark-gray Isom. The vitrophyre overlies as much as 30 feet (9 m) of volcaniclastic pebbly sandstone with planar and low-angle cross-stratification and whose clasts are angular to subangular fragments of Isom Formation. This volcaniclastic unit in turn overlies several tens of feet of flow breccia or possibly volcanic mudflow breccia whose angular Isom clasts are completely cemented by calcite.*

west of the Markagunt Plateau, Maldonado and others (1990) proposed an informal name "sedimentary and volcanic rocks of the Red Hills" for a much-restricted part of the interval, and Anderson (1993) reintroduced the name "Brian Head Formation" for the same restricted unit in the Markagunt Plateau. Sable and Maldonado (1997a) provided a detailed discussion and type section of the redefined Brian Head Formation at Brian Head peak, which they divided into three units: (1) an upper volcanic unit, locally present in the northern Markagunt Plateau but not in the map area, characterized by volcanic mudflow breccia, mafic lava flows, volcaniclastic sandstone and conglomerate, and ash-flow tuff; (2) a middle unit of thick, soft, gray, greenish-gray, and yellowish-gray, bioturbated, thin-bedded, volcaniclastic clayey sandstone, conglomeratic sandstone, claystone, micritic limestone (commonly replaced by chalcedony), and ash-fall tuff; and (3) a lower unit of soft, thin-bedded, reddish-brown and pink, nontuffaceous, calcareous siltstone and mudstone with minor silty sandstone and micritic limestone and a thin, capping, non-volcaniclastic pebble conglomerate, reassigned by Biek and others (2012) to a new uppermost unit (Tcwt) of the white member of the Claron Formation. Largely because of the ash-fall tuff, which has weathered to bentonitic clay, the middle member of Sable and Maldonado (1997a) is weak and prone to landsliding virtually wherever exposed; the Markagunt Megabreccia is interpreted to have slid primarily on this unit in the map area.

The Brian Head Formation is early Oligocene to latest middle Eocene in age, about 30 to 36 million years old. The upper part of the middle unit in Lowder Creek is overlain by the 29.5-Ma Wah Wah Springs Formation (Tnw) (Rowley and others, 1994a; Sable and Maldonado, 1997a; Hatfield and others, 2000b, 2010). 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; see also UGA and A-to-Z, 2013) obtained U-Pb ages on zircon from an ash-fall tuff at the base of the formation at Cedar Breaks National Monument of 35.77 ± 0.28 Ma, and from the Sevier Plateau of 36.51 ± 1.69 Ma. In the Red Hills to the west, 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

Figure 10. *Flow foliation in the Isom Formation at Brian Head peak.*

that lies in the upper part of the formation, and in the Panguitch Lake area, tuffs in the upper part of the formation yielded $^{40}Ar/^{39}Ar$ ages on sanidine of 35.04 ± 0.23 Ma and 33.80 ± 0.05 Ma (Biek and others, 2012; UGS and NIGL, 2012). As mapped, the Brian Head Formation is rarely exposed because it is largely buried beneath a residual and colluvial mantle of debris let down from the overlying Isom and Leach Canyon Formations and the Markagunt Megabreccia. The Brian Head Formation is about 500 feet (150 m) thick at its type section on Brian Head peak.

unconformity

Claron Formation (Eocene and Paleocene)—The Claron Formation has traditionally been divided into two informal members, a lower pink member and an upper white member, and the formation has a long and complicated nomenclatural history as described by Anderson and Rowley (1975) and Biek and others (2012). We map the Claron Formation as five informal lithostratigraphic units described below: an upper white member (Tcw, which, where exposures are good, is itself divided into an uppermost mudstone unit [Tcwt], an upper limestone unit (Tcwu), a middle mudstone and sandstone unit [Tcwm], and a lower limestone unit [Tcwl]), and the lower pink member (Tcp). The Claron Formation consists of mudstone, siltstone, sandstone, limestone, and minor conglomerate, all calcareous, 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).

The Claron Formation forms a bold escarpment 900 to 1100 feet (270–340 m) high at the edge of the Markagunt Plateau and is spectacularly exposed as the colorful beds and hoodoos of the "Pink Cliffs" at Cedar Breaks National Monument (figure 2); this unit also makes up the famous similar landforms of Bryce Canyon National Park, 50 miles (80 km) east of the mapped area. Dissolution of faulted and fractured limestone, especially in the pink member and especially to the south (Moore and others, 2004), has resulted in sinkholes that are well expressed at the surface and thus mapped; many sinkholes have dropped down overlying rock units, especially basaltic flows. Hatfield and others (2000a, 2000b, 2000c, 2010) suggested that, over time, growth of multiple sinkholes let down much of the Markagunt Megabreccia (Tm) in the southern part of the map area and farther to the south; if so, this would explain why little of that formerly extensive gravity-slide mass remains intact there.

The age of the Claron Formation is poorly constrained because of a general lack of diagnostic fossils and because soil-forming processes (Mullett and others, 1988a, 1988b; Mullett, 1989; Mullett and Wells, 1990; see also Bown and others, 1997) obliterated many of the beds and fossils. The age of the white member is late middle Eocene (Duchesnean Land Mammal Age) based on (1) sparse vertebrate fossils from this unit on the eastern Markagunt Plateau (Eaton and others, 2011), (2) 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, and (3) by a U-Pb detrital zircon age of 37.97 +1.78/- 2.70 Ma from the overlying conglomerate at Boat Mesa on the southwestern Sevier Plateau.

The maximum age of the pink member, however, is poorly constrained. Goldstrand (1994) reported on gastropods he collected from the lower Claron that were analyzed by J.G. Eaton, who concluded that they are identical to those from the Flagstaff Formation of central Utah and used by LaRocque (1960) to assign a Paleocene to Eocene age to that formation; Goldstrand (1994) also found late Paleocene palynomorph (spores and pollen) fossils in basal Claron rocks from the eastern Pine Valley Mountains, 30 miles (50 km) southwest of the map area. Goldstrand and Eaton (2001) considered the Claron to be entirely Eocene, but J.G. Eaton (written communication, 2008) currently considers the Claron to be Paleocene and Eocene based on study of charophyte and vertebrate fossils in the Claron and overlying Brian Head Formation from the Sevier Plateau (Feist and others, 1997; Korth and Eaton, 2004). 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.

Tcw **White member, undivided** (Eocene)—The white member, individual units of which are described below, is undivided in the northwest part of the map area due to incomplete, poor exposures. In aggregate, Hatfield and others (2000b, 2010) reported that the white member is 360 feet (110 m) thick at Cedar Breaks National Monument, but including the lower sandstone and conglomerate unit of Sable and Maldonado (1997b), as suggested here, the thickness is 440 feet (135 m).

Tcwt **Uppermost mudstone, siltstone, and sandstone unit of white member** (upper and middle Eocene)—Varicolored and commonly mottled, light-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 in the

northern part of Cedar Breaks National Monument (figure 11), where it is best exposed near the North View Overlook. There, it is 109 feet (33 m) (Schneider, 1967) of mudstone and siltstone capped by a thin calcareous sandstone and pebbly conglomerate, described below.

Schneider (1967) reported biotite in some of these beds, and while some beds exhibit slightly expansive soils, we found no biotite—even so, it was the apparent presence of biotite-bearing strata, and possible correlation to variegated strata on the southern Sevier Plateau (see Feist and others, 1997), that led Sable and Maldonado (1997b) to provisionally include these strata on the Markagunt Plateau as part of their Brian Head Formation. However, the Markagunt Plateau exposures strongly suggest to us that the nontuffaceous sandstone and conglomerate as defined by Sable and Maldonado (1997b) is simply our uppermost facies of the Claron Formation (Tcwt) and the overlying conglomerate at Boat Mesa. We place an unconformity at the base of the thin sandstone and conglomerate (not at the top of the limestone ledge of the white member), thereby including the Claron-like red beds as a new upper unit of the white member.

Tcwu **Upper limestone unit of white member** (upper and middle Eocene)—White, light-yellowish-gray, pinkish-gray, and light-orange micritic limestone and uncommon pelmicritic limestone, lo-

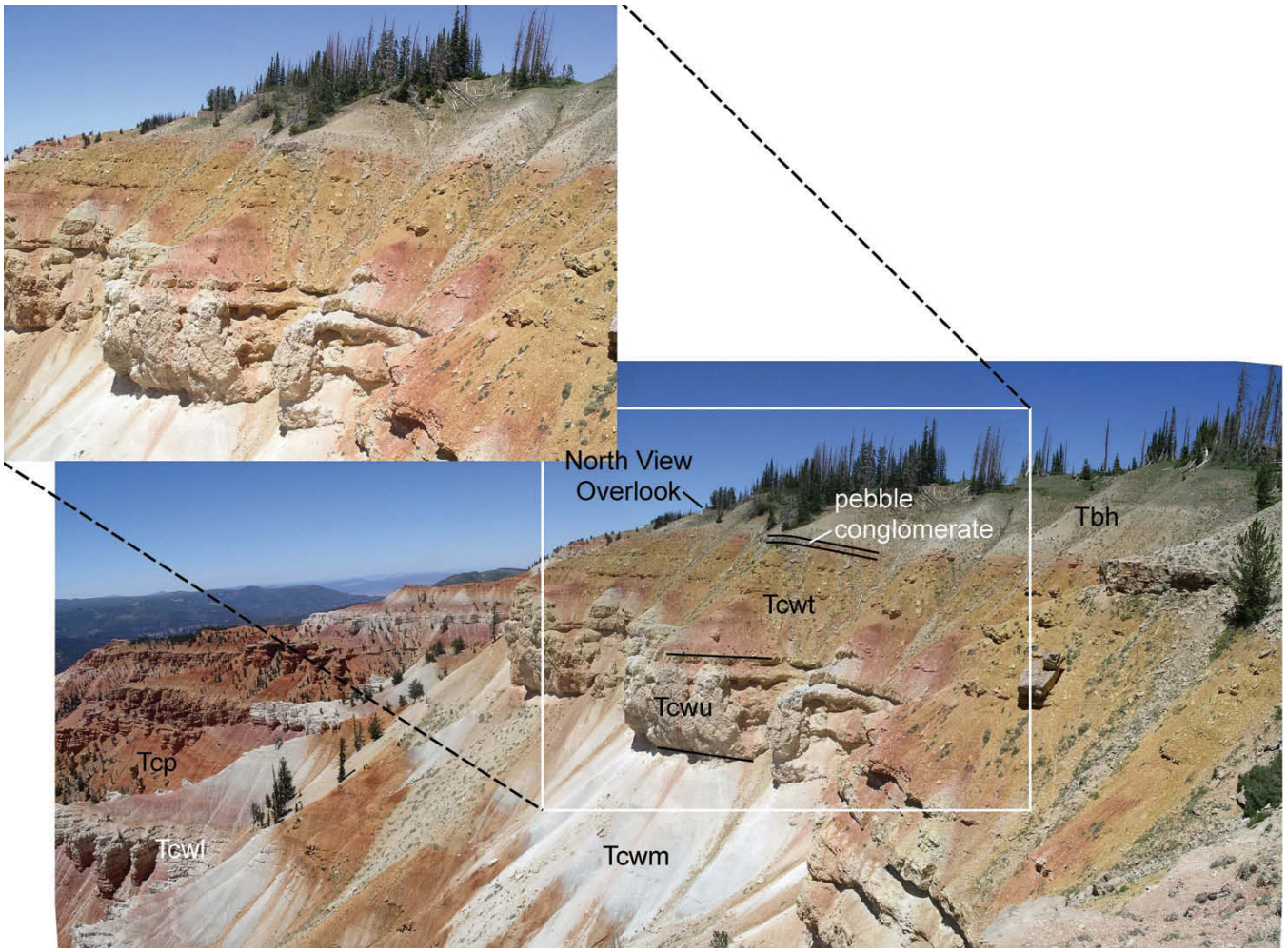

Figure 11. *View northwest to North View Overlook at Cedar Breaks National Monument showing contact between Claron and Brian Head strata (the North View Overlook is on basal strata of the gray volcaniclastic unit of the Brian Head Formation, Tbh). Sable and Maldonado (1997b) assigned variegated, nontuffaceous mudstone, siltstone, and minor sandstone and pebble conglomerate (here labeled Tcwt, 109 feet [33 m] thick) to their lower Brian Head Formation. However, these strata appear identical to strata of the middle white unit (Tcwm); they are nontuffaceous and appear simply to be an uppermost facies of the white member of the Claron Formation, to which we assign them. The top of the Claron, as defined here, is marked by a thin, calcareous, pebbly conglomerate that has rounded clasts of chert, quartzite, and Claron limestone but no volcanic clasts; this conglomerate may be equivalent to the informally named conglomerate at Boat Mesa on the Paunsaugunt Plateau, which marks a significant unconformity in southwest Utah.*

cally 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, forms prominent ledge and flat ridge tops; upper conformable contact with Tcwt corresponds to a pronounced color change from white to light-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 across 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).

Tcwm **Middle mudstone, siltstone, and sandstone unit of white member** (upper middle Eocene)—Varicolored and commonly mottled, light-reddish-orange, reddish-brown, moderate-orange-pink, yellowish-gray, dark-yellowish-orange, and grayish-pink calcareous mudstone and siltstone, and minor fine-grained calcareous sandstone and chert-pebble conglomerate that weathers to a poorly exposed slope; upper conformable contact corresponds to a pronounced color change from slope-forming, brightly colored reddish-orange mudstone and siltstone below to ledge-forming, white to light-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. At Cedar Breaks National Monument, Schneider (1967) measured 227 feet (69 m) of strata we assign to Tcwm, but we find that this interval is 310 feet (94 m) thick in this same area.

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); contains sparse charophytes; upper conformable contact corresponds to a pronounced color change from white to light-orange micritic limestone below to brightly colored reddish-orange mudstone and siltstone above. Like the upper limestone unit, the lower limestone unit of the white member thickens irregularly to the east (Biek and others, 2012). This unit is only about 47 feet (14 m) thick at Cedar Breaks National Monument (Schneider, 1967).

Tcp **Pink member** (Eocene and Paleocene) —Alternating beds of light-red, pink, grayish-orange, and dark-yellowish-orange, calcite-cemented sandstone, calcareous mudstone and siltstone, sandy limestone, and minor pebble conglomerate. 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' (1972) term "pink member" for the lower Claron, noting that these strata have been informally known as the red member on the Markagunt Plateau.

Most limestone beds are massive (3 to 6 feet [1–2 m] thick), structureless micrite that is locally argillaceous and generally sandy (2 to 20 percent uniformly dispersed fine quartz sand); much of the pink member was 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 others, 1997); limestone commonly contains calcite spar-filled vugs and thin branching veinlets of calcite spar, with crystals 0.02 to 0.08 inch (0.5–2 mm) long, as well as stylolites; calcite spar- and micrite-filled vertical burrows 0.2 to 2 inches (0.5–4 cm) in diameter and 4 to 20 inches (10–50 cm) long are abundant in some limestone beds, and some contain pebble-sized intraclasts that are in places angular and chaotically juxtaposed and so impart a breccia-like appearance to the rock; rare limestone beds contain oncolites, micrite balls 0.08 to 1 inch (0.2–2 cm) in diameter that have concentric laminations, or "onion-like" structure.

Interbedded throughout the unit is sandstone and mudstone; the sandstone forms ledges and is a varicolored, thick-bedded, calcite-cemented quartz arenite that is cross-bedded in places; the mudstone is silty and calcareous, contains calcareous nodules, and weathers to earthy, steep slopes between ledges of sandstone and limestone. Conglomerate crops out as lenticular beds, 6 to 16 feet (2–5 m) thick, and it interfingers with grayish-pink to medium-gray, firmly cemented, quartzose sandstone; sandy quartzite-pebble conglomerate was seen at 30 feet (9 m), 39 feet (12 m), 138 feet (42 m), and 207 feet (63 m) above the base of the pink member in the Navajo Lake quadrangle (Moore and others, 2004); conglomerate beds persist 300 to 1000 feet (100–300 m) laterally before pinching out; they apparently are fluvial point-bar and channel deposits. The member is locally cavernous, with abundant dissolution cavities and surficial sinkholes. These sinkholes capture local runoff and serve to shunt

shallow groundwater rapidly down dip where it emerges as springs, including the large Mammoth and Asay Springs (Wilson and Thomas, 1964; Spangler, 2010).

The base of the pink member is placed at the bottom of the lowest limestone (calcic paleosol) bed following Moore and Straub (2001). The pink member is mostly nonfossiliferous and its age is poorly constrained as Eocene to Paleocene(?) (Goldstrand, 1994), but Nichols (1997) reported Late Cretaceous (Santonian?) pollen from underlying strata here mapped as Km south and west of Blowhard Mountain; Biek and others (2012) recovered late Campanian to Maastrichtian pollen from this same interval. We see no evidence of a significant unconformity between these apparently Upper Cretaceous strata and overlying Claron Formation, suggesting that the lower part of the Claron Formation may be older than previously thought. Measurements from the map suggest that the pink member is about 1000 feet (305 m) thick at Cedar Breaks National Monument, 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), considerably less than the 1300 feet (400 m) reported in Sable and Maldonado (1997b).

Km **Cretaceous strata on the Markagunt Plateau** (Upper Cretaceous, Maastrichtian? to Santonian?)—Yellowish-brown, commonly stained dark-reddish-brown, fine-grained sandstone and lesser interbedded, similarly colored mudstone and siltstone; bedding is thin to thick and appears tabular from a distance; weathers to ledgy slope or cliff; outcrop habit and surficial color make it look like the pink member of the Claron Formation from a distance (figure 12); not mapped in Parowan Canyon, where basal Claron strata are conglomeratic and identification of this interval, if present, is uncertain; farther south, along the western part of the map area, the upper contact is placed at the base of the lowest sandy limestone bed (calcic paleosol) of the pink member of the Claron Formation, following Moore and Straub

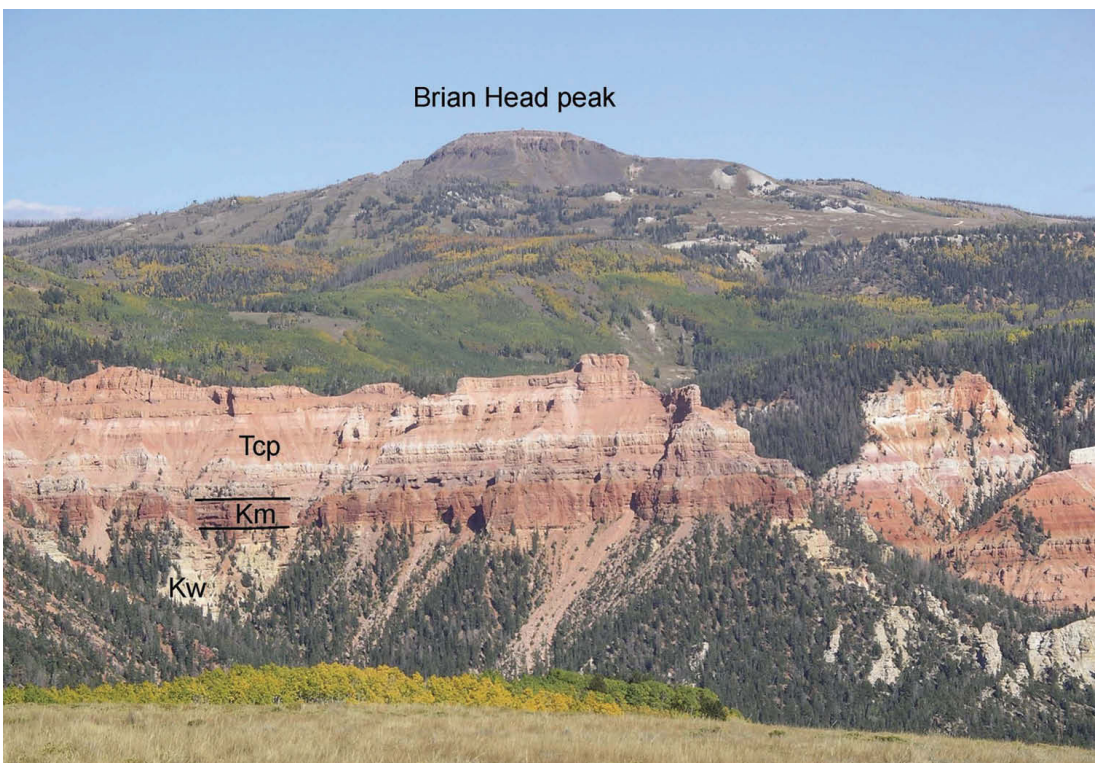

Figure 12. *View east-northeast to Brian Head peak from High Mountain, which is just west of the map area. Lake Creek is just beyond the meadow in the foreground, and Rattlesnake Creek is beyond the red ridge. Sandstone cliff (Km) is stained dark reddish brown from runoff from overlying pink member of the Claron Formation (Tcp). In most areas south of Parowan Canyon, the base of Km corresponds to the top of a thin pebble to small cobble conglomerate containing rounded quartzite and limestone clasts correlated with the Grand Castle Formation (redefined), although in some areas, as here, the conglomerate appears to be missing. Underlying yellowish-brown mudstone, siltstone, and sandstone are assigned to the Wahweap Formation (Kw). The base of the Claron Formation corresponds to the base of the first limestone bed, likely a calcic paleosol.*

(2001). Map unit represents fluvial and floodplain environments apparently gradationally overlain by the Claron Formation. Like Moore and Straub (2001), we recognize no significant erosion beneath the Claron Formation at the western edge of the Markagunt Plateau, leading to uncertainty as to the age of this interval and the age of basal Claron strata. However, Nichols (1997) reported Late Cretaceous (Santonian?) pollen from strata we map as Km south and west of Blowhard Mountain, and Biek and others (2012) reported Maastrichtian to late Campanian pollen from this same interval. The apparently gradationally overlying basal Claron Formation is widely believed to be late Paleocene(?) (Goldstrand, 1994) based on one report of late Paleocene palynomorphs from basal Claron strata on the eastern flank of the Pine Valley Mountains and the gastropods *Viviparus trochiformis, Goniobasis,* and *Physa* from the pink Claron on the Table Cliff Plateau, eastern Pine Valley Mountains, and Bryce Point, respectively (Goldstrand, 1991). We treat these strata as a separate informal unit, but it is possible that they are better assigned to the base of the Kaiparowits Formation (Biek and others, 2012). The unit is about 200 feet (60 m) thick near State Highway 14 at the western edge of the Markagunt Plateau (about 3 miles [5 km] south of the map area), where it correlates with the "dirty salt-and-pepper sandstone" of Moore and Nealey (1993), but thins to the north where it may be about 60 feet (20 m) thick in Parowan Canyon (Biek and others, 2012).

Kgc **Grand Castle Formation, redefined** (Upper Cretaceous)—Light-gray and light-red massive conglomerate; clasts are well-rounded, pebble- to boulder-size quartzite, limestone, sandstone, and chert; cliff-forming in the Parowan Canyon area where it locally weathers to form hoodoos; redefined and restricted to only the upper of three informal members (resistant upper conglomerate, nonresistant middle sandstone, and resistant lower conglomerate) of the Grand Castle Formation of Goldstrand and Mullett (1997), with their type section in First Left Hand Canyon southeast of Parowan and 3 miles (5 km) north of the map area. The upper contact with strata here mapped as Km appears gradational and corresponds to the base of ledge- and cliff-forming, tabular bedded sandstone that is stained dark reddish brown from overlying Claron strata (figure 12).

Map unit deposited in a braided fluvial environment with paleoflow principally to the east to south-southeast, suggesting source areas in the Wah Wah, Blue Mountain, and Iron Springs thrust sheets of southwest Utah (Goldstrand and Mullett, 1997). Goldstrand and Mullett (1997) inferred a Paleocene age for their entire Grand Castle Formation based on distant correlations with the Canaan Peak and Pine Hollow Formations on the Table Cliff Plateau. Biek and others (2012), however, reported evidence that the lower two members of the originally defined Grand Castle Formation are Late Cretaceous and thus were reassigned, in descending order, as the capping sandstone member of the Wahweap Formation (Kwcs) and the Drip Tank Member of the Straight Cliffs Formation (Ksd), as described below. The age of the remaining, restricted Grand Castle Formation (redefined) is not well constrained, but must be Late Cretaceous because it is overlain by strata that yielded Late Cretaceous palynomorphs as described below. A debris-flow deposit within the map unit at its type section yielded Late Cretaceous (Santonian?) pollen that Goldstrand and Mullett (1997) interpreted as recycled from older strata. However, this pollen is more likely to be in place and to represent the age of the map unit because Nichols (1997) reported Late Cretaceous *Proteacidites* sp. pollen, which he interpreted as Coniacian and Santonian, from overlying beds here mapped as Km west and south of Blowhard Mountain, and Biek and others (2012) recovered late Campanian to Maastrichtian pollen from that same interval. About 183 feet (56 m) thick at the type section (Goldstrand and Mullet, 1997), and about 200 feet (60 m) thick in Parowan Canyon in the northern part of the map area, from where it thins abruptly to the south and may locally be absent in Rattlesnake Canyon at the west-central edge of the map area (where it was not recognized in the measured sections of Goldstrand, 1991), but this interval is typically mantled in talus and colluvium that may obscure its presence. In fact, Biek and others (2012) found the map unit at five places just west, southwest, and south of the map area: at Sugarloaf Mountain (about 3 miles [5 km] west of Brian Head), in Last Chance Canyon (a tributary to Cedar Canyon), in the upper reaches of Spring Creek Canyon below Cedar Breaks National Monument, west of Blowhard Mountain, and west of Navajo Lake; this unit ranges in thickness from several feet (1 m) west of Navajo Lake to 25 feet (8 m) in Last Chance Canyon. Thus, although the Grand Castle Formation (redefined) is dramatically thinner in, west, and south of the map area than at its type section, apart from a few local areas, it is present along the entire western margin of the Markagunt Plateau; because it is thin, it is mapped as a marker bed in the southwestern part of the map area.

Unconformity

Wahweap Formation (Upper Cretaceous, lower? to middle Campanian)—Eaton (1991) divided the formation into four informal members in the Kaiparowits Basin, originally defined based principally on sandstone-to-mudstone ratios and fluvial architecture. In descending order, these include his capping sandstone, and upper, middle, and lower members. However, because of extensive vegetative cover and poor geomorphic expression in this map area, we map his lower three members simply as Wahweap Formation, undivided (Kw). The distinctive capping sandstone (Kwcs) is mapped separately.

The Wahweap Formation was deposited in braided and meandering river and floodplain environments of a coastal plain (Tilton, 1991; Pollock, 1999; Lawton and others, 2003; Jinnah and Roberts, 2011). Detrital zircon and provenance studies of Eaton's lower three members show that these rivers flowed longitudinally to the foreland basin and tapped sources in the Cordilleran magmatic arc in southern California or western Nevada and the Mogollon Highlands of southern Arizona, but that the capping sandstone member was deposited by transverse streams that tapped Mesozoic quartzose sandstones in the Sevier orogenic belt (Pollock, 1999; Lawton and others, 2003; Eaton, 2006; Jinnah and others, 2009). Thus the basal contact of the capping sandstone member represents an abrupt change in color, petrology, grain size, and fluvial style, documenting a major shift in depositional environments from meandering to braided rivers, and in source areas from arc to orogenic belt.

Kwcs **Capping sandstone member** (Upper Cretaceous, middle? Campanian)—White to light-orange, locally iron stained, fine to coarse-grained, mostly medium-grained, trough cross-bedded quartz arenite that "caps" the Wahweap Formation; upper part contains abundant pebble stringers and conglomeratic beds with rounded quartzite, dolostone, chert, and limestone clasts; clasts are typically about 1 inch (2.5 cm) in diameter but as large as 2 to 3 inches (5–7.5 cm), and include common reddish-brown and purple quartzite clasts; quartz grains are typically well rounded and commonly frosted, recycled from Mesozoic eolianites (Pollock, 1999; Lawton and others, 2003); locally contains carbonized or petrified plant debris, small mudstone rip-up clasts, iron concretions, and soft-sediment deformation features; typically poorly cemented and therefore poorly exposed in this map area.

Hunt and others (2011) and Biek and others (2012) reported Campanian to Santonian palynomorphs and a theropod dinosaur track (the latter found by Eric Roberts, formerly with Southern Utah University and now at James Cook University, Australia) in the lower part of the member in an unnamed canyon about 2 miles (3 km) southwest of Parowan, confirming a Late Cretaceous age for this interval on the Markagunt Plateau.

The unit is equivalent to the now-abandoned middle member of the original Grand Castle Formation, as suggested by Lawton and others (2003), confirmed by the mapping of Biek and others (2012), and supported by preliminary detrital zircon analyses of Johnson and others (2011) who examined detrital zircon populations of three samples from the Markagunt and Paunsaugunt Plateaus and concluded that they represent sediments of a Late Cretaceous braided stream system that drained thrust sheets of the Sevier orogenic belt to the west. Goldstrand and Mullett (1997) and Lawton and others (2003) also showed that the member was deposited in a braided fluvial environment with a paleoflow direction principally to the east to south-southeast, suggesting source areas in Navajo Sandstone exposed in the upper plate of the Iron Springs thrust, now exposed in the Red Hills.

Along much of the west flank of the Markagunt Plateau south of Parowan Canyon, the capping sandstone member is commonly covered by talus and colluvium derived from the overlying Claron Formation. There, we use a dashed lower contact to indicate our uncertainty as to its true thickness. Our mapping confirms the finding of Goldstrand and Mullet (1997), who first correlated the sandstone at the Webster Flat turnoff with their middle sandstone member of the Grand Castle Formation. The capping sandstone member attains its maximum thickness of 277 feet (85 m) at the type section of the equivalent and now-abandoned middle member of the Grand Castle Formation in First Left Hand Canyon southeast of Parowan, about 3 miles (5 km) north of the map area.

unconformity

Kw **Wahweap Formation, lower, middle, and upper members, undivided** (Campanian)—Varicolored and mottled mudstone of brown, gray, reddish-brown, and pinkish hues, and yellowish-brown fine-grained sandstone and silty sandstone. Typically heavily vegetated and poorly exposed on the Markagunt Plateau, but likely equivalent to the lower, middle, and upper members as defined by Eaton (1991). The upper third, below the capping sandstone member, contains more sandstone than mudstone, also noted by

Moore and Straub (2001) and Moore and others (2004). Measurements from the map show that the Wahweap Formation, excluding the capping sandstone member, is about 800 feet (245 m) thick below Cedar Breaks National Monument, and Moore and Straub (2001) measured 760 feet (230 m) of strata in Cedar Canyon that Biek and others (2012) assigned to the Wahweap Formation (not including the capping sandstone member). The Wahweap (undivided) is only a few tens of feet thick beneath the capping sandstone member in Parowan Canyon, illustrating a dramatic southward thickening of the unit south of Parowan Canyon (Biek and others, 2012). Eaton and others (1999a) and Moore and Straub (2001) initially proposed correlation of Cedar Canyon strata in the map area with early to middle Campanian Wahweap strata on the Kaiparowits Plateau.

Jinnah and others (2009) reported an $^{40}Ar/^{39}Ar$ age of 80.6 ± 0.3 Ma (Campanian) for a devitrified volcanic ash located about 130 feet (40 m) above the base of the Wahweap Formation on the Kaiparowits Plateau, and further noted that the formation was deposited between about 81 and 76 Ma. Eaton and others (1999a) and Eaton (2006) reported enigmatic fossil mammals from near the base and top of the formation in Cedar Canyon that may be Campanian, and Lawton and others (2003) reported middle Campanian pollen from the upper part of the formation near Webster Flat, just southwest of Blowhard Mountain on the western rim of the Markagunt Plateau. Biek and others (2012) also recovered Campanian to Santonian pollen immediately below the capping sandstone near Webster Flat, just south of the map area.

Straight Cliffs Formation (Upper Cretaceous, Santonian? to Turonian)—Peterson (1969) divided the Straight Cliffs Formation into four members on the Kaiparowits Plateau: in descending order, the Drip Tank, John Henry, Smoky Hollow, and Tibbet Canyon Members. Only the upper two members are exposed in the map area. The Drip Tank Member is the same interval as the now-abandoned lower conglomerate member of the Grand Castle Formation, as originally suggested by Eaton and others (2001), Moore and Straub (2001), Lawton and others (2003), and Eaton (2006), and is a key unit in differentiating and mapping Upper Cretaceous strata along the western flank of the Markagunt Plateau (Biek and others, 2012). The Straight Cliffs Formation forms an overall regressive sequence that followed the last marine incursion of the Western Interior Seaway (see, for example, Eaton and others, 2001; Moore and Straub, 2001; Tibert and others, 2003). The Tibbet Canyon Member represents initial progradational (overall regressive) strata of the Greenhorn Cycle deposited in shoreface, beach, lagoonal, and estuarine environments adjacent to a coastal plain (Laurin and Sageman, 2001; Tibert and others, 2003). The overlying Smoky Hollow, John Henry, and Drip Tank Members were deposited in fluvial and floodplain environments of a coastal plain (Peterson, 1969; Eaton and others, 2001).

Ksd **Drip Tank Member** (Upper Cretaceous, late Santonian)—Massive, typically cliff-forming, light-gray conglomerate with well-rounded, pebble- to boulder-sized clasts of quartzite, limestone, and minor sandstone and chert. On the Markagunt Plateau, unit was formerly referred to as the lower conglomerate member of the Grand Castle Formation (Goldstrand and Mullet, 1997), but shown by Biek and others (2012) to be the same unit as the Drip Tank, whose name has nomenclatural priority. It is 135 feet (41 m) thick at the type section in First Left Hand Canyon southeast of Parowan (Goldstrand and Mullet, 1997), and is of similar thickness southwest to Sugarloaf Mountain (about 3 miles [5 km] west of Brian Head). South of this area, however, the Drip Tank thins irregularly southward, ranging from a few feet to nearly 100 feet (30 m) thick, and locally, as in the Ashdown Creek drainage, appears as two conglomerate intervals separated by a few feet to a few tens of feet of yellowish-brown, fine-grained sandstone or variegated mudstone; where thin, we map it simply as a marker bed. The Drip Tank Member typically overlies stacked or amalgamated sandstone beds, but locally overlies variegated mudstone, as along Ashdown Creek. On the northern Markagunt Plateau, the member locally weathers to form conically shaped hoodoos that resemble old-fashioned beehives known as bee skeps, but it forms a resistant ledge in the northwestern corner of the map area and a typically poorly exposed slope in the Ashdown Creek drainage. The Drip Tank was deposited by east- and northeast-flowing braided streams (Tilton, 1991, 2001a, 2001b; Lawton and others, 2003); its age is constrained by the ages of enclosing well-dated strata.

unconformity

Ksj **John Henry Member** (Upper Cretaceous, Santonian to upper Coniacian)—Slope-forming, variegated, gray, brown, and reddish-brown mudstone and thin- to thick-bedded, grayish-orange to yellowish-brown, fine-grained subarkosic sandstone; forms ledgy slopes; sandstone is commonly bioturbated and locally stained by iron-manganese oxides; stacked or amalgamated sandstone beds make up most of the upper part of the unit;

upper contact corresponds to a break in slope at the base of the Drip Tank Member; biotite from an ash bed about 800 feet (245 m) above the base of the member in Cedar Canyon yielded an $^{40}Ar/^{39}Ar$ age of 86.72 ± 0.58 Ma (early Coniacian) (Eaton, 1999; Eaton and others, 1999b); Eaton and others (1999b) also reported an $^{40}Ar/^{39}Ar$ age of 83.0 ± 1.1 Ma for an ash bed that is 712 feet (217 m) below the top of the member in Parowan Canyon; incomplete section is about 400 feet (120 m) thick in the map area, but the entire member is about 900 to 1000 feet (275–300 m) thick to the west in Cedar Canyon (Moore and Straub, 2001),

In the adjacent Navajo Lake quadrangle (Moore and others, 2004), where the upper unit is better exposed, John Henry strata consist predominantly of light-gray, yellowish-gray, light-yellowish-brown, and reddish-brown, silty and sandy mudstone containing numerous thin (1 to 6 feet [0.3–2 m]) lenticular sandstone beds; a few light-orange, grayish-orange, and yellowish-brown, lenticular, trough cross-bedded, feldspathic sandstone beds as thick as 20 feet (6 m), and one or two similar but 50-foot-thick (15 m) cliff-forming sandstone beds, are exposed in the upper quarter of the unit; the rocks in this part of the section contain iron oxide-cemented laminations, nodules, and fossil leaf impressions, silicified fossil wood pieces, carbonaceous plant fragments and films, and local mud-pellet conglomeratic lenses.

REFERENCES

Agenbroad, L.D., Brunelle, A.R., and Ort, M., 1996, The Mammoth Summit glacier, Iron County, Utah [abs.]: Flagstaff, Arizona, American Quaternary Association Program and Abstracts, p. 146.

Anderson, J.J., 1971, Geology of the southwestern High Plateaus of Utah—Bear Valley Formation, an Oligocene–Miocene volcanic arenite: Geological Society of America Bulletin, v. 82, p. 1179–1205.

Anderson, J.J., 1993, The Markagunt Megabreccia—large Miocene gravity slides mantling the northern Markagunt Plateau, southwestern Utah: Utah Geological Survey Miscellaneous Publication 93-2, 37 p.

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

Anderson, J.J., and Rowley, P.D., 1987, Geologic map of the Panguitch NW quadrangle, Iron and Garfield Counties, Utah: Utah Geolofical and Mineral Survey Map 103, 8 p., 2 plates, scale 1:24,000.

Anderson, J.J., 2001, Late Oligocene-early Miocene normal faulting along west-northwest strikes, northern Markagunt Plateau, Utah, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—a symposium and field guide (The Mackin volume): Utah Geological Association Publication 30 and Pacific Section AAPG Guidebook GB 78, p. 97–112.

Anderson, J.J., Rowley, P.D., Blackman, J.T., Mehnert, H.H., and Grant, T.C., 1990a, Geologic map of the Circleville Canyon area, southern Tushar Mountains and northern Markagunt Plateau, Beaver, Garfield, Iron, and Piute Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2000, scale 1:50,000.

Anderson, J.J., Rowley, P.D., Machette, M.M., Decatur, S.H., and Mehnert, H.H., 1990b, Geologic map of the Nevershine Hollow area, eastern Black Mountains, southern Tushar Mountains, and northern Markagunt Plateau, Beaver and Iron Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1999, scale 1:50,000.

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

Anderson, R.S., Hasbargen, J., Koehler, P.A., and Feiler, E.J., 1999, Late Wisconsin and Holocene subalpine forests of the Markagunt Plateau of Utah, southwestern Colorado Plateau, U.S.A.: Arctic, Antarctic, and Alpine Research, v. 31, no. 4, p. 366–378.

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

Atwater, T., 1970 Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536.

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

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

Best, M.G., Christiansen, E.H., and Blank, R.H., Jr., 1989a, Oligocene caldera complex and calc-alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and

Utah: Geological Society of America Bulletin, v. 101, p. 1076–1090.

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

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

Best, M.G., Scott, R.B., Rowley, P.D., Swadley, WC, Anderson, R.E., Gromme, C.S., Harding, A.E., Deino, A.L., Christiansen, E.H., Tingey, D.G., and Sullivan, K.R., 1993, Oligocene-Miocene caldera complexes, ash-flow sheets, and tectonism in the central and southeastern Great Basin, *in* Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., editors, Crustal evolution of the Great Basin and Sierra Nevada: Geological Society of America, Cordilleran and Rocky Mountain Section Guidebook, p. 285–311.

Biek, R.F., 2013, Whole-rock geochemical data for the Panguitch 30' x 60' quadrangle, Garfield, Iron, and Kane Counties, Utah: Utah Geological Survey Open-File Report 623, variously paginated.

Biek, R.F., Moore, D.W., and Nealey, L.D., 2011, Geologic map of the Henrie Knolls quadrangle, Garfield, Kane, and Iron Counties, Utah: Utah Geological Survey Map 252DM, 2 plates, scale 1:24,000.

Biek, R.F., Rowley, P.D., Anderson, J.J., Maldonado, F., Moore, D.W., Eaton, J.G., Hereford, R., and Matyjasik, B., 2012, Interim geologic map of the Panguitch 30′ x 60′ quadrangle, Garfield, Iron, and Kane Counties, Utah: Utah Geological Survey Open-File Report 599, 3 plates, 127 p., scale 1:62,500.

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

Blank, H.R., Butler, W.C., and Saltus, R.W., 1998, Neogene uplift and radial collapse of the Colorado Plateau—regional implications of gravity and aeromagnetic data, *in* Friedman, J.D., and Huffman, A.C., Jr., editors, Laccolith complexes of southeastern Utah—time of emplacement and tectonic setting, workshop proceedings: U.S. Geological Survey Bulletin 2158, p. 9–32.

Blank, H.R., and Kucks, R.P., 1989, Preliminary aeromagnetic, gravity, and generalized geologic maps of the USGS Basin and Range–Colorado Plateau transition zone study area in southwestern Utah, southeastern Nevada, and northwestern Arizona (the "BARCO" project): U.S. Geological Survey Open-File Report 89-432, 16 p.

Boswell, J.T., Colberg, M., Rowley, P.D., Maxwell, D.J., Lohrengel, C.F., II, and Lund, W.R., 2008, Geologic map of the Brian Head municipality portion of the Brian Head quadrangle, Iron County, Utah: Cedar City, Utah, Southern Utah University, unpublished geologic map, scale 1:12,000.

Bowers, W.E., 1972, The Canaan Peak, Pine Hollow, and Wasatch Formations in the Table Cliff region, Garfield County, Utah: U.S. Geological Survey Bulletin 1331-B, 39 p.

Bowers, W.E., 1990, Geologic map of Bryce Canyon National Park and vicinity, southwestern Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2108, 15 p., scale 1:24,000.

Bown, T.M., Hasiotis, S.T., Genise, J.F., Maldonado, F., and Bowers, E.M., 1997, Trace fossils of *Hymenoptera* and other insects, and paleoenvironments of the Claron Formation (Paleocene and Eocene), southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 43–58.

Canaday, T.W., Bakewell, E.F., Chengyu, W., Corson, P.L., Ferris, D.E., Elias, S.A., Funkhouser, G.S., Hughes, R.E., Jackson, S.T., Madsen, D.B., Perry, L., Sarna-Wojciki, A., and Thompson, R.S., 2001, High-altitude archeological investigations at Cedar Breaks National Monument, Utah: National Park Service Cultural Resources Selections Series no. 17, 203 p.

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

Cook, E.F., 1965, Stratigraphy of Tertiary volcanic rocks in eastern Nevada: Nevada Bureau of Mines Report 11, 59 p.

Cunningham, C.G., Unruh, D.M., Steven, T.A., Rowley, P.D., Naeser, C.W., Mehnert, H.H., Hedge, C.E., and Ludwig, K.R., 1998, Geochemistry of volcanic rocks in the Marysvale volcanic field, west-central Utah—time of emplacement and tectonic setting—workshop proceedings: U.S. Geological Survey Bulletin 2158, p. 223-232.

Cunningham, C.G., Rowley, P.D., Steven, T.A., and Rye, R.O., 2007, Geologic evolution and mineral resources of the Marysvale volcanic field, west-central Utah, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., editors, Central Utah—diverse geology of a dynamic landscape: Utah Geological Association Publication 36, p. 143–161.

Currey, D.R., Mulvey, W.E., and Lindsay, L.M.W., 1986, Markagunt Plateau, Utah—southern margin of late Wisconsinan montane glaciation in the great Basin

[abs.]: American Quaternary Association Program and Abstracts, v. 35, no. 9, p. 126.

Davis, G.H., 1999, Structural geology of the Colorado Plateau region of southern Utah, with special emphasis on deformation bands [abs.]: Geological Society of America Special Paper 342, 157 p.

Davis, G.H., and Krantz, R.W., 1986, Post-"Laramide" thrust faults in the Claron Formation, Bryce Canyon National Park, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 18, no. 5, p. 98.

Davis, G.H., and Rowley, P.D., 1993, Miocene thrusting, gravity sliding, and near-surface batholithic emplacement, Marysvale volcanic field, southwestern Utah [abs.]: Eos (Transactions, American Geophysical Union), v. 74, no. 43, p. 647.

Davis, S.J., Mulch, A., Carroll, A.R., Horton, T.W., and Chamberlain, C.P., 2009, Paleogene landscape evolution of the central North American Cordillera—developing topography and hydrology in the Laramide foreland: Geological Society of America Bulletin, v. 121, no. 1/2, p. 100–116.

Eaton, J.G., 1991, Biostratigraphic framework for the Upper Cretaceous rocks of the Kaiparowits Plateau, southern Utah, *in* Nations, J.D., and Eaton, J.G., editors, Stratigraphy, depositional environments, and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway: Geological Society of America Special Paper 260, p. 47–63.

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

Eaton, J.G., 2006, Late Cretaceous mammals from Cedar Canyon, southwestern Utah, *in* Lucas, S.G., and Sullivan, R.M., editors, Late Cretaceous vertebrates from the Western Interior: New Mexico Museum of Natural History Science Bulletin 35, p. 1–30.

Eaton, J.G., Diem, S., Archibald, J.D., Schierup, C., and Munk, H., 1999a, Vertebrate paleontology of the Upper Cretaceous rocks of the Markagunt Plateau, southwestern Utah, *in* Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 323–333.

Eaton, J.G., Laurin, J., Kirkland, J.I., Tibert, N.E., Leckie, R.M., Sageman, B.B., Goldstrand, P.M., Moore, D.W., Straub, A.W., Cobban, W.A., and Dalebout, J.D., 2001, Cretaceous and early Tertiary geology of Cedar and Parowan Canyons, western Markagunt Plateau, Utah: Utah Geological Association field trip road log, September, 2001, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—a symposium and field guide (The Mackin Volume): Utah Geological Association Publication 30 and Pacific Section AAPG Guidebook GB 78, p. 337–363.

Eaton, J.G., Maldonado, F., and McIntosh, W.C., 1999b, New radiometric dates from Upper Cretaceous rocks of the Markagunt Plateau, southwestern Utah, and their bearing on subsidence histories [abs.]: Geological Society of America Abstracts with Programs, v. 31, no. 4, p. A–11.

Eaton, J.G., Tibert, N.E., and Biek, R.F., 2011, First mammals and ostracodes from the Paleogene Claron Formation, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 4, p. 77.

Feist, M., Eaton, J.G., Brouwers, E.M., and Maldonado, F., 1997, Significance of charophytes from the lower Tertiary variegated and volcaniclastic units, Brian Head Formation, Casto Canyon area, southern Sevier Plateau, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 27–42.

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill Book Company, Inc., 534 p.

Fleck, R.J., Anderson, J.J., and Rowley, P.D., 1975, Chronology of mid-Tertiary volcanism in High Plateaus region of Utah: Geological Society of America Special Paper 160, p. 53–61.

Goldstrand, P.M., 1990, Stratigraphy and paleogeography of Late Cretaceous and Early Tertiary rocks of southwest Utah: Utah Geological Survey Miscellaneous Publication 90-2, 58 p.

Goldstrand, P.M., 1991, Tectonostratigraphy, petrology, and paleogeography of the Upper Cretaceous to Eocene rocks of southwest Utah: Reno, University of Nevada, Ph.D. dissertation, 205 p.

Goldstrand, P.M., 1992, Evolution of Late Cretaceous and early Tertiary basins of southwest Utah based on clastic petrology: Journal of Sedimentary Petrology, v. 63, p. 495–507.

Goldstrand, P.M., 1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, p. 145–154.

Goldstrand, P., and Eaton, J.G., 2001, Paleocene to early Oligocene basin evolution, southwestern Utah, *in* Young, R.A., and Spamer, E.E., editors, Colorado River, origin and evolution: Grand Canyon, Arizona, Grand Canyon Association, p. 25–29.

Goldstrand, P.M., and Mullett, D.J., 1997, The Paleocene Grand Castle Formation—a new formation on the Markagunt Plateau of southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in

the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 59–78.

Gosse, J.C., Klein, J., Evenson, E.B., Lawn, B., and Middleton, R., 1995, Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence: Science, v. 268, p. 1329–1333.

Gosse, J.C., and Phillips, F.M., 2001, Terrestrial *in situ* cosmogenic nuclides—theory and application: Quaternary Science Reviews, v. 20, p. 1475–1560.

Gregory, H.E., 1944, Geologic observation in the upper Sevier River Valley, Utah: American Journal of Science, v. 242, no. 11, p. 577–606.

Gregory, H.E., 1950, Geology of eastern Iron County, Utah: Utah Geological and Mineralogical Survey Bulletin 37, 153 p.

Hamblin, W.K., 1963, Late Cenozoic basalts of the St. George basin, Utah, *in* Heylmun, E.B., editor, Guidebook to the geology of southwestern Utah—transition between the Basin-Range and Colorado Plateau provinces: Salt Lake City, Intermountain Association of Petroleum Geologists 12th Annual Field Conference, p. 84–89.

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

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

Hamilton, W.B., 1989, Crustal geologic processes of the United States, *in* Pakiser, L.C., and Mooney, W.D., editors, Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 743–781.

Hamilton, W.B., 1995, Subduction systems and magmatism, *in* Smellie, J.L., editor, Volcanism associated with extension of consuming plate margins: Geological Society Special Publication 81, p. 3–28.

Hart, M.W., Shaller, P.J., and Farrand, G.T., 2012, When landslides are misinterpreted as faults—case studies from the western United States: Environmental and Engineering Geoscience, v. 18, n. 4, p. 313–325.

Hatfield, S.C., Rowley, P.D., and Anderson, J.J., 2000a, Cedar Breaks National Monument, Utah—giant gravity slides complicate an otherwise simple story [abs.]: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-263.

Hatfield, S.C., Rowley, P.D., Sable, E.G., Maxwell, D.J., Cox, B.V., McKell, M.D., and Kiel, D.E., 2000b, Geology of Cedar Breaks National Monument, Utah, *in* Sprinkel, D.A., Chidsey, T.C., Jr., and Anderson, P.B., editors, Geology of Utah's Parks and Monuments: Utah Geological Association Publication 28, p. 139–154.

Hatfield, S.C., Rowley, P.D., Sable, E.G., Maxwell, D.J., Cox, B.V., McKell, M.D., and Kiel, D.E., 2000c, Geologic road log of Cedar Breaks National Monument, Utah, *in* Anderson, P.B., and Sprinkel, D.A., editors, Geologic road, trail, and lake guides to Utah's parks and monuments: Utah Geological Association Publication 29, CD.

Hatfield, S.C., Rowley, P.D., Sable, E.G., Maxwell, D.J., Cox, B.V., McKell, M.D., and Kiel, D.E., 2004, Geologic road log of Cedar Breaks National Monument, Utah, *in* Anderson, P.B., and Sprinkel, D.A., editors, Geologic road, trail, and lake guides to Utah's parks and monuments: Utah Geological Association Publication 29, Second Edition, p. 109, CD.

Hatfield, S.C., Rowley, P.D., Sable, E.G., Maxwell, D.J., Cox, B.V., McKell, M.D., and Kiel, D.E., 2010, Geology of Cedar Breaks National Monument, Utah, *in* Sprinkel, D.A., Chidsey, T.C., Jr., and Anderson, P.B., editors, Geology of Utah's Parks and Monuments: Utah Geological Association Publication 28, Third Edition, p. 145–160

Hilton, D.A., 1984, The petrology, sedimentology, and stratigraphy of the Late Cretaceous(?) and early Tertiary sedimentary rocks of southwest Markagunt Plateau, Utah: Kent, Ohio, Kent State University, M.S. thesis, 137 p.

Hintze, L.F., 2005, Utah's spectacular geology—how it came to be: Provo, Utah, Brigham Young University Geology Studies, Special Publication 8, 203 p.

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

Hunt, G.J., Lawton, T.F., and Kirkland, J.I., 2011, Detrital zircon U-Pb geochronological provenance of Lower Cretaceous strata, foreland basin, Utah, *in* Sprinkel, D.A., Yonkee, W.A., and Chidsey. T.C., Jr., editors, Sevier thrust belt—northern and central Utah and adjacent areas: Utah Geological Association Publication 40, p. 193–211.

Hurlow, H.A., 2002, The geology of Cedar Valley, Iron County, Utah, and its relation to ground-water conditions: Utah Geological Survey Special Study 103, 74 p.

Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., and Shackleton, N.J., 1984, The orbital theory of Pleistocene climate—support from a revised chronology of the marine ^{18}O record, *in* Berger, A., Imbrie, J., Hays. J., Kukla, G., and Saltzman, B., editors, Milankovitch and climate part 1: Dordrecht, Holland, Reidel, p. 269–306.

Jinnah, Z.A., and Roberts, E.M., 2011, Facies associations, paleoenvironment, and base-level changes in the

Upper Cretaceous Wahweap Formation, Utah, U.S.A.: Journal of Sedimentary Research, v. 81, p. 266–283.

Jinnah, Z.A., Roberts, E.M., Deino, A.L., Larsen, J.S., Link, P.K., and Fanning, C.M., 2009, New $^{40}Ar/^{39}Ar$ and detrital zircon U-Pb ages for the Upper Cretaceous Wahweap and Kaiparowits Formations on the Kaiparowits Plateau, Utah—implications for regional correlation, provenance, and biostratigraphy: Cretaceous Research, v. 30, p. 287–299.

Johnson, H.D., Krevitsky, R.D., Link, P.K., and Biek, R.F., 2011, Detrital zircon from the Late Cretaceous middle member Grand Castle Formation, south-central Utah—recycled Mesozoic aeolianites [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 4, p. 68.

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

Judy, J.R., 1974, Cenozoic stratigraphy and structural evolution of the west-central Markagunt Plateau, Utah: Kent, Ohio, Kent State University, M.S. thesis, 107 p.

Korth, W.W., and Eaton, J.G., 2004, Rodents and a marsupial (Mammalia) from the Duschesnean (Eocene) of the Sevier Plateau, Utah, *in* Dawson, M.R., and Lillegraven, J.A., editors, Fanfare for an uncommon paleontologist—papers on vertebrate evolution in honor of Malcolm C. McKenna: Carnegie Museum of Natural History Bulletin, no. 36, p. 109–119.

Laabs, B.J.C., and Carson, E.C., 2005, Glacial geology of the southern Uinta Mountains, *in* Dehler, C.M., Pederson, J.L., Sprinkel, D.A., and Kowallis, B.J., editors, Uinta Mountain geology: Utah Geological Association Publication 33, p. 235–253.

LaRocque, A., 1960, Molluscan faunas of the Flagstaff Formation of central Utah: Geological Society of America Memoir 78, 100 p.

Laurin, J., and Sageman, B.B., 2001, Cenomanian-Turonian coastal record in SW Utah, U.S.A.—orbital-scale transgressive-regressive events during oceanic anoxic event II: Journal of Sedimentary Research, v. 77, p. 731–756.

Lawton, T.F., Pollock, S.L., and Robinson, R.A.J., 2003, Integrating sandstone petrology and nonmarine sequence stratigraphy—application to the Late Cretaceous fluvial systems of southwestern Utah, U.S.A.: Journal of Sedimentary Research, v. 73, no. 3, p. 389–406.

Lipman, P.W., Prostka, H.J., and Christiansen, R.L., 1972, Cenozoic volcanism and plate-tectonic evolution of the Western United States—I. Early and middle Cenozoic: Philosophical Transactions of the Royal Society of London, v. A271, p. 217–248.

Lund, W.R., Hozik, M.J., and Hatfield, S.C., 2007, Paleoseismic investigation and long-term slip history of the Hurricane fault in southwestern Utah: Utah Geological Survey Special Study 119, 81 p., CD.

Lundin, E.R., 1989, Thrusting of the Claron Formation, Bryce Canyon region, Utah: Geological Society of America Bulletin, v. 101, p. 1038–1050.

Mackin, J.H., 1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: American Journal of Science, v. 258, p. 81–131.

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

Madsen, D.B., Sarna-Wojcicki, A.M., and Thompson, R.S., 2002, A late Pleistocene tephra layer in the southern Great Basin and Colorado Plateau derived from Mono Craters, California: Quaternary Research, v. 57, p. 382–390.

Maldonado, F., and Moore, R.C., 1995, Geologic map of the Parowan quadrangle, Iron County, Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-1762, scale 1:24,000.

Maldonado, F., Sable, E.G., and Anderson, J.J., 1990, Shallow detachment of mid-Tertiary rocks, Red Hills (Basin and Range), with implications for a regional detachment zone in the adjacent Markagunt Plateau (Colorado Plateau), southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 94.

Maldonado, F., Sable, E.G., and Anderson, J.J., 1992, Evidence for a Tertiary low-angle shear zone, Red Hills, Utah, with implications for a regional shear zone in the adjacent Colorado Plateau, *in* Harty, K.M., editor, Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, p. 315–323.

Maldonado, F., Sable, E.G., and Nealey, D.L., 1997, Cenozoic low-angle faults, thrust faults, and anastomosing high-angle faults, western Markagunt Plateau, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 151–176.

Marchetti, D.W., Cerling, T.E., Dohrenwend, J.C., and Gallin, W., 2007, Ages and significance of glacial and mass movement deposits on the west side of Boulder Mountain, Utah, USA: Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 252, p. 503–513.

Marchetti, D.W., Cerling, T.E., and Lips, E.W., 2005, A glacial chronology for the Fish Creek drainage of Boulder Mountain, Utah, USA: Quaternary Research, v. 64, p. 263–271.

Marchetti, D.W., Harris, M.S., Bailey, C.M., Cerling, T.E., and Bergman, S., 2011, Timing of glaciation and last glacial maximum paleoclimate estimates from the Fish Lake Plateau, Utah: Quaternary Research, v. 75, p. 183–195.

Merle, O.R., Davis, G.H., Nickelsen, R.P., and Gourlay, P.A., 1993, Relation of thin-skinned thrusting of Colorado Plateau strata in southwestern Utah to Cenozoic magmatism: Geological Society of America Bulletin, v. 105, p. 387–398.

Moore, D.W., 1992, Origin of breccia of the Isom Formation near Cedar Breaks National Monument, Markagunt Plateau, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 54.

Moore, D.W., and Nealey, L.D., 1993, Preliminary geologic map of Navajo Lake quadrangle, Kane and Iron Counties, Utah: U.S. Geological Survey Open-File Report 93-190, 20 p., scale 1:24,000.

Moore, D.W., Nealey, L.D., Rowley, P.D., Hatfield, S.C., Maxwell, D.J., and Mitchell, E., 2004, Geologic map of the Navajo Lake quadrangle, Kane and Iron Counties, Utah: Utah Geological Survey Map 199, scale 1:24,000.

Moore, D.W., Nealey, L.D., and Sable, E.G., 1994, Preliminary report, measured sections, and map of the geology of the Asay Bench quadrangle, Garfield and Kane Counties, Utah: U.S. Geological Survey Open-File Report 94-10, 26 p., scale 1:24,000.

Moore, D.W., and Straub, A.W., 2001, Correlation of Upper Cretaceous and Paleogene(?) rocks beneath the Claron Formation, Crow Creek, western Markagunt Plateau, southwest Utah, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—a symposium and field guide (The Mackin Volume): Utah Geological Association Publication 30 and Pacific Section AAPG Guidebook GB 78, p. 75–96.

Moore, R.C., 1982, The geology of a portion of the west-central Markagunt Plateau, southwestern Utah: Kent, Ohio, Kent State University, M.S. thesis, 72 p.

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

Mullett, D.J., and Wells, N.A., 1990, Soil fabrics and horizontal cracking in the Paleogene Claron Formation of southern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 7, p. 335.

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

Mullett, D.J., Wells, N.A., and Anderson, J.J., 1988b, Unusually intense pedogenic modification of the Paleocene-Eocene Claron Formation of southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 5, p. 382.

Mulvey, W.E., Currey, D.R., and Lindsay, L.M.W., 1984, Southernmost occurrence of later Pleistocene glaciations in Utah—Brian Head–Signey [sic] Peaks area, Markagunt Plateau: Encyclia, v. 61, p. 97–104.

Nealey, L.D., Budahn, J.R., Maldonado, F., and Unruh, D.M., 1997, Geochemistry and petrogenesis of Quaternary basaltic rocks from the Red Hills and western Markagunt Plateau, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 177–198.

Nealey, L.D., Maldonado, F., Unruh, D.M., and Budahn, J.R., 1994, Tectonic implications of Quaternary volcanism in the western Markagunt Plateau and Red Hills area, southwestern Utah—geochemical and geochronological evidence, *in* Blackett, R.E., and Moore, J.S., editors, Cenozoic geology and geothermal systems of southwestern Utah: Utah Geological Association Publication 23, p. 117–124.

Nichols, D.J., 1997, Palynology and ages of some Upper Cretaceous formations in the Markagunt and northwestern Kaiparowits plateaus, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 79–106.

Nickelsen, R.P., and Merle, O., 1991, Structural evolution at the tip line of a mid-Tertiary compressional event in southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 109.

Nickelsen, R.P., Merle, O., and Davis, G.H., 1992, Structures of the mid-Tertiary radial compression in the High Plateaus of southern Utah in relation to Sevier, Laramide and basin and range deformation [abs.]: Geological Society of America Abstracts with Programs, v. 24, no. 6, p. 55.

Peterson, F., 1969, Four new members of the Upper Cretaceous Straight Cliffs Formation in the southeastern Kaiparowits region, Kane County, Utah: U.S. Geological Survey Bulletin 1274-J, 28 p.

Pollock, S.L., 1999, Provenance, geometry, lithofacies, and age of the Upper Cretaceous Wahweap Formation, Cordilleran foreland basin, southern Utah: Las Cruces, New Mexico State University, M.S. thesis, 117 p.

Rowley, P.D., 1998, Cenozoic transverse zones and igneous belts in the Great Basin, western United States—their tectonic and economic implications, *in* Faulds,

J.E., and Stewart, J.H., editors, Accommodation zones and transfer zones—the regional segmentation of the Basin and Range province: Geological Society of America Special Paper 323, p. 195–228.

Rowley, P.D., Anderson, J.J., Williams, P.L., and Fleck, R.J., 1978, Age of structural differentiation between the Colorado Plateaus and Basin and Range provinces in southwestern Utah: Geology, v. 6, p. 51–55.

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

Rowley, P.D., Cunningham, C.G., Steven, T.A., Workman, J.B., Anderson, J.J., and Theissen, K.M., 2002, Geologic map of the central Marysvale volcanic field, southwestern Utah: U.S. Geological Survey Geologic Investigations Series Map I-2645-A, scale 1:100,000.

Rowley, P.D., and Dixon, G.L., 2001, The Cenozoic evolution of the Great Basin area, U.S.A.—new interpretations based on regional geologic mapping, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., editors, The geologic transition, High Plateaus to Great Basin—a symposium and field guide (The Mackin Volume): Utah Geological Association Publication 30 and Pacific Section AAPG Guidebook GB 78, p. 169–188.

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

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

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

Rowley, P.D., Steven, T.A., Anderson, J.J., and Cunningham, C.G., 1979, Cenozoic stratigraphic and structural framework of southwestern Utah: U.S. Geological Survey Professional Paper 1149, 22 p.

Rowley, P.D., Vice, G.S., McDonald, R.E., Anderson, J.J., Machette, M.N., Maxwell, D.J., Ekren, E.B., Cunningham, C.G., Steven, T.A., and Wardlaw, B.R., 2005, Interim geologic map of the Beaver 30' x 60' quadrangle, Beaver, Piute, Iron, and Garfield Counties, Utah: Utah Geological Survey Open-File Report 454, 27 p., 1 plate, scale 1:100,000.

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

Sable, E.G., and Anderson, J.J., 1985, Tertiary tectonic slide megabreccias, Markagunt Plateau, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 17, no. 3, p. 263.

Sable, E.G., and Maldonado, F., 1997a, The Brian Head Formation (revised) and selected Tertiary sedimentary rock units, Markagunt Plateau and adjacent areas, southwestern Utah, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 5–26.

Sable, E.G., and Maldonado, F., 1997b, Breccias and megabreccias, Markagunt Plateau, southwestern Utah—origin, age, and transport directions, *in* Maldonado, F., and Nealey, L.D., editors, Geologic studies in the Basin and Range–Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 151–176.

Schneider, M.C., 1967, Early Tertiary continental sediments of central and south-central Utah: Brigham Young University Geology Studies, v. 14, p. 143–194.

Severinghaus, J., and Atwater, T., 1990, Cenozoic geometry and thermal state of the subducting slabs beneath western North America, *in* Wernicke, B.P., editor, Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 1–22.

Sharp, W.D., Ludwig, K.R., Chadwick, O.A., Amundson, R., and Glaser, L.L., 2003, Dating fluvial terraces by ^{230}Th/U on pedogenic carbonate, Wind River Basin, Wyoming: Quaternary Research, v. 59, p. 139–150.

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

Spangler, L.E., 2010, Hydrology of the Markagunt Plateau, southwestern Utah, *in* Carney, S.M., Tabet, D.E., and Johnson, C.L., editors, Geology and geologic resources of south-central Utah: Utah Geological Association Guidebook 39, p. 93–108.

Spurney, J.C., 1984, Geology of the Iron Peak intrusion, Iron County, Utah: Kent, Ohio, Kent State University, M.S. thesis, 84 p.

Stewart, J.H., Moore, W.J., and Zietz, I., 1977, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah: Geological Society of America Bulletin, v. 88, p. 67–77.

Stowell, S.L., 2006, Volcanology and petrogenesis of the Navajo Lake volcanic field: University of Nevada, Las Vegas, M.S. thesis, 86 p.

Stowell, S., and Smith, E.I., 2003, Volcanology of the Navajo Lake volcanic field, southwestern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 35, no. 5, p. 12.

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

Tilton, T.L., 1991, Upper Cretaceous stratigraphy of the southern Paunsaugunt Plateau, Kane County, Utah: Salt Lake City, University of Utah, Ph.D. dissertation, 2 plates, scale 1:24,000, 162 p.

Tilton, T.L., 2001a, Geologic map of the Alton quadrangle, Kane County, Utah: Utah Geological Survey Miscellaneous Publication 01-4, 22 p., 2 plates, scale 1:24,000.

Tilton, T.L., 2001b, Geologic map of the Podunk Creek quadrangle, Kane County, Utah: Utah Geological Survey Miscellaneous Publication 01-3, 18 p., 2 plates, scale 1:24,000.

Titus, A.L., Powell, J.D., Roberts, E.M., Sampson, S.D., Pollock, S.L., Kirkland, J.I., and Albright, L.B., 2005, Late Cretaceous stratigraphy, depositional environments, and macrovertebrate paleontology of the Kaiparowits Plateau, Grand Staircase–Escalante National Monument, Utah, *in* Pederson, J., and Dehler, C.M., editors, Interior Western United States: Geological Society of America Field Guide 6, p. 101–128.

Utah Geological Survey and Apatite to Zircon, Inc, 2013, U-Pb geochronology results for the Panguitch 30' x 60' quadrangle, Utah: Utah Geological Survey Open-File Report 621, variously paginated, also available online, http://geology.utah.gov/online/ofr/ofr-621.pdf.

Utah Geological Survey and Nevada Isotope Geochronology Laboratory (UGS and NIGL), 2012, $^{40}Ar/^{39}Ar$ geochronology results for the Gooseberry Creek, Haycock Mountain, Mercur, Stockton, and Tabbys Peak quadrangles, Utah: Utah Geological Survey Open-File Report 590, variously paginated, also available online, http://geology.utah.gov/online/ofr/ofr-590.pdf.

Weaver, W.J., IV, Marchetti, D.W., Stoll, D.K., Harris, M.S., and Bailey, C.M., 2006, ^{3}He exposure ages for glacial deposits, Fish Lake Plateau, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 38, no. 6, p. 30.

Williams, P.L., 1960, A stained slice method for rapid determination of phenocryst composition of volcanic rocks: American Journal of Science, v. 258, p. 148–152.

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

Wilson, M.T., and Thomas, H.E., 1964, Hydrology and hydrogeology of Navajo Lake, Kane County, Utah: U.S. Geological Survey Professional Paper 417-C, 26 p.

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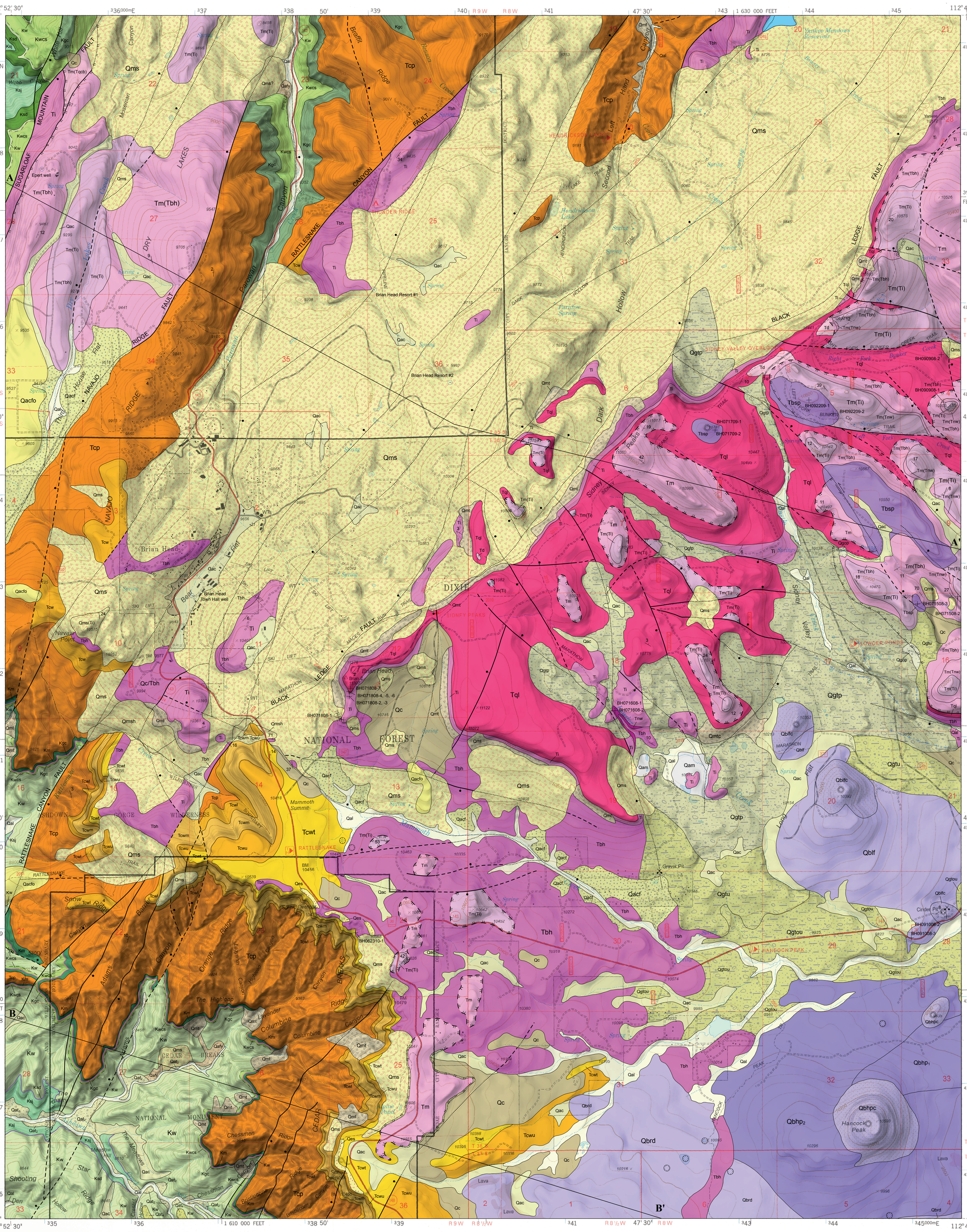

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SCALE 1:24,000

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

QUADRANGLE LOCATION

GEOLOGIC MAP OF THE BRIAN HEAD QUADRANGLE, IRON COUNTY, UTAH

by

Peter D. Rowley[1], Robert F. Biek[2], Edward G. Sable[3], Jonathan T. Boswell[4], Garrett S. Vice[5], Stanley C. Hatfield[6], David J. Maxwell[7], and John J. Anderson[8]

2013

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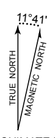


APPROXIMATE MEAN DECLINATION, 2013

Base from USDA Forest Service Brian Head 7.5' Quadrangle (2012)
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1886

Project Manager: Douglas A. Sprinkel
GIS and Cartography: Jay C.Hill, Basia Matyjasik and David J. Maxwell

Utah Geological Survey
1594 West North Temple, Suite 3110
P.O. Box 146100, Salt Lake City, UT 84114-6100
(801) 537-3300
geology.utah.gov

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

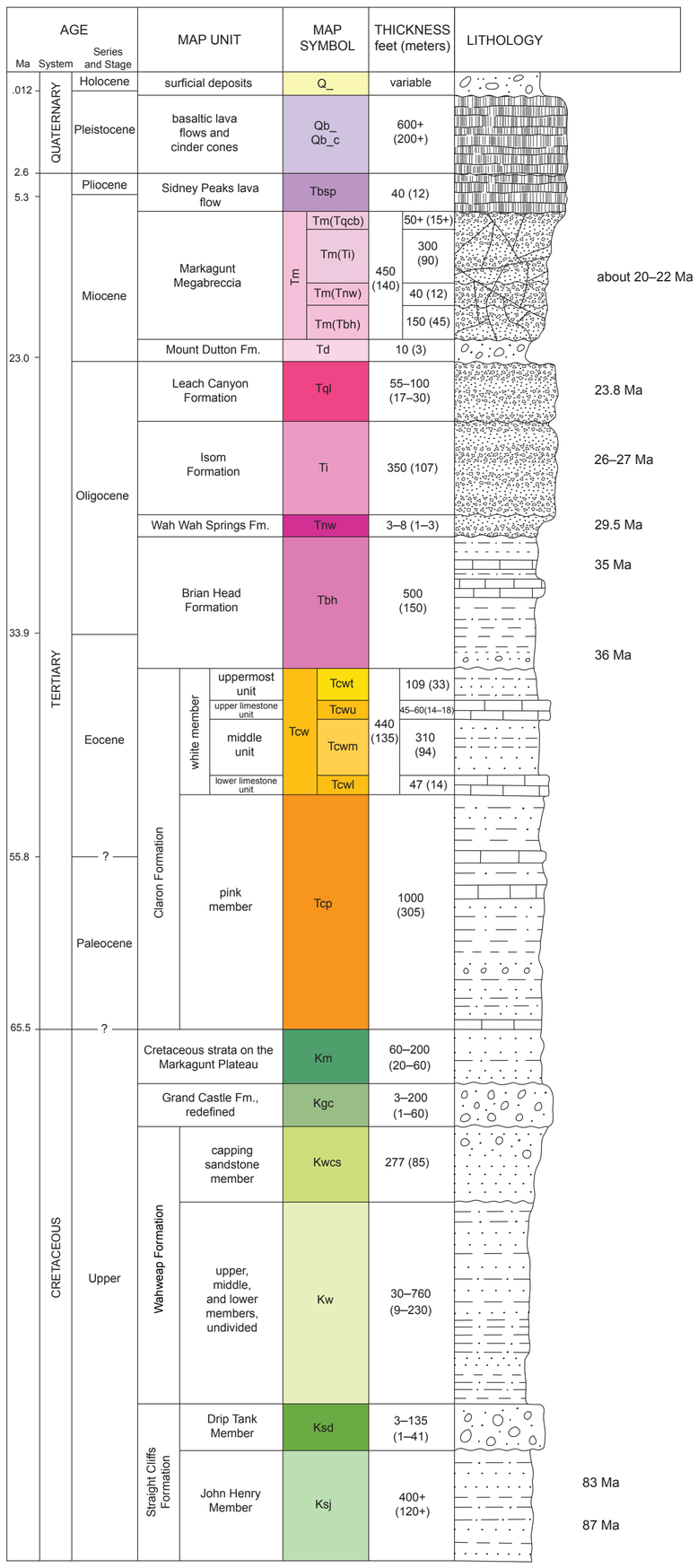
1	2	3
4	·	5
6	7	8

1. Summit
2. Parowan
3. Red Creek Reservoir
4. Flanigan Arch
5. Panguitch Lake
6. Webster Flat
7. Navajo Lake
8. Henrie Knolls

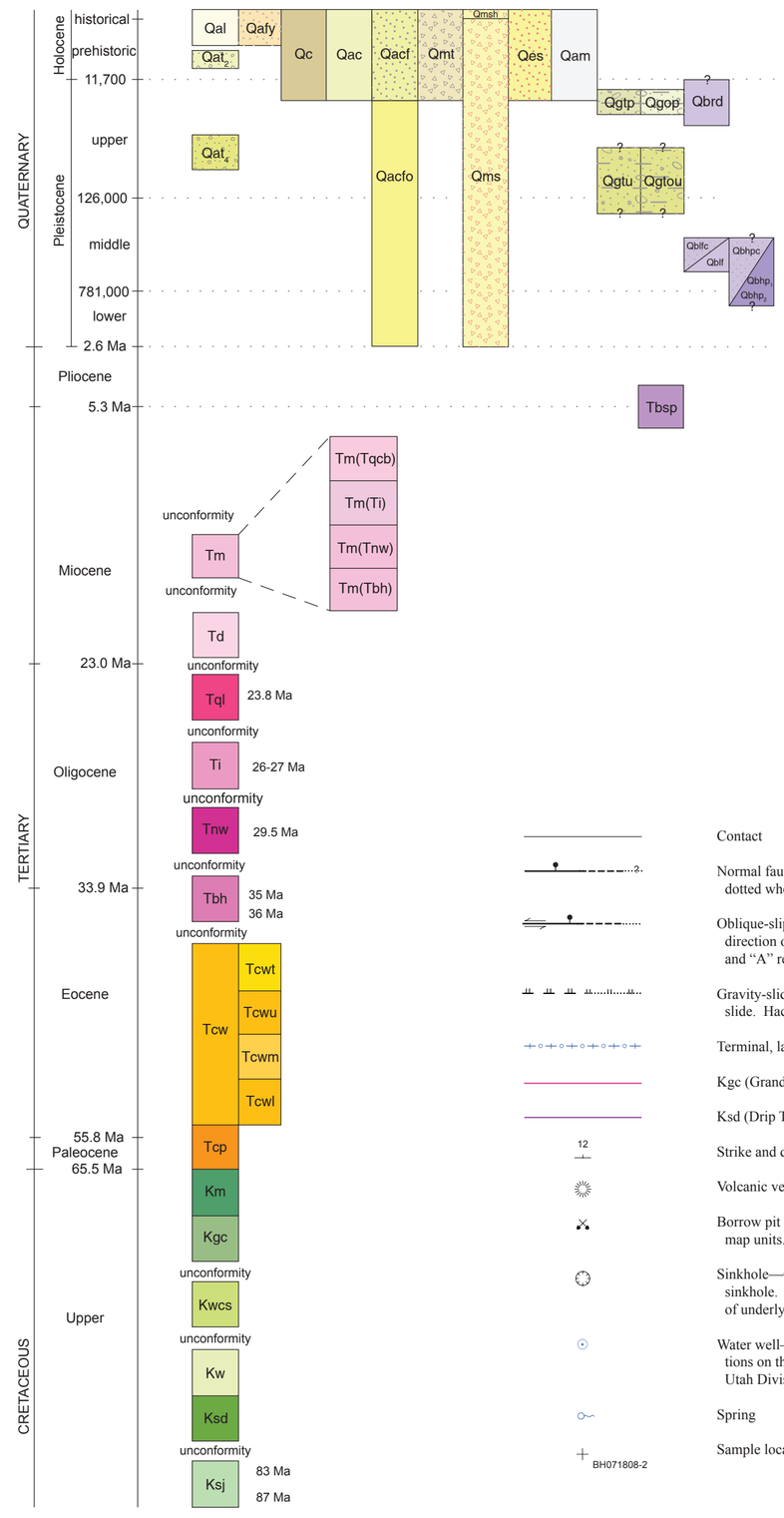
ADJOINING 7.5' QUADRANGLE NAMES

ISBN 978-1-55791-881-9

STRATIGRAPHIC COLUMN



CORRELATION OF MAP UNITS



MAP SYMBOLS

Contact

Normal fault—Bar and ball on downthrown side. Dashed where approximately located, dotted where concealed, queried where uncertain

Oblique-slip fault—Bar and ball on downthrown side; arrows on map show relative direction of strike-slip displacement. On cross sections, "T" refers to toward the reader and "A" refers to away. Dashed where approximately located, dotted where concealed

Gravity-slide fault—Subhorizontal basal shear plane of the Markagunt Megabreccia gravity slide. Hachures on the upper plate. Approximately located; dotted where concealed

Terminal, lateral, and recessional moraines of Pinedale age

Kgc (Grand Castle Formation) marker bed

Ksd (Drip Tank Member) marker bed

12 Strike and dip of beds

Volcanic vent

Borrow pit for sand, gravel, and cinders—Sand and gravel are from Quaternary alluvial map units. Loose basaltic cinders are at or near volcanic vents

Sinkhole—Closed depression containing collapsed material of the same rock as outside the sinkhole. Generally shown by closed topographic contours. Caused by solution collapse of underlying limestone beds of the Claron Formation

Water well—Water well whose geologic log contains information that assisted interpretations on the geologic map and cross sections. Well logs are available online from the Utah Division of Water Rights website: http://waterrights.utah.gov/

Spring

BH071808-2 Sample location and number; see Biek (2013) and UGS and A-to-Z (2013) for analyses