THE MARKAGUNT MEGABRECCIA: LARGE MIOCENE GRAVITY SLIDES MANTLING THE NORTHERN MARKAGUNT PLATEAU, SOUTHWESTERN UTAH

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ABSTRACT

The Markagunt megabreccia, which mantles much of the northern Markagunt Plateau, consists of a structurally chaotic assemblage of large masses of the Brian Head (Eocene?-Oligocene; name restricted and re-introduced), Wah Wah Springs (Oligocene), Isom (Oligocene), Bear Valley (Oligocene?-Miocene), and Mount Dutton (Miocene) Formations. The megabreccia typically consists of house- to city block-sized masses of these rock units, found in any structural attitude in a groundmass of either sheared and folded sedimentary strata of the Brian Head Formation, sheared and shattered sandstone and tuff of the Bear Valley Formation, or unstratified lahar of the Mount Dutton Formation. The megabreccia overlies either the upper "white" member of the Claron Formation (Paleocene-Eocene), the Baldhills Tuff Member of the Isom Formation, or the Narrows Tuff Member of the Leach Canyon Formation (Miocene). Locally it also overlies undisturbed strata of the Bear Valley and Mount Dutton Formations.

The Markagunt megabreccia was formed about 22-23 m.y. (early Miocene) largely by northward gravity sliding from the central Markagunt Plateau. The uplift down the northern flank of which this sliding took place probably was a batholith that aeromagnetic data suggest underlies the central Markagunt Plateau, or perhaps a cupola on a much larger batholith that may underlie much of southwestern Utah.

To a lesser extent, the Markagunt megabreccia also formed as the result of southward gravity sliding down the dip slopes of tilted fault blocks bounded by west-northwestward-striking faults that formed in the northern Markagunt Plateau roughly simultaneously with the batholithic intrusion in the central Markagunt, and by the collapse of the associated west-northwest-trending fault scarps. These faults are not related to the late Miocene-Pliocene(?) block faulting that produced the present structural configuration of the Markagunt Plateau.

The gravity sliding that produced the Markagunt megabreccia took place along two stratigraphic zones of structural weakness. The lower of these was in tuffaceous sedimentary strata of the Brian Head Formation; the upper was in the lower Bear Valley Formation. The sliding occurred while the sandstone and bimodal volcanic rocks that make up the upper Bear Valley Formation still were being formed. The same time also was marked in the northern Markagunt Plateau by emplacement of lahar of the Mount Dutton Formation, derived from the Marysvale volcanic field to the north. The result of these simultaneous events was the structural and stratigraphic chaos that is the Markagunt megabreccia.

As well as re-introducing and restricting the Brian Head Formation, this paper also proposes a new unit, the Haycock Mountain Tuff and provides the type section. A reference locality is defined for the Markagunt megabreccia.

INTRODUCTION

The Markagunt Plateau is the southwesternmost of the High Plateaus of Utah, which comprise part of the Colorado Plateaus province (figure 1). The general configuration of the southern half of the Markagunt Plateau is that of an antithetic fault block, bounded by the Hurricane

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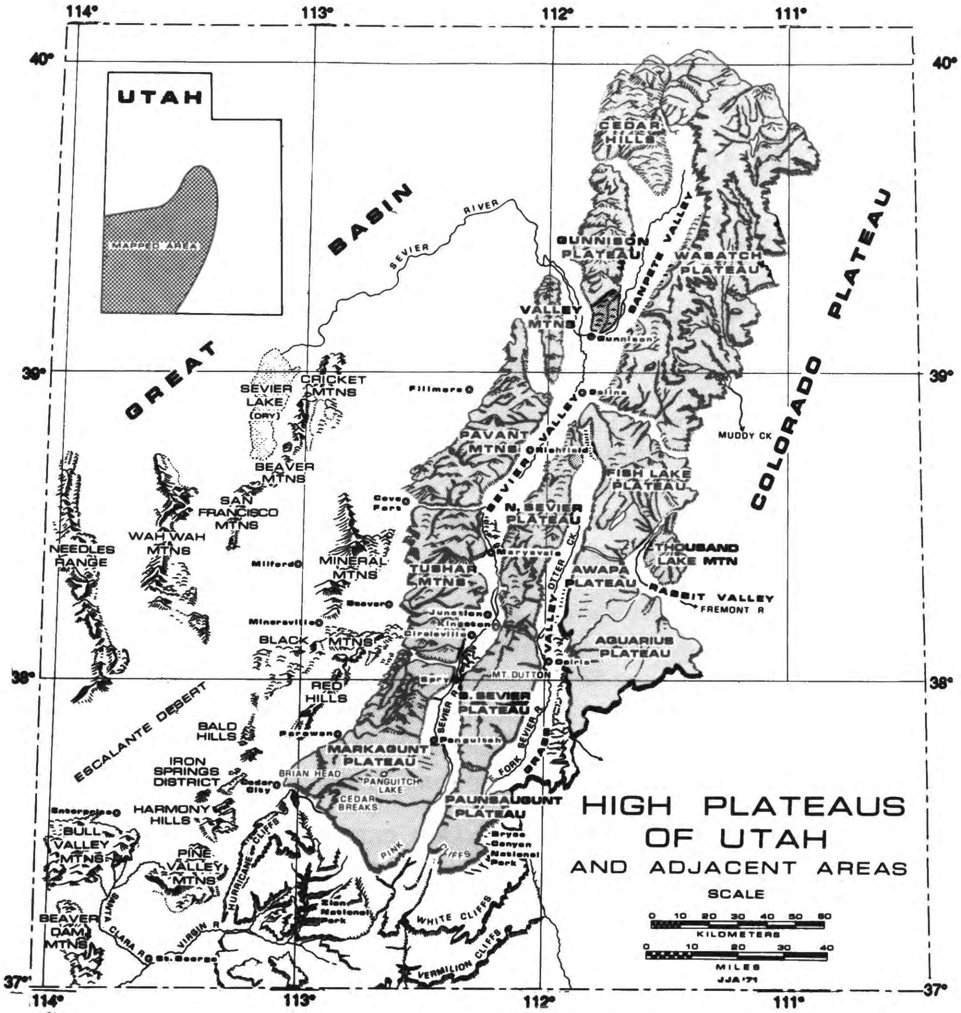

Figure 1. *Index map of southwestern Utah. High Plateaus are shaded.*

Cliffs on the west and with strata gently dipping eastward toward the Sevier River valley. This half of the plateau is rimmed on the south by the Pink Cliffs, an erosional escarpment. The portion of it that lies east of Cedar Breaks National Monument, much of it above 10,000 feet (3,000 m) in elevation, here is referred to as the high Markagunt Plateau. In contrast, the northern half of the Markagunt is some 1,000 feet (300 m) lower in elevation, and also is more structurally complex. Faults of north-northeasterly strikes have broken the northern half into three upthrown blocks — two horsts on the west and an eastward-tilted fault block to the east. From west to east, these blocks are separated by the Buckskin Valley graben and the Bear Valley graben.

On the high Markagunt Plateau much of the exposed rock that is younger than the Claron Formation (Paleocene-Eocene), and most of it that is younger than the Baldhills Tuff Member of the Isom Formation (late Oligocene), is not found in place. Instead, over an area of more than 200 square miles (500 sq km) post-Claron and/or post-Baldhills rocks are found in a chaotic jumble. This is the Markagunt megabreccia.

The Markagunt megabreccia was formed about 22-23 m.y. (early Miocene) largely by northward gravity sliding from the central Markagunt Plateau. The uplift down the northern flank of which this sliding took place probably was the result of emplacement of a batholith that aeromagnetic data suggest underlies the central Markagunt Plateau (Blank and Kuchs, 1989), or a cupola on a much larger batholith that may underlie much of southwestern Utah. Other possible cupolas on this batholith, with ages that cluster around 21 m.y., are exposed throughout southwestern Utah (H. R. Blank, Jr., oral communication, 1991, 1992), and in several other places large megabreccias have formed as gravity slides down their flanks (Mackin, 1960; Rowley and others, 1989; Blank and others, 1992).

To a lesser extent, the Markagunt megabreccia also formed as the result of southward gravity sliding down the dip slopes of tilted fault blocks bounded by west-northwestward-striking faults that formed roughly simultaneously with the batholithic intrusion, and by the collapse of the associated west-northwest trending fault scarps. These faults are not related to the late Miocene-Pliocene(?) block faulting that produced the present structural configuration of the Markagunt Plateau.

The gravity sliding that produced the Markagunt megabreccia took place along two stratigraphic zones of structural weakness. The lower of these was in a post-Claron sequence of tuffaceous sedimentary strata of Oligocene age, here re-named the Brian Head Formation (restricted); the upper was in the lower Bear Valley Formation (Miocene). The sliding occurred while the sandstone and bimodal volcanic rocks that make up the upper Bear Valley Formation still were being formed. The same time also was marked in the northern Markagunt Plateau by emplacement of lahar of the Mount Dutton Formation, derived from the Marysvale volcanic field to the north. The result of these simultaneous events was the structural and stratigraphic chaos that is the Markagunt megabreccia.

PREVIOUS INVESTIGATIONS

Although the Markagunt Plateau was part of the area investigated in reconnaissance by the great geological surveys of the last century (Wheeler, 1874, 1875, 1889; Gilbert, 1875; Dutton, 1879, 1880), no detailed studies of its geology were carried out until those of Gregory (1944, 1945, 1949, 1950). Much of Gregory's work is now dated, but his contributions nevertheless were substantial.

My own studies in the Markagunt Plateau began in 1963. At that time I was working on my Ph.D. at the University of Texas at Austin. My supervisor was the late J. Hoover Mackin, who earlier had recognized that many of the volcanic strata in southwestern Utah are ash-flow tuffs which are useful in the solution of structural and stratigraphic problems (Mackin, 1947, 1954, 1960; Mackin and Nelson, 1950; Mackin and others, 1954). My dissertation studies (Anderson, 1965) involved using the concepts developed by Mackin during his early work in the Basin and Range province, extending them into study of the High Plateaus. This I did by mapping an area of about 225 square miles (560 sq km) of the northern Markagunt Plateau. I was assisted in this work by Peter D. Rowley, now of the U.S. Geological Survey.

This early mapping included areas of several small allochthonous rock masses. At the time, I attributed the origin of all such masses to gravity sliding down the flanks of small structural domes. This origin still appears to be valid for most of them. Later work, however, has revealed that some of these chaotic assemblages probably resulted from the collapse of fault scarps.

From 1965 to 1991, although residing in Ohio where I taught at Kent State University, my principal research continued to be in the southwestern High Plateaus. Throughout this time, my cooperation with Peter Rowley continued; and in the past few years I also have worked closely with Edward G. Sable and Florian Maldonado, both of the U.S. Geological Survey. I also was assisted throughout this time by Kent State graduate students. Together, my students and I mapped most of the northern half of the Markagunt Plateau and southern third of the Tushar Mountains. Publications from these years that have a bearing on the present report included stratigraphic studies (Anderson, 1971; Anderson and Rowley, 1975; Rowley and others, 1975; 1979), structural studies (Rowley and Anderson, 1972; Rowley and others, 1978a, 1978b, 1978c; 1979; Anderson, 1980, 1982, 1985), a report on the chronology of mid-Tertiary volcanic units in southwestern Utah (Fleck and others, 1975), geologic maps (Anderson and Grant, 1986; Anderson and Rowley, 1987; Anderson and others, 1987, 1990a, 1990b; Kurlich and Anderson, in press), and a preliminary report on the tectonic slide megabreccia of the Markagunt Plateau (Sable and Anderson, 1985). Unpublished Kent State University master's theses relevant to the present report include those of Judy (1974), Iivari (1979), Grant (1979), Moore (1982), Yannacci (1986), Wagner (1984), Fryman (1987), and Kurlich (1990).

The thesis studies of Judy (1974) and Iivari (1979) were early efforts, carried out before anyone had any clear idea of the existence and magnitude of the Markagunt megabreccia. Thus, although they mapped in the high Markagunt Plateau, today recognized as being almost entirely mantled by the megabreccia, they "failed to see the forest for the trees." Both recognized the presence of many allochthonous rock masses, but both failed to see that in large part they were resting *in* rock that was out of place, not *on* undisturbed strata. Iivari also interpreted areas of unmistakably chaotic structure as the result of very complex patterns of normal faults. In their defence, I must admit that I was of no great help to them; in my field checking of their mapped areas, I, too, was deceived. Yet we all knew that we had missed something of significance, and thus it was that I vowed to myself to re-investigate the geology of the central Markagunt Plateau when circumstances permitted it. These circumstances came about as the result of my employment by the U.S. Geological Survey during the summers from 1978 to 1986. I spent the first five of these eight years mapping in the southern Tushar Mountains. In 1984 I returned to the Markagunt Plateau to work with E. G. Sable of the U.S. Geological Survey in the finalization of its mapping. We were later joined in this project by D. W. Moore, David Nealy, and Florian Maldonado, all also of the U.S. Geological Survey. My debt to these Survey geologists, especially Sable and Maldonado, is very great; many of the data incorporated in the present report are from them, and many of the concepts employed herein are either theirs or else were jointly arrived at. I also am indebted to the U.S. Geological

Survey for logistical support from 1987 to date, and during the past two years to the Utah Geological Survey for a contract to produce the present report.

In 1985, E. G. Sable and I (Sable and Anderson, 1985) presented the first description of the Markagunt megabreccia. In that same year, I presented a preliminary interpretation of its origin (Anderson, 1985), which I related entirely to gravity sliding of an inherently unstable succession of rock down the dip slopes of tilted fault blocks, this along detachment zones above the Brian Head and Isom Formations; and to the collapse of the related fault scarps. This interpretation was based in part on the thesis mapping of the Haycock Mountain quadrangle by Wagner (1984), who interpreted the Markagunt megabreccia there as having slid southward. It was, however, set forth before I had completed the mapping of much of the area covered in the present report, and before the thesis mapping of the Hatch quadrangle by Kurlich (1990) revealed that the Baldhills Tuff Member, 100+ feet (30 m) thick in the adjacent Haycock Mountain quadrangle, was missing from the section over most of the Hatch quadrangle. It also was set forth before H. R. Blank, Jr. suggested to me that there may be a batholith at depth in the central Markagunt Plateau.

Since 1985, Maldonado (Maldonado, in press; Maldonado and others, 1990, 1992; Maldonado and Williams, in press a and b), working in the Red Hills, has arrived at the same conclusion that megabreccia found there, in many ways similar to the Markagunt megabreccia, formed by tectonic detachment of mid-Tertiary rocks along a zone or zones of weakness within the Brian Head Formation. He has named this zone "the Red Hills low-angle shear zone," and relates its origin to regional tilting of the basin in which units of his "upper plate" (the rocks above the shear zone) were emplaced. He has suggested two possible mechanisms for tilting of this ancestral basin: (1) local uplift caused by magmatic intrusion, and (2) block rotations associated with normal faulting and regional extension.

PRE-MEGABRECCIA STRATIGRAPHY

An understanding of the physical characteristics of the rocks involved in the Markagunt megabreccia is a key to an understanding of its origin. An example of the control that stratigraphy had in the formation of the Markagunt megabreccia is the distribution of rock of the Wah Wah Springs Formation of the Needles Range Group. Allochthonous masses of the Wah Wah Springs Formation are uncommon but widespread throughout the northern Markagunt Plateau, both within and outside of the area of autochthonous outcrop. These isolated masses usually are exposed, so it is probable that allochthonous Wah Wah Springs rock originally was much more extensive but since has been eroded. Such masses commonly are found in a chaotic structural configuration together with masses of the overlying Isom, Bear Valley, and Mount Dutton Formations, and above autochthonous strata of the Isom. Thus it would appear that the gravity sliding that produced the Markagunt megabreccia was initiated in the incompetent Brian Head Formation and carried with it rocks of the competent Wah Wah Springs Formation together with all overlying rocks, this in a manner similar to that described by Maldonado (Maldonado, in press; Maldonado and others, 1990,1992; Maldonado and Williams, in press a and b) above his proposed Red Hills low-angle shear zone in the Red Hills west of the Markagunt Plateau. In the Markagunt Plateau, however, the sliding apparently ramped upward through the Isom Formation and into the lower Bear Valley Formation, along which it transported the entire post-Claron Tertiary stratigraphic sequence.

Standard descriptions of the Tertiary stratigraphy of the Markagunt Plateau can be found in numerous sources (e.g., Anderson and Rowley, 1975). Therefore the description that follows emphasizes only those features that played a role in the formation of the megabreccia rather than lithologic and petrographic details.

Claron Formation

The Claron Formation (Paleocene-Eocene) is a colorful sequence of fluvial and lacustrine strata more than 1,400 feet (400 m) thick which, in the Markagunt Plateau, is most spectacularly exposed at Cedar Breaks National Monument. Unfortunately, no regional study of the Claron has to date been published, and therefore many questions about it remain to be answered. Most authors, however, have recognized an informal lower "red" member and an upper "white" member in the Claron. The "red" member consists of a basal quartzite conglomerate overlain by a thick sequence of reddish fine-grained argillaceous limestone, calcareous shale, sandstone, and minor conglomerate. The most conspicuous rocks of the "white" member consist in most places of two massive beds of white to tan and gray, argillaceous limestone, interbedded between which are light-colored calcareous shale, siltstone, sandstone, and conglomerate. Recent studies indicate that the top of the Claron is marked by a regional erosional unconformity, and that in places the "white" member and an unknown amount of the "red" member therefore are missing from the section (Mullett, 1989; Mullett and others, 1988a).

Just as is the case with the Red Hills low-angle shear zone described by Maldonado (Maldonado, in press; Maldonado and others, 1990, 1992; Maldonado and Williams, in press a and b), the Claron Formation is not involved in the Markagunt megabreccia except as the "basement" above which gravity slides that formed a large part of the megabreccia took place. That the sliding did not occur within the Claron probably resulted from three factors. First, intensive bioturbation of the Claron strata (Mullett and others, 1988b) destroyed many bedding planes that otherwise might have acted as surfaces on which sliding could take place. Second, the rocks that make up the formation doubtlessly were reasonably well indurated, and thus at least fairly competent structurally, when the sliding took place. And third, the structural competence of the massive limestone beds that in most places in the Markagunt Plateau make up the uppermost Claron is in marked contrast with the friable nature of the immediately overlying tuffaceous fluvial and lacustrine strata of the Brian Head Formation (restricted) and the eolian sand of the Bear Valley Formation, the two units in which the sliding did take place.

Brian Head Formation (Restricted)

Paraconformably overlying the Claron Formation throughout the southwestern High Plateaus Province and adjacent portions of the Great Basin is a heterogeneous assemblage of dominantly tuffaceous fluvial and lacustrine, and minor eolian, sedimentary strata as much as 350 feet (100+ m) thick. These strata probably are, or were, widespread throughout the northern Markagunt Plateau. Today they are found as discontinuous exposures along the western margin of the plateau between the towns of Summit and Parowan, on higher parts of the plateau from Cedar Breaks National Monument eastward beyond Panguitch Lake, along the eastern margin of the plateau from Long Valley Junction northward nearly to the town of Hatch, in the structural dome west of Bear Valley Junction, and in the mountains west of Bear Valley. In the last two locations the sedimentary strata are overlain by volcanic rocks probably of local origin. Correlative strata elsewhere include rocks in the Red Hills (Maldonado and others, 1990; Maldonado and others, in press a and b), and, judging from descriptions of the upper Claron Formation (Mackin, 1960), also in the Iron Springs district. They also include rocks in the southern Sevier, Paunsaugunt, Table Cliffs, Awapa, and Fish Lake Plateaus (E. G. Sable, manuscript in preparation).

Discussion of the history of nomenclature and correlation of these strata has been presented by Bowers (1972) and Anderson and Rowley (1975). Briefly stated, this unit originally was placed in the upper "white" member of the Claron Formation by most workers. Originally, I, too, mapped the unit as part of the Claron, but as a discrete "undifferentiated uppermost member" overlying the "white" Claron (Anderson, 1965).

Gregory (1944) had named these strata, along with older and younger beds, the Brian Head Formation. Early work by Peter Rowley and myself, however, revealed that the younger beds included by Gregory (1945) as "Units 3, 4 and 5" within the type section of his Brian Head Formation contained members of the Isom and Leach Canyon Formations. In addition, Gregory's definition of the Brian Head Formation included the Bear Valley and Mount Dutton Formations. All of these units not only were defined as separate rock-stratigraphic units elsewhere, but also are much better understood when granted such status. Therefore Rowley and I suggested that the Brian Head Formation be abandoned (Anderson and Rowley, 1975).

In the years since this abandonment, these rocks have been treated in various ways. Rowley and I removed them from the Claron Formation and mapped them as "local sedimentary and volcanic strata" (Anderson and Rowley, 1987; Anderson and others, 1987). Even more recently, correlative rocks have been termed "sedimentary and volcanic rocks of the Red Hills" by Maldonado (in press; Maldonado and others, 1990, 1992; Maldonado and Williams, in press a and b).

Now, however, following a suggestion of E. G. Sable, I propose that the Brian Head Formation be resurrected, but that it be restricted to a basal conglomerate and non-tuffaceous red and gray sandstone and the tuffaceous sedimentary strata here described. I exclude, however, the locally derived volcanic strata that in places overlie these sedimentary strata, which I believe should be treated separately. The Brian Head Formation (restricted) therefore includes the rocks that paraconformably overlie the Claron Formation and most commonly underlie the Needles Range Group or, where it is missing, the Isom Formation; or elsewhere underlie other volcanic strata, including ash-flow tuff, lava, flow breccia, and lahar, but not airfall tuff; or cap the local section.

Regionally, diagnostic lithologies used as mapping criteria for these strata include abundant "salt and pepper," texturally bimodal, fluvial and minor eolian volcanic arenite; varicolored chalcedony masses as much as a few meters in diameter; thin white limestone beds that contain root casts and burrow fillings; a high content of clay of volcanic origin; thin ash-flow tuffs; and conglomerates containing generally well-rounded clasts of volcanic and sedimentary rocks (E. G. Sable, manuscript in preparation).

In the extreme northern Markagunt Plateau, volcanic rocks locally overlie the tuffaceous sedimentary strata of the Brian Head Formation. A potassium-argon age determination of 31.1 Ma has been reported on biotite from a welded tuff at the top of this volcanic sequence (Fleck and others, 1975). Other K-Ar determinations from the upper part of the Brian Head Formation include two of 29.1 ± 1.0 and 30.4 ± 3.1 Ma on airfall biotite and hornblende from a volcanic arenite from a locality along Lowder Creek in the extreme western Markagunt Plateau (Mehnert and others, in press). The Brian Head Formation therefore is at least in large part Oligocene. Recent vertebrate paleontological evidence, however, indicates that the Brian Head Formation may be as old as Eocene (J. Eaton, oral communication, 1992).

Of significance to the origin of the Markagunt megabreccia is that the Brian Head Formation is a structurally incompetent unit lying between two competent ones. In the high Markagunt Plateau the Brian Head usually rests on the massive limestone that caps the Claron Formation and, in normal stratigraphic sequence, is overlain by welded tuff of either the Needles Range Group or the Isom Formation, or by unnamed local volcanics. Its bedding is generally thin and its clay content high. Friable and porous even today, the unit quite possibly was only poorly indurated by the early Miocene and at that time in many places probably was water saturated. All of these factors combined to make of these strata a zone along which gravity sliding could take place if they were tilted at even a low angle.

Needles Range Group

From about Lat 38°45' N, the Brian Head Formation (restricted) is conformably overlain in the northern Markagunt Plateau by welded tuff of the Needles Range Group. First described by Dutton (1880), the Needles Range Formation was defined by Mackin (1960) in the Needle (Mountain Home) Range that lies along the southern border of Utah and Nevada. Its stratigraphic rank raised by Best and Grant (1987), the Needles Range Group comprises what well may be areally the most extensive and volumetrically the largest succession of ash-flow tuffs in North America. It spread over an area in excess of 6,000 square miles (22,000 sq km) and had a minimum volume of 1,600 cubic miles (6,600 cu km). The source for this vast volcanic outpouring was along the southern Utah-Nevada border; eruption of it formed the large Indian Peak caldera (Best and Grant, 1987; Best and others, 1989).

The Needles Range Group consists chiefly of crystal-rich, moderately to highly welded ash-flow tuffs. Of the many units within the group, only ash-flow tuffs of the Wah Wah Springs Formation, with an average age of 29.5 m.y. (Best and others, 1989), and the Lund Formation, with an average age of 27.9 m.y. (Best and others, 1989), are present in the the area of the northern Markagunt Plateau covered by this report. Of these, only the Wah Wah Springs is widespread; it occurs as a resistant, ledge-forming, obviously competent single cooling unit about 50 feet (15 m) thick.

Both the Lund and Wah Wah Springs tuffs apparently spread without obstruction across the northern Markagunt Plateau except at one locality. This was at the site of a fault, here named the Bear Creek fault, located about 1.8 miles (3 km) north of the present confluence of Bear Creek and the Sevier River (Anderson and Rowley, 1987). The Bear Creek fault formed a south-facing, west-northwest- (WNW-) striking fault scarp that could not be overridden by the tuffs of the Needles Range Group, and also presented a similar barrier to the emplacement of later rock units. This was the earliest example of structural control on the distribution of Tertiary rocks in the northern Markagunt. Younger faults of similar strikes were to exert a similar control on the emplacement of younger rock units. Such faults also were to be instrumental in the formation of the Markagunt megabreccia (Anderson, 1985).

Isom Formation

As defined by Mackin (1960) in the Iron Springs district west of Cedar City, Utah, the Isom Formation included two members, the Baldhills Tuff Member and the overlying Hole-in-the-Wall Tuff Member. To these Anderson and Rowley (1975) added a lowermost unit, the Blue Meadows Tuff Member. All three members consist primarily of crystal-poor, moderately to highly welded ash-flow tuff. The age of all three is about 26-27 Ma (Fleck and others, 1975; Best and others, 1989)). The Baldhills Tuff Member is the most widespread of the three, being found over an area in excess of 4,000 square miles (10,000 sq km) that is largely within the Great Basin but includes the northern Markagunt Plateau. The Blue Meadows Tuff Member, on the other hand, is found only in the Markagunt Plateau, and the Hole-in-the-Wall Tuff Member is found only in the Great Basin.

Blue Meadows Tuff Member

The Blue Meadows Tuff Member is a composite ash-flow tuff (Smith, 1960) consisting of two cooling units in places joined by welding, but grading laterally into two separate cooling units separated by a few meters of tuffaceous sedimentary rock (Fryman, 1987). Forty to 75 feet (15-25 m) thick, it generally consists of a black basal vitrophyre overlain by a massive, reddish-brown to brownish-gray vapor-phase zone which has the appearance of crystal-studded unglazed porcelain.

The source of the Blue Meadows Tuff Member is unknown. It was emplaced over an area of about 250 square miles (640 sq km) of the northern Markagunt Plateau, unobstructed in its passage except by the Bear Creek fault scarp.

Most of the outcrop area of the Blue Meadows Tuff Member is north of the the main body of the Markagunt megabreccia. Where small allochthonous masses of the member are found, their origin can be attributed to gravity sliding down the flanks of small structural domes (Anderson and others, 1987). These isolated masses are considered part of the Markagunt megabreccia because of the similarity of their mechanisms of origin.

Baldhills Tuff Member

The Baldhills Tuff Member was erupted from vents that probably occur along the western side of, and under, the Escalante Desert of southwestern Utah (Best and others, 1989). At its type locality in the Iron Springs district, the member consists of at least six lithologically similar cooling units. Most are dark brown, medium gray, or purplish, moderately to highly welded tuffs, with five to 20 percent phenocrysts of plagioclase and minor pyroxene and Fe-Ti oxides in a glassy to devitrified groundmass. Several of the units have thin black vitrophyres at their bases, and the upper portions of some units contain abundant spherical and elongated vesicles (Anderson and Rowley, 1975).

Of the six Baldhills cooling units at the type locality, two, and possibly more, are present in the northern Markagunt Plateau. They include the uppermost one of the type locality, which apparently is not only the most voluminous and widespread of the entire member, but also lithologically the most distinctive. In the Iron Springs district and the Markagunt Plateau, it is characterized by a prominent platy lamination that in most places has a sub-horizontal attitude but locally is wildly convoluted. The laminae commonly are separated by thin, gray lenticules of pumiceous appearance. It also has a characteristic weathering habit which produces "popcorn"-shaped and -sized granules that litter slopes downhill from its outcrops. This cooling unit, and others lower in the section as well, are good examples of "tufflava" (Cook, 1966). Thus there is excellent evidence that they spread as turbulent ash-flow near their source, but that their mode of emplacement changed to that of lava-like laminar flowage before they finally came to rest (Anderson and others, 1990c).

The Baldhills Tuff Member spread without obstruction eastward across the present boundary between the Great Basin and into the Markagunt Plateau, where its thickness typically is about 100-200 feet (30-60 m). Its northward spread, however, was prevented by south-facing, WNW-trending fault scarps in the vicinity of Sandy Creek in the northern Markagunt Plateau. Immediately south of these faults, here termed the Sandy Creek faults, the Baldhills accumulated to a thickness of more than 600 feet (200 m). North of the faults the Baldhills is missing (Anderson, 1985; Anderson and others, 1987).

The upper surface of the massive and competent uppermost cooling unit of the Baldhills Tuff Member became the major surface over which gravity sliding took place throughout much of the north-central Markagunt Plateau (figure 2). Thus this unit was to become of great significance in the formation of the Markagunt megabreccia. In addition, the platy partings produced by laminar flowage of the uppermost Baldhills cooling unit were to facilitate plucking of large blocks from it when this gravity sliding took place across its upper surface.

Within the Markagunt megabreccia, rock of the Baldhills Tuff Member commonly is completely shattered into a pulverized groundmass that contains fragments

Figure 2. *Baldhills Tuff Member, 250+ feet (75+ m) thick, along Ipson Creek northwest of Panguitch Lake. Markagunt megabreccia formed on upper surface of unit, here stripped.*

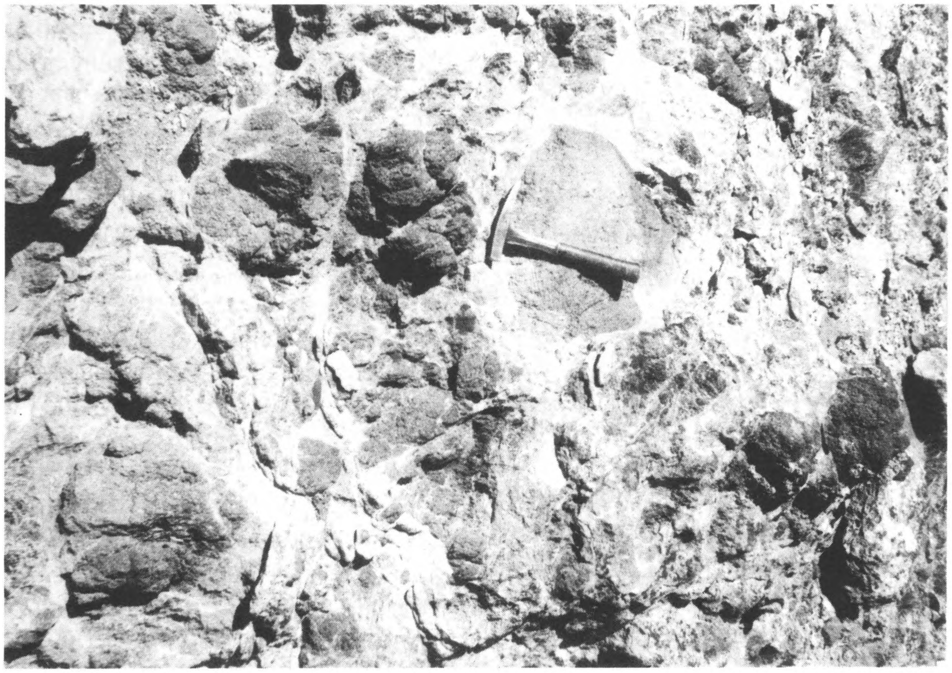

Figure 3. Shattered tuff of the Baldhills Tuff Member within the Markagunt megabreccia. Hammer for scale.

ranging in size from less than one inch to more than one foot (1-30 cm) across (figure 3). Since being shattered, the rock has been healed, probably by devitrification of the groundmass, so that today it is as resistant as its unshattered, autochthonous counterpart. The shattering probably resulted from stress release by a mechanism similar to the one that takes place in an underground rock-burst or when an automobile windshield is hit. This idea was suggested to me by Dwight Schmidt of the U.S. Geological Survey and hypothesizes that, like rock in mines at great depth and safety glass, the Baldhills rock was pre-stressed, in its case probably more as the result of the welding process than of the weight of the overburden. The movement during the sliding that produced the Markagunt megabreccia was too sudden to allow this stress to be released gradually, and the result was almost instantaneous shattering.

Buckskin Breccia

The Buckskin Breccia, defined by Anderson and Rowley (1975) and described in detail by Yannacci (1986), is a block and ash-flow tuff that originated as an eruptive phase of the igneous activity that emplaced the Spry intrusion in the northeasternmost Markagunt Plateau (Grant and Anderson, 1979; Anderson and others, 1990a). The areal extent of the Buckskin Breccia is about 250 square miles (640 sq km). Locally it is interbedded with the Isom Formation, which establishes its age as about 26 m.y., late Oligocene.

Distribution of the Buckskin Breccia to a very large extent was controlled by WNW-striking faults related to the same episode of faulting that produced the Bear Creek and Sandy Creek faults. No more than 50-100 feet (15-30 m) thick over most of its outcrop area, its greatest accumulation of more than 800 feet (250 m) was in a WNW-trending graben in the vicinity of lower Bear Valley. Because the faulting occurred before its emplacement, any tilting of fault blocks and scarp collapse that may have accompanied it did not lead to any significant megabrecciation of the Buckskin Breccia. Where allochthonous masses of the Buckskin Breccia are found, their origin can be attributed to the same gravity sliding off the flanks of small structural domes that affected the Blue Meadows Tuff Member of the Isom Formation, and these masses also are considered part of the Markagunt megabreccia.

Narrows Tuff Member of the Leach Canyon Formation

The Leach Canyon unit of Mackin (1960) was defined as a formation by Cook (1965). Williams (1967) divided the formation into a Narrows Tuff Member and an overlying Table Butte Tuff Member. Armstrong (1970) established the age of the Leach Canyon Formation as early Miocene by K-Ar age determinations of 22-24 Ma on samples of the Narrows Tuff Member.

Only the Narrows Tuff Member is found in the high Markagunt Plateau, and this only in a limited area north and east of Cedar Breaks National Monument. At Brian Head (Peak), which it caps as a single, massive, ledge-forming unit about 50 feet (15 m) thick overlying the Isom Formation, it consists of light-gray to pale-salmon welded tuff containing conspicuous lithic fragments and numerous quartz phenocrysts.

The massive Narrows Tuff Member, where it was present at the time the Markagunt megabreccia formed, combined with the equally massive underlying Baldhills Tuff Member of the Isom Formation to make a single structurally competent unit on top of which gravity sliding took place. Striated surfaces within the Narrows Tuff Member indicate that the sliding also took place within the unit, however (E. G. Sable, written communication, 1992). How widespread the sliding was on top of the Narrows Tuff Member cannot be determined, however, because in most places today erosion has exposed this surface.

Bear Valley Formation

The Bear Valley Formation (Anderson, 1971) is largely a deposit of eolian sand that during the latest Oligocene(?) and early Miocene blanketed the northern Markagunt Plateau, Red Hills, and Black Mountains. Generally it conformably overlies the Buckskin Breccia, or, where this latter unit was not emplaced, either the Blue Meadows Tuff Member or the Baldhills Tuff Member of the Isom Formation. The early Miocene age of at least the upper half of the Bear Valley Formation has been established by two K-Ar age determinations about 24-25 Ma on volcanic strata interbedded within it (Fleck and others, 1975). Locally, however, the lower part of the formation may be as old as latest Oligocene, the age of the underlying Isom Formation

Over 1,000 feet (300 m) thick at its type section northwest of the junction of Highways U.S. 89 and Utah 20, where it accumulated against the Bear Creek fault scarp, the sandstone of the formation thins to a feather edge on the high Markagunt Plateau near Panguitch Lake. In this vicinity, however, the closing stages of sand deposition were accompanied not only by bimodal volcanism, but also by both emplacement of mudflows of the Mount Dutton Formation and the gravity sliding that produced the Markagunt megabreccia.

Friable today, the sandstone of the Bear Valley Formation probably was at most poorly indurated at the time the Markagunt megabreccia formed. The upper part of the formation also had a high content of volcanic ash and dust (Anderson, 1971). Interbedded with and overlain by newly emplaced, water-saturated mudflows of the Mount Dutton Formation, the sandstone also probably had a high water content. These factors contributed to make of the Bear Valley sandstone on the high Markagunt Plateau an incompetent, highly unstable sequence of strata exposed at

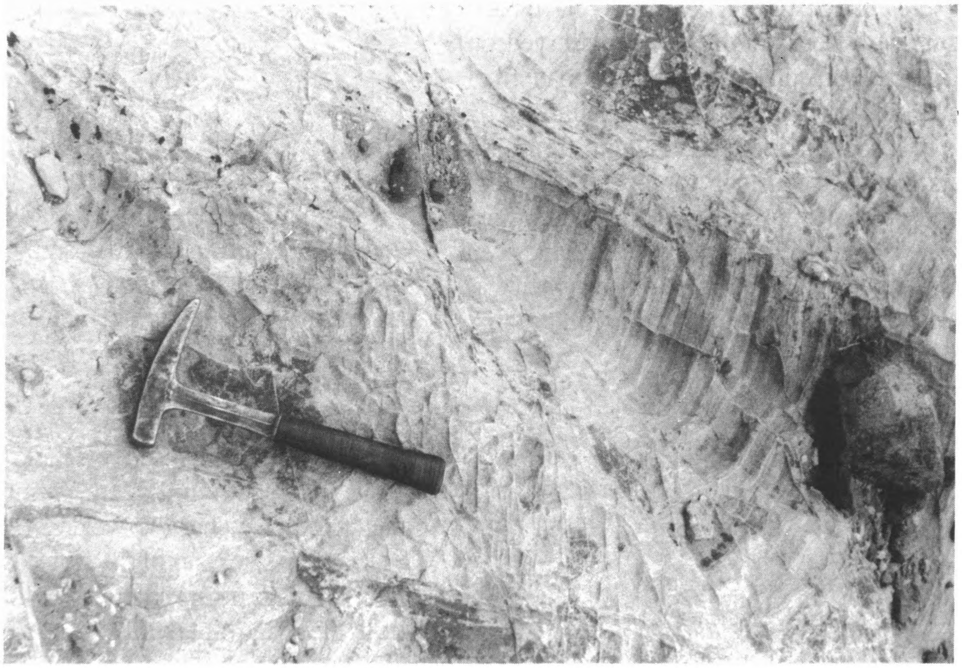

Figure 4. *Sandstone of the Bear Valley Formation in the Markagunt megabreccia. Note "box-work" pattern of healed shears in rock that does not display bedding, and offset along similar shears where bedding has been preserved. Hammer for scale.*

Figure 5. *Conjugate faults of small displacement in two specimens of the Bear Valley sandstone within the Markagunt megabreccia. Pen for scale.*

and near the surface, one highly susceptible to mass movement if tilted.

That the Bear Valley sandstone was poorly indurated at the time the Markagunt megabreccia was formed is indicated by the fact that, where incorporated within the megabreccia, most signs of the ubiquitous cross-stratification that elsewhere characterizes it commonly have been obliterated (figure 4). Where stratification is preserved, on the other hand, it usually displays a "box-work" pattern of healed conjugate shears that in places are marked by displacements of less than one inch (1-2 cm; figure 5). Thus it appears that the sandstone responded in both a ductile and a brittle manner during the sliding that formed the megabreccia. The different responses may have been a function of where it was water-saturated and where it was dry, or perhaps a function of the amount of clay in the matrix of the rock.

The bimodal volcanism that accompanied the closing stages of Bear Valley sand deposition on the high Markagunt Plateau produced unwelded to highly welded felsic ash-flow tuffs and mafic lava flows. The same time and place also were marked by the emplacement of lahars of the Mount Dutton Formation and by the gravity sliding that produced the Markagunt megabreccia.

The unwelded felsic tuff of the Bear Valley Formation has been described in an earlier paper (Anderson, 1971, p. 1,195). Its estimated areal extent of 25 square miles (60 sq km) given therein was much too low, however. Further mapping has revealed it to be present over an area of about 150 square miles (375 sq km) in the north-central Markagunt Plateau. Many of the outcrops are allochthonous, however, so the original areal extent of the tuff is uncertain. An excellent exposure of the tuff may be seen at White Rocks north of Utah Highway 143 about 5.5 miles (8.8 km) east of Panguitch Lake (Fivemile Ridge quadrangle; sections 9 and 16, T. 35 S., R. 6 W.). In addition, one more possible source vent for the tuff has been located, this in the Little Valleys area about 5 miles (8 km) north of Panguitch Lake (Fivemile Ridge quadrangle; SW $\frac{1}{4}$, section 34, T. 34 S., R. 7 W.).

A highly welded tuff erupted about the same time as the unwelded tuff also was described in the paper naming the Bear Valley Formation (Anderson, 1971, p. 1,194-5). Like the unwelded tuffs, it is more extensive than originally believed, and can be found over an area of about 200 square miles (500 sq km). Its striking similarity with the welded tuffs of the Isom Formation, however, creates great problems of identification and correlation where allochthonous masses of both units are found in the Markagunt megabreccia. That the welded tuff of the Bear Valley Formation is not part of the Isom Formation was revealed by a K-Ar age determination of 24.5 ± 0.4 Ma on a sample of it (Fleck and others, 1975), but this knowledge is of little use in mapping when hand specimens of the two are virtually identical. Of some use in distinguishing between the two is that the Bear Valley tuff commonly is brick red with an almost waxy luster, and that it does not display the "popcorn" weathering habit of the uppermost known cooling unit of the Baldhills Tuff Member. Because, however, the internal stratigraphy of the Baldhills Tuff Member has yet to be worked out in detail, it is possible that the red welded tuff found in the western Markagunt Plateau may not belong to the Bear Valley Formation but may instead be a Baldhills cooling unit.

The mafic lava in the upper Bear Valley Formation that was erupted at about the same time as the ash-flow tuffs rarely is found in place. One such autochthonous lava flow is exposed south of Panguitch Creek near White Rocks (Fivemile Ridge quadrangle, NE ¼ section 16, T. 35 S., R. 6 W.). The lava is characterized by small phenocrysts of pyroxene and plagioclase set in a dark-gray to black aphanitic groundmass. The feeder dike for this flow cuts the southern part of White Rocks just north of Panguitch Creek. Because the felsic tuff that makes up White Rocks probably is allochthonous, however, the mafic dike and lava flow probably postdate formation of the Markagunt megabreccia.

Most of the mafic lava in the upper Bear Valley Formation is incorporated in Mount Dutton Formation lahar masses that in turn are incorporated into the Markagunt megabreccia. Such lahar masses typically consist of a groundmass of clay- to sand-sized material in which are set rounded pebbles and cobbles of intermediate lava and very large, angular boulders of mafic lava (figure 6). Commonly the mafic lava is pyroxene bearing. That the mafic lava clasts were not derived from Mount Dutton Formation source vents is attested to by three factors. First, their size, which ranges up to 12 feet (4 m) in diameter, makes it seem improbable that they were transported some 30 miles (50 km) from vents in the Marysvale volcanic field (figure 7). Second, the only vents in the Markagunt Plateau known to have contributed to the Mount Dutton Formation were fissures, and these produced only lava flows, not lahars. And third, numerous mafic dikes that probably were the source of the mafic lava flows are found cutting strata of the Bear Valley Formation in the northern Markagunt Plateau.

Thus it appears that most of the dike-fed mafic lava flows of the Bear Valley Formation were blocky, much like many of the more recent ones today widely exposed in the northern Markagunt Plateau, and that they were interbedded with lahars of the Mount Dutton Formation. The gravity sliding that produced the Markagunt megabreccia then occurred while the lahars still were mobile. The result was to comingle the lahar with blocks of mafic lava.

Mount Dutton Formation

The Mount Dutton Formation (Anderson and Rowley, 1975) comprises most of the rock exposed on the southern flank of the Marysvale volcanic field. It consists largely of intermediate (dacite-andesite) volcanic rock, which locally

Figure 6. *Angular fragments of mafic lava of the Bear Valley Formation incorporated in lahar of the Mount Dutton Formation. Hammer for scale.*

Figure 7. Large boulder of mafic lava of the Bear Valley Formation weathered from lahar of the Mount Dutton Formation. Note other large boulders in background. Hammer for scale.

is interbedded with mafic lava flows, felsic tuff and tuffaceous sandstone. In accordance with the concepts of Parsons (1965, 1969) and Smedes and Prostka (1973), I divide the formation into a vent facies and an interfingering alluvial facies, both the products of stratovolcanoes and dikes most of which are found in the southernmost Tushar Mountains. The age of the Mount Dutton Formation is late Oligocene and early Miocene, this established by K-Ar age determinations on vent facies rocks that range from about 27 m.y. to 21 m.y. (Fleck and others, 1975).

Only rocks assigned to the alluvial facies of the Mount Dutton Formation are found in that part of the northern Markagunt Plateau considered in this report. They consist for the most part of soft to resistant, mostly light- to dark-gray and brown lahar characterized by subrounded to angular clasts of intermediate volcanic rock supported by a muddy to sandy matrix. Typically, the clasts are cobbles and make up one-third to one-half of the rock. Individual flows are 5-100 feet (2-30 m) thick.

North of the area affected by the gravity sliding that produced the Markagunt megabreccia (roughly, Lat. 37°53' N.), as along Utah Highway 20, the lahars of the Mount Dutton Formation display excellent sub-horizontal to horizontal stratification and clearly are autochthonous. Within the area affected by the gravity sliding, however, the lahars are both allochthonous and autochthonous. The allochthonous lahars are found as large, unstratified or poorly stratified masses within the Markagunt megabreccia. Such masses commonly contain abundant large, angular clasts of mafic lava of the Bear Valley Formation (figure 5) and are found in chaotic juxtaposition with all rock units younger than the Claron Formation and older than themselves. The autochthonous lahars, on the other hand, are well stratified and cap the Markagunt megabreccia. They, too, however, also contain large clasts of mafic lava of the Bear Valley Formation.

It therefore appears that the Markagunt megabreccia was formed during the time of emplacement of the Mount Dutton Formation, a time that also saw the closing stages of deposition of sandstone of the Bear Valley Formation and the eruption of the bimodal volcanic strata interbedded with the sandstone. That at this time the Mount Dutton lahars were still wet and therefore highly mobile seems clear. This conclusion is based on the absence of stratification within very large lahar masses found in the megabreccia, plus, as described above, their content of mafic lava blocks of the Bear Valley Formation. It also is suggested by the manner in which the unstratified lahar incorporates large masses of the Needles Range Group, Isom Formation, and Bear Valley Formation.

POST-MEGABRECCIA STRATIGRAPHY

Rock units that formed after the Markagunt megabreccia are of significance because of what they reveal about the geologic history of the Markagunt Plateau between the time that the megabreccia was formed and the present. These units include local stream gravels, an overlying felsic tuff, widespread stream gravels, and two generations of mafic lava flows.

Local Stream Gravels

Following the formation of the Markagunt megabreccia, the area of the Markagunt Plateau probably

Figure 8. *Haycock Mountain Tuff type section.*

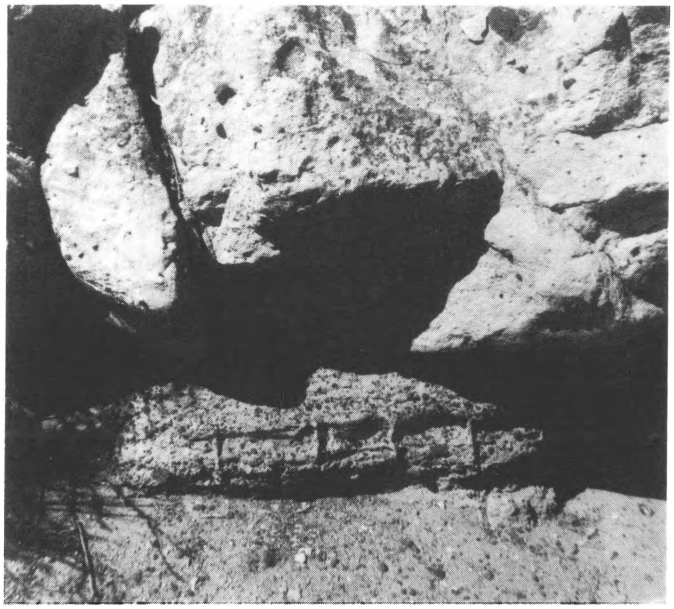

Figure 9. *Fluvial gravel underlying Haycock Mountain Tuff at type section, and airfall tuff of Unit 1 (in shadow) and lower portion of ash-flow tuff of Unit 2 of the type section. Note the infilling of dessication cracks in gravel.*

displayed the hilly and hummocky topography characteristic of large landslides. Probably also all rock units younger than the Claron Formation were exposed at the surface as masses of various sizes within the megabreccia. On this topography a drainage system developed, which appears to have flowed generally northward. The stream channels of this system contained clasts of all post-Claron rocks. Today these gravels occur in the north-central Markagunt Plateau as isolated exposures preserved under a protective cap of the Haycock Mountain Tuff.

Haycock Mountain Tuff

The eruption of felsic ash-flow tuff that marked the closing stages of deposition of the Bear Valley Formation continued in the high Markagunt Plateau area after the formation of the Markagunt megabreccia. Today the post-megabreccia tuff is found as widespread but isolated autochthonous exposures limited to the Fivemile Ridge quadrangle plus the northern Haycock Mountain quadrangle, where they cap the eastern end of Haycock Mountain. The tuffs usually overlie stream gravels deposited in channels cut into the Markagunt megabreccia. It thus appears that these ash flows were channeled along the stream cuts that formed on the Markagunt megabreccia. Their source is unknown. However, the fact that they cap Haycock Mountain, which must have had its present northward dip when they erupted, suggests that this source was south of Haycock Mountain somewhere on the southern flank of the structural uplift down which the Markagunt megabreccia slid.

A K-Ar determination on plagioclase indicates that the age of the tuff is 22.3 ± 1.1 Ma, early Miocene (Mehnert and others, in press). The significance of this date is that it constrains the upper age of the gravity sliding that led to the Markagunt megabreccia.

The Haycock Mountain Tuff (new), Miocene, is here defined to include these felsic ash-flow tuffs that unconformably overlie the Markagunt megabreccia and underlie much younger gravels. The name is derived from Haycock Mountain, which rises just south of the type section. The type section, in turn, is north of Panguitch Creek at the 36-mile post of Utah Highway 143 about 1 $\frac{1}{2}$ mile (2.4 km) east of Panguitch Lake (NW $\frac{1}{4}$ section 35, T. 35 S., R. 7 W., Haycock Mountain quadrangle). There the unit caps a small hill; the exposure is a small south-facing scarp that consists of a thin felsic airfall tuff overlain by two cooling units of unwelded to poorly welded ash-flow tuff (figure 8). The airfall tuff overlies well-bedded, fluvial gravels in a stream cut formed on a mass of sheared and shattered welded tuff of the Baldhills Tuff Member of the Isom Formation, part of the Markagunt megabreccia (figure 9).

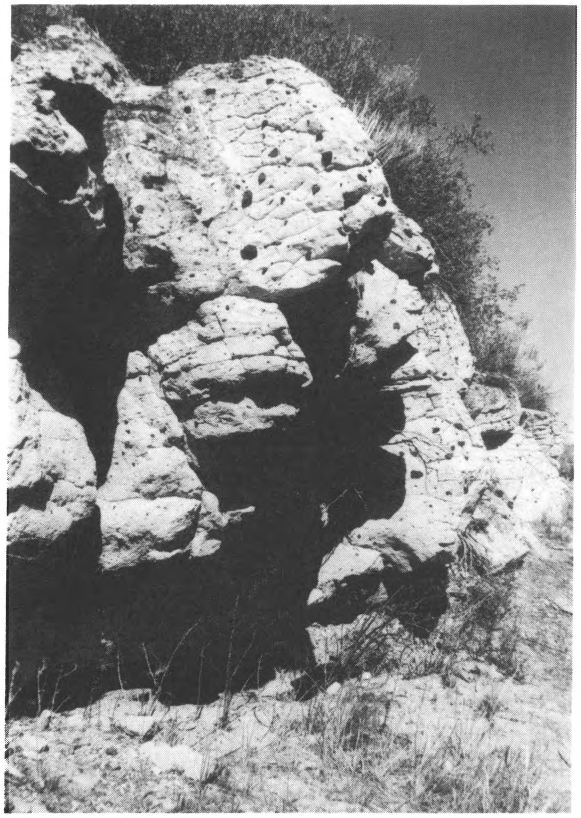

Figure 10. *Felsic ash-flow tuff of Unit 3, Haycock Mountain Tuff type section. Note the numerous mafic lava fragments throughout the unit.*

Type Section

Top of Section

Unit Thickness

3 35 feet (10.7 m) **Haycock Mountain Tuff**

Felsic ash-flow tuff; light gray on fresh surface, weathers orangish-tan; dense and well indurated as the result of devitrification of groundmass. Consists of 10-20% small (¼-1 mm) phenocrysts (50% plagioclase; 15% sanidine, quartz, and bronzy biotite; and 1-2% clinopyroxene, hornblende, and Fe-Ti oxides); 5-15% small (1-5 cm), sub-angular to sub-rounded, uncollapsed pumice fragments; and ca. 5% small (<1 mm-2 cm) mafic aphanite xenoliths; all set in a groundmass of poorly, if at all, welded glass shards and devitrified dust. Vuggy on weathered surface as result of weathered-out pumice fragments; prominently vertically jointed (figure 10). (NOTE: All petrographic data extrapolated from Wagner, 1984.)

2 10 feet (3.05 m) Felsic ash-flow tuff; light grayish-white on fresh surface, weathers light pinkish-tannish white; punky, porous, and friable. Consists of 5-10% small (<½ mm) phenocrysts (50% plagioclase; 15% sanidine, quartz and bronzy biotite; and 1-2% pyroxene, hornblende, and Fe-Ti oxides); 5-10% small (1-5 cm), sub-angular to sub-rounded, uncollapsed pumice fragments; and 10-15% poorly sorted (1-10 cm), mostly sub-angular xenoliths of dark brown to black, scoriaceous to dense mafic aphanite (figure 11).

1 2 inches (5 cm) Felsic airfall tuff; very light-gray to white, finely laminated, partially reworked. Consists of 2-5% small (¼-½ mm) phenocrysts of plagioclase, sanidine, quartz, and biotite in a groundmass of very fine glass shards and dust.

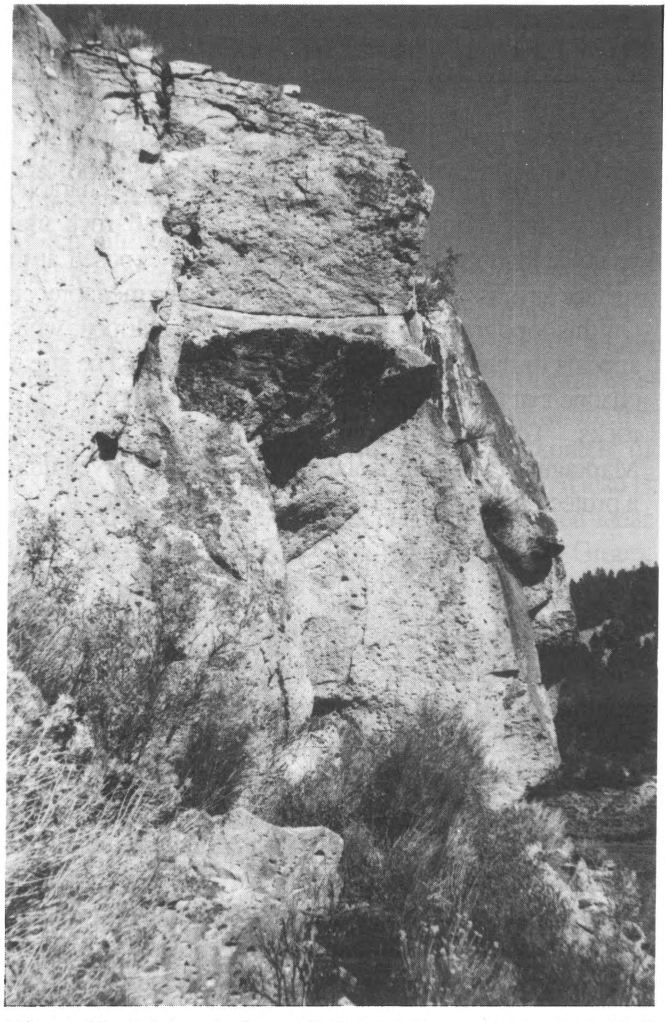

Figure 11. *Felsic ash-flow tuff of Unit 2 Haycock Mountain Tuff type section. Small fragments of mafic lava stud the unit.*

Upper Tertiary Gravels

From about Panguitch Lake eastward to within the Sevier River valley, a blanket of fluvially deposited gravel caps the Markagunt megabreccia and the Haycock Mountain Tuff. In places more than 200 feet (60 m) thick, these gravels consist predominantly of mafic and intermediate volcanic clasts. They probably in most part were eroded from lahar of the Mount Dutton Formation that probably covered the northern Markagunt Plateau after the Markagunt megabreccia was formed, this in response to the faulting and eastward tilting that produced the plateau of today. Their age therefore probably is latest Miocene(?) to Pliocene(?).

Basalts of Horse Bench

Thick basalt flows named by Iivari (1979) "the flows of Horse Bench" after the prominent landmark that they cap, overlie, and locally are interbedded with, the upper Tertiary gravels. They are here re-named the basalts of Horse Bench (plural *basalts* because they consist of two different lithologic varieties). These flows are widespread in the southeastern Fivemile Ridge quadrangle and southwestern Panguitch quadrangle. Dark gray to black, they range in thickness from 20 to 100 feet (6 to 30 m). Typically the upper part of each flow is vesicular. Their source is unknown.

The description that follows is from Iivari (1979). The basalts of Horse Bench are classified in thin section as tholeitic basalt and olivine basalt. The tholeitic basalt typically has a trachytic-pilotaxitic texture. It is made up of about 20% microlitic euhedral plagioclase laths, trace amounts of Fe-Ti oxides, and less than 1% larger phenocrysts of plagioclase and hypersthene, in a cryptocrystalline or devitrified glassy matrix. The olivine basalt is a medium-gray porphyritic aphanite, with phenocrysts averaging 0.5-1 mm across. It is made up of 20-30% phenocrysts consisting of 10-70% plagioclase, (An 68-73), 25-75% olivine, and 2-15% clinopyroxene in a groundmass of very finely crystalline euhedral plagioclase, anhedral clinopyroxene, and glass.

If the gravels with which the basalts of Horse Bench are interbedded are at least in part latest Miocene, then the lava flows are as well. They may be correlative with remnants of other basalt flows scattered but widespread over the Markagunt Plateau from north of Hatch (Kurlich, 1990) to near Cedar Breaks National Monument (D. W. Moore, oral communication, 1992). Under all circumstances, the basalts of Horse Bench probably are unrelated to the mafic volcanism that produced the widespread cinder cones and their related lava fields that today are present over much of the northern Markagunt Plateau (Gregory, 1949; D. W. Moore and D. Nealy, work in progress). The age of the latter probably is Quaternary, possibly in part Holocene (Anderson and Rowley, 1975). Therefore the basalts of Horse Bench may be part of a significant episode of Miocene basaltic volcanism that to date is only poorly documented in the Markagunt Plateau.

MARKAGUNT MEGABRECCIA

The Markagunt megabreccia, which mantles much of the high Markagunt Plateau, consists of a structurally chaotic assemblage of large masses of the Brian Head, Wah Wah Springs, Isom, Bear Valley, and Mount Dutton Formations. The megabreccia typically consists of house- to city block-sized masses of these rock units, found in any structural attitude in a groundmass of either sheared and folded strata of the Brian Head Formation, sheared and shattered sandstone and tuff of the Bear Valley Formation, or unstratified lahar of the Mount Dutton Formation. The megabreccia overlies either the upper "white" member of the Claron Formation, the Baldhills Tuff Member of the Isom Formation, or the Narrows Tuff Member of the Leach Canyon Formation. Locally it also overlies undisturbed strata of the Bear Valley and Mount Dutton Formations.

Reference Locality

The reference locality for the Markagunt megabreccia consists of a series of outcrops exposed between mileposts 36 and 38 west to east along Utah Highway 143 where it winds beside Panguitch Creek about 2-4 miles (3.2-6.4 km) east of Panguitch Lake. Not only is this locality readily accessible but, because of stream and road cuts, it also provides exposures of the megabreccia as good as any to be found. The log of the reference locality that follows describes these exposures and generally excludes mention of covered areas. The log begins at milepost 36, which is designated mile 0.0. At appropriate mileage intervals from this starting point (e.g., mile 1.3), exposures on the north and west (NW) side of Highway 143 are described first, then those on the south and east (SE) side.

Mile 0.0

NW: Panguitch Creek floodplain NW of highway, bordered on north by low hills on which there are no exposures but which probably are underlain by megabrecciated sandstone of the Bear Valley Formation and/or lahars of the Mount Dutton Formation.

SE: Road cut in rubble slope on SE side of highway. Rubble consists of pebbles and cobbles of intermediate to mafic volcanic rock that are in a disaggregated matrix of brownish sand, silt, and clay along the first three-fourths of the cut, and in a matrix of pulverized "salt and pepper" sandstone along the last one-fourth of the cut. The exposure is capped by 1-2 feet (0.3-0.6 m) of hillslope debris consisting of smaller volcanic clasts in a brown, soily matrix. The rubble may be Quaternary landslide debris rather than part of the megabreccia. Whatever its origin, it lies on a hill of shattered Baldhills Tuff Member, which can be seen just to the west.

Mile 0.05

NW: Hill on NW side of highway in part capped by Haycock Mountain Tuff, which rests on stream gravels in a channel fill cut into shattered tuff of the Baldhills Tuff Member of the Isom Formation (figure 8). The Baldhills that makes up most of hill is obscured by Haycock Mountain Tuff float; however, shattered Baldhills can be seen cropping out on top of the hill east of the Haycock Mountain Tuff caprock, and below the Haycock Mountain Tuff cap one large allochthonous monolith of Baldhills is visible.

SE: Roadcut on SE side of highway in pulverized salt-and-pepper sandstone and conglomerate of either the Bear Valley or Brian Head Formations, overlain by 2-4 feet (0.6-1.2 m) of hillslope debris of pebbles and cobbles of volcanic rock in a brown, soily matrix.

Mile 0.25

SE: SE of highway, Brian Head Formation consisting of shattered light-gray to white sandstone and marlstone containing pods of chalcedony replacing marlstone.

Mile 0.3

SE: Contact between shattered Brian Head Formation and Baldhills Tuff Member on SE side of road. Although the Baldhills also is shattered, its flow layering can be seen to dip about 40° S 30° W.

Mile 0.4

NW: Road cut on NW side of highway in shattered Baldhills Tuff Member marked by numerous shear zones, most of which dip 70-80° E or W, but some of which are subhorizontal. Some of the shear zones are marked by 1-3 feet (0.3-1 m) of brecciation (figure 12).

Mile 0.45

NW: Gully on NW side of highway gives good exposures of sheared and shattered Baldhills Tuff Member. Shear zones generally dip 70-80° E or W; flow layering dips 10-20° N 10-20° W.

Figure 12. *Mile 0.4, Markagunt megabreccia reference locality. Sheared and shattered Baldhills Tuff Member, NW side of highway. Note sub-horizontal shear zone about one-third up the outcrop (A); and sub-vertical shear zone, which is marked by a brecciated zone about 3 feet (1 m) thick, near right side of photo (B).*

Figure 13. Mile 0.65, Markagunt megabreccia reference locality. Hoodoo of Mount Dutton lahar containing large, angular boulders of Bear Valley mafic lava.

SE: Hillslope on SE side of highway covered largely with rubble of Baldhills Tuff Member, but some outcrop reveals flow layering dipping 30-40° N 10-20° W.

Mile 0.65

NW: Large masses of Mount Dutton lahar on NW side of highway lie adjacent to slopes of sheared and shattered Baldhills Tuff Member. Lahar is an outlier of the much larger mass of similar material on other side of highway.

SE: Very large monolith of Mount Dutton lahar, a prominent landmark, on SE side of highway (figure 13). This is part of a much larger mass of lahar, which on this side of highway is in contact with the Baldhills Tuff Member about 100 feet (30 m) W of the monolith. The lahar consists of a light reddish-tan groundmass with small (1-5 in; 2.5-8 cm), subrounded to rounded pebbles and cobbles of heterolithologic intermediate volcanic rock and very large (up to 6 ft; 2 m) angular boulders of mafic volcanic rock consisting of a black aphanitic groundmass in which are set a few to many small phenocrysts of plagioclase and pyroxene. This outcrop provides an excellent opportunity to consider the interpretation offered herein that Mount Dutton lahars, derived from the Marysvale volcanic field, and blocky mafic lava of the Bear Valley Formation were emplaced one on top of the other; and then, while the lahar still was viscous, both were mobilized by gravity sliding, thereby incorporating blocks of the Bear Valley lava within the Mount Dutton lahar.

Mile 0.65-0.8

NW: Slope on NW side of highway mantled with rubble of Baldhills Tuff Member, with a few large intact blocks present on the upper slope. Poorly exposed Mount Dutton lahar mass on SE side of highway.

Mile 0.75

NW: Small outcrop of Baldhills Tuff Member caps Mount Dutton lahar mass on NW side of highway.

Mile 0.8

NW: Poorly exposed contact between Baldhills Tuff Member and Bear Valley sandstone on NW side of highway.

Figure 14. Mile 0.85+, Markagunt megabreccia reference locality. Shear zone in Bear Valley sandstone (dark) and tuff (light). Note how sandstone has been smeared out along the shear.

Mile 0.85-0.9

NW: Road cut on NW side of highway in sheared Bear Valley sandstone and tuff and Mount Dutton lahar, capped at E end by Baldhills Tuff. Two major shears cut the outcrop; both strike about N 10° W; one dips about 60° W and the other about 30° W. Movement on the latter appears thrust-like, juxtaposing Bear Valley sandstone and tuff and smearing sandstone out along the contact (figure 14).

Various rock types exhibit different small-scale structures, probably as a result of their degree of induration at the time the shearing took place. The tuff is shattered, indicating brittle response of an indurated rock. Sedimentary rocks, on the other hand, not only are shattered but also exhibit convoluted and offset contacts, seemingly indicative of both the brittle and ductile responses of a poorly indurated rock. The "blob-like" nature of lahar masses at the W and E end of the road cut indicates a similar ductile response.

Mile 0.95-1.0

NW: Hillslope exposures of sheared and shattered Bear Valley sandstone rubble on NW side of highway.

SE: Outcrop of sheared Bear Valley sandstone and conglomerate on SE side of highway. Bedding dips 40-65° N. Sandstone is typical of Bear Valley Formation, but conglomerate is unusual both in its red color and its content of pebble- to cobble-sized clasts of intermediate to mafic volcanic rock.

Mile 1.0-1.1

NW: Road cut on NW side of highway in sheared and brecciated Bear Valley sandstone and conglomerate containing large, angular blocks of Baldhills Tuff Member. Both the bedding of the sandstone and the flow structures of the tuff are in chaotic attitudes. Slope above outcrop is capped by large mass(es?) of Baldhills Tuff Member. Away from road cut, hill is capped by the upper Tertiary gravels.

Mile 1.05

NW: Outcrop of sheared and brecciated Bear Valley sandstone.

Mile 1.2 (figure 15)

NW: Gulley on side of highway flanked by large shattered masses of Baldhills Tuff Member resting on and in Bear Valley sandstone.

SE: Mount Dutton lahar resting on Baldhills Tuff Member SE of highway. A short distance to the east, the Baldhills at creek level is outcrop of the autochthonous northward-tilted caprock of much of Haycock Mountain.

Mile 1.2+

NW: Poorly exposed contact between Bear Valley and Brian Head Formations on NW side of highway.

Figure 15. Looking east near mile 1.2, Markagunt megabreccia reference locality. Tree-covered slope on right is dip slope of autochthonous Baldhills Tuff Member, down which the Markagunt megabreccia slid. Hill at left is described at mile 1.25.

Mile 1.25

NW: Road cut on NW side of highway in sheared and shattered Brian Head Formation containing large, angular boulders of Baldhills Tuff Member (figure 16). The hill above the road cut consists for the most part of the Brian Head Formation which incorporates large masses of Mount Dutton lahar, forming very prominent hoodoos, as well as masses of Baldhills Tuff Member. Shattered, almost pulverized Baldhills at eastern end of road cut is interpreted as the top of a large shear zone better exposed at mile 1.4. Away from highway, gently northward-dipping Haycock Mountain Tuff, capped by upper Tertiary gravels, crops out near top of hill.

Mile 1.35

NW: Road cut on NW side of highway has a base of autochthonous Baldhills Tuff Member. Above the autochthonous Baldhills is a large shear zone within allochthonous Baldhills, the top few feet (1 m) of which is marked by shattered, almost granulated, Baldhills Tuff. Apparent dip of shear zone is about 10-15° E; true dip, including any northward component, cannot be determined. Overlying the shear zone is Bear Valley tuff incorporating numerous xenoliths, which in turn is overlain by Mount Dutton lahar which develops very prominent hoodoos (figure 17).

SE: SE of Panguitch Creek, massive, northward-dipping, autochthonous Baldhills Tuff Member exhibits well-developed flow layering that in places is deformed into folds, some of them overturned (figure 18). Although this outcrop is marked by numerous sub-vertical joints, it does not display the shear zones and shattering of the allochthonous Baldhills NW of highway.

Mile 1.45

NW: Poorly exposed, apparently eastward-dipping contact between Mount Dutton lahar and Bear Valley tuff of mile 1.4 on NW side of highway.

SE: Autochtonous Baldhills Tuff Member outcrop continues southeast of Panguitch Creek. The upper surface of the Baldhills, which dips about 10° NE, is clearly visible from this vantage point.

Mile 1.5

NW: Highway level here is at, or slightly below, the contact between the autochthonous Baldhills Tuff Member and the overlying allochthonous Brian Head Formation.

Figure 16. *Mile 1.25, Markagunt megabreccia reference locality. Sheared and shattered Brian Head Formation (light) containing large angular boulders of Baldhills Tuff Member (dark).*

Figure 17. *Mile 1.4, Markagunt megabreccia reference locality. Base of outcrop is autochthonous Baldhills Tuff Member (A), above which are: a large shear zone within allochthonous Baldhills (B), Bear Valley tuff incorporating numerous xenoliths (C), and Mount Dutton lahar which develops very prominent hoodoos (D).*

Figure 18. *Mile 1.4, Markagunt megabreccia reference locality. At right is massive autochthonous Baldhills Tuff Member; at left, road cut in allochthonous Brian Head Formation overlying the Baldhills.*

On NW side of highway, Brian Head Formation displays chaotic structures including recumbent folds, the axes of which trend about N 10° E; and juxtaposition of different rock types along surfaces, many of which are shears of widely different orientations (figure 19). The rock of the Brian Head Formation is not shattered like the nearby allocthonous Baldhills tuff, however, indicating that it was poorly indurated, and probably water saturated, at the time of its deformation.

SE: Small road cut SE of highway has shattered Baldhills Tuff Member at its base, overlain by 3 feet (1 m) of sandstone or lahar containing numerous clasts of mafic aphanite. The top surface of the latter unit is marked by slickensides plunging 10° N 10° W. This surface is overlain by about 3 feet (1 m) of the Brian Head Formation.

Mile 1.55

NW: Road cut on NW side of highway in Brian Head Formation. The overturned fold defined by a 3-foot (1-m) thick sandstone bed at the southwestern end of this cut appears to be a drag fold developed above a shear that strikes about N 40° W and dips about 60° NE (figure 20). The rock within the folded sandstone is marked by "box-work" shears as well as by undergoing considerable plastic deformation into a chaotic structural configuration.

SE: Road cut on SE side of highway in sheared and shattered Baldhills Tuff Member.

Mile 1.6-1.75

NW: Highway level is at or very near the top of autochthonous Baldhills Tuff Member. Low hills about 300 feet (100 m) NW of highway are underlain by the Brian Head Formation. White outcrop seen in distance is structurally chaotic sandstone and tuff of the Bear Valley Formation, which is in normal fault contact with the Brian Head Formation.

SE: Gently northeastward-dipping topographic surface SE of highway is developed on top of autochthonous Baldhills Tuff Member.

Mile 1.75-1.8

NW: Road cut on NW side of highway provides poor exposure of gently northward-dipping sandstone and minor marlstone of the Brian Head Formation.

SE: Excellent exposure of allochthonous sandstone and tuff of the Bear Valley Formation overlain by lahar of the Mount Dutton Formation SE of Panguitch Creek (figure 21). General dip of both units dip is 45° W, but the Bear Valley is a structurally chaotic assemblage that juxtaposes large masses of sandstone and tuff as well as masses of the Brian Head Formation. These allochthonous strata are truncated by an erosion surface that dips about 5° N, conformably overlain by about 30 feet (10 m) of stratified upper Tertiary gravels.

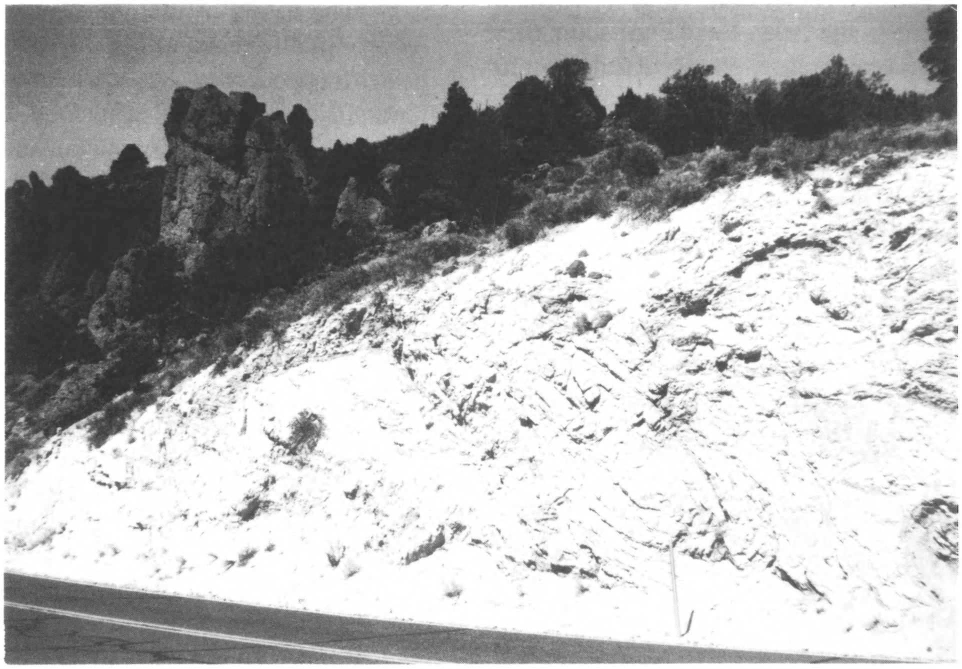

Figure 19. Mile 1.5, Markagunt megabreccia reference locality. Note large recumbent fold in Brian Head Formation and hoodoos of Mount Dutton lahar.

Figure 20. Mile 1.55, Markagunt megabreccia reference locality. Overturned drag fold in Brian Head Formation developed above shear dipping toward east (right).

Mile 1.85-1.9

NW: Road cut on NW side of highway in sandstone and minor marlstone of the Brian Head Formation; these strata dip about 25° SW at southern end of cut and about 10° NE at northern end.

Mile 2.0

NW: Road cut on NW side of highway in rubble of the Brian Head Formattion. The hill above the road cut consists in stratigraphic order of additional allochthonous Brian Head Formation, a channel fill of the older gravels, two autochthonous cooling units of the Haycock Mountain Tuff, and a cap of well-stratified upper Tertiary gravels (figure 22).

Nature and Distribution

The nature of the Markagunt megabreccia differs widely in different areas of the northern Markagunt Plateau. It appears that these differences are in some places primarily the result of differential erosion, in others of different processes of formation, and in still others of the different rock units involved. Probably, however, all three of these factors everywhere played some role. It therefore is necessary to describe the Markagunt megabreccia by relating it to the individual areas in which it is found. Seven separate areas of exposure are here defined (figure 23). The boundaries between these areas, however, although sharply drawn for descriptive purposes, must be understood to be gradational in nature; that is, elements of the features that characterize one area may be found in an adjoining area.

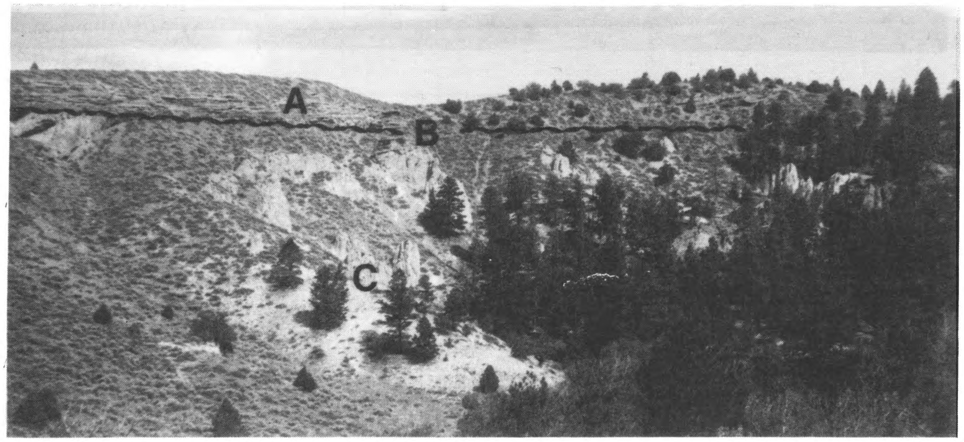

Figure 21. *Mile 1.75-1.9, Markagunt megabreccia reference locality. Valley wall south of Panguitch Creek capped by upper Tertiary gravels (A) resting on erosion surface (B) cut on megabreccia (C).*

Figure 22. *Mile 2.0, Markagunt megabreccia reference locality. Allochthonous Brian Head Formation (A) overlain by Haycock Mountain Tuff (ledge in trees at right of hill, B) and upper Tertiary gravels (higher ledge at left, C).*

I limit my discussion of the Markagunt megabreccia to these seven areas plus the area north of them as far as Utah Highway 20. In this latter area small, isolated masses of allochthonous rock which I include within the Markagunt megabreccia are found. I exclude from my discussion all elements of megabreccia found farther west in the Markagunt Plateau. I am of the opinion that these, which have been mapped by E. G. Sable, at least in largest part probably belong to the Markagunt megabreccia. Because I have not studied them in detail, however, it would be presumptuous for me to do other than state this as an opinion. This is made doubly the case because Maldonado (in press) believes that these megabreccia elements in the western Markagunt Plateau are related to similar megabreccia that he has studied in the Red Hills to the west, to which he attributes a completely different origin from the one that I believe formed the Markagunt megabreccia.

Area 1.

Area 1 is that of the reference locality exposed along Panguitch Creek east of Panguitch Lake, described above. Panguitch Creek and the construction of Utah Highway 143 have combined here to present cross sections through the megabreccia elsewhere unsurpassed, and only rarely equalled, for the structural details they reveal. In areas where the megabreccia can be seen only in map view, similar structures probably are common, but this cannot be demonstrated.

Area 2.

Area 2 is that of Haycock Mountain and vicinity, a forested highland south of Panguitch Creek that trends northeastward between The Pass and South Canyon. To the south of Haycock Mountain are the drainages of Pass Creek and Rock Canyon. Haycock Mountain is basically a gently (5-10°) northward-dipping hogback. It is largely capped by the Baldhills Tuff Member of the Isom Formation, except near its western end, where it is capped by the Haycock Mountain Tuff. The south-facing scarp of Haycock Mountain that overlooks Pass Creek exposes an excellent section, almost 350 feet (110 m) thick, of the Brian Head Formation.

The southeasternmost exposures of the Markagunt megabreccia are found on Haycock Mountain. To the south lies a relative lowland developed on strata of the Brian Head and Claron Formations. The megabreccia on Haycock Mountain consists for the most part of scattered, large, allochthonous masses of sheared and shattered welded tuff of the Baldills Tuff Member and lahar of the Mount Dutton Formation that rest on the surface of the massive, northward-dipping autochthonous Baldhills caprock. Several small, allochthonous masses of Bear Valley Formation sandstone and tuff also dot the dip slope of Haycock Mountain, as well as one small mass of rock of the Wah Wah Springs Formation. The latter is the southeasternmost known occurrence of any rock of the Needles Range Group.

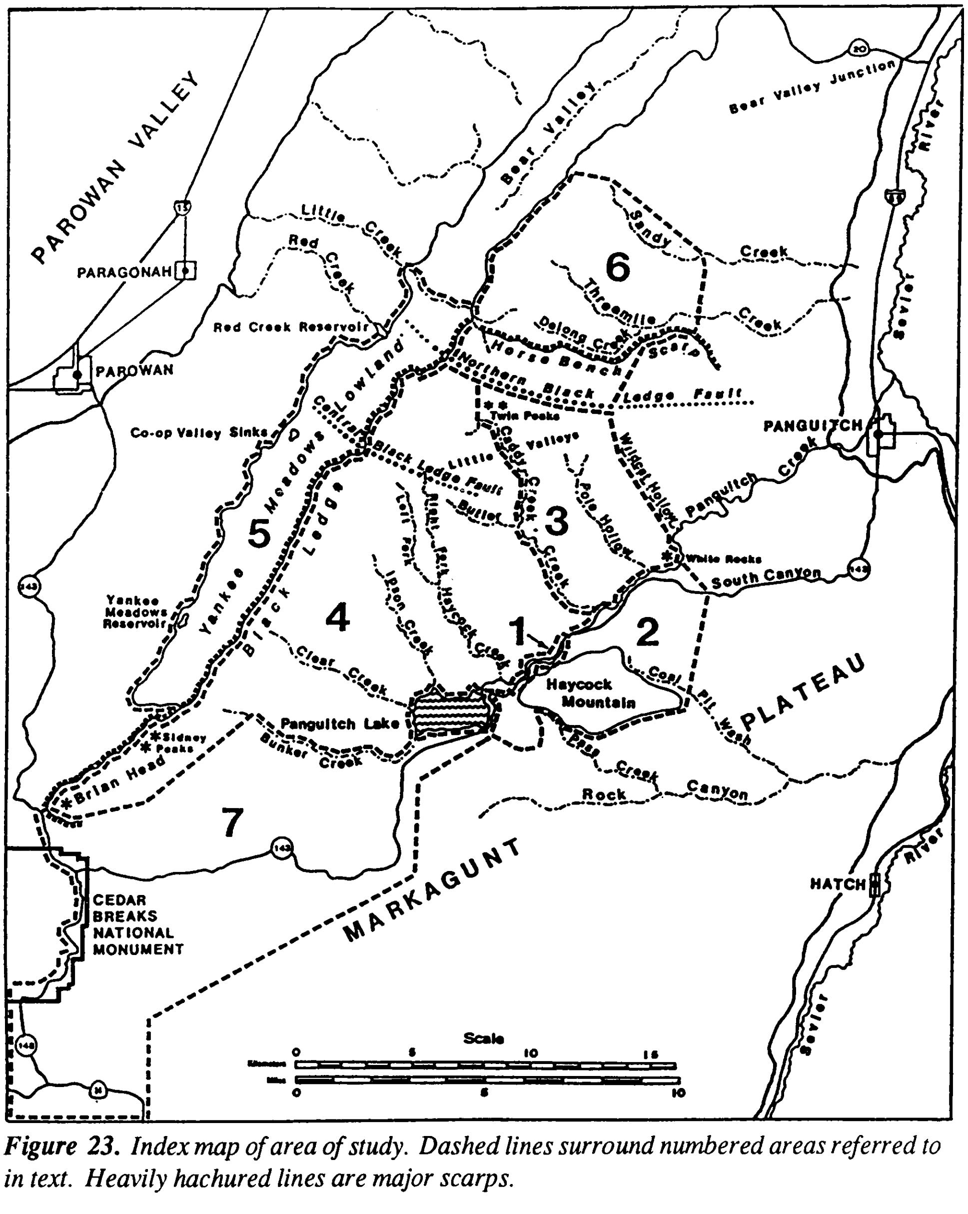

Figure 23. Index map of area of study. Dashed lines surround numbered areas referred to in text. Heavily hachured lines are major scarps.

South of Haycock Mountain, several masses of the Baldhills Tuff Member are found lying on strata well down in the section of the Brian Head Formation. It is impossible to say whether these are "lag" from a let-down megabreccia that once extended south of Haycock Mountain, or are simply masses derived from mass wasting on the south-facing slope of Haycock Mountain.

Area 3.

Area 3 is a largely treeless terrain that lies between the reference locality of the Markagunt megabreccia and a WNW-striking fault, downthrown to the north more than 1,000 feet (300 m), about 7.5 miles (12 km) to the north. About a half mile (1 km) farther north, a prominent north-facing scarp parallels the fault. This scarp, here termed Horse Bench scarp after the most prominent highland along its length, marks the northern edge of the high Markagunt Plateau. North of Horse Bench scarp at its western end lies the westward-flowing headwaters of Little Creek; to the north on the east are the eastward drainages of DeLong and Three Mile Creeks. Area 3 is bounded on the east by Wildcat Hollow, east of which gently southeastward-dipping, gravel-capped basalt of Horse Bench conceals the megabreccia. The western edge of Area 3 is at the base of the forest-covered, mountainous terrain that, on the south, lies west of Butler Creek and, north of its confluence with Caddy Creek, west of the latter. To the north the forested higher country that marks the western margin of Area 3 is west of the Little Valleys and Twin Peaks.

The southern half of Area 3 can be seen to the north from Utah Highway 143, where it runs eastward from Panguitch Lake, to consist of several high but softly rounded, treeless, north-northeast-ascending ridges. These ridges are capped by the younger gravels, but themselves consist solely of the megabreccia.

A good dirt road leads northward up Pole Hollow from Highway 143 just west of White Rocks; White Rocks itself consists of probably allochthonous felsic tuff of the Bear Valley Formation. The dirt road leads to the northern half of Area 3, a hilly and largely treeless area between the Little Valleys and Horse Bench. Here again virtually all exposed rock is part of the megabreccia.

If any area can be considered the "heart" of the Markagunt megabreccia, then it is Area 3. Deep incision by Butler Creek and Caddy Creek reveals that here the megabreccia rests on a thick sheet of the uppermost cooling unit of the Baldhills Tuff Member. The megabreccia itself is chaos on a grand scale.

The most common rocks that make up the megabreccia of Area 3 are sandstone and felsic tuff of the Bear Valley Formation; next in quantity is lahar of the Mount Dutton Formation. Lesser amounts of welded tuff of the Wah Wah Springs Formation, Baldhills Tuff Member of the Isom Formation, and Bear Valley Formation also are found within it, as are mafic lava flows of the upper Bear Valley Formation. All of these have been thrown into a jumbled configuration that juxtaposes masses of sandstone, tuff, lava and lahar, ranging in size from several hundred to several thousand feet (100-1,000 m) across and in any structural attitude. These sandstone, lava, lahar, and tuff masses are themselves commonly internally disrupted into smaller masses that in turn enclose masses of the other rock types.

Several smaller scale features within the megabreccia are worth noting. First, most of the Mount Dutton lahar exhibits no stratification but does contain an admixture of large, angular boulders of mafic lava of the Bear Valley Formation. Second, large masses of Bear Valley Formation sandstone in some places exhibit excellent cross-bedding, but in others show no stratification or other primary structural features. Where stratified, the sandstone usually exhibits a systematic pattern of commonly conjugate shears and micro-faults (figures 4 and 5). The attitudes of such features are unique to such outcrop as have been studied, however, and therefore to date have revealed nothing about any regional stress field in which they may have formed. Third, allochthonous masses of welded tuff, both of the Isom and Bear Valley Formations, commonly have been unsystematically shattered into small fragments, ranging in size from less than an inch to more than a foot (0.01-0.5 m) across, enclosed in a matrix of pulverized tuff (figure 3). These shattered allochthonous masses have since been healed, probably largely by devitrification, so that now they are cohesive and as resistant as any unshattered autochthonous counterpart.

Two additional features of Area 3 are worth mentioning, even though they apparently had nothing to do with the formation of the megabreccia. First, in a few places well-stratified, seemingly autochthonous lahars of the Mount Dutton Formation, containing a large admixture of angular blocks of mafic lava, cap the megabreccia. These indicate that both Bear Valley and Mount Dutton volcanism continued after the megabreccia formed. Second, in several places in Area 3, intermediate to mafic dikes cut the megabreccia. These dikes strike about N 60° W. They, together with the Haycock Mountain Tuff, indicate that the bimodal volcanism that marked the closing stages of deposition of the Bear Valley Formation continued after the formation of the megabreccia. It also seems probable that these dikes were the source of the mafic lava blocks that are incorporated in the autochthonous lahars of the Mount Dutton Formation.

Area 4.

Area 4 lies west of Area 3. Mountainous and heavily forested, it extends westward to a very prominent west-facing, north-northeast-trending scarp that overlooks a parallel lowland in which are located Yankee Meadows Reservoir and the Co-Op Valley Sinks. This scarp, which is visible from the Great Basin west of Paragonah, terminates to the south at Brian Head. Gregory (1950) informally termed this scarp the Black Ledge, and I follow this practice herein. Brian Head and Bunker Creek mark the southwestern boundary of Area 3, and Panguitch Lake marks its southeastern corner. Horse Bench scarp where it overlooks the headwaters of Little Creek marks its northern edge.

Although Area 4 has a heavy forest cover that on the flanks of most uplands obscures bedrock, numerous streamcuts provide good bedrock exposures, revealing that a thick (>250 ft; >75 m) section of the Baldhills Tuff Member is, or was, present throughout the area, and that everywhere the Baldhills is either mantled by or incorporated within the Markagunt megabreccia. The megabreccia itself throughout most of Area 4 consists largely of lahar of the Mount Dutton Formation in which are incorporated large blocks in random attitudes of welded tuffs of the Wah Wah Springs and Isom Formations, and welded and unwelded tuff, but very little sandstone, of the Bear Valley Formation. The lahar exhibits little if any stratification, even in sections more than 100 feet (30 m) thick. Where stratification is present, it may be in any structural attitude.

The west-facing Black Ledge that marks the western edge of Area 4 is a 15 mile- (24 km-) long north-northeast-trending fault scarp that formed during the late Miocene(?)-Quaternary episode of block faulting that produced today's Markagunt Plateau. It is of particular interest because along its length it exposes a cross section of the Markagunt megabreccia. The ledge itself is held up by the Baldhills Tuff Member along most of its length; locally, however, it is held up by the underlying Blue Meadows Tuff Member. These units can be seen to be underlain by the Brian Head Formation at and for a few miles north of Brian Head (Peak). Farther north, heavy forest and talus obscure the underlying rock; where visible, however, the underying rock also is the Brian Head Formation. Overlying the Isom along the southern third of the Black Ledge is the Narrows Tuff Member of the Leach Canyon Formation. Along the northern two-thirds of the Black Ledge only the megabreccia, consisting largely of the Mount Dutton Formation, overlies the Baldhills.

The Black Ledge is cut by two major WNW-striking faults or fault zones, downthrown to the north. These are here termed the Black Ledge faults. The ledge is terminated at the north near Horse Bench scarp by one, the northern Black Ledge fault, which offset of the Baldhills Tuff Member reveals has a throw of about 1,000 feet (350 m). About three miles (5 km) to the south, it is cut by the second fault or fault zone, the central Black Ledge fault, which offset of the Baldhills also reveals has a throw of about 800 feet (250 m). In addition, several other faults of similar strike but smaller displacement, both down toward the north and the south, cut the Black Ledge.

The character of the Markagunt megabreccia is markedly different across the northern and central Black Ledge faults. Along their strike and to the north of them for a distance of about 2 miles (3.2 km), it consists of a chaotic jumble of house-sized blocks. In the case of the northern fault, these blocks are made up of the Wah Wah Springs, Isom, Bear Valley, and Mount Dutton Formations; in the case of the central fault, they consist almost exclusively of the Isom Formation. In contrast, between these jumbles that mark the northern and central Black Ledge faults, and south of the central Black Ledge fault to about the headwaters of Clear Creek, the megabreccia in most places is typical of that mantling most of Area 4, that is, lahar of the Mount Dutton Formation incorporating large allochthonous blocks of other rock units.

In the vicinity of the headwaters of Clear Creek, about half the distance to Brian Head south of the central Black Ledge fault, the Baldhills Tuff Member is missing from the section over an area of about 3 square miles (7.5 sq km); in this area, the Blue Meadows Tuff Member is exposed (Judy, 1974). To the south along the Black Ledge the Markagunt megabreccia is represented by large, shattered, allochthonous blocks of the Baldhills Tuff Member, together with minor amounts of Mount Dutton lahar, that rest on the surface of the Narrows Tuff Member, which in turn overlies the autochthonous Baldhills Tuff Member. The Sidney Peaks are such allochthonous Baldhills masses (figure 24).

One additional area of particular interest is that of the Left Fork of Haycock Creek, where there is evidence that the gravity sliding that produced the Markagunt megabreccia ramped from below the Isom Formation to above it. Along the southern half of the Left Fork the thick Baldhills Tuff Member that is present throughout Area 4 is at creek level. This autochthonous sheet of the Baldhills terminates abruptly along a north-facing, ENE-trending scarp about half-way to the headwaters of the creek (SW ¼, sec. 8, T. 35 S., R. 7 W.). There is no sign of a fault trace on the higher valley sides above this scarp to indicate that it was formed subsequent to the megabreccia by a high-angle, dip-slip

Figure 24. View toward northeast of whale-backed mass of Baldhills Tuff Member (on skyline) overlying ledge of Narrows Tuff Member (foreground) at Sidney Peaks on the Black Ledge northeast of Brian Head.

fault, downthrown to the north. Instead, the scarp disappears on both sides of the Left Fork valley under an unbroken sheet of megabreccia containing numerous very large blocks of the Baldhills Tuff Member (figure 25).

It therefore appears that the megabreccia slid from north to south in this area, and that the surface of sliding ramped upward from below the Baldhills Tuff to above it at the site of the scarp that terminates the autochthonous Baldhills sheet of the southern Left Fork valley. Less likely is that the movement was northward and that the sliding surface jumped downward to the north.

Area 5.

Area 5 is the rugged, hilly, and forested lowland east of the Black Ledge, which here is termed the Yankee Meadows lowland. Structurally it is the southward extension of the Bear Valley graben, flanked on the east by the Black Ledge and on the west by a scarp that along most of its length exposes strata of the Claron and Brian Head Formations. Although I am familiar with much of the geology of this area, and have mapped that part of it that lies immediately north of the central Black Ledge fault, the only other mapping data available to me are those of of Judy (1974), completed before the nature and extent of the Markagunt megabreccia were recognized. The description of it that follows therefore is both incomplete and preliminary.

The salient feature of the Yankee Meadows lowland is the chaotic assemblage of large masses of the Isom Formation found over about 5 square miles (12.5 sq km) in its northern part, between the Co-Op Valley Sinks and Red Creek Reservoir. The Isom masses could be interpreted as a gigantic Quaternary landslide from the Black Ledge, but for three reasons are here interpreted as belonging to the Markagunt megabreccia. First, this area lies just north of the strike of the central Black Ledge fault zone where it can be projected into the lowland. Second, elsewhere along the Black Ledge mass wasting has produced nothing similar. Instead, the base of the Black Ledge for almost the entire rest of its length is masked by a very broad and thick accumulation of Isom and Mount Dutton talus of much smaller size that doubtlessly accumulated as the result of the sapping of the Isom that caps the Black Ledge by the weathering and erosion of the underlying Brian Head Formation. Third, and of greatest significance, is that very little, if any, Mount Dutton lahar masses are found with the chaotic Isom masses between Co-Op Valley Sinks and Red Creek Reservoir. If this chaos resulted from a Quaternary landslide, it seemingly should include a large amount of Mount Dutton lahar, which is the chief component of a thick section of the Markagunt megabreccia that caps the Black Ledge along its entire northern half except at the site of this supposed landslide. I, on the other hand, attribute the absence of the Mount Dutton lahar in the vicinity of the central Black Ledge fault to gravity sliding southward from the scarp produced by the fault having preceded the collapse of the scarp. I believe that at some early stage in the formation of the central Black Ledge fault, the then-unstable Mount Dutton lahar that lay on the Baldhills Tuff Member slid southward down the dip slope of the tilted fault block produced by the fault. When the throw of the

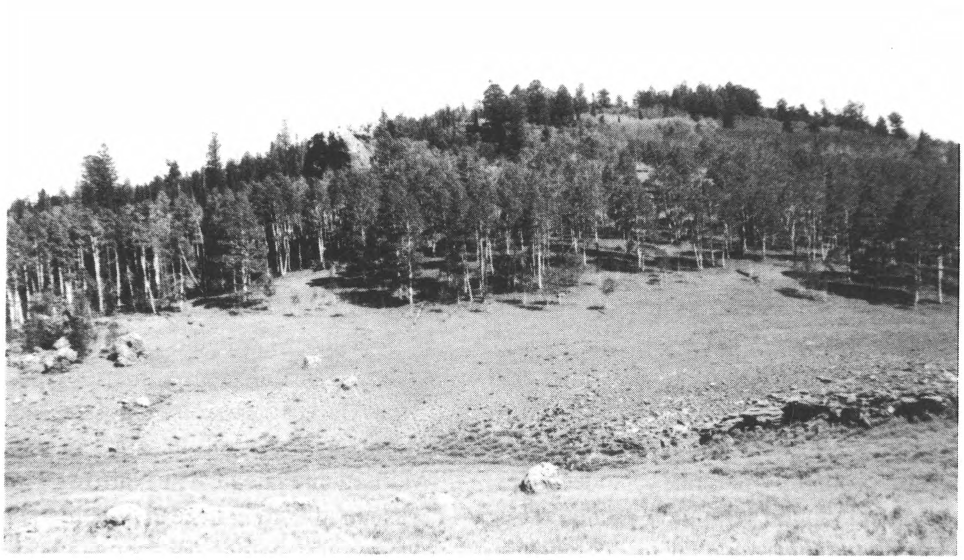

Figure 25. *Site of inferred upward ramping of the Markagunt megabreccia from below to above the Baldhills Tuff Member, Left Fork of Haycock Creek. Small scarp (lower right) marks northern end of autochthonous Baldhills that is continuous south-eastward (toward right) along Left Fork. Forested hill (background) consists of megabreccia in which are found very large masses of the Baldhills (note large mass protruding above tree tops and smaller ones littering slope below trees) as well as masses of the Wah Wah Springs Formation in a groundmass of brecciated lahar of the Mount Dutton Formation. Only megabreccia similar to that found on the hill is found down to stream level north of this site (toward left).*

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fault became great enough to expose the underlying weak Brian Head Formation, the central Black Ledge fault scarp, now capped by the Baldhills Tuff Member, collapsed to produce the Baldhills rubble now exposed to the north.

Area 6.

Area 6 lies parallel to Horse Bench scarp. It begins about 1 to 2 miles (1.6-3.2 km) south of the scarp, and extends northward for about 5 miles (8 km). This area is drained by Sandy Creek, Threemile Creek, and their tributaries. The western limit of Area 6 is Bear Valley, the eastern limit about halfway between Bear Valley and the Sevier River Valley.

Horse Bench scarp is 1-2 miles (1.6-3.2 km) north of and parallel to the strike of the northern Black Ledge fault where this fault can be projected eastward to mark the northern boundaries of Areas 3 and 4. The thick Baldhills Tuff Member that is found at and near the surface of the northern parts of Areas 3 and 4, however, is nowhere exposed along the north-facing Horse Bench scarp as might be expected if it were continuous to the scarp. Instead, north of the projected strike of the northern Black Ledge fault and on the face of Horse Bench scarp itself, the Baldhills is found as part of the Markagunt megabreccia in a structurally chaotic assemblage of very large blocks that also includes rock of pre-Wah Wah Springs Formation volcanics, and the Wah Wah Springs, Bear Valley, and Mount Dutton Formations. Excellent three-dimensional exposures of this megabreccia assemblage can be seen in canyon cut by the headwaters of Little Creek north of Area 4 and Indian Hollow north of Area 3.

North of Horse Bench scarp, in the drainage area of Three Mile Creek and its southern tributary, DeLong Creek, only isolated exposures of the Markagunt megabreccia are present. All rest on, or are embedded in, autochthonous sandstone of the Bear Valley Formation or lahar of the Mount Dutton Formation. They may be monolithologic masses of any of the Brian Head, Wah Wah Springs, Isom, Bear Valley, and Mount Dutton Formations that range in maximum dimension from 10 feet (3 m) to as much as 300 feet (100 m); or they may be chaotically juxtaposed masses of two or more of these units that cover irregularly shaped areas up to about 50,000 square feet (20,000 sq m) in area. Since most of these megabreccia masses are formed of resistant rock, they usually form topographic highs where they rest on sandstone of the Bear Valley Formation.

Only a few, small, widely isolated allochthonous rock masses are found north and west of Area 6, and their origin in all cases appears to be attributable to gravity sliding off the flanks of the several small intrusive domes that are present in the extreme northern Markagunt Plateau (Anderson and others, 1987). Although these small masses are removed from the major area mantled by the Markagunt megabreccia, they nevertheless are considered part of the Markagunt megabreccia because of the similarity of their origin to that found in the major area.

Area 7.

Area 7 is a high, rolling upland of meadows and heavily forested hills east of Cedar Breaks that extends northeastward to Panguitch Lake south of Area 4. It is dotted with numerous, probably Quaternary, cinder cones; and over broad areas is mantled with their related mafic lava flows. The meadows, forest, and lava all combine to obscure most of whatever Markagunt megabreccia is present in Area 7. What I know about the geology of Area 7 is based in equal part on reconnaissance that I have carried out in it and the geologic mapping of it by E. G. Sable and D. W. Moore.

That the megabreccia is, or was, present over most of Area 7 is attested to by allochthonous rock of the Baldhills Tuff Member that in many places litters its surface either as single boulders or as local boulder accumulations from 5 to 50 feet (2-15 m) thick. The meadows that lie alongside Utah Highway 148 immediately south of Cedar Breaks National Monument are an excellent example of such a boulder-scattered area (figure 26). The terrain at this site has the softly rounded contours of a glaciated area, and its hummocky surface, marked by numerous closed depressions, resembles glacial ground moraine. The visible Baldhills boulders are part of a blanket deposit of unconsolidated breccia that consists of Baldhills clasts together with a very few clasts of the Brian Head Formation. This deposit rests on either the Claron or the Brian Head Formation, as is the case over most of Area 7.

The Baldhills boulder field south of Cedar Breaks National Monument, as well as the allochthonous Baldhills boulders and boulder fields found elsewhere in Area 7, are part of the Markagunt megabreccia. This conclusion is based on the following scenario: Gravity sliding within the Brian Head Formation rafted and brecciated the Baldhills in this area as it did in much of the rest of the northern Markagunt Plateau. The Narrows Tuff Member, however, was not affected. Instead, where the Narrows locally was present, movement of the megabreccia was from the north, down the dip slope of the fault block bounded by the central Black Ledge fault. This movement emplaced the Baldhills Tuff Member on top of the Narrows Tuff Member, just as in other localities it emplaced Baldhills on top of Baldhills.

I thus view the allochthonous Baldhills boulders and boulder fields of Area 7 as essentially lag gravel, that is, the residuum of a Baldhills tuff sheet sheared and shattered during formation of the Markagunt megabreccia and then let down by the differential weathering and erosion of the Brian Head Formation on which it lies. That this Baldhills residuum has a different character near Cedar Breaks from what it has elsewhere I, in agreement with Moore (1992) and E. G. Sable (oral communication), attribute to more severe weathering, including frost shattering, at the higher elevation at Cedar Breaks and possibly to solifluction and

Figure 26. *Shattered Baldhills Tuff Member within the Markagunt megabreccia along Utah Highway 148 south of Cedar Breaks National Monument. Compare with figure 27.*

Figure 27. *Brecciated monolithologic Baldhills Tuff Member within the Markagunt megabreccia in Area 3 east of Panguitch Lake. Compare with figure 26.*

transport by ice there during the Pleistocene. Comparison of the Baldhills where it is part of the Markagunt megabreccia at the relatively low elevation near Panguitch Lake with its appearance in the boulder field south of Cedar Breaks lends credence to this conclusion (figure 27). Near Panguitch Lake the individual masses of the Baldhills within the Markagunt megabreccia, although internally sheared and shattered, are much larger than those near Cedar Breaks, where they usually are single boulders. Given time and additional weathering, however, the Baldhills masses near Panguitch Lake probably will resemble the boulder fields near Cedar Breaks.

ORIGIN OF THE MARKAGUNT MEGABRECCIA

General Statement

I interpret that the Markagunt megabreccia formed as the result of (1) gravity sliding of an inherently unstable stratigraphic succession of rock down low-angle slopes, northward off a large structural uplift and, (2) almost simultaneously, southward down the dip slopes of tilted fault blocks; and (3) collapse of the N-facing, WNW-trending scarps that bounded these fault blocks. The uplift may have been the result of the intrusion of a batholith in the central Markagunt Plateau, or may have been above a cupola on a much larger batholithic complex that underlies much of southwestern Utah.

Stratigraphic Control

Critical to the formation of the Markagunt megabreccia was the inherently unstable nature of the stratigraphic sequence involved. This instability resulted in the first place from the interbedding of sedimentary rock units of relatively low density with massive sheets of relatively high-density welded tuff. Instability also resulted from the physical characteristics of the sedimentary rock units at the time the megabreccia formed. These strata were probably poorly indurated at best; indeed, much of the sand of the Bear Valley Formation and many lahars of the Mount Dutton Formation may not have been indurated at all. In addition, the tuffaceous sedimentary strata of both the Brian Head and Bear Valley Formations had a high content of volcanic ash, and probably were water-saturated.

Thus the floor over which much of the megabreccia slid was the competent, massive white limestone at the top of the Claron Formation. Where such sliding took place within the overlying incompetent Brian Head Formation, as in much of Area 7, it displaced and brecciated all overlying rock units. Elsewhere, as in most of Areas 1-6, the surface on which the sliding took place either was on, or else ramped upward through, the competent Baldhills Tuff Member of the Isom Formation, which locally was underlain by the Wah Wah Springs Formation and/or the Blue Meadows Tuff Member of the Isom Formation, into the lower Bear Valley Formation. Where this happened, it not only created a structural chaos of the Bear Valley and intertonguing Mount Dutton Formations, but also rafted upward brecciated masses of the Brian Head, Wah Wah Springs, and Isom Formations to incorporate them within this chaos. Finally, in still other places such as the SW part of Area 4, the sliding surface ramped upward from above the Baldhills Tuff Member to above the Narrows Tuff Member of the Leach Canyon Formation, to emplace rock of the Baldhills on top of the Narrows.

Structural Uplift

Gravity sliding of large rock masses requires a slope down which it can take place, and for such a slope to form requires uplift. In the case of the Markagunt megabreccia, the major uplift appears to have been in the central Markagunt Plateau, a few miles south of the area considered in this report. Such an uplift may have been the result of intrusive doming. Although no intrusive bodies are exposed in the central Markagunt Plateau, aeromagnetic data provide indirect evidence that they may exist, remaining to be deroofed. Such data reveal several positive small-amplitude anomalies between 1 and 4 miles (1.6-6.4 km) south of Haycock Mountain (Blank and Kuchs, 1989). As H. R. Blank, Jr., pointed out to me (oral communication, 1991, 1992), these anomalies may represent near-surface cupolas of a batholith at depth. As Blank also suggested, such a batholith in turn may be part of a much larger batholithic complex that underlies much of southwestern Utah. Such a batholithic complex might extend under the entire northern Markagunt Plateau, and the several intrusive bodies exposed north of and within the area where the Markagunt megabreccia is found (Anderson and Rowley, 1987; Anderson and others, 1987) may be cupolas on it, too. Likewise, Blank believes it possible that the numerous igneous bodies in the nearby "Iron Axis" region of the southeastern Great Basin (Blank and others, 1992) may also be such cupolas. As they note, many of these bodies are interconnected and much more extensive at depth than their surface exposures indicate.

If the intrusion of a batholith in the central Markagunt Plateau did create a domal structure down the northern flank of which the Markagunt megabreccia slid, then it seems probable that this batholith was emplaced about 22-20 m.y. ago, the time during which most exposed plutons in southwestern Utah were emplaced (Blank and others, 1992). This would correspond very well with the age of the formation of the megabreccia as deduced from the 22 Ma age of the overlying Haycock Mountain Tuff.

Gravity Sliding

It seems clear to me that the Markagunt megabreccia formed by gravity sliding. That such sliding could and did take place during the Tertiary elsewhere in southwestern Utah was first documented by Mackin (1960), who summarized his studies in the Iron Springs district west of Cedar City by noting (p. 122), "...sliding is a possible or even likely alternative to Tertiary thrusting in the Great Basin as an explanation of structural complexities involving Tertiary rocks, particularly if these complexities are localized near major structural features, whether intrusive or tectonic." More recently, Rowley and others (1989) described the slides in the Iron Springs district in greater detail, Blank and others (1992) described even larger gravity slides and the megabreccias associated with them in the northern Pine Valley Mountains and eastern Bull Valley Mountains, and Maldonado (in press; Maldonado and others, 1990, 1992; Maldonado and Williams, in press a and b) described the chaotic structures that formed in the Red Hills above his Red Hills low-angle shear zone. The descriptions that Blank and others (1992) give of the structures within the megabreccias that they studied could be used verbatim to describe those within the Markagunt megabreccia.

Transport Direction

The available evidence seems to indicate that the Markagunt megabreccia in largest part slid northward to its present position. Where slickensides are found on the surface over which the megabreccia moved, and within the megabreccia itself, they indicate a transport direction between N 20° W and N 20° E, but do not unequivocally reveal whether the movement was toward the north or south. Most of these slickensided surfaces, which number no more than about a score, have been found in Areas 4 and 7 by E. G. Sable (oral and written communication.). Although such a small number can only be considered suggestive of the transport direction, the evidence it provides cannot be ignored. Therefore when any suggestion about the transport direction(s) of the Markagunt megabreccia is set forth, it should provide evidence that either corroborates or denies that provided by the slickensides.

Such corroborative evidence is found in the present distribution of the Baldhills Tuff Member of the Isom Formation. Since the Baldhills makes up a substantial portion of the Markagunt megabreccia, movement of the megabreccia cannot have been from areas where the Baldhills remains intact. Thus large-scale movement from north of Horse Bench scarp seems unlikely, for in this area the Baldhills is exposed wherever it can be exposed, in undisturbed sections as much as 600 feet (200 m) thick.

The presence or absence of the Baldhills cannot be used as evidence for movement from either the west or east. West of Cedar Breaks National Monument and the Black Ledge, erosion in many places has removed the entire Tertiary section, and in others left only the Claron Formation. Where rocks younger than the Claron are exposed, they include both autochthonous and allochthonous Baldhills Tuff Member as widely separated outcrops that offer no clues as to which direction the allochthonous masses moved. Yet if the Markagunt megabreccia of the high Markagunt Plateau slid from the west, it seemingly should include within it clasts of the Narrows Tuff Member of the Leach Canyon Formation, which E. G. Sable (oral and written communication) has mapped in the Markagunt Plateau west of Cedar Breaks, but it does not. Therefore it seems unlikely that the megabreccia slid from the west.

In the eastern Markagunt Plateau, on the other hand, the Baldhills dips eastward under a cover of the Horse Bench basalts and upper Tertiary gravel just east of the Markagunt megabreccia reference locality. It does not reappear in the up-faulted Sevier and Paunsaugunt Plateaus east of the alluviated Sevier River Valley, where it apparently never was emplaced.

North and west of Hatch, however, the Baldhills Tuff Member is missing from the stratigraphic section, with no evidence that it once was present but was removed by erosion. Yet the Baldhills is more than 250 feet (75 m) thick less than 15 mi (24 km) to the northwest where it is exposed along Ipson Creek and at least 100 feet (30 m) thick less than 8 miles (13 km) to the north where it is exposed along Panguitch Creek and on Haycock Mountain. Still capable of transporting such a mass after having travelled some 80 miles (150 km) from a presumed source west of the Escalante Desert, the Baldhills ash-flows seemingly should have been emplaced as at least a thin sheet only a few more miles to the east in the southern Hatch quadrangle, especially since there was no known barrier to prevent their eastward spread.

Therefore it seems probable that the Baldhills Tuff Member at one time was present farther south than where it today crops out. If so, it is not unreasonable to conclude that its absence north and west of Hatch is the result of gravity sliding from an uplift in the area where it is missing. This conclusion is supported not only by the generally N-S-oriented slickensides at the reference locality of the Markagunt megabreccia (Area 1), but also by the anomolous NNE dip of the Baldhills Tuff Member where it caps Haycock Mountain. Everywhere else east of Cedar Breaks National Monument and the Black Ledge, except where demonstrably deformed by faults and local uplifts, the autochthonous Baldhills tuff sheet that covers most of this area dips gently (1-2°) eastward or southeastward. Since no ENE-striking fault is found either north or south of Haycock Mountain (Wagner, 1984), it cannot be a tilted fault block, and therefore its northward tilt must be attributed to another cause.

In summary, I conclude that uplift in the central Markagunt Plateau, probably caused by intrusive doming, led to northward gravity sliding along the base of, or within, the Brian Head Formation. Somewhere south of Haycock Mountain, the sole on which this sliding took place ramped upward to above the Baldhills Tuff Member. Farther northward sliding then displaced the Brian Head and the overlying Baldhills Tuff Member and Bear Valley and Mount Dutton Formations to where they now are exposed as part of the Markagunt megabreccia where it overlies the autochthonous Baldhills on the northward dip slope and north of Haycock Mountain. I believe that this conclusion best fits the available data.

Fault Control

Northward sliding down the slope of an intrusive(?) uplift does not appear to have been the only mechanism involved in the formation of the Markagunt megabreccia, however. Sliding also appears to have been southward down the dip slopes of tilted fault blocks bounded by the Black Ledge faults. This sliding was accompanied by collapse of the WNW-trending Black Ledge fault scarps to add another element to the Markagunt megabreccia.

Collapse of the north-facing northern Black Ledge fault scarp is indicated by the the nature of the megabreccia north of, and in places mantling, its trace. Along Horse Bench scarp, which parallels the northern Black Ledge fault, the megabreccia does not give the appearance of allochthonous sheets, slabs, and wedges that were rafted to their present position on top of either the upper Claron Formation or the Baldhills Tuff Member. Instead, it involves all post-Claron rock units thrown together in a chaotic assemblage of house-sized and larger blocks resting on either undisturbed sandstone of the Bear Valley Formation or undisturbed lahar of the Mount Dutton Formation. This is quite unlike the megabreccia found elsewhere, which always completely incorporates these units in an assemblage that rests on either the upper Claron Formation or the Baldhills Tuff Member.

It therefore seems probable that the northern Horse Bench fault, which offset the Baldhills Tuff Member about 1,000 feet (300 m), exposed along its scarp all rock units younger than the Claron Formation, and that this scarp collapsed to produce the megabreccia found along its length. Factors that probably contributed to the collapse were seismic shaking caused by the faulting and the poor induration of the Bear Valley sandstone. That seismic shaking can generate landslides and avalanches even in well-indurated rock is well known (Voight and Pariseau, 1978; Keefer, 1984), and it would be even more significant in the case of poorly indurated sediments.

It cannot be demonstrated conclusively that gravity sliding took place southward from the northern Black Ledge fault. That it did, however, to remobilize or later be remobilized by megabreccia that slid northward, is suggested by the extremely complex structural nature of the megabreccia of Area 3 about halfway between Horse Bench scarp and Haycock Mountain. In places such as upper Pole Hollow, it would take mapping at a scale no smaller than 1" = 500' (1:6000) to depict it in detail.

There is better evidence of southward sliding down the dip slope of the tilted fault block formed by the central Black ledge fault, in this case followed by collapse of the related WNW-trending fault scarp. I have summarized this evidence in my earlier discussion of the nature of the Markagunt megabreccia in Area 5.

Transport Distance

How far the Markagunt megabreccia slid is problematic. Although the data available to solve this problem are inconclusive, they suggest that the distance typically was between 2 and 5 miles (3.2-8 km). Thus one minimum distance is provided by the allochthonous Brian Head Formation where it overlies the autochthonous Baldhills Tuff Member at the reference locality of the Markagunt megabreccia. Assuming that the upper part of the Brian Head slid northward down the dip slope of Haycock Mountain, it must have travelled a distance of at least 2.5 miles (4 km), and probably twice that, from where its lower part is exposed south of Haycock Mountain in the Pass Creek drainage basin. A second estimate can be made for the transport distance of the allochthonous masses of the Baldhills Tuff Member that overlie the autochthonous Narrows Tuff Member of the Leach Canyon Formation along the Black Ledge northeast of Brian Head. If they slid southward down the dip slope of a tilted fault block bounded by the central Black Ledge fault, then the nearest locality from which they could have come was near the headwaters of Clear Creek, where the Baldhills either is missing or unusually thin. This is a distance of between 1 and 5 miles (1.6-8 km). Third, transport distances of from 3 to 5 miles (4.8-8 km) can also be postulated for the allochthonous masses of the Wah Wah Springs Formation that are incorporated in the megabreccia. These are the distances to Horse Bench scarp, north of or along which was the nearest area from which the Wah Wah Springs probably could have been derived at the time the Markagunt megabreccia formed.

Alternative Explanations

Other origins may be postulated for any or all of the Markagunt megabreccia described herein and for similar megabreccia found in a similar stratigraphic position in the extreme western Markagunt Plateau and the nearby Red Hills. Thus Maldonado (Maldonado, in press; Maldonado and others, 1990, 1992) suggested that megabreccia of the Red Hills, and possibly the megabreccia of the Markagunt Plateau, both formed above his Red Hills low-angle shear zone. As a junior author of two of these papers, I agree that the megabreccia of the Red Hills, and perhaps that of the extreme western Markagunt Plateau, formed above the Red Hills low-angle shear zone. I do not, however, believe that the Markagunt megabreccia on the high Markagunt Plateau did. My disagreement stems in large part from the evidence of N-S movement of the Markagunt megabreccia provided by slickensides mapped by E. G. Sable on the high Markagunt Plateau. These slickensides directly contradict Maldonado's conclusion that movement above his Red Hills low-angle shear zone formed the Markagunt megabreccia of the high Markagunt Plateau, because he postulates movement above this shear zone as having been either to the east or west.

Thrusting also seems improbable as the cause of the Markagunt megabreccia. This is shown by the absence throughout most of the northern Markagunt Plateau of any mid-Tertiary structures other than those found in the megabreccia itself that could have been produced by compression during the time the megabreccia was formed. Thus, although many of the structures within the megabreccia doubtlessly were produced by compression related to friction within the sliding mass, there is abundant evidence for NNE-SSW extension rather than compression throughout the area of the northern Markagunt Plateau during the late Oligocene and early Miocene. First, this area underwent block faulting along WNW trends from about 30 m.y. at least until the time the Black Ledge faults formed, probably about 22-23 m.y. The timing of most of these faults can be demonstrated by the control they exerted on the deposition of regional and local rock units, such as ash-flow tuffs of the Needles Range Group and the Baldhills Tuff Member of the Isom Formation and sandstone of the Bear Valley Formation (Anderson, 1965, 1971, 1985; Anderson and Rowley, 1987; Anderson and others, 1987). Second, numerous WNW-striking dikes besides those reported herein were emplaced in the northern Markagunt during the same time span (Anderson and others, 1987). These extensional features correspond well with the conclusion of Best (1988) that a roughly north-south least principal stress existed throughout much of the southwestern United States from about 50 to 30 m.y., possibly until 26 m.y., and conceivably as recently as 18 m.y. in certain areas.

Paradoxically, however, there also is evidence of mid-Tertiary compression in the northern Markagunt Plateau. R. P. Nickelsen has shown me some of the structures indicative of this, and has published a brief description of them (Nickelsen, Merle, and Davis, 1991). The structures are thrust and strike-slip faults; small, conjugate, intra-bed thrusts and backthrusts forming wedges; and spaced cleavage. All these are found in Cretaceous rocks and the Claron

Formation in the southern High Plateaus. These structures, which can be traced for about 50 mi (85 km) from Bryce Canyon to Cedar Breaks, indicate horizontal compression which verges radially from S 80° E near Bryce Canyon to S 30° E near Cedar Breaks. None of these structures, however, appear to me to have involved compressive stress great enough to have formed the Markagunt megabreccia.

To add to the confusion, in the extreme western Markagunt Plateau E. G. Sable has shown me structures that resemble thrusts, with Cretaceous rocks seemingly thrust eastward over strata of the Claron Formation. If these indeed are thrusts that resulted from eastward compression, however, it seems unlikely that they are related to the Markagunt megabreccia because of the evidence shown by slickensides of N-S movement of the megabreccia.

Three other origins may also be postulated for the scattered boulders and boulder fields of the Baldhills Tuff Member found in Area 7. First, they may simply be the weathered residuum, not far removed from its original location, of the Baldhills tuff sheet that once mantled the area. Second, they may be glacial deposits. Third, they may be unrelated to the Markagunt megabreccia and instead, as has been suggested by Moore (1992), be gravity-slide breccia formed in response to the later NNE-striking faults that elevated the Markagunt Plateau, and since modified by weathering and mass movement.

It seems improbable that the breccia is the weathered residuum of the Baldhills Tuff Member because weathering and erosion of the Baldhills simply do not produce subhorizontal, areally extensive Baldhills boulder beds unless the unit first has been brecciated. This is especially true where the resistant Baldhills overlies weak rock like that of the Claron or Brian Head Formations. Invariably, downcutting in such a geologic setting leads to the sapping of the Baldhills by the underlying rock, thereby producing a steep, back-wasting Baldhills scarp at the foot of which talus accumulates. Such talus temporarily may armor the foot of the slope, thereby slowing the back-wasting of the scarp. In order for the process to continue, however, the talus must be removed by erosion; it cannot and does not "lie down" to form a boulder bed.

The fact that the breccia is essentially monolithologic militates against it being either a glacial deposit or related to the faults that elevated the Markagunt Plateau of today. Under either of these scenarios, the breccia seemingly would have to include clasts of the post-Baldhills ash-flow tuffs that are, or were, present in the area where the breccia is found. At the very least, it should include clasts of the Narrows Tuff Member of the Leach Canyon Formation, which today caps Brian Head (Peak), geographically close to and topographically above all sites where isolated Baldhills boulders as well as Baldhills boulder fields are found.

DISCUSSION

It seems clear to me that the Markagunt megabreccia in large part formed about 22 m.y. by gravity sliding of an unstable stratigraphic sequence of rock, and to a lesser extent by the collapse of fault scarps formed about the same time. This statement, however, begs as many questions as it answers, questions to which definitive answers remain to be found. First, is the Markagunt megabreccia in any way related to the megabreccia of the Red Hills (Maldonado, in press; Maldonado and others, 1990, 1992; Maldonado and Williams, in press a and b)? I believe this is not the case, for reasons that I have stated. Critical to the answer of this question, however, is a second one: Were the slope(s) down which the Markagunt megabreccia slid, as suggested herein, a structural, probably intrusive, uplift in the central Markagunt Plateau and the dip slopes of the fault blocks associated with the Black Ledge faults; or, as has been suggested by Maldonado (Maldonado, in press; Maldonado and others, 1990, 1992) and Moore (1992), did some or all of the slopes have other origins in place of or in addition to these? Again, for reasons already stated, I would answer the first part of this question affirmatively and the second part negatively. The definitive answers to all these questions, however, hinge on answering yet a third: In which direction(s) did the sliding take place; from north and/or south, as directly indicated by slickensides and suggested by other evidence, or from either the east or west as well?

I made scores of measurements of the attitudes of structures within the megabreccia indicative of movement direction, such as the ubiquitous shears found within it, but no clear pattern(s) of such movement direction(s) emerged from these data. My feeling is that many of these structures were displaced by sliding after they had formed, yet an exhaustive study of them has been beyond the scope of my investigation to date. If carried out, such a study might provide one or more areal patterns of structural vergence, which in turn could point to probable megabreccia source areas where they converge. Study of these areas might in turn provide evidence of uplift in the Claron Formation and older rock units. If uplifts are located, their origin(s) might be revealed by direct evidence such as faults or exposed intrusions, or indirect evidence such as that provided by gravity and aeromagnetic data.

This list of "ifs" admittedly is a formidable one. Yet I am of the opinion that only when a detailed study of structures indicative of the transport directions of the megabreccias of both the Markagunt Plateau and the Red

Hills has been carried out can definitive answers to the questions of their origin(s) be set forth. As Blank and others (1992) have pointed out in their discussion of the megabreccias of the Bull Valley and Pine Valley Mountains, "...there is no compelling reason to attribute a common origin to all occurrences (of megabreccia in southwestern Utah)." 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 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.

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