Utah's Ancient Mega-Landslides

Geology, Discovery, and Guide to

EARTH'S LARGEST TERRESTRIAL LANDSLIDES

By Robert F. Biek, Peter D. Rowley, and David B. Hacker

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Front Cover: *Casto Bluff, at the south end of the Sevier Plateau, is one of many places that reveals the extraordinary story of repeated catastrophic collapse of the Marysvale volcanic field between 25 and 18 million years ago. Southwest Utah's ancient volcanic mountains may seem ordinary from a distance, but many rock outcrops show highly deformed strata (left), unusal injectites derived from overpressured ground-up rocks at the base of the landslides (center), "skid marks" at the base of the slides (right), and many other examples of deformation that have allowed geologists to piece together this amazing new discovery.*

Back Cover: *Extent of the Sevier (yellow), Markagunt (green), and Black Mountains (blue) mega-landslides, each among Earth's largest terrestrial landslides. This guide tells the history of their discovery, describes many of their unique and unusual features, and offers over a dozen places visitors can go to see the rocks that tell this fascinating story.*

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INTRODUCTION

Southwest Utah contains what may be the largest landslide complex on land in the world. This complex includes three ancient side-by-side gigantic slides that cover an area roughly the size of Yellowstone National Park with a volume of slide debris that would nearly fill the Grand Canyon to its rim. Geologists call it the Marysvale gravity slide complex—"Marysvale" for the namesake volcanic field that partly failed catastrophically three separate times, and "gravity slide" to call attention to a special class of extremely large and geologically complex landslides several tens to thousands of square miles in extent. Here we refer to them simply as mega-landslides or slides—they are larger and far more interesting than geologists could ever have imagined.

Though crisscrossed by highways and dotted with a dozen small towns including Beaver, Parowan, Panguitch, and Cedar City, the mega-landslides remained hidden in the landscape until the mid-2010s. These ancient landslides are home to thousands of Utahns and are traversed by millions of tourists each year travelling to southern Utah's famous red rock country and national and state parks and monuments. You might ask yourself, "How can something so large escape our notice for so long?" We answer that fascinating question by noting that this discovery reflects decades of work by dozens of geologists—ants on the back of an elephant unaware of the beast's size or even that such a beast existed in the first place. It is a classic story of how science works, of how knowledge incrementally grows until once-seemingly disparate observations reveal a larger truth.

Our story describes our current understanding of this exciting new discovery, but much remains unknown. We do not yet know the exact trigger of each mega-slide, what the landscape looked like immediately prior to and following the slides, or what plants and animals may have been around to bear witness to such catastrophic events, but we do know enough to begin to piece together their story. Because they are virtually unique, these mega-landslides are now the focus of research to better understand their extent, age, and emplacement mechanisms, and for what they can tell us about the inherent instability of volcanic fields elsewhere in the world.

These mega-landslides are so large that there is no single earthly vantage point from which they can be seen. Their remains are chopped up by subsequent faulting and are deeply eroded and partly buried by younger deposits, obscuring diagnostic landslide features (one reason they remained hidden for so long!). Classic modern landslides, the scourge of building and highway engineers and some unlucky homeowners, represent relatively recent failures of steep or even modest slopes, and the resulting unconsolidated masses of broken rock at the bases of the slopes are obvious and rarely exceed a few square miles in size. Yet classic landslide features of hummocky terrain, water-filled depressions, and overall distinctive shape no longer exist in the Marysvale slide complex. Indeed, the slide complex is so old that its remains are lithified into solid rock, and it is so large that individual parts are on the scale of mountain-size displaced blocks. Still, key pieces of the puzzle remain, and the picture they paint is one of extraordinary—and repeated—calamity during growth of the Marysvale volcanic field. Our research, built upon decades of geologic studies in southwest Utah, shows that as multiple volcanoes grew above a weak underlying foundation of clay-rich sedimentary rock layers, the volcanoes collapsed not just once, but three separate times over the span of 7 million years. Deformed rocks and structures show that each collapse was rapid and catastrophic, as the failure of volcanoes tends to be. Each mega-slide moved southward away from the center of the volcanic highlands to and beyond its distal slopes.

Geology is first and foremost a science of the earth and our bias is to the rocks that record bits and pieces of Earth's unimaginably long history. As we will see, Utah's ancient landscape was far different than what we see today. Yet it is exciting to think that some of that landscape is indeed preserved in the mountains and high plateaus of southwest Utah. We will guide you to several of the more accessible examples of rock deformation and structures associated with these slides. We hope to give readers an appreciation of what this region must have looked like 25 to 18 million years ago when the slides occurred. We also attempt to answer the big questions of when, why, and how some of the largest landslides on the surface of the earth came to be. Odds are you will drive across one or more of the mega-slides on your way to Utah's scenic red rock country, maybe even delaying your arrival there as you spend an afternoon or a day discovering Utah's extraordinary mega-landslides.

What is the Marysvale Gravity Slide Complex?

The Marysvale gravity slide complex comprises three ancient, gigantic landslides (figure 1). Each slide is made up of volcanic rocks that erupted from Cascade-like stratovolcanoes of the Marysvale volcanic field, and of distinctive, interbedded ash-flow tuffs erupted from both distant and local Yellowstone-like calderas.

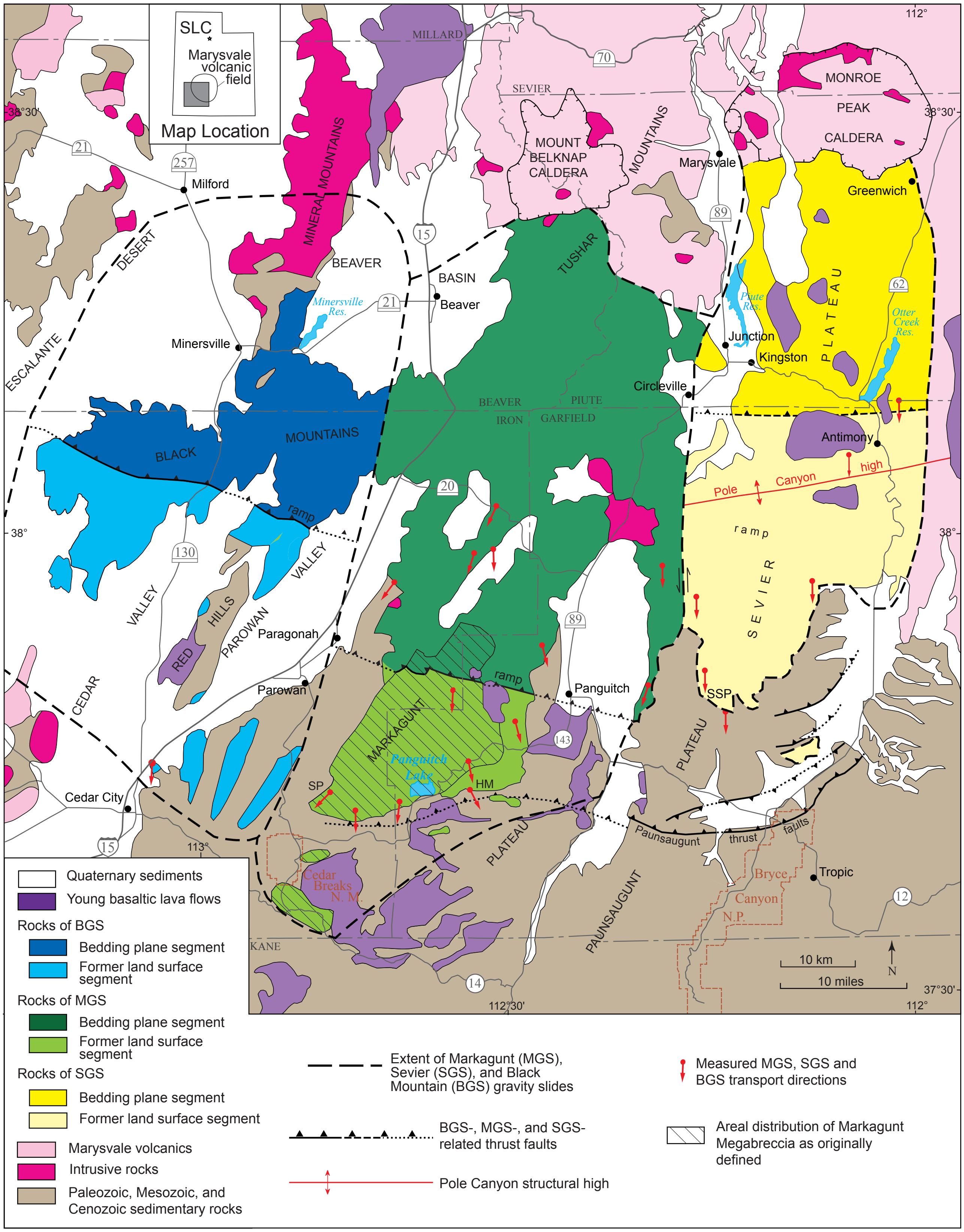


Figure 1. Location of the Sevier (SGS), Markagunt (MGS), and Black Mountains (BGS) gravity slides, each among Earth's largest terrestrial landslides; parts of the mega-slides are inferred to be buried under Quaternary valley sediments. The Markagunt Megabreccia, formally defined in 1993 as a chaos of volcanic rocks, is where researchers first realized the Markagunt Plateau was covered by something other than a normal sequence of volcanic rocks. Haycock Mountain (HM), Sidney Peaks (SP), and the southern Sevier Plateau (SSP) reveal particularly fascinating exposures as described later. See figure 2 for illustration of bedding plane and former land surface segments.

The three slides are each named for the plateau or mountain range where it is best exposed (perhaps we should have named them the Bob, Pete, and David slides!). The Markagunt mega-landslide, discovered in 2014, is named for the Markagunt Plateau, a Southern Piute name meaning "Highland of the trees," alluding to the comparatively lush aspen and fir forests that crown the plateau high above the sagebrush- and juniper-covered basins below. The Sevier mega-landslide, discovered in 2016, is named for the Sevier Plateau, itself named after the Sevier River, whose East and main forks bound the southern part of the plateau and whose name is anglicized from the Spanish *Rio Severo* (wild river). The Black Mountains mega-landslide, discovered in 2019, is named for the Black Mountains, a dry landscape with complex geology we are only beginning to decipher.

Each mega-landslide exhibits the full range of structural features commonly seen in modern landslides, but on an enormous scale (figure 2). These features include:

- extensional slip surfaces in the breakaway part of the slide that separate slide blocks from undeformed volcanic rocks to the north and that break up some internal parts of the slide;
- translational (horizontal) southward movement of the main body of the slide, which is characterized by mountain-size blocks jostled together;
- thrust slip surfaces at the ramp, where older, broken rocks of the slide are pushed up and over younger rocks and soil on the land surface; and
- jumbled chaotic debris in the distal toe area, what we call debris-avalanche deposits, where the slide mass broke apart.

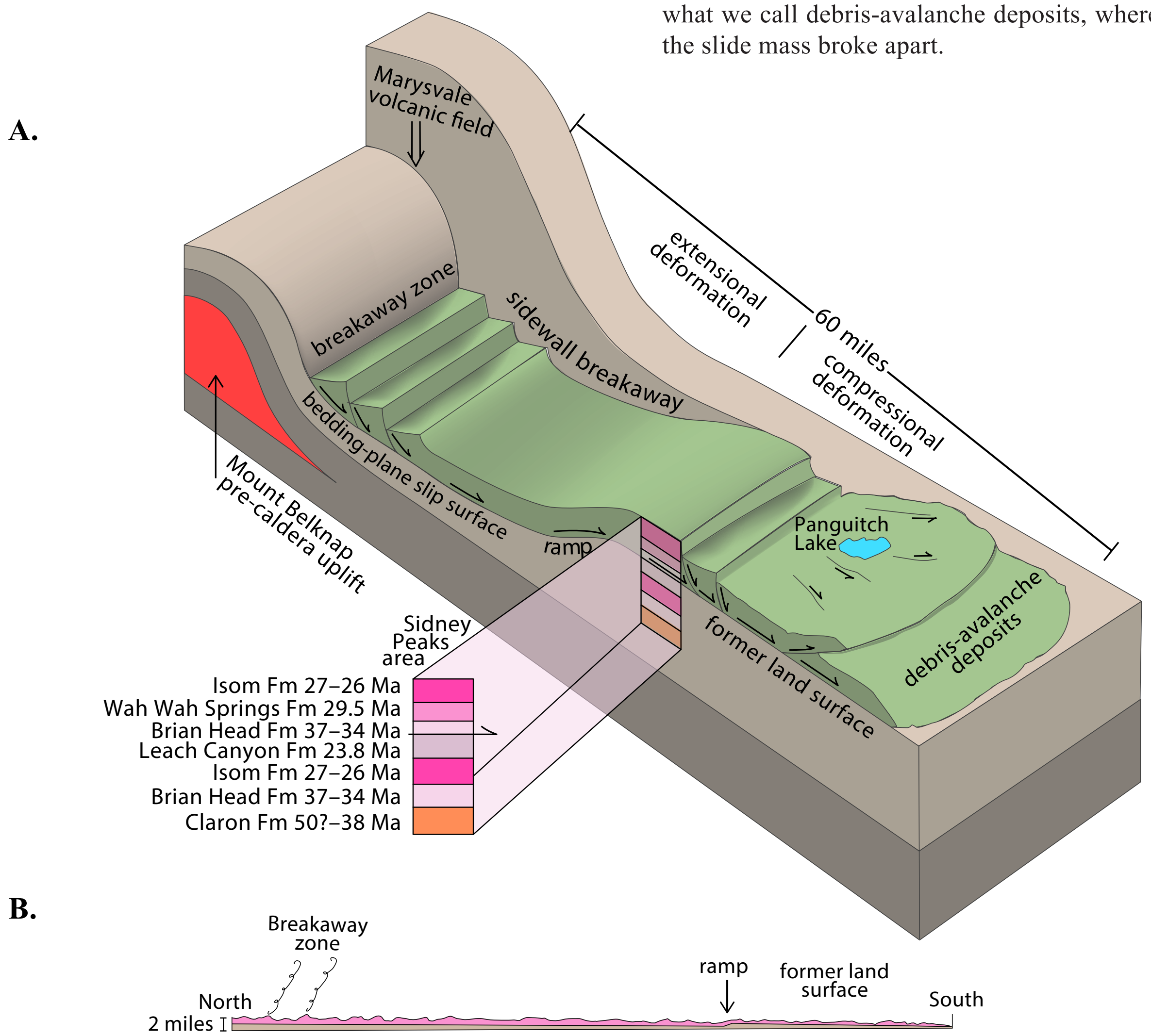


Figure 2. (A) *Idealized Markagunt mega-landslide, vertically exaggerated to show slide, as viewed towards the northeast. Here, the trigger is suggested to be pre-caldera inflation of the Mount Belknap area, causing uplift and tilting of overlying strata and consequent failure on over-steepened slopes. The ramp is where the basal detachment (bedding plane slip surface) angled upward and "daylighted" as the slide mass moved up and over the former land surface and southward at least 20 miles (32 km). Rock layers thinned like a partially spread-out deck of cards, and older-on-younger rock relationships, characterize the slide mass in the former land surface area. The Sidney Peaks area is where remnants of the mega-landslide were first discovered—note older-on-younger strata.* ***(B)*** *Hypothetical relief of land surface with no vertical exaggeration prior to gravity slide, assuming volcanoes stood about 2 miles (3 km) above the distal plateau.*

One unique characteristic of all landslides is that they exhibit three major types of deformation—extension, translation, and compression—within a single geologic feature. Typically, each of these modes of deformation is dominant over vast regions of the earth. For example, extensional deformation created the Basin and Range Province between western Utah and eastern California, translational deformation is taking place along California's San Andreas fault, and compressional deformation results from head-on collision of tectonic plates like where the Indian subcontinent continues to plow into Asia to create the Himalayas. Landslides encompass all such modes of deformation in a largely predictable fashion but on a smaller scale and driven by different geologic processes.

Furthermore, the three styles of deformation are essentially contemporaneous on an individual landslide. This makes landslides unique in the geologic record. A great many geologic events can mimic parts of a gigantic landslide, but nothing else can recreate the whole. In fact, parts of what we now understand to be the Marysvale gravity slide complex were originally and reasonably interpreted as something else until enough of the region had been geologically mapped to reassess relationships among distant features. As we will see, this history of mega-slide discovery—a multi-decade effort by geologists piecing together the puzzle of what we now understand to be the repeated catastrophic failure of the Marysvale volcanic field—is as fascinating as the slides themselves.

Where is the Marysvale Gravity Slide Complex?

The Sevier, Markagunt and Black Mountains mega-landslides are located on the south side of the Marysvale volcanic field in and west of Utah's High Plateaus, a region of geologic transition between the Colorado Plateau and adjacent Basin and Range Province (figure 3). The High Plateaus contain elements of both great physiographic provinces—a two-for-one deal, with a foundation of Colorado Plateau red rock stratigraphy overlain by volcanic rocks and cut by both ancient and modern faults. It is a geologist's paradise that exhibits a deep and extensive sampling of Utah's geologic history.

Utah's High Plateaus

The High Plateaus are dominated by north- to northeast-striking faults that drop large blocks of the earth's crust progressively down to the west, forming gently east-tilted plateaus. These faults, a type known to geologists as "normal" faults (a term derived from coal mining in England where these were the most common type of fault encountered), are still active today and can produce earthquakes large enough to cause widespread damage, especially to the region's unreinforced brick buildings and homes. In the southern part of the High Plateaus, large normal faults bound the Markagunt, Paunsaugunt, Sevier, Table Cliff, and Aquarius Plateaus (figure 4). Each plateau is carved from 250 to 35 Ma (million-year-old; Ma is shorthand for the Latin mega-annum) Mesozoic and Paleogene strata typical of the nearby Colorado Plateau, but apart from the Paunsaugunt Plateau, these strata are mostly or partly buried by younger volcanic rocks of the Marysvale volcanic field and still younger basaltic lava flows and cinder cones. Erosional windows through this vast pile of volcanic rocks reveal red slickrock sandstone deposited in coastal deserts, yellow-brown shallow-marine and coastal-plain strata famous for dinosaur fossils, and brilliant orange and white layers of a high-elevation river and lake basin that cap the highest and youngest parts of the plateaus. Most visitors to southern Utah understandably come to see these colorful rocks, but the volcanic legacy of this region has recently captured the attention of geologists.

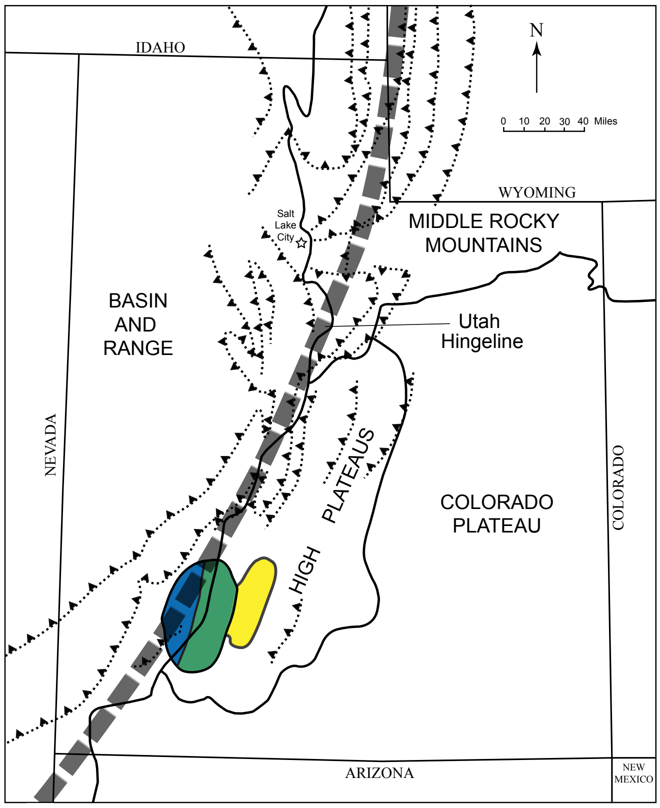


Figure 3. Physiographic provinces and regional-scale tectonic features of Utah. The Sevier (yellow), Markagunt (green) and Black Mountains (blue) mega-slides occupy the southwest part of the High Plateaus and an adjacent part of the Basin and Range Province. Major thrust faults of the Sevier orogenic belt are shown as dotted lines with barbed teeth on upper-plate rocks. The location of such thrust faults and of the eastern margin of the Basin and Range is controlled by the Utah hingeline (wide dashed line), a former continental slope and a long-lived boundary between a stable continental shelf to the east and a subsiding marine basin to the west (the hingeline originated about 700 million years ago during the protracted breakup of the supercontinent Rodinia). Southward movement of the mega-slides is at right angles to regional compression recorded by thrust faults of the Sevier orogenic belt, aiding recognition of structures and features produced by surficial landslide processes versus those produced by crustal tectonic forces.

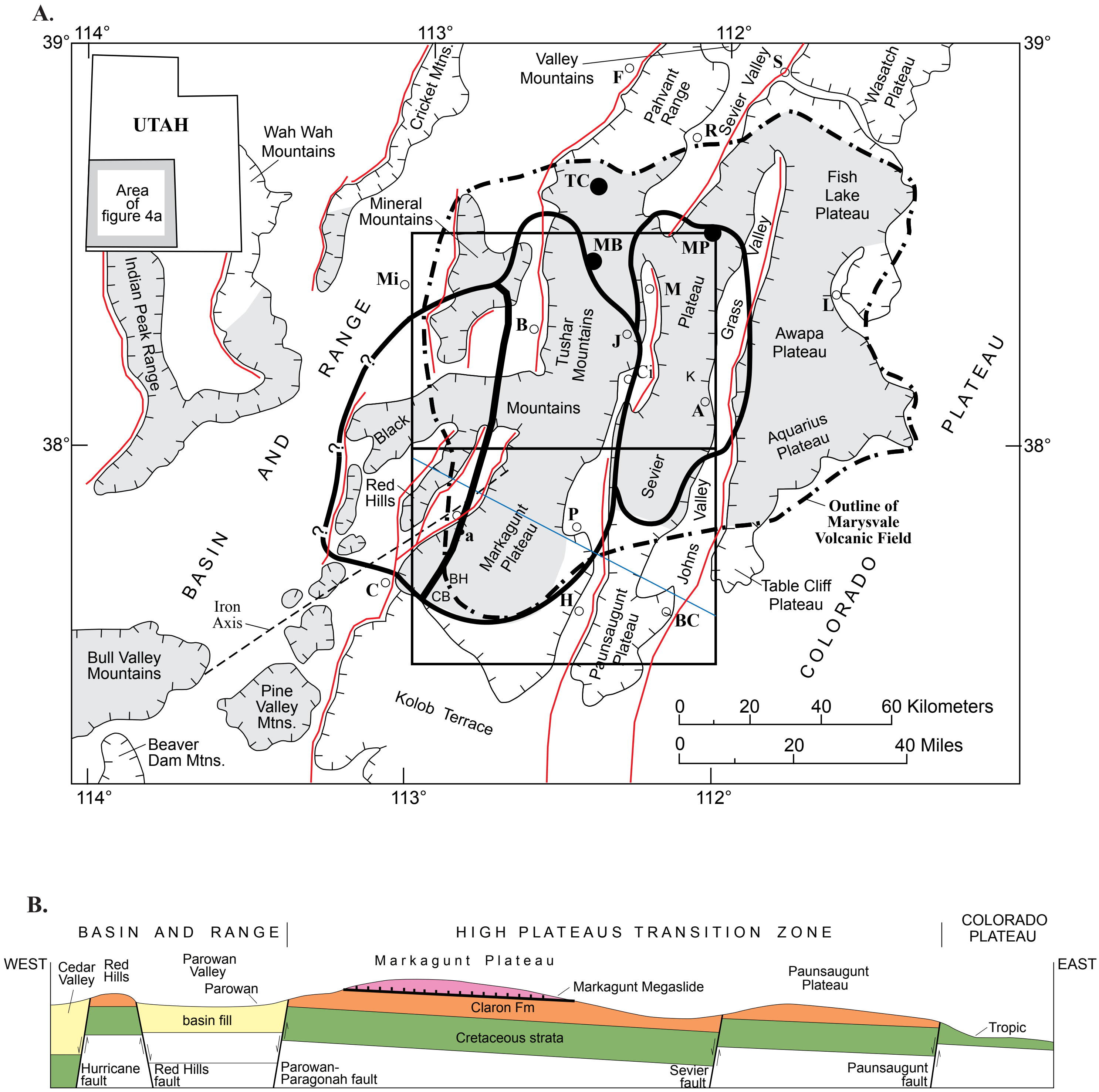


*Figure 4. (A) The Marysvale volcanic field (outlined by heavy dot-dash line), southern High Plateaus, and adjacent areas. Heavy black lines show extent of mega-slides. Black dots show central part of calderas (MB = Mount Belknap, MP = Monroe Peak, TC = Three Creeks). Major range-bounding normal faults are shown in red. Gray areas are underlain by volcanic rocks. Large rectangles show the Panguitch (southern) and Beaver (northern) 30' x 60' quadrangles. Blue line shows location of cross section in 4b. A—Antimony, B—Beaver; BC—Bryce Canyon; BH—Brian Head; C—Cedar City; CB—Cedar Breaks; Ci—Circleville; F—Fillmore; H—Hatch; J—Junction, K—Kingston Canyon; L—Loa; M—Marysvale; Mi—Milford; P—Panguitch; Pa—Parowan; R—Richfield; S—Salina). **(B)** Schematic west-to-east cross section through the Panguitch 30' x 60' quadrangle. Note gentle east dip of strata on the Markagunt and Paunsaugunt Plateaus, which are dropped down to the west along the Sevier and Paunsaugunt faults. The Red Hills horst block is bounded by the Hurricane and Red Hills faults to create the easternmost range of the Basin and Range Province at this latitude.*

Utah's High Plateaus are overprinted onto the leading edge of the much older Sevier orogenic belt, which is part of the Cordilleran orogeny, a mountain-building event that produced a zone of deformation that extends from southern Mexico to Alaska along the western margin of North America. The Sevier orogeny was a direct result of the subduction of part of an earlier Pacific Ocean basin (called the Farallon tectonic plate) beneath the North American tectonic plate. The orogenic belt consists of, from west to east, a thrust belt, foredeep basin, forebulge, and back-bulge basin (figure 5). Each of these four parts of the thrust system slowly migrated eastward through the area over time, and each created unique environments of deposition or erosion. The back-bulge basin is where colorful Middle Jurassic-age strata of the Carmel and Arapien Formations, with vast thicknesses of salt and gypsum, accumulated. The forebulge was a relatively broad area above sea level and thus subject to modest erosion. In the foredeep basin, thousands of feet of sediment accumulated from erosion of the thrust belt highlands, creating a wedge of strata, coarse in the west where rivers were powerful enough to transport cobbles and boulders, becoming finer eastward on the Cretaceous coastal plain with its meandering muddy rivers and swamps once full of dinosaur life and now the source of Utah's coal resources. Imagine such a continental-scale, mountain-building system slowly migrating eastward over tens of millions of years. The result in southwest Utah is Middle Jurassic-age evaporite-bearing strata overlain by Late Cretaceous-age conglomerate, sandstone, shale, and coal-rich strata. Late Jurassic to Early Cretaceous strata, although present in central and eastern Utah, were either never deposited here or were removed by erosion associated with the forebulge high.

Deformation (compression) associated with the Sevier orogeny is expressed as long, generally north-trending folds and thrust faults that formed as the thrust belt advanced eastward into central Utah from about 100 to 45 million years ago (thrust faults are a type of reverse fault, the latter of which was less commonly encountered in English coal mines than normal faults). The folds and thrust faults record cumulative displacement of several tens of miles where the upper layers of the earth's crust were shortened, much like the folds in a rug that slips in front of your feet; rock strata originally deposited farther west were shoved up and over younger strata deposited in the east. Folds and thrust faults are dramatically displayed near Cedar City and as far east as Bryce Canyon National Park. Importantly for our landslide story, they represent east-directed compressional deformation that predates deposition of the colorful strata of Bryce Canyon National Park and the still younger Marysvale volcanic rocks. Also important, thrust faults provided pathways for magma that fed the Marysvale volcanoes.

These folds and thrust faults are just one part of the Cordilleran orogeny, what geologists call "thin-skinned" deformation because the upper sedimentary layers of the earth's crust were deformed. The other part of the orogeny is known as the Laramide. The Laramide orogeny partly overlapped in time and space with the Sevier orogeny, and both were the result of the collision of the Farallon and North American plates; they are regional names for two parts of the Cordilleran orogeny, distinguished by differing styles of deformation. East of the Utah hingeline where strata are much thinner and did not easily decouple from basement rocks, plate tectonic compression produced a different structural style characterized by basement-cored uplifts and intervening basins—the Laramide orogeny. The San Rafael Swell, Circle Cliffs Uplift, and Kaibab Plateau are examples of classic Laramide structures in the western Colorado Plateau (figure 6).

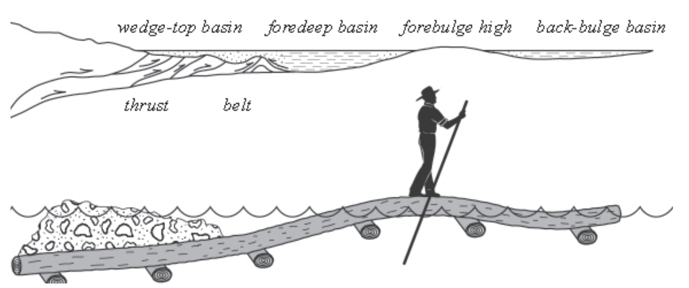


Figure 5. *Typical parts of a thrust system. The thickened, eastward-moving, leading-edge thrust wedge on the left overloads the earth's crust, which flexes in response, like loading rock on a wooden raft floating on water. In Utah, the entire thrust system migrated eastward during the middle Mesozoic to early Tertiary, but this simple pattern is commonly complicated due to variations in crustal strength and pre-existing faults. From Willis (1999)****.***

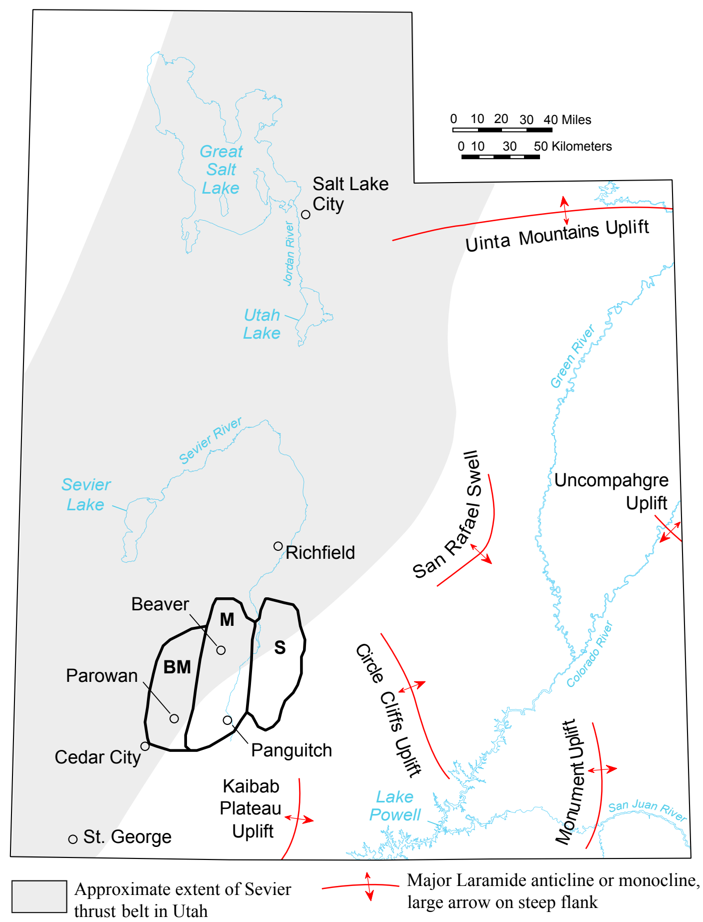


Figure 6. *Major Laramide anticlines and monoclines and location of the Sevier (S), Markagunt (M), and Black Mountains (BM) mega-landslides. Modified from Willis (1999).*

Each is an asymmetric, doubly-plunging anticline with a conspicuous monocline along its steep eastern flank, formed above "blind" reverse faults ("blind" referring to the fact that the faults do not completely cut through the rocks, rather they transition upward into a great fault-tip fold). Apart from hosting some of Utah's most sought-after red rock country, these uplifts are intriguing in that they formed above reactivated extensional faults that initially formed during the breakup of the Rodinian supercontinent. The Laramide uplifts are thus fault-propagation folds formed at the tip of faults rooted in Precambrian basement. Intriguingly, they reflect "inversion tectonics," fault-bounded former basins that now stand as structurally high features.

One Laramide basin important to our story of gravitational collapse of the Marysvale volcanic field is the Claron basin, whose eponymous orange and white layers are famously exposed at Cedar Breaks National Monument and Bryce Canyon National Park, forming the Pink Cliffs, the uppermost riser and tread of the Grand Staircase (figure 7). Except for the upper white part of the Claron Formation, which records deposition in a large Eocene-age lake, most Claron strata were deposited in floodplains and minor stream channels of a seasonally arid, high-elevation basin at a time when early mammals underwent a rapid diversification of species. But rather than serving as an archive of early mammal fossils, the Claron beds instead preserve a series of fossil soil horizons stacked one upon the other, a delight to specialists who study trace fossils such as animal tracks and burrows preserved in the ancient soils, but a grand disappointment to paleontologists yearning for fossils of primitive horses and other early Paleocene and Eocene mammals.

The flat-lying Claron Formation overlies tilted and erosionally beveled Late Cretaceous strata—Claron strata truncate and thus postdate Sevier orogenic deformation that resulted in folding of those older Cretaceous rock layers. Yet in places in and near Bryce Canyon, Claron strata are indeed folded and thrust faulted, but with a southward sense of compression, not the east-directed vergence associated with the Sevier orogeny. Such deformation made no sense to pioneering geologists who worked in this region, but as we shall see, it is directly tied to slow gravitationally driven spreading of the Marysvale volcanic field and its subsequent catastrophic collapse.

Figure 7. *The southern end of the Sevier Plateau and Sevier mega-landslide is visible on the horizon nearly 15 miles (24 km) north of Bryce Point in Bryce Canyon National Park. Compared to the fantastically sculpted hoodoos in the Claron Formation, few people have reason to look northward to the gray volcanic rocks of the southern Sevier Plateau. But ironically, it was here below Bryce Point that, beginning in the mid-1980s, geologists discovered small reverse faults in Claron strata that ultimately led to the idea of gravitational collapse of the Marysvale volcanic field as a mechanism to produce the once enigmatic, post-Sevier-age Paunsaugunt thrust faults. Bryce Point, at left, itself is capped by a brown ledge of pebble conglomerate that lies in subtle angular unconformity on underlying Claron strata. The conglomerate, named after Boat Mesa in the northern part of the park, was deposited immediately before the start of volcanism in southwest Utah about 37 million years ago.*

Marysvale Volcanic Field

Utah's High Plateaus are home to most of the Marysvale volcanic field, one of the major, ancient volcanic fields of the southwest United States. It is the south half of this field that collapsed catastrophically three separate times to produce Utah's mega-landslides. Most igneous activity in the Marysvale volcanic field occurred during the Oligocene and early Miocene, from about 32 to 14 million years ago. The vast majority of the field is built from volcanic rocks, many thousands of feet thick, and related intrusions of "intermediate" composition—mostly andesitic and dacitic rocks that resulted from explosive volcanic eruptions of stratovolcanoes and other vents. Beginning about 20 million years ago, volcanism changed to what geologists call "bimodal volcanism" that consisted of mostly smaller, localized and typically less explosive eruptions that produced more fluid basaltic lava flows (similar to those of Hawaii) and viscous, high-silica rhyolite domes (like those of Yellowstone). That trend—from voluminous, explosive volcanism to smaller less explosive eruptions—is a hallmark of volcanism in the southwest U.S. and reflects changing plate tectonic interactions along the western margin of North America.

Importantly again for our landslide story, the Marysvale volcanic field is built on a weak foundation of volcanic ash-rich, fine-grained sedimentary strata known to geologists as the Brian Head Formation and to planners and engineers as a devilishly difficult and unstable material on which to build (figure 8). Brian Head strata, which overlie the colorful Claron Formation, are the causal agent in many modern landslides in southwest Utah. Not only are the ancient volcanoes built on a weak foundation, but older underlying strata are cut by thrust faults that formed during the Sevier orogeny. The thrust faults subsequently acted as conduits for magma to intrude the uppermost layers of the earth's crust, likely locally leading to over-steepened, unstable slopes as described later.

During Marysvale volcanism, western Utah's landscape looked strikingly 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 modern Sierra Nevada Mountains in eastern California eastward to what is now the Colorado Plateau. At that time, there was no Markagunt Plateau, no Great Basin with its alternating, fault-bounded basins and ranges. The Nevadaplano was studded with volcanic mountains, calderas, and intervening basins (figure 9), analogous perhaps to the modern Andean Altiplano of South America. The Marysvale volcanic field developed at the east end of this high-elevation region and in its heyday was a cluster of stratovolcanoes, likely similar to the 10,000- to 14,000-foot-tall (3000–4300 m) modern Cascade volcanoes of the Pacific Northwest. The Marysvale volcanic field was also home to three large Yellowstone-like calderas.

__Figure 8.__ The Brian Head Formation on the southwest flank of the Sevier Plateau capped by volcanic mudflow deposits of the Mount Dutton Formation that are part of the Sevier mega-landslide. Brian Head strata contain large amounts of volcanic ash and preserve a record of the first volcanic activity in southwest Utah. Much of the ash has since been altered to clays that swell when wet and shrink when dry. Brian Head strata create the weak foundation upon which the Marysvale volcanic field erupted, and to this day they are the leading culprit in foundation problems and many modern landslides in the region. A volcanic ash bed near the base of the Brian Head here yielded an age of about 37 Ma.

The Marysvale stratovolcanoes erupted a monotonous series of gray lava flows (what we call vent facies that made up the bulk of the volcanic cones) and produced a far larger volume of volcanic breccia (what we call the alluvial facies, lahar or volcanic mudflow deposits preserved on the lower flanks of the volcanoes). Volcanic breccia collectively accounts for more than 90 percent of the volume of Marysvale volcanic rocks. Even to a trained eye, these rocks tend to look much alike and it is difficult to distinguish rocks from different volcanoes or to decipher the relative ages and relationships among them. The volcanic cones have long since eroded away and what we are left with is complexly interfingering and cross-cutting vent and alluvial facies derived from overlapping stratovolcanoes and other vents. This vast pile is more than 6000 feet (2000 m) thick, a nightmare to try to map and decipher. Geologists have lumped most of these rocks on the field's south flank into a single formation called the Mount Dutton Formation, named for the highest peak on the southern Sevier Plateau overlooking the broad, round valley containing Circleville. Mount Dutton takes its name from Clarence E. Dutton, who pioneered geologic research in Utah's High Plateaus for the U.S. Geological Survey (USGS) in the late 1870s.

However, interlayered within that monotonous sequence are distinctive ash-flow tuffs erupted from calderas within the field and from as far away as eastern Nevada. Ash-flow tuffs are the deposits of pyroclastic flows, density currents of hot volcanic ash, rock fragments, 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. These and other ash-flow tuffs are important to the story of Utah's mega-landslides because they are distinctive and thus easily

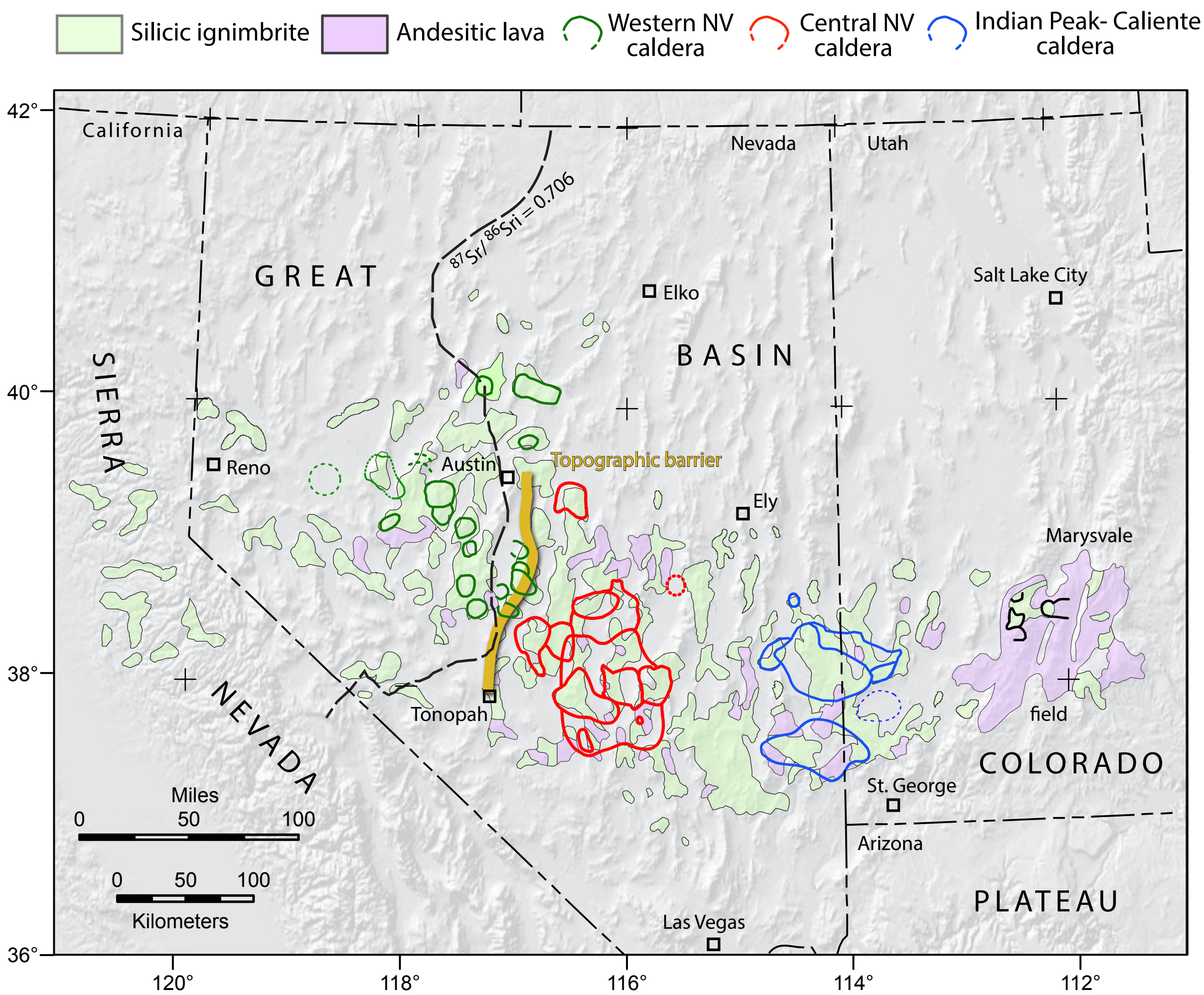


Figure 9. *Volcanic rocks and eruptive centers of the southern Great Basin region during what geologists call the middle Cenozoic (36 to 18 Ma) "ignimbrite flare-up." This prolonged period of mostly caldera eruptions produced some of the largest ash-flow tuff (ignimbrite in European parlance) eruptions known in Earth's history. Several ash-flow tuffs from the Indian Peak and Caliente caldera complexes (blue lines) on the Utah-Nevada border spread eastward into southwest Utah and into the Marysvale volcanic field where they serve as useful marker beds in a mostly nondescript pile of andesitic and dacitic lava flows and volcanic breccia deposits. The thick yellow line marks the drainage divide on the Nevadaplano; tuffs erupted from western Nevada calderas flowed mostly west down the west flank of the highlands and are now preserved in exhumed paleovalleys across today's Sierra Nevada Mountains. From Best and others (2013).*

recognizable in what is otherwise a vast pile of similar-looking volcanic rocks. The tuffs are that brightly colored, distinctive part of a jigsaw puzzle that allows puzzle fiends to flesh out the framework of what might otherwise be a frustrating task. And because they were deposited in a geological instant, ash-flow tuffs serve as useful time horizons that allow geologists to reconstruct past landscapes and better understand the extent and magnitude of deformation associated not only with gravitational collapse of the Marysvale volcanic field, but also with subsequent basin-range extensional deformation. The principal ash-flow tuffs and other volcanic rocks of the Marysvale volcanic field are shown in figure 10.

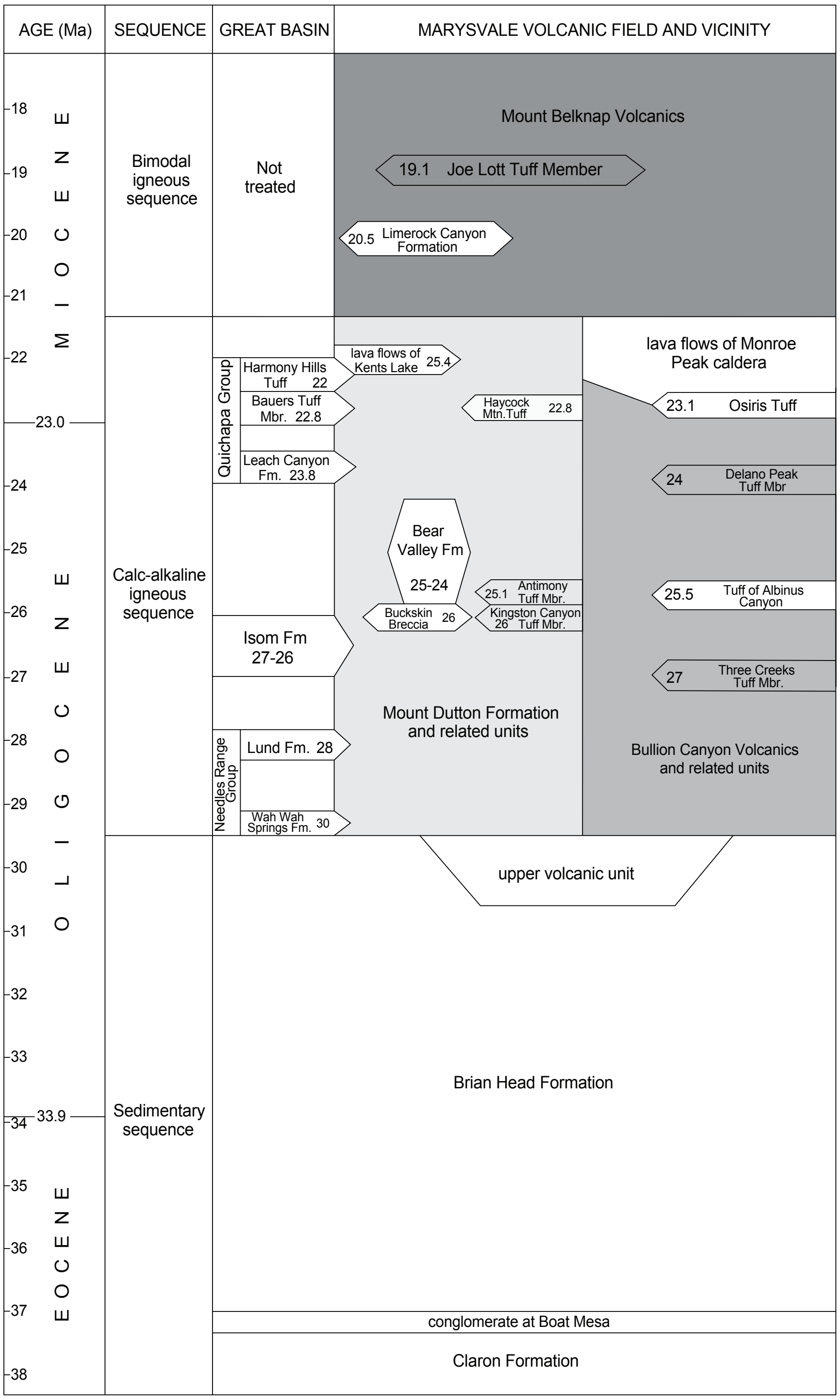


Figure 10. Stratigraphic column of volcanic rocks in and near the Marysvale volcanic field. Numbers refer to radiometric ages of volcanic rocks in millions of years (Ma). Most rock units intertongue with units shown to their left or right. Shading indicates groups of rocks from different volcanic centers. Modified from Rowley and others (1994).

How Big is the Marysvale Gravity Slide Complex?

The Marysvale gravity slide complex covers nearly 3000 square miles (>8000 km^2), an area roughly that of Yellowstone National Park (or twice that of Rhode Island, or more than half the size of Connecticut, if you prefer), with a volume of slide debris that would nearly fill up the Grand Canyon. Yet even for geologists who excel at conjuring up long-vanished landscapes and who calibrate their sense of time to the extraordinarily long stretches of deep geologic time, it is hard to imagine how big the landslides must have been. It is hard for anyone to appreciate their enormous size, especially because they are, in essence, simply landslides, surficial features of which we all have an intuitive sense. Perhaps by superimposing the outline of the mega-slides over urban areas can we better appreciate their footprint (figure 11).

The Markagunt slide has an overall length of about 60 miles (96 km) and breadth of about 23 miles (32 km), making the deposit at least 1150 square miles (>3000 km^2) in extent. It is also over a mile (1.6 km) thick in its northern reaches at the breakaway zone in the modern-day Tushar Mountains, tapering southward to several hundred feet thick on the central Markagunt Plateau. The slide's volume is hard to estimate because we do not know precisely what the pre-slide landscape was like, and because much of the slide mass has been eroded or buried, but we believe it to be at least 480 cubic miles (2000 km^3). Vital statistics of the Sevier and Black Mountains mega-landslides are similarly impressive (table 1), and runout over the former land surface of each slide was at least 20 miles (32 km).

Only the early Eocene, 49 million-year-old Heart Mountain mega-landslide in northwest Wyoming is a terrestrial slide of comparable size; it was considered unique until discovery of the Markagunt and its sister mega-slides.

The Heart Mountain slide, in the Absaroka volcanic field, covers an area of at least 1300 square miles (3400 km^2), and possibly nearly 2000 square miles (5000 km^2), and was long considered to be Earth's largest terrestrial landslide since its discovery in the late 1800s. Researchers at Southern Illinois State University and Macalester College, among others, continue to learn more about the Heart Mountain slide, including the fact that it may have been triggered by emplacement of igneous dikes that led to expansion and destabilization of the volcanic field. Submarine landslides, derived from earth's continental shelves or volcanic seamounts, are larger still. For example, the 63 million-year-old Halibut slide in the North Sea Basin is nearly 190 miles (300 km) long and covers 2700 square miles (7000 km^2); the largest of the relatively young Hawaiian landslides, the Nuuanu slide derived from the north flank of Oahu, covers nearly 9000 square miles (23,000 km^2) and extends for more than 125 miles (200 km) across the abyssal plain.

EVIDENCE FOR CATASTROPHIC FAILURE

Recognizing most modern landslides is straightforward given their telltale signs of raw scarps, open cracks, hummocky topography, and all-too-often damaged infrastructure. But the Markagunt gravity slide complex exhibits nothing so obvious. It is old. It is deeply eroded and partly buried by younger deposits and dismembered by younger faults. Utah's mega-landslides are, by any geologic standard, insanely big. Still, key pieces of the puzzle remain, and the picture they paint is one of extraordinary calamity near the height of volcanism of the Marysvale field.

Several lines of evidence collectively define the extent, age, and characteristics of Utah's mega-landslides, including: (1) a variety of unusual, deformed rocks, (2) micro- to large-scale structures that record movement of the slide masses, and (3) isotopic ages and cross-cutting relationships that constrain their extent and time of emplacement. Finding and deciphering such geologic clues is the true intellectual joy in our profession as mapping geologists, and here we share our interpretations of some of our favorite discoveries.

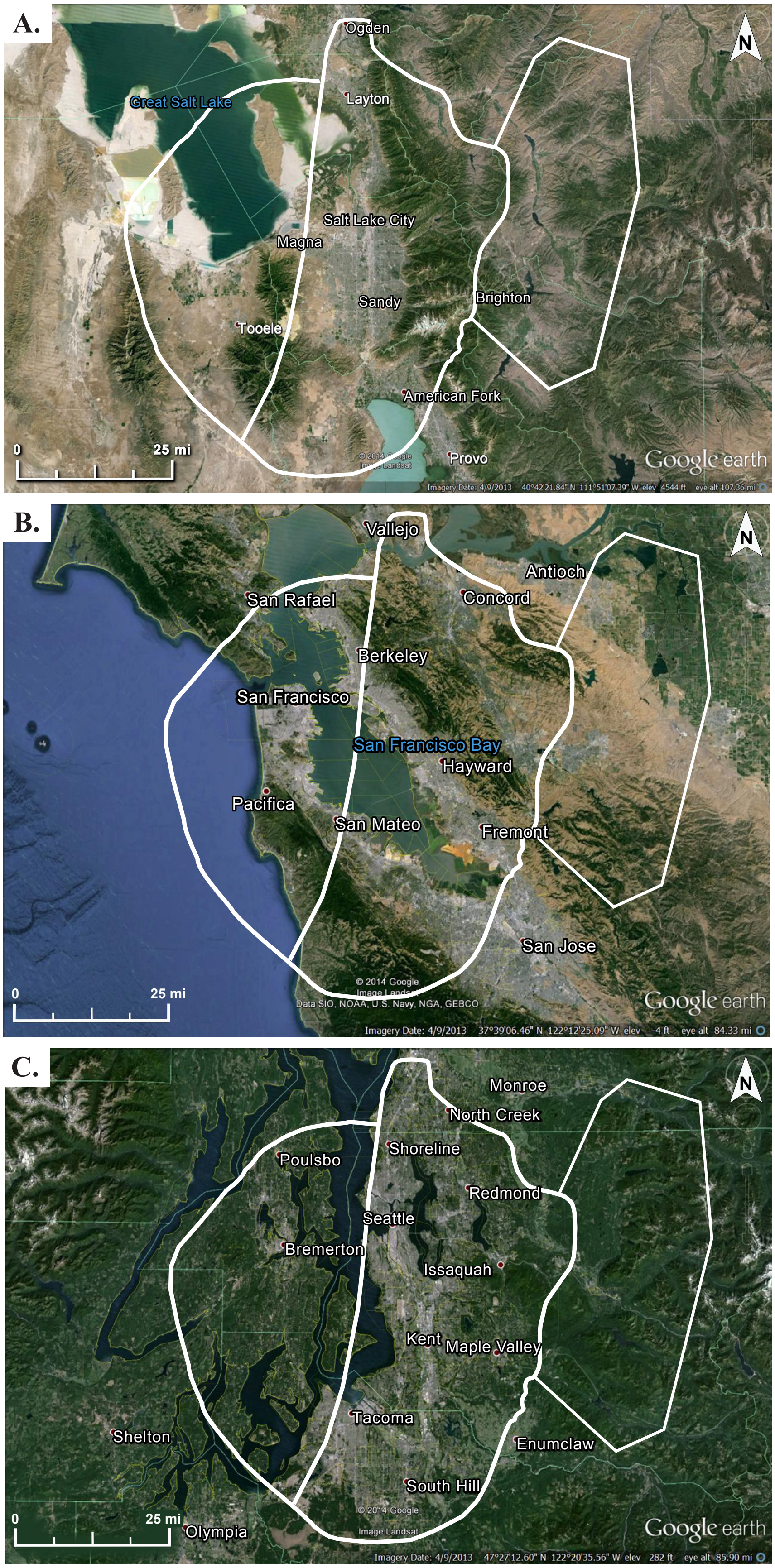


Figure 11. *Size of the Marysvale gravity slide complex compared to three urban areas to dramatically show its gigantic scale.* ***(A)*** *Wasatch Front,* ***(B)*** *San Francisco Bay area,* ***(C)*** *Seattle area.*

Table 1. Vital statistics of the Sevier, Markagunt, and Black Mountains mega-landslides. All measurements are approximate minimum estimates.

Mega-landslide	Length, miles (km)	Width, miles (km)	Area, sq. miles (km^2)
Black Mountains	50 (80)	25 (40)	900 (2300)
Markagunt	60 (96)	23 (37)	1150 (3000)
Sevier	50 (80)	18 (29)	750 (1900)

Deformed Rocks

Severely deformed rocks that we interpret to be produced by catastrophic collapse of the Marysvale volcanic field include:

(1) thin layers at the base of the slides that consist of ground-up rock. This "rock" behaved as an overpressured fluid, reducing effective friction at the base of the mega-landslides and was injected under pressure during movement into overlying fractured landslide rocks, forming clastic dikes;

(2) rare, friction-generated melt rock, a glass known as pseudotachylyte, which demonstrates high-velocity movement of the mega-slides;

(3) thoroughly crushed rocks known as ultracataclasite that are molded into bizarre, elongated masses, which we don't pretend to understand;

(4) pervasively fractured and rehealed ash-flow tuffs and lava flows; and

(5) cobbles and boulders with unusual "jigsaw" fractures, which although not unique to mega-landslides, demonstrate fracturing under high confining pressures.

Basal Layers and Clastic Dikes

One of the most intriguing rock types associated with these gigantic landslides is found at their base, directly above the slip surface that marks the bottom of the slides. It is a breccia formed by the grinding action of rock against rock—we call it a basal layer. Basal layers are made up of unsorted, crushed, deformed, and intact mineral and rock fragments that float in a fine-grained matrix of pulverized rock (figure 12). This layer can be paper-thin to over 100 feet (30 m) thick, but typically is about one foot (0.3 m) thick. Where the slides overrode the former land surface, basal layers are a mix of ground-up rock and surface sediment. Surficial sediments are important in that they may contain zircon crystals derived from volcanic eruptions shortly before mega-slide emplacement, thus giving geologists an independent way to estimate the age of the slides as described later.

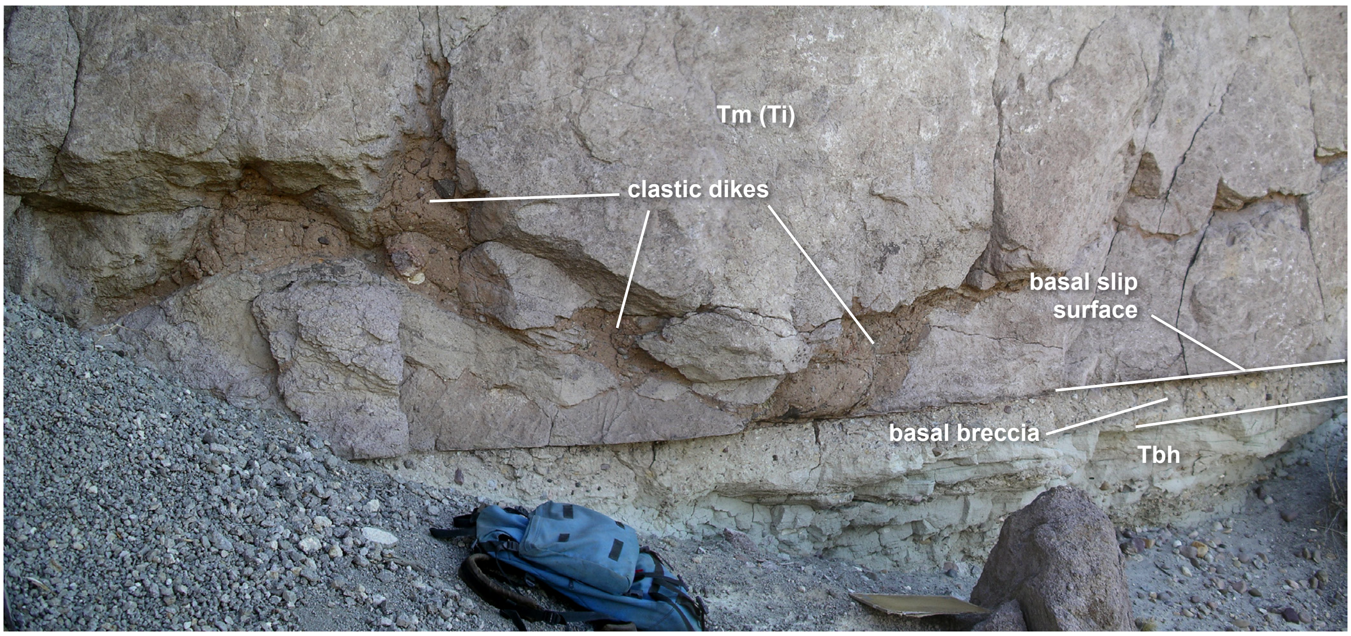


Figure 12. Basal layer and clastic dikes at Haycock Mountain. Note planar basal slip surface, which here overlies pebbly sandstone of the Brian Head Formation (Tbh). The basal layer is a poorly sorted mixture of rock and sediment that behaved as an overpressured fluid, facilitating slide movement, and that was injected into cracks in crushed and pulverized upper plate rocks of the Isom Formation (Tm[Ti]). The slightly different colors of the basal layer (light brown) and dikes (reddish brown) are thought to result from the dikes being sourced slightly farther north from different materials encountered shortly before the block came to a final rest. Typically, basal layers and dikes comprise the exact same material and record only the very last stage of emplacement.

Pulverized material of the basal layers also fills fractures at the base of the slide masses. These clastic dikes, or injectites, indicate that the material behaved as an overpressured fluid during transport, serving to reduce friction at the slide's base and facilitating extraordinarily long runout distances. Most dikes probably record the final stages of movement of the slides, perhaps the final few tens or hundreds of feet, as they came to a stop and fractures opened and were injected with the overpressured muddy debris. The composition and extent of basal layers and injectites are useful to differentiate landslide structures from tectonic structures related to earthquake faults, helping to constrain tectonic histories. Basal layers are well exposed on the south side of Haycock Mountain, at the southern end of the Sevier Plateau, and nearly everywhere the base of the slide masses is visible.

Pseudotachylyte

Pseudotachylyte (pseudo-TACH-e-light) is an uncommon and very interesting rock. Tachylyte is itself a rare, low-silica glass formed by rapid cooling of basaltic magma. The name pseudotachylyte, or false tachylyte, was coined in 1916 to describe glass-like dikes found in what is now known as the 2-billion-year-old Vredefort impact crater in South Africa, the largest (and one of the oldest) impact crater yet recognized on Earth. Pseudotachylyte results from friction associated with high-strain rates, like the heat generated when you rub your hands together rapidly. It is an instantaneously generated friction melt, and for this reason is also called frictionite.

Pseudotachylyte forms from impact events, but it is also found on exhumed earthquake fault planes, having originally formed at great depth, typically greater than 6 miles (10 km). Only recently, however, has pseudotachylyte been discovered on shear surfaces of exceptionally large landslides. In 2013, Hacker discovered pseudotachylyte on subsidiary slip surfaces near the ramp of the Markagunt mega-slide. This is the first reported occurrence of landslide-generated pseudotachylyte in North America. The few examples of pseudotachylyte associated with gigantic landslides or rockslides elsewhere in the world include the Arequipa debris-avalanche deposit from Pichu-Pichu volcano in southern Peru, Köfels in the Austrian Alps, and Tsergo Ri in Nepal, among others described in a 2014 summary of gigantic rockslides by University of Salzburg geologist Johannes Weidinger and his colleagues. The volume of pseudotachylyte associated with the Markagunt and Sevier mega-slides, though small, may dwarf that of previously reported landslide-related occurrences.

Most pseudotachylyte that we have discovered looks like jet black obsidian. Some is vesicular yet still glassy, similar to the scoria found at cinder cones. Some is altered, looking like a dull, chalky cousin of its former self, the glass having changed into radiating aggregates of microscopic, needle-like feldspar phenocrysts. Analysis of the glass by University of Utah geologist Barb Nash shows that it is a low-silica, low-potassium glass of basaltic bulk composition—tachylyte, but not of volcanic origin. The bulk composition of our glass may indicate preferential melting of biotite and other iron-rich minerals, with water in the crystalline structure of the biotite acting as a flux to lower its melting temperature. Regardless, the glass is found on shear planes and in dikes emanating from those shears, clearly showing it is not of volcanic origin (figure 13). The glass-filled fractures are commonly <1 to 3 inches (1 to 10 cm) in width, but as wide as 12 inches (30 cm). The presence of glass in dikes again points to high frictional heating and overpressured fluids at the base of the slide.

Utah is justly famous for its black volcanic glass—obsidian, which is a high-silica, high-potassium glass of rhyolitic composition—known from many areas in western Utah and once widely used by Native Americans. The volume of the mega-slide pseudotachylyte is miniscule by comparison but extraordinary for its scientific importance.

Analysis of the magnetic properties of the pseudotachylyte, led by researchers at the University of Louisiana at Layafette, showed that it records southward-directed emplacement consistent with our regional observations. Magnetic properties of these rocks thus provide a wholly independent way to document movement of the slide masses.

Even more importantly, the presence of pseudotachylyte demonstrates high temperatures on slip surfaces, hot enough to melt rock and so likely at least 2200ºF (>1200ºC). It also implies high slip rates to generate that heat. Researchers are now working on the problem of how fast the slides may have moved, but our best guess now is that if, 23 million years ago, one were driving south on I-15 at 80 mph (130 km per hour), the Markagunt slide mass would have rolled right over the top of you!

Ultracataclasite

Highly elongated, intensely deformed fragments of ash-flow tuffs are locally present in basal layers of the Sevier and Markagunt mega-slides. These fragments occur as thin, wavy layers or as elongate blobs (figure 14). They are silicified and so are resistant compared to the basal layer itself. Although such rock fragments are crushed nearly beyond recognition, the basal layer also contains undeformed, rounded pebbles—we don't understand why or how this happened. At Haycock Mountain, the fragments in Markagunt basal layers are likely derived from the Isom and Wah Wah Springs Formations, the two oldest ash-flow tuffs derived from calderas 100 miles (160 km) to the west. The deformed fragments from the southern Sevier mega-slide may be derived from the Three Creeks Tuff Member, an ash-flow tuff derived from a caldera in the northern Marysvale field and part of a larger group of rocks known as the Bullion Canyon Volcanics.

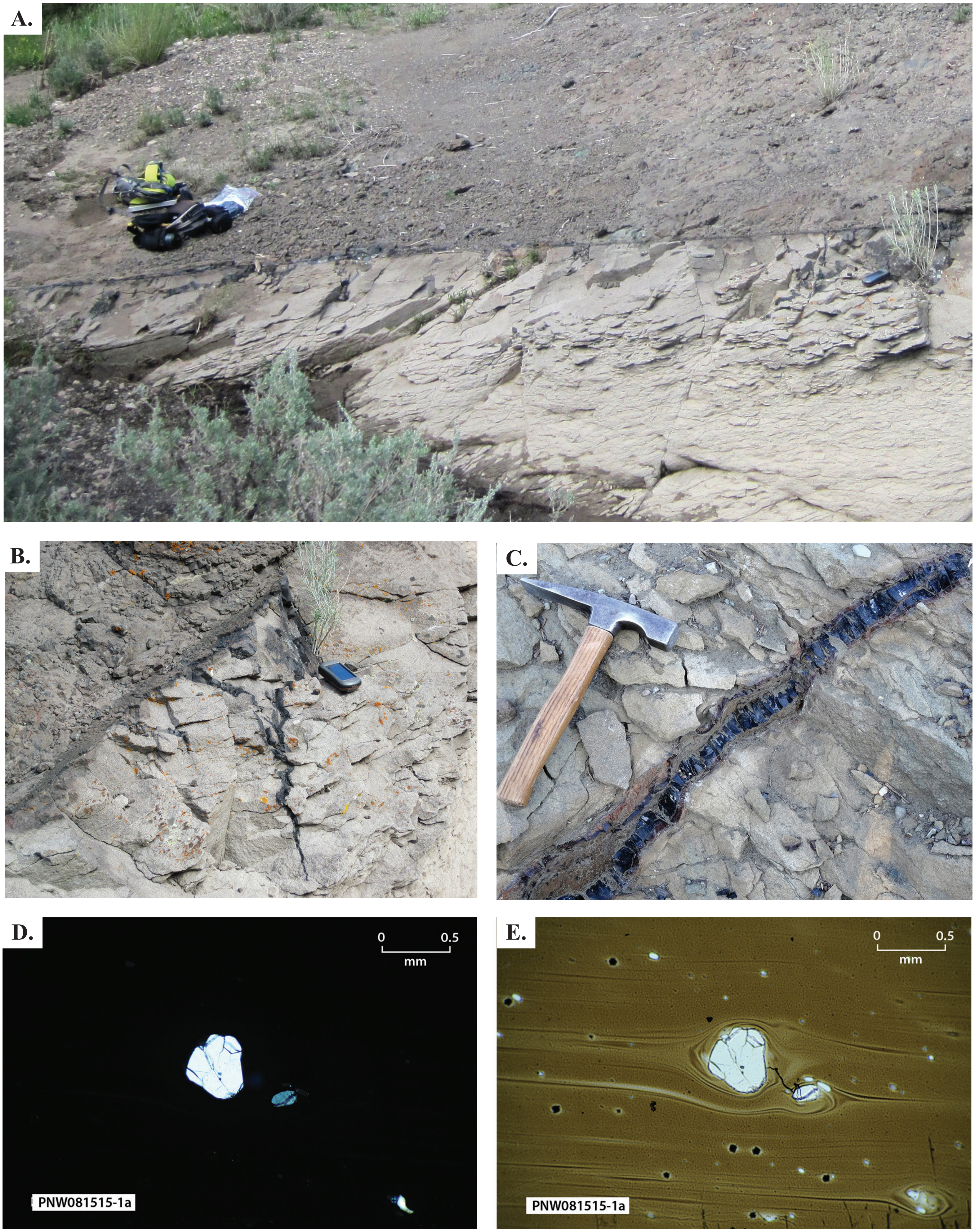


Figure 13. (A) *Pseudotachylyte-lined shear plane between highly fractured, biotite-rich sandstone of the Bear Valley Formation below and volcanic mudflow deposits of the Mount Dutton Formation above.* ***(B)*** *Close-up of shear and pseudotachylyte dike, with a GPS receiver for scale.* ***(C)*** *Pseudotachylyte dike. Photomicrographs showing* ***(D)*** *partially melted feldspar crystals surrounded by glass, which is black in this view as it is for all glass when viewed in crossed-polarized light and* ***(E)*** *flow structures visible in plain light.*

Figure 14. (A) *View north towards large block of the basal layer of the Sevier gravity slide at the south end of the Sevier Plateau; the source of the rockfall block is in the brown cliff above the light-gray layers of the Brian Head Formation (Tbh). Here, participants of the September 2017 Geological Society of America-sponsored Thompson Field Forum debate the origin of catastrophically deformed pieces of ash-flow tuff (one of which is shown by arrow) encased in the poorly sorted matrix of the basal layer.* ***(B)*** *Close-up of deformed ash-flow tuff; quarter for scale at "tail" on base on block.* ***(C)*** *Many elongated and deformed ultracataclasite blocks (silicified and so shiny in this view straight up the cliff face) are found in this exceptionally thick basal layer.* ***(D)*** *Deformed block of ash-flow tuff (likely Isom) in the basal layer at Haycock Mountain. We remain perplexed as to how such a deposit can contain both severely deformed clasts and undeformed, rounded pebbles such as the one at the top of the photograph.*

We initially referred to these deformed rocks as "taffy clasts" because they look at first glance like stretched out pieces of warm candy (although one as much as 10 feet [3 m] or more in length!). But, when we showed these amazing outcrops to participants of the 2017 Geological Society of America Thompson Field Forum, we were roundly—and correctly—criticized by rock mechanics specialists. They noted that the deformation was not due to ductile processes (those that cause a rock to flow or bend without fracturing, typically under immense pressure and heat deep in the earth's crust), rather it appears to be a result of extreme cataclasis. Cataclasis is a progressive process of brittle deformation—fracturing and grinding and comminution (grain size reduction) that produces a rock that ranges from badly fractured to one that is a powder, in which case we modify the name as ultracataclasite. Individual pieces of the rock were rotated during the crushing process and then lithified after deformation ceased. Cataclastically deformed rocks are commonly produced along earthquake faults and in meteorite impact events; here they are produced along major slip surfaces of Utah's mega-slides.

Pervasively Fractured Ash-flow Tuffs and Lava Flows

Some ash-flow tuffs and lava flows in the slide masses form unusual breccias—angular fragments of rocks of all sizes in a matrix of the same material. Such deformed rocks mimic what geologists call flow breccias, of which the classic Hawaiian "aa" lava flows are prime examples; commonly the breccia is restricted to the base of such lava flows. Yet at many places on the mega-slides we find the entire thickness of a lava flow or ash-flow tuff is thoroughly brecciated and locally cut by shears (figure 15). Volcanic mudflow deposits that lie above and below such brecciated horizons appear relatively undeformed. It thus appears that lava flows and ash-flow tuffs locally respond differently to mega-slide deformation—they behave in a brittle fashion whereas mudflow deposits may accommodate strain through shearing or possibly partial refluidization of the mudflow matrix. We suggest that such pervasive brecciation indicates deformation of the lava flows and ash-flow tuffs during sliding rather than original deposition.

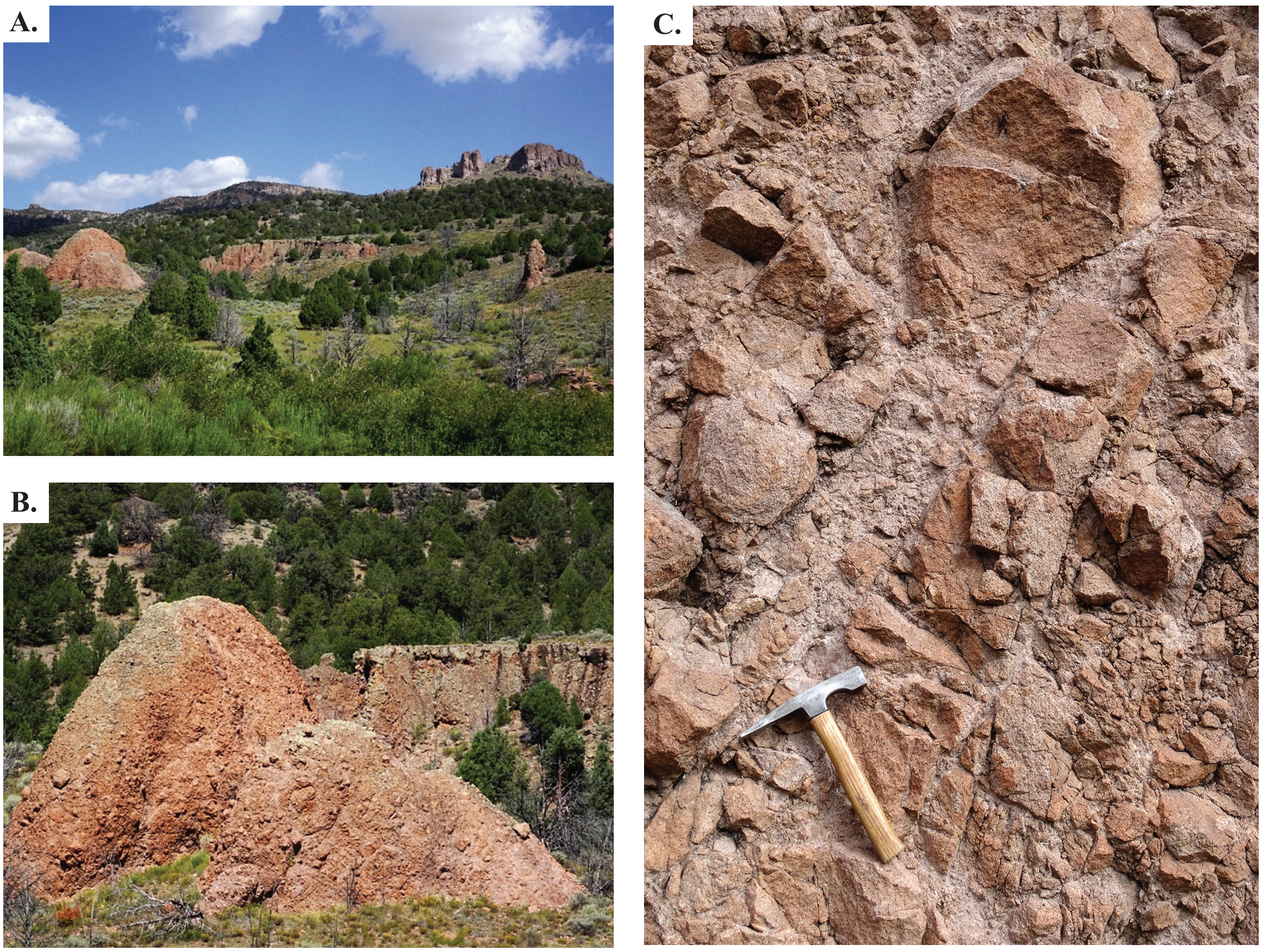


Figure 15. ***(A)*** *Base of the Sevier mega-slide in Cottonwood Wash showing brecciated outcrops of the Three Creeks Tuff Member in the middle distance; view northward.* ***(B)*** *Telephoto view of Three Creeks Tuff Member, with its sheared, flat top in distance at right.* ***(C)*** *Close-up showing pervasively brecciated and sheared nature of this rock indicative of deformation after the tuff was deposited.*

Jigsaw Clasts

Deformed cobbles and boulders that we call "jigsaw" clasts are locally found in volcanic mudflow deposits of the Mount Dutton Formation and can be especially abundant near major slip surfaces and where clasts are in contact with each other ("grain-supported" mudflows) as opposed to surrounded by a mud matrix. Jigsaw clasts are those that are cut by small shears with small amounts of offset, a few inches or less, such that mentally we can move them back to their original place, as in a puzzle (figure 16); the fractures are "rehealed" so that these clasts are as solid and as durable as the original unbroken clasts. Such clasts are also commonly associated with other geologically active settings such as basin-range extensional faults, thrust faults, and in volcanic debris-avalanche deposits. Furthermore, jigsaw clasts are similar to clasts that have "bread-cut-to-slices" fabric that are widely known from impact breccias. Importantly, however, such jigsaw clasts are absent in primary, undeformed volcanic mudflow deposits, in which broken "puzzle pieces" would be torn apart during mudflow movement.

Thus, although jigsaw clasts are not diagnostic of gravity slide movement, they are useful in that their occurrence, especially where abundant, signals the presence of nearby, low-angle slip surfaces at and near the base of the slides (at least in areas not obviously associated with younger basin-range extensional deformation). In areas with monotonous, poorly exposed volcanic mudflow deposits, not uncommon in the Mount Dutton Formation, the presence of jigsaw clasts is a significant clue that the rocks are deformed, likely due to slide emplacement.

Jigsaw clasts form as a result of brittle failure under high confining pressures. They may have formed as the slide masses moved rapidly over an uneven landscape, alternately plowing through low hillsides and filling in former low areas. The former would lead to local increased momentary compression in the slide mass; the latter, extension or inflation as the slide mass suddenly expanded to fill a low area. We envision that jigsaw clasts may form during these transient episodes of highly localized flexing, with compression and inflation near the base of the slides. Still, the clasts had hundreds of feet of rock above them—providing the confining pressure—so as to not be completely torn apart. Perhaps this is not unlike the weightless feeling one gets when driving rapidly over the crest of a sharp hill.

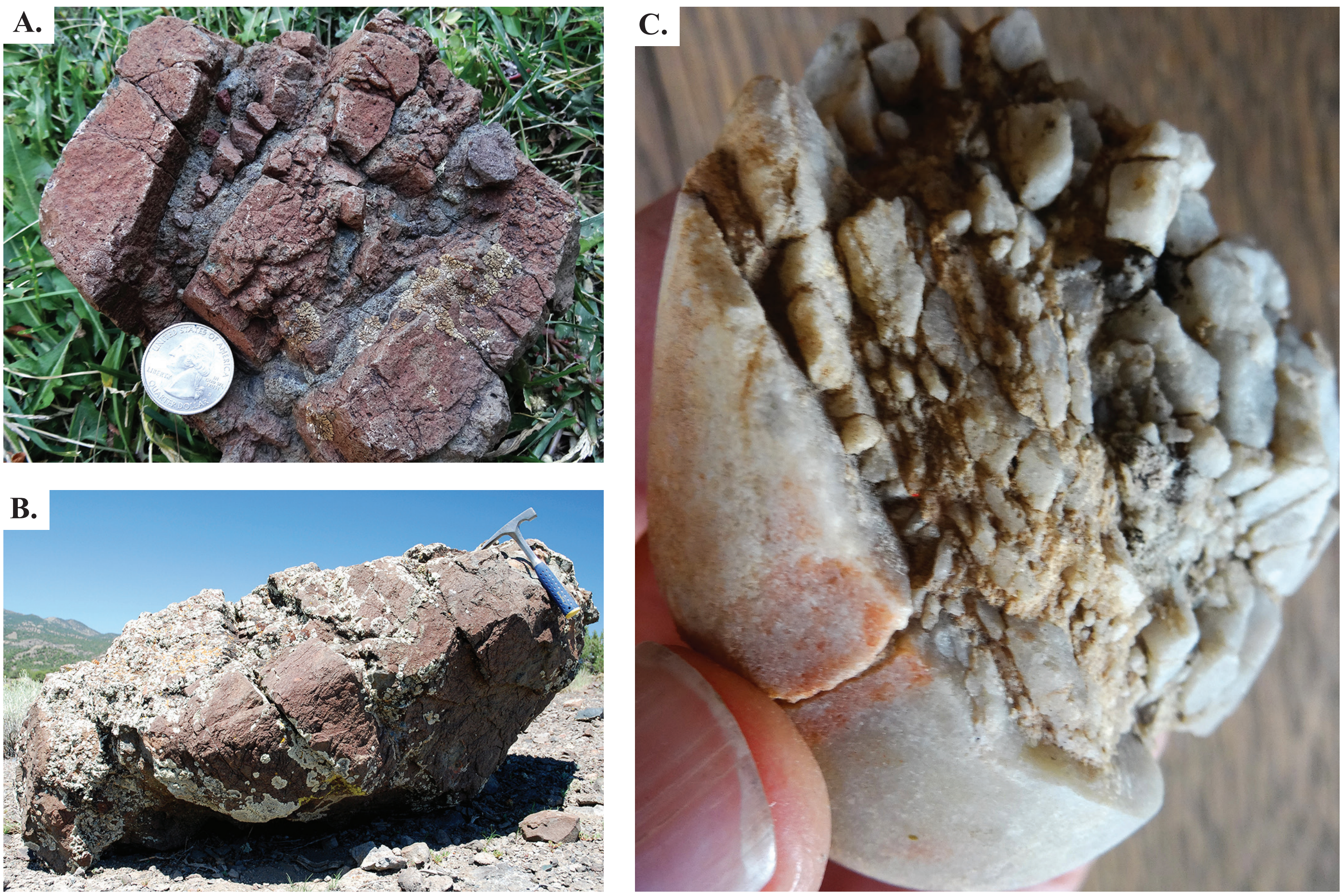


***Figure 16. (A and B)** Typical deformed clasts from volcanic mudflow deposits of the Mount Dutton Formation. Note rehealed fractures, some injected with fine-grained matrix from original mudflow, that offset the clasts but that can easily be shifted in one's mind back into place. **(C)** Deformed quartzite pebble from upper Claron strata. Such pebbles and boulders record brittle failure under high confining pressures. Despite poor exposures in many areas, such fractured yet rehealed clasts are indicative of nearby significant slip surfaces.*

Micro- to Large-scale Structures

Geologic structures such as faults, folds, tilted or rotated blocks, and groove marks and fractures that record movement directions provide additional evidence of deformation of Utah's mega-landslides. Interpretation of these and other features allows us to evaluate and refine our model of mega-landslide emplacement and, importantly, to continue to evaluate other possible ideas to explain what we observe.

The base of each mega-landslide is commonly grooved and striated by the grinding action of the slide mass moving over underlying rocks, much like the grinding action of sediment-filled ice at the base of a glacier or the sides of a fault as they rub past one another. Think of these linear features as skid marks at the base of each slide, dramatic evidence documenting the direction the slide mass was moving (figure 17). Coupled with fractures known as Reidel shears, we can demonstrate the absolute direction of movement—not, say, that the slide moved either to the south or to the north, but that it unequivocally moved from north to south. That is a powerful tool to document slide movement, and we find such north-to-south indicators across the breadth of the mega-slides.

Figure 17. *Grooved and striated surface developed on the Isom Formation due to emplacement of the Markagunt mega-slide, showing that the slide moved nearly due south (toward the senior author!).*

Tilted and rotated blocks of all sizes also record evidence of past slide movement. Near Castle Valley, east of Brian Head peak near the west edge of the Markagunt Plateau, a large block of north-tilted, 37 to 33 Ma Brian Head Formation, 29.5 Ma Wah Wah Springs Formation, and 27 to 26 Ma Isom Formation overlies undeformed 23.8 Ma Leach Canyon Formation. We envision that as the slide moved southward over the former land surface, it broke up into progressively smaller blocks, many of which are back-tilted and obviously out of place, with older rocks such as those near Castle Valley resting on top of younger rocks. We suspect that blocks are also rotated about a vertical axis as they were jostled about moving over the former land surface. Rotation and tilting naturally result from the landslide mass spreading out as it moves across the former land surface. Evidence of vertical-axis rotation of blocks, some as large as mountains, is difficult or impossible to see with your own eyes if the rock layers are not otherwise tilted. However, such rotations can be deciphered by determining the paleomagnetic characteristics of the rocks. Certain minerals in many rocks lock-in a record of the direction and intensity of the earth's magnetic field when they form. Geologists who specialize in paleomagnetism, sometimes endearingly called paleomagicians for their ability to tease out crucial and otherwise invisible information, sample rocks by collecting oriented drill cores extracted with a modified chainsaw that runs not a wickedly sharp-toothed chain but rather a water-cooled diamond drill core. Back at the lab, the cores are processed to yield their remnant magnetic signature, which is then compared to the paleomagnetic timescale. Researchers have yet to systematically employ this method to assess Utah's mega-slides, but in theory, paleomagnetic studies will help to independently determine the magnitude and extent of block rotations and possibly even constrain transport distances. Interestingly, one early regional paleomagnetic study of the Wah Wah Springs Formation—a widespread ash-flow tuff that preserves a record of the inclination and declination of the earth's magnetic field when it was deposited—offers a preview of what researchers may find. Wherever the Wah Wah Springs was sampled in Nevada and Utah, its paleomagnetic signature fit with what researchers expected, except in the southern Marysvale volcanic field where samples returned seemingly spurious declination and inclination measurements. We suspect that this is a result of the Wah Wah Springs being subtly tilted and rotated as landslide blocks moved away from their original area of deposition.

The Paunsaugunt thrust faults are one additional large-scale feature intimately connected to the Marysvale volcanic field. We describe these once-enigmatic faults in more detail later as part of our historical understanding of Utah's mega-slides, but they are important in demonstrating gravitational collapse of the volcanic field. Earth's crust simply is not rigid enough to support the weight of massive volcanoes. Slowly, over thousands to several million years, the volcanic field spreads outward in the upper plate of such thrust faults to a larger footprint and thus to a more stable profile. This process is common to volcanoes worldwide, and it commonly precedes rapid, catastrophic failure of volcanic cones.

Cross-cutting Relationships

Basal layers, clastic dikes, pseudotachylyte, cataclasite, unusual deformed "jigsaw" rocks, a variety of kinematic indicators and "skid marks" at the base of the slides, and tilted and rotated blocks are compelling evidence of catastrophic landslide movement, but the context in which they are found is also important. Each mega-slide was emplaced from the north to the south, from the highlands of the Marysvale volcanic field toward and beyond its southern distal edge. Each slide is replete with south-directed movement indicators oriented at right angles to regional and older compressional tectonic structures.

Recall that the Marysvale volcanic field overlies the leading edge of the Sevier orogenic belt, whose folds and thrust faults are oriented roughly north-south and in southwest Utah involve strata no younger than Late Cretaceous, about 66 Ma. Sliding postdates all deformation associated with the Cordilleran orogeny, at which time the Marysvale volcanic field did not yet exist. Thus, in the Marysvale volcanic area, when we observe older rocks deformed by eastward-directed compressional forces, we can be reasonably sure that they are related to the Sevier mountain-building event. When we observe rocks deformed by southward-directed forces, we should start thinking about gravitational collapse of the volcanic field. Structures of the mega-slides cut across older, Sevier-age structures.

Later, beginning about 20 million years ago, long after landsliding, ongoing west-to-east extension associated with development of the Basin and Range Province produced north-trending ranges and intervening basins and, in the High Plateaus, gently east-tilted plateaus. The Hurricane, Sevier, Paunsaugunt and related down-to-the-west normal faults cut the mega-slides, revealing exceptionally instructive longitudinal profiles through each mega-slide. In places, faulting has exposed the base of the slides, showing the subhorizontal basal slip surface and the ramp where it rises up onto the former land surface. The ramp is where the basal slip surface "daylighted" as the slide mass continued to move southward, leading to the placement of older rocks on younger rocks and soils on the former land surface. The ramp clearly shows that the basal slip surfaces are not rooted deep in the earth's crust and are thus not true tectonic features driven by tectonic forces.

Summary of Evidence for Catastrophic Failure

Parts of each mega-slide could, in isolation, be reasonably interpreted as having been generated by tectonic structures rather than the comparatively simple process of gravitational failure of a large volcanic edifice built on a weak foundation. Three examples include: (1) subhorizontal slip surfaces that form the base of the slides possess many attributes in common with low-angle tectonic faults (the Red Hills shear zone, described later, is one example); (2) cataclastic breccias and jigsaw clasts are also produced in earthquake fault zones and during impact events; and (3) pseudotachylyte is most commonly found on once deeply buried parts of fault zones, having formed one earthquake at a time over the span of millions of years. The key, however, is not only to understand such features individually, but rather collectively, to know how they relate to one another in time and space.

Some primary volcanic deposits can mimic features that we attribute to mega-slide emplacement. The most important red herring that we worry about is what volcanologists call debris-avalanche deposits that result from partial collapse of volcanic cones. These can look remarkably similar to some mega-landslide deposits. Such deposits are known from hundreds of active volcanoes worldwide, but one became famous when the north flank of Mount St. Helens (underlain by "the bulge") collapsed at 8:32 a.m. on May 18, 1980, when triggered by a magnitude 5.1 earthquake beneath the mountain. This debris avalanche removed the top of the magma chamber. Like popping the cork of a bottle of champagne, the released pressure immediately produced a northward-directed blast, which caused most of the fatalities (57); huge ash-flow eruptions immediately followed. Like virtually all volcanic areas, the Marysvale volcanic field contains primary debris-avalanche deposits; some were first described during the blitz of research and mapping in the region in the 1980s following the Mount St. Helens eruption. So, how do we distinguish them from landslide deposits? Known debris-avalanche deposits in the Marysvale field are relatively small and are buried within the alluvial aprons of vent areas, the flanks of former volcanoes. Furthermore, primary debris-avalanche deposits should be of multiple ages and record failure in multiple directions.

Another primary volcanic feature that we worry about is a flow breccia, which is a lava flow, such as can be seen in videos of active volcanoes. The rapidly solidifying front of a moving molten lava flow breaks apart and tumbles down the front, where it then is rolled over by the advancing flow, creating a breccia in a matrix of the same material. Primary lava flow and mudflow breccias and debris-avalanche deposits can readily be seen for what they are given sufficient exposures, but small windows of such rocks in vegetated or otherwise mostly covered areas can be difficult to correctly identify.

The most compelling arguments behind our interpretation of catastrophically emplaced gigantic landslides are: (1) the ramp, where the basal slip surface "daylights," proving it is not a tectonic low-angle normal fault; (2) pseudotachylyte on slip surfaces and in associated fracture-filled veins that formed near the earth's surface, requiring rapid movement; (3) basal layers and associated clastic dikes, which are characteristic of modern landslides worldwide and rarely associated with tectonic faults; and (4) rock structures and fabrics showing a single episode of formation not overprinted by repeated episodes of movement as is typical of tectonic faults. Coupled with the extent and geometry of the slides, the uniformity of skid mark-like movement indicators, their known age, and limitations imposed by a host of other structural features, the evidence shows that each mega-landslide represents a single catastrophic emplacement event. Our landslide model provides a simple, elegant solution to understanding these gigantic and at times still puzzling features.

Our hypothesis of mega-landslide formation yields testable predictions. Over the coming decades, researchers will put our hypothesis to the test, assessing its weak points and continually refining our understanding, much as we were recently forced to do. Initially, we thought that the Markagunt slide extended farther west, but later discovered that this western part must have been emplaced several million years later as what we now call the Black Mountains mega-slide. As Lawrence University geologist Marcia Bjornerud recently wrote in her mesmerizing book on deep geologic time and its important perspective in everyday life, "…rocks are not nouns, but verbs—visible evidence of processes: a volcanic eruption, the accretion of a coral reef, the growth of a mountain belt. Everywhere one looks, rocks bear witness to events that unfolded over long stretches of time." Our goal is to have others in the scientific community, with different interests and skill sets, work to gain a more complete and accurate understanding of what happened on the south flank of the Marysvale volcanic field so many millions of years ago, to tease out what the rocks have borne witness to.

Finally, we have struggled with the best terminology to describe these features. There are two schools of thought regarding the description of truly gigantic landslides, one that uses terminology adopted from the field of structural geology, and the other from the study of modern landslides. Descriptive terms thus reflect the inherent bias of geologic specialization and of scale, but confusion also results from inferred rates and styles of emplacement and from whether movement takes place near the earth's surface or deeper in the upper crust. Descriptive terminology is also confusing because every style of tectonic faulting can be produced by landsliding, and it is not always readily apparent whether such features result from gravitational or tectonic forces. Our profession has an ongoing problem of describing tectonic-scale features that resulted from near-surface, gravitationally driven processes.

Landslide names exist for features along a continuum of scales, from the smallest slides and slumps no larger than a child's sandbox to features many, many miles in extent, and in a continuum of types defined by their dominant mode of failure. Landslide specialists recognize a dizzying array of slumps, rotational slides, translational slides, rock avalanches, and many other types of these relatively shallow, gravitationally driven slope failures. But all we really need to remember is that gravity is king—something up high wants to be down low to reduce its potential energy. Slopes fail as landslides when gravity overcomes the inherent strength of rocks or soil. Still, the numerous names for types of landslides are important for they yield information about the mechanical properties of the soil and rock and the mechanics of landslide movement.

Yet none of these landslide names adequately capture the scale and complexity of Utah's mega-slides. For that reason, in our technical scientific publications (but not here), we use the term "gravity slide" and define it as an exceptionally large landslide. We intend the term to encompass multiple modes of failure during a single catastrophic episode of slumping, sliding, and breaking apart as debris avalanches and ultimately as debris flows. "Gravity slide" is needed because the term landslide implies a small, relatively simple and young terrestrial feature whose effects, mechanisms, and distribution are generally clear. "Gravity slide" describes a feature of much larger scale and complexity that is generally older, thus commonly lithified and eroded. Use of "gravity slide" is also necessary to distinguish it from typically smaller volcano flank failures, sector collapses, or debris avalanches now known to be common at modern volcanoes worldwide. The name "gravity slide" was introduced by pioneering geologist J. Hoover Mackin in his classic 1960 work recognizing and defining the widespread ash-flow tuffs of southeastern Nevada and southwestern Utah and their utility as isochronous markers (rock layers deposited essentially instantaneously) to document basin-range extension. Interestingly, in his report, Mackin also first recognized shallow magmatic intrusions called laccoliths and their role in forming huge hematite ore bodies in the Iron Springs mining district, with concomitant gravity slides shed off the laccoliths' growing, over-steepened flanks. Names are more than identity; they give one access to reams of knowledge that would otherwise be inaccessible if you didn't know the language in which to ask a question. Some may be satisfied with "little gray bird," but "gray flycatcher" (*Empidonax wrightii*) opens a portal into a world of knowledge and discovery.

WHEN DID THE MARYSVALE GRAVITY SLIDE COMPLEX FORM?

The timing of geologic events can be constrained by cross-cutting relationships, what every student learns in their basic Geology 101 introductory course. In the same way that a bee cannot pollinate a flower that has yet to bloom, a landslide cannot be older than the youngest rocks involved in the slide—something must exist before it can be deformed (or pollinated). Conversely, a landslide cannot be younger than the oldest rocks that lie undisturbed on top of the slide—if it were, those rocks would be deformed too. Thus, the timing of each mega-landslide emplacement is constrained by the age of the youngest rocks it overlies or deforms, and by the oldest undeformed rocks that overlie it.

Understanding cross-cutting relationships is a powerful tool to establish the relative age of geologic events, to put things in the proper order of when they happened— for example, an ash-flow tuff erupted, then a landslide happened, then a different, younger ash-flow tuff partly buried the slide. This is nothing less than the establishment of one small part of

Earth's immense history. However, establishing the *absolute* age of geologic events—how many thousands or millions of years ago something happened—is determined by precise dating using "clocks" within the rocks themselves. Dating is the purview of geochronology, the science of determining the age of geologic materials. Some minerals, such as zircon and potassium feldspar, contain trace amounts of uranium locked in their crystal structure, which naturally decays—"parent" to "daughter"—at a constant rate over time. Geochronologists have identified a half-dozen parent-daughter isotope systems useful for radiometric dating. The laboratory procedures required to precisely measure these isotopes are extraordinarily complex, but the math is remarkably simple. The only numbers required are the parent/daughter ratio and the decay constant for the parent. With accurate measurements of those two variables geochronologists are able to precisely date a variety of rocks. It is impossible to overstate the importance of such geochronological developments over the past century. Unshackled from its Victorian roots, geology has blossomed into a full-fledged analytical science, exploring not just the true age of rocks and sediments, but rates of geological processes and the deep history of every corner of the globe.

As described below, currently our evidence constrains emplacement of the:

- Sevier mega-landslide between about 26.2 and 25.1 Ma,
- Markagunt mega-landslide between about 23.1 and 22.75 Ma, and the
- Black Mountains mega-landslide after 19.5 Ma and possibly about 18 Ma or younger.

Interestingly, the slides get younger westward, mimicking the westward progression of volcanism in the volcanic field.

Sevier Mega-landslide

The oldest rocks known to postdate emplacement of the Sevier mega-landslide belong to the 25.1 Ma Antimony Tuff Member of the Mount Dutton Formation, which lies undisturbed on top of the slide at the east end of Kingston Canyon and nearby areas. We describe the Antimony Tuff Member as a "gray, densely welded, phenocryst-poor ash-flow tuff that exhibits pronounced platy compaction foliation and lighter-colored flattened gas bubbles." Hidden in that jargon is a fascinating rock named for outcrops in Kingston Canyon, just north of the small town of Antimony. The tuff was so hot when it erupted that it flowed like a lava flow during its final stages (few tens of feet) of emplacement, creating linear vesicles, locally contorted flow layering, and flow breccias; it is known for its platy weathering habit, a result of severely flattened gas bubbles and pumice fragments. Today it is found as a resistant ledge that can be traced for miles across the landscape.

The youngest rocks so far discovered underlying the Sevier mega-slide belong to the Buckskin Breccia, where a remnant of the slide is exposed in Dry Wash east of Antimony. The Buckskin Breccia is a series of dacitic lava flows, thin ash-flow tuffs, mudflow breccias and conglomerate that contain granitic clasts like those of the Spry and Showalter intrusions (the intrusions are technically quartz monzonite porphyry, meaning that they contain conspicuous crystals of quartz, feldspar, and biotite in a fine-grained groundmass, like plums in a pudding, showing that the intrusions were emplaced at a relatively shallow depth where they cooled quickly). The Buckskin Breccia is itself not yet dated, but is believed to be about 26.2 Ma, the age of the distinctive quartz monzonite intrusions. Emplacement of the Sevier mega-landslide is thus presently constrained as between about 26.2 and 25.1 Ma.

Our discovery of a family of ash-flow tuffs we collectively call the tuff of Tibadore, after Tibadore Canyon east of Piute Reservoir where Rowley first understood its significance, may further constrain the age of the Sevier slide. The tuff of Tibadore looks remarkably like the Antimony Tuff—it too is a crystal-poor, densely welded ash-flow tuff with a similar bulk chemistry and look to it, and it rests at nearly the same stratigraphic horizon—but the Tibadore rocks are deformed whereas the Antimony is not. The deformation is typically subtle, best observed under a microscope, but locally Tibadore rocks are severely crushed and mixed with adjacent strata, a clear sign of involvement in the mega-slide. Tibadore rocks are off to the laboratory and we do not yet have a result (the math may be easy but the techniques involved are laborious and typically take a year or more), but we suspect that they are slightly older than 25.1 Ma and younger than about 25.5 Ma. The Tibadore and Antimony ash-flow tuffs may have profound implications for triggering failure of the Sevier slide as described later.

Another way to constrain the age of this and other mega-slides is to date a mineral known as zircon found in the basal layer of the slides. Zircon crystals are typically abundant in these layers of ground-up rock and sediment that the slide overrode as it moved over the former land surface, and they are a geochronologist's dream. They form in certain types of hot magma deep in the earth and were derived from erosion of older volcanic rocks, and, importantly, from volcanic eruptions that once blanketed the former land surface with ash. It is those youngest pre-slide eruptions that we hope to capture when analyzing zircons, for they will give us a maximum depositional age for slide emplacement (the slide cannot be older than the youngest rocks or sediments it overlies). Zircon is a hard, physically tough mineral that contains trace amounts of uranium in its crystal structure, making it amenable to radiometric dating (uranium [parent] decays to lead [daughter] which accumulates over time but which is not present when zircon forms). It also has a very high melting temperature, meaning that it can be recycled many times through mountain-building events and metamorphism and still retain a vivid history of those journeys.

Zircon is common in many volcanic rocks, including those of the Marysvale field, and in sediments derived from erosion of those rocks. In one of the greatest advances in geochronological techniques of the past few decades, geologists have figured out how to extract the history of ancient environments and volcanic eruptions from these zircons.

By analyzing the detrital zircon signature of basal layers, geologists can determine the age of the youngest group of zircon crystals. Two such samples from the Sevier mega-landslide, analyzed by a team from Kent State University and Southern Illinois State University, show that the Sevier basal layer can be no older than about 25.5 Ma, the age of the youngest group of zircons. Zircon ages derived from basal layers provide a wholly independent way to constrain the age of slide emplacement, and their results mesh well with constraints imposed by the ages of over- and underlying volcanic rocks.

Markagunt Mega-landslide

The oldest rocks known to postdate emplacement of the Markagunt mega-slide belong to the Haycock Mountain Tuff, which lies undisturbed on top of the slide northeast of Panguitch Lake. By analyzing its paleomagnetic properties, researchers at Kent State University determined that the tuff erupted from a now-buried caldera in the northwest part of the Marysvale volcanic field. Several high-precision radiometric ages show that the tuff is about 22.75 Ma. The tuff partly fills stream channels eroded into the gravity slide and clearly postdates slide emplacement (figure 18). The Markagunt mega-slide thus must be no younger than 22.75 Ma.

The youngest rocks known to be deformed as part of the Markagunt mega-slide belong to the Osiris Tuff, which erupted 23.1 million years ago from the Monroe Peak caldera. This ash-flow tuff is one of the most widespread and distinctive in the Marysvale volcanic field and has an estimated volume of 60 cubic miles (250 km^3). Interestingly, the Osiris Tuff is not deformed as part of the Sevier mega-slide—it did not yet exist at the time that slide event happened. Thus, our best estimate is that the Markagunt mega-slide was emplaced between about 23.1 and 22.75 Ma. Analysis of basal layer zircons of the Markagunt mega-slide by researchers at Southern Illinois State University confirms that the slide can be no older than about 23.02 Ma.

Researchers are also working to date pseudotachylyte, that rare, friction-generated melt rock locally present near the base of the slide. In theory, this will allow us to directly date the slide event. Unfortunately, accurate dating of glass is notoriously difficult for a host of reasons, including that the Markagunt glass is low in potassium and thus has a low radiogenic yield (a low daughter/parent ratio that leads to imprecise measurements). Still, using the latest high-precision argon isotope geochronology, researchers at Westminster College in Salt Lake City and at the University of Wisconsin-Madison determined an age of about 21.5 Ma but with a large error of plus or minus nearly 900,000 years; the age appears too young given the constraints of cross-cutting relationships described above, possibly due to loss of radiogenic daughter products. A different sample, collected by geologist Harry Filkorn at Pierce College and analyzed at the University of New Mexico Geochronology Research Lab, yielded an age of 22.6 Ma with a smaller error of plus or minus 180,000 years, which better

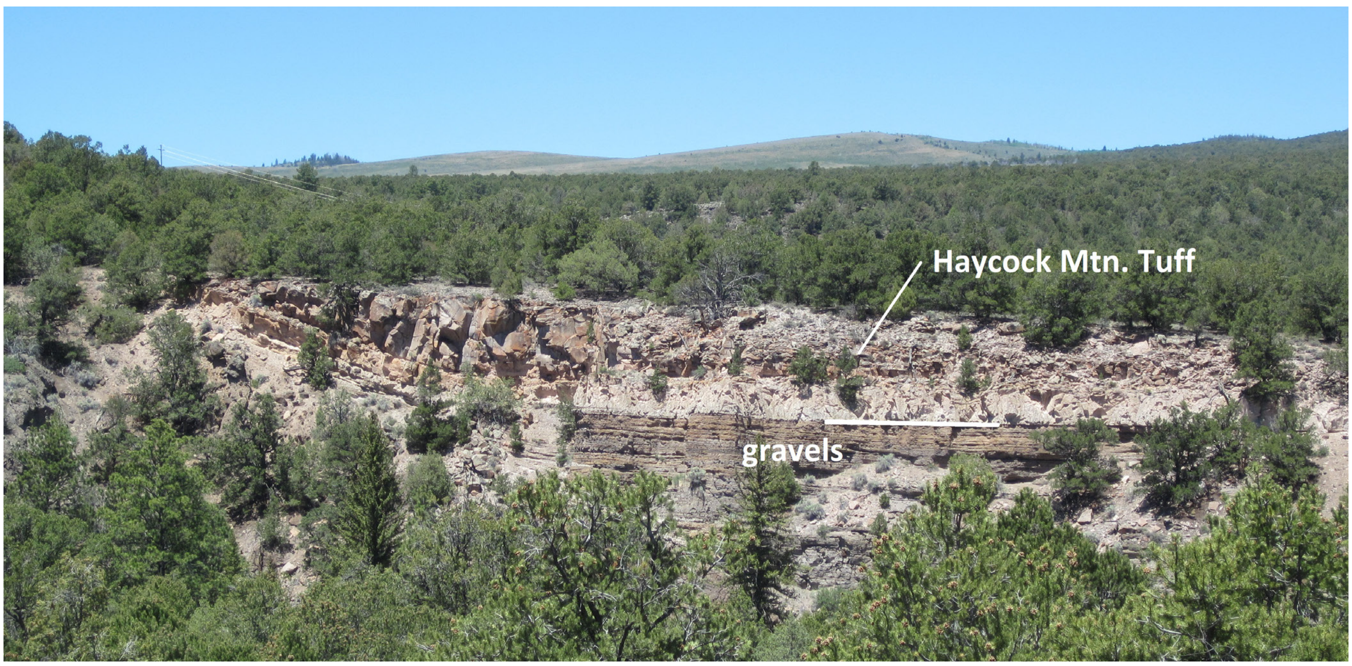


Figure 18. *Haycock Mountain Tuff exposed along the north side of Panguitch Creek. Here, the 22.75 Ma ash-flow tuff lies above gravels of a stream channel eroded into the top of the Markagunt mega-slide (hidden in the trees below), showing that it must postdate slide emplacement.*

agrees with our preferred age of slightly less than 23 Ma. Ultimately, we hope that future research on pseudotachylyte will provide yet another independent way to constrain slide emplacement ages.

Black Mountains Mega-landslide

Geologists are still trying to understand which are the oldest rocks that postdate emplacement of the Black Mountains mega-landslide. Most of the Black Mountains are eroded from similar-looking volcanic mudflow deposits and lava flows of the Mount Dutton and Horse Valley Formations. Given that both groups of rocks were derived from multiple volcanoes over a span of several million years, they are of little use for helping to constrain emplacement ages, or even, because they are non-descript, for being able to clearly distinguish what rocks are deformed and what rocks may postdate slide emplacement. All that we truly understand at this point is that rocks of the Horse Valley Formation are at least as young as about 19.5 Ma and appear to be involved in the Black Mountains mega-slide. Furthermore, this slide lies immediately south of Utah's largest exposed granitic intrusion. That intrusion is about 18 to 17 Ma, unusually young for such a huge body in this region (most intrusions of the nearby Iron Axis west and north of Cedar City are about 21 to 26 Ma); it forms the bulk of the Mineral Mountains. The magma chamber that included the granite is particularly long lived because it produced rhyolite domes, tuffs, and lava flows of only about 0.5 Ma that sit on top of the granite—in effect, it is still active today. Even though the granite was emplaced deep in the earth's crust, a magma mass this large must have intruded upwards and may have inflated the upper crust, resulting in oversteepened slopes that would have facilitated sliding. The granite is also cut by younger dikes of about 11 Ma that may have fed an upper crustal intrusion or volcano now since eroded. We also know that the crustal block that includes the granite rose rapidly to the surface during early basin-range extension between about 11 and 8 Ma. Conceivably, the Black Mountains slide is unrelated to granite emplacement and may be related to the dikes and inferred younger volcanic system and so may be as young as about 10 Ma.

The youngest rocks so far discovered underlying the Black Mountains mega-landslide belong to the 22.0 Ma Harmony Hills Tuff, a distinctive, crystal-rich ash-flow tuff that erupted from the Bull Valley Mountains, about 40 miles (65 km) west-southwest of Cedar City. This tuff is wonderfully exposed in Parowan Canyon at the west edge of the Markagunt Plateau where an east-tilted block of highly fractured 27 to 26 Ma Isom Formation lies on top of the 22.0 Ma Harmony Hills Tuff, separated by a thin layer of slippery, clay-rich strata of the 37 to 33 Ma Brian Head Formation. This same older-on-younger relationship is also present a few miles to the west in Summit Canyon. Therefore, the Black Mountains slide must be younger than about 22.0 Ma, which we already knew given the 19.5 Ma age of deformed Horse Valley strata. There is much yet to learn about the Black Mountains mega-slide.

HOW AND WHY DID THE MARYSVALE GRAVITY SLIDE COMPLEX FORM?

Ongoing research will more fully answer when each mega-landslide occurred, what event may have precipitated each catastrophic failure, and how such huge volumes of rock moved possibly faster than freeway speeds more than 20 miles (32 km) across the landscape. That landscape, remember, was vastly different than the fault-bounded plateaus and valleys we see today. It was a high-elevation region studded with overlapping volcanoes sloping gently away in all directions from high areas at the heart of the field. But for now, we suspect several events came together to set the stage for catastrophic failure of the south flank of the Marysvale volcanic field. Here's where we let our imaginations loose, constrained of course by our interpretations of available data.

The first event that preceded catastrophic failure was slow, radial (outward) spreading of the volcanic field, forming low-angle faults of the unusual Paunsaugunt thrust fault zone south of the field. The thrust faults formed because Earth's crust simply is not rigid enough to support massive volcanoes—slowly, over thousands to several million years, the volcanic field spread to a larger footprint and thus to a more stable profile. Even without Middle Jurassic-age evaporites that served to localize this thrust faulting—salt and anhydrite (common table salt and anhydrous calcium sulfate, respectively) are among the tectonically weakest rocks and minerals—Earth's crust would have slowly deformed under the mass of volcanic rocks as it does due to glacial ice sheets or large water supply reservoirs. This Paunsaugunt compressional deformation was directed southward and involved strata younger than rocks involved in the east-directed compressional deformation of the older Sevier orogeny as we illustrate in the next chapter.

Second, catastrophic failure was near the end of peak local volcanism. Stratovolcanoes are inherently unstable features—large, steep piles of hydrothermally altered and thus weakened volcanic rock—perched above actively inflating and deflating magma chambers, so it is no wonder that growth and subsequent collapse are typical features of so many stratovolcanoes worldwide. The USGS publication, *When Volcanoes Fall Down* (http://doi.org/10.3133/fs20193023), provides a richly illustrated summary of this process. Only since the 1980 landslide and eruption of Mount St. Helens did geologists fully realize that partial collapse of stratovolcanoes is a normal part of their evolution. Today, over 400 collapse features are known at modern volcanoes worldwide, consisting of arcuate scars that result from partial collapse of their summit cones and the telltale hummocky terrain downslope of the landslide deposit itself, all readily visible in aerial imagery or when flying overhead. Here, however, we envision not just a single volcano that collapsed, but volcanic highlands made up of multiple volcanoes and including the foundation upon which they were built.

Third, the volcanic field was built on a "greasy" foundation of ash-rich sedimentary strata. We surmise that inflation of the volcanic field by intrusion of partially molten rock into its center may have tilted these strata on the south flank gently southward, providing gently dipping planes in underlying weak strata that would be ideal for sliding. Ancient Sevier-age thrust faults doubtless provided conduits for the magma through the uppermost crust, as we know they did for the many intrusions of the Iron Axis west and south of Cedar City, each of which shed smaller gravity slides during their rapid emplacement as laccoliths in the earth's uppermost crust (figure 19).

Thus we envision that rocks in the breakaway area slipped southward just far enough to give a push to strata lower on the flanks of the volcanic field, primed to slip on their weak foundation. Once south of the ramp, gravitational potential energy and momentum, aided by overpressured fluids at the slide's base, enabled each slide to race across the countryside, spreading out and burying everything in its path. The slides did not move as a jumbled chaotic mass, rather as great sheets of rock the size of mountains bounded below by a subhorizontal slip surface. Only as the slides came to a rest did blocks pile up on one another near the slide's south margin and ultimately break apart into a chaotic mess. The rumbling and shaking would have lasted a few tens of minutes at most, but still an eternity compared to the four minutes or so of shaking generated by today's largest earthquakes. Dust may have blotted out the sun for the rest of the day and drifted east towards Kansas.

Interestingly, the volcanic field failed catastrophically three separate times when its weak foundation could no longer support the growing volcanic mass. The three mega-slides mimic the westward progression of volcanism in the Marysvale field over the span of about 12 million years from about 30 to 18 Ma. Volcanoes grew. The foundation failed. Repeat, again and again.

We don't know the original slope of this region so many millions of years ago, but it is reasonable to assume that the volcanoes may have reached 15,000 feet (4570 m) or more in

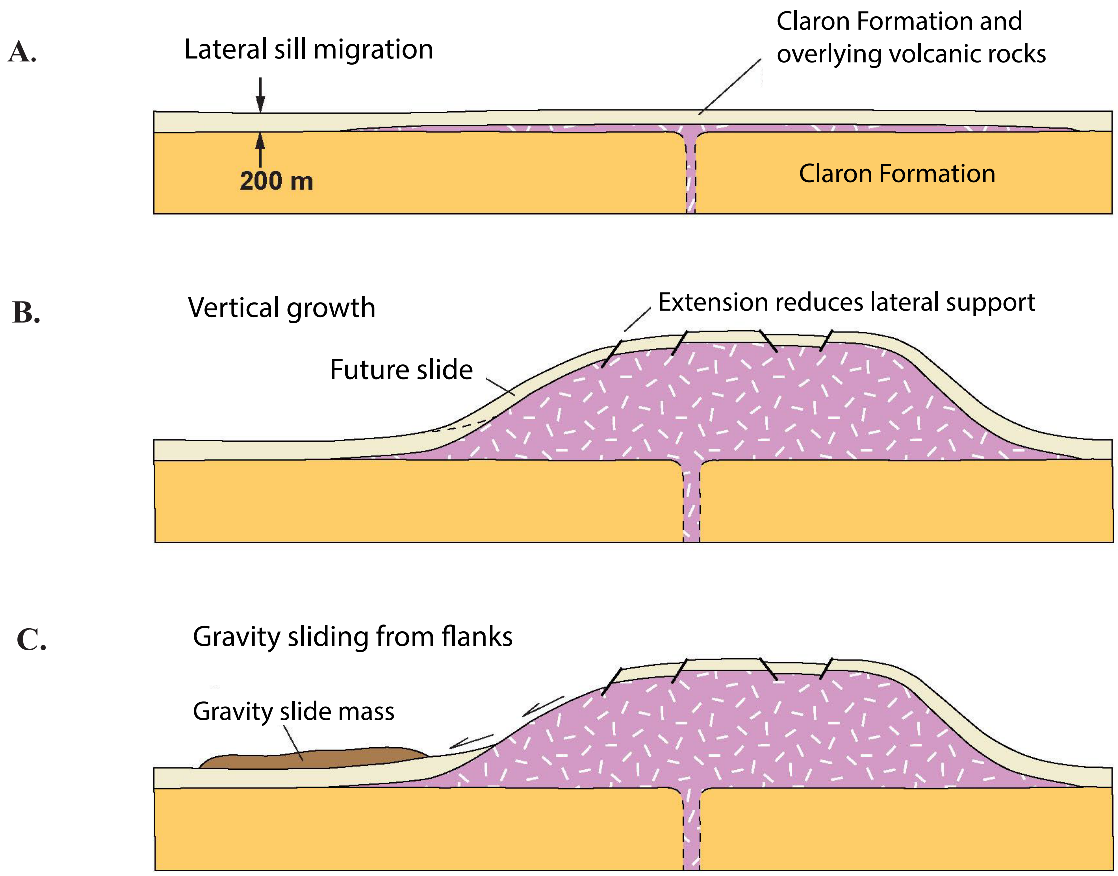


__Figure 19.__ Schematic diagram illustrating growth of a shallow igneous intrusion known as a laccolith. __(A)__ Initial lateral migration of a sill within the Claron Formation to its fullest extent at a relatively shallow depth, __(B)__ vertical growth of the laccolith by continued injection of magma, and __(C)__ gravity sliding of oversteepened flanks. Slope failure commonly triggers eruption of lava flows and ash-flow tuff that bury the slide mass. Modified from Willis (2002) and Hacker and others (2002).

elevation, perhaps 5000 feet (1525 m) above the surrounding plateau. Simple math shows that an elevation difference of 5000 feet from the heart of the field to the southern toe of the slides nearly 60 miles (100 km) away yields an overall slope of less than 2 degrees. Envisioning even taller mountains that would match today's largest active volcanoes barely gets us a 3 degree slope.

One of the most common questions we hear is how can gigantic slides move so far, apparently so fast, across such low-angle slopes? We suspect that overpressured fluids at the base of the slides acted to reduce friction, perhaps in concert with thermal pressurization, which would expand the fluids and gases and decrease the resistance to sliding. The mechanics of rapid movement and long runout of gigantic slides has bedeviled generations of geologists and physicists. Modelling of Utah's mega-slides, now in its early stages, may shed light on this most puzzling problem.

As to a trigger for each of the mega-slides, honestly, we do not know. We do know that the breakaway area of each mega-slide is overprinted by one of the largest volcanic features in the region, namely two calderas and Utah's largest exposed batholith. Those of us beholden to Occam's Razor, the principle that favors simple, elegant explanations over convoluted ones, would like to believe there is a causal relationship here yet to be proven. We need more and better constrained geochronology to tease out relationships, but it is possible the Sevier mega-slide is related to eruptions that produced the family of Tibadore and Antimony ash-flow tuffs. Inflation (uplift) of the region may have accompanied eruption of the smaller Tibadore tuffs, which then triggered landsliding (deforming the Tibadore tuffs), which then led to a larger explosive eruption of the Antimony Tuff that rests undeformed on the landslide mass. A causal relationship between these two ash-flow tuffs is intriguing but not yet proven. One problem is we do not know the location of the vent or caldera of these ash-flow tuffs. Possibly it was destroyed by the later Monroe Peak caldera, which now occupies the breakaway area of the Sevier mega-slide. As far as the Markagunt mega-slide goes, the breakaway area is well mapped to show that it was partly destroyed by the younger (about 19 Ma) Mount Belknap caldera, which now occupies the crest of the Tushar Mountains. The Black Mountains mega-slide has no breakaway slip surfaces exposed, having been eroded away as the Mineral Mountains were uplifted rapidly along younger basin-range faults to expose its once-deeply buried granitic rocks. The Mineral Mountains granite occupies a huge area north of all known Black Mountains slide rocks, so the likely cause of sliding stares one in the face even though proof is unavailable in the field evidence. For all three slides, all we can do at this early stage in our understanding is say that, after growth and inflation made them unstable, an earthquake or eruption likely triggered each of the slides. Or, perhaps, it was the proverbial butterfly landing on a volcanic peak that was already primed and ready to fail at the slightest provocation.

HISTORY OF DISCOVERY

Like any scientific endeavor, geologic mapping builds on the work of others by extending mapping into little studied areas, or remapping in more detail using new technology and new insight, or simply having the gift of more time and funding. In either case, multiple studies allow geologists to learn more about the deep history of the earth and its geologic resources and geologic hazards. But to make a geologic map one must first learn the local language—the normal order of layered sedimentary rocks, the age and relationships among volcanic rocks, the expected style and amounts of deformation given consideration of regional tectonics, and many other facets of this science of the earth. In the same way that cultural insight, appreciation, and understanding are proportional to one's vocabulary and knowledge of the rules of grammar, deeper understanding of geology enables one to more fully appreciate what the rocks tell us and, importantly, what questions to ask to further our understanding.

In trying to explain the process of geologic mapping, one of our favorite analogies is to compare it to putting together a puzzle. To stretch the analogy even further, consider it a three-dimensional puzzle of many thousands of pieces, many of which are missing, and that is already out of its box (which has, much to your dismay, been thrown away!). You have no picture to refer to, so you start to scan the pieces, becoming familiar with their colors and patterns and perhaps developing an idea of what the picture may be. The rest is hard work, fitting the pieces together into a coherent whole—walking the mountains and valleys observing sediments, rocks and structures and piecing them together into a coherent map. Each outcrop you visit is another piece of the puzzle.

That hard work began in earnest in southwest Utah with the first detailed geologic mapping of the Marysvale volcanic field and adjacent areas from the 1950s to mid-1990s. Initial work began as dissertations supervised by J. Hoover Mackin of the University of Washington, then University of Texas. These were in the Red Hills by Richard Threet in 1952, northern Markagunt Plateau by John Anderson in 1965, and southern Sevier Plateau by Pete Rowley in 1968. These studies were part of a broad investigation by Mackin and his students of the structural geology and volcanic stratigraphy in southwest Utah and adjacent Nevada, centered on the Iron Springs mining district. This district was the largest iron-producing district in the West, which Mackin mapped during World War II as part of the war-effort when he was on loan to the USGS, and continuing after the war, when the iron mines remained one of the largest employers in the area. After 1965, geologic mapping began again by John Anderson (by then a professor at Kent State University) and his students in the Markagunt Plateau and southern Tushar Mountains; and by Pete Rowley, first at Kent State University and then the USGS, in the Black Mountains and areas to the south to publish the 7.5-minute quadrangles that Mackin had started in the Iron Springs district.

More recent geologic mapping of most of the northern and central Marysvale field, which includes the northern part of Utah's mega-slides, was part of a long-term analysis of mineral potential of the Marysvale field by the USGS beginning in the mid-1970s. This USGS work resulted in well over 200 publications that outlined the volcanic stratigraphy and structure of the Marysvale volcanic field, including the first inklings that something unusual beset the south margin of the field.

What was unusual of course was the Markagunt Megabreccia, the deposit of what we now call the Markagunt mega-slide, which Anderson described in 1993, nearly two decades after he and his students first realized that the gently east-tilted, high-elevation northern Markagunt Plateau was capped by something other than the normal sequence of volcanic rock commonly found in southwestern Utah. The Megabreccia was originally thought to cover more than 200 square miles (500 km^2; only a fraction of its current 3000 square miles [8000 km^2]). It was interpreted as being derived from multiple sources about 23 to 22 Ma—some very good deductions in 1993, considering that much of the Markagunt Plateau was mapped at only a reconnaissance scale. Concurrently with Anderson's work, USGS geologist Florian Maldonado discovered and mapped what he called the Red Hills shear zone in the northern Red Hills and western Markagunt Plateau, west of Anderson's field area. We discuss the relationship of the Markagunt Megabreccia and Red Hills shear zone in some detail in the following sections. However, by the mid-1990s, the full extent of the Markagunt Megabreccia and many of its critically instructive exposures had yet to be discovered.

Publication of the regional-scale geologic maps of the Panguitch and Loa 30′ x 60′ quadrangles opened the door to our current understanding. In 2014 in a leading international geology journal, we formally defined the Markagunt gravity slide, integrating once disparate observations of the Markagunt Megabreccia and Red Hills shear zone into a coherent whole. In 2016, we discovered that the adjacent Sevier Plateau preserved the remains of a second enormous, slightly older gravity slide we now call the Sevier mega-slide (and which we unfortunately missed during the rush to publish our Panguitch map!). The adjacent Beaver 30′ x 60′ quadrangle, previously mapped and compiled in preliminary form without recognizing either slide, was next recognized to contain their breakaway or source areas; that geologic map is now being revised.

Finally, in the late winter of 2019, working with colleagues at Westminster College in Salt Lake City and at the University of Wisconsin-Madison, we realized that what we initially thought was the western half of the Markagunt slide is in fact a younger slide we now call the Black Mountains mega-slide. This is science in action, an exciting but messy process of discovery, and we are deep in the thick of it as outlined below.

Markagunt Megabreccia

The discovery and our still-unfolding understanding of the Markagunt Megabreccia began in the early to mid-1970s when James Judy, during thesis mapping supervised by John Anderson of Kent State University, identified older-on-younger rock relationships (29.5 Ma Wah Wah Springs Formation and 27 to 26 Ma Isom Formation resting on 23.8 Ma Leach Canyon Formation) at Sidney Peaks on the high west rim of the Markagunt Plateau. Here was a student charged with starting to map a small part of the plateau in detail and finding not the normal sequence of volcanic rocks promised by earlier reconnaissance-level maps, but something else entirely. It is as if his jigsaw puzzle (of course lacking a picture on the cover) contained pieces from multiple boxes—imagine the confusion! He and his advisor speculated this to be the result of landsliding off an inferred high area (no longer present) west of the plateau or possibly from intrusion of the then-undated Iron Peak laccolith. Older rocks sitting on top of younger rocks at the highest elevations of the plateau—where could they have come from?

At the end of that decade, another of Anderson's students, Thomas Iivari, continued mapping to the northeast where he discovered several smaller landslide blocks resting on Bear Valley strata northwest of Panguitch. He too was uncertain of their origin, but we can now show that these smaller blocks are contemporaneous with Bear Valley deposition, part of an older, smaller landslide possibly shed off the 26 Ma Spry, Showalter, or other intrusions and later incorporated as part of the much larger Markagunt mega-slide. It wasn't until the late 1980s to early 1990s, when Anderson and several of his USGS-supported master's students, in addition to a crew of USGS geologists, continued stratigraphic and geologic mapping studies in this area, that they finally had enough information to begin to understand what they were dealing with. Unfortunately, their effort, part of the USGS BARCO project (a multidisciplinary federal effort to better understand the geology of the Basin and Range–Colorado Plateau transition in southwestern Utah and adjacent Nevada and Arizona), was disbanded following reorganization (a reduction in force of about 600 geologists) of the USGS in the mid-1990s; Anderson, too, was unable to continue mapping on the Markagunt Plateau. Nevertheless, their combined work laid a solid foundation for Utah Geological Survey-led geologic mapping, described at the end of this section, in the region that began some dozen years later.

Apart from unpublished thesis work under Anderson's direction, the early history of what would come to be known as the Markagunt Megabreccia began with a flurry of abstracts presented at professional meetings from 1982 to 1993. In one of these first abstracts, USGS mapping geologist Ed Sable described the older-on-younger rocks at Sidney Peaks (the same rocks described by Judy) that rest atop a striated surface of the Leach Canyon Formation, suggesting to him northeast-directed movement. Sable was uncertain if the striations were of glacial or landslide origin (we now know that they demonstrate Markagunt mega-slide emplacement from the north; see Sidney Peaks locality description in field guide). Three years later, in 1985, Sable and Anderson reported on widespread gravity-slide blocks on the northern Markagunt Plateau, some of which had previously been mapped by Anderson's student, Iivari.

In 1989 and 1990, USGS geologist Florian Maldonado and his colleagues introduced the term "Red Hills detachment zone," which they interpreted as everywhere separating volcanic strata from the underlying non-volcanic Claron Formation in the Red Hills and western Markagunt Plateau. For mapping purposes, they placed the detachment at the top of the Brian Head Formation, the weak sedimentary strata at the base of the volcanic rocks. Two years later David Moore, also with the USGS, first briefly described an unusual collection of huge boulders derived from the Isom Formation that litter the ground in and around Cedar Breaks National Monument. In 1993, Maldonado and Sable reported on continued work on the Red Hills shear zone and suggested that it resulted from gravity slides of multiple ages and causes between 22.5 and 20 Ma. Later that same year, University of Arizona structural geologist George Davis and Rowley (then with the USGS) noted recognition elsewhere of gravitational spreading of large volcanoes, then linked the rediscovered Paunsaugunt thrust fault system with the Markagunt Megabreccia in a "two-tiered" structural system, with gravity sliding taking place on the "backs" of active "thin-skinned" thrust faults.

The Markagunt Megabreccia was formally defined by Anderson in 1993 at a time when our understanding of it was incomplete and still controversial. He designated a reference locality for the Markagunt Megabreccia along Utah Highway 143 about 2 to 4 miles (3–6 km) east of Panguitch Lake (see Highway 143 locality description in field guide). He also recognized that the Markagunt Megabreccia, as then defined, differed widely in appearance across its then-known extent, and so identified and described seven general areas on the Markagunt Plateau that illustrate this variation (figure 20). Further study by Sable and Maldonado, published in 1997, correctly restricted the definition of the Markagunt Megabreccia and showed that it was emplaced from north to south, but they were uncertain whether emplacement was catastrophic, possibly due to failure on the flank of the Iron Peak laccolith, or slow, due to shallow, south-vergent thrust faulting associated with slow gravitational collapse of the volcanic field. In 2001 in his last report on the megabreccia, Anderson suggested instead that failure was along large, late Oligocene- to early Miocene-age scarps from west-northwest-striking faults.

One needs only to read these reports to gain an appreciation of how much was still unknown at the time—they offer a beautiful and classic example of the use of multiple working hypotheses, continually refined after each season's field studies, employed by true, boots-on-the-ground field geologists working to understand one of Utah's most enigmatic and complex terranes.

Red Hills Shear Zone

USGS geologist Florian Maldonado spent much of the late 1980s and early 1990s mapping and working to understand his discovery of what he called the Red Hills shear zone, culminating in a 1997 USGS Bulletin that described these unusual structures at the west margin of the Markagunt Plateau and nearby areas. He described a section of volcanic rocks 2000 feet (600 m) thick in the northern Red Hills and western Markagunt Plateau that he interpreted was tectonically detached from a lower plate sedimentary section along this shear zone. He astutely recognized this detached plate based on (1) a low-angle pulverized zone, variously present within or at the top of the Brian Head Formation, (2) upper plate strata that dip more steeply than lower plate strata, (3) intense faulting and fragmentation of upper plate rocks, (4) faults that appear to be restricted to the upper plate, and (5) omission of strata along the shear zone. Based on the age of the youngest rocks in the upper plate and of dikes that apparently cut the shear zone, he suggested that the shear zone was active between 22.5 and 20 Ma. He interpreted the Red Hills shear zone as a shallow structure that formed at a depth of less than about 1.3 miles (2 km) because of the absence of structures associated with detachments that form at mid-crustal depth. Further, he mapped numerous blocks of megabreccia derived from upper plate rocks, noted similar blocks on the Markagunt Plateau, and speculated on emplacement directions and mechanisms.

The Red Hills shear zone is indeed the same slip surface that separates the Markagunt Megabreccia from undisturbed lower plate strata. Importantly, however, this statement holds true only north of what we now recognize as the ramp of the Markagunt mega-slide. Following additional field mapping, we can now show that the main part of the Red Hills and the Markagunt Plateau south of the ramp (including the prominent Isom cliff that forms the Black Ledge escarpment, which leads northward 12 miles [19 km] from Brian Head as an unbroken ledge at the west rim of the plateau) are undisturbed lower plate strata, not part of the upper plate of the Red Hills shear zone as Maldonado originally envisioned. We interpret the Red Hills shear zone north of the ramp to be the basal slip surface of the mega-slide.

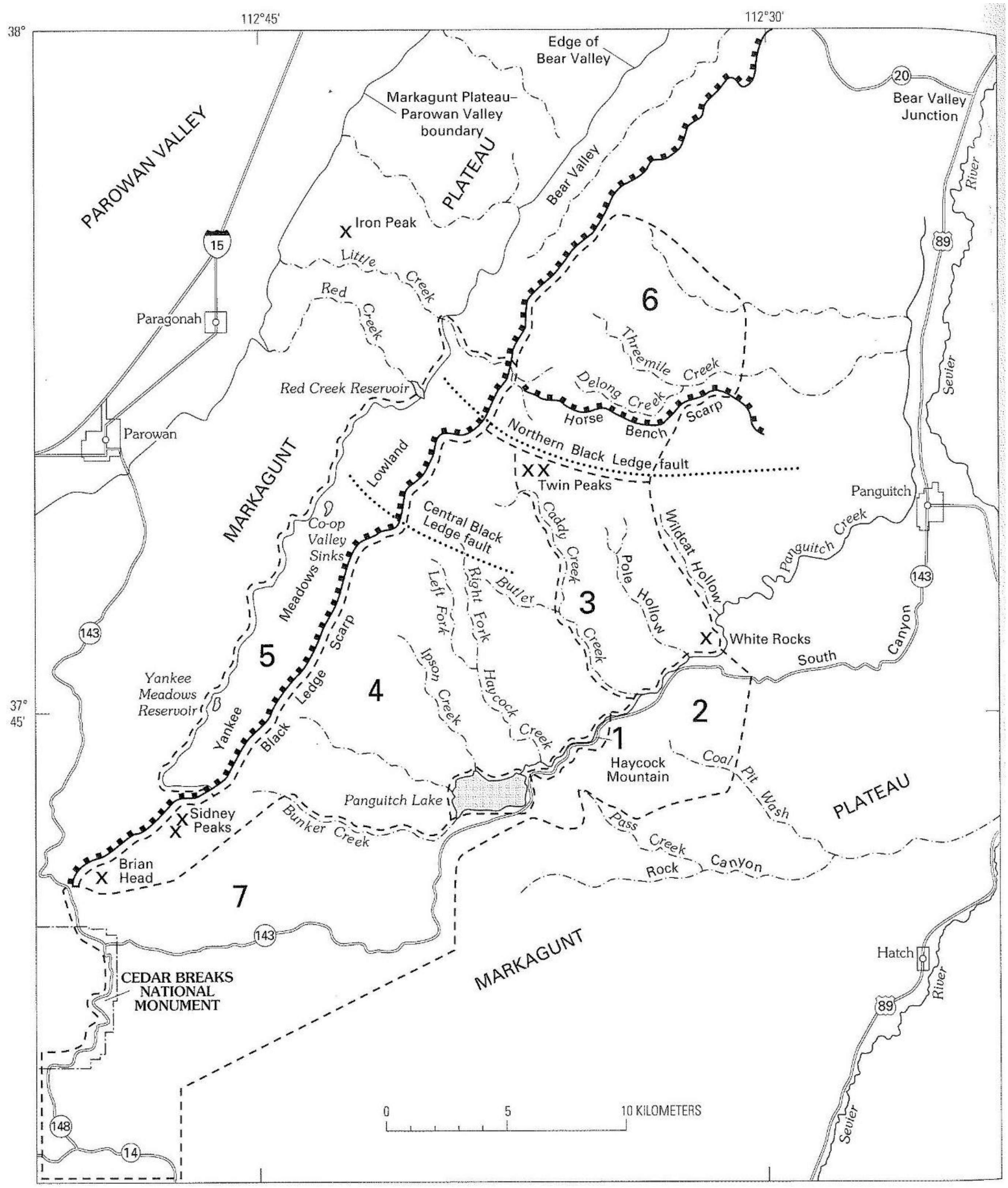


Figure 20. Extent of Markagunt Megabreccia as originally defined by John Anderson in 1993. Dashed lines surround numbered areas that illustrate variations in the Megabreccia. Line with black squares denotes Black Ledge escarpment. From Sable and Maldonado (1997a).

Paunsaugunt Thrust Faults

Bryce Canyon National Park is famous for its fantastic hoodoos eroded from brightly colored rock layers at the east escarpment of the Paunsaugunt Plateau. Yet the park and surrounding area is also famous, at least among geologists, for an unusual series of faults known as the Paunsaugunt or Rubys Inn thrust faults that form an arcuate belt around the southeast margin of the Marysvale volcanic field (figure 21). These south-vergent thrust faults—meaning strata in their upper plate moved incrementally southward over time, earthquake by earthquake—involve strata that postdate the Sevier orogeny (whose eastward-directed compression created thrust sheets that moved eastward through time). Rock layers that did not exist at the time of that mountain-building episode are deformed by thrust faults of an odd orientation. How could this be? No other such structures exist in all of Utah.

Another odd thing about this once-enigmatic fault zone is that Chevron geologists had seismically imaged, drilled, and correctly understood the faults in the mid-1950s, but, given proprietary interests, did not publish their findings. The faults were rediscovered in the mid-1980s, when University of Arizona geologists George Davis and Robert Krantz noticed small-displacement thrust faults at Bryce Canyon National Park; their "discovery" fault is none other than the small south-dipping back thrust at Bryce Point (figure 22). Though small, this fault is so prominent that it is hard to believe it could go undetected for so long, especially considering the scores of geologists who have cast their eyes over that landscape. That tiny fault has outsize implications for understanding the geology of this corner of the state.

We now know that the Paunsaugunt thrust fault zone consists of several thrust faults of which the frontal Rubys Inn thrust fault

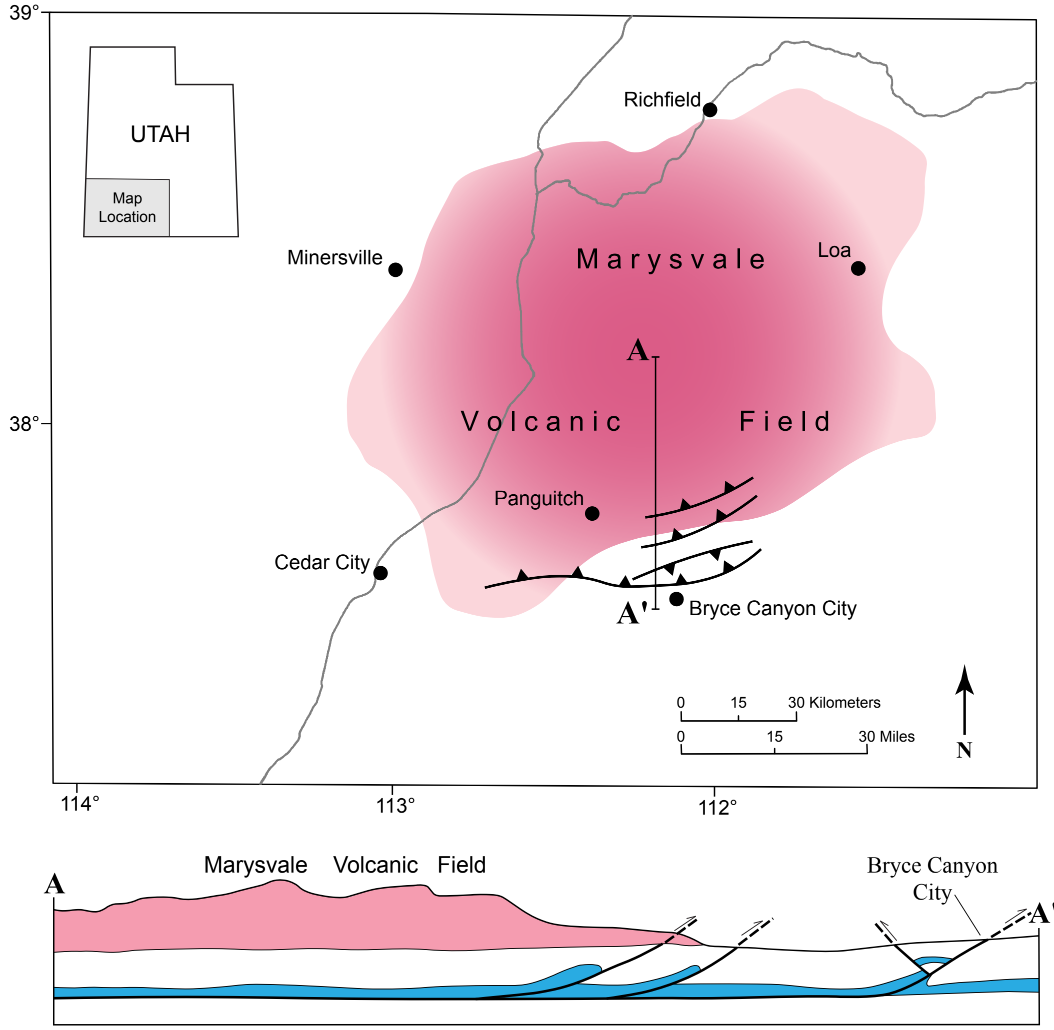


Figure 21. *Location of Paunsaugunt thrust faults (heavy lines with black triangles on upthrown side) in relation to the Marysvale volcanic field (pink). Cross section A-A' shows thrust faults originate in Middle Jurassic-age evaporite-bearing strata of the Carmel and Arapien Formations (blue) at a depth of about 1.2 miles (2 km). The main thrust faults, from south to north, are the Rubys Inn thrust, Pine Hills backthrust, Johns Valley thrust, and Hunt Creek thrust.*

and the Pine Hills back thrust fault are the best known. On the northern Paunsaugunt Plateau, these faults place Upper Cretaceous strata on top of the younger, Eocene-age pink member of the Claron Formation with a southward sense of displacement. To a geologist well versed in the geologic history of this part of Utah, that should elicit a response not unlike someone saying to a farmer that Utah's Fruit Way, home to cherry, apple, and other hardy fruit orchards, produces wonderful oranges and grapefruit. It is impossible.

Citrus groves in northern Utah may be impossible, but the Paunsaugunt faults do exist and were first understood by the wider geologic community in 1993 when Davis and his colleagues suggested that this unusual thrust deformation formed between 30 and 20 million years ago in response to gravitational collapse of the Marysvale volcanic field. Davis's student Eric Lundin first mapped the fault zone in detail, outlining many of its salient features in the late 1980s. As noted previously, the earth's crust simply is not rigid enough to support massive volcanoes—slowly, over thousands to several million years, the volcanic field spread outward to a larger footprint and thus to a more stable profile. Davis's "two-tiered" model envisions an upper, catastrophic part above a deeper series of thrust faults directed outward from the southern Marysvale volcanic field, which spread and collapsed under its own weight, resulting in southward-directed thrust faults rooted in evaporite strata of the Middle Jurassic Carmel and Arapien Formations. Our subsequent work showed that the faults were active prior to emplacement of the Sevier megalandslide about 25 million years ago. Researchers at Ohio State University are now working to better understand gravitational spreading and subsequent catastrophic collapse of the Marysvale volcanic field.

Based on earlier work and our new mapping, the age of thrusting on the Paunsaugunt Plateau can only be definitively constrained as postdating the 37 to 33 Ma Brian Head Formation and predating basin-fill deposits of the 22 to 21 Ma Limerock Canyon Formation. Former University of Nevada student Kevin Rafferty showed that the lack of south-vergent compressional deformation in Limerock Canyon strata constrains movement on the Paunsaugunt thrust faults to no younger than

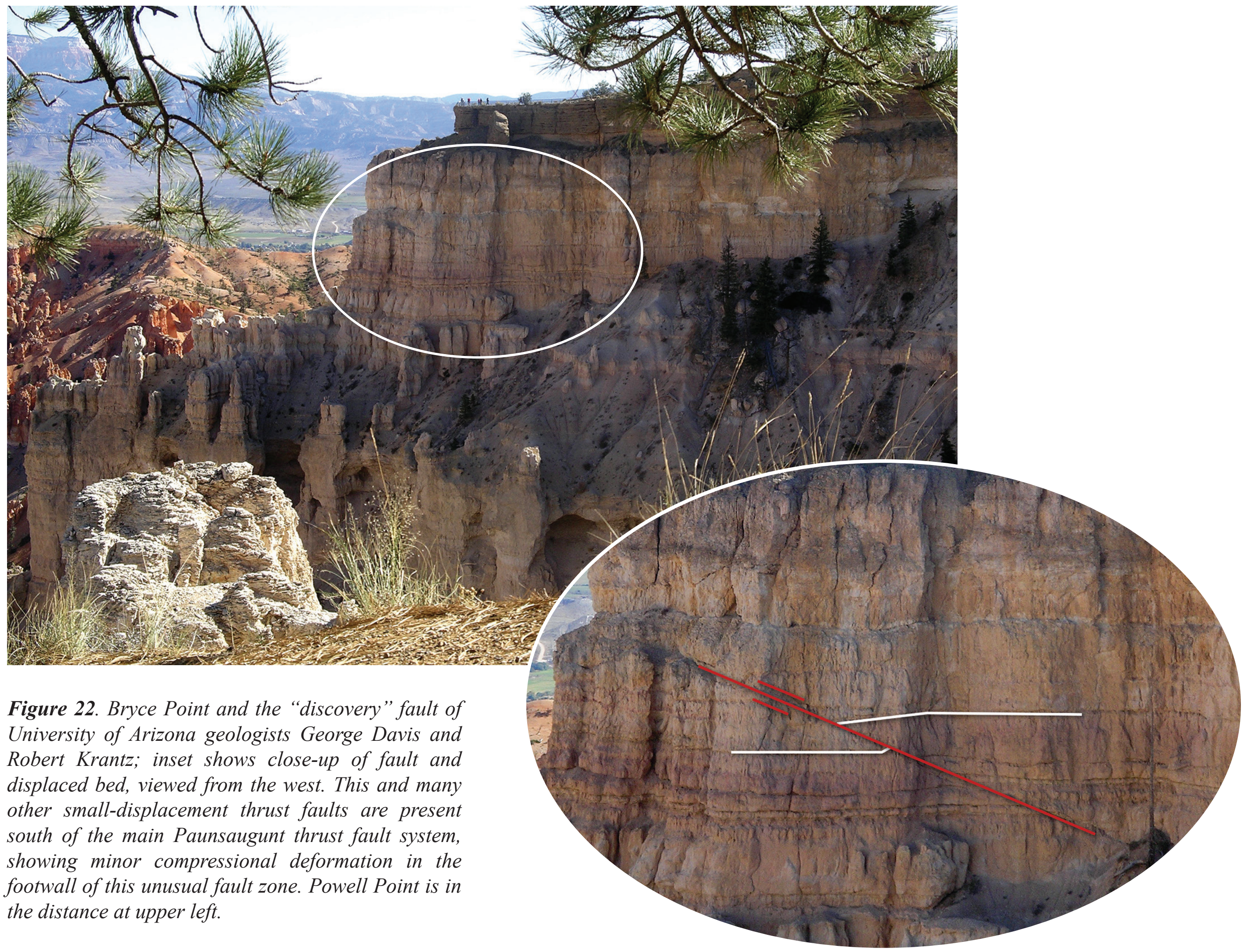


Figure 22. Bryce Point and the "discovery" fault of University of Arizona geologists George Davis and Robert Krantz; inset shows close-up of fault and displaced bed, viewed from the west. This and many other small-displacement thrust faults are present south of the main Paunsaugunt thrust fault system, showing minor compressional deformation in the footwall of this unusual fault zone. Powell Point is in the distance at upper left.

about 21 Ma. Limerock Canyon strata had long perplexed geologists, but Rafferty's work showed that this rock formation records erosion of the Markagunt mega-slide and deposition in a subtle basin at the southern toe of the slide, yet another case of the power of simple cross-cutting relationships to constrain the timing of geologic events.

On the Markagunt Plateau, north-tilted Claron and Brian Head strata near Panguitch Lake and north-tilted Isom Formation at Haycock Mountain suggest that these rocks moved southward above a blind thrust, the displacement of which was large enough to tilt but not cut through and duplicate the section. That inferred fault appears to be the westward expression of the Paunsaugunt thrust fault zone. These thrust faults may be better expressed on the northern Paunsaugunt Plateau because it lies due south of known evaporite-bearing strata of the Arapien Formation (leading to a weaker foundation under the east half of the volcanic field), whereas evaporite strata of the similar Carmel Formation are much less abundant and occur in thinner beds in areas underlying the west part of the field.

Markagunt Mega-landslide

In 2006, a decade after the demise of the USGS BARCO Program, the Utah Geological Survey initiated geologic mapping of the Panguitch 30′ x 60′ quadrangle, funded in part by the USGS. Mapping began in the south-central part of the quadrangle, which, as it turned out, includes the wonderfully instructive south margin of the Markagunt mega-slide. Over the next several years, I (Biek) worked closely with John Anderson (then Kent State University, Emeritus) and many of the original BARCO crew, including Pete Rowley, Florian Maldonado, David Moore, and Ed Sable, to compile their original mapping and reinterpret some of it based on our new discoveries. The Markagunt Megabreccia began to grow in size! Following publication of the preliminary Panguitch geologic map in 2012, we continued to refine our understanding of the Megabreccia, principally through collaboration with our colleague David Hacker, who then had a wealth of experience with smaller, laccolith-generated gravity slides of the nearby Iron axis and Pine Valley Mountains. Ultimately, we published three key 7.5′ quadrangles (Brian Head, Haycock Mountain, and Panguitch Lake) and the "final" Panguitch 30′ x 60′ quadrangle in 2013 through 2015. We are now, however, revising the Panguitch map because we missed finding the Sevier mega-landslide before it was rushed to publication in 2015! We are also revising the adjacent Beaver 30′ x 60′ quadrangle, originally published in 2005 before we realized that much of the Beaver map area is underlain by the northern parts of all three mega-slides! Those readers who are scientists know that publication of new discoveries cannot wait until all loose ends are nicely tied up, for other scientists need to know results soon so that they can apply them to their areas; government geologists particularly need to publish maps quickly so that the taxpayers, land managers, and a multitude of others are alerted to geologic hazards and resources that may exist in the map area.

We formally defined the Markagunt gravity slide in a prestigious international geology journal in 2014 as the gravitationally induced catastrophic collapse, about 22 to 21 Ma, of the southwest sector of the Marysvale volcanic field. The Markagunt Megabreccia is the formal geologic name for the deposit of the mega-slide. In 2014, we understood the slide to be about 1300 square miles (3400 km^2) in size, coincidently about the same size as the Heart Mountain slide in northwestern Wyoming was then widely accepted to be. The Heart Mountain slide, discovered over 100 years earlier, was until then considered to be unique on the land surface as a landslide whose size was far greater than anything else then known. Our 2014 report noted that it was no longer unique, thus opening the door to re-evaluate the potential for other volcanic fields to host other as-yet unrecognized gigantic gravity slides.

Our work pulls together the many disparate parts of a puzzle uncovered by previous widely spaced geologic mapping. Three singular events collectively yielded our "eureka moment" when we finally realized that the size of the Markagunt Megabreccia was far larger than previously thought. The first occurred with Biek's discovery in October 2008 (just after the September 29 market crash leading to the Great Recession, a rather good time to be out in the field away from news and internet access) of exposures on the south side of Haycock Mountain that showed the entire north-tilted, seemingly intact panel of Isom Formation is part of the gravity slide (see Haycock Mountain locality descriptions in field guide). The second occurred with the discovery, by Biek and Hacker in August 2013, of widespread shearing and cataclasis of the basal few feet of upper plate strata in areas north of the ramp, some areas of which were previously recognized as the Red Hills shear zone by Maldonado. The third was the discovery that same month, by Hacker, of pseudotachylyte on low-angle slip surfaces and as thin dikes, to our knowledge the first report of landslide-related pseudotachylyte in North America. These discoveries challenged us to refine our hypotheses and look for a still larger framework to accommodate these and other widely spaced observations that might be part of a unifying whole.

Refining our hypotheses included looking north of the Panguitch 30′ x 60′ map area at the Beaver 30′ x 60′ map area, where the head of the gravity slide, namely the breakaway, had to be present. In fact, it "had to be" present there because Biek's new mapping carried the mega-slide up to the north boundary of the Panguitch map! The Beaver map area had been compiled in preliminary form by Rowley and colleagues in 2005, but the Markagunt mega-slide was missed—understandably so, given the typical subtle deformation characteristic of the breakaway area. One interesting map pattern noted in the south to central Tushar Mountains of the Beaver map area was the so-called Big John caldera, the suggested source of the Delano Peak Tuff Member of the Bullion Canyon Volcanics. Its west- and south-facing "caldera margin" seemed like a good candidate for the high-angle breakaway of the mega-slide, and its north-facing "caldera margin" might be an antithetic, north-dipping, high-angle slip surface that fed into the breakaway. From the spring through fall of 2014, fieldwork largely by Rowley confirmed these ideas, and then extended the breakaway, plus additional related antithetic and synthetic slip surfaces, eastward across the Tushar Mountains into Sevier Valley and westward across the Tushar Mountains into the Beaver basin, then still farther westward across the Mineral Mountains into the Escalante Desert. In subsequent years, the western sidewall breakaway was followed southward, through the Black Mountains, almost to Iron Springs. Then, looking farther eastward to the Sevier Plateau, we discovered the Sevier mega-slide!

Sevier Mega-landslide

When I (Biek) started mapping the west half of the Loa 30′ x 60′ quadrangle in 2014, I was glad to finally be off the Markagunt mega-slide, able to map and appreciate volcanic rocks that had no known complicated history as did those of the Markagunt Plateau. Little did I know that I was getting into—I felt much as Judy must have felt four decades previously on the Markagunt Plateau. In September 2014, in an area east of Otter Creek Reservoir never before mapped in detail, I stumbled across volcanic rocks faulted down against pre-volcanic middle Eocene strata. That volcanic section looked eerily like what I'd seen on the Markagunt Plateau—messed up volcanic rocks above undeformed volcanic rocks separated by a remarkably planar and grooved surface. This was one of those rare moments in the field, mapping alone, when a huge smile comes across your face. You recognize an old friend, although one I confess I really did not want to see.

The Dry Wash megabreccia, as we originally called it, covers a relatively small area of less than one-half of a square mile (1.3 km^2) yet contains stunning exposures of its basal slide plane, with grooves and striations that demonstrate emplacement from the north. Clastic dikes reach up through the entire deposit, sourced from a thin basal layer.

After returning from the field I called Pete Rowley to tell him of this discovery, and he recalled that across the valley to the west, in and near Pole Canyon on the eastern slope of the Sevier Plateau, he had seen and mapped similar deformed rocks during his dissertation work in the mid-1960s. Pete was discovering unusual rocks back when I was hard at work building forts in the woods behind my family's home. Although at the time Pete wasn't certain of the significance of his earlier discovery, by now we knew that we had to reassess the geology of the southern Sevier Plateau lest there lie hidden yet another unknown mega-slide.

In short order, we ended up at the south end of the Sevier Plateau where we initially thought that the Hunt Creek thrust, a splay of the Paunsaugunt thrust fault zone, was responsible for tilted Mount Dutton strata along the plateau's south margin. Closer inspection, however, showed that Mount Dutton strata were underlain by a grooved and striated slip surface and, you guessed it, a basal layer and associated clastic dikes. The basal layer contains unusual ultracataclastically deformed pieces of ash-flow tuff (our "taffy rocks") and is locally exceptionally thick and well exposed. In 2019 as part of his thesis work, David Hacker's student Zach Loffer mapped this basal zone for nearly 20 miles (32 km) along the east flank of the plateau; his detrital zircon work, done in collaboration with Dave Malone at Southern Illinois State University, showed that the basal layer can be no older than about 25.5 Ma.

We now understand that the Dry Wash, Pole Canyon, and southern Sevier Plateau exposures are parts of what we named the Sevier mega-landslide. We continue to evaluate the characteristics and extent of the Sevier slide. Interestingly, in 1993 while measuring a section of the Brian Head Formation at the head of Hancock Canyon on the southwest flank of the Sevier Plateau, biostratigrapher Jeff Eaton, then at Weber State University, noted deformed uppermost Brian Head and basal Mount Dutton strata, but his interest in the paleontology and stratigraphy of Brian Head strata outweighed further investigation of these structural problems! Several million people a year drive through Red Canyon and past the south end of the Sevier Plateau, glance northward at the gray "boring" volcanic rocks, and continue on their way to the admittedly spectacular red rock scenery of Bryce Canyon. In our guide that follows we will show you why these rocks are anything but boring.

The southern Sevier Plateau reveals some of the most remarkable exposures of mega-slide deformation yet found. Led by structural geologist Ashley Griffith at The Ohio State University, his students Mike Braunagel and Danika Maybeck are working to characterize these deformed rocks and build a numerical model to investigate mobility and emplacement of the mega-slide.

Black Mountains Mega-landslide

For years we had a sneaking suspicion that the Markagunt mega-slide was more complicated than we first envisioned. The first clue came with the apparent offset in ramps between the west and east parts of the slide; we attributed that offset to displacement on an inferred strike-slip fault now buried under Parowan Valley, allowing the east part to move independently and farther south than the west part. A second clue came from the fact that, as we defined it in 2014, the Markagunt slide was extraordinarily wide for its length. The thought then as now is that gigantic landslides are significantly longer than wide, given the interpreted mechanisms that caused failure in the breakaway area. Our initial interpretation was not a very satisfactory resolution to these problems, but it was the best we could do given our understanding at the time.

What finally forced us to split off a younger, western portion of the Markagunt mega-slide resulted from new high-precision isotopic ages of two key units—the Haycock Mountain Tuff and the Harmony Hills Tuff—obtained by Tiffany Rivera and her Westminster College student McKenna Holiday and their University of Wisconsin-Madison colleague Brian Jicha. The 22.75 Ma Haycock Mountain Tuff sits undeformed on the Markagunt slide whereas the 22.0 Ma Harmony Hills Tuff underlies slide rocks. Think about it and you'll convince yourself this is impossible—there must be some previously unrecognized structural complication, and that is the presence of the younger Black Mountains gravity slide. Furthermore, old K-Ar ages determined by Bob Fleck of Ohio State University and published in 1975 in collaboration with Anderson and Rowley were 22.5, 21.1, and 19.5 Ma on rocks (Horse Valley Formation) in the Black Mountains that were deformed in what we then called the Markagunt mega-slide. The only solution is that the western part of what we initially called the Markagunt slide is instead a younger, post-22 Ma slide; thankfully, doing so resolves our geometric problems too. We call this new slide the Black Mountains slide and we are only beginning to understand its secrets.

Summary of Discovery

Because they lacked the perspective of an enormous gravity slide (let alone three such slides!), key components of which had yet to be discovered, early workers (including us!) necessarily offered interpretations that turned out to be incomplete or at odds with what we now understand. For example, in speculating about the possible relationship between the Markagunt Megabreccia as he defined it and the Red Hills shear zone of Maldonado, especially given the known existence of many separate smaller gravity slide blocks farther southwest in the Iron Axis, Anderson (1993, p. 34) perceptively wrote:

> It therefore may well be that the megabreccias of the Red Hills and the Markagunt Plateau are unrelated, or that the megabreccia of the western Markagunt Plateau is related to that of the Red Hills whereas the megabreccia of the high Markagunt Plateau had a separate origin. Yet I must admit that I would like to believe that there was a common denominator in the formation of most of the megabreccias of southwestern Utah. Consequently, I find intriguing and not at all implausible the theory suggested to me by [USGS geologist] H.R. Blank, Jr., to which I have referred earlier. This theory is that much of southwestern Utah is underlain at depth by a very large batholith emplaced about 22 m.y., only a few cupolas of which are seen as small deroofed plutons; other, still buried, cupolas formed the structural uplifts down the flanks of which megabreccias such as those of the Markagunt Plateau and Red Hills slid. This may be an outrageous hypothesis, but then so was continental drift until the advent of plate tectonics.

All of this is a rather long-winded way to say that different geologists worked on different parts of what we now call the Marysvale gravity slide complex and thus understandably came to different interpretations depending upon where on this vast feature they were working. There is no modern analog to terrestrial mega-slides of this magnitude, but we suspect that many people will be interested in this story, if only for its ability to stretch one's mind. After all, there are no modern analogs of extinction-causing meteorite impact events nor of truly cataclysmic volcanic eruptions like those of the Yellowstone caldera. Still, Utah's mega-landslides are there for all to see—doubtless, our interpretations are just one more step in the evolving understanding of these extraordinary features.

WHY IS THE MARYSVALE GRAVITY SLIDE COMPLEX IMPORTANT?

The Marysvale gravity slide complex is possibly the largest terrestrial landslide complex on Earth and exhibits exceptional evidence of catastrophic emplacement. Only the Heart Mountain mega-landslide in Wyoming is a terrestrial slide of comparable size and it was considered unique until discovery of Utah's mega-landslides. Like the Heart Mountain slide that resulted from the collapse of the Absaroka volcanic field 49 million years ago, the collapse of the Marysvale volcanic field produced mega-landslide structures so large that parts were originally and understandably mistaken as having formed by faults deeply rooted in the earth's crust and whose movement is governed by plate tectonics. We must wonder if other ancient and modern volcanic fields contain as-yet unrecognized gigantic landslides. Perhaps such mega-slides are more common than geologists once believed?

There is a certain cachet accorded to things that are the biggest of their kind—the tallest building, the largest pumpkin, the most fearsome predator. Yet more than that, Utah's mega-landslides are important for the window they open into our science of geology. Their discovery literally spanned decades and it will be decades more before we fully understand what the slides reveal about the evolution of volcanic fields and about the potential for modern active volcanic fields to generate such gigantic slides. We are in the middle of a paradigm shift in geology, one of many that have occurred over the past few decades. Not only from studies in the Marysvale area, but from work in different terrains all over the world, geologists are slowly coming to realize the role of simple gravitational processes as drivers of landscape change on an extraordinary scale.

Emplacement of each mega-slide doubtless led to massive rearrangement of the local landscape. Stream valleys and mountains were obliterated, and a new, initially hummocky topography took their place. Over the span of thousands to hundreds of thousands of years new drainage networks were established. Erosion stripped off classic landslide geomorphic features, but it—and the fact that the slides are cut and offset longitudinally by younger basin-range faults—ultimately gave us our modern-day view deep into the guts of the slides, parts seldom seen in modern landslides. It also appears that the mega-slides may have repeatedly disrupted regional, east-directed drainage off the Indian Peak and Caliente caldera complex highlands on the present-day Utah-Nevada border. Ash-flow tuffs derived from those calderas spread eastward and ultimately became entrained in broad paleovalleys that served to channel pyroclastic flows far to the east. As each ash-flow tuff filled former stream valleys, the streams shifted southward off the resistant, brand new volcanic rock and preferentially eroded less resistant strata of the valley walls. Older ash-flow tuffs are generally found farther to the east and north than younger tuffs, possibly a result of former broad valleys becoming blocked first by the Sevier mega-slide in the east, then by the Markagunt mega-slide to its west, and finally by the Black Mountains mega-slide on the southwest side of the Marysvale volcanic field.

The Marysvale gravity slide complex contains the first reported occurrence of landslide-generated pseudotachylyte in North America and one of the few examples known in the world. Previously, few geologists understood that this friction-generated melt rock could be produced by anything other than tectonic forces deep in the earth's crust, or by rare (thankfully) high-energy impact events. Pseudotachylyte, the friction-generated melt glass now known from a dozen localities on the Sevier and Markagunt slides, is important to demonstrate that emplacement was extremely rapid, that the mega-slides were emplaced in a matter of tens of minutes, not slowly over a span of hundreds or thousands of years.

NEW RESEARCH ON THE MARYSVALE GRAVITY SLIDE COMPLEX

There is much we do not yet know about the Marysvale gravity slide complex. Yet our hypothesis of gigantic landslides—a holistic view of three types of geologic deformation (extension, simple translation or horizontal movement, and compression) not otherwise directly related to one another in most geologic environments—is a valuable tool to focus efforts to better understand these mega-landslides. Future research will focus on (1) new age and geochemical data to better constrain development of the volcanic field and its repeated partial collapse by catastrophic mega-landslides, (2) geologic mapping to discover important details about each mega-landslide's characteristics and history, and (3) analog and computer models to understand the mechanics of sliding such large masses long distances over low slopes. Much of this work is just now beginning thanks to a three-year, multi-university and multi-disciplinary National Science Foundation-funded research effort to better understand the mega-slides.

This is a good point at which to reflect on one potential problem of any scientific endeavor (indeed any human endeavor, from deciphering world news to finding a soulmate!): confirmation bias. With a hypothesis or model in mind, it is all too easy to inadvertently sift through and cherry pick observations that support your hypothesis, to fall prey to one's preferred solution. It is an easy mistake to see what you are looking for but to miss or ignore that which is not on your mind, runs contrary to your hypothesis, or which you are not trained to see. Yet the process of making a geologic map, which is what led to the discovery of Utah's mega-slides, is a powerful tool that significantly restricts the subtle yet powerful forces that drive confirmation bias. Each new outcrop you visit has the power to destroy your working hypothesis. The great thing about making a geologic map is that it encourages you to see the world without an agenda, to be open to what you observe whether or not it fits in with your current working hypothesis. This is harder than it sounds, and we must continually revise our ideas in light of new evidence, evidence gained only by walking and walking and walking, seeing as much of the landscape as possible. Keep it simple, revise as necessary. As Occam implies, and the *New York Times Magazine* author Lisa Sanders so evocatively summarized, "…when you hear hoof beats, chances are good that it is a horse. But we must remember that sometimes the circus is in town."

PLACES TO VISIT

Because the Sevier, Markagunt, and Black Mountains mega-landslides are so large, there is no single place that encapsulates their entire story. However, parts can be seen in many places. Here we offer brief descriptions of several of our favorite, particularly instructive and relatively accessible exposures (figure 23). Several of these sites are along paved roads, others are accessed on generally well-maintained dirt roads, whereas others require hiking a half mile or more off trail over rough terrain. All are on land managed by the U.S. Forest Service (USFS) or U.S. Bureau of Land Management (BLM), but are undeveloped and lack visitor services. Details about roads, trails, distances, and geographic names used here are given on standard USGS 7.5′ topographic maps and on USFS trail maps. In places, access to these localities crosses private land, typically on USFS or BLM rights-of-way, so please respect landowner rights, obey all posted signs, and note that access may change after this report is published. The usual requests for personal responsibility and safety apply: drive only on approved roads and remember that rain or snowmelt may turn some impassible; always use caution around traffic; pay heed to weather and forecasts—weather can change rapidly and severely at high elevations; do not tag outcrops; pack out what you pack in; be aware that you are entering the home of rattlesnakes, black bears, and mountain lions; be vigilant, be respectful. We strongly discourage souvenir sampling and use of hammers, especially of rare lithologies such as pseudotachylyte.

Know that accessibility is a relative term—visitors must determine for themselves if they are able to safely navigate to the sites described below. Apart from Utah Highway 143 exposures, these sites are much more remote, rugged, and challenging than popular sites in national parks. Elevations are as high as 11,000 feet (3400 m), and given heavy winter snowpack, summer and fall are the best times to visit. GPS coordinates are reported in NAD83.

Refer to the geologic maps of the Panguitch and Beaver 30' x 60' quadrangles to place these sites in regional perspective; each of these maps is now being revised in light of new mega-slide discoveries. More detailed geologic maps of selected 7.5′ quadrangles, most that predate discovery of the mega-landslides, are available via the Utah Geological Survey (UGS) website (https://geology.utah.gov) and through the USGS National Geologic Map Database (https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html).

Utah's mega-landslides are located near several national and state parks and monuments of exceptional geologic interest. We encourage visitors to make use of other published geologic guides and popular accounts of the region's geology, including those of Bryce Canyon National Park, Cedar Breaks National Monument, Grand Staircase–Escalante National Monument, and others featuring southwestern Utah's fascinating geology (see references). Also available is a virtual geologic map and guide of the Panguitch 30′ x 60′ quadrangle, one of several virtual tours available on the UGS website (https://geology.utah.gov/map-pub/maps/geologic-maps/virtual-overlay-field-guides/).

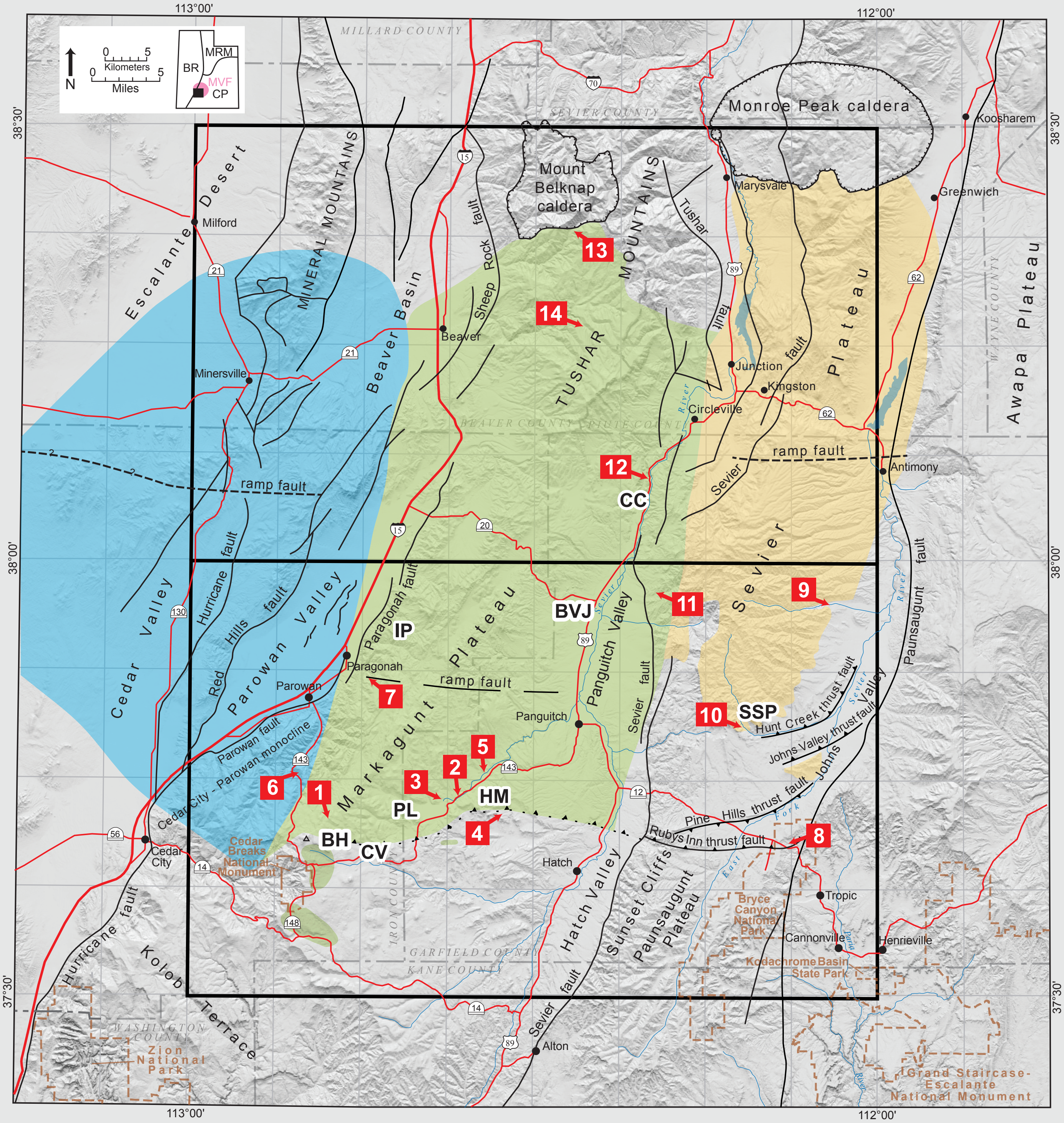


Figure 23. Map showing 14 localities, described in the text, that collectively give visitors a glimpse of the types of geologic structures and deformed rocks that characterize Utah's mega-landslides. All but a few roadside localities require off-trail hiking over uneven terrain, and access to several localities requires a high-clearance four-wheel drive (4WD) vehicle.

Heavy black lines mark boundaries of the Beaver (top) and Panguitch (bottom) 30' x 60' quadrangles. Extent of mega-slides shown in yellow (Sevier), green (Markagunt), and blue (Black Mountains). Black lines show major faults. Utah Highway 143 reference locality of the Markagunt Megabreccia, designated by Anderson (1993), lies between localities 2 and 5 just east of Panguitch Lake. Inset shows major physiographic provinces of Utah: BR—Basin and Range; CP—Colorado Plateau; MRM—Middle Rocky Mountains; MVF is Marysvale volcanic field. Key sites discussed in text: BH—Brian Head peak; BVJ—Bear Valley Junction; CC—Circleville Canyon; CV—Castle Valley; HM—Haycock Mountain; IP—Iron Peak; PL—Panguitch Lake.

Localities: 1—Sidney Peaks, 2—Highway 143, 3—Panguitch Lake dam, 4—Haycock Mountain, 5—Haycock Mountain Tuff, 6—Parowan Canyon, 7—ramp, 8—Paunsaugunt thrust faults, 9—Cottonwood Canyon, 10—south end Sevier Plateau, 11—Smith Canyon, 12—Circleville Canyon, 13—Mount Belknap breakaway, 14—Puffer Lake.

Locality 1: Sidney Peaks

At Sidney Peaks, high on the west margin of the Markagunt Plateau, older volcanic rocks are found on top of younger volcanic rocks (figure A-1). Both are flat lying and to the casual observer nothing seems to be amiss. However, they are separated by a horizontal surface of remarkable interest, one that is scoured and grooved and marked by a thin layer of crushed and broken rock. The first person to notice something unusual here was James Judy, a Kent State University master's student who worked under John Anderson. In the early 1970s, Judy identified the distinctive, 29.5 Ma Wah Wah Springs Formation resting *on top* of the 23.8 Ma Leach Canyon Formation. This older-on-younger relationship breaks a fundamental law of geology, that of superposition, which states that all else being equal, younger layered rocks are always found on top of older rocks. Something unusual had happened here.

What Judy and Anderson could not have known at the time (because the region's geology was only beginning to be geologically mapped in detail and so was still not well understood) was that they had stumbled upon one small part of a much larger feature, what in 1993 Anderson described as the Markagunt Megabreccia. The Megabreccia is a chaos of volcanic rocks that we now understand to be the deposit of the Markagunt mega-landslide, the remains of which stretch 50 miles (80 km) to the north into the heart of the Tushar Mountains.

Location

The northern Sidney Peaks locality (coordinates 342511mE, 4175034mN; 37º 42' 32.5" N, –112º 47' 12.0" W) is accessible via unpaved U.S. Forest Service road FR048 (Sidney Valley Road along Castle Creek) that heads north from Utah Highway 143 (figure A-2); the road is closed during winter. Park at the Sidney Valley overlook at FR 4066 (elevation about 10,500 feet [3200 m]) and walk on the trail about 0.75 mile (1.2 km) southwest along the Black Ledge escarpment. The base of the slide is best exposed along the rim west of where the trail continues due south up to Sidney Peaks (figure A-3). Climb to the top of Sidney Peaks to see the best exposures of Wah Wah Springs tuff on the peaks' west side.

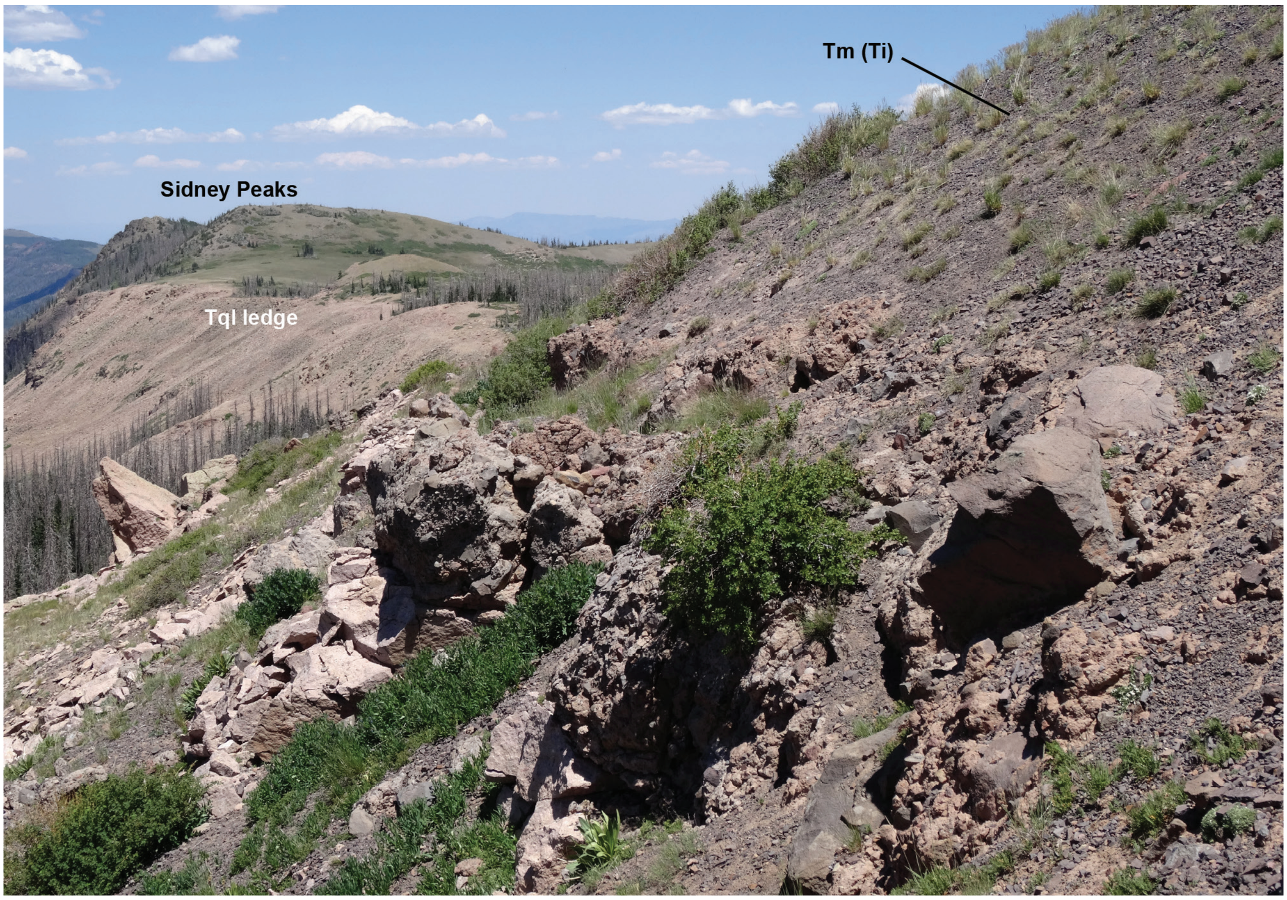


Figure A-1. Hill at right shows highly fractured Isom Formation as part of the Markagunt mega-slide (Tm[Ti]) overlying undisturbed lower-plate rocks of a thin layer of Mount Dutton volcanic mudflow breccia (Td) and thick ledge of 23.8 Ma Leach Canyon Formation (Tql). The best exposures of the slide plane itself are at the north end of this small hill, our southern Sidney Peaks locality. Sidney Peaks to the north are held up by 29.5 Ma Wah Wah Springs Formation that rests on top of the younger Leach Canyon. The Tushar Mountains, breakaway area of the mega-slide, is barely visible on the north-central horizon.

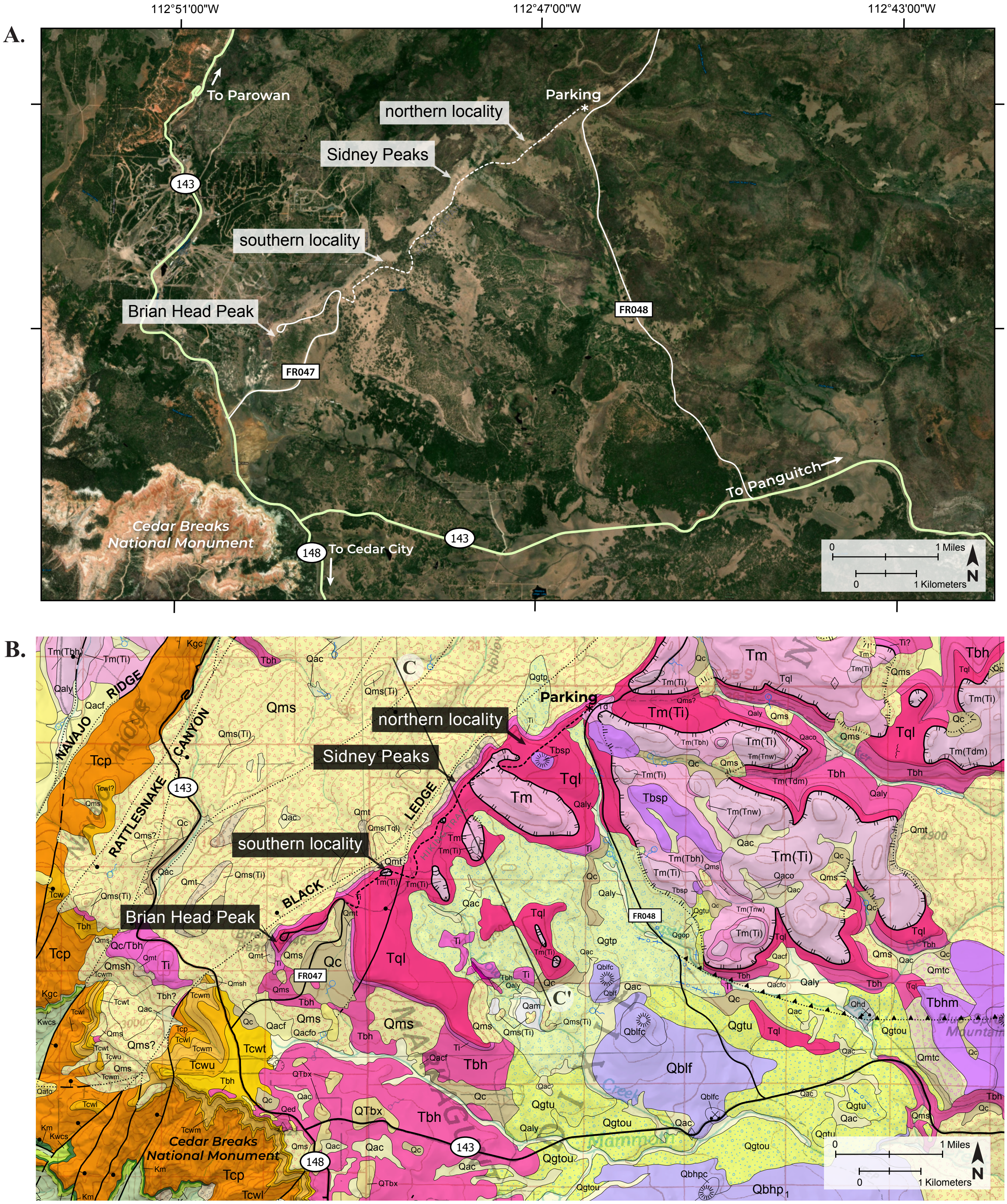


Figure A-2. (A) *Northern and southern Sidney Peaks localities at the west edge of the Markagunt Plateau.* ***(B)*** *Geologic map of the Sidney Peaks area. Note the large area of modern landslides in Yankee Meadows graben in the upper left quadrant of the map, which resulted from modern landslide failure of the Brian Head Formation at the base of Black Ledge. The Brian Head ski area is immediately northwest of Brian Head Peak. Relevant bedrock map units are shown on figure A-2C. Older Cretaceous strata are green on this map; surficial deposits are various shades of light yellow, and Pleistocene-age basaltic lava flows are purple. Normal faults are shown with a bar and ball on the down-dropped side; gravity slide slip surfaces have double tic marks on upper plate. Note that at the Sidney Peaks north locality, debris eroded from the Markagunt mega-slide mantles the slope north of where the slide (Tm) is mapped. Modified from Biek and others (2015).*

STRATIGRAPHIC COLUMN

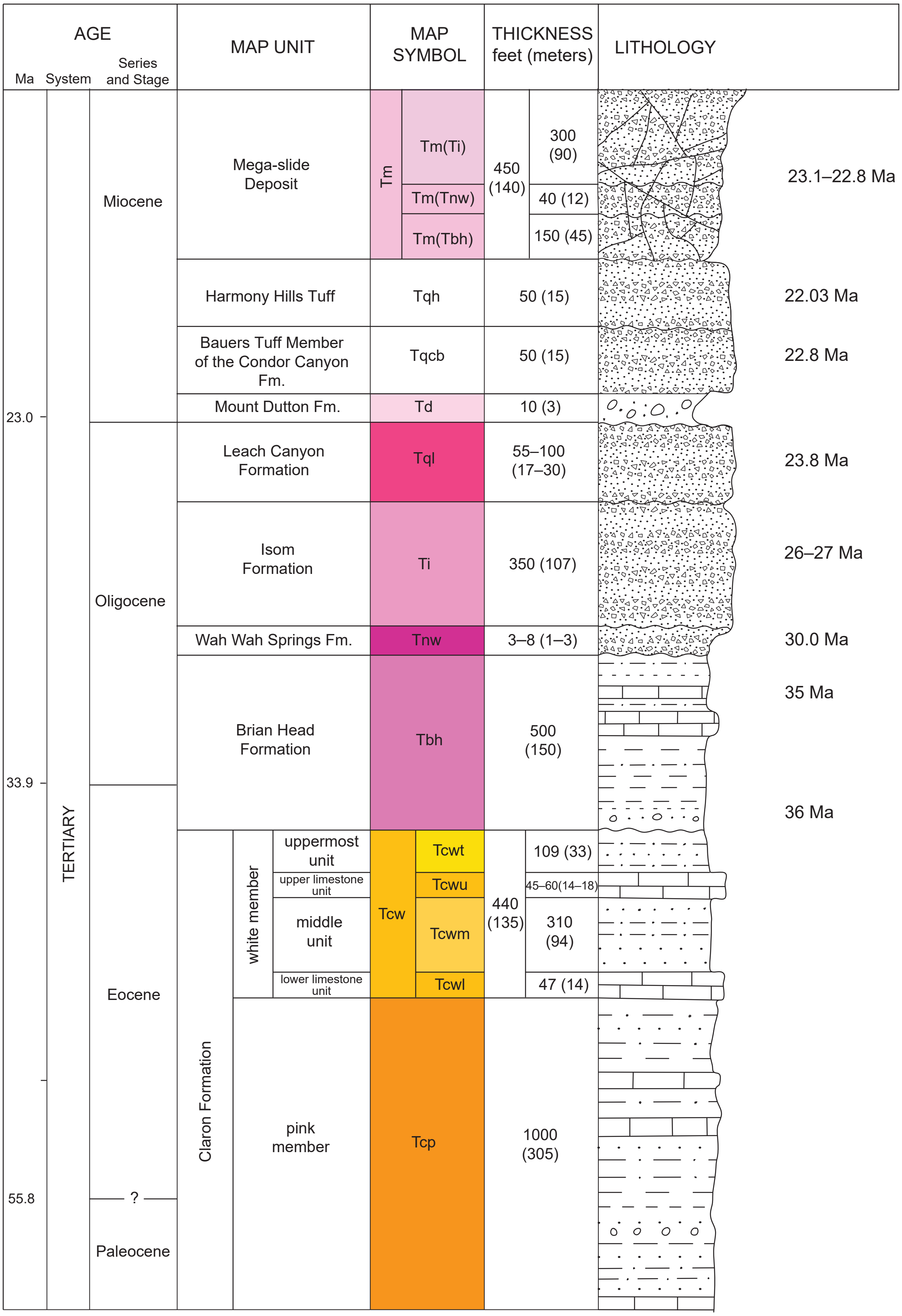


Figure A-2C. *Stratigraphic column showing rock units of the Sidney Peaks and western Markagunt Plateau area.*

The southern Sidney Peaks locality (coordinates 340337mE, 4173170mN; 37º 41' 30.7", –112º 48' 39.28"), our personal favorite, is accessible via unpaved FR047 (Brian Head peak road, also closed during winter) off Utah Highway 143. From the trailhead parking area (elevation about 11,000 feet [3350 m]) just below the summit of Brian Head peak, walk on the trail about 0.3 mile (0.5 km) northeast along the Black Ledge escarpment. Where the trail bends to the east, continue straight for about 0.15 mile (0.25 km) cross country along the rim until reaching the small hill (figures A-1, A-2).

What You Will See

Here, at Sidney Peaks, you will see remains of the Markagunt mega-landslide and exceptional views northward to the slide's source area in the distant Tushar Mountains and westward into the Great Basin. There is no better place to gain an appreciation of the scale of this gigantic landslide. Furthermore, the hike to Sidney Peaks, approached from the south or from the north, must be one of the most beautiful in all of southwestern Utah.

At the northern locality you will find that the top of the Leach Canyon Formation is locally grooved and striated, originally, and reasonably, thought to be a result of late Pleistocene glaciation that spilled northward off Black Ledge (figure A-3). However, the remains of a thin layer of Brian Head debris (small pieces of white mudstone, sandstone, and limestone, as well as chalcedony) and Isom debris (crushed and rehealed blocks)—both from strata older than the Leach Canyon—is present on top of the Leach Canyon, and above this is a thick section of the older Wah Springs Formation. The same north-south striations are present on the heavily forested northwest side of Sidney Peaks where they parallel the cliff face in an area that could not have supported glacial ice (and even if it had, the ice would have flowed westward, not northward). The striations thus reflect emplacement of the Markagunt mega-slide along its basal slip surface. The Brian Head Formation acted as the "grease" at the base of the slide that facilitated slide movement.

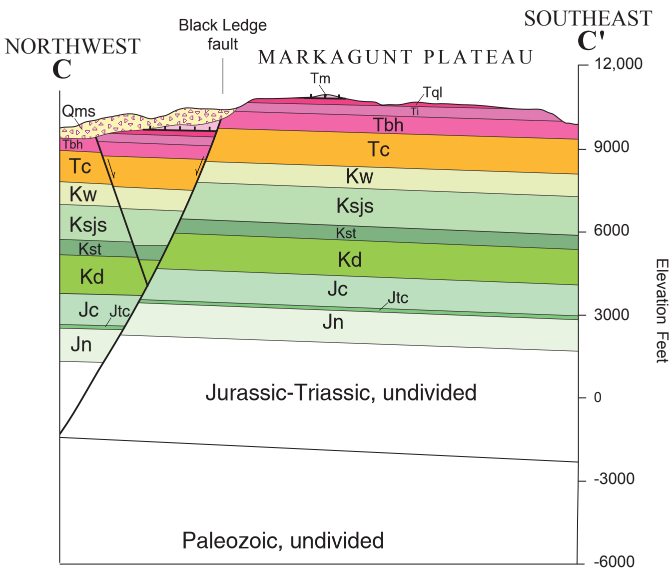


Figure A-2D. *Cross section through Black Ledge and Sidney Peaks.*

The southern Sidney Peaks locality also reveals a striated surface on the Leach Canyon Formation and cataclastically deformed and jumbled Wah Wah Springs, Isom, and Mount Dutton debris (figure A-1). The best exposures are at the north end of this low hill. There, small blocks of the Wah Wah Springs Formation exhibit striking reddish-brown shear zones, and small blocks of Isom Formation show evidence of having been crushed and rehealed (figure A-4).

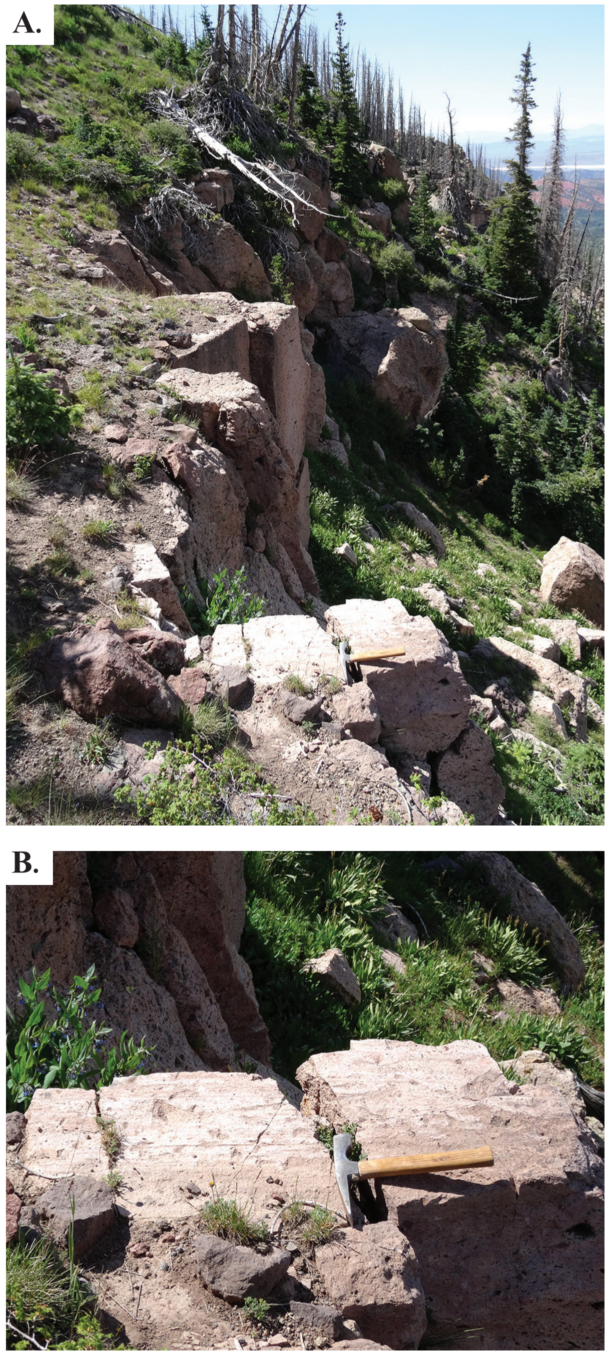
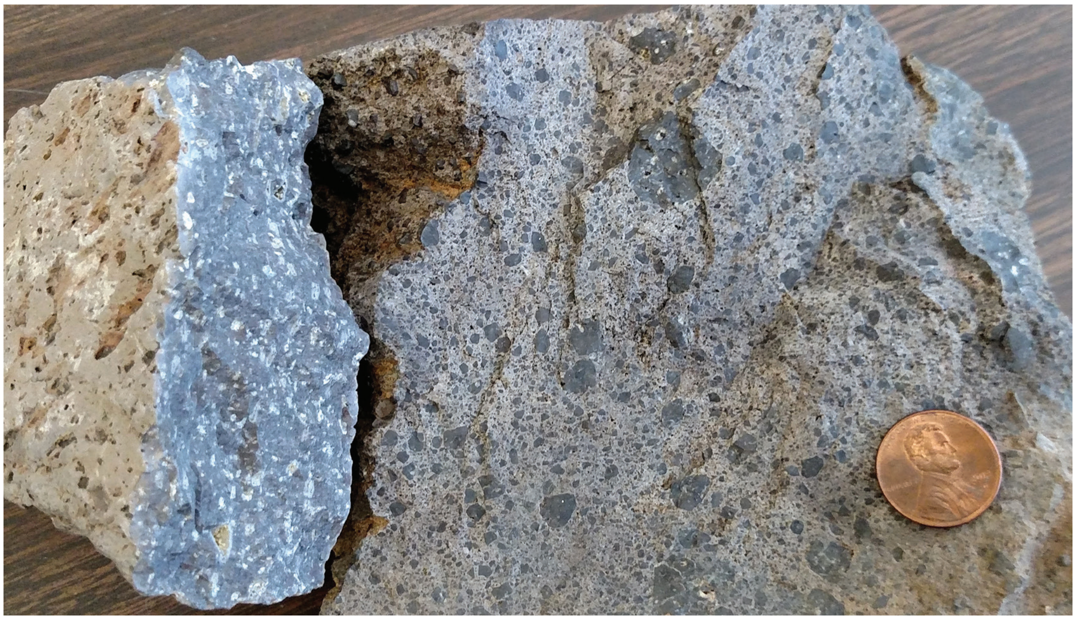


Figure A-3. (A) *View southwest along striated ledge of Leach Canyon Formation; hammer handle is parallel to striae.* ***(B)*** *Close-up showing striated Leach Canyon surface. The striations are like skid marks at the base of the Markagunt mega-slide, showing that it came from the north.*

Both the Wah Wah Springs and Leach Canyon Formations are ash-flow tuffs that resulted from what are popularly known as “super eruptions,” each having ejected more than 240 cubic miles (1000 km^3) of rock, more than 1000 times the volume of the 1980 Mount St. Helens eruption. The Wah Wah Springs Formation is a crystal-rich, dacitic ash-flow tuff erupted from the Indian Peak caldera on the present-day Utah-Nevada border. The rock sparkles with phenocrysts of plagioclase, hornblende, and biotite, which constitute about 40% of the rock; its estimated volume of about 720 cubic miles (3000 km^3), all from one huge eruption, makes it among Earth’s largest ash-flow tuff eruptions ever. The Leach Canyon is a slightly less crystal-rich but more silica-rich rhyolite ash-flow tuff that likely erupted from the Caliente caldera complex, also on the Utah-Nevada border. It contains abundant white or light-pink, flattened pumice fragments and several percent rock fragments, many of which are reddish brown.

A.



B.

Figure A-4. (A) *Broken and rehealed piece of Isom Formation; piece at left is undeformed Isom with white feldspar phenocrysts.* ***(B)*** *Wah Wah Springs Formation showing red, crushed and sheared zones; undeformed Wah Wah Springs at upper left. Such deformation is typical of rocks at the base of the Markagunt slide.*

Locality 2: Utah Highway 143

Utah Highway 143 northeast of Panguitch Lake is part of John Anderson's reference area for the Markagunt Megabreccia, which he formally described in 1993. This area is one of seven on the northern Markagunt Plateau that he chose to illustrate the wide variety of deformation seen in this "chaos of volcanic rocks" (figure 18). Here, along Highway 143, each road cut reveals a different rock unit or jumble of different units with no rhyme or reason to their distribution. Without such road cuts, it is difficult to see such complexity in the surrounding hillsides, but what a story they hold if one is eager and nimble enough to scramble up these steep slopes!

Location

Our main locality (coordinates: 359548mE, 4177686mN; 37º 44' 8.5" N, –112º 35' 31.83" W) is a small pullout at a sharp bend in the road (figure A-5). Several nearby road cuts are also described that passengers can see as they drive slowly through this chaotic mass of volcanic rocks.

What You Will See

This south-facing road cut reveals the basal slip surface of the Markagunt mega-slide about 30 feet (10 m) above road level (figure A-6A). The lower two-thirds of the road cut is the Isom Formation. Notice that the upper few feet of the Isom are deeply weathered and overlain by volcanic mudflow deposits of the Mount Dutton Formation. Their contact is a slip surface lined with basal breccia and a very thin, millimeter-thick pseudotachylyte—the basal slip surface of the slide. We interpret the weathered Isom as the former land surface that was overridden by the slide. About 250 feet (80 m) to the east, this surface, basal layer, and small clastic dikes are exposed in a small cut just above road level (figure A-6B).

A low road cut on the south side of the road about 650 feet (200 m) to the east reveals weathered Isom Formation overlain by a thin remnant of volcanic mudflow deposits of the Mount Dutton Formation (figure A-6C). A striated and grooved slip surface is developed on top of Mount Dutton strata, above which are sandstone and mudstone of the Brian Head Formation, all showing inverted or out-of-order strata.

Figure A-5. Map showing Anderson's (1993) reference area for the Markagunt Megabreccia (the deposit of the Markagunt mega-landslide) and the Panguitch Lake dam and Haycock Mountain Tuff localities. 1=type section of the Haycock Mountain Tuff; 2=folded, white volcaniclastic strata of the Brian Head Formation exposed in road cut.

The striations, or "skid marks," show that the slide rocks moved either northward or southward; coupled with fractures seen elsewhere we can say with certainty that the rocks moved southward.

The Isom Formation is also spectacularly exposed in the gorge of Panguitch Creek as a gray, densely welded, crystal-poor ash-flow tuff (figure A-7). The Isom is noted for its platy weathering habit, a result of severely flattened gas bubbles and pumice fragments. The Isom Formation is unusual in that it was so hot when erupted that it flowed like a lava flow 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. Look closely and you can see a large-scale flow fold representing contemporaneous deformation during emplacement. In fact, 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 pioneering geologists J. Hoover Mackin and colleagues mapped its widespread distribution and found evidence of glass shards, thus showing its true ash-flow tuff nature. The Isom Formation is 26 to 27 Ma and likely erupted from the Indian Peak caldera complex near the Utah-Nevada border. Like the Leach Canyon and Wah Wah Springs ash-flow tuffs, it too resulted from a super eruption, one that ejected 300 cubic miles (1300 km^3) of ash spread over an area of 9500 square miles (25,000 km^2).

At the next small pullout about 750 feet (230 m) east of the main locality (number 2 on figure A-5), Brian Head strata are spectacularly folded in the south-facing road cut (figure A-8). Much of the volcanic ash in Brian Head strata is altered to clay, making the unit especially susceptible to modern landslides where exposed on steep slopes. We commonly find Brian Head debris at the base of the mega-slides, leading us to conclude that it was an important factor in facilitating movement of Utah's mega-slides.

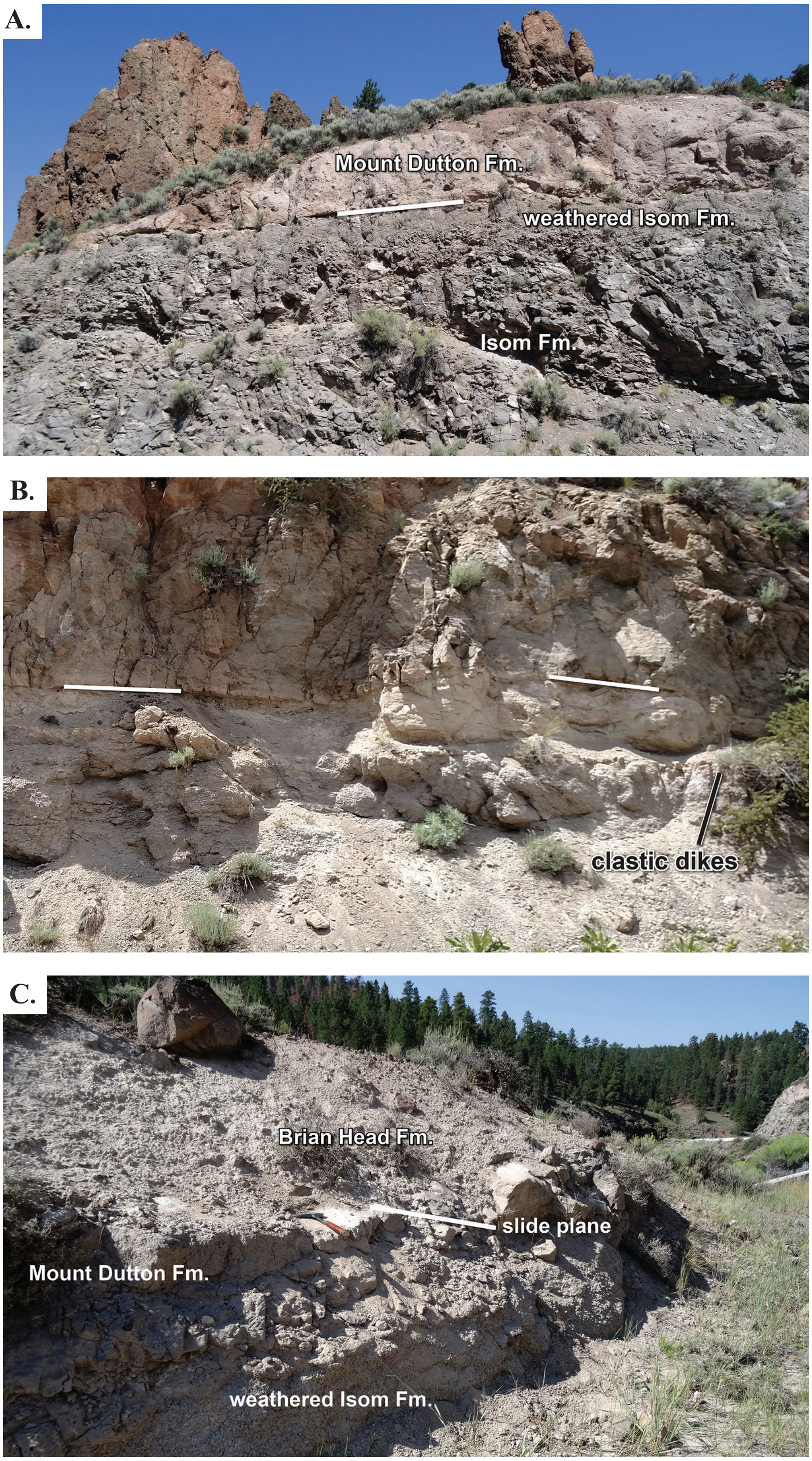


Figure A-6. (A) *Road cut showing the basal slip surface (white line) of the Markagunt mega-slide, here placing volcanic mudflow deposits of the Mount Dutton Formation on Isom Formation.* ***(B)*** *Slip surface (white line) where it is near road level; small clastic dikes are present below the thin basal layer near right edge of photo.* **(C)** *Small road cut exposure of the basal slip surface; hammer lies parallel to grooves and striations on a surface of volcanic mudflow breccia (Mount Dutton Formation) planed off by slide movement. Deeply weathered Isom Formation marks the former land surface; weak mudstone of the Brian Head Formation facilitated movement.*

Figure A-7. *Isom Formation in Panguitch Creek. Note large recumbent flow fold (white line), showing that this ash-flow tuff was so hot that it flowed like a lava flow during its final stages of emplacement.*

Figure A-8. *Fine-grained sandstone and mudstone of the Brian Head Formation here folded at the base of the Markagunt mega-slide; David Hacker gives scale, view to the north. These rocks were originally misinterpreted as belonging to the younger Bear Valley Formation in our original mapping of this complex area.*

Locality 3: Panguitch Lake Dam

The basal slip surface of the Markagunt slide is exposed immediately downstream of this small dam along both sides of the creek. We include this locality not because it is especially dramatic—quite the opposite actually—but to show the subtle deformation expressed by much of this great landslide. It is all too easy to walk over exposures such as this and not realize their significance.

Location

About 250 feet (75 m) north of the Panguitch Lake dam, west of the creek and continuing northward for about 250 feet (75 m) (figure A-5) (coordinates: between about 356486mE, 4176589mN and 356509mE, 4176656mN; between about 37º 43' 31.2" N, –112º 37' 42.6" W and 37º 43' 33.4" N, –112º 37' 41.7" W).

What You Will See

Here, the Isom Formation is overlain by a low ledge of volcaniclastic sandstone of the Bear Valley Formation (figure A-9A). Bear Valley sandstone typically exhibits grand, sweeping cross-beds not unlike those of Zion National Park's Navajo Sandstone because it too is a deposit of wind-blown sand, but here sedimentary structures are mostly obliterated by pervasive fractures and shears. The contact between Isom and Bear Valley is the slide's basal slip surface, including a basal layer that pinches and swells to as much as about 3 feet (1 m) thick. Not much to look at perhaps, but geologists at Southern Illinois State University analyzed zircons from this basal layer and discovered that it can be no older than about 23.5 Ma. That comports with findings at nearby Haycock Mountain and provides a way to independently constrain the timing of emplacement of the Markagunt mega-slide. This surface can be traced many miles to the north where upper plate rocks also include jumbled blocks of Wah Wah Springs, Isom, and Bear Valley strata. On the east side of the creek, faint grooves are etched into the top of the Isom Formation, a subtle example of the "skid marks" at the base of the slide (figure A-9B).

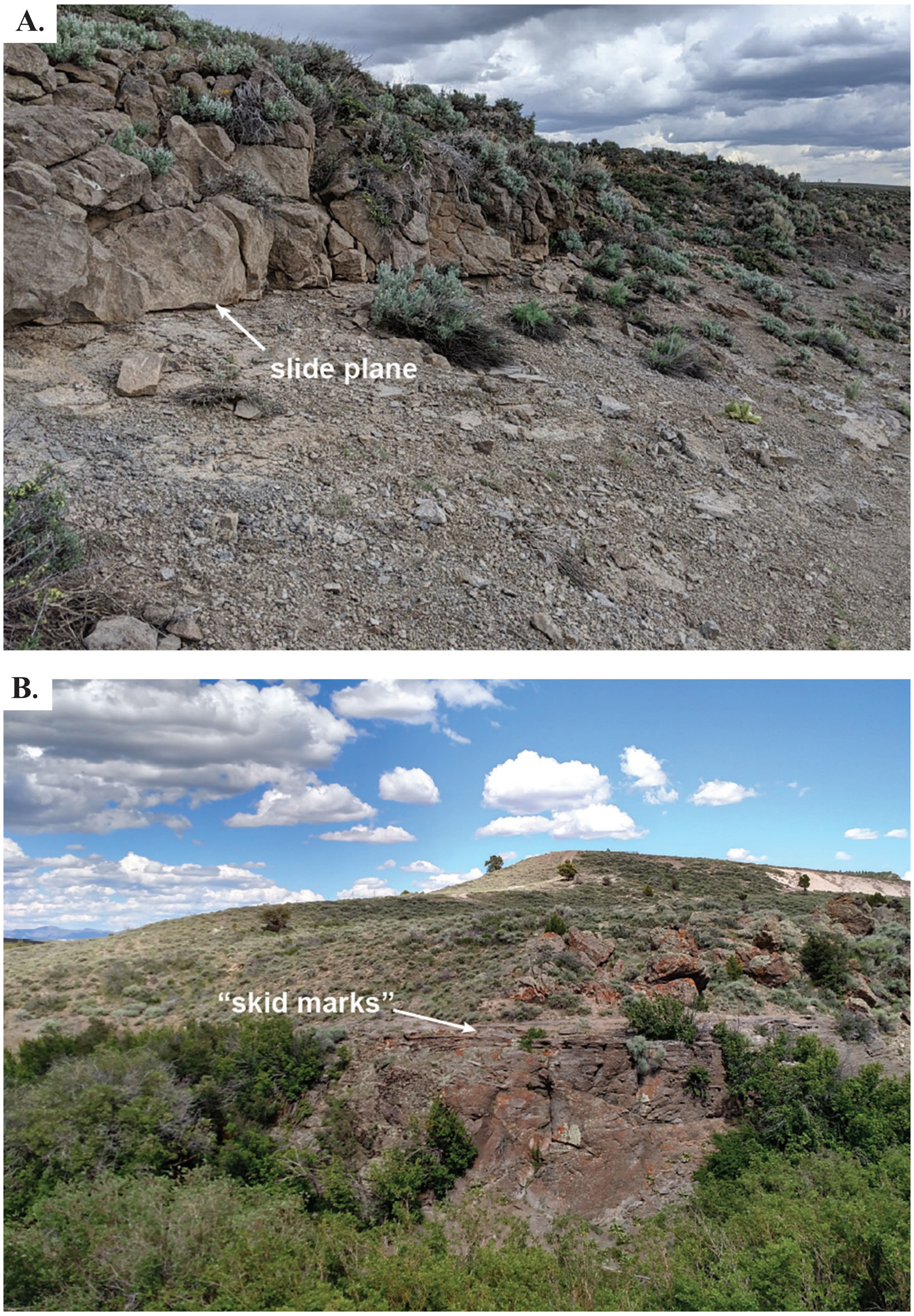


***Figure A-9. (A)** View north to base of Markagunt mega-slide exposed along the west side of Panguitch Creek near the Panguitch Lake dam. Here, the mega-slide is volcaniclastic sandstone of the Bear Valley Formation overlying undisturbed Isom Formation; close inspection reveals a thin basal layer. Note that the top of the Isom is grussy (small, angular fragments) above its typical platy outcrop, which we interpret to be a result of weathering on the former land surface before mega-slide emplacement. **(B)** View east towards subtle, poorly preserved "skid marks" at the base of the mega-slide are present at the top of the Isom Formation along the east side of Panguitch Creek.*

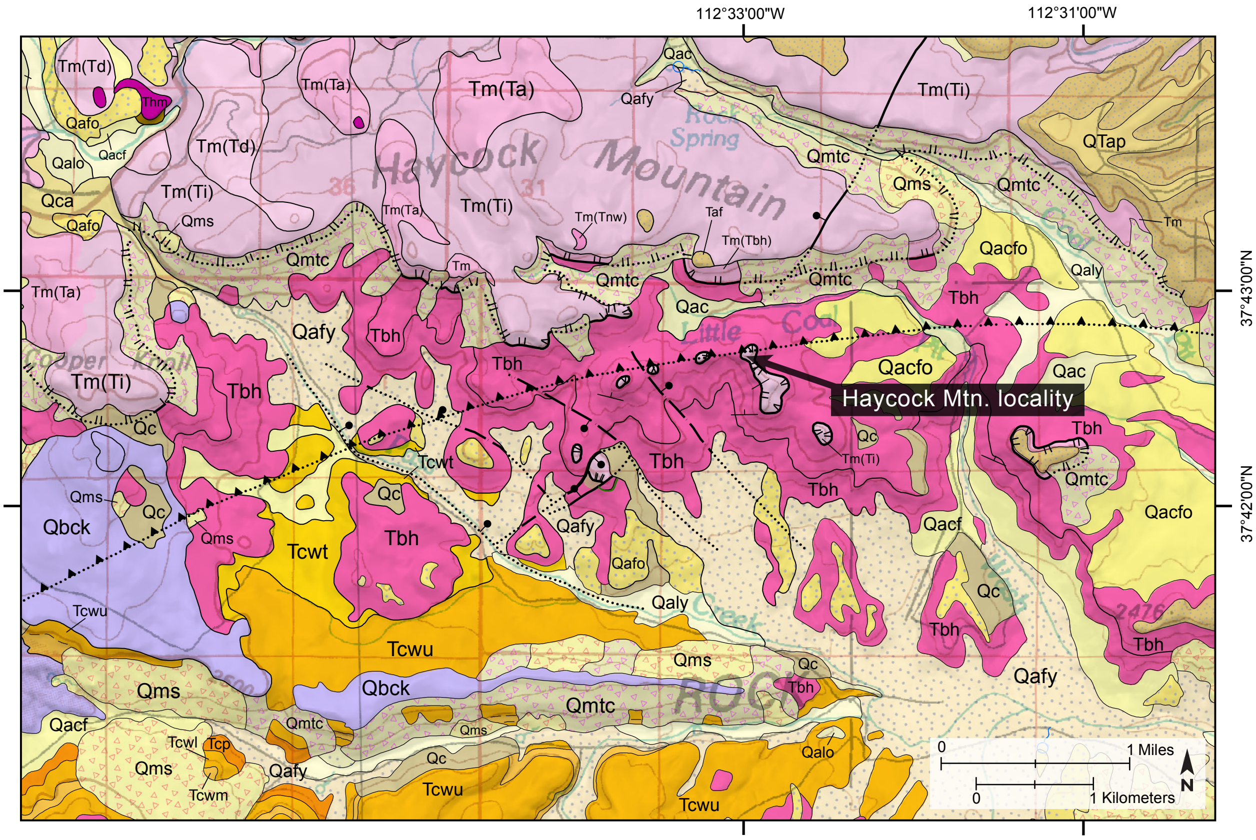
Locality 4: Haycock Mountain

The southern escarpment of Haycock Mountain, east of Panguitch Lake, provides exceptionally informative exposures of the Markagunt basal slide plane and deformation of upper plate rocks. These exposures are where we first realized that the Markagunt Megabreccia—that chaos of volcanic rocks as John Anderson described it in 1993—was just one part of something much, much larger. Dozens of geologists have now visited this location and it will doubtless intrigue researchers for years to come. The site described below is, unfortunately, difficult to access, as is much of Haycock Mountain's southern escarpment. This short explanation and photos will have to suffice for all but the fittest of visitors.

Location

Haycock Mountain is crisscrossed by rugged ATV trails that enable visitors to get close to the southern escarpment, but still access to this and nearby sites requires off-trail hiking over rugged terrain. The coordinates of this site are: 363302mE, 4174884mN; 37º 42' 39.66" N, -112º 33' 03.08" W. We leave it to you to figure out how to safely get there and whether you are willing to scramble up cliffs at the site itself. The hike is not for the faint of heart, but for those able to reach it, this site is among the most important exposures of the entire mega-landslide complex (figure A-10A and B).

A.



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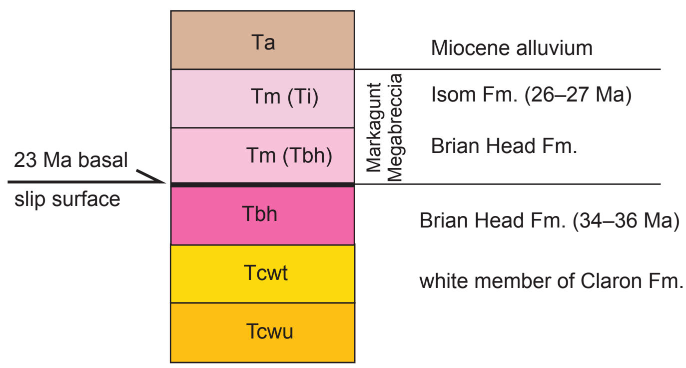


***Figure A-10. (A)** Geologic map of Haycock Mountain. See Biek and others (2015) for a full explanation of map units. **(B)** Selected map units at Haycock Mountain.*

What You Will See

At Haycock Mountain, 26 to 27 Ma Isom Formation overlies 34 Ma Brian Head Formation in what appears to be a normal stratigraphic section like it is farther west at Black Ledge and Brian Head peak on the west rim of the plateau (figure A-11A). However, close inspection shows that the Isom is severely brecciated—broken and pulverized—and its base marked by a prominent shear plane, basal layer, and clastic dikes. The lower part of the Isom Formation at the site is technically a cataclasite that grades upward into fractured but otherwise little disturbed Isom. Cataclasis is a progressive process of brittle deformation that results from fracturing, grinding, and comminution typical of fault zones everywhere. This hard, densely welded ash-flow tuff was crushed and pulverized into sand and gravel-size pieces and then silicified (figure A-11B and C). Compared to undeformed exposures of the Isom Formation, this Isom looks badly abused, like a shattered piece of china hastily glued back together.

The base of the Isom cliff is flat and marked by grooves, striations, and fractures that collectively demonstrate emplacement of the upper plate rocks from the north. Directly under the Isom is a basal layer as much as 3 feet (1 m) thick that consists of both angular (Isom) and rounded (volcanic and quartzite) clasts in a moderately cemented and poorly sorted sandy matrix (figure A-11D). Material from the basal layer is also present as clastic dikes in the lower part of the Isom cliff, showing that basal layer debris behaved as an overpressured fluid at the base of the slide, reducing effective friction and facilitating slide movement. Southern Illinois University geologists analyzed zircons recovered from this basal layer

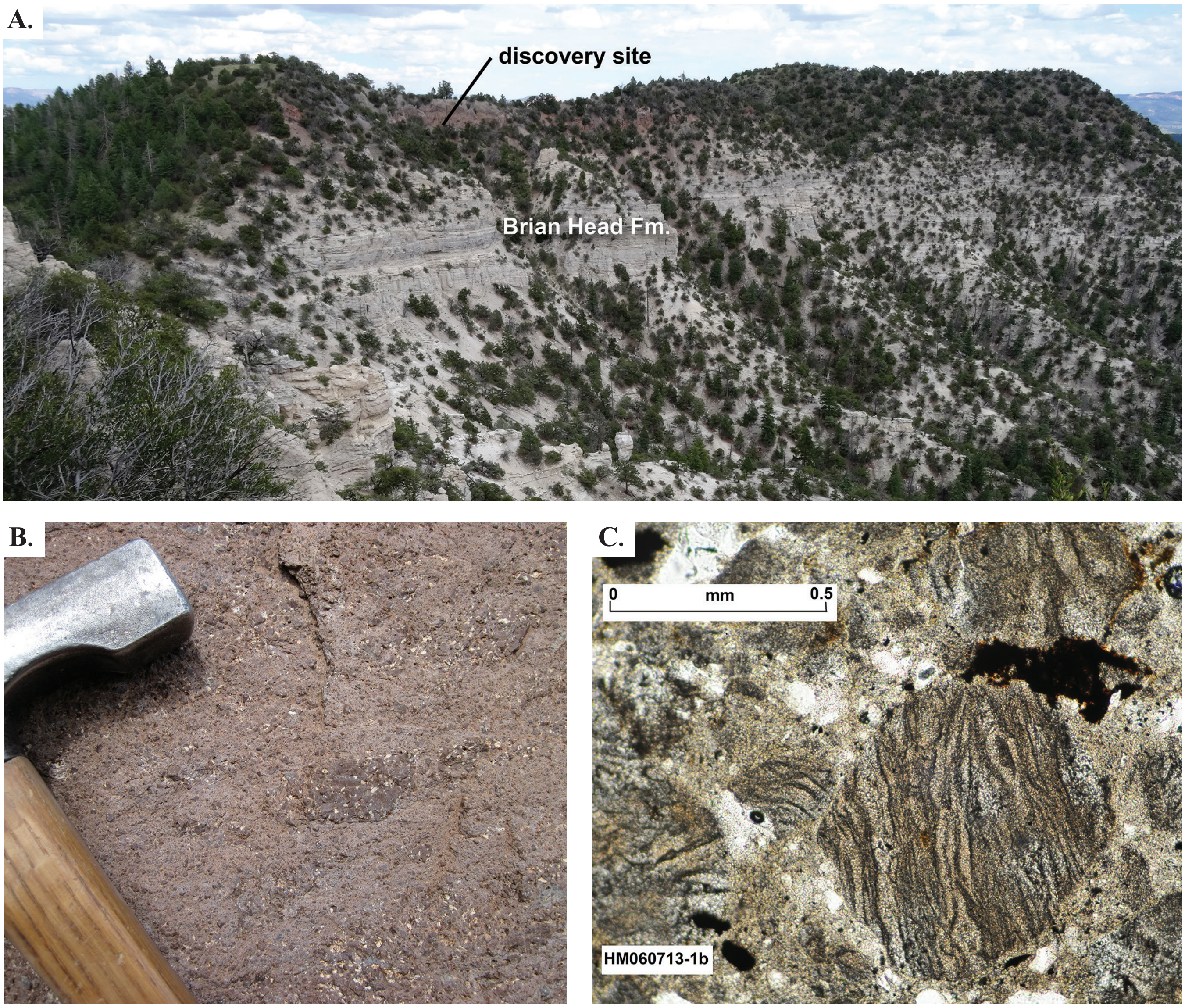


Figure A-11. ***(A)*** *View southeast of our "discovery site" just south of Haycock Mountain on the southwest side of hill 8652, NW¼SE¼ section 5, T. 36 S., R. 6 W.* ***(B)*** *Close-up of cataclastically deformed Isom Formation from this site.* ***(C)*** *Photomicrograph (plane polarized light) of cataclastically deformed Isom Formation. Note jumbled nature of micro-blocks and interstices filled with finely comminuted Isom debris.*

and showed that it can be no older than about 23.5 Ma, independently confirming our observation that the Isom is part of the slide. This older-on-younger relationship—26 to 27 Ma Isom over less than 23.5 Ma basal layer debris—is what we expect of landslides where they lie on the former land surface. Farther west along Haycock Mountain, Isom locally overlies stream gravels that fill a paleochannel eroded into the Brian Head Formation; the gravels contain rounded clasts of the Isom Formation itself, once again creating an obvious older-on-younger relationship. The stream gravels are locally deformed, likely a result of slide emplacement over unconsolidated deposits.

Having no knowledge of this deformation at the base of the Isom Formation at Haycock Mountain, previous geologists reasonably interpreted the Isom capping Haycock Mountain was undeformed, part of a normal stratigraphic section. But this site, and other sites along the south flank of Haycock Mountain, show that the entire Isom Formation caprock of Haycock Mountain is part of the Markagunt Megabreccia. This exposure continues southward for nearly 1000 feet (300 m) where the basal layer swells in thickness and complexity. There it contains intensely sheared and ultracataclastically deformed fragments of ash-flow tuff (figure A-11E and F).

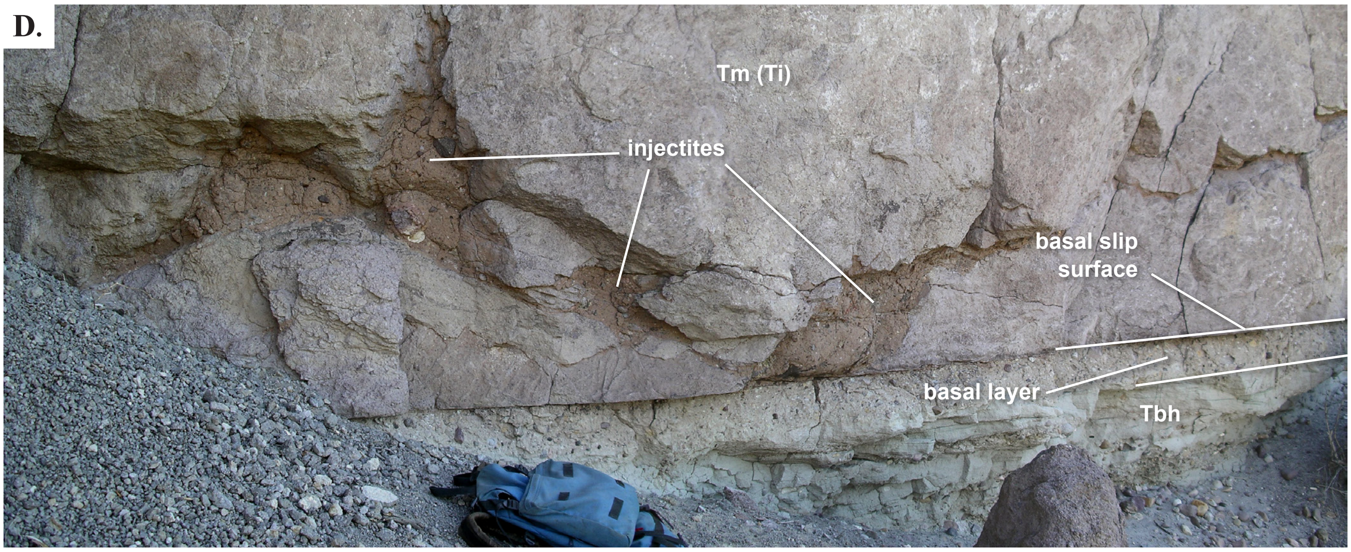


Figure A-11 continued. (D) *Closer view of exposure in (A). Note planar basal slip surface and underlying thin basal layer, which in turn unconformably overlies pebbly sandstone of the Brian Head Formation (Tbh). The basal layer is light-brown and consists of both angular (Isom) and rounded (volcanic and quartzite) clasts floating in a well-cemented sandy matrix. The clastic dikes (injectites) consist of similar but light-reddish-brown material, suggesting a different source area possibly far to the north at the ramp. The clastic dikes intrude the lower part of the slide, which here consists of resistant cataclasite derived from the Isom Formation (Tm[Ti]). This cataclasite grades upward into fractured but otherwise undisturbed Isom Formation at the top of the cliff.* ***(E)*** *Basal layer showing deformed block, possibly of the Isom Formation, encased in basal layer matrix; note rounded, undeformed pebbles.* ***(F)*** *Basal layer showing locally sheared nature of outcrop; note quarter for scale (Tnw, Wah Wah Springs Formation; Ti?, possible Isom Formation).*

Locality 5: Haycock Mountain Tuff

The Haycock Mountain Tuff, the oldest rock unit known to postdate emplacement of the Markagunt mega-landslide, is readily accessible along Utah Highway 143 (figure A-12). This light-brown, unwelded to moderately welded, crystal-poor, rhyolite ash-flow tuff contains pumice fragments and fragments of black, fine-grained volcanic rock. The tuff commonly overlies undeformed stream gravels preserved in channels eroded into deformed volcanic rocks of the slide (figure 17); here, the tuff overlies Brian Head strata, which we originally incorrectly identified as the Bear Valley Formation in our 2014 and 2015 geologic maps of the area.

Location

Park your car at a small pullout on the south side of the highway just west of Panguitch Creek. The tuff itself caps the ridge to the north (figures A-5 and A-12) (coordinates: 359915mE, 4178651mN; 37º 44' 40" N, -112º 35' 24" W). For those who don't wish to scramble up the hillside, small blocks of the tuff are present at the bottom of the slope.

What You Will See

The Haycock Mountain Tuff plays an outsize role in our understanding of the age of the Markagunt mega-landslide. The tuff is restricted to a relatively small area northeast of Panguitch Lake where it is no more than a few tens of feet thick. It is relatively small in volume and apparently erupted from the northern Marysvale volcanic field, possibly from a vent now concealed by younger deposits; we don't know its exact source. Some previous workers thought it was a distal part of the similar but older Leach Canyon Formation, which caps Brian Head peak to the west, but our mapping reconfirmed the idea of Anderson that they are indeed separate ash-flow tuffs erupted from different locations at different times. So far so good.

But, the Haycock Mountain Tuff was known to be 22.75 Ma based on isotopic dating. We initially did not trust that age because we knew that the Markagunt mega-slide overlies 22.0 Ma Harmony Hills Tuff at the west edge of the plateau. The Markagunt slide couldn't be older than 22.75 Ma but younger than 22.0 Ma—something was amiss. We re-dated the Haycock Mountain Tuff using zicron geochronology and found a small population of crystals as young as about 21.6 Ma. That seemed to peg Markagunt mega-slide emplacement between 22.0 and 21.6 Ma. But it turns out that interpreting zircon age data is complex and that simply picking the youngest grains does not reliably date the sample (due to several factors including the possibility of loss of the daughter product, lead, from the crystal structure). Additional high-precision isotopic ages on the Haycock Mountain Tuff confirmed that it is 22.75 Ma—our problem was back! Resolution of this problem thus requires that the west part of the gravity slide complex at the west edge of the plateau is a younger slide, what we now call the Black Mountains slide, which was later confirmed by other evidence. No one said this stuff is easy. Science is messy and an ongoing struggle to understand what lies before our eyes.

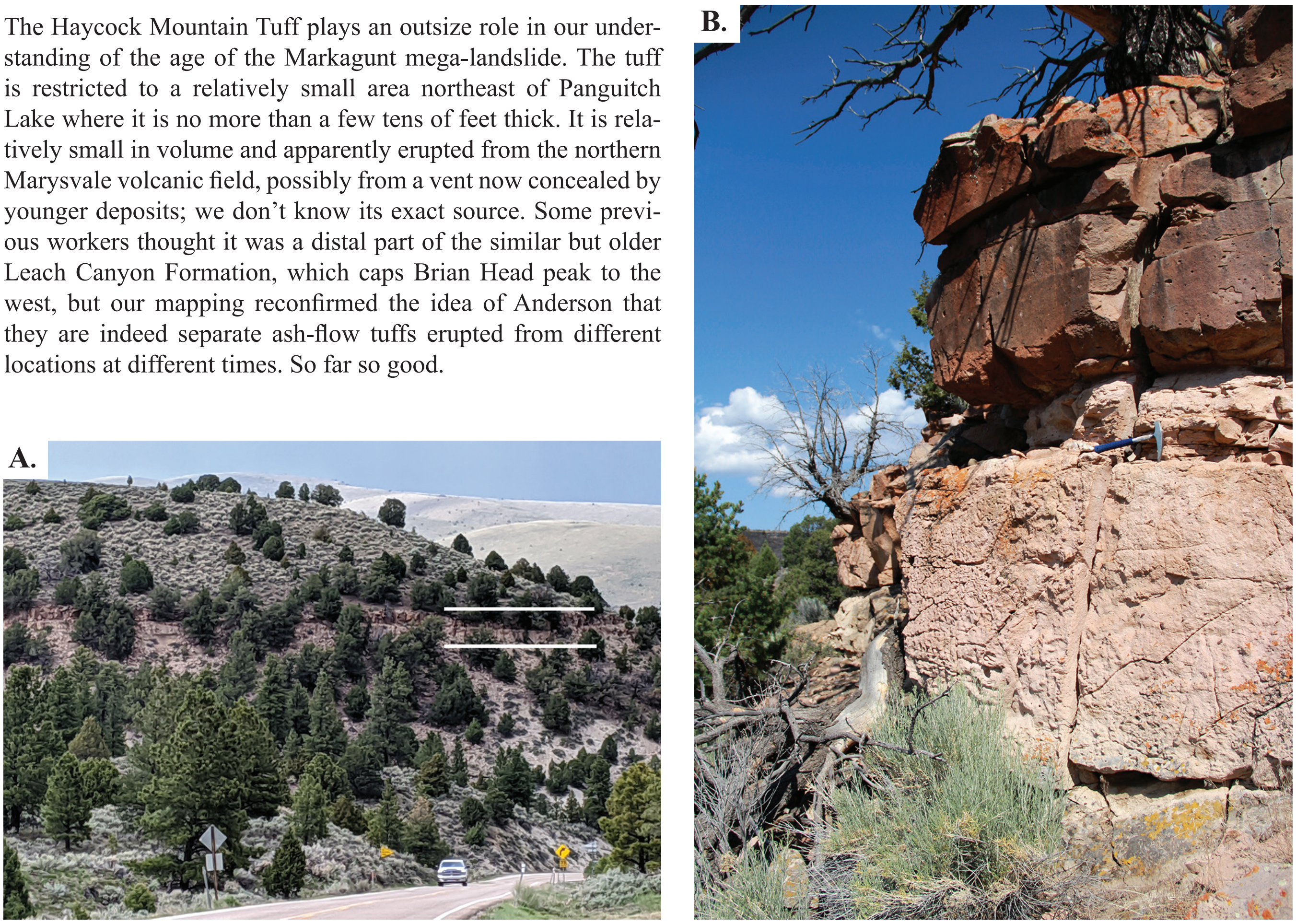
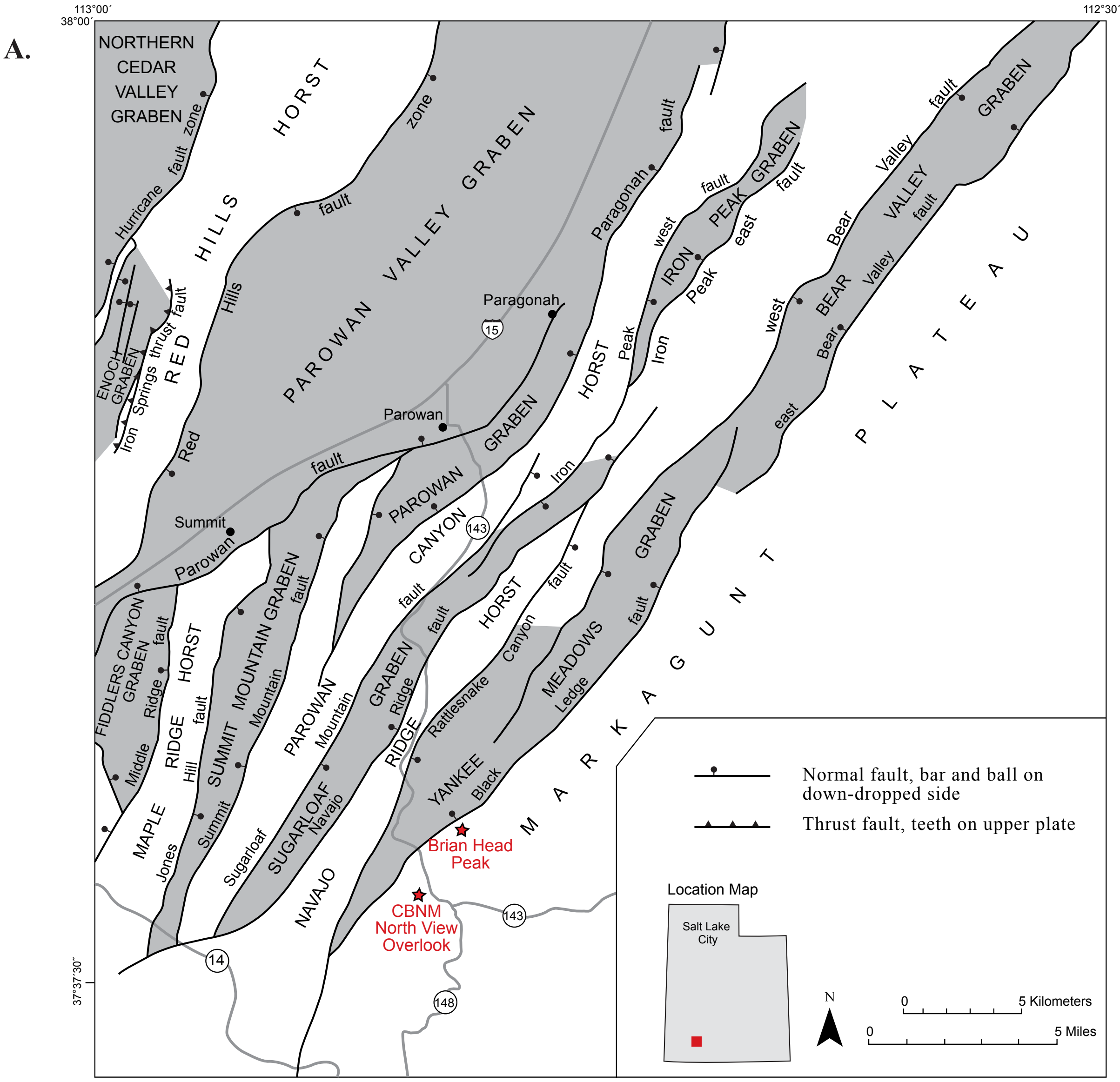


*Figure A-12. **(A)** The 22.7 Ma Haycock Mountain Tuff immediately west of the White Bridge campground; view north. **(B)** Close-up of the tuff showing its slightly more resistant upper part. Photo courtesy of Shannon Hunter.*

Locality 6: Parowan Canyon

Parowan Canyon drains the west flank of the Markagunt Plateau and provides a route for Utah Highway 143 to climb to the plateau's summit over 5000 feet (>1500 m) above the floor of Parowan Valley. The plateau is uplifted with respect to the adjacent valley by high-angle normal faults, some of which create a series of horsts and grabens at the plateau's west edge (figure A-13A). 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 (German, respectively, for "heap" and "ditch or trench") step down from the plateau



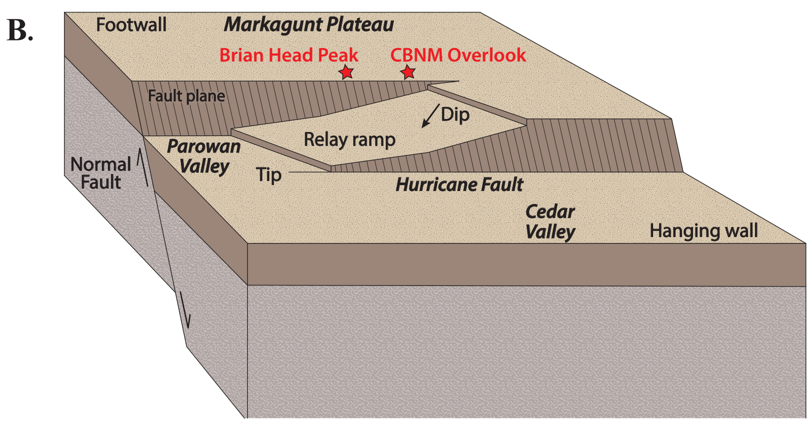


***Figure A-13. (A)** Major faults of the western Markagunt Plateau and Red Hills and named grabens (shaded) and horsts. CBNM = Cedar Breaks National Monument. **(B)** Diagram of a relay ramp between parallel strands of a fault zone. The relay ramp links displacement between the faults and is a different structural feature than the mega-slide ramps. From Biek and others (2015).*

to the valley floor forming a highly faulted relay ramp between the Paragonah fault and the Hurricane fault (figure A-13B). The grabens preserve younger rocks, including those of the Black Mountains mega-slide, since stripped off the adjacent upthrown horst blocks. They also preserve the colorful Claron Formation (famously exposed at nearby Cedar Breaks National Monument), which stands in vivid contrast to the brown Cretaceous strata of the horst blocks, a sight readily apparent from the vantage point of Brian Head peak or even Google Earth imagery.

Location

This overview location is about 0.75 mile (1.2 km) south of Utah Highway 143 on Dry Lakes Road, at a bend in the road under the powerline (coordinates: 337605mE, 4180297mN; 37º 45' 20.1" N, -112º 50' 36.5" W). Turn around just uphill around the bend; private land abuts both sides of the Dry Lakes Road south of the highway.

What You Will See

Here at the northwest end of Braffit Ridge the 27 to 26 Ma Isom Formation rests on the 22.0 Ma Harmony Hills Tuff in a classic older-on-younger relationship characteristic of the slide mass on the former land surface (figure A-14). Older geologic maps of the area show these ash-flow tuffs separated by a concealed and unusually sinuous normal fault. But upon closer examination, we see that this fault is tilted gently southeast, with older Isom as part of the slide in its upper plate and younger Harmony Hills of the former land surface below. Better exposures of this slip surface are on the corresponding ridge just south of Utah Highway 143, where it is marked by a thin layer of Brian Head debris (the "grease" at the base of the mega-slide), but these outcrops are on private land. The same relationship is better exposed to the west in Summit Canyon, which provides some of the most complete exposures of regional ash-flow tuffs commonly found on the Markagunt Plateau.

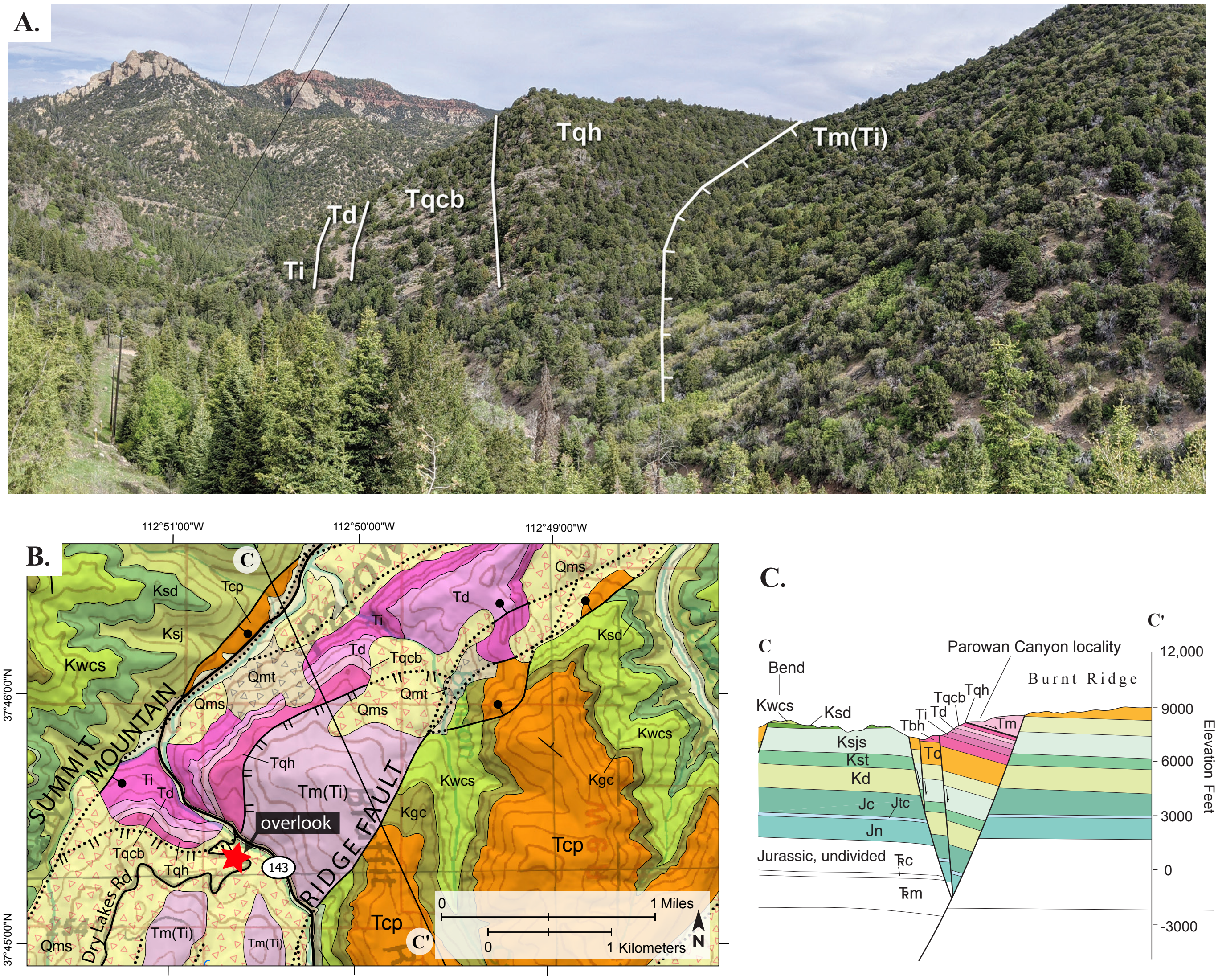


*Figure A-14. **(A)** Northwest end of Braffit Ridge showing densely wooded older Isom Formation (Tm[Ti]) as part of the Black Mountains mega-slide atop younger Harmony Hills Tuff (Tqh). White line with tic marks shows basal slip surface of mega-slide. Craggy exposures of the Late Cretaceous Grand Castle Formation are on the skyline at left. **(B)** Geologic map of Parowan Canyon; red star shows location of overlook and **(C)** cross section through Braffit Ridge (from Biek and others, 2015). See figure A-2c for stratigraphic column of rock units in this area.*

Locality 7: Ramp

The ramp is where the basal slip surface of the mega-landslide climbs up onto the former land surface. This is where the basal slip surface "daylights," unambiguous evidence that it is not a low-angle earthquake fault deeply rooted in the earth's crust. The Markagunt ramp is well exposed in a perfect cross section at the north end of Black Ledge because here the slide mass was cut longitudinally by the younger Black Ledge basin-range normal fault.

Location

A cross section of the Markagunt ramp is located about 2 miles (3 km) southwest of Little Creek Peak, southeast of Red Creek Reservoir. The ramp is best viewed from a distance in the afternoon, for example near the intersection of FR077 (Little Creek Canyon Road/Upper Bear Valley Road) and Horse Valley Road (figure A-15A) (coordinates: 353790mN, 4194500mN; 37º 53' 10.6" N, -112º 39' 45.7" W). The coordinates of the ramp itself are about 354930mE, 4190299mN; 37º 50' 55" N, -112º 38' 56" W).

What You Will See

The north-dipping ramp separates a lower plate of undeformed Isom Formation in the footwall from Isom, Bear Valley, and Mount Dutton Formations in the hanging wall; slivers of Brian Head and Wah Wah Springs strata are also present at the base of the mega-slide (figure A-15B). The formations of the upper plate can be traced continuously up the ramp and onto the former land surface. Upper plate rocks are highly attenuated south of the ramp, having spread out and thus thinned as they moved southward. Prior to emplacement of the Markagunt mega-slide, the area south of what was to become the ramp was a landscape developed on resistant Isom ash-flow tuff. Only a few thin tongues of Mount Dutton volcanic mudflow breccia, likely confined to broad channels eroded into the Isom, reached this far south before slide emplacement; locally we can see them below the slide mass. The ramp area was, in essence, the southern margin of the Marysvale volcanic field.

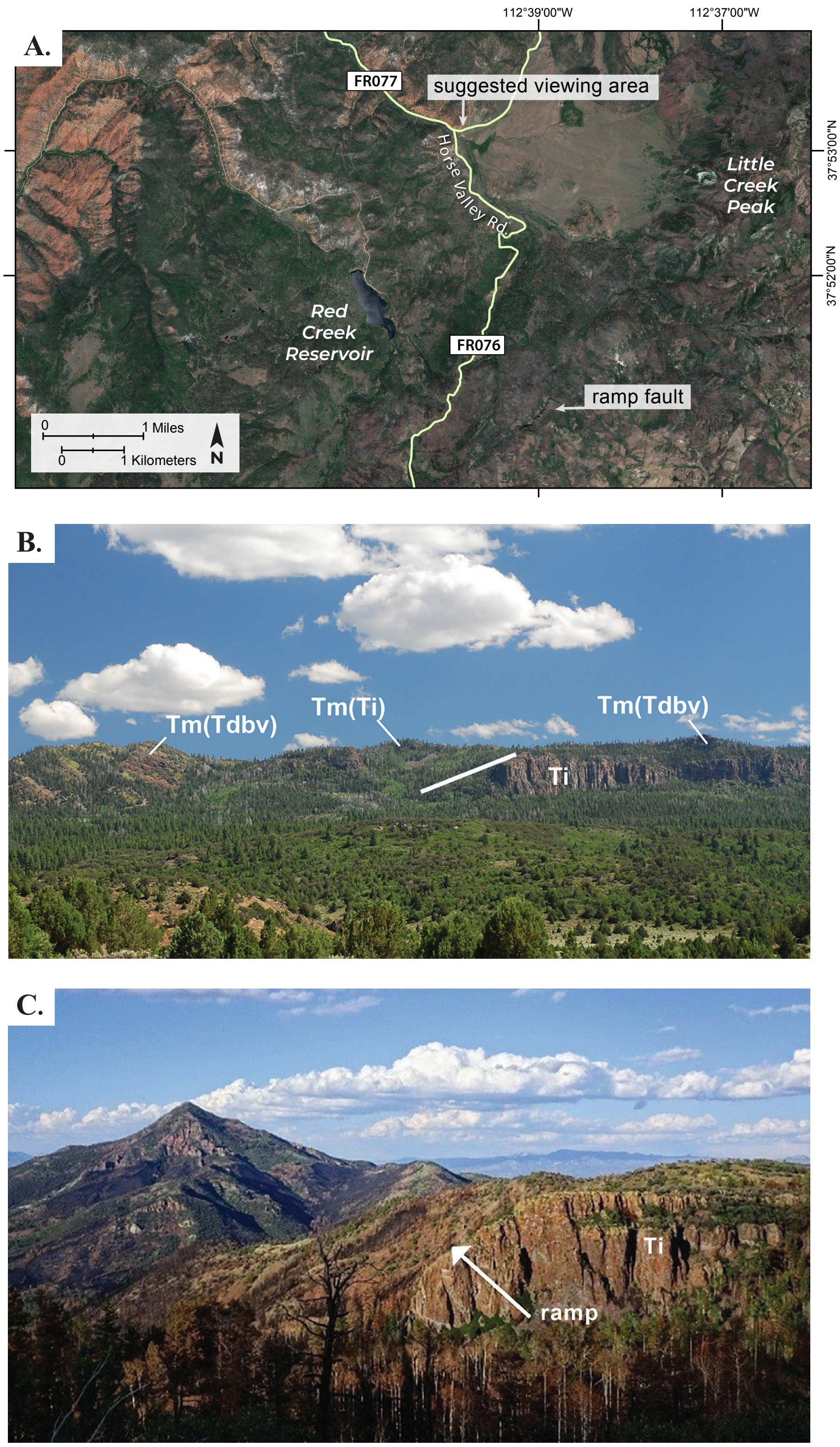


Figure A-15. (A) *Map showing viewing location of the Markagunt mega-slide ramp.* ***(B)*** *View southeast of Black Ledge, showing north-dipping ramp (white line) that places deformed Mount Dutton and Bear Valley Formations (Tm[Tdbv]), and Isom Formation (Tm[Ti]), on top of undeformed Isom Formation (Ti). The ramp is where the basal slip surface of the mega-slide "daylights," showing that it is not a tectonically rooted earthquake fault. South of the ramp, undeformed Isom Formation forms Black Ledge, an unbroken cliff that extends southward to Brian Head peak.* ***(C)*** *View northeast toward Little Creek Peak. North- (left) dipping ramp, visible in center, cuts up and over cliffs of lower-plate Isom Formation (Ti). Upper plate rocks are mostly Mount Dutton and Bear Valley volcanic mudflow breccia and lava flows.*

Locality 8: Paunsaugunt Thrust Faults

The Paunsaugunt thrust fault zone is an odd geologic feature, seemingly out of place in both time and space. As described earlier in the History of Discovery section, the zone consists of several thrust faults that form an arcuate belt around the southeast margin of the Marysvale volcanic field (figure 19). These south-vergent thrust faults involve strata that postdate the Sevier orogeny and they lie at right angles to older Sevier-age compressional structures. Rock layers that did not exist at the time of that mountain-building episode are deformed by thrust faults of an odd orientation. How could this be?

Geologists at the University of Arizona figured out this conundrum in the late 1980s and early 1990s when they showed that this unusual thrust deformation formed between 30 and 20 million years ago in response to gravitational spreading of the Marysvale volcanic field.

Location

This locality is in Bryce Canyon National Park and, although only a few tens of feet off Utah Highway 12, is managed as wilderness. The site is best viewed from the Bryce Canyon "Dark Skies" pullout, whose coordinates are 400815mE, 4171233mN; 37º 40' 58.6" N, -112º 07' 29.5" W.

What You Will See

Here, the lower splay of the Paunsaugunt thrust fault duplicates the pink member of the Claron Formation (figure A-16). As described earlier, for Utah, such a fault is unusual in that it displaces strata that postdate the Sevier orogeny and does so with a sense of motion oriented at a right angle to those earlier compressional structures.

***Figure A-16. (A)** Oblique aerial view of the lower Rubys Inn thrust fault (white line, the main thrust of the Paunsaugunt thrust fault zone), which here duplicates Claron strata in Bryce Canyon National Park. The "Dark Skies" turnout on Utah Highway 12 is at the lower right. **(B)** Biek "holding up the roof" of the lower splay of Rubys Inn thrust fault just above the turnout.*

Locality 9: Cottonwood Canyon

Cottonwood Canyon, on the east flank of the Sevier Plateau, exposes what we interpret to be the basal deformation zone of the Sevier mega-slide that here sits on undeformed Wah Wah Springs Formation. This zone contains broken and jumbled blocks of Brian Head and Three Creeks Tuff Member strata all cut by shears and clastic dikes. But the most important feature here is the thoroughly broken chaotic mass of the Three Creeks Tuff Member itself (figure 14A and B). This crystal-rich ash-flow tuff erupted 27 million years ago from a caldera on the north flank of the Marysvale volcanic field. It looks remarkably similar to the 30 Ma Wah Wah Springs ash-flow tuff, which erupted from the Indian Peak caldera on the Utah-Nevada border. Both are well exposed north of the ramp, one on top of the other, in normal sequence in Kingston Canyon not far to the north. Here, however, the Three Creeks Tuff Member looks like a rubbly flow breccia, something that for an ash-flow tuff of this composition is unknown elsewhere. We interpret the brecciation to be a result of proximity to the Sevier ramp, where the slide mass, with Three Creeks Tuff at the base of the upper plate, moved up onto the former land surface.

Location

FR125 provides access to Cottonwood Canyon, but the last mile (1.6 km) of the road to the Table Mountain–Hunt Creek trailhead parking area is often passable only by high-clearance vehicles (figure A-17). The coordinates of the parking area are 402324mE, 4200308mN (37º 56' 42.4" N, -112º 06' 42" W); breccia of the Three Creeks Member is widely exposed, but a good locality is at 402248mE, 4200466mN (37º 56' 47.5" N, -112º 06' 45.2" W); the basal shear plane, developed on a thin Mount Dutton volcanic mudflow, is present east of the parking area at 402656mE, 4200654mN (37º 56' 53.75" N, -112º 06' 28.6" W); injectites and cataclastically deformed Three Creeks are exposed at and near 402107mE, 4200509mN (37º 56' 48.85" N, -112º 06' 51" W); a secondary shear surface, developed on the Kingston Canyon Tuff Member vitrophyre carries Mount Dutton mudflows in its upper plate at 401651mE, 4200535mN (37º 56' 49.5" N, -112º 07' 09.7" W). A geologic map of the area (figure A-17B) and stratigraphic column of rock units (figure A-17C) give context to these localities.

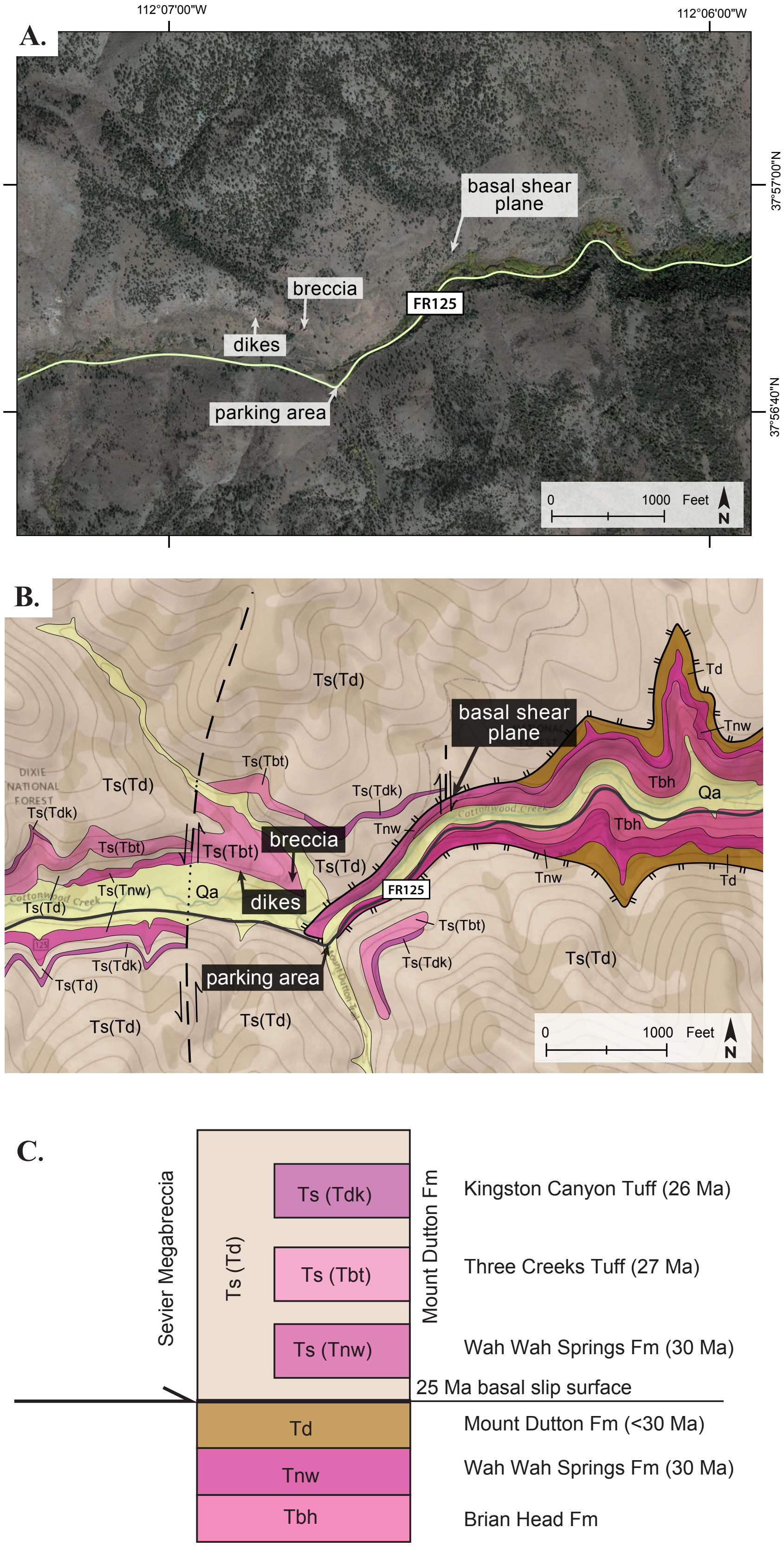


Figure A-17. ***(A)*** *Map showing Cottonwood Creek area. Access is via FR125, typically passable by high-clearance vehicles.* ***(B)*** *Geologic map of the Cottonwood Canyon area, courtesy of Zach Loffer.* ***(C)*** *Stratigraphic column showing selected map units in Cottonwood Canyon.*

What You Will See

Here, visitors can see blocks of the Three Creeks Tuff Member and Brian Head strata jumbled together and cut by clastic dikes (figure A-18A and B), a small exposure of the grooved and striated basal slip surface (figure A-18C), and a secondary shear surface, developed on the Kingston Canyon Tuff Member a bit higher in the hillside. The main attraction, however, is the Three Creeks Tuff Member itself which is thoroughly brecciated from top to bottom (figure 14). Such deformation postdates eruption of the tuff and records brittle failure during slide emplacement.

A.

B.

C.

Figure A-18. (A) *Three Creeks Tuff Member cut by shears and clastic dikes (above hammer).* ***(B)*** *Clastic dikes in Three Creeks strata.* ***(C)*** *View southwest up Cottonwood Creek. Ledge shows Wah Wah Springs Formation, here capped by a thin remnant volcanic mudflow breccia that has faint, north-south grooves and striations (parallel to hammer handle).*

Locality 10: South End Sevier Plateau

The south end of the Sevier Plateau exposes an unusual, exceptionally thick mega-slide basal layer and underlying Brian Head strata containing small-displacement, south-vergent thrust faults and folds. This zone of deformation is well exposed for about 300 feet (100 m) along the Brian Head–Mount Dutton contact. The basal layer is at least 80 feet (25 m) thick and contains severely deformed, silicified blocks likely of the Three Creeks Tuff Member; they appear almost as stretched pieces of taffy but likely resulted from extreme cataclastic flow (figures 13A–C). The resistant, elongated blocks are encased in a sheared matrix of crushed Mount Dutton and Brian Head strata, which we interpret as the basal layer formed during emplacement of the Sevier mega-slide.

Location

Well-graded FR116 (Tom Best Springs Road) provides access to the southern Sevier Plateau, but the last 2 miles (3.2 km) to this locality on FR183 requires a high-clearance vehicle (figure A-19A). The coordinates of the suggested parking area are 4200535mE, 4184376mN (37º 48' 02.2" N, -112º 12' 17.7" W). The hike to the outcrop itself at 394145mE, 4185046mN (37º 48' 24" N, -112º 12' 09" W) is a difficult, steep, off-trail scramble of nearly one mile (1.6 km). In lieu of that, a large rockfall block of the basal layer is more accessible near the base of the slope at 394094mE, 4184797mN (37º 48' 15.91" N, -112º 12' 10.96" W.). For comparison, a block of typical Mount Dutton volcanic mudflow breccia is about 400 feet (120 m) to the southwest at 394026mE, 4184709mN (37º 48' 13.03" N, -112º 12' 13.70" W).

What You Will See

The large, angular boulder that tumbled to the base of the hillside (figure 13A) is part of the exceptionally thick basal layer (figure A-20A) that separates fine-grained, volcanic ash-rich sandstone and mudstone of the Brian Head Formation from overlying volcanic mudflow

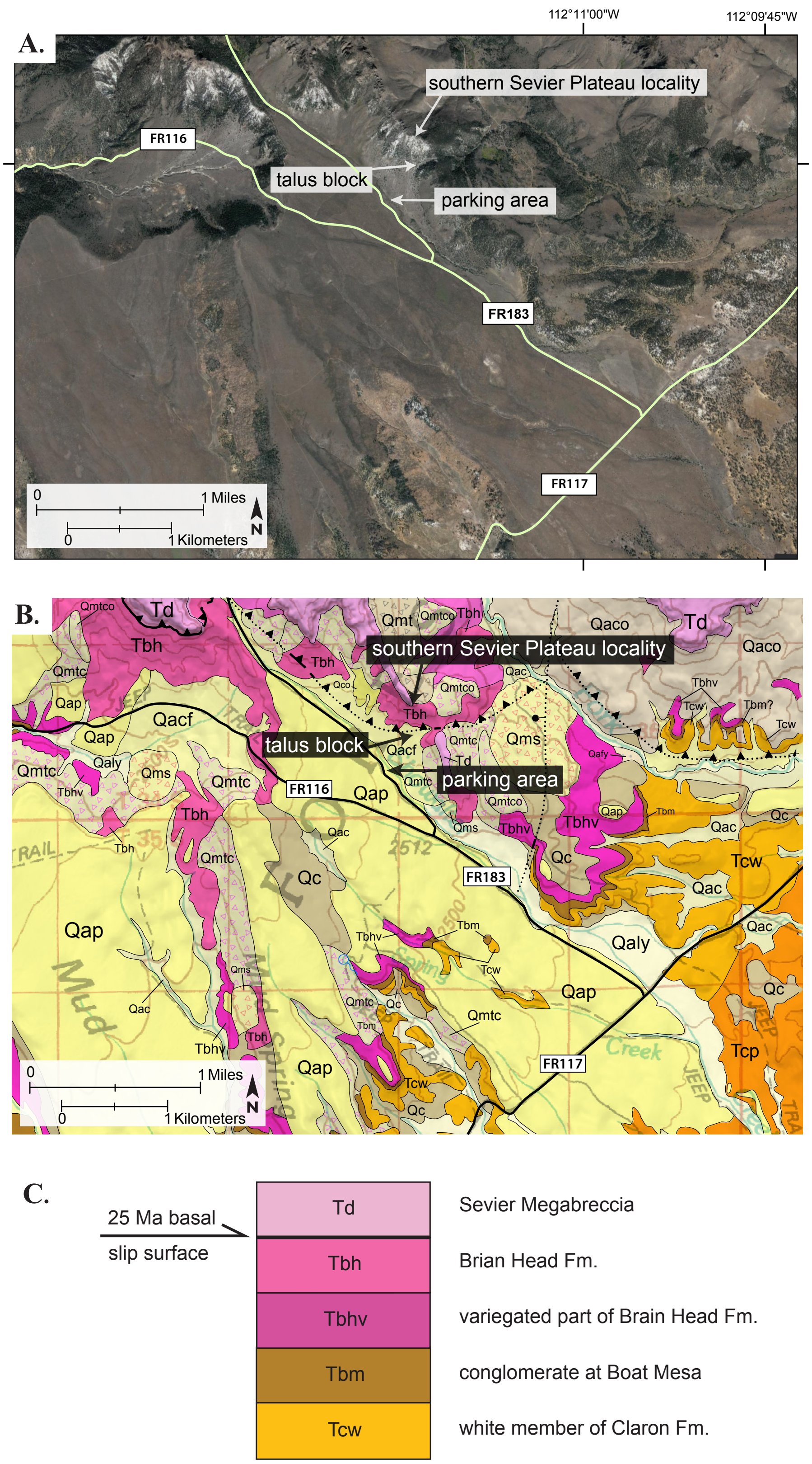


Figure A-19. (A) *Location map of the southern Sevier Plateau area.* ***(B)*** *Geologic map of the southern Sevier Plateau from Biek and others (2015). Note that we originally interpreted deformation there to be a result of an inferred splay of the Paunsaugunt thrust fault zone (dotted line with black triangles), but now know that the contact of the Brian Head Fm. (Tbh) and the overlying Mount Dutton Fm. (Td, light pink) is the basal slip surface of the Sevier megalandslide and so is better labeled as Ts(Td).* ***(C)*** *stratigraphic column of selected map units at the southern Sevier Plateau* deposits of the Mount Dutton Formation. The basal layer is cut by shears and contains intensely deformed fragments of ash-flow tuff (figure A-20B). In some places along the length of the Sevier mega-slide, the basal slip surface is sharp, with delicate sedimentary structures preserved in Brian Head strata immediately below the slide plane. But here, in the cliffs above the boulder, the base of the Sevier mega-slide is characterized by a zone of deformation that reaches down into uppermost Brian Head strata, revealing small-displacement thrust faults and folds (figure A-20C), and, farther west, chaotically jumbled Brian Head blocks (figure A-20D).

A.

B.

C.

D.

Figure A-20. ***(A)*** *Exceptionally thick (~80 feet [25 m]) basal layer at the south end of the Sevier Plateau, with Brian Head (Tbh) and Mount Dutton strata as part of the Sevier mega-landslide (Ts[Td])* ***(B)*** *Three-foot-long (1 m) silicified block of ultracataclastically deformed ash-flow tuff (probably the Three Creeks Tuff Member).* ***(C)*** *Base of the Sevier mega-slide (red line) showing small fault-propagation fold (white line) at base of slide, and* ***(D)*** *chaotic zone of jumbled Brian Head blocks.*

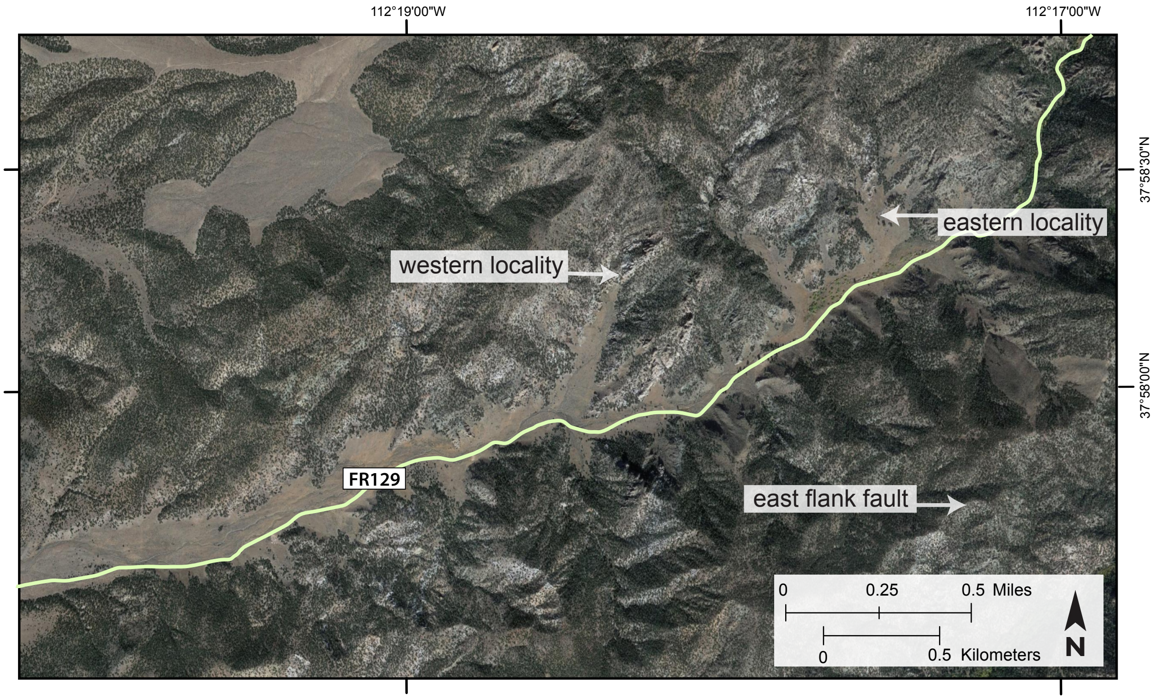
Locality 11: Smith Canyon

Smith Canyon, on the west side of the Sevier Plateau, provides high-clearance 4WD access to the crest of the Sevier Plateau and the east flank of the Markagunt mega-slide and west part of the Sevier mega-slide. The lower reaches of the canyon, in the Markagunt slide, offer exceptional exposures of intensely fractured lava flows and less-deformed mudflow breccias of the Mount Dutton Formation, both of which are tilted westward near the east flanking sidewall breakaway of the Markagunt mega-slide. For reasons yet to be understood, the two lithologies responded differently to stresses involved in slide emplacement.

Location

We offer two locations in the lower reaches of the canyon that may be accessible by high-clearance vehicles but that may require 4WD depending on conditions of FR129 (figure A-21). The western area coordinates are 385331mE, 4203407mN (37º 58' 15.8" N, –112º 18' 19.9" W) and require a walk of about 1 mile (1.6 km) round trip across an alluvial fan followed by a short, steep scramble of about 100 feet (30 m) to the outcrop above. The eastern area coordinates are 386471mE, 4203660mN (37º 58' 24.5" N, –112º 17' 33.3" W) and are only about 800 feet (245 m) north of the road. FR129 is a popular ATV route, so be sure not to block the road and be sure not to park on dry grass.

A.



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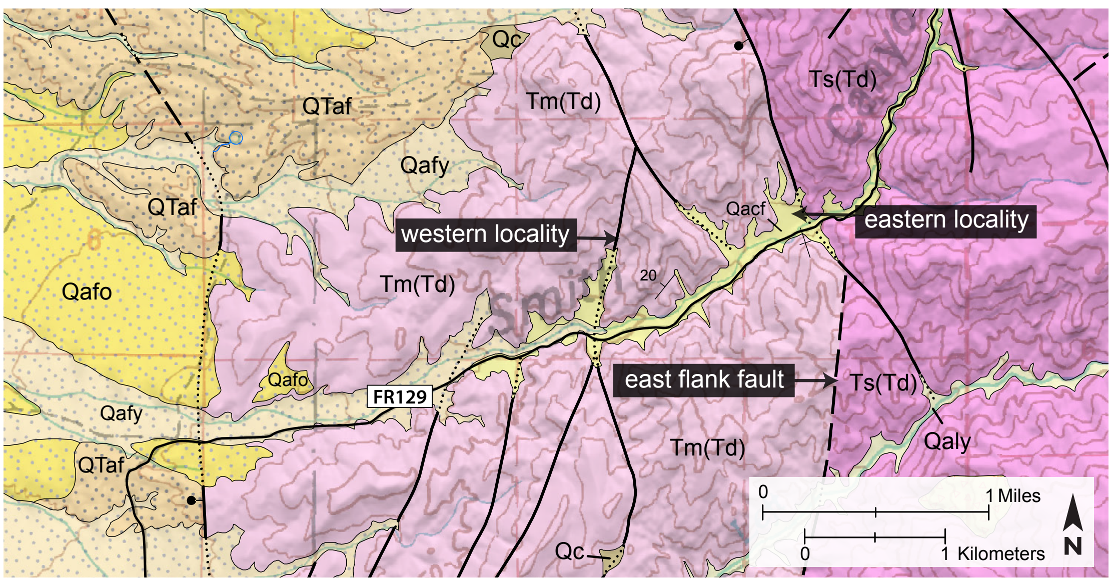


***Figure A-21. (A)** Location map of the Smith Canyon area showing western and eastern localities. **(B)** Geologic map. Ts(Td) and Tm(Td), Mount Dutton Formation volcanic mudflow deposits as part of the Sevier and Markagunt mega-landslides, respectively.*

What You Will See

At the western locality (figure A-22A), the base of a thick, thoroughly brecciated lava flow is well exposed, bounded below by a remarkable shear plane. The shear lies above a brown basal layer that ranges from less than 1 inch (2.5 cm) to 3 feet (1 m) thick and that is the source of clastic dikes in both lower and upper plate rocks. Grooves and slickenlines on the shear ("skid marks"), together with fractures, demonstrate emplacement from the north (figure A-22B). The lower part of this lava flow consists of a distinctly reddish-brown, exceptionally thick cataclasite with a prominent shear fabric and deformed blocks of the white overlying lava flow (figure A-22C).

A.

B.

C.

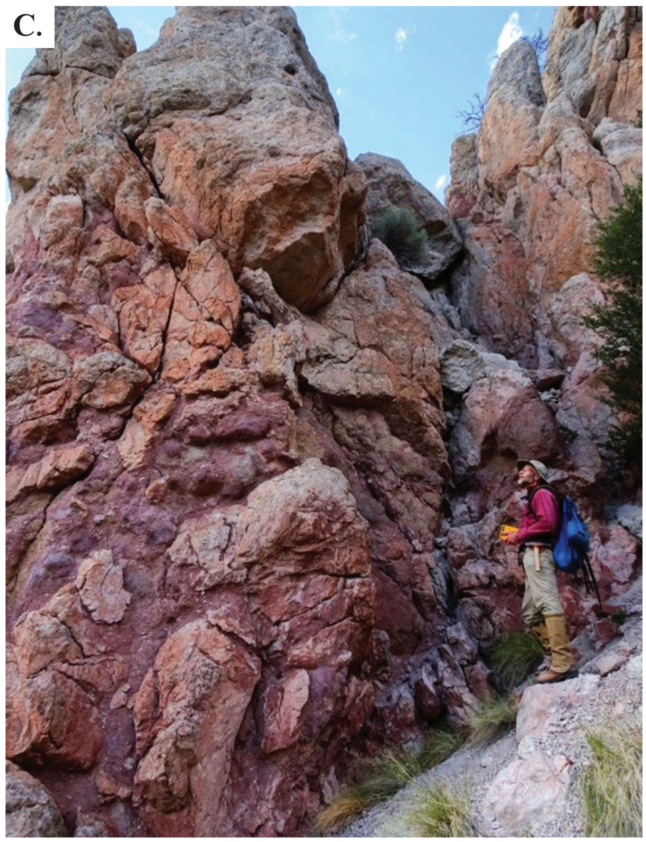


Figure A-22. (A) *View north to pale-gray, brecciated Mount Dutton lava flow with a prominent reddish-brown base.* ***(B)*** *Base of this deformed flow is a grooved and striated shear plane that lies above a thin basal layer (below hammer head). Clastic dikes derived from the basal layer are present in both lower and upper plate rocks.* ***(C)*** *Bob Biek at the base of the deformed lava flow, blocks of which are incorporated into a red, sheared cataclastic matrix. The matrix is present as injectites that reach 30 feet (9 m) or more up into the flow.*

The eastern locality is adjacent to the eastern sidewall breakaway of the Markagunt mega-slide. Here, the breakaway juxtaposes intensely sheared and brecciated lava flows and volcanic mudflows of the Mountain Dutton Formation to the west with relatively undeformed, subhorizontal Mount Dutton mudflows to the east (figure A-23A). Strata west of the breakaway dip moderately to steeply west (figure A-23B). We can track this breakaway, a left-lateral strike-slip fault that bounds the east edge of the Markagunt mega-slide, southward over 7 miles (11 km) along the west flank of the plateau; when looking across such a strike-slip feature, rocks on the opposite side appear displaced to the left. Here, that displacement is about 20 miles (32 km)!

A.

B.

***Figure A-23. (A)** Brecciated and sheared Mount Dutton Formation lava flow exposed along the eastern sidewall breakaway. **(B)** View south across Smith Canyon showing steeply west-dipping volcanic mudflow breccia and lava flows characteristic of the hanging wall of the eastern sidewall breakaway. The breakaway strikes southward through the saddle in center of the photo. Note subhorizontal Mount Dutton strata east (left) of the breakaway. White lines indicate bedding orientation.*

Locality 12: Circleville Canyon

Circleville Canyon, the northern end of which is just southwest of Circleville, is about 12 miles (20 km) long and at least 1000 feet (300 m) deep, along the bottom of which is U.S. Highway 89. The rocks on both sides consist largely of andesitic volcanic mudflow breccias and lesser lava flows of the Mount Dutton Formation, the alluvial and vent facies, respectively, of multiple volcanic vents. The sequence must be at least 3300 feet (1000 m) thick here, striking and dipping at various angles and with few marker beds to tell us relative age of one area with respect to the other. Some of the attitudes are depositional as a result of having been built up at different eruptive areas.

The Spry intrusion, a large, 26.1 Ma laccolith, marks the south end of the canyon. Like many of southwest Utah's mushroom-shaped intrusions, it was emplaced into the Claron Formation likely at a depth less than 1000 feet (300 m). Arching of the overlying crust produced gravity-slide blocks shed into then-low areas surrounding the intrusion, like most other laccoliths we have mapped. All deposits we see in the canyon, including the Spry intrusion, are part of the Markagunt megaslide, even the blocks previously shed off the Spry (unfortunately not visible from the highway). Some rocks thus have a two-fold history of gravity-slide deformation!

Location

This locality is a road cut on the west side of U.S. Highway 89, with coordinates: 384580mE, 4221212mN; 38° 07' 53" N, –112° 19' 01" W. A low ridge just east of the road offers a good vantage point for viewing and morning photography (figure A-24).

What You Will See

This road cut exposes a half-dozen small-displacement normal slip surfaces along which the rocks are tilted (figure A-25). The slip surfaces are oriented east-west, perpendicular to the southerly movement direction of the gravity slides (and perpendicular to younger, mostly north-south-oriented basin-range faults). These east-west slip surfaces are common features in the northern parts of the slides and record extension as the slide mass moved away from the Marysvale highlands. Features like these with small displacement are difficult to see without such road cuts, but they mimic similar and much larger slip surfaces clearly visible on aerial imagery.

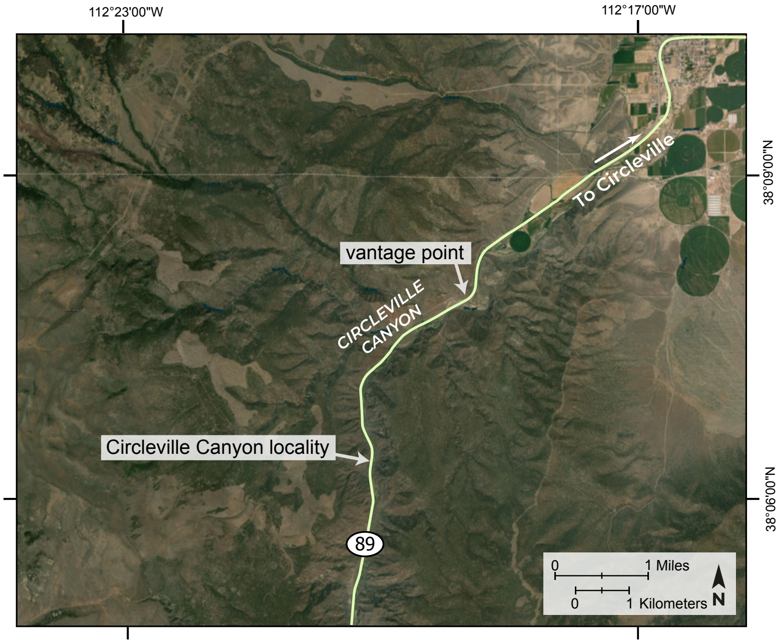


Figure A-24. Location map of the Circleville Canyon area.

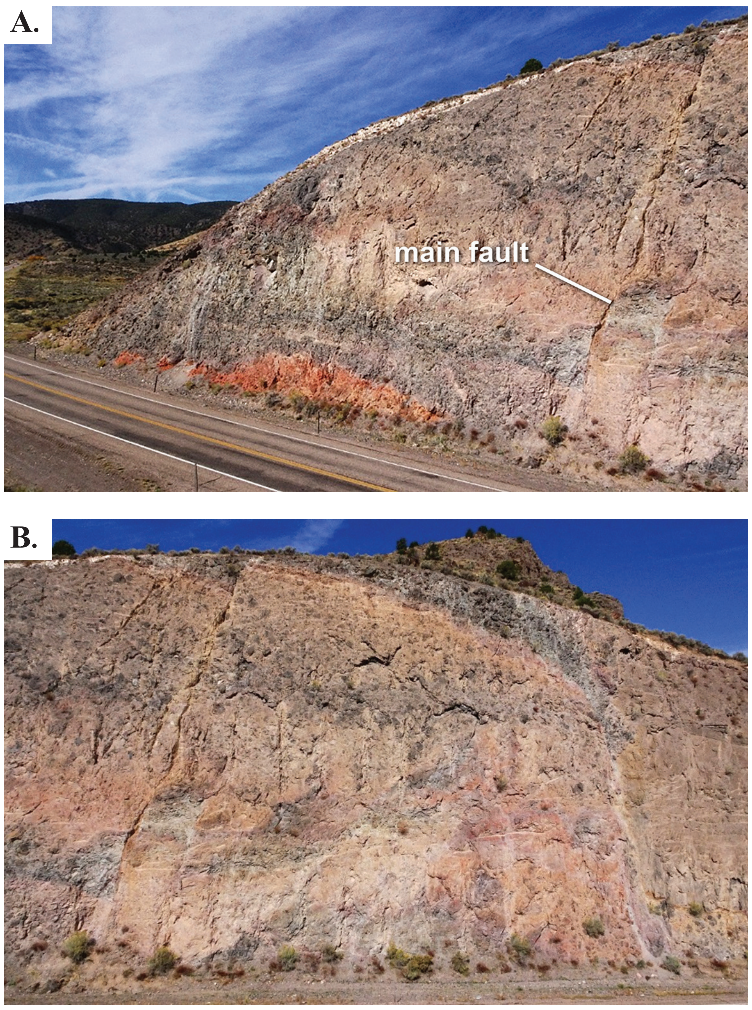


Figure A-25. East-striking, alternating north- and south-dipping slip surfaces in a U.S. Highway 89 road cut. ***(A)*** South end of road cut. ***(B)*** Central part of road cut. Photos overlap at main slip surface.

Locality 13: Mount Belknap Breakaway

The gleaming white top of the Tushar Mountains, much of it above timberline and reaching elevations of 12,000 feet (nearly 3700 m), is underlain by intracaldera lava flows and unwelded ash-flow tuff within the 19 to 18 Ma Mount Belknap caldera. The steep wall of the caldera is dramatically exposed just north of our breakaway locality (figure A-26A). The caldera is younger than the Markagunt mega-slide and mostly destroyed its main breakaway, but parts of the mega-slide are still visible. Here, the west flank of the Tushar Mountains is largely made up of dacitic lava flows of the Bullion Canyon Volcanics, into which the caldera was emplaced. This locality was previously mapped as the margin of the so-called Big John caldera, a major structure that we now interpret to be the main Markagunt breakaway. Here, you stand at the eroded main scarp of the mega-slide, whose deposits extend 60 miles (100 km) south past Brian Head peak.

Location

This locality lies immediately west of FR 123 at the head of the Markagunt mega-slide high in the Tushar Mountains at an elevation of nearly 11,500 feet (3500 m) at coordinates 377875mE, 4249577mN (38° 23' 9.85" N, –112° 23' 53.95" W) (figures A-26B and C). Park at the wide spot in the road just 300 feet (100 m) north of this locality. During the summer and early fall, FR123 is generally accessible by high-clearance 4WD vehicles; the last half mile (0.8 km) is narrow with many switchbacks and not recommended for inexperienced off-road drivers.

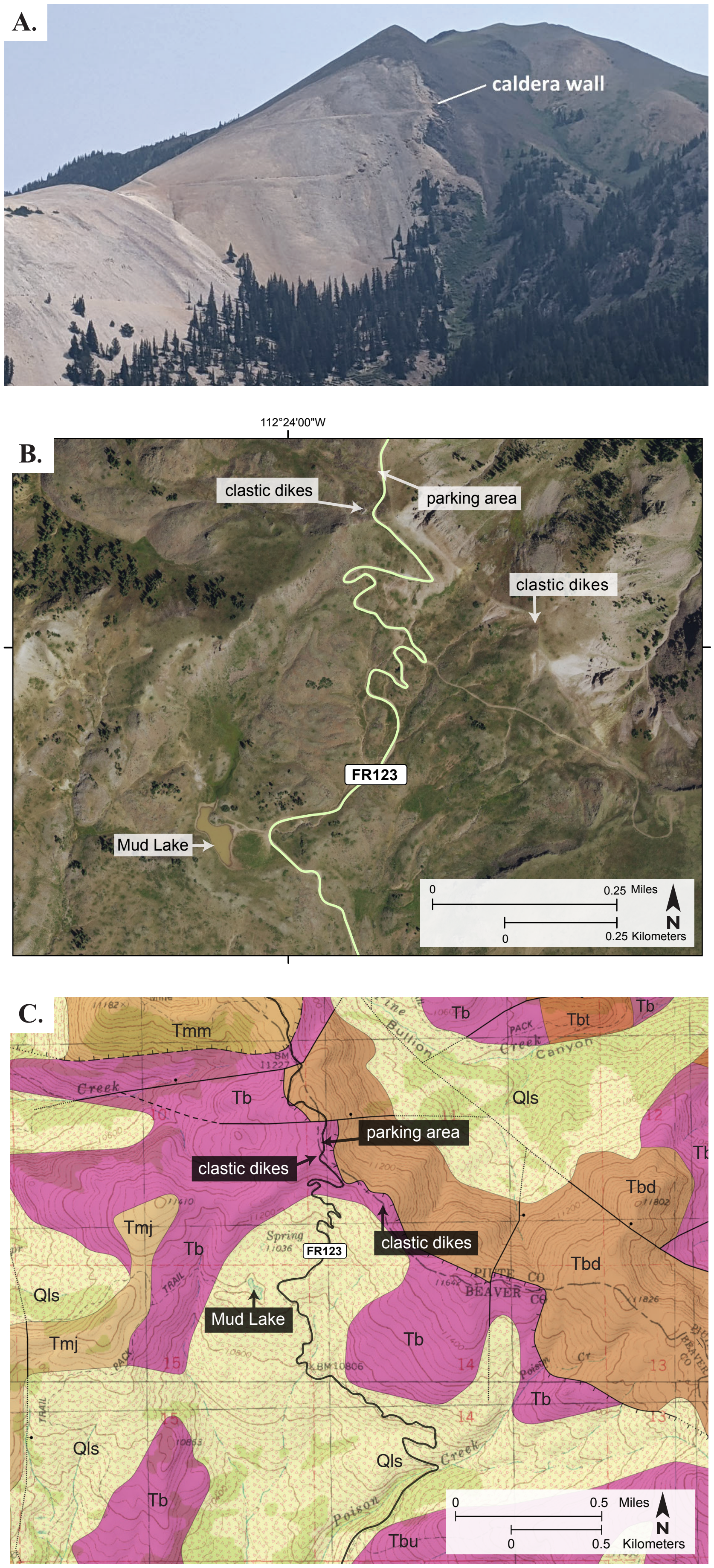


*Figure A-26. **(A)** Mount Belknap caldera wall seen from FR 123 on the east flank of Mount Belknap, about 2 miles (3.2 km) north of our breakaway locality. Note lighter-colored, intracaldera rhyolite lava flows juxtaposed against older, darker-colored Bullion Canyon Volcanics. The caldera, or crater, formed following the eruption of the 19 Ma Joe Lott Tuff. **(B)** Location map of the Mount Belknap breakaway; note hummocky surface of modern landslide north of Mud Lake and FR123. **(C)** Geologic map of the area; hachured line indicates main breakaway of the Markagunt mega-slide, with Bullion Canyon Volcanics shown in pink down to the south against the Delano Peak Tuff Member shown in brown.*

What You Will See

The parking area here is in a low saddle underlain by nonresistant, fine-grained fault gouge that marks the contact between the thick, undeformed Delano Peak Tuff Member of the Bullion Canyon Volcanics to the north and deformed lava flows of the Bullion Canyon Volcanics to the south. Hydrothermal fluids from the Mount Belknap caldera have slightly altered the rocks in the breakaway. Large blocks of the deformed rocks are present, however, at the head of a modern landslide immediately southwest of the parking area (figure A-27A and B), which is a popular spot for viewing Rocky Mountain bighorn sheep. Here, gray, highly brecciated and sheared lava flows of the Bullion Canyon Volcanics are cut by reddish-brown clastic dikes. Such dikes are also present along the ridgecrest to the southeast, midway to an abandoned communication site (figure A-27C and D).

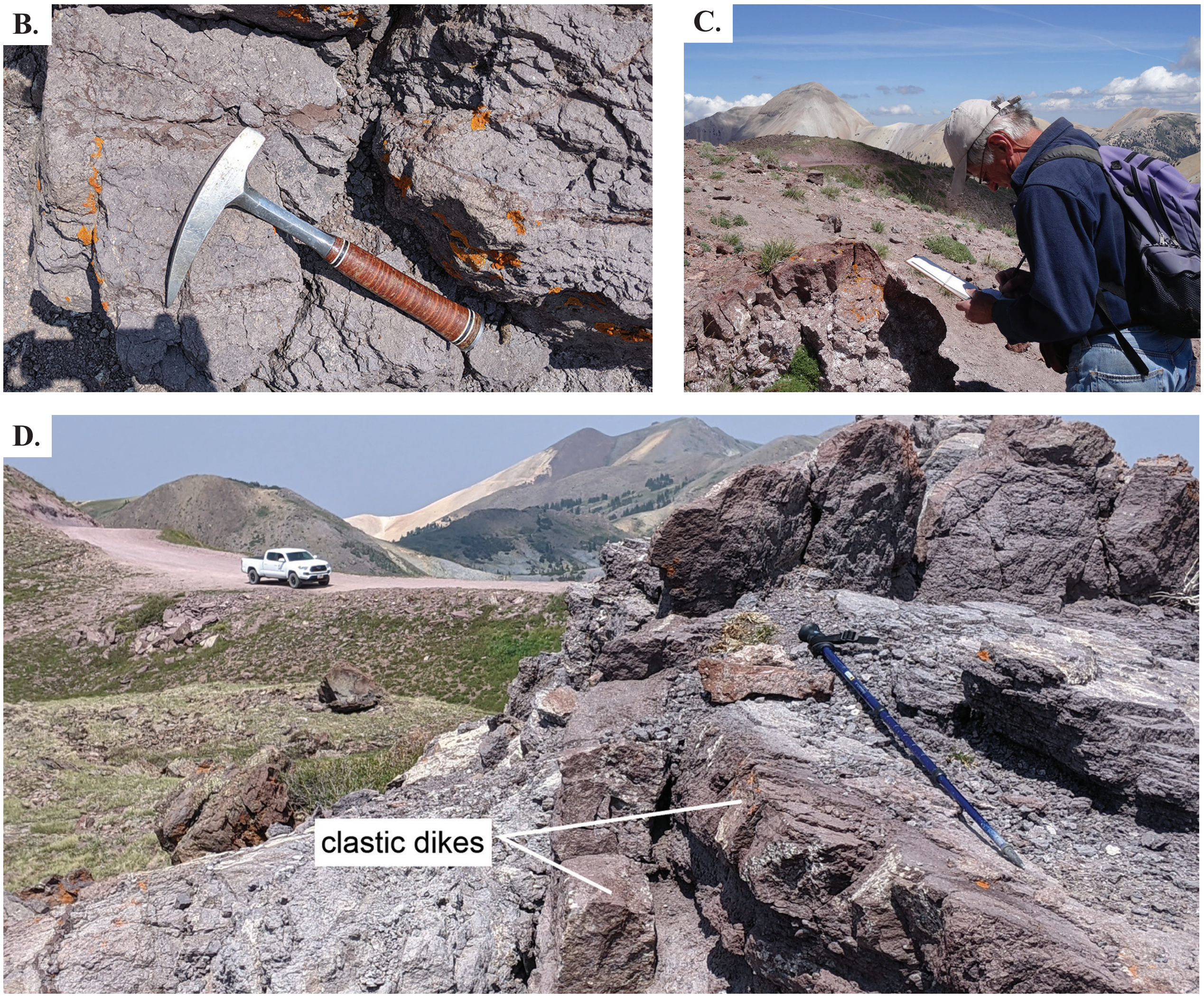


Figure A-27. (A and B) *Resistant, darker-colored clastic dikes in deformed Bullion Canyon Volcanics.* ***(C)*** *Clastic dikes exposed along the ridge crest to the southeast of the parking area, with Pete Rowley in the foreground and FR 123 and Mount Belknap in the distance.* ***(D)*** *Clastic dikes near parking area..*

Locality 14: Puffer Lake

The south shore of Puffer Lake exposes a badly fractured ash-flow tuff erupted 23.1 million years ago from the Monroe Peak caldera on the northern Sevier Plateau. This is the Osiris Tuff, one of the most distinctive and widespread ash-flow tuffs in the Marysvale volcanic field. The tuff is deformed here in the Tushar Mountains but not on the Sevier Plateau itself; it postdates emplacement of the older Sevier mega-slide but predates Markagunt mega-slide emplacement. The Osiris Tuff is thus an important unit in helping to differentiate adjacent masses of the Markagunt and Sevier slides elsewhere. Deformed Osiris Tuff at Puffer Lake was originally thought to be a result of eruption of the former "Big John caldera," but we now believe that what was formerly interpreted as the caldera wall is actually the main breakaway of the Markagunt mega-slide.

Location

This locality on the south shore of Puffer Lake is at coordinates 380740mE, 4241554mN (38° 18' 51" N, –112° 21' 51" W) (figure A-28). Utah Highway 153 is a well-graded gravel road accessible by car.

What You Will See

The rocks on the south shore of the lake and west of the breakaway are the Osiris Tuff, which is spectacularly sheared and brecciated with local quartz veins (figure A-29A and B). The shears mostly dip steeply south to southwest, locally contain slickensides, and in places have fractures known as Reidel shears that demonstrate down-to-the-south movement. Some of the shears are closely spaced and deformation resembles that of a sliding deck of cards.

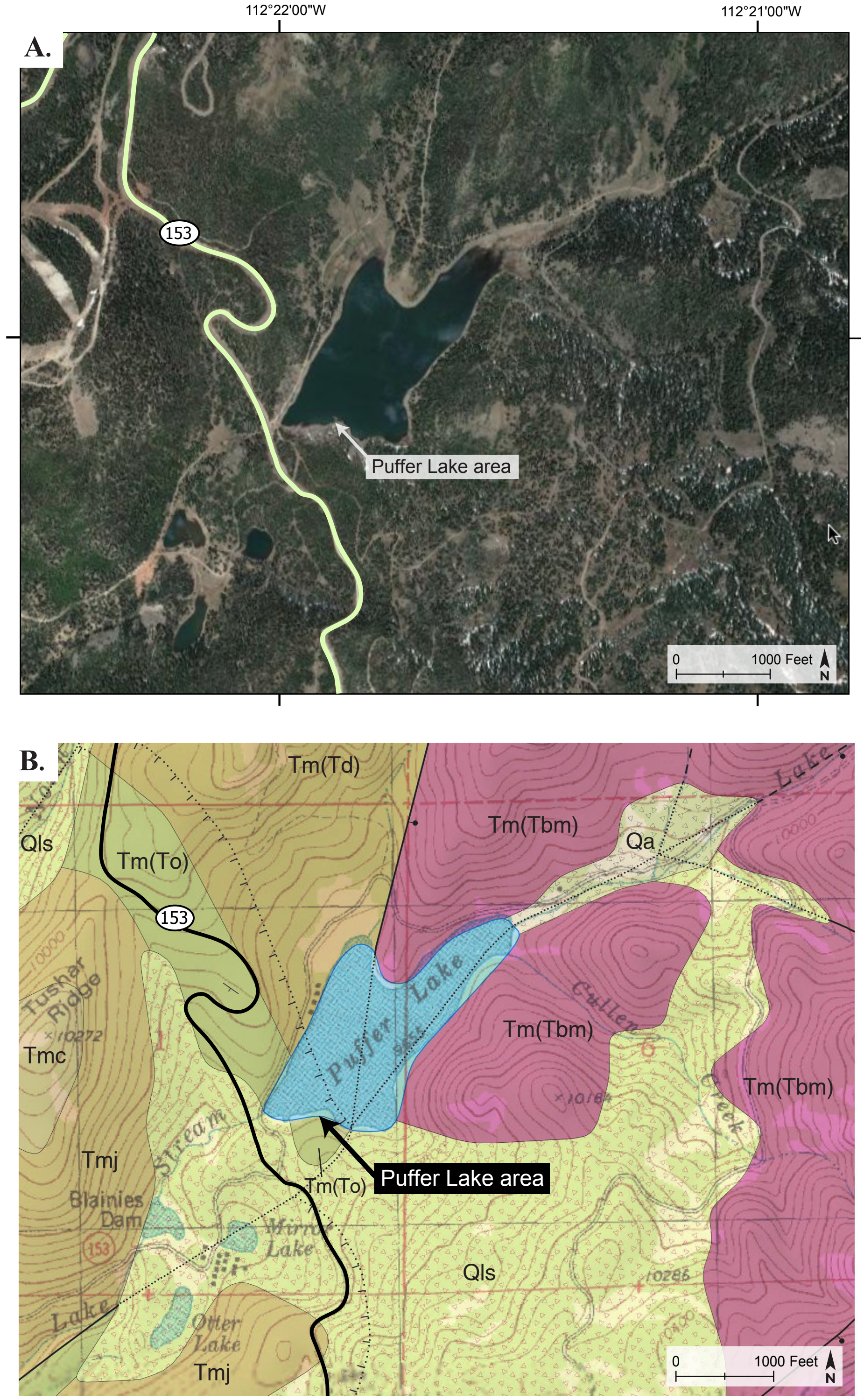
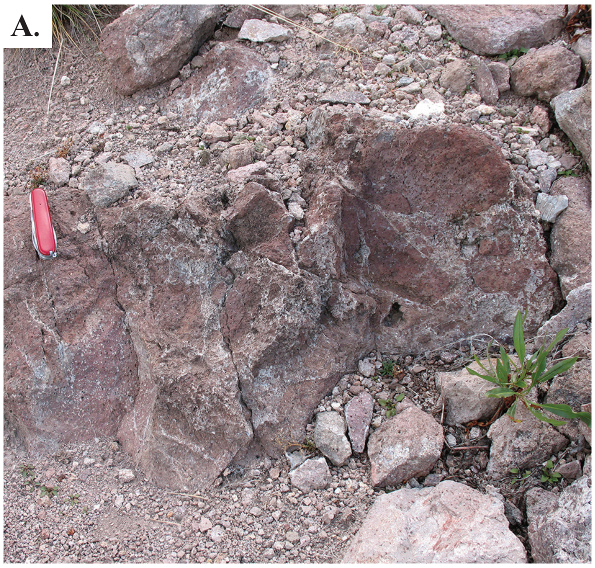


Figure A-28. ***(A)*** *Map showing Puffer Lake area and outcrops of brecciated Osiris Tuff.* ***(B)*** *Geologic map of the area showing Osiris Tuff (light green) on the south shore of Puffer Lake. Tmc, crystal-rich tuff member of Mount Belknap Volcanics; Tmj, Joe Lott Tuff Member of Mount Belknap Volcanics; Tm(Td), Mount Dutton Formation as part of Markagunt megaslide; Tm(Tbm), Bullion Canyon Volcanics as part of megaslide.*

Deformation along the slip surface here is at least 60 feet (20 m) wide. From Puffer Lake the main breakaway strikes generally southeast (although cut by many younger basin-range faults) and passes just east of City Creek Peak and down the canyon of City Creek to Circleville Valley south of Junction. At least four subordinate breakaway structures are exposed in the nearby Eagle Mountain ski area just west of Puffer Lake (figure A-29C).



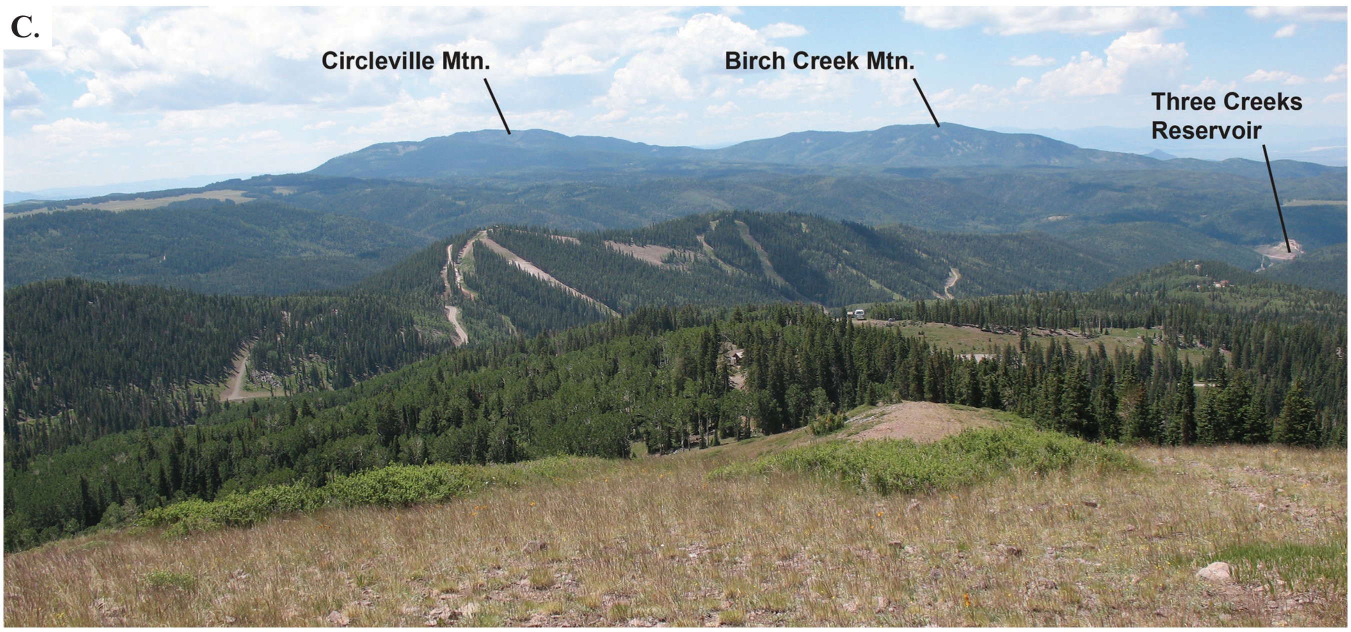


*Figure A-29. **(A)** Sheared and shattered Osiris Tuff on the south edge of Puffer Lake. **(B)** View west of high-angle shears in the Osiris Tuff. Puffer Lake is in the upper right. **(C)** View south of the southern Tushar Mountains from the footwall of one of the subordinate breakaways (at base of slope in foreground), beyond which are facilities and runs of the Eagle Mountain ski area. The area north of Circleville Mountain and Birch Creek Mountain is lower partly due to rocks being downthrown along several antithetic slip surfaces. All rocks in the view, including the barely visible farthest horizons, belong to the Markagunt mega-slide.*

ACKNOWLEDGMENTS

Our work builds on geologic mapping of the northern Markagunt Plateau begun by the late John Anderson with completion of his dissertation in 1965, and by Pete Rowley's mapping of the Sevier Plateau with completion of his dissertation in 1968. John's work and that of his many master's students, as well as Pete's work, eventually contributed to a larger 1970s to 1990s USGS project to map and understand the geology of the Marysvale volcanic field and nearby areas in southwest Utah and adjacent Nevada. This combined work laid a solid foundation for our geologic mapping of the south flank of the Marysvale volcanic field and adjacent areas. Our discoveries would not have been possible without these foundational studies by dozens of geoscientists.

Jeff Eaton (Weber State University, retired) continues to work and publish on Claron and Brian Head strata—his enthusiasm for these Marysvale gravity-slide-complex "foundational strata" is infectious, the knowledge he shares is invaluable, and his camaraderie is a joy to share. We thank Harry Filkorn (Pierce College, California) for sharing his knowledge of the extraordinarily complicated Fivemile Ridge quadrangle, Florian Maldonado (USGS, retired) for our time in the field together and for making us think hard about the Red Hills shear zone, Ed Sable (USGS, retired) for sharing his unpublished mapping of the greater Panguitch Lake area, and Gene Smith (University of Nevada, Las Vegas) for sharing his knowledge of volcanism in southwest Utah. Participants of the Geological Society of America-sponsored 2017 Thompson Field Forum "Catastrophic Mega-Scale Landslide Failure of Large Volcanic Fields" enlightened and challenged us with their observations, and several of them are now working on their own mega-slide research. We especially thank former Kent State University students Shannon Hunter, Zach Loffer, and Cody Kale, and Southern Utah University student Zach Smith (now at University of California, Berkeley, following his M.S. degree at The Ohio State University) for their geologic mapping and stratigraphic studies of especially complicated areas. Students McKenna Holliday (formerly Westminster College with her advisor Tiffany Rivera, Salt Lake City, now University of Florida) and Danika Maybeck (formerly Southern Illinois State University with advisor Dave Malone, now The Ohio State University) are continuing their important geochronology work. Eric Ferré (University of Louisana-Lafayette) and his student Nina Zamanialavijeh recently published their analysis of pseudotachylyte principally using novel mini-AMS techniques. Ashley Griffith (The Ohio State University) and his student Mike Braunagel (and Danika) are working on characterization and analytical models to better understand these long-runout mega-slides.

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SUGGESTIONS FOR FURTHER READING

This publication was written for the intellectually curious who do not have a background in geology but who do have a love of the outdoors and want to know more about what secrets southwest Utah's landscape holds (more treasures, certainly, than its iconic red rock scenery as by now you know!). Our story draws on several hundred published maps and reports by dozens of geologists, a list far too cumbersome for an introductory guide of this type. A comprehensive reference list is available in our 2019 technical guide published by the Geological Society of America (Biek and others, 2019) and in the many geologic maps of the greater Marysvale volcanic field; this technical guide and other publications are listed below for those who wish to delve deeper into the geology of Utah's mega-slides and of Utah's nearby national parks and monuments.

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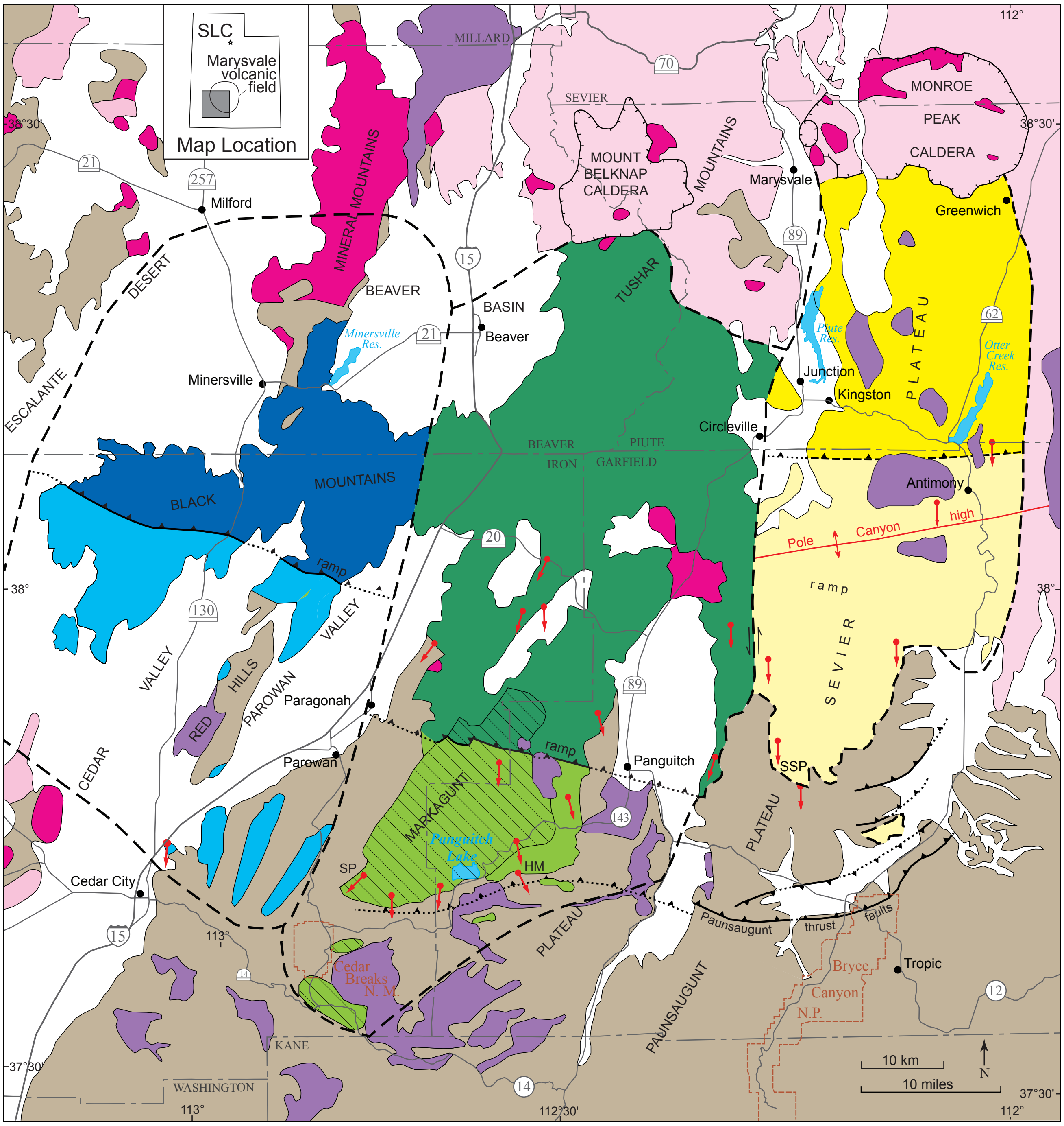

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