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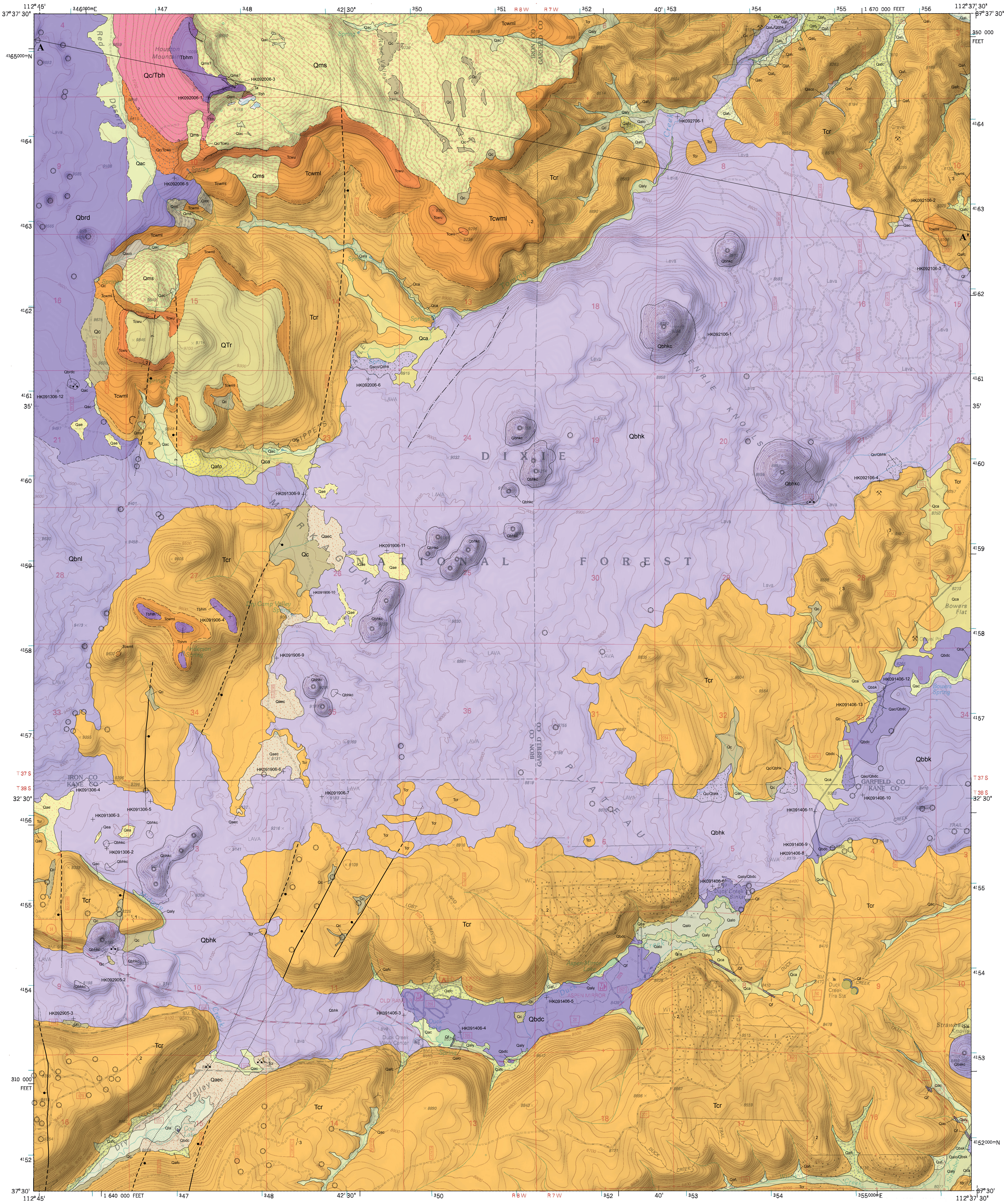

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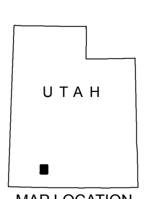

SCALE 1:24,000

1 0.5 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 0.5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

GEOLOGIC MAP OF THE HENRIE KNOLLS QUADRANGLE, GARFIELD, IRON, AND KANE COUNTIES, UTAH

by

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2011

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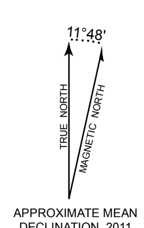

Base from U.S. Geological Survey Henrie Knolls 7.5' Quadrangle (1985)
Revision U.S. Forest Service (2002)
Projection: UTM Zone 12
Datum: NAD 1927
Spheroid: Clarke 1866

Project Manager: Donald L. Clark
GIS and Cartography: Jay C. Hill, Kent D. Brown and J. Buck Ehler

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1	2	3
4		5
6	7	8

1. Brian Head
2. Panguitch Lake
3. Haycock Mountain
4. Navajo Lake
5. Asay Bench
6. Straight Canyon
7. Strawberry Point
8. Long Valley Junction

ADJOINING 7.5' QUADRANGLE NAMES

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MAP UNIT DESCRIPTIONS

QUATERNARY

Alluvial deposits

Qal$_1$ — **Stream alluvium** (Holocene) − Moderately sorted sand, silt, clay, and pebble to boulder gravel deposited in active stream channels and floodplains; locally includes small alluvial fans and colluvium, and minor terraces as much as about 10 feet (3 m) above current base level; mapped along Mammoth Creek and the lower reaches of Tommy Creek in the northeast corner of the quadrangle; typically less than 20 feet (<6 m) thick.

Qat$_2$, Qat$_3$, Qat$_4$ — **Stream-terrace alluvium** (Holocene to upper Pleistocene) − Moderately sorted sand, silt, clay, and pebble to boulder gravel that forms incised gently sloping surfaces above Mammoth Creek and Tommy Creek in the northeast corner of the quadrangle; deposited in stream-channel environment and locally includes small alluvial fans and colluvium; subscript denotes relative age and height above adjacent drainage; Qat$_2$ ranges from about 5 to 10 feet (2–3 m), Qat$_3$ ranges from about 10 to 20 feet (3–6 m), and Qat$_4$ ranges from about 40 to 60 feet (12–18 m) above the adjacent Tommy and Mammoth Creeks; typically less than 20 feet (<6 m) thick.

Qaly — **Undifferentiated younger stream alluvium** (Holocene) − Similar to stream alluvium (Qal$_1$) and low-level stream-terrace alluvium (Qat$_2$), but mapped in upland drainages not well graded to Mammoth Creek, the principal stream on this part of the Markagunt Plateau; mapped along the upper reaches of Tommy Creek and in the Duck Creek and Strawberry Creek drainages; typically less than 20 feet (<6 m) thick.

Qalo — **Undifferentiated older stream alluvium** (Holocene to middle? Pleistocene) − Similar to stream-terrace alluvium (Qat$_3$ and Qat$_4$), but mapped in upland drainages not well graded to Mammoth Creek; mapped along Tommy Creek and in the Duck Creek and Strawberry Creek drainages; typically less than 20 feet (<6 m) thick.

Qam — **Marsh alluvium** (Holocene to upper Pleistocene) − Dark-yellowish-brown clay, silt, sand, and minor gravel lenses deposited in closed depressions on landslides south of Houston Mountain (in the northwest corner of the quadrangle); forms small marshy areas characterized by cattails and other hydrophilic vegetation; probably less than 10 feet (3 m) thick.

Qaf$_1$ — **Level-1 fan alluvium** (Holocene) − Poorly to moderately sorted, non-stratified, clay- to boulder-size sediment deposited principally by debris flows and debris floods at the mouths of active drainages; equivalent to the upper part of younger undifferentiated fan alluvium (Qafy, which is mapped in nearby quadrangles), but differentiated because they form smaller, isolated fans; probably less than 30 feet (<9 m) thick.

Qaf$_2$ — **Level-2 fan alluvium** (Holocene) − Similar to level-1 fan alluvium (Qaf$_1$), but now forms inactive, incised surface cut by level-2 stream-terrace alluvium (Qat$_2$) in the lower reaches of Tommy Creek; equivalent to the older, lower part of younger undifferentiated fan alluvium (Qafy, which is mapped in nearby quadrangles); probably less than 30 feet (<9 m) thick.

Qafo — **Older fan alluvium** (upper to middle? Pleistocene) − Poorly to moderately sorted, non-stratified, clay- to boulder-size sediment that forms incised remnants in the upper part of Tippets Valley and near Tommy Creek; both deposits contain boulders of basalt (probably the Houston Mountain lava flow), Claron Formation limestone and sandstone, and rare chalcedony fragments over a heavily vegetated surface; thickness uncertain, but may be as much as 30 feet (9 m) thick.

Artificial deposits

Qf — **Artificial fill** (Historical) − Engineered fill and general borrow material used to construct roadbeds and small dams; although only the larger deposits are mapped, fill of variable thickness and composition should be anticipated in all developed or disturbed areas; typically less than 20 feet (6 m) thick.

Colluvial deposits

Qc — **Colluvium** (Holocene to upper Pleistocene) − Poorly to moderately sorted, angular, clay- to boulder-size, locally derived sediment deposited by slope wash and soil creep on moderate slopes and in shallow depressions; locally grades downslope into mixed alluvium, colluvium, and eolian sand; mapped only where it conceals contacts or fills broad depressions; however, the Claron and Brian Head Formations shed enormous amounts of colluvium, such that an apron of heavily vegetated colluvium, unmapped because it forms a veneer with poor geomorphic expression, typically envelops at least the lower part of steep slopes along their outcrop belt; typically less than 20 feet (6 m) thick.

Mass-movement deposits

Qms — **Landslides** (Historical? to upper Pleistocene?) − Very poorly sorted, locally derived material deposited by rotational and translational movement; composed of clay- to boulder-size debris as well as large, partly intact, bedrock blocks; characterized by hummocky topography, numerous internal scarps, chaotic bedding attitudes, and local small ponds, marshy depressions, and meadows; large landslide complex mapped in the northwest corner of the quadrangle on the south and east flanks of Houston Mountain has a basal slip surface in the landslide-prone Brian Head Formation, which is here capped by the Houston Mountain lava flow; this landslide deposit includes large blocks of the Houston Mountain lava flow as much as several meters in size that are both widely scattered and clustered on hillocks; smaller landslides in the Claron Formation are mapped immediately to the south, west of Tippets Valley; undivided as to inferred age because research shows that even landslides with subdued morphology (suggesting that they are older, weathered, and have not moved recently) may continue to exhibit slow creep or are capable of renewed movement if stability thresholds are exceeded (Ashland, 2003); age and stability determinations require detailed geotechnical investigations; query indicates large slump blocks on the east side of Houston Mountain that may exhibit incipient failure; thickness highly variable, but typically several tens of feet or more thick.

Qmt — **Talus** (Holocene to upper Pleistocene) − Very poorly sorted, angular cobbles and boulders and finer-grained interstitial sediment deposited principally by rock fall on or at the base of steep slopes; mapped in the upper reaches of Tommy Creek where it consists of basaltic blocks derived from the Red Desert lava flow; likely less than 20 feet (6 m) thick.

Mixed-environment deposits

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

Qaco — **Older alluvium and colluvium** (upper Pleistocene) − Similar to mixed alluvium and colluvium (Qac), but forms incised, isolated remnants in the northeast corner of the quadrangle and in the upper reaches of the Tommy Creek drainage; probably about 10 to 20 feet (3–6 m) thick.

Qafc — **Fan alluvium and colluvium** (Holocene to middle Pleistocene) − Poorly to moderately sorted, non-stratified, clay- to boulder-size sediment deposited principally by debris flows, debris floods, and slope wash at the mouths of active drainages and the base of steep slopes; locally reworked by small, ephemeral streams; forms coalescing apron of fan alluvium and colluvium impractical to map separately at this scale; typically 10 to 40 feet (3–12 m) thick.

Qca — **Colluvium and alluvium** (Holocene to middle Pleistocene) − Poorly to moderately sorted, angular, clay- to boulder-size, locally derived sediment deposited principally by slope wash in shallow depressions and in the upper reaches of small drainages; locally reworked by alluvial processes; distal, finer-grained parts typically form broad, open meadows; thickness uncertain, but likely less than about 10 feet (3 m) thick.

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

Qea — **Eolian sand and alluvium** (Holocene to upper Pleistocene) − Well-sorted, light-reddish-brown silt and sand deposited by wind and reworked by sheetwash in swales on the Henrie Knolls lava flow in the southwest part of the quadrangle; probably less than 10 feet (3 m) thick.

Qaec — **Alluvium, eolian sand, and colluvium** (Holocene to upper Pleistocene) − Moderately sorted, light-reddish-brown and moderate- to dark-yellowish-brown silt and sand deposited in swales and small drainages on and adjacent to the Henrie Knolls lava flow in the west-central part of the quadrangle; locally includes gravelly lenses, and the margins of the deposits include significant colluvium derived from adjacent slopes developed on the Claron Formation and basaltic lava flows; also mapped in Dry Valley, in the southwest corner of the quadrangle, where the distal margins of the deposit likely are interbedded with lacustrine sediment and alluvium (Qla); soils developed on this unit have an argillic horizon 1 to 1.5 feet (0.3–0.5 m) thick of moderate-reddish-brown sandy clay and clayey fine-grained sand; typically less than 10 feet (3 m) thick, although Duck Creek deposits are likely as much as 20 feet (6 m) thick.

Qla — **Lacustrine sediment and alluvium** (Holocene to upper Pleistocene) − Moderately to well sorted, thinly bedded, yellowish-brown and light-gray, fine-grained sand, silt, and clay derived from adjacent Claron Formation slopes and deposited in the ephemeral Cow Lake in the southwest corner of the quadrangle; mostly conceals vesicular basalt that is likely part of the Duck Creek lava flow; probably less than 15 feet (4 m) thick.

Stacked unit deposits

Qac/Qdbc — **Alluvium and colluvium over the Duck Creek lava flow** (Holocene to upper Pleistocene/Pleistocene) − Mapped southwest of Bowers Flat, near the east-central edge of the quadrangle, where mixed alluvium and colluvium mostly conceals the underlying Duck Creek lava flow; surficial cover generally less than 3 feet (1 m) thick.

Qc/Qbhk — **Colluvium over the Henrie Knolls lava flow** (Holocene to upper Pleistocene/Pleistocene) − Mapped in the east-central part of the quadrangle where mostly fine-grained colluvium derived from the red member of the Claron Formation mostly conceals the underlying Henrie Knolls lava flow; surficial cover generally less than 6 feet (2 m) thick.

Qalo/Qbdc — **Undifferentiated older stream alluvium over the Duck Creek lava flow** (Holocene to middle? Pleistocene/Pleistocene) − Mapped near Duck Creek Sinks where older stream alluvium mostly conceals the underlying Duck Creek lava flow; surficial cover generally less than 6 feet (2 m) thick.

Qalo/Qbsk — **Undifferentiated older stream alluvium over the Strawberry Knolls lava flow** (Holocene to middle? Pleistocene/Pleistocene) − Mapped along Strawberry Creek where older stream alluvium mostly conceals the underlying Strawberry Knolls lava flow; surficial cover generally less than 6 feet (2 m) thick.

Qaco/Qbhk — **Older alluvium and colluvium over the Henrie Knolls lava flow** (upper Pleistocene/Pleistocene) − Mapped at Tippets Valley where scattered subrounded cobbles and boulders of basalt and Claron Formation limestone and sandstone show through a densely vegetated surface, apparently concealing the underlying Henrie Knolls lava flow; surficial cover typically less than 6 feet (2 m) thick.

Qat$_4$/Qbhk — **Level-4 stream-terrace alluvium over the Henrie Knolls lava flow** (upper Pleistocene/Pleistocene) − Mapped along the lower reaches of Tommy Creek where high-level stream-terrace alluvium conceals the underlying Henrie Knolls lava flow; surficial cover typically less than 6 feet (2 m) thick.

Qc/Tbh — **Colluvium over the Brian Head Formation** (Holocene to upper Pleistocene/Oligocene to Eocene) – Mapped on the west side of Houston Mountain in the northwest corner of the quadrangle where colluvium and possibly small landslides conceal the underlying Brian Head Formation; colluvium includes large blocks of the Houston Mountain lava flow enclosed in a matrix of colluvium derived from weathered, tuffaceous Brian Head strata and oldest stream alluvium (Ta); surficial cover may exceed 20 feet (6 m) thick.

Qc/Tcwu — **Colluvium over the upper limestone interval of the white member of the Claron Formation** (Holocene to upper Pleistocene/Eocene to Paleocene) – Mapped on the southwest side of Houston Mountain in the northwest corner of the quadrangle where colluvium conceals the underlying upper limestone interval of the white member of the Claron Formation; colluvium includes large blocks of the Houston Mountain lava flow enclosed in a matrix of colluvium derived from weathered, tuffaceous Brian Head strata and the upper limestone interval of the white member of the Claron Formation; surficial cover may exceed 10 feet (3 m) thick.

Basaltic lava flows

Basaltic lava flows in the Henrie Knolls quadrangle are at the northern edge of the Western Grand Canyon basaltic field, which extends across the southwest part of the Colorado Plateau and adjacent transition zone with the Basin and Range Province in southwest Utah, northwest Arizona, and adjacent Nevada (Hamblin, 1963, 1970, 1987; Best and Brimhall, 1970, 1974; Best and others, 1980; Smith and others, 1999; Johnson and others, 2010). This volcanic field contains hundreds of relatively small-volume, widely scattered, mostly basaltic lava flows and cinder cones that range in age from Miocene to Holocene.

In southwestern Utah, basalts are synchronous with basin-range deformation and are part of mostly small, bimodal (basalt and high-silica rhyolite) eruptive centers (Christiansen and Lipman, 1972; Rowley and Dixon, 2001). The oldest basalts in southwestern Utah are about 17 to 20 Ma (Rowley and others, 2006; Biek and others, 2009). The youngest dated lava flow in southwest Utah is the 32,000-year-old Santa Clara basaltic lava flow (Willis and others, 2006; Biek and others, 2009), but the nearby Miller Knoll, Dry Valley, and Panguitch Lake lava flows south of Panguitch Lake may be younger still (Biek and others, 2011). The oldest basaltic lava flows on the Markagunt Plateau are the Houston Mountain flow (Tbhm), for which we report a new $^{40}Ar/^{39}Ar$ plateau age of 5.27 ± 0.14 Ma, and the 5.3 Ma Dickinson Hill and Rock Canyon flows (Biek and others, 2011); major- and trace-element geochemical data for these and other lava flows will be available as part of a larger mapping project of the Panguitch 30' x 60' quadrangle (Biek, in preparation).

Lava flows in the map area typically have a rubbly base, a dense, jointed middle part, and—if not eroded away—a vesicular upper part that has a rough aa (a Hawaiian term for a blocky, jagged flow) or, rarely, a poorly developed pahoehoe (a Hawaiian term for a smooth or ropy flow) surface. Several lava flows, including the Duck Creek and Bowers Knoll lava flows, contain open lava tubes; the best known is Mammoth Cave (6 miles [10 km] northeast of Duck Creek Village). The flows commonly overlie stream-gravel and other surficial deposits. Most lava flows are dark gray, fine grained, and contain small olivine phenocrysts and common crystal clusters of olivine, plagioclase, and clinopyroxene. These lava flows are difficult to distinguish by hand sample alone. They are distinguished for this geologic map by detailed geologic mapping and trace-element geochemistry. Rock names follow the total alkali versus silica (TAS) classification diagram of LeBas and others (1986).

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

Qbnl — **Navajo Lake lava flow** (upper Pleistocene?) – Medium- to dark-gray mugearite (sodium-rich basaltic trachyandesite) containing clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; some lava flows contain common small plagioclase phenocrysts; lava flows erupted from vents at cinder cones in the east-central part of the adjacent Navajo Lake quadrangle (Moore and others, 2004) and coalesced into flow complexes not mapped separately; margins of flows typically form steep, blocky flow fronts 10 to 30 feet (3–9 m) high; cinder cone (in adjacent quadrangle) is well vegetated, but lava flows are mostly barren with a rough, blocky surface; age uncertain, but Moore and others (2004) considered it as probably Holocene in age; based on the degree of incision and weathering, Biek considers the lava flow to be late Pleistocene in age, slightly younger than the nearby, more vegetated, Red Desert and Henrie Knolls lava flows; lava flows are typically several tens of feet thick, but thicker where they fill paleotopography.

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

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

Qbsk, Qbskc — **Strawberry Knolls lava flow and cinder cone** (upper to middle Pleistocene) – Medium- to dark-gray potassic trachybasalt that contains clusters of olivine and clinopyroxene phenocrysts in an aphanitic to fine-grained groundmass; lava flows (Qbsk) erupted from Strawberry Knolls (Qbskc), two cinder cones located about 2 miles (3 km) east of Duck Creek village, and flowed mostly northeast along Strawberry Creek to Uinta Flat in the adjacent Asay Bench quadrangle (Moore and others, 1994); age uncertain, but cinder cones are well vegetated and flow is incised by Strawberry Creek as much as 40 feet (12 m) at its downstream end and so is probably late to middle Pleistocene; lava flows are typically 20 to 30 feet (6–9 m) thick, but doubtless many tens of feet thick near vent areas.

Qbdc — **Duck Creek lava flow** (upper to middle Pleistocene) – Medium-gray basalt that contains clusters of olivine and clinopyroxene phenocrysts and abundant small plagioclase phenocrysts in a fine-grained groundmass; location of vent unknown, but it may be concealed by the Henrie Knolls or Navajo Lake lava flows; alternatively, geochemical data suggest that the Duck Creek lava flow may be the distal part of either the Midway Creek or Horse Pasture lava flows; the lava flowed from west to east down the ancestral Duck Creek drainage and continued northeastward to at least the Bowers Flat area at the west edge of the Asay Bench quadrangle; contains a long, open lava tube near Aspen Mirror Lake, just west of Duck Creek village (U.S. Forest Service restricts access); lava flow is typically partly concealed by a veneer of unmapped alluvium, colluvium, and eolian sand; age uncertain, but it locally covers the Bowers Knoll lava flow (Qbbk) and in turn is locally covered by the Henrie Knolls lava flow (Qbhk), thus is probably late to middle Pleistocene; however, Johnson and others (2010) suggested that the distal end of the Bowers Knoll flow as mapped by Biek and others (2011), including the part that contains Mammoth Cave, may be the Duck Creek flow—if so, incision there suggests that the Duck Creek flow is about 500,000 years old, far older than the degree of incision suggests along the upstream part of the flow; maximum exposed thickness is about 15 feet (5 m) near Aspen Mirror Lake, but likely several tens of feet thick where it fills paleotopography in the Duck Creek drainage.

Qbbk — **Bowers Knoll lava flow** (middle Pleistocene?) – Medium-gray mugearite (sodium-rich basaltic trachyandesite) with abundant olivine phenocrysts and less common plagioclase and clinopyroxene phenocrysts in a fine-grained groundmass; erupted from Bowers Knoll in the adjacent Asay Bench quadrangle; forms rugged, heavily vegetated, blocky surface with steep flow fronts 40 feet (12 m) or more high; age uncertain, but predates the Duck Creek lava flow, so is probably middle Pleistocene in age; Best and others (1980) reported a K-Ar age of 0.52 ± 0.05 Ma for the nearby Asay Knoll lava flow, which exhibits a similar degree of incision and weathering; typically 40 feet (12 m) or more thick near flow margins, but may exceed 100 feet (30 m) thick near the central part of the flow.

unconformity

QUATERNARY-TERTIARY

QTr — **Blocky residuum** (Holocene to Pliocene?) – A high-elevation (9300 to 9800 feet [2835–2990 m]) deposit present west of Tippets Valley where blocky remnants of the Houston Mountain lava flow (Tbhm) have been let down by erosion of underlying beds; angular to subangular blocks of the former lava flow, typically 3 feet (1 m) or less in diameter but locally as large as about 12 feet (4 m), tend to accumulate in swales and on ridge crests; locally, the blocks form a basaltic pavement on the white member of the Claron Formation, but typically they are only widely scattered; other than uncommon small fragments of chalcedony, no other exotic rock types are present; probably formed as former basalt-capped hilltops succumbed to hillslope erosion, undermining the lava flow and leading to scattered resistant blocks being dispersed over underlying bedrock; unmapped colluvium derived from this unit blankets much of the underlying Claron Formation west of Tippets Valley and south of Tommy Creek; typically less than a few feet thick.

unconformity

TERTIARY

Tbhm — **Houston Mountain lava flow** (Pliocene or Miocene) – Medium-gray basalt containing clusters of olivine and clinopyroxene phenocrysts in a fine-grained groundmass; commonly platy weathering; unconformably overlies the Brian Head Formation (Tbh) and late Tertiary stream alluvium (Ta) at Houston Mountain (in the northwest corner of the quadrangle) and, 4 miles (6 km) to the south, the Claron Formation (Tcwml and Tcr) in the vicinity of Anderson Spring; also comprises the blocks of residual deposits (QTr) capping the hill west of Tippets Valley, and is involved in the large landslide complex (Qms) east of Houston Mountain; source vent unknown and margins of lava flow are entirely eroded away, but elevation of remnants suggests flow was derived from the west in the Brian Head quadrangle, likely at a vent now eroded and concealed by younger deposits; sample HK092006-3 yielded an $^{40}Ar/^{39}Ar$ whole-rock age of 5.27 ± 0.14 Ma (UGS and NMGRL, 2009); maximum exposed thickness is about 140 feet (43 m) at Houston Mountain.

Ta — **Oldest stream alluvium** (Pliocene or Miocene) – Light-gray to white, moderately cemented pebbly conglomerate and gritstone present in one small exposure at the head of a landslide just southeast of Houston Mountain; clasts include subangular to subrounded Claron limestone and sandstone, black and gray chert, a variety of ash-flow tuffs of uncertain provenance but possibly including the Leach Canyon Formation, and chalcedony; neither upper nor lower contacts are exposed, but these deposits are presumed to represent fluvial channel deposits that were covered by the Houston Mountain lava flow; maximum exposed thickness is about 30 feet (9 m).

unconformity

Tbh — **Brian Head Formation** (lower Oligocene to upper Eocene) – The Brian Head Formation is the oldest widespread Tertiary volcaniclastic unit in the region; it disconformably overlies the Claron Formation on the Markagunt Plateau. Sable and Maldonado (1997) divided the Brian Head Formation into three informal units, ascending: (1) nontuffaceous sandstone and conglomerate, (2) a volcaniclastic unit that has minor but conspicuous limestone and chalcedony, and (3) a volcanic unit, locally present, characterized by volcanic mudflow breccia, mafic lava flows, volcaniclastic sandstone and conglomerate, and ash-flow tuff; we include the basal nontuffaceous sandstone and conglomerate as a new uppermost part of the Claron Formation (Biek and others, 2011), so that only their middle volcaniclastic unit is present in the map area; on the Markagunt Plateau, Brian Head strata are unconformably overlain by the 30 Ma Wah Wah Springs Formation, or locally by the 26 to 27 Ma Isom Formation, or the 24 Ma Leach Canyon Formation, and so is early Oligocene at the youngest; Maldonado and Moore (1995) reported $^{40}Ar/^{39}Ar$ ages of 33.00 ± 0.13 Ma (plagioclase) and 33.70 ± 0.14 Ma (biotite) on an ash-flow tuff in the Red Hills that lies in the upper part of the formation. Biek and others (2011) reported a U-Pb age on zircon from an airfall tuff at the base of the formation at Cedar Breaks National Monument of 35.77 ± 0.28 Ma.

The Brian Head Formation underlies (Houston Mountain) in the northwest corner of the quadrangle; it is nearly everywhere heavily vegetated and covered by colluvium; because of abundant bentonitic clay derived from weathered volcanic ash, the formation weathers to strongly swelling soils (unlike the underlying Claron Formation) and forms large landslide complexes. Two small exposures are present, however, at the head of a landslide on the southeast side of Houston Mountain. These exposures reveal a light-yellowish-gray to white volcanic ash, mostly weathered to clay, and fine-grained tuffaceous sandstone, both of which are non-resistant and poorly exposed. Deposited in low-relief fluvial, floodplain, and lacustrine environments in which large amounts of volcanic ash accumulated; maximum exposed thickness is about 40 feet (12 m), but outcrop patterns suggest that an incomplete section of the formation may be as much as 300 feet (90 m) thick at Houston Mountain; it is about 500 feet (150 m) thick at Brian Head peak (Biek and others, 2011).

unconformity

Claron Formation (Eocene to Paleocene) – Mapped as three informal lithostratigraphic units described below: an upper white member—itself divided into an upper limestone interval and a lower mudstone, siltstone, sandstone, and limestone interval—and a lower red member; at nearby Cedar Breaks National Monument, a 50- to 100-foot-thick (15–30 m) mudstone interval (Tcwt of Biek and others, 2011) forms the top of the member, but exposures are inadequate to determine if that unit is preserved at Houston Mountain. The Claron Formation consists of mudstone, siltstone, sandstone, limestone, and minor conglomerate deposited in fluvial, floodplain, and lacustrine environments of an intermontaine basin bounded by Laramide uplifts (Schneider, 1967; Goldstrand, 1990, 1991, 1992; Taylor, 1993; Ott, 1999). The red member, and to a much lesser extent the white member, were greatly modified by bioturbation and pedogenic processes, creating a stacked series of paleosols (Mullett and others, 1988a, 1988b; Mullett, 1989; Mullett and Wells, 1990; see also Bown and others, 1997). The Claron Formation is typically forested and covered by colluvium, but it forms the Pink Cliffs, the uppermost riser of the Grand Staircase, and is spectacularly exposed at Cedar Breaks National Monument and near Cascade Falls, immediately west and southwest of the Henrie Knolls quadrangle, respectively. It is mostly nonfossiliferous and its age is poorly constrained as Eocene to Paleocene (Goldstrand, 1994; Feist and others, 1997), but Nichols (1997) reported Late Cretaceous (Santonian?) pollen from gradationally underlying strata that Biek and others (2011) mapped as TKu south and west of Blowhard Mountain, thus suggesting that the Claron Formation may be older than previously thought.

The entire white member is about 340 feet (100 m) thick in Rock Canyon; Hatfield and others (2010) reported that it is 360 feet (110 m) thick at Cedar Breaks National Monument, but if the lower sandstone and conglomerate unit of Sable and Maldonado (1997) is included as part of the white member, as suggested here, the thickness is 440 feet (135 m); Moore and others (1994) reported significant facies changes in the white member in the adjacent Asay Bench quadrangle, but there, in aggregate, it is 448 feet (137 m) thick. Sinkholes are common in the white member and upper part of the red member on the central Markagunt Plateau (Moore and others, 2004; Hatfield and others, 2010; Biek and others, 2011); large sinkholes visible on 1:20,000-scale aerial photographs are plotted on the geologic map, and doubtless many smaller sinkholes are present; these sinkholes capture local runoff and serve to shunt shallow groundwater rapidly down dip where it emerges as springs, including the large Mammoth and Asay Springs several miles east of the map area (Wilson and Thomas, 1964; Spangler, 2010).

Tcwu — **Upper limestone interval of white member** – White, pale-yellowish-gray, pinkish-gray, and very pale orange micritic limestone and uncommon pelmicritic limestone, locally with intraformational rip-up clasts; locally contains very sparse charophytes and planispiraled snails; typically poorly bedded and knobby weathering; locally vuggy with calcite spar and commonly cut by calcite veinlets; lower half of interval forms a prominent ledge and is typically better exposed than the lower white limestone at the base of the white member, but upper half, on Houston Mountain, is not exposed; upper, unconformable contact with the landslide-prone Brian Head Formation is not exposed; in this quadrangle, the upper limestone interval of the white member is about 150 to 180 feet (45–55 m) thick; it is 45 to 60 feet (14–18 m) thick at Cedar Breaks (Schneider, 1967; Moore and others, 2004; Rowley and others, in preparation) and 80 to 165 feet (24–50 m) thick in the adjacent Asay Bench quadrangle (Moore and others, 1994).

Tcwml — **Lower limestone interval and middle mudstone, siltstone, and sandstone interval of white member, undivided** – Basal part is a 30- to 40-foot-thick (10–12 m) micritic limestone interval similar to the upper limestone interval (Tcwu) of the white member; this lower limestone interval is locally well exposed, as near the Iron-Garfield County line in the SW¼SW¼SW¼ section 7, T. 37 S., R. 7 W., and adjacent areas, where it forms a conspicuous cliff equivalent to the lower white limestone (Tcwl) in the Cedar Breaks National Monument area, but in this quadrangle it typically weathers to poorly exposed ledgey slopes; southwest of hill 9295, in the SW¼ section 12, T. 37 S., R. 8 W., the lower part contains white-weathering, clear to light-brown chalcedony, possibly in a single bed as much as 1 foot (0.3 m) thick. The overlying middle mudstone, siltstone, and sandstone interval contains white, yellowish-gray, and moderate-yellowish-brown calcareous mudstone and siltstone and lesser fine- to medium-grained sandstone and minor chert-pebble conglomerate that in this quadrangle everywhere weathers to a poorly exposed slope. Contact with upper limestone interval of the white member typically corresponds to the base of a steeper slope. In this quadrangle, this undivided interval is about 220 to 250 feet (67–75 m) thick; at Cedar Breaks National Monument, Schneider (1967) measured 227 feet (69 m) of strata that Biek and others (2011) assign to the middle mudstone, siltstone, and sandstone interval (Tcwm) and about 47 feet (14 m) to the lower limestone (Tcwl); Moore and others (1994) reported that in the adjacent Asay Bench quadrangle, their middle sandy unit is 175 to at least 220 feet (54–67 m) thick and that their lower white limestone is generally 85 to 120 feet (26–36 m) thick, but as much as 180 feet (55 m) thick.

Tcr — **Red member** − Alternating beds of varicolored and commonly mottled, pale-reddish-orange, reddish-brown, moderate-orange-pink, dark-yellowish-orange, and grayish-pink sandy and micritic limestone, calcite-cemented sandstone, calcareous mudstone, and minor pebbly conglomerate, that, in this quadrangle, generally weathers to colluvium-covered slopes, rounded ridges, and small hills. The colluvium typically is moderate-yellowish-brown, silty, clayey sand that contains white limestone and pale-reddish-orange rock fragments and minor pebbles of black chert and brown quartzite. Limestone is poorly bedded, microcrystalline, generally sandy with 2 to 20 percent fine-grained quartz sand, and is locally argillaceous; contains common calcite veinlets, calcite spar-filled vugs, stylolites, and very sparse small bivalves and planispiral gastropods; the limestone is also locally cavernous and sinkholes are common; many of these limestone beds may be calcic paleosols (Mullett and others, 1988a, 1988b; Mullett, 1989; Mullett and Wells, 1990). Sandstone is thick-bedded, fine- to coarse-grained, calcareous, locally cross-bedded quartz arenite that typically weathers to sculpted or fluted ledges that pinch out laterally; it locally contains pebble stringers. Mudstone is generally moderate reddish orange, silty, calcareous, contains calcareous nodules, and weathers to earthy, steep slopes between ledges of sandstone and limestone. Pebbly conglomerate is uncommon in this quadrangle, where it forms lenticular beds 5 to 15 feet (2–5 m) thick with limestone, quartzite, and chert clasts.

In the Henrie Knolls quadrangle, the upper contact of the red member is only well exposed near the Iron-Garfield County line in the SW¼SW¼SW¼ section 7, T. 37 S., R. 7 W., and adjacent areas, where it corresponds to a pronounced color change from brightly colored reddish-orange mudstone and siltstone below to a conspicuous 30- to 40-foot-high (10–12 m) cliff of white to very pale orange micritic limestone (informally called the "lower white limestone" in the Cedar Breaks National Monument area). In areas of discontinuous outcrop, it is difficult to distinguish this limestone bed at the base of the white member (base of Tcwl) from other limestone beds in the upper part of the red member.

The lower contact of the Claron Formation is not exposed in the Henrie Knolls quadrangle. Moore and others (2004) noted that it corresponds to the base of a prominent, 62- to 75-foot-high (19–23 m), locally cavernous limestone cliff, below which lies mudstone and sandstone assigned to their informal formation of Cedar Canyon. The red member is about 1000 feet (300 m) thick at Cedar Breaks National Monument (Biek and others, 2011), similar to the measured thickness of Schneider (1967), who reported that the red member there was 993 feet (303 m) thick (the lower 56 feet [17 m] of his section includes beds we assign to TKu, thus the red member there is 937 feet [286 m] thick), considerably less than the 1300 feet (400 m) reported by Sable and Maldonado (1997); the maximum exposed thickness in this quadrangle is about 500 to 600 feet (150–180 m).

TERTIARY-CRETACEOUS

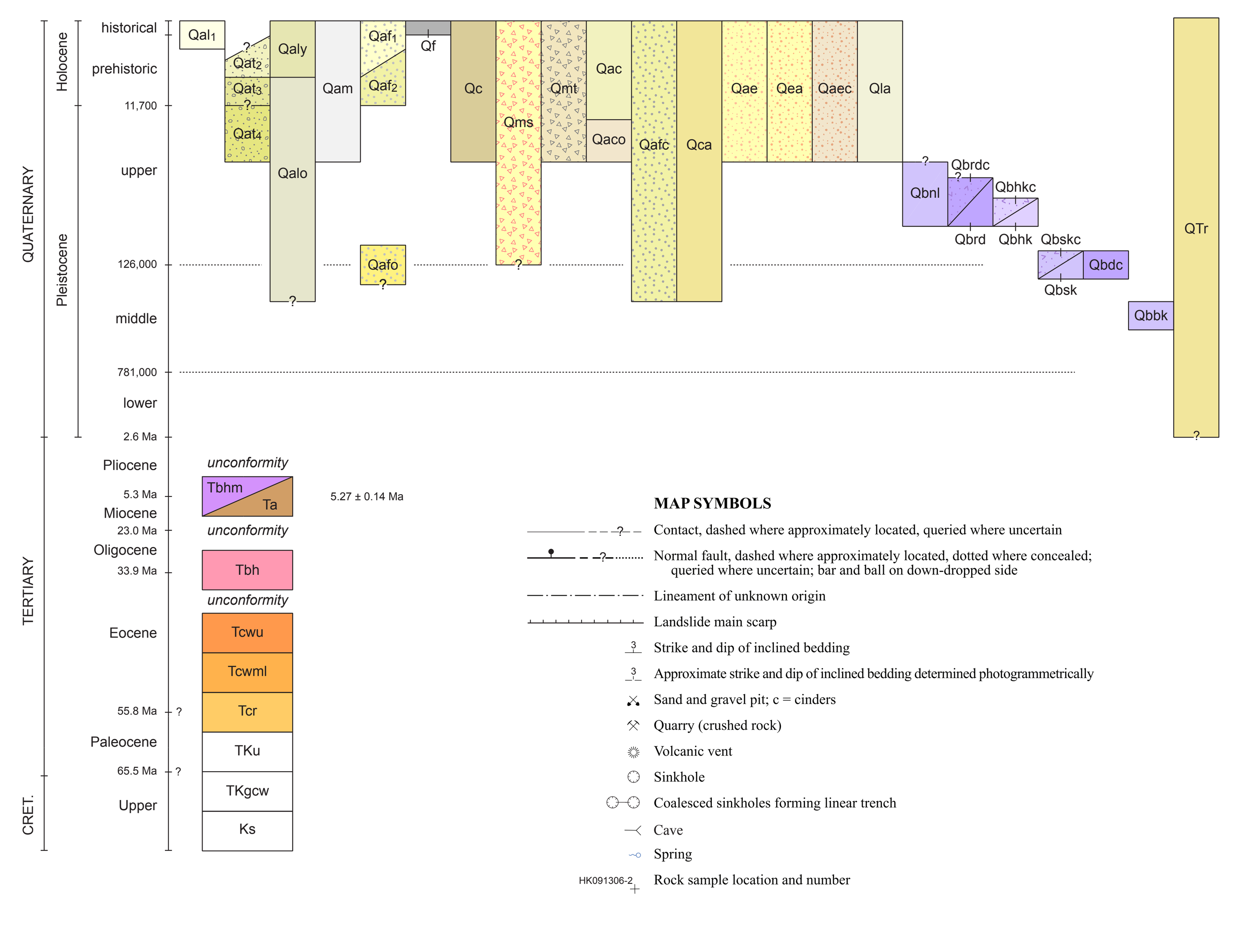
Upper Cretaceous strata undergo significant west-to-east and north-to-south facies changes on the Markagunt Plateau, thus presenting significant challenges to correlation and mapping as described by Eaton and others (2001), Moore and Straub (2001), Moore and others (2004), Biek and others (2011), and Rowley and others (in preparation). These strata consist of coastal plain, marginal marine, and a westward-thinning wedge of marine strata deposited in a foreland basin east of the Sevier orogenic belt. Collectively, this sedimentary package, represented by the Dakota, Tropic, and Straight Cliffs Formations, was deposited during the Greenhorn Marine Cycle, a large-scale sea-level rise and fall recognized worldwide and that here corresponds to the maximum transgression of the Western Interior Seaway. It is overlain by fluvial and floodplain strata that we assign to the Grand Castle Formation, Wahweap Formation, and undifferentiated Tertiary-Cretaceous strata; alternatively, these fluvial strata may represent an exceptionally thick section of the underlying John Henry Member of the Straight Cliffs Formation. Ongoing mapping of the Panguitch 30' x 60' quadrangle (see Biek and others, 2011) may further elucidate relationships among these foredeep basin strata.

TKu — **Tertiary-Cretaceous strata, undivided** (Paleocene? to Upper Cretaceous) – Shown on cross section only. As much as about 200 feet (60 m) thick near State Highway 14 at the west edge of the Markagunt Plateau (Biek and others, 2011).

TKgcw — **Grand Castle Formation and Wahweap? Formation, undivided** (Paleocene? to Upper Cretaceous) – Shown on cross section only. As much as about 1200 feet (365 m) thick at the west edge of the Markagunt Plateau (Biek and others, 2011).

Ks — **Straight Cliffs Formation, undivided** (Upper Cretaceous) – Shown on cross section only. As much as about 2200 feet (670 m) thick at the west edge of the Markagunt Plateau (Biek and others, 2011).

CORRELATION OF MAP UNITS



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This mapping project is part of a larger effort to map the geology of the Panguitch 30' x 60' quadrangle, originally begun in 1988 by U.S. Geological Survey geologists and their colleagues under the Basin and Range to Colorado Plateau Transition (BARCO) Study Unit. The BARCO project was active through the mid-1990s, but disbanded at the height of its efforts following reorganization of the USGS. Biek mapped the Henrie Knolls quadrangle using standard field methods and VR-2 photogrammetry; Moore, lead author on the adjacent Navajo Lake and Asay Bench quadrangles, reviewed the map and shared his knowledge of local geology, as did Nealey, who did extensive work on the basaltic lava flows of the region.

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