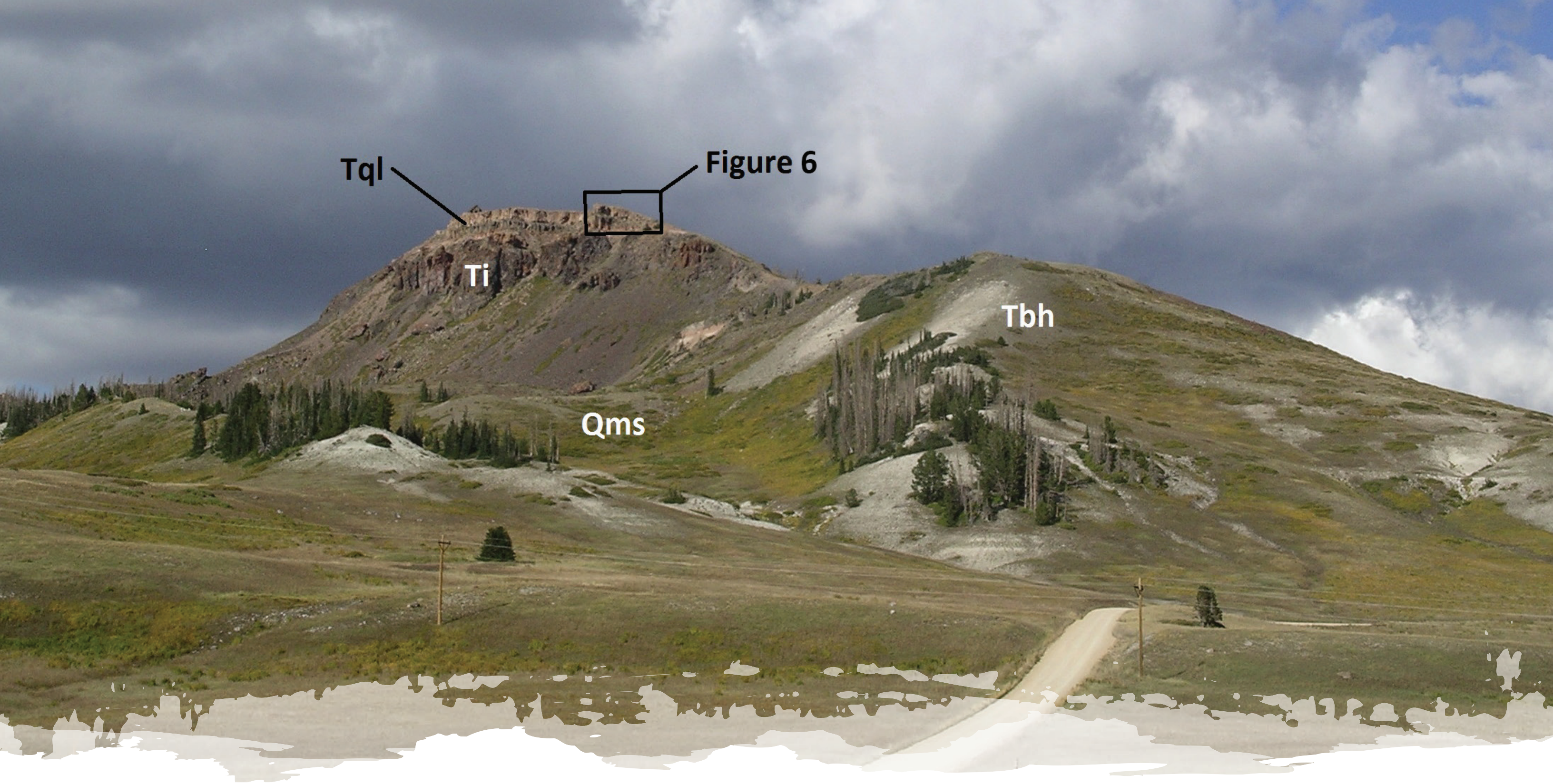


# Brian Head Peak, Iron County

Robert F. Biek[1] and Peter D. Rowley[2]
[1]Utah Geological Survey, P.O. Box 146100, Salt Lake City, UT 84114-6100, bobbiek@utah.gov
[2]Geologic Mapping Inc., P.O. Box 651, New Harmony, UT 84757

Utah Geosites
2019
Utah Geological Association Publication 48
M. Milligan, R.F. Biek, P. Inkenbrandt, and P. Nielsen, editors

***Cover Image:*** *The type section of the Brian Head Formation (Tbh) is on the ridge just right of center (by the Tbh label). Brian Head peak is capped by the Leach Canyon Formation (Tql), which overlies the Isom Formation (Ti). A modern landslide (Qms) is west and south of the peak.*

Utah Geosites
2019

Utah Geological Association Publication 48

M. Milligan, R.F. Biek, P. Inkenbrandt, and P. Nielsen, editors

*Utah Geosites* showcases some of Utah's spectacular geology, both little-known localities and sites seen by visitors to Utah's many national and state parks and monuments. The geosites reflect the interests of the many volunteers who wrote to share some of their favorite geologic sites. The list is eclectic and far from complete, and we hope that additional geosites will be added in the coming years. The Utah Geological Survey also maintains a list of geosites https://geology.utah.gov/apps/geosights/index.htm.

We thank the many authors for their geosite contributions, Utah Geological Association members who make annual UGA publications possible, and the American Association of Petroleum Geologists—Rocky Mountain Section Foundation for a generous grant for desktop publishing of these geosite papers.

Design and desktop publishing by Jenny Erickson, Graphic Designer, dutchiedesign.com, Salt Lake City, Utah.



*Suggested citation for this geosite:*

Biek, R.F., and Rowley P.D., 2019, Brian Head Peak, Iron County, *in* Milligan, M., Biek, R.F., Inkenbrandt, P., and Nielsen, P., editors, Utah Geosites: Utah Geological Association Publication 48, 11 p., https://doi.org/10.31711/geosites.v1i1.47.

## Presidents Message

I have had the pleasure of working with many different geologists from all around the world. As I have traveled around Utah for work and pleasure, many times I have observed vehicles parked alongside the road with many people climbing around an outcrop or walking up a trail in a canyon. Whether these people are from Utah or from another state or country, they all are quick to mention to me how wonderful our geology is here in Utah.

Utah is at the junction of several different geological provinces. We have the Basin and Range to the west and the Central Utah Hingeline and Thrust Belt down the middle. The Uinta Mountains have outcrops of some of the oldest sedimentary rock in Utah. Utah also has its share of young cinder cones and basaltic lava flows, and ancient laccoliths, stratovolcanoes, and plutonic rocks. The general public comes to Utah to experience our wonderful scenic geology throughout our state and national parks. Driving between our national and state parks is a breathtaking experience.

The "Utah Geosites" has been a great undertaking by many people. I wanted to involve as many people as we could in preparing this guidebook. We have had great response from authors that visit or work here in the state. Several authors have more than one site that they consider unique and want to share with the rest of us. I wanted to make the guidebook usable by geologists wanting to see outcrops and to the informed general public. The articles are well written and the editorial work on this guidebook has been top quality.

I would like to personally thank Mark Milligan, Bob Biek, and Paul Inkenbrandt for their editorial work on this guidebook. This guidebook could not have happened without their support. I would like to thank Jenny Erickson for doing the great desktop publishing and the many authors and reviewers that helped prepare the articles. Your work has been outstanding and will certainly showcase the many great places and geology of Utah. Last, but not least, Thank you to the American Association of Petroleum Geologists, Rocky Mountain Section Foundation for their financial support for this publication.

Guidebook 48 will hopefully be a dynamic document with the potential to add additional "geosites" in the future. I hope more authors will volunteer articles on their favorite sites. I would like to fill the map with locations so that a person or family looking at the map or articles will see a great location to read about and visit. Enjoy Guidebook 48 and enjoy the geology of Utah.

Peter J. Nielsen
*2019 UGA President*

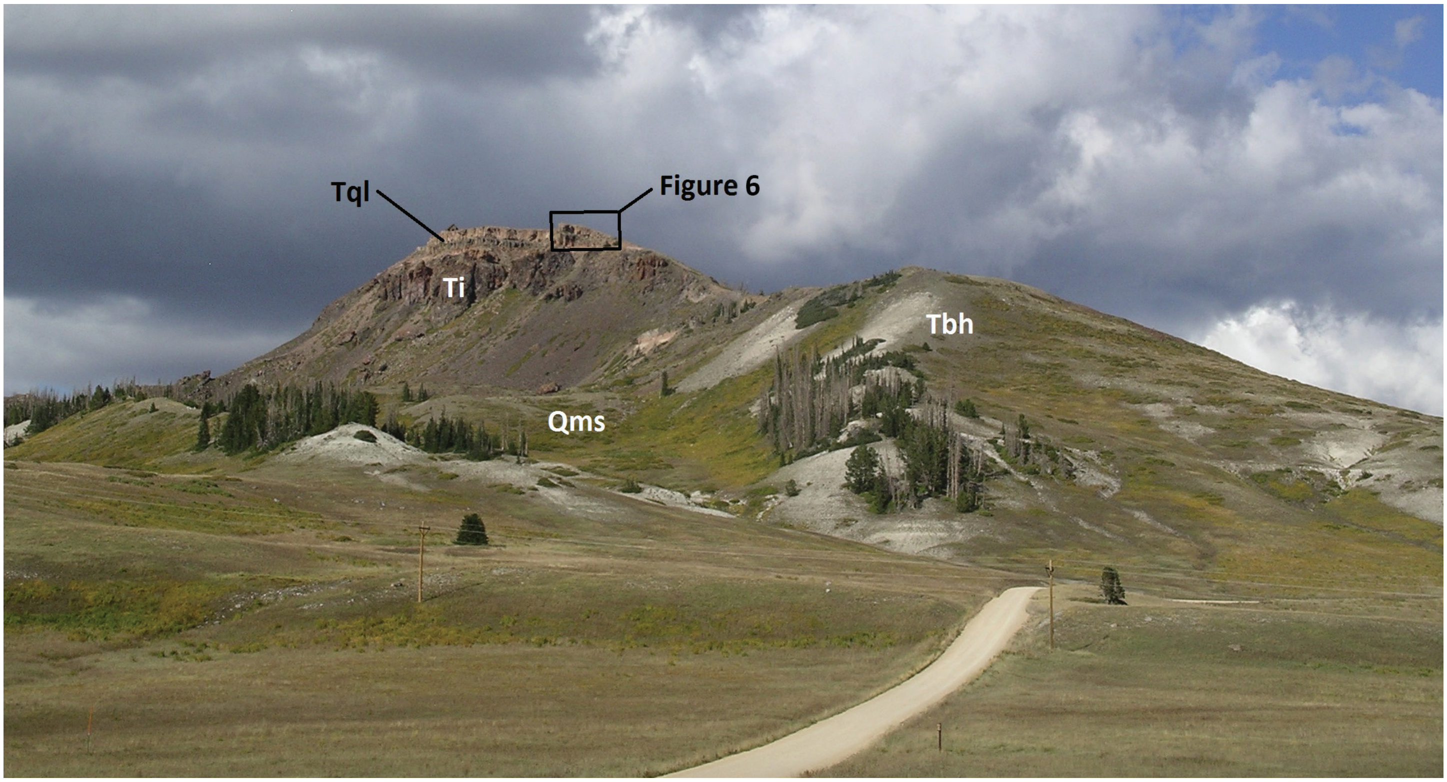


*Figure 1. The type section of the Brian Head Formation (Tbh) is on the ridge just right of center (by the Tbh label). Brian Head peak is capped by the Leach Canyon Formation (Tql), which overlies the Isom Formation (Ti). A modern landslide (Qms) is west and south of the peak.*

## INTRODUCTION

Brian Head peak, the highest point on the west edge of the Markagunt Plateau at 11,307 feet (3447 m), provides stunning views westward into the Great Basin. The plateau is part of the High Plateaus, a subprovince of the Colorado Plateau. Few views in southern Utah so well demonstrate the huge difference between the badly broken Great Basin, where east-west crustal extension (pulling apart) produced north-trending faulted basins and intervening ranges, and the much less deformed and here higher Colorado Plateau. The southwestern flank of the peak is the type section of the Brian Head Formation, an Eocene to Oligocene stream and lake deposit that is overlain by densely welded ash-flow tuff of the 27 to 26 Ma Isom Formation. The peak itself is capped by the moderately welded, 23.8 Ma ash-flow tuff of the Leach Canyon Formation (figure 1). These two regionally extensive, upper Oligocene ash-flow tuffs erupted suddenly and explosively from calderas near the Utah-Nevada border and made their way in minutes to their present position, devastating everything in between, millions of years before the episode of basin-range deformation formed the Great Basin and uplifted the High Plateaus. Both bear on the timing of basin-range deformation, and both can be visited on Brian Head. Furthermore, the Isom Formation itself is a key player in understanding Earth's largest terrestrial landslide, the Markagunt gravity slide (see Sidney Peaks geosite). The south side of the peak offers the best exposures of the Leach Canyon Formation, including its vitrophyre and basal surge deposits, which are seldom exposed glassy and sandy parts of typical ash-flow tuffs.

## LOCATION

Brian Head peak, just off Utah Highway 143 north of Cedar Breaks National Monument, is accessible via Brian Head Peak Road (Forest Service Road 047) during the summer to early fall; it is closed by snow the remainder of the year. The first 1.9 miles (3 km), to a Forest Service trailhead parking area with pit toilet, is an improved gravel road typically accessible by cars. The last 0.75 miles (1.2 km) is rougher but usually still passable by high-clearance, two-wheel drive vehicles. An open shelter, built by the CCC (Civilian Conservation Corps) of local stone (the Leach Canyon Formation), caps the summit plateau. The best place to see the entire Leach Canyon Formation is at the south end of the peak at 37° 40' 48.2", 112° 49' 51", about 140 yards (125 m) south of the CCC shelter. Figures 2, 3, and 4 provide a geologic map, stratigraphic column, and cross section for the area.

## STRATIGRAPHY

### Regional Ash-flow Tuffs

Utah's middle Cenozoic landscape looked unimaginably different from that of today. Geologists refer to that former landscape as the Great Basin altiplano or Nevadaplano, a high-elevation region that stretched from the Sierra Nevada in eastern California eastward to what is now the Colorado Plateau (DeCelles, 2004; Best and others, 2009, 2013). The altiplano was studded with volcanic mountains and intervening basins, analogous perhaps to the modern Andean Altiplano of South America. It was onto this landscape

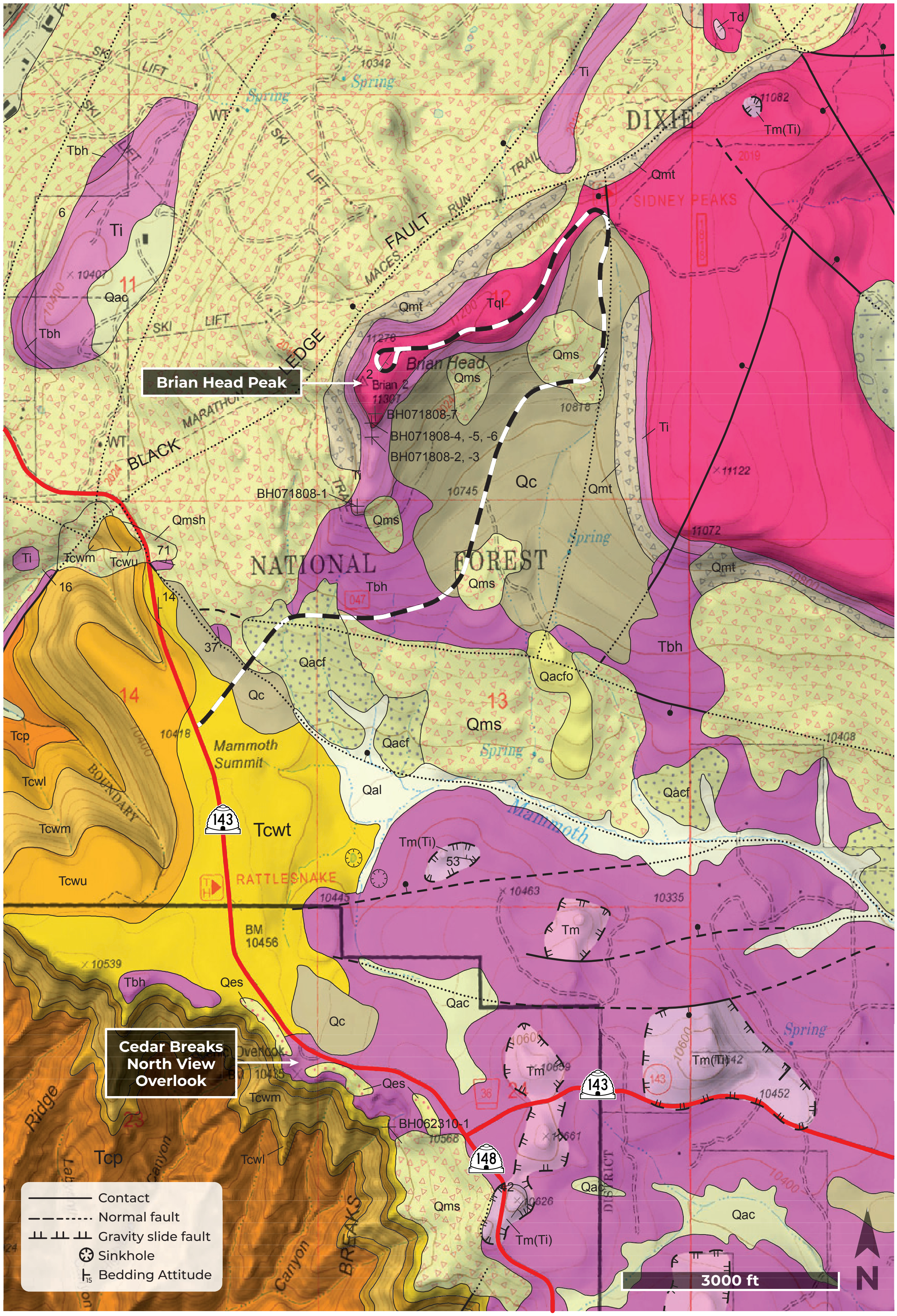


*Figure 2.* *Geologic map of the Brian Head peak area. Map units are shown on figure 3 (surficial deposits are various shades of light yellow). Note the large area of modern landslides (yellow with red triangle pattern) that resulted from failure of the Brian Head Formation. The Brian Head ski area, and the southern end of the Yankee Meadows graben, is in the upper left part of the map. From Rowley and others (2013).*

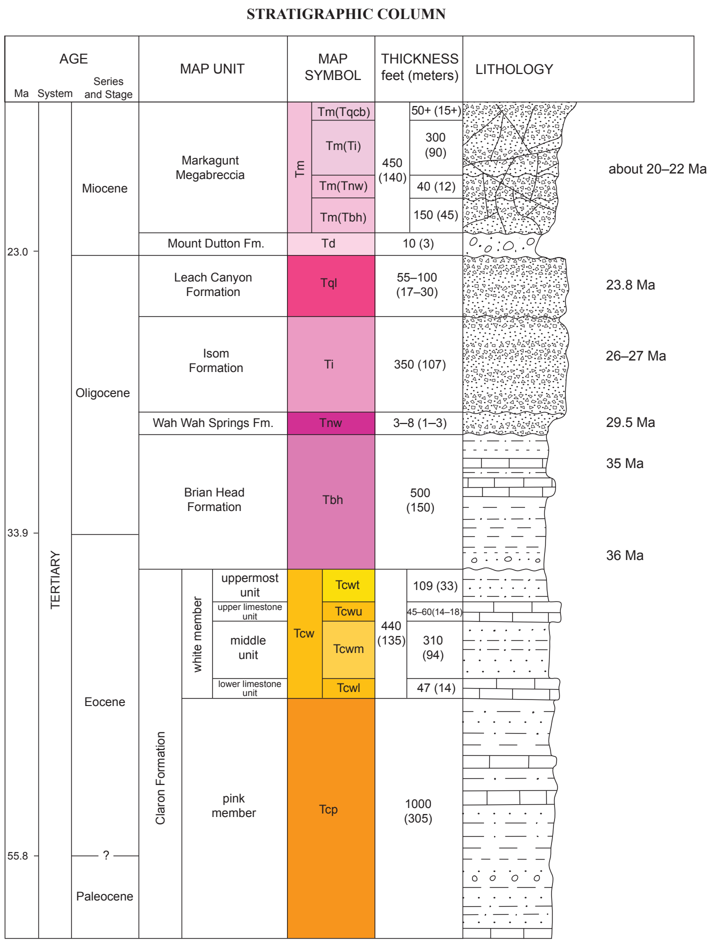


*Figure 3. Stratigraphic column showing rock units of the Brian Head peak area. The Markagunt Megabreccia is the deposit of the Markagunt gravity slide. From Rowley and others (2013).*

that dozens of widespread ash-flow tuffs accumulated—part of the middle Cenozoic "ignimbrite flare-up" of southwestern North America, which represents one of the largest episodes of subduction-related, silicic volcanism known on Earth (figure 5).

Ash-flow tuffs (ignimbrites in European parlance) are the deposits of pyroclastic flows, density currents of hot volcanic rock, ash, and gases derived from explosive volcanic eruptions. Pyroclastic flows can travel rapidly more than 100 miles (160 km) across the landscape, filling valleys that radiate away from volcanic highlands. One interesting and very useful characteristic of ash-flow tuffs, noted by Mackin (1960), is that ash-flow tuffs are emplaced in a geological instant over broad areas, and thus serve as important time horizons for correlating rock formations and understanding structural development of the region. Best and others (2013) summarized how our understanding of these ash-flow tuffs has evolved, beginning in the 1950s with J. Hoover Mackin who first realized that they were indeed the products of enormous catastrophic eruptions of volcanic ash, not simply lava flows. Today, the calderas themselves are recognizable only through mapping of stratigraphic and structural relations between caldera in-fill and outflow deposits, inasmuch as 20 million years of subsequent basin-range extension, erosion, and burial under intervening basins makes the calderas all but invisible in the modern landscape.

The eruption of Oligocene to Miocene ash-flow tuffs in Nevada and Utah is part of a broad pattern of volcanism that migrated southward through time across northwestern North America from about 55 to 20 million years ago (Mackin, 1960; Cook, 1965; Armstrong and others, 1969; Stewart and Carlson, 1976; Stewart and others, 1977; Rowley, 1998; Rowley and Dixon, 2001). The southward migration resulted from complex plate tectonic interactions along the western margin of North America as outlined by Dickinson (2006) and Humphreys (2009). Ultimately, these and other researchers hypothesize a tear in the relatively cold and dense oceanic crust of a subduction zone. The tear allowed the subducting slab to peel away from the less dense continental crust above, opening a window through which relatively hot upper mantle rock ascended, feeding the magmatic flare-up.

Best and others (2013) provided a comprehensive summary of the Great Basin ash-flow tuff province of Nevada and western Utah, where, from about 36 to 18 million years ago, more than 200 large eruptions from 42 calderas resulted in more than 16,500 cubic miles (70,000 km$^3$) of tuff deposited over the landscape (figure 5). In the Indian Peak and Caliente caldera complexes in the eastern part of the tuff province, more than 50 large eruptions produced

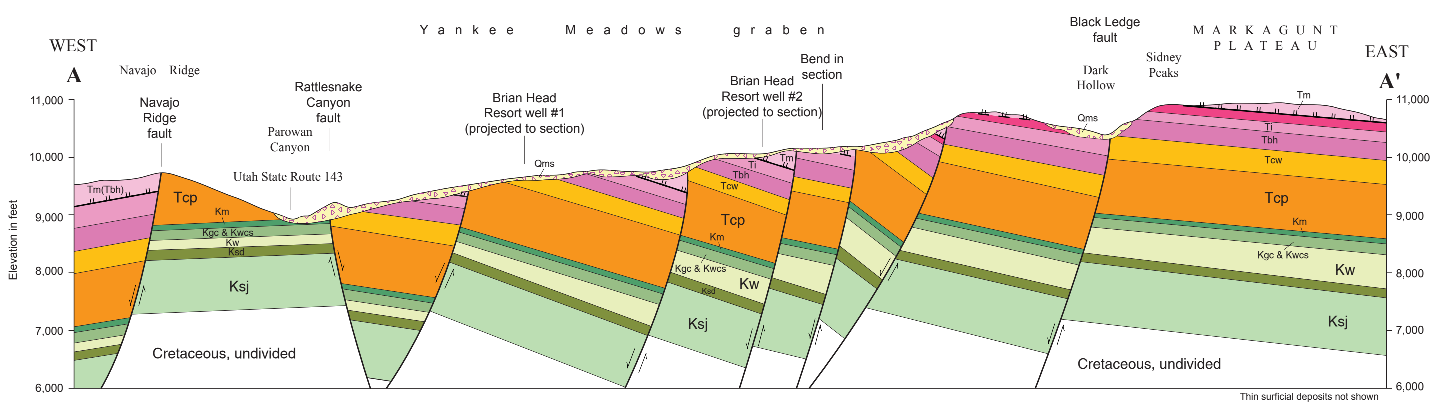


*Figure 4. Cross section through Black Ledge at Sydney Peaks. Note that line of cross section lies just north of and covers a wider area than that shown in figure 2. The Yankee Meadows graben, down-dropped blocks between the Black ledge and Rattlesnake Canyon faults, is covered with modern landslide deposits derived from the clay-rich Brian Head Formation. From Rowley and others (2013).*

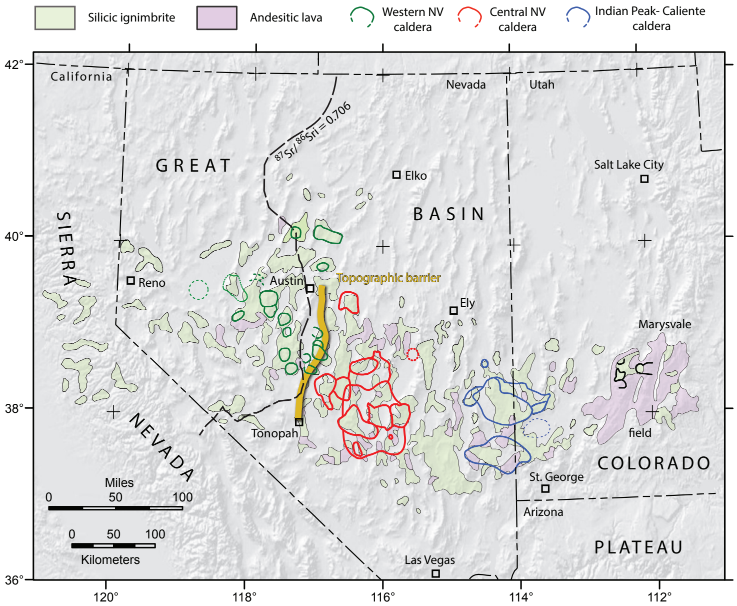


*Figure 5. Southern Great Basin ash-flow tuff province that resulted from the middle Cenozoic (36 to 18 Ma) "ignimbrite flare-up." Several ash-flow tuffs (ignimbrites) from the Indian Peak and Caliente caldera complexes (blue lines) on the Utah-Nevada border spread eastward into southwest Utah and as far east as the Marysvale volcanic field. The coeval Marysvale field (purple, in southwest Utah) and calderas (black) are shown to emphasize the contrasting dominance of andesitic lavas and mudflows (most of the Marysvale field) over more silica-rich ash-flow tuffs (most of the Great Basin). This figure does not show pre-36 Ma ash-flow tuffs and calderas from more northern igneous belts, nor does it show post-18 Ma tuffs and calderas from more southern igneous belts. The thick yellow line marks the western edge of the Great Basin altiplano; tuffs erupted from western Nevada calderas flowed mostly west down the west flank of the altiplano and are now preserved in exhumed paleovalleys across today's Sierra Nevada Mountains. The western edge of Precambrian continental basement is defined geochemically by the dashed $^{87}Sr/^{86}Sr = 0.706$ line. From Best and others (2013).*

an estimated 7600 cubic miles (32,000 km$^3$) of ash-flow tuffs now spread over an area of 15,000 square miles (63,000 km$^2$) in east-central Nevada and southwestern Utah (this volume is roughly enough to fill the Grand Canyon nearly eight times over). Nine of those eruptions are popularly known as "super eruptions," each having ejected more than 240 cubic miles (1000 km$^3$) of rock, including from older to younger the Wah Wah Springs, Lund, Isom, and Leach Canyon Formations, the latter two of which are found at Brian Head peak. In addition to ash-flow tuffs, these eruptions produced voluminous ash falls—fine-grained ash fall from the Wah Wah Springs eruption, for example, is recognized in western Nebraska (Best and others, 2013). Over time, repeated eruptions of the Indian Peak and Caliente caldera complexes produced ash-flow tuffs that filled topographic low areas in the Great Basin altiplano.

Because ash-flow tuffs tend to be confined to former river valleys far from their source area, the distal ends of many ash-flow tuffs behave geomorphically like basaltic lava flows (see the St. George inverted valleys geosite). Because it is relatively fluid when it erupts, basaltic lava flows downhill until it becomes entrained in old stream valleys. This buries and displaces the stream, and because the basalt is typically harder than enclosing rocks and sediments of the valley walls, the stream shifts to the side of the flow and preferentially erodes adjacent, less-resistant rock. Ultimately, through a process called topographic inversion, this leaves the lava flow as a sinuous high ridge above the surrounding landscape—the ridge marks the location of the former stream channel. Topographic inversion of the distal ends of many ash-flow tuffs naturally ensues as it does for basaltic lava flows. The distribution of regional ash-flow tuffs on the Markagunt Plateau and Sevier Plateau (the next range to the east) suggests that they may have been controlled by broad, east-flowing stream valleys (Biek and others, 2015). When an ash-flow tuff blocked a stream valley, displaced streams stepped southward to create another valley later to be filled by a subsequent, younger ash-flow tuff. In this way, older ash-flow tuffs are typically found farther north in this part of southwestern Utah.

## Leach Canyon Formation

The Leach Canyon Formation is a pinkish-brown, moderately welded (welding refers to the compaction of ash shards at the time of emplacement, resulting in a resistant rock even when welding is poor), moderately crystal-rich rhyolite ash-flow tuff that erupted from a caldera on the Utah-Nevada border nearly 24 million years ago. The formation has a volume of at least 430 cubic miles (1800 km$^3$) and a distribution of at least 6000 square miles (15,000 km$^2$) (Best and others, 1989b). For comparison, the volume of erupted products from the 1980 Mount St. Helens eruptions was about 1 cubic mile (4 km$^3$). The south side of Brian Head peak reveals the most complete section of the Leach Canyon Formation on the Markagunt Plateau (Biek and others, 2015). There, the classic three-part section of an ash-flow tuff is exposed, including an unwelded basal surge deposit, a thick vitrophyre (black glassy layer), and the moderately welded ash-flow tuff that caps Brian Head peak (figure 6). The seldom exposed basal surge deposit is crystal-rich, tuffaceous sandstone with wavy and low-angle cross-bedding, resembling sand dunes. It records deposition by relatively low-concentration, turbulent density currents as the ash-flow tuff moved rapidly across the landscape.

The Leach Canyon Formation contains abundant white or light-pink, collapsed pumice fragments and several percent rock fragments, many of which are reddish brown; phenocrysts of plagioclase, slightly less but subequal amounts of quartz and sanidine, and minor biotite, hornblende, Fe-Ti oxides, and a trace of pyroxene make up 25% to 35% of the rock. The formation is about


*Figure 6. Leach Canyon Formation on the south side of Brian Head peak. Here, the classic three-part section of an ash-flow tuff is exposed, including an unwelded basal surge deposit, a thick vitrophyre, and moderately welded ash-flow tuff that caps Brian Head peak. A flow breccia of the Isom Formation (Ti) is present in the lower left corner of the photograph.*

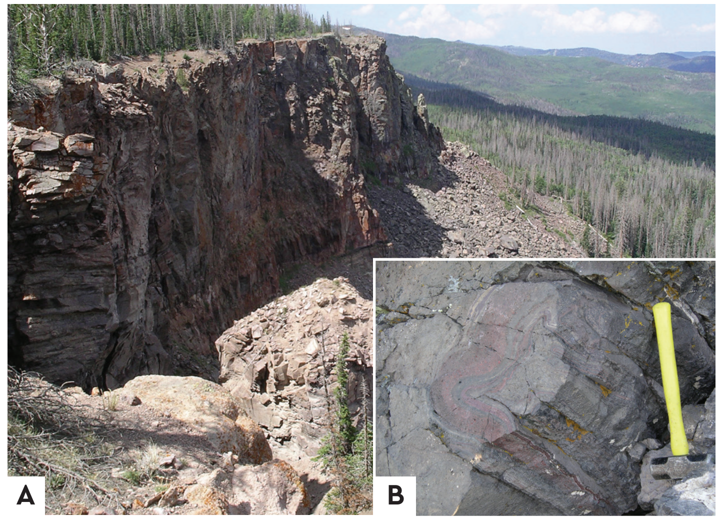


*Figure 7. **A.** The resistant Isom Formation at Black Ledge, looking south towards Brian Head peak. **B.** Contorted flow layering of this densely welded ash-flow tuff, an example of its rheomorphic nature.*

100 feet (30 m) thick where it forms the resistant caprock of Brian Head peak. Interestingly, the Leach Canyon Formation is petrographically and chemically similar to the Haycock Mountain Tuff, a small, locally derived ash-flow tuff exposed to the east. This similarity led to confusion about the age of landslide deposits eventually called the Markagunt gravity slide (Biek and others, 2015). The 22.8 Ma Haycock Mountain Tuff unconformably overlies the Markagunt gravity slide a dozen miles (20 km) east of Brian Head. The older, 23.8 Ma Leach Canyon Formation underlies and is locally involved in the slide.

## Isom Formation

The 26 to 27 Ma, crystal-poor, densely welded, trachydacitic ash-flow tuff of the Isom Formation is present as far south as Brian Head peak and is spectacularly exposed for many miles along Black Ledge where it is about 350 feet (110 m) thick (figure 7). The Isom Formation is unusual in that it was so hot when erupted that it flowed like lava during its final stages (few tens of feet) of emplacement. For that reason it is commonly referred to as a tufflava or a rheomorphic ash-flow tuff—see, for example, Anderson and Rowley (1975, 2002), Andrews and Branney (2005), and Geissman and others (2010). Many Isom outcrops reveal secondary flow characteristics, including flow breccias, contorted flow layering, and linear vesicles, such that the unit was considered a lava flow until Mackin (1960) mapped its widespread distribution (300 cubic miles [1300 km$^3$] today spread over an area of 9500 square miles [25,000 km$^2$] [Best and others, 1989a]) and found evidence of glass shards, thus showing its true ash-flow tuff nature. The Isom is exposed at Brian Head peak where the lower part of the formation is classic tufflava about 80 feet (24 m) thick and the upper part is a flow breccia 60 to 90 feet (18-27 m) thick (Biek and others, 2015).

## Brian Head Formation

The Brian Head Formation is characterized by white volcaniclastic mudstone, siltstone, sandstone, volcanic ash, muddy limestone, and minor conglomerate and multi-hued chalcedony, and it is known for its propensity for landsliding. These strata, rich in volcanic ash, were deposited in low-relief fluvial, floodplain, and lacustrine environments; they record the inception of volcanism in southwest Utah beginning about 37 million years ago (Sable and Maldonado, 1997) (figure 8). The base of the section is well exposed near the North Rim Overlook in Cedar Breaks National Monument; there, a thin rhyolitic ash bed overlies a thin pebbly conglomerate likely equivalent to the conglomerate at Boat Mesa in Bryce Canyon National Park. This ash bed yielded a U-Pb age on zircon of 35.77 ± 0.28 Ma, and several additional radiometric ages from Brian Head strata throughout the region show that it was deposited from about 37 to 33 million years ago (Biek and others, 2015). Thus, it is mostly late Eocene in age, barely reaching into the Oligocene.

The Brian Head Formation contains abundant trace fossils, including possible crayfish burrows and root traces (Golder and Wizevich, 2009; Golder and others, 2009), but aside from its basal variegated interval it is surprisingly unfossiliferous (Eaton and others, 1999). It also has colorful beds of chalcedony in various shades of white, gray, yellow, red, black, and brown, all typically with a white weathering rind. The chalcedony forms resistant beds as much as 10 feet (3 m) thick and is thought to have resulted from silicification of limestone beds (Maldonado, 1995; Sable and Maldonado,

*Figure 8. Air-fall ash bed (white unit) in the Brian Head Formation just south of Haycock Mountain, which yielded a U-Pb age on zircon of 34.95 ± 0.83 Ma.*

1997; Schinkel, 2012). Being resistant, the chalcedony commonly litters slopes developed on Brian Head strata; it was commonly used for tools and arrowheads by Native Americans.

Above all, however, the Brian Head Formation is known for its swelling soils and for its susceptibility to landsliding. Nearly all exposures on steep hillsides form large landslide complexes, including one that fills the 15-mile (24 km) length of Yankee Meadows graben, home to the resort town of Brian Head. The formation is susceptible to landslides because of its abundant clay derived from weathered volcanic ash.

A more complete section of the Brian Head Formation is well exposed on the southwest flank of the Sevier Plateau (figure 9). There, a transitional interval as much as 160 feet (50 m) thick, not present elsewhere, of fine-grained, slope-forming sandstone, siltstone, and mudstone of red, pink, yellowish-brown, and purplish-gray hues forms the base of the formation. This variegated interval yielded fossil turtles, charophytes (freshwater green algae), and fish suggestive of lacustrine environments of the Duchesnean North American Land Mammal Age (end of middle Eocene) (Feist and others, 1997; Eaton and others, 1999; Korth and Eaton, 2004).

## STRUCTURE

The Markagunt Plateau is uplifted with respect to the Great Basin by high-angle normal faults, some of which create a series of horsts and grabens west and north of Brian Head peak. Horsts are blocks that are upthrown by faults on each side, whereas grabens are blocks that are downthrown by faults on each side. These horsts and grabens step down from the plateau to the adjacent Great Basin (figure 10) (Maldonado and others, 1997; Biek and others, 2015). The most prominent of these faults is the active Hurricane fault at the base of the plateau, which has a down-to-the-west vertical displacement of at least 6000 feet (1800 m)

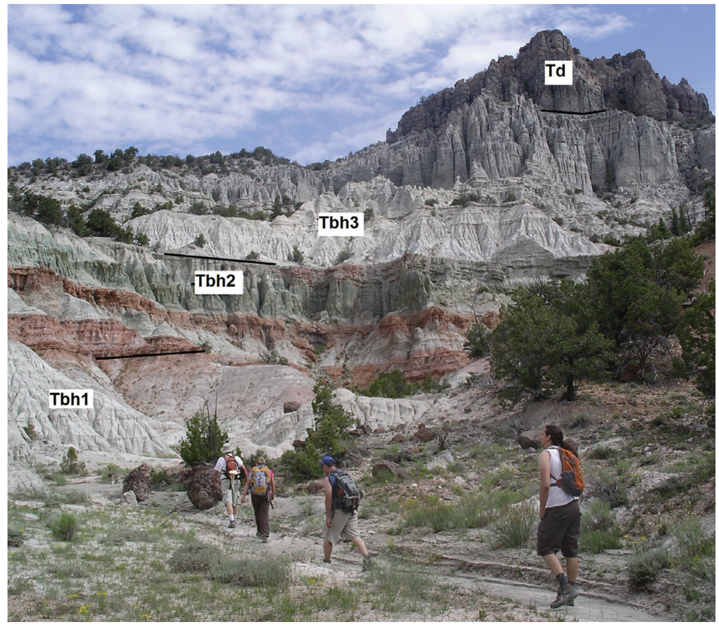


*Figure 9. Exceptional exposures of the Brian Head Formation on the southwest flank of the Sevier Plateau. Here, Brian Head strata are divisible into four parts: (1) a basal variegated unit (below the hikers and so not visible), (2) a lower, light-gray, fine-grained volcaniclastic unit, which includes a thick, bluish-gray bentonitic mudstone at its base (Tbh1), (3) a distinctive red-green-gray banded, fine-grained volcaniclastic unit (Tbh2), and (4) a thick, upper volcaniclastic unit (Tbh3). Brian Head strata are capped by Mount Dutton Formation volcanic mudflow deposits (Td), which here mark the base of the Sevier gravity slide..*

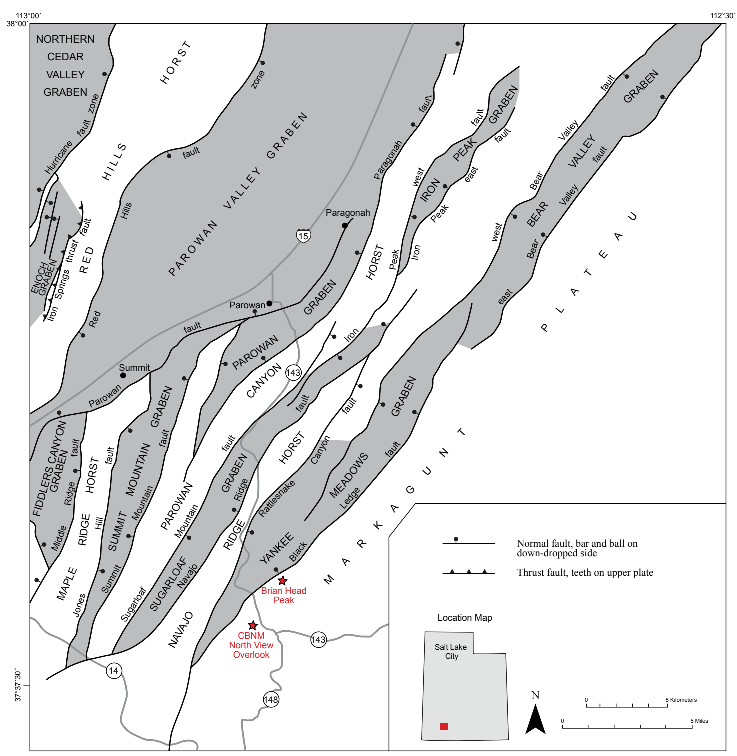


*Figure 10. Major faults of the western Markagunt Plateau and Red Hills, and named grabens (shaded) and horsts. CBNM = Cedar Breaks National Monument. From Biek and others (2015).*

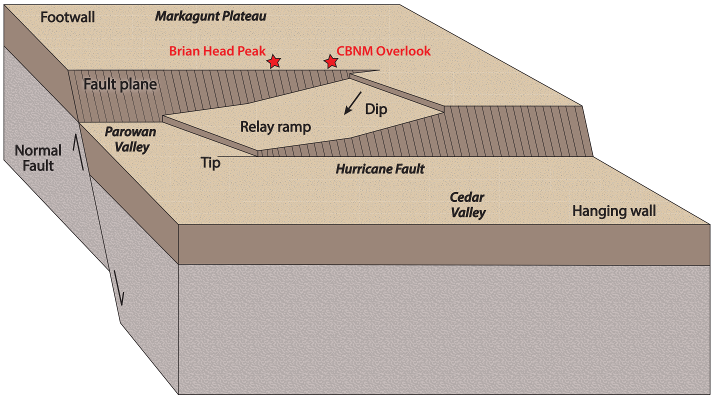


*Figure 11. Diagram of a relay ramp between parallel strands of a fault zone. The ramp links displacement between the faults. CBNM = Cedar Breaks National Monument.*

(Hurlow, 2002; Lund and others, 2007). Overall, the collection of horsts and grabens forms a highly faulted relay ramp between the Paragonah fault and the Hurricane fault (figure 11).

The question of when this faulting began can be answered in part by the distribution of ash-flow tuffs. Whereas modern basin-range extension that led to the topography we see today likely began about 10 to 12 million years ago in the Cedar City area (Rowley and others, 1981; Hurlow, 2002), the initiation of such extension is much older. Because ash-flow tuffs like the Isom are widespread and were emplaced "in the blink of an eye," they now serve as important timelines that help constrain structural interpretations of southwestern Utah. The eruption of the Isom Formation was followed by the eruption of three regionally distinctive ash-flow tuffs: the 23.8 Ma Leach Canyon Formation, the 22.8 Ma Bauers Tuff Member of the Condor Canyon Formation, and the 22.0 Ma Harmony Hills Tuff, all part of the Quichapa Group. Only the Leach Canyon is preserved as far east as Panguitch Lake; the Bauers and Harmony Hills tuffs are restricted to the western part of the Markagunt Plateau. The distribution of these ash-flow tuffs suggests that a west-facing topographic escarpment associated with early basin-range extension may have impeded eastward distribution of the latter two tuffs, as first noted by Rowley and Barker (1978). Furthermore, a graben north of nearby Parowan juxtaposes Bear Valley and Brian Head strata that were later intruded by the 20 Ma Iron Peak laccolith, showing that early extension was active prior to about 20 million years ago (Biek and others, 2015).

## ACKNOWLEDGMENTS

Our knowledge of southwestern Utah geology comes from combined decades of geologic mapping supported largely by the Utah Geological Survey and U.S. Geological Survey. As the acknowledgments of our many published geologic maps attest, we are indebted to a great many people for their help over the years. Thanks to Grant Willis, Stephanie Carney, and Mike Hylland (all with the Utah Geological Survey) for their insightful reviews, and to Jenny Erickson (UGS) for drafting the figures.

## REFERENCES

Anderson, J.J., and Rowley, P.D., 1975, Cenozoic stratigraphy of 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. 1–51.

Anderson, J.J., and Rowley, P.D., 2002, The Oligocene Isom Formation, Utah and Nevada—a regional ash-flow tuff sheet containing fluidal features of a lava flow [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 4, p. 9.

Andrews, G.D.M., and Branney, M.J., 2005, Folds, fabrics, and kinematic criteria in rheomorphic ignimbrites of the Snake River Plain, Idaho—insights into emplacement and flow, *in* Pederson, J., and Dehler, C.M., editors, Interior Western United States: Geological Society of America Field Guide 6, p. 311–327.

Armstrong, R.L., Ekren, E.B., McKee, E.H., and Noble, D.C., 1969, Space-time relations of Cenozoic silicic volcanism in the Great Basin of the western United States: American Journal of Science, v. 267, p. 478–490.

Best, M.G., Baar, D.L., Christiansen, E.H., Grommé, C.S., Deino, A.L., and Tingey, D.G., 2009, The Great Basin altiplano during the middle Cenozoic ignimbrite flareup—insights from volcanic rocks: International Geology Review, v. 51, p. 589–633.

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., Grommé, C.S., Hart, G.L., and Tingey, D.G., 2013, The 36-18 Ma Indian Peak-Caliente ignimbrite field and calderas, southeastern Great Basin, USA—multicyclic super-eruptions: Geosphere, v. 9, no. 4, p. 1–87.

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.

Biek, R.F., Rowley, P.D., Anderson, J.J., Maldonado, F., Moore, D.W., Hacker, D.B., Eaton, J.G., Hereford, R., Filkorn, H.F., and Matyjasik, B., 2015, Geologic map of the Panguitch 30' x 60' quadrangle, Garfield, Iron, and Kane Counties, Utah: Utah Geological Survey Map 270DM, 162 p., 3 plates, scale 1:62,500.

Cook, E.F., 1965, Stratigraphy of Tertiary volcanic rocks in eastern Nevada: Nevada Bureau of Mines Report 11, 61 p.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.:

American Journal of Science, v. 304, p. 105–168.

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, p. 353–368.

Eaton, J.G., Hutchinson, J.H., Holroyd, P.A., Korth, W.W., and Goldstrand, P.M., 1999, Vertebrates of the turtle basin local fauna, middle Eocene, Sevier Plateau, south-central Utah, *in* Gillette, D.D., editor, Vertebrate paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 463–468.

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.

Geissman, J.W., Holm, D., Harlan, S.S., and Embree, G.F., 2010, Rapid, high-temperature formation of large-scale rheomorphic structures in the 2.06 Ma Huckleberry Ridge Tuff, Idaho, USA: Geology, v. 38, p. 263–266.

Golder, K.B., and Wizevich, M.C., 2009, Wetland trace fossils in the Paleogene Brian Head Formation, southwest Utah [abs.]: Geological Society of America Abstracts with Programs, v. 41, no. 3, p. 88.

Golder, K.B., Wizevich, M.C., Simpson, E.L., and Storm, L.P., 2009, Oligocene ichnofossils in non-marine limestone of the Brian Head Formation, Utah [abs.]: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 262.

Humphreys, E., 2009, Relation of flat subduction to magmatism and deformation in the western United States, *in* Kay, S.M., Ramos, V.A., and Dickinson, W.R., editors, Backbone of the Americas—shallow subduction, plateau uplift, and ridge and terrane collision: Geological Society of America Memoir 204, p. 85–98.

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., 2 plates.

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.

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, Paleoseismology of Utah, v. 14: Utah Geological Survey Special Study 119, CD, 81 p.

Mackin, J.H., 1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: American Journal of Science, v. 258, no. 2, p. 81–131.

Maldonado, F., 1995, Decoupling of mid-Tertiary rocks, Red Hills-western Markagunt Plateau, 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. 233–254.

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.

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., and Barker, D.S., 1978, Geology of the Iron Springs mining district, Utah, *in* Shawe, D.R., and Rowley, P.D., editors, Guidebook to mineral deposits of southwestern Utah: Utah Geological Association Publication 7, p. 49–58.

Rowley, P.D., Biek, R.F., Sable, E.G., Boswell, J.T., Vice, G.S., Hatfield, S.C., Maxwell, D.J., and Anderson, J.J., 2013, Geologic map of the Brian Head quadrangle, Iron County, Utah: Utah Geological Survey Map 263DM, 38 p., 2 plates, scale 1:24,000.

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 Basina symposium and field guide (The Mackin Volume): Utah Geological Association and Pacific Section of the American Association of Petroleum Geologists, Utah Geological Association Publication 30, p. 169–188.

Rowley, P.D., Steven, T.A., and Mehnert, H.H., 1981, Origin and structural implications of upper Miocene rhyolites in Kingston Canyon, Piute County, Utah: Geological Society of America Bulletin, Part I, v. 92, p. 590–602.

Sable, E.G., and Maldonado, F., 1997, 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 zone in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1995: U.S. Geological Survey Bulletin 2153, p. 7–26.

Schinkel, T., 2012, Investigation of the origin of silicified layers within Paleogene-aged volcaniclastic Brian Head Formation, southern Utah: New Britain, Central Connecticut University, M.S. thesis, 100 p.

Stewart, J.H., and Carlson, J.E., 1976, Cenozoic rocks of Nevada—four maps and a brief description of distribution, lithology, age, and centers of volcanism: Nevada Bureau of Mines and Geology Map 52, scale 1:100,000.

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.