GEOLOGY AND MINERAL RESOURCES OF THE MARYSVALE VOLCANIC FIELD, SOUTHWESTERN UTAH

Geological Society of America
2002 Rocky Mountain Section Annual Meeting, Cedar City, Utah
May 6, 2002

View southward of the hydrothermally altered rocks at Big Rock Candy Mountain, five miles north of Marysvale, Utah.

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ABSTRACT

The Marysvale volcanic field, one of the largest such fields in the West, sits astride the Colorado Plateau-Great Basin transition zone. Most igneous rocks belong to a middle Cenozoic (32? to 22 million years old) calc-alkaline sequence, in which deposits from clustered stratovolcanoes dominate but ash-flow tuffs and their source calderas also are significant. About 5 percent of the igneous rocks belong to an upper Cenozoic (23 million years old to Holocene) bimodal (basalt and high-silica rhyolite) sequence, which was deposited as lava flows and ash-flow tuffs from calderas, volcanic domes, and cinder cones, and which was synchronous with major basin-range extension. Each of the two chemical rock sequences has its own distinctive mineral deposits, with gold in the older sequence and gold, molybdenum, uranium, and base metals in the younger.

INTRODUCTION

This field trip will visit the Marysvale volcanic field, one of the largest in the western United States, and one of significant mineral potential (fig. 1). We will begin the trip in Cedar City, Utah, at the border between the Great Basin and the Colorado Plateau, and just southwest of the volcanic field. From Cedar City, we will travel north on I-15 along those parts of the field (Black Mountains and Mineral Mountains) that are in the Great Basin, which is the area of greatest continental crustal extension in the world (fig. 2). Most of the volcanic field is in the High Plateaus subprovince of the Colorado Plateau, which is a geologic transition zone between the Great Basin and the main, unfaulted part of the Colorado Plateau to the east. So we will then travel east on I-70 into the center of the field, in the Tushar Mountains, Sevier Plateau, and northern Markagunt Plateau, where most eruptive centers and mineralized areas are located. On the trip, we will visit stratovolcano deposits, which dominate in the field, as well as ash-flow tuffs and their source calderas. Less significant vents that we will see are cinder cones, volcanic domes, and dikes. We will visit the uranium district, a mine for replacement alunite, and the only active mine in the area, which is developed in base and precious metal deposits.

The main part of the Marysvale volcanic field lies at the eastern end of the east-northeast-trending Pioche-Marysvale igneous belt, a site of extensive, mostly Oligocene and Miocene, volcanism and mineralization above a major batholith complex. The southern part of the field, containing deeper magmatic sources and less evolved rocks, lies at the eastern end of a second, generally younger belt of similar trend, the Delamar-Iron Springs igneous belt. Among structures that partly control vents, and thus mineral deposits, are two major east-west transverse zones. The northern one, the Cove Fort transverse zone, defines the northern side of the Pioche-

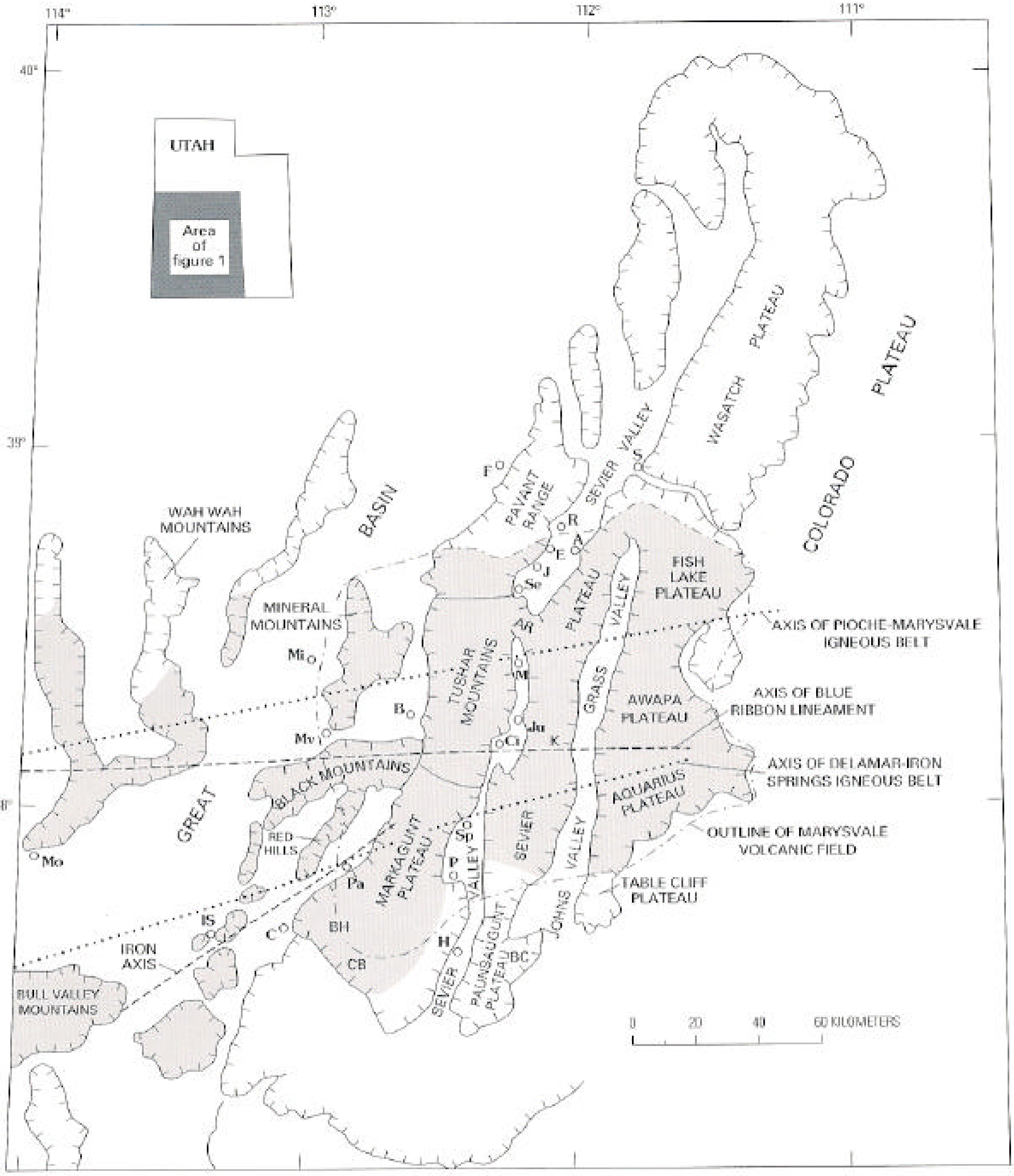

Figure 1. Index map showing location of the Marysvale volcanic field, plateaus and ranges of the High Plateaus, and adjacent areas in Utah, modified from Anderson and Rowley (1975, fig. 1) and Steven and others (1979, fig. 1). A, Annabella; AR, Antelope Range; B, Beaver; BC, Bryce Canyon National Park; BH, Brian Head; C, Cedar City; CB, Cedar Breaks National Monument; Ci, Circleville; E, Elsinore; F, Fillmore; H, Hatch; IS, Iron Springs; J, Joseph; Ju, Junction; K, Kingston Canyon; M, Marysvale; Mi, Milford; Mo, Modena; Mv, Minersville; P, Panguitch; Pa, Parowan; R, Richfield; S, Salina; Se, Sevier; Sp, Spry. Great Basin–Colorado Plateau boundary is just west of the towns of Fillmore, Beaver, Parowan, and Cedar City. Patterned areas are underlain largely by volcanic rocks.

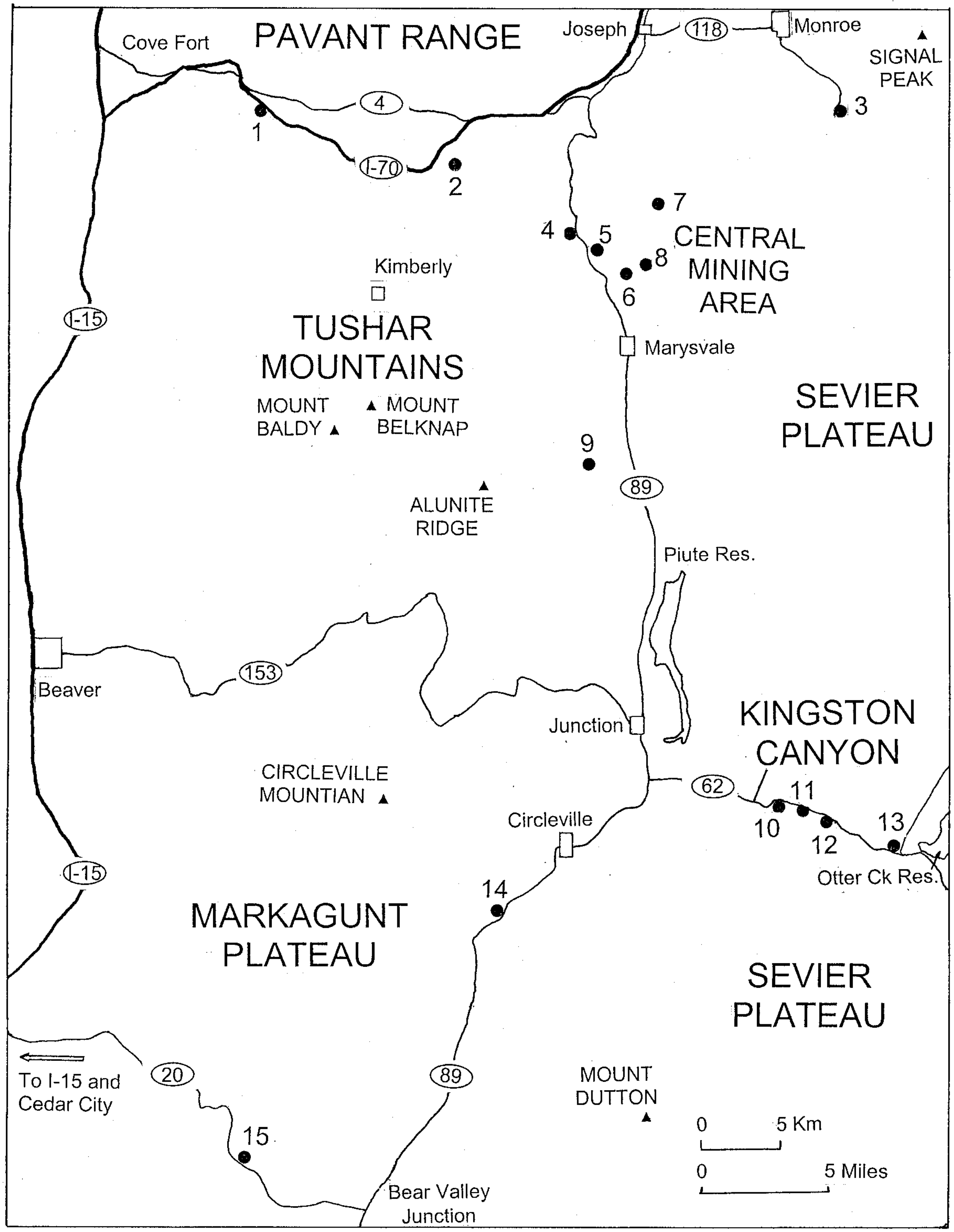

Figure 2. Index map showing major topographic features, roads, and stops (numbered dots) of the field trip

the southern vents in the field.

Cenozoic rocks in and adjacent to the Marysvale volcanic field consist of three main stratigraphic sequences: (1) lower Cenozoic (Paleocene to lower Oligocene) fluvial and lacustrine sedimentary rocks, exemplified by the Claron Formation; (2) voluminous middle Cenozoic (Oligocene and lower Miocene), 32- to 22-million-year-old intermediate-composition calc-alkaline igneous rocks; and (3) upper Cenozoic (middle Miocene, 23 million years old, to Holocene) compositionally bimodal (basaltic and high-silica rhyolite) igneous rocks, which intertongue with clastic sedimentary rocks resulting from erosion of landforms due mostly to regional extension. All of the igneous rocks were synchronous with extensional tectonics but, unlike many other parts of the Great Basin, faulting was relatively minor in the Marysvale area during the middle Cenozoic episode. During the upper Cenozoic episode, basin-range extension created most of the topography we will see today, although the most evident faulting did not begin until about 10 million years ago.

The geologic studies leading to this report began in 1963, when dissertation mapping was initiated in the southern Marysvale volcanic field by J.J. Anderson (1965) and P.D. Rowley (1968), supervised by J.H. Mackin at the University of Texas. Mapping continued as we became employed at Kent State University and the U.S. Geological Survey (USGS), respectively. This work concentrated in the southern and western parts of the field, with work in the northern Markagunt Plateau by Anderson, and the Black and southern Mineral Mountains and adjacent Iron Springs mining district by Rowley. In 1975, the USGS began mapping and related petrologic and mineral-resource studies in the Tushar Mountains and adjacent Sevier River valley, in the heart of the field where known mineral resources are located. T.A. Steven and C.G. Cunningham led this work, and both have continued with it off and on ever since. The work expanded into a broader study of the geology and mineral resources of the Richfield 1^{o} by 2^{o} quadrangle in 1978. The Marysvale field segment of the quadrangle was studied generally full time by Steven, Cunningham, and Rowley and part time by many others from the USGS and academia for more than a decade. H.T. Morris (USGS), J.J. Anderson (Kent State University and USGS), and M.G. Best (Brigham Young University and USGS) were prominent among the many participants of the Richfield work. K-Ar and fission-track dating by H.H. Mehnert and C.W. Naeser (both USGS) was an important part of the study early on, and others have continued this work to the present. Geophysics was likewise an important part of the work, and the recent publication of Campbell and others (1999) summarized these efforts at 1:100,000 scale. The overall Richfield investigation resulted in more than 200 open-file and published reports and maps; many of these are cited in Steven and Morris (1987). Most project conclusions about the Marysvale field are based upon detailed geologic mapping. All the Marysvale field was covered except the eastern flank, which Williams and Hackman (1971) mapped earlier in reconnaissance fashion. Much of the detailed and reconnaissance field data from the project have been published in a series of geologic, geophysical, and mineral-resource maps. Cunningham and others (1983) compiled a detailed (1:50,000 scale) geologic map of the heart of the field, which was followed by geophysical and mineral-resource maps of the same area, only one of which (Cunningham and others, 1984b) is cited here. Steven and others (1990) released a summary map (1:250,000) of the Richfield quadrangle. A new revised geologic map (Rowley and others, 2001a), including access to the digital map data, of the same area covered by Cunningham and others (1983) and Campbell and others (1999), at 1:100,000 scale, is in press with the USGS and will be, we hope, available by the time of this field trip.

GEOLOGIC SETTING

We discuss the Marysvale volcanic field chronologically, first the middle Cenozoic rocks and structures, then the late Cenozoic rocks and structures (Cunningham and others, 2002). The middle Cenozoic igneous rocks are part of a magmatic arc in a plate-tectonic setting that resulted from subduction of Pacific plates beneath western North America (Lipman and others, 1972; Hamilton, 1989, 1995; Severinghaus and Atwater, 1990; Christiansen and Yeats, 1992). Voluminous calc-alkaline igneous rocks ranging in composition from andesite to low-silica rhyolite were emplaced (e.g., Lipman and others, 1972). In the Great Basin and the Colorado Plateau transition zone, most of the eruptive centers for these rocks were in east-west igneous belts, with outflow in areas between the belts (e.g., Rowley, 1998). As is common above other subduction zones, extension prevailed (Hamilton, 1989, 1995), but in the Great Basin and the transition zone, it was expressed by north-northwest- and north-northeast-striking oblique-slip faults and normal faults (Zoback and others, 1981; Rowley and Dixon, 2001), whose presence has not been well recognized. Rowley (1998), Rowley and others (1998), and Rowley and Dixon (2001) proposed that extension was expressed by shallow plutons as well as by faults, and that in any one place extension would result in either or both mechanisms. The faults of this middle Cenozoic episode, when present, did not produce anything resembling the later basin-range structure that we are familiar with, in part because the extension direction (σ_3) for many areas of the West was oriented east-northeast (Zoback and others, 1981), and partly because the maximum principal stress direction (σ_1) appears to have been north or north-northwest rather than vertical (Anderson and Barnhard, 1993; Anderson and others, 1994; Rowley and Dixon, 2001). In the Marysvale area, faults of middle Cenozoic age generally are uncommon, probably because most extension was expressed by shallow plutonism. Transverse zones, which are parallel to extension directions (or, in the earlier Laramide, to compression directions), evolved in the late Mesozoic and the middle Cenozoic (e.g., Ekren and others, 1976; Rowley, 1998). They serve, as do transform faults of similar strike in the Pacific Ocean basin, to allow the crust north and south of them to extend by different amounts, styles, and rates of strain. Depending on the extension direction of the local area, middle Cenozoic transverse zones in the Great Basin generally strike east or east-northeast.

In the late Cenozoic (starting at about 25 to 20 million years ago, depending on the area), continental crust continued to extend, but the plate-tectonic setting changed radically. Except under the Cascade Range, the subducted slab beneath the western United States had given way to transform movement across a broad zone extending from the San Andreas fault zone to the Walker Lane belt (Severinghaus and Atwater, 1990; Christiansen and Yeats, 1992). As a result, the Great Basin area underwent oblique extension (Hamilton and Myers, 1966). At first, extension during the late Cenozoic seems to have been expressed by broad folding, but by about 10 million years ago, the present north-trending, basin-range topography started to form along normal faults (Gilbert, 1928; Mackin, 1960; Eaton and others, 1978; Zoback and others, 1981; Anderson and others, 1983; Anderson, 1989; Wernicke, 1992). This is referred to as the basin-range episode (Gilbert, 1928; Mackin, 1960). Contemporaneous magmatism in the western United States was largely bimodal in composition, consisting of basalts and high-silica rhyolites (Christiansen and Lipman, 1972). The volume of eruptive products in most areas of the West, however, was much less than that of the middle Cenozoic, being at Marysvale only about 5 percent that of the middle Cenozoic. In the Marysvale area, where high-angle normal faults dominate, most faults and topography represent the effect of basin-range extension. In two areas we will visit on this field trip, the age of the main phase of basin-range extension is particularly well constrained: (1) at Sevier, it postdates tephra in the Sevier River Formation of 7 Ma (Steven and others, 1979), and in Kingston Canyon, it took place between rhyolites dated at 8 and 5 Ma (Rowley and others, 1981). Transverse zones continued to be active in the late Cenozoic and, because the extension direction was in most places east-west (Zoback and others, 1981), so was the orientation of the transverse zones. It appears possible that a giant mantle plume underlay the entire Great Basin during this time (Eaton and others, 1978; Pierce and Morgan, 1992; Parsons and others, 1994; Zoback and others, 1994; Parsons, 1995; Saltus and Thompson, 1995; Thompson, 1998). For a more detailed discussion of these regional topics and their implications, see Rowley and Dixon (2001).

Middle Cenozoic Episode. The dominant middle Cenozoic rock types of the Marysvale volcanic field are volcanic mudflow breccia and subordinate lava flows, most from clustered stratovolcanoes (Rowley and others, 1979; Steven and others, 1979). These, as well as tuffs and other rock types of the middle Cenozoic episode, are compositionally calc-alkaline. Where the clasts in the mudflows and the lithologically similar flows are distinctive, the rock units made up of these rocks were mapped separately and given formal or informal names. Where such stratovolcano units were mapped, they commonly were separated into either vent facies or alluvial facies, following the concepts of Parsons (1969) and Smedes and Prostka (1973). The vent facies, as the name implies, consists of deposits that are concentrated near vents and high on volcano flanks, whereas the alluvial facies is concentrated lower on the flanks and beyond the flanks, becoming a grain-supported conglomerate with distance from the source. Volcanic mudflow breccia is the main component of both facies but, in vent facies, these breccias tend to be monolithologic and they may be intertongued with lava flows, flow breccia, and dikes. In the Marysvale field, most of the stratovolcano sequences were mapped as two formations. The most voluminous (at least 5,000 km^3) of these is the Mount Dutton Formation (Anderson and Rowley, 1975), which is largely exposed in the southern half of the volcanic field (Rowley and others, 1998). Some stratigraphic sections, as along the western scarp of the Sevier Plateau at Mount Dutton, are at least 2,000 meters thick. Mapping in the southern Tushar Mountains and northern Markagunt Plateau suggests that many stratovolcano vents of the Mount Dutton Formation line up along the Blue Ribbon transverse zone. The formation has produced isotopic dates that range between 27 and 21 Ma (Fleck and others, 1975; Rowley and others, 1994), and stratigraphic relations indicate that some rocks predate regional ash-flow tuffs of 30 million years age. The clasts and flows of the Mount Dutton are largely andesite that contains sparse, small phenocrysts. Corresponding source intrusive rocks for the Mount Dutton Formation are rarely exposed in the southern half of the Marysvale field, and thus we interpret that Mount Dutton Formation magma chambers were very deep below their volcanic edifices (Cunningham and others, 1994, 1998a). An exception to these deep magma chambers in the southern part of the field (that is, in the Delamar-Iron Springs igneous belt) is a belt of shallow laccoliths. One of these is the large (50 km^3), 26-Ma Spry Intrusion in the Markagunt Plateau, which is a cupola on a batholith that produced other laccoliths (Blank and Kucks, 1989; Anderson, 1993). Another laccolith in the Markagunt Plateau, the Iron Peak (Anderson and Rowley, 1975), is at the northeastern end of the Iron Axis. Some of these shallow laccoliths vented, but their contribution to the volcanic field was minor.

The second most voluminous rock unit in the Marysvale field is the Bullion Canyon Volcanics (Callaghan, 1939; Steven and others, 1979). This unit consists largely of stratovolcano deposits mapped in the heart and northern half of the Marysvale volcanic field. Some sections of this map unit are at least 1,500 meters thick, not including intertongued ash-flow tuffs. The volume of the unit is conservatively estimated at 1,700 km^3. Isotopic dates and stratigraphic relations indicate a nearly identical age as the Mount Dutton Formation. Weathered basal parts have dates as old as 34 Ma (Willis, 1985; Kowallis and Best, 1990), and the Mount Dutton and Bullion Canyon sequences intertongue along the east-trending boundary between the Tushar Mountains and northern Markagunt Plateau. In contrast to the Mount Dutton, the dominant rock type in the Bullion Canyon is dacite that in most places contains 20 to 30 percent large phenocrysts. Source intrusive rocks are widely exposed throughout the sequence and it is thus clear that, for this unit and others in the heart of the field, the magma chambers were shallow and the rocks were more highly evolved (differentiated) (Cunningham and others, 1994, 1998a).

Ash-flow tuffs make up about only 10 percent of the volume of the calc-alkaline sequence, but their calderas are common (Rowley and others, 1979; Steven and others, 1979, 1984a). The most voluminous tuffs were derived from the northern half of the volcanic field, some as members of the Bullion Canyon Volcanics (Callaghan, 1939; Steven and others, 1979). Possibly the largest tuff in the field is the Three Creeks Tuff Member, derived from the Three Creeks caldera in the southern Pavant Range (Steven, 1981) about 27 million years ago. This moderately welded dacitic unit is crystal-rich, with nearly 50 percent large phenocrysts. It is widely distributed near the base of the Bullion Canyon and Mount Dutton sequences, but it is also commonly covered by other rocks so an estimate of its intracaldera and outflow volume is only 200 km^3. In hand specimen, it resembles another crystal-rich ash-flow sheet, the widespread 30-million-year-old Wah Wah Springs Formation of the Needles Range Group. In fact, the Three Creeks Tuff Member was originally included within the Needles Range Group until Best and others (1989a, b) did the regional correlations needed to work out the correct stratigraphy. Needles Range units were derived from the huge Indian Peak caldera complex that straddles the Utah-Nevada border (Best and others, 1989a, b). The Wah Wah Springs is below the Three Creeks Tuff Member, of course, and near the base of the stratovolcano sequences at Marysvale.

The 24-million-year old Delano Peak Tuff Member of the Bullion Canyon Volcanics (Callaghan, 1939; Steven and others, 1979) is a well welded dacitic ash-flow tuff that had an initial volume of at least 100 km^3. Its source is the Big John caldera in the central Tushar

Mountains (Steven and others, 1984b), but it is not widely exposed outside that mountain range. It is seen near the upper part of the Bullion Canyon section. Two thin, small-volume, densely welded, trachydacite ash-flow tuffs are members of the Mount Dutton Formation; these are the Kingston Tuff Member (26 Ma) and the Antimony Tuff Member (25 Ma). Named for exposures in Kingston Canyon of the southern Sevier Plateau (Anderson and Rowley, 1975), they are widely exposed throughout the southern and eastern Marysvale field. They are lithologically similar to each other and also resemble another small unit, the tuff of Albinus Canyon (Cunningham and others, 1983; Rowley and others, 1994), found in the northern part of the field. These three tuffs probably came from the same source, but its location is unknown. Based on the higher volume of these rocks, and their greater tendency for late rheomorphic flow in the mountains surrounding the town of Joseph, in the northern part of the field, we suggest that the source may be buried beneath a graben there. High-temperature ash-flow tuffs such as this, including the Isom Formation of the Iron Springs mining district (Mackin, 1960; Anderson and Rowley, 2002) and some in southwestern Idaho (Ekren and others, 1984), appear to have been so hot that their sources are likely deep and not expressed as calderas (Ekren and others, 1984).

The largest caldera in the Marysvale field, and the youngest of the calc-alkaline sequence, is the Monroe Peak caldera in the northern part of the volcanic field (Steven and others, 1984a; Rowley and others, 1986a, b, 1988a, b). As with the source caldera for the other large ash-flow tuff (the Three Creeks Member), the Monroe Peak caldera is along and likely was controlled by the Cove Fort transverse zone. The Monroe Peak caldera was the source of the 23-million-year-old densely welded, trachydacitic Osiris Tuff (Williams and Hackman, 1971; Anderson and Rowley, 1975). This tuff spread widely throughout the volcanic field and, in places, outward across its flanks to form an isolated sheet. The initial volume of the Osiris is estimated at 250 km^3, including a thick intracaldera fill. Immediately after its eruption, the Monroe Peak caldera fill was capped by a series of lava flows that totaled another 100 km^3. Preliminary Ar-Ar dating by L.W. Snee of the USGS shows that all of the Osiris erupted between 22.92 and 22.81 Ma, and that the intracaldera post-Osiris lava flows are 22.48, 22.43, and 22.32 Ma. These data indicate that all volcanic activity of the Monroe Peak caldera took place in about 0.6 million years or less (unpublished data, 2001).

In addition to the stratigraphic units mentioned, many other calc-alkaline units formed during the middle Cenozoic eruptive episode. Few of these will be visited during the field trip, so many are not mentioned here; others are covered in passing in the road log. For details on these units, see other project maps and reports.

Late Cenozoic Episode. As in other volcanic fields in the western United States, the petrologic regime of the Marysvale volcanic field (Cunningham and others, 1998a) changed drastically from calc-alkaline to fundamentally bimodal somewhat before 20 million years ago (Christiansen and Lipman, 1978). This change is inferred to coincide with renewed crustal extension, but in a crust that was probably cooler and thicker overall than that of the calc-alkaline episode (Lucchitta, 1990; Wernicke, 1992). As a result, basaltic magmas rose along more deeply penetrating fractures to higher in the crust, raising the isotherms and forming alkali-rhyolite eutectic partial melts. Generally the first product of bimodal volcanism appears to have been rocks of small volume from local centers scattered around the field that were originally mapped as "older basalts" (Anderson and Rowley, 1975) or as "basalts" by previous workers. Later petrologic work (e.g., Best and others, 1980) showed that they are not true basalts, so we since have called them "potassium-rich mafic volcanic rocks." They have ages that range from 23 to 21 million years old, although some may be as old as 26 million years (Mattox, 1991a, b, 1992).

The largest volume of bimodal rocks in the Marysvale field formed the rhyolite of the Mount Belknap Vocanics (Callaghan, 1939; Cunningham and Steven, 1979a), which was erupted between 22 and 14 million years ago from two concurrently active eruptive centers, one in the central Tushar Mountains and the other in the Sevier River valley. Thus these rhyolite eruptive centers generally coincided with areas where the older intrusive and volcanic rocks of the calc-alkaline episode were deposited. The western and most voluminous of these two source areas subsided to form the large Mount Belknap caldera after its main ash-flow sheet, the Joe Lott Tuff Member of the Mount Belknap Volcanics, erupted 19 million years ago (Budding and others, 1987). The volume of rocks from this western source, including intracaldera and outflow Joe Lott

Tuff and associated lava flows, is at least 300 km^3. The volume of rocks in the eastern source, which is near Marysvale, is much less. It includes the Red Hills Tuff Member of the Mount Belknap Volcanics and its source, the Red Hills caldera, as well as a series of local volcanic domes and flows, all north of Marysvale. Both source areas include granite intrusions. In the eastern source area, these hosted the Central Mining Area, the main uranium district associated with the Marysvale volcanic field (Cunningham and Steven, 1979b). In the eastern Tushar Mountains about 10 km south-southwest of Marysvale, a 14-million-year-old intrusion domed the rocks at Alunite Ridge (Cunningham and Steven, 1979c), forming mineral deposits that have been mined for years (Cunningham and others, 1984a).

The Mineral Mountains, at the western margin of the Marysvale field, are underlain by a 25- to 9-million-year-old composite batholith, the largest exposed in Utah (Nielson and others, 1986; Steven and others, 1990; Coleman and Walker, 1992; Coleman and others, 2001). It is part of the huge batholith that underlies much of the Pioche-Marysvale igneous belt (Steven and Morris, 1987). Although minor early phases (those of 25 Ma) probably represent the calc-alkaline episode, the great majority of the batholith (22-11 Ma) is granitic and alkaline and interpreted to represent the bimodal episode; still later granites (9 Ma) are clearly bimodal. The granites were uplifted rapidly along listric faults and perhaps along detachment faults that are exposed on the western side of the range (Nielson and others, 1986). The uplift is interpreted to be the product of a metamorphic core complex (Price and Bartley, 1992; Coleman and others, 2001). Rhyolites accompanied the granites, although erosion has removed most of those except younger ones resting on the exposed batholith in the northern part of the Mineral Mountains. Ranging in age from 0.8 to 0.5 million years old, these consist of volcanic domes on the crest of the range, which shed ash-flow tuff and rhyolite flows down canyons on the western side of the range (Lipman and others, 1978). Some of these erupted volcanic rocks are obsidian flows that are devoid of phenocrysts and in prehistoric time were widely exported for use as points and tools by Indians.

Lava flows and cinder cones of true basalt began to be erupted in small volumes in the general area at about 14 million years ago (Best and others, 1980). These include many basalts in the Marysvale field, but basalts are not confined to the field, and their vents do not coincide with the older vent areas of calc-alkaline rocks or even of the older (23 to 16 million years old) rhyolites. Basalts are exposed, however, in association with many post-16-million-year-old rhyolite vents. Basalts continued to be erupted in the general area well into the Quaternary, and some on the Markagunt Plateau west of Cedar City are unvegetated and probably are Holocene (Hatfield and others, 2000). Beginning about 10 million years ago, basin-range faulting became widespread. Generally small rhyolite domes continued to be emplaced in the Marysvale field. These include the rhyolite of Gillies Hill and buried plutons at the Sheeprock Mine (9 to 8 Ma; Evans and Steven, 1982; Cunningham and others, 1984c) north of Beaver, rhyolites in Kingston Canyon (8 to 5 Ma; Rowley and others, 1981), rhyolites along the northern side of the Black Mountains (9 to 8 Ma; Anderson and others, 1990b) that continue westward along the Blue Ribbon transverse zone (Rowley and others, 1978), and the rhyolites of the Mineral Mountains (9 to 0.5 Ma; Lipman and others, 1978).

ECONOMIC GEOLOGY

Mineral deposits of the Marysvale field formed during three ages (Cunningham and others, 1994, 1998a). The first, at about 34 to 22 million years old, is associated with rocks of the calc-alkaline episode. The second (22-14 million years old) and third (9-5 million years old) are associated with rocks of the bimodal episode. Ore deposits of the calc-alkaline episode tend to be epithermal gold deposits, whereas those of the bimodal episode tend to be gold, molybdenum, uranium, and base metals. The many calc-alkaline plutons in the central to northern Tushar Mountains resulted in adjacent highly propylitized and argillic altered areas that contain pyrite-bearing quartz-carbonate veins (Cunningham and others, 1984b). In some areas these veins have gold and silver values, and this broad area has been widely prospected. The only area of significant production, however, was the Kimberly district, where mining produced several million dollars worth of gold and silver between 1892 and 1937 (Lindgren, 1906; Steven and Morris, 1987). Most ores came from the oxidized parts of two persistent vein zones cutting propylitized quartz monzonite intrusions. Metal values dropped off sharply in lower levels of the mines, where the ores were unoxidized. Other areas where gold- and silver-bearing quartz-carbonate veins cut altered volcanic rocks are in lower Deer Creek, the Butler-Beck mine area in the headwaters of Deer Creek (5 kilometers east of Kimberly), a few kilometers south of Sulphurdale, the Rob Roy mine near the mouth of Indian Creek Canyon, and the Cork Ridge area south of the Mount Belknap caldera (Cunningham and others, 1984b, c; Steven and Morris, 1987).

Replacement alunite (for potash, alumina, and sulfuric acid) was mined in areas formed by alteration adjacent to shallow intracaldera plutons of the 23-million-year-old Monroe Peak caldera (Cunningham and others, 1984a, b; Steven and Morris, 1987). The hosts were volcanic rocks adjacent to and overlying these plutons, which were locally intensely altered to argillic and advanced-argillic mineral grades (Cunningham and others, 1984b). The Marysvale Peak and Manning Creek alunite deposits on the Sevier Plateau east to northeast of Marysvale, and the Box Creek kaolinite deposit farther east in the caldera are examples. One of the intracaldera plutons that is distinctive enough to be mapped separately is the Central Intrusion. Several geologists have studied the effects of sub-circular hydrothermal ground-water convection cells caused by and surrounding that intrusion (Podwysocki and Segal, 1983; Cunningham and others, 1994; Rockwell and others, 2002). Alunite formed in a near-surface environment from hydrothermal cells that reacted with evaporite-bearing strata at depth to supply sedimentary sulfur. Reaction with volcanic rocks at depth reduced some of the sulfur, and some sulfur may have been contributed by the magma. Near-surface reaction of this hydrogen sulfide with atmospheric oxygen formed a strongly acidic solution that altered the volcanic rocks and resulted in alunite and related products. The alunite at the Whitehorse and Yellow Jacket mines north and northeast of Marysvale are examples.

The best known mineral resources of the bimodal episode are the uranium deposits of the Central Mining Area northeast of Marysvale, which were mined between 1949 and 1967 (Cunningham and Steven, 1979b; Steven and others, 1981; Cunningham and others, 1982, 1994, 1998b, 1999; Rowley and others, 1988a, b). The uranium in the eastern source area of the Mount Belknap Volcanics is in veins formed about 19 million years ago that are associated with glassy rhyolite dikes widely exposed in the mines. The host rocks consist of the Central Intrusion and the fine-grained granite northeast of the Red Hills caldera. Molybdenum is associated with the uranium and becomes increasingly abundant with depth. Cunningham and others (1982) interpreted the uranium-molybdenum deposits to be derived from a hidden intrusion that possibly contains a porphyry-type disseminated molybdenum deposit. Extensive exploration drilling by industry encountered only low-grade uranium values east of the Central Mining Area. The western source area (Mount Belknap caldera) of the Mount Belknap Volcanics contains anomalous values of uranium, molybdenum, and beryllium but no deposits are yet known. In the Indian Creek area northeast of Beaver, anomalous fluorite and uranium in rocks of 16 million year old suggest a granite pluton at depth. The Sheep Rock alunite deposit, and the Sunday gold deposit in quartz-calcite veins are associated with granite source plutons of the 9- to 8-Ma rhyolite of Gillies Hill (Cunningham and others, 1984c).

Along the eastern margin of the central Tushar Mountains, hydrothermal mineral deposits dated at 14 Ma are exposed on two adjacent peaks that Cunningham and Steven (1979c) and Cunningham and others (1984a) interpreted to overlie cupolas on a hidden stock. On Alunite Ridge, alunite veins as wide as 20 meters filled open fissures in a structural dome cut by radial faults, and on Deer Trail Mountain, highly kaolinitized rocks mark another radial fracture pattern. An annular ring of base- and precious-metal deposits surround these altered areas. Quartz veins containing gold, silver, and minor base metals cut propylitized volcanic rocks in part of the ring, and the Deer Trail mine exploits a base-metal manto and associated precious-metal veins in carbonate strata along the eastern side of the ring (Beaty and others, 1986). Hidden igneous cupolas that may host porphyry-type disseminated copper and molybdenum deposits, and adjacent metal-bearing skarn deposits have been interpreted to underlie the altered areas (Cunningham and others, 1979c; Cunningham and others, 1984a; Beaty and others, 1986).

Other deposits associated with either the calc-alkaline or bimodal episodes are adjacent to intrusive rocks of the Mineral Mountains (Steven and Morris, 1987). The Bradshaw and Lincoln districts at the southern end of the range were mostly gold-silver-copper-lead-zinc-tungsten replacement deposits in Paleozoic limestones associated with east-striking fractures and with underlying and adjacent stocks associated with the Mineral Mountain batholith. At the northern end of the range, the Antelope district shipped a little ore from small lead replacement bodies in limestone. East of the range, the Fortuna mine area at the northern end of the Beaver basin is adjacent to an extensive area of propylitically altered lava flows and consists of intensely altered rock and sparse gold-bearing quartz veins. At the southeastern end of the range, small ore deposits containing tungsten, and pegmatites with beryllium occur in skarn associated with the bimodal parts of the granite (Steven and Morris, 1987).

Hot springs are common in the area of the field trip. Although some of these, such as Monroe Hot Springs and spring deposits along the Dry Wash fault zone east of Joseph, are probably due to rapid upward movement of ground water along fault zones and thus reflect the geothermal gradient, others are likely due to heating of ground water by magma masses at depth. One of these is the Roosevelt Hot Springs geothermal area on the western side of the Mineral Mountains, which is heated by the same magma that fed young rhyolites on the crest of the range (Lipman and others, 1978) and which runs a power plant northeast of Milford, Utah (Blackett and Moore, 1994). Two others are the Sulphurdale geothermal area, along the western side of the Tushar Mountains south of Cove Fort, and the Cove Fort geothermal area along the western side of the Pavant Range east of Cove Fort (Blackett and others, 1994). The Sulphurdale area also was developed as a power plant. Both of these spring areas may have been heated by basaltic or rhyolitic magma at depth. Thus hydrothermal activity continues in the area, and mineral deposits continue to be formed.

ACKNOWLEDGMENTS

Our work is based on a foundation provided by Eugene Callaghan, J. Hoover Mackin, and P.L. Williams, which we gratefully acknowledge. This trip tells a story that many of our colleagues contributed to. H.T. Morris, H.H. Mehnert, and C.W. Naeser of the USGS, M.G. Best and L.F. Hintze of Brigham Young University, and D.B. Simon of Simon-Bymaster, Inc. are only a small number of these persons, to whom we are much obliged. Students of J.J Anderson of Kent State University, Kent, Ohio, aided in some of our interpretations. We thank D.E. Ferris, who helped log the trip. Joan and Jim Anderson and Ada Hoover of Hoover's Truck Stop, and Sheren and Dean Pierson of Kanab helped for many years with logistics. We are grateful to W.R. Lund of the Utah Geological Survey, Cedar City, for his excellent technical review of the manuscript.

ROAD LOG

Increment Mileage	*Cumulative Mileage*	*Description*
0	0	BEGIN TRIP AT PARKING LOT at northwest corner of 200 South and 1150 West, Cedar City (west of Eccles Coliseum, at the southwest edge of the Southern Utah University campus). Drive north on 1150 West. On the left, west of I-15, the Cross Hollow Hills are made up of basin-fill and alluvial-fan deposits uplifted along faults and locally containing intertongued basalt lava flows of about 1 Ma (Averitt, 1967; Averitt and Threet, 1973; Fleck and others, 1975; Anderson and Mehnert, 1979; W.R. Lund, written communication, 2000). According to gravity data, the major normal faults of the Hurricane fault zone are west of the Cross Hollow Hills (Cook and Hardman, 1967).
0.4	0.4	AT SECOND STOP SIGN, TURN LEFT (WEST) ONTO 200 NORTH (STATE ROAD-56).
0.1	0.5	AT THE NORTHBOUND ENTRANCE RAMP TO I-15, TURN RIGHT (NORTH). As you enter I-15 from Exit 59 (the middle Cedar City exit), note at 9:00 the hills 10 km to the west, which make up the Iron Springs mining district, the largest U.S. iron

district west of the Great Lakes region but no longer being worked. The district is defined by a north-northeast-trending string (the Iron Axis) of quartz monzonite porphyry laccoliths of about 22-21.5 Ma (Mackin, 1947, 1960, 1968; Blank and Mackin, 1967; Mackin and others, 1976; Mackin and Rowley, 1976; Rowley and Barker, 1978; Barker, 1995). The iron deposits consist of huge hematite replacement bodies in the Homestake Limestone Member of the Jurassic Carmel Formation, adjacent to the concordant intrusive contacts. The southern part of the Iron Axis, especially the huge Pine Valley laccolith (Hacker, 1998), will be visited during a post-meeting field trip (Hacker and others, 2002) to see massive gravity slides that were shed off the flanks of the rising laccoliths and the volcanic products that erupted following the deroofing (Blank and others, 1992; Hacker, 1998; Rowley and others, 2001b). At 3:00, the red ridge on the northern side of Cedar Canyon, east of Cedar City, is the eastern flank (Triassic Moenkopi, Chinle, Moenave, and Kayenta formations, with Jurassic Navajo Sandstone and Carmel Formation east of the ridge) of a Sevier-age anticline whose western flank has been cut off and downthrown along the Hurricane fault zone (Averitt and Threet, 1973). The anticline is the leading edge above an eastward-verging blind Sevier thrust. Capping the Markagunt Plateau at the skyline is Brian Head, which is underlain by a ski resort and 26-Ma ash-flow tuffs of the Leach Canyon Formation and of the 27-Ma Isom Formation; Cedar Breaks National Monument is just southwest of Brian Head (Anderson, 1993; Hatfield and others, 2000).

2.7 3.2 The exit ramp to Exit 62, the north exit to Cedar City. At 2:30, the west limb of the Cedar City-Parowan monocline, probably a Sevier fold, is shown by the gray Cretaceous Straight Cliffs Formation. Ahead are the snow-capped peaks of the Tushar Mountains, the highest part of the Marysvale volcanic field. At 9:00 is a ring of hills making up The Three Peaks, the northeasternmost of the laccoliths of the Iron Springs district. An oil well spudded on the western flank of this laccolith drilled through the pluton into underlying sedimentary rocks (Van Kooten, 1988). The eastern side of the intrusion has been cut off by a fault that defines the western side of the Cedar Valley graben. The mostly brush-covered surface sloping toward us is a pediment cut on soft altered rock making up the interior phase of the intrusion. Geophysics indicates that the basin-fill deposits in the underlying basin-range graben west of the Hurricane fault zone are about 3 kilometers thick (Cook and Hardman, 1967).

4.1 7.3 Blue water tank on the left is on the northern side of Enoch, a suburb of Cedar City. Just north of Enoch and the water tank is the southern end of the Red Hills, a low range that is a horst defined by mostly Pliocene and Quaternary normal faults (Threet, 1952, 1963). The predominant red color of the range is from the Paleocene and Eocene Claron Formation, a fluvial and lacustrine sedimentary sequence that in some places is the basal Tertiary unit in southwestern Utah (Mackin, 1960), and is well known for its hoodoos and related landforms that characterize Bryce Canyon National Park (Davis and Pollock, 2000) and Cedar Breaks National Monument (Hatfield and

		others, 2000). The northward continuation of the Hurricane fault zone likely defines the western side of the Red Hills. The Great Basin-Colorado Plateau boundary swings to the east of us and is defined by a series of north- to north-northeast-striking en echelon fault zones that die out southward into the Markagunt Plateau (Maldonado and Moore, 1995). The rocks to the right of us consist of huge landslides off these fault scarps (Averitt and Threet, 1973; Rowley and Threet, 1976).
3.4	10.7	Hay barn on left (west). Farther west, basaltic lava flows of late Tertiary or Quaternary age are abundant in the southern Red Hills, where they rest on Claron Formation. An oil well, spudded in these basalts about 4 kilometers north of these rocks, was drilled on an aeromagnetic anomaly likely due to iron deposits. It encountered an intrusion of quartz monzonite porphyry at 1,060 meters depth, probably the continuation of the Iron Axis (Rowley and Threet, 1976). Enter Parowan Valley, a graben between the Red Hills and the Markagunt Plateau.
5.7	16.4	Exit 75, Parowan. At 8:00, Parowan Gap cuts through the Red Hills. The antecedent stream that flowed west and carved the canyon there was dammed by the latest movement (Quaternary) on the fault that defines the eastern side of the Red Hills, thus forming Little Salt Lake (Threet, 1963; Maldonado and Williams, 1993a, b). At 10:00, gray rocks farther north in the Red Hills are a series of huge Tertiary ash-flow sheets that overlie the Claron and were derived from caldera sources in the Great Basin (Maldonado and Williams, 1993b). The lowest of these is the 30-Ma Wah Wah Springs Formation of the Needles Range Group and the 27-Ma Isom Formation, both derived from the huge Indian Peak caldera complex that straddles the Utah-Nevada border (Best and others, 1989a, b). These are overlain by additional ash-flow tuffs of the Quichapa Group (among them the Leach Canyon Formation), also derived from the Great Basin (Williams, 1967; Anderson and Rowley, 1975; Rowley and others, 2001b). All these tuffs interfinger with locally derived volcanic rocks along the southwestern side of the Marysvale volcanic field. At 3:00, these locally derived volcanics and intertongued Great Basin tuffs cap the Markagunt Plateau (Anderson, 1963, 1993; Anderson and Rowley, 1975; Maldonado and Moore, 1995; Hatfield and others, 2000).
2.5	18.9	Exit 78, Parowan and Paragonah. The easternmost fault zone of the en echelon assemblage, which continues north along the range front east of Parowan and Paragonah, is the Parowan fault zone (Maldonado and Williams, 1963b; Maldonado and Moore, 1995). Red Claron rocks can be seen east of the fault zone, underlain by the light-gray Paleocene Grand Castle Formation, and in turn by the yellow and grayish-green Upper Cretaceous Iron Springs Formation (Maldonado and Moore, 1995).
3.1	22.0	Paragonah on the right, south of which are low ledges of basalt lava flows that flowed down the canyon into Parowan Valley and were in turn displaced by the latest movement on the Parowan fault zone (Anderson and Rowley, 1975; Maldonado and Williams, 1993b; Maldonado and Moore, 1995). The basalts

have K-Ar dates of about 450,000 years (Fleck and others, 1975). Northeast of Paragonah, the 20-Ma Iron Peak laccolith marks the northeast end of the Iron Axis, and like many of these laccoliths, it breached the surface and erupted volcanic rocks (Anderson and Rowley, 1975; Fleck and others, 1975; Rowley and others, 1994).

6.7 28.7 Exit to a Rest Area on I-15. The gray mountain at 2:00 consists of thick stratovolcano deposits, mostly volcanic mudflow breccia, of the Mount Dutton Formation, which overlies the Claron Formation here and to the north (Anderson and Rowley, 1975; Rowley and others, 1998). The dark-gray fault scarp at 10:00 is surmounted by Black Mountain, which also is made up of the Mount Dutton Formation. These outcrops look well bedded but consist entirely of volcanic mudflow breccia. Straight ahead, the lower hills consist of fault tilt blocks of mudflow breccia; those west of the highway belong to the southeastern Black Mountains, whereas those east of the highway belong to the Markagunt Plateau.

6.6 35.3 Exit 95, intersection with State Road (SR) 20, where we will return at the end of the day. Virtually all rocks you see to the west, north, and east consist of volcanic mudflow breccia of the Mount Dutton Formation. The high Tushar Mountains ahead are mostly rhyolites of the Mount Belknap Volcanics, within the Mount Belknap caldera (Callaghan, 1939; Cunningham and Steven, 1979a; Cunningham and others, 1983). The area west of this exit was mapped by Anderson (1965), some of which was published in Anderson and others (1990b). Just to the north, we enter the area of the Richfield 1:250,000 quadrangle (Steven and others, 1990).

5.2 40.5 Exit 100, ranch exit. Black Mountains to left; Markagunt Plateau to right. The east-trending scarp at 1:00 to 2:30 is a 30-kilometer-long, generally south-facing mountain front, with the Tushar Mountains making up both the scarp and the mountains north of it. The scarp follows an east-trending string of stratovolcanoes that shed part of the Mount Dutton Formation. The scarp is not linear, in part because it was controlled by these resistant but older and eroded vents and also by north-northwest-striking faults (Anderson, 2001). Most of the shallow intrusions, and thus most vents and mineral deposits, of the Marysvale field lie along and north of the scarp (Rowley and others, 1998). This east-west feature is part of a major structure called the Blue Ribbon transverse zone and interpreted to be about 25 km wide and 600 km long, spanning the entire Great Basin and Great Basin - High Plateaus transition zone. It and many others like it in the Great Basin are long lived and control the locations of many volcanic vents, plutons, mineral deposits, topographic features, and structures along them (Rowley and others, 1978; Rowley, 1998; Rowley and Dixon, 2001). Besides the southern margin of the Tushar Mountains, the transverse zone controls the northern side of the Black Mountains, which trends east-west for about 50 km, and Kingston Canyon, a 15-kilometer long east-west canyon that cuts through the Sevier Plateau to the east.

2.3	42.8	Roadcuts on the left and right expose scoria and airfall tuff from nearby basalt cinder cones. Continue north from this low summit through Nevershine Hollow (Anderson and others,1990a) into Beaver basin, a graben.
1.5	44.3	The high hill to the left and the roadcut coming up on the right are made up of thick dacitic lava flows of the 26-Ma Beaver Member of the Mount Dutton Formation (Anderson and Rowley, 1975; Fleck and others, 1975). The Mineral Mountains are at 11:00. The southern half of the crest is held up by light-gray granite pinnacles of the Mineral Mountains batholith, the largest exposed batholith in Utah. Despite its size and prominent expression, most of it is younger than 22 Ma (Nielson and others, 1986; Coleman and Walker, 1992; Coleman and others, 2001). The northern half of the crest is largely underlain by the batholith too, but these rocks are wooded and largely concealed by rounded rhyolite domes younger than 1 Ma (Lipman and others, 1978). The rhyolites are similar to the granite in composition and probably represent recurring upward invasion of magma from a common source area at depth. Their chambers provide geothermal heat for the Milford power plant, the largest geothermal power plant in Utah (Blackett and Moore, 1994).
4.0	48.3	On right, Quaternary fault scarps in basin-fill deposits of the Beaver basin. The basin-fill deposits here are at least 1.5 kilometers thick, the upper part of which has been well studied by Machette and others (1984) and Machette (1985). Dating of this upper part of the sequence is particularly complete, in part because of interbedded dated tephra beds and a basaltic lava flow, and in part by the study of calcrete soil deposits. This enabled mapping of a complicated series of Quaternary faults, which are clearly as young as late Pleistocene and perhaps early Holocene (Anderson and others, 1978; Machette, 1985). Basin formation began probably at about 12-9 Ma based on the oldest rhyolites on its northern margins (Evans and Steven, 1982), which were erupted along basin-range faults. Deposition was in a closed basin, which was breached at about 750,000 years ago. This was followed by formation of a series of pediments, the most prominent of which is Last Chance Bench that was cut about 500,000 years ago.
1.2	49.5	Exit 109, Beaver and Milford. The fault scarp just to the right has springs issuing from it, and it exposes on its east side basin-fill deposits of late Pliocene to early(?) Pleistocene age (Machette and others, 1984). Just to show you how we aim to please and give you choices, from about this point on, until we reach the town of Junction, we will be on two geologic maps with overlapping authorships, the more detailed (1:50,000) but older and thus slightly obsolete map by Cunningham and others (1983), and the less detailed (1:100,000) but new map by Rowley and others (2001a). Of course, we are also on the 1:250,000 geologic map of Steven and others (1990). The geology has not changed but its interpretation has evolved! We will not generally cite these maps along the way. The western

		crest of the Tushar Mountains east of Beaver contains a ski area.
2.9	52.4	Exit 112, Beaver. White, snow-capped peak at 2:00 is rhyolite within the 19-Ma Mount Belknap caldera (Cunningham and Steven, 1979a).
3.1	55.5	Crest of Last Chance Bench, resistant because of a well developed calcrete soil beneath it (Machette, 1985). On the right, a major fault scarp underlies the base of the Tushar Mountains; most of the scarp is made up of stratovolcano deposits of the Bullion Canyon Volcanics (Steven and others, 1979).
5.3	60.8	Exit 120, Manderfield. The hill at 11:00 with the radio towers on it is Gillies Hill, and both it and Woodtick Hill north of it represent a large rhyolite dome complex (rhyolite of Gillies Hill) of about 9-8 Ma, interpreted to have formed at about the time the Beaver basin began to be blocked out (Evans and Steven, 1982; Cunningham and others, 1984c, 1994). At 2:30, low on the range front, the 24-23 Ma calc-alkaline Indian Creek stock probably was a local source for flows and mudflows in the Bullion Canyon Volcanics. Emplacement of the stock was the first in a series of events of hydrothermal alteration and mineralization in the area, which formed propylitic alteration and gold-bearing veins. This was followed by alteration and lithophile mineralization (uranium and molybdenum) associated with intrusions in the nearby wall of the 19-Ma Mount Belknap caldera. The later alteration and mineralization adjacent to the intrusions resulted in gold deposits and alunite at about 16 Ma and later during emplacement of the rhyolite of Gillies Hill in the same area (Cunningham and others, 1984c).
4.9	65.7	Exit 125, ranch exit, about a mile north of roadcuts in the rhyolite dome complex. Cross a low pass, leaving the Beaver basin.
1.4	67.1	Exit ramp to a Rest Area. High hill at 11:00 is a Pleistocene basaltic cinder cone, surrounded by smooth wooded slopes (basalt lava flows) (Steven and Morris, 1983). Dated by Best and others (1980) at 500,000 years old. Capping the Tushar Mountains to our right is the Mount Belknap caldera, part of the bimodal sequence with an age of about 20 Ma (Cunningham and Steven, 1979a).
2.8	69.9	Exit 129, Sulphurdale. Small rhyolite domes (rhyolite of Gillies Hill) to the left, about a mile from the Interstate and at the southern base of the cinder cone mentioned above, then another basaltic cinder cone a mile farther to the west. Western strands of the north-striking Sulphurdale fault zone (Cunningham and others, 1983) are a few hundred yards to our right. This zone lifts up the Tushar Mountains and controls hot springs and a broad area of hydrothermally altered rocks in the hills at 1:00-2:00 that have been mined for sulphur for many years. The geothermal resource is discussed in Blackett and Moore (1994), and a small geothermal power plant now is operating at the springs.

2.7	72.6	BEAR RIGHT AT EXIT 132, AND HEAD EAST ON I-70. Pleistocene basaltic flows to the left. Much of the Tushar flank to the right is made up of calc-alkaline intermediate composition intrusive rocks that were the local source for stratovolcanoes of the Bullion Canyon Volcanics (Steven and Morris, 1983). The flat top to the northwestern end of the range here, however, is the younger, nearly flat, 23-Ma Osiris Tuff (Anderson and Rowley, 1975). We will visit its source caldera, the Monroe Peak caldera, shortly. A patch of the 19-Ma Joe Lott Tuff Member of the Mount Belknap Volcanics (Callaghan, 1939; Cunningham and Steven, 1979a; Budding and others, 1987) rests on the Osiris there; the Joe Lott is the main product of the Mount Belknap caldera, and we will visit thicker sections of this unit shortly.
1.1	73.7	Exit 1. At about 10:00 is the small community of Cove Fort, named for a pioneer fort that now is a tourist attraction.
2.6	76.3	Cove Fort geothermal area is in highly faulted and deeply altered low hills to the left (Blackett and Moore, 1994). Native sulfur is exposed near its center, and a small fluorite deposit is along its northwestern side. This geothermal resource area has not been developed. The interstate here follows an east-striking fault, the Cove Creek fault (Steven and Morris, 1983), that is one expression of a major east-striking structural feature that is well expressed in geophysics, folds, topography, and an alignment of the edges of calderas and vents (Campbell and others, 1999; Rowley and others, 2001a). It is the Cove Fort transverse zone (Rowley, 1998; Rowley and others, 1998).
3.7	80.0	Top of the pass, following the Cove Creek fault (Steven and Morris, 1983); enter the Clear Creek drainage to the east. Pavant Range on the left; Tushar Mountains on the right. The Pavant Range is well known for its exposures of east-verging Sevier thrusts (Steven and Morris, 1983; Steven and others, 1990). The volcanics of the Maryvale field get into only the southern part of the range, so the thrusts and the Paleozoic and Mesozoic section are well exposed farther north.
0.2	80.2	BEAR RIGHT AT EXIT 8, RANCH EXIT.
0.4	80.6	Go through the stop sign and up the entrance ramp back toward I-70. **STOP NO. 1**, MOUNT BELKNAP CALDERA VIEWPOINT. Overview of the Marysvale volcanic field, Mount Belknap Volcanics, Cove Fort transverse zone, and the ghost town of Kimberly. The cream-colored rocks on the skyline to the south are within the Mount Belknap caldera. It formed 19 million years ago in response to the eruption of alkali rhyolite ash-flow tuffs of the Joe Lott Tuff Member of the Mount Belknap Volcanics, which we will see soon (Cunningham and Steven, 1979a; Budding and others, 1987). The caldera is filled with three major ash-flow units and associated lava flows and volcaniclastic rocks. Mt. Belknap is the high peak on the left and Mt. Baldy is on the right; both are capped by rhyolite flows. The light-colored ridge extending toward you is Gold Mountain, which is made up of the

middle tuff member of the intracaldera facies. The Kimberly mining district, located just north of the caldera wall, was discovered in 1888 and was a significant gold producer around the turn of the century. Gold was produced from quartz-pyrite-carbonate veins within and adjacent to a propylitically-altered 23-Ma quartz monzonite stock. The Annie Laurie and Sevier mines were the major producers (Lindgren, 1906). Entertaining popular accounts of life in the associated town of Kimberly are given by Herring (1989) and Utley (1992). The red outcrops in the middle distance are from a kaolinite mine developed in the Joe Lott Tuff. CONTINUE UP THE ENTRANCE RAMP AND BACK ON EAST-BOUND I-70.

1.5 82.1 At 2:00, views of the high Tushars, within the Mount Belknap caldera.

1.8 83.9 Start across a long bridge above Clear Creek Canyon. Cliffs on the left belong to the 27-Ma Three Creeks Tuff Member of the Bullion Canyon Volcanics, one of the most voluminous ash-flow sheets derived from the Marysvale field (Steven and others, 1979). These outcrops probably are within the Three Creeks caldera (Steven, 1981), but only parts of the walls of the caldera are exposed, just to the east of these cliffs.

1.6 85.5 Exit to Brake Test area. Kimberly is at about 2:00.

1.7 87.2 Start across a bridge that crosses Mill Creek, a tributary to Clear Creek. Upstream on Mill Creek, at about 4:00, is the site of the former stagecoach road to Kimberly, which was kept open even during the winter, although for this the stagecoach wheels were removed and sleigh runners installed instead (Utley, 1992). Joe Lott drove wagons up that road for many years (see preface of Budding and others, 1987).

0.5 87.7 Tan Sevier River Formation overlies the Joe Lott Tuff Member below and to the east. The Three Creeks Tuff Member on the left. All rocks are gently dipping into an east-striking syncline, the Clear Creek downwarp, and shorter flanking gentle anticlines. To the right, basalt flows dated at 9 and 7 Ma (Best and others, 1980) are interbedded with the Sevier River Formation. Two white tuff beds, dated at 14 (near the base) and 7 Ma (near the top) (Steven and others, 1979), can be seen in the formation. The unit resulted from erosion of highlands raised during initial phases of basin-range extension, but the basins in which the unit was deposited are not those of the main phase of basin-range extension, which are close to those we see today (Rowley and others, 2001a).

1.7 89.4 TAKE EXIT 17, FREMONT INDIAN STATE PARK. Outcrops of Joe Lott Tuff Member, characterized by cooling joints, on both sides of the road. Although we will not visit Fremont Indian State Park, we strongly recommend that you do so some day. It was established only a few years ago, when construction for the Interstate uncovered a major archeological site of pithouses, residences, and artifacts from Fremont Indians who lived here while farming this part of Clear Creek valley.

0.3	89.7	AT THE STOP SIGN AT THE TOP OF THE RAMP, TURN RIGHT. THEN IN 30 METERS TAKE ANOTHER RIGHT ONTO DIRT USFS ROAD-478. This road, in the canyon of Mill Creek, parallels the south side of the freeway.
0.6	90.3	The dirt road bears left (south) and enters the tributary canyon of Joe Lott Creek and the entrance to USFS Castle Rock Campground.
0.8	91.1	**STOP NO. 2**, CASTLE ROCK CAMPGROUND. Examine outcrops of the Joe Lott Tuff Member and the Sevier River Formation. These outcrops, of course, provided the type area of the Joe Lott Member (Callaghan, 1939). TURN AROUND AND RETURN TO THE ENTRANCE RAMP TO I-70.
1.4	92.5	AT THE TOP OF THE ENTRANCE RAMP, TURN RIGHT ONTO I-70. Off to the left, Mill Creek enters Clear Creek, near the location of the Lott family pioneer cabin. Joe Lott grew up here, one of 9 children; he in turn married, had a family, and ranched elsewhere in Clear Creek Canyon.
0.9	93.4	The sharp white hill on the right is where the main Fremont-age community was found and excavated. Fremont State Park headquarters at 10:00. Observe several cooling units of the unwelded Joe Lott Tuff Member. The tuff flowed north to this location, where it is at its thickest.
3.3	96.7	On left, good exposures of the Sevier River Formation. We are now in the Dry Wash fault zone, made up of several north-northeast-striking left-lateral strike-slip faults (Anderson and Barnhard, 1992). The zone can be thought of as accommodation faults created during east-west basin-range extension.
1.4	98.1	Exit 23, Sevier. At 10:00, along the southern edge of an older Quaternary pediment, Sevier River Formation is exposed. Tan clastic piedmont facies, interpreted to be a basin-margin facies, is on the west and partly underlies white to light-green lacustrine facies, on the east. These two facies of the Sevier River Formation are faulted against each other along a strand of the Dry Wash fault zone (Rowley and others, 1988b).
0.9	99.0	Adjacent to the lacustrine facies on the left. The flat-topped mountain at 2:00 is Monroe Peak, capping the Sevier Plateau. Because it caps a sequence of intracaldera tuffs related to the eruption of the Osiris Tuff, it gives its name to the Monroe Peak caldera, the largest in the Marysvale field (Steven and others, 1984a; Rowley and others, 1986a, b, 1988a, b). The Sevier Plateau was uplifted and tilted about 3^{o} to the east along the Sevier fault zone, which runs along its western base.
1.5	100.5	TAKE EXIT 26, JOSEPH AND MONROE.
0.5	101.0	TURN RIGHT ON SR-118 AT THE BOTTOM OF THE RAMP.

0.4	101.4	Stop sign at intersection with US-89. Downtown Joseph. Continue straight on SR-118. A small tilt block straight ahead is uplifted by one strand of the Dry Wash fault zone, which passes along the western side (Rowley and others, 1988b). So here, the zone has a dip-slip component. Light-gray Three Creeks Tuff Member at the base of the block is overlain in turn by thin basaltic lava flows, the Osiris Tuff, and the Joe Lott Tuff Member. Cross the Sevier River about 2 kilometers east of the intersection.
1.9	103.3	Start to climb up over the small tilt block, going through faulted basin-fill deposits along its western side and an older uplifted pediment deposit on top. We use the term “basin-fill deposit” for sediments deposited in downthrown areas that are synchronous with the main episode of basin-range faulting (Rowley and others, 2001a). Hot springs and hot-spring deposits are exposed along the fault south of here. As we go over the top of the fault block, we see Monroe ahead, east of which is the Sevier fault zone and the uplifted northern Sevier Plateau. Monroe Canyon, where we are headed, is southeast of town.
3.5	106.8	Stop sign as SR-118 (100 South) intersects with Main Street, downtown Monroe. TURN RIGHT ON MAIN STREET. On left, the Three Creeks Tuff Member and the Bullion Canyon Volcanics in the mountain front behind Monroe are hydrothermally altered, and a popular recreation area at the base of the Sevier fault scarp is Monroe Hot Springs.
0.8	107.6	Road bends sharply left. At the base of the fault scarp at 12:00 to 2:00 is light-gray Three Creeks Tuff Member overlain by mudflows of the Bullion Canyon Volcanics.
1.3	108.9	House with duck pond on right, soon after entering Monroe Canyon.
1.3	110.2	Just past a narrowing of the canyon as it cuts through a thick andesitic lava flow of the Bullion Canyon Volcanics. The road becomes dirt.
0.3	110.5	Road forks. TAKE RIGHT FORK ACROSS THE BRIDGE. Left fork goes to Monrovian Park, a local picnic spot less than a kilometer away, at the contact of an intracaldera pluton in the Monroe Peak caldera.
1.6	112.1	**STOP NO. 3**, MONROE PEAK CALDERA MEGABRECCIA. Stop at the sharp switchback to the right, then hike several hundred meters up an old road along a stream that passes beneath the switchback. Pass along a lateral moraine and cross the concealed northern wall of the Monroe Peak caldera. Then climb up left (east) into propylitically altered megabreccia blocks adjacent to an intracaldera pluton that is farther to the east. Return to the vehicles. TURN AROUND AND RETRACE OUR STEPS TO THE STOP SIGN AT US-89 AT JOSEPH.
10.7	122.8	Intersection with US-89. Cross US-89 and continue on SR-118.

0.5	123.3	Pass beneath I-70 to the entrance ramp for westbound I-70. AT THE ENTRANCE RAMP, TURN LEFT AND ENTER FREEWAY.
1.8	125.1	TAKE EXIT 23, PANGUITCH AND KANAB.
1.6	126.7	US-89 (from the town of Sevier) enters on the left. Continue south on US-89. Low hill to the left, about 50 meters south of this intersection, contains a tuff bed in the Sevier River Formation that Steven and others (1979) dated at 7 Ma. The formation just predates main-phase basin-range deformation, which formed the present topography. Thus this date supplies evidence that basin-range faulting here is younger than 7 million years ago.
0.7	127.4	Cross the Sevier River and enter Marysvale Canyon, made up mostly of Bullion Canyon Volcanics, which here consists of volcanic mudflow breccia, subordinate lava flows, and minor ash-flow tuffs, all of dacitic composition.
0.8	128.2	On left, the upper, east-dipping unit is the Joe Lott Tuff Member.
2.2	130.4	Straight ahead, east of the Sevier River, is a monzonite stock of the calc-alkaline episode, synchronous with and a likely source of some parts of the Bullion Canyon Volcanics here. It is less than 1 kilometer in diameter and rises almost vertically about 200 meters above the canyon floor. Its fluted walls coincide with its intrusive contact. It was referred to as “The Plug” by Kerr and others (1957). About 400 meters above the floor of Marysvale Canyon, a subhorizontal surface beveled on the Bullion Canyon Volcanics is capped by poorly consolidated sandstone and conglomerate of the Sevier River Formation (Rowley and others, 1988a, b). This represents a higher level erosion surface, cut during an earlier episode of extension, probably when the Sevier River Formation was deposited but before the main episode of extension that led to the present canyon cutting.
2.3	132.7	View of Big Rock Candy Mountain, the same as shown in the photograph on the cover page of the field-trip log. This mountain is a well-known landmark for variegated altered volcanic rocks in west-central Utah. It consists of the eroded remnants of an alunite deposit that replaced intermediate-composition lava flows about 21 million years ago. The alunite formed in steam-heated conditions near the top of a hydrothermal plume that was one of at least six, spaced at 3- to 4-kilometer intervals, surrounding a monzonite stock (Cunningham and others, 1984a). Big Rock Candy Mountain is horizontally zoned outward from an alunite core to respective kaolinite, dickite, and propylite envelopes and is the lower part of a vertically zoned sequence from a lower pyrite-propylite assemblage upward through assemblages successively dominated by hypogene alunite, jarosite, and hematite, to a flooded silica cap. This hydrothermal assemblage is undergoing natural destruction in a steep canyon as a result of exposure owing to downcutting of the Sevier River in Marysvale Canyon. Integrated geologic, mineralogic, spectroscopic remote sensing using AVIRIS data, argon radiometric, and stable isotopic studies trace the hypogene origin and supergene

destruction of the deposit and permit distinction of primary and secondary processes. This destruction has led to the formation of widespread supergene gypsum in cross-cutting fractures and as surficial crusts, and of natrojarosite, which gives Big Rock Candy Mountain its buff color along ridges facing the canyon. A small spring, Lemonade Spring, with a pH of 2.6, containing Ca, Mg, Si, Al, Fe, Mn, Cl, and SO_4, is located near the back of the motel. A $^{40}Ar/^{39}Ar$ date (21.32$\pm$0.07 Ma) on the alunite is similar to that for other replacement alunites at Marysvale. However, the age sprectrum contains evidence of a 6.6-Ma thermal event that can be related to tectonic events (that is, main-phase basin-range extension) responsible for uplift that led to the downcutting of Big Rock Candy Mountain by the Sevier River. This 6.6-Ma event also is present in the age spectrum of supergene natrojarosite forming today and probably dates the beginning of supergene alteration of Big Rock Candy Mountain.

0.5 133.2 **STOP NO. 4**, BIG ROCK CANDY MOUNTAIN. PULL OVER TO THE RIGHT, at Big Rock Candy Mountain Resort. Made popular by a song of the same name by Burl Ives, the predecessor resort to this motel flourished in the 1940s and earlier as a dude ranch and place to hunt mountain lions; its inside is decorated with autographed pictures of movie actors, actresses, and other celebrities. Please do not break rocks or dig within view of the motel or climb to the alunite outcrops. Excellent samples and observations of altered rock relationships can be obtained by a short walk south along the cliff face. Be sure to visit, but do not drink from, Lemonade Spring behind the motel! RETURN TO THE VEHICLES AND CONTINUE SOUTHWARD ALONG US-89. Hoover pluton at 9:00 to 1:00, on the eastern side of the river.

0.9 134.1 **STOP NO. 5**, HOOVER'S TRUCK STOP. IF WE HAVE CALCULATED CORRECTLY, THIS WILL BE OUR LUNCH STOP. PULL OVER TO THE LEFT. For several years, USGS mapping of the Marysvale field was centered out of Hoover's, using government trailer homes. To the east of Hoover's Truck Stop is Hoover Peak, and the Hoover pluton, which is a large quartz monzonite stock of the calc-alkaline sequence. Steeply south-dipping ash-flow tuffs of the Mount Belknap Volcanics are on the right, including the gray Joe Lott Member and the overlying red Red Hills Member. The rhyolites are downdropped by a well-exposed east-striking basin-range fault.

1.3 135.4 Curve sharply to the right. Red rocks to the left belong to the Red Hills Tuff Member, within the Red Hills caldera. Flow foliations in this tuff are inclined steeply inward into the caldera, suggesting rheomorphic flowage back into the collapsing hole.

0.9 136.3 Black knob on the right is the basal glass of a lava flow in the Mount Belknap Volcanics. Enter Marysvale Valley, another graben between the Tushar fault zone on the west and the Sevier fault zone on the east.

0.8 137.1 Views of the Sevier Plateau to the left and the Tushar Mountains to the right. The Central Mining Area is at 8:00 (Cunningham

		and Steven, 1979b; Steven and others, 1981; Cunningham and others, 1982, 1998b).
0.9	138.0	Enter Marysvale, on Main Street.
0.4	138.4	AT THE INTERSECTION OF MAIN AND CENTER STREETS, TURN LEFT ON CENTER STREET (DIRT). "Our Bar" is on the southeastern corner of this intersection, and an Amoco gas station and convenience store is on the northeastern corner.
0.6	139.0	Cross the Sevier River. Then the dirt road bears left (north).
0.6	139.6	Maintaining "M" hill on the right has obviously kept a lot of high-school students occupied and thus more or less out of trouble. This hill is Bullion Canyon Volcanics, but a few hundred meters to the east it is intruded by intracaldera plutons at the western edge of the Monroe Peak caldera (Rowley and others, 1988a).
0.9	140.5	Hydrothermally altered intracaldera Osiris Tuff. The Monroe Peak caldera margin here is interpreted to be west of the road, and this margin continues north, through the middle of the Red Hills caldera. Thus the Monroe Peak caldera is interpreted to enclose the entire Central Mining Area.
0.3	140.8	The road forks. TAKE THE LEFT FORK. The flat-topped mountain at 1:00 is the high point of the Central Intrusion, an intracaldera intrusion within the Monroe Peak caldera and a host to some of the uranium deposits in the district. The Central Mining Area is from 11:00 to 1:00.
0.3	141.1	The road forks again. TAKE THE LEFT FORK.
0.2	141.3	The road forks a third time. AGAIN, TAKE THE LEFT FORK. At the fork is a Piute trail marker for all-terrain vehicles (ATVs).
0.6	141.9	Cross the wall of the Red Hills caldera. **STOP NO. 6**, RED HILLS CALDERA. Take a quick look at the Red Hills Tuff Member on the right. CONTINUE NORTH ON THE DIRT ROAD.
0.9	142.8	Electric substation on the right, in the middle of the Red Hills caldera. Highest flat-topped hill, with its many switchbacks, at 2:30 is horizontal Red Hills Member (19 Ma) sitting on the Central Intrusion (22 Ma) (Cunningham and Steven, 1979b; Cunningham and others, 1982, 1998b; Rowley and others, 1988b). Uranium veins occur in the Central Intrusion, fine-grained granite, and Red Hills Tuff Member.
0.6	143.4	The road forks. TAKE THE LEFT FORK. The heart of the Central Mining Area is on the right (Cunningham and Steven, 1979b; Cunningham and others, 1982, 1998b). Notice the flat-lying outflow Red Hills Tuff Member on the right. The highest hill at 3:00 is in the Central Intrusion, and the right fork would go into the Central Mining Area and the intrusion. The Central Intrusion is interpreted to be part of the calc-alkaline episode, but it is a host for many of the uranium deposits. A more important host is

		the fine-grained silicic pluton, which makes up much of the rock containing the switchbacks and mines we can see. This pluton, with an age of is about 21 Ma, is interpreted to belong to the bimodal episode (Cunningham and Steven, 1979b; Rowley and others, 1988a, b). But the source and control for the uranium is a series of younger glassy rhyolite dikes of the Mount Belknap Volcanics that are dated at 19-18 Ma and cut the Central Intrusion and fine-grained silicic pluton (Cunningham and others, 1982). These dikes are interpreted to widen downward into an unexposed stock that provided the uranium to the district and that may host a porphyry molybdenum deposit (Cunningham and others, 1982).
1.3	144.7	Top of a hill, with outcrop of altered rhyolite to our right. We are now outside the Monroe Peak caldera, as are most rocks (Bullion Canyon Volcanics) surrounding Sage Flat, the valley ahead and below us (Rowley and others, 1988b). This valley is a shallow closed basin formed behind a young fault to the west. The caldera wall, however, passes through the eastern side of Sage Flat, then north. The red peak at 12:00 is made up of Monroe Peak intracaldera volcanic rocks that have been altered by one of the hydrothermal convection cells surrounding the Central Intrusion (Podwysocki and Segal, 1983). In these cells, a lower alunite zone passes upward into jarosite, hematite, and flooded silica zones (Cunningham and others, 1984a). When it breached the surface, the silica zone formed hot spring sinter at the surface and also silicified (replaced) the immediately underlying rocks. Surficial silica includes hydrothermal breccia ("blowouts") deposited under geyser conditions after pressure built up and was released explosively. The red peak is capped by a thick replacement silica zone, but slightly lower on the mountain, red hematite was mined at the Iron Cap mine from the underlying hematite zone. Quartz knobs that represent hot spring sinter and related hydrothermal breccia, as well as replacement silica are abundant in a 90^{o} arc that ranges between north and east of our location (Rowley and others, 1988b).
1.2	145.9	Road forks after crossing Sage Flat and up a canyon in Bullion Canyon Volcanics. TAKE RIGHT FORK.
1.2	147.1	On right, entrance to Yellow Jacket mine. **STOP NO. 7**, YELLOW JACKET MINE. Discussion will focus on replacement alunite deposits that have been directly dated at about 23-22 Ma, the age of the Central Intrusion (Cunningham and others, 1984a). TURN AROUND AND RETRACE OUR STEPS TO THE FORK CONTAINING THE ATV TRAIL MARKER.
5.8	152.9	AT THE FORK CONTAINING THE PIUTE TRAIL MARKER, TAKE A SHARP LEFT (NORTH).
0.7	153.6	Approximate location of intrusive contact to the Central Intrusion, to the north. Enter the southern part of the Central Mining Area.
0.5	154.1	Intersection, on the left, with an old road that comes down from the VCA mine. **STOP NO. 8**, VCA MINE. Please stay away

		from old mine workings! Hike up the old road, looking at mineralized Central Intrusion, the horizontal contact between the Central Intrusion and overlying Red Hills Tuff Member, and the VCA mine. The VCA mine, emplaced into the Central Intrusion at the southern edge of the Antelope Range quadrangle (Cunningham and Steven, 1979b; Cunningham and others, 1982, 1998b; Rowley and others, 1988b) was an important underground uranium mine. The glassy rhyolite dikes associated with uranium mineralization are exposed at depth, and molybdenum values increase in the veins downward (at 200 meters depth), suggesting that the dikes pass into a buried stock (Cunningham and others, 1982). RETURN TO THE VEHICLES AND RETRACE OUR TRACKS TO MARYSVALE. As we turn around the vehicles and head south, you will see roads, white outcrops, dumps, and mines at 12:30 to 1:30 that belong to the Whitehorse mine, which mined replacement alunite in another hydrothermal cell caused by emplacement of the Central Intrusion (Cunningham and others, 1984a, b).
4.1	158.2	AT INTERSECTION WITH US-89 IN DOWNTOWN MARYSVALE, TURN LEFT AND HEAD SOUTH ON US-89.
1.2	159.4	Dairy farm on left is on an older piedmont-slope (Pleistocene pediment and fan) deposit that in turn rests on Pliocene and Pleistocene basin-fill deposits that were deposited during basin-range extension. These deposits rest on Sevier River Formation, well exposed east of the Sevier River to our left (Rowley and others, 1988a). A western strand of the Sevier fault zone runs along the low scarp just east of the river, whereas an eastern strand runs along the base of the main scarp of the Sevier Plateau. Flat-topped mountain on the Sevier Plateau at 9:30 is Big Table, held up by basalt lava flows that cap outflow Osiris Tuff; below the Osiris are thick sequences of andesitic lava flows and volcanic mudflow breccia of a shield volcano that predates and lies just south of the Monroe Peak caldera. The rocks in the caldera just north of Big Table consist, from the base of the scarp to the top, of an intracaldera intrusion (lower 300 meters), intruded into heavily altered intracaldera Osiris Tuff that makes up the overlying 200 meters. This is overlain by fresh intracaldera lava flows that form the upper peaks and postdate the main intracaldera intrusion exposed at the base of the scarp.
2.3	161.7	Dirt road on right, with a sign on it “UNICO, Inc. Deer Trail mine.” TURN RIGHT ONTO THAT ROAD. The Tushar fault zone, which runs along the base of the scarp, has raised the Tushar Mountains as a giant horst. The lower 1,000 meters of the scarp consist of sedimentary rocks, ranging from the Permian Queantoweap Sandstone at the base upward through the Jurassic Arapien Formation, in turn overlain unconformably by a thin unnamed lower Tertiary conglomerate less than 30 meters thick (Cunningham and Steven, 1979c). The Bullion Canyon Volcanics make up the rest of the rocks to the top of the Tushar Mountains.
2.0	163.7	Fork in road. BEAR RIGHT ON THE MAIN FORK.

0.2	163.9	Fork in road. TAKE RIGHT FORK TO THE LOCKED GATE. **STOP NO. 9**, DEER TRAIL MINE. The Deer Trail mine is an underground mine developed in a halo of gold-bearing veins and base- and precious-metal manto deposits adjacent to the easternmost of two cupolas on a blind intrusion (Cunningham and others, 1984a; Beaty and others, 1986). The western cupola has spectacularly domed up and split open its host rocks, then degassed (Cunningham and Steven, 1979c). These extension joints in the roof were filled by coarse-grained vein alunite at the crest of the dome, on Alunite Ridge. The alunite was dated at 14 Ma, the same age as the Deer Trail ore (Cunningham and others, 1984a). Details of the deposit will be discussed at the mine. The dump is a good place to collect samples of Deer Trail rocks and ore. TURN AROUND AND RETURN TO US-89.
2.2	166.1	STOP SIGN. TURN RIGHT AND HEAD SOUTH ON US-89. White outcrops on the eastern side of the river at 9:30 are made up of the Joe Lott Tuff Member, which underlies the tan Sevier River Formation well exposed north of it. These rocks are bounded by a fault at the base of the low scarp.
3.5	169.6	Dirt road on the left, with a large dirt stock tank along it. Hill at 9:30 is a tilt block. The strong ledge in the middle of the slope is outflow Osiris Tuff, overlain in turn by soft rocks of the Joe Lott Tuff Member and Sevier River Formation, then by a resistant caprock of basalt lava flows dated at 13 Ma (Best and others, 1980).
1.5	171.1	Paved road on left to Piute Lake State Park. The earthen dam to this lake, at the northern end of the lake but hidden from our view here, is old, has a late Quaternary fault through it, and may have to be replaced (D.B. Simon of Simon-Bymaster, Inc. and colleagues, written commun., 2001). The spectacular basin-range fault scarp east of the lake exposes the Three Creeks Tuff Member at the base, volcanic mudflow breccia of mostly the Mount Dutton Formation above, then at the top the same units as in the previously mentioned tilt block. Most of the black rocks in the hanging wall of the Sevier fault zone, including those west of the reservoir, are potassium rich mafic volcanic rocks that here and elsewhere have ages of between 25 and 21 Ma (Rowley and others, 1994). On the right, the Tushar Mountains flank we see is made up of the Bullion Canyon Volcanics, which intertongues southward with the Mount Dutton Formation, which in turn makes up most of the mountain flank another few kilometers to the south. The upper unit of the Bullion Canyon Volcanics to our right is the 23-Ma Delano Peak Tuff Member of the Bullion Canyon, a major ash-flow sheet derived from the Big John caldera just west of the crest of the Tushars 7 kilometers west of us (Steven and others, 1984b).
3.4	174.5	Former US-89 joins us on the left. The highest part of the Sevier Plateau on the horizon to our left is capped by a thick rhyolite lava flow that Rowley and others (1981) dated at about 8 Ma. It and the rocks below it dip gently eastward at about 3^{o}, due to normal movement of at least 2.5 kilometers along the Sevier fault

		zone. When we get to Kingston Canyon, we will stop at the rhyolite dome of Phonolite Hill that further constrains the movement of this fault zone. Ahead at 1:00, the highest point of the Sevier Plateau is called Mount Dutton and, to the left of it is Mount Pierson, named for Lynn Pierson, a Utah Highway Patrolman killed in the line of duty.
1.8	176.3	Piute County International Airport on the right, as we enter the town of Junction, the county seat.
0.9	177.2	Downtown Junction. The former courthouse is on the right, just south of which is a road that heads west across the Tushar Mountains to Beaver. Hills sticking out of the graben to the left and ahead are tilt blocks caught along the Sevier fault zone. We soon will leave the area shown by the maps of Cunningham and others (1983) and Rowley and others (2001a).
1.8	179.0	Intersection with SR-62 on the left. TURN LEFT TOWARD KINGSTON CANYON.
1.8	180.8	Enter the outskirts of Kingston.
0.4	181.2	Leave Kingston and enter Kingston Canyon. The canyon is an antecedent canyon formed when an east-flowing stream, the East Fork of the Sevier River, maintained its course as the Sevier Plateau was uplifted along the Sevier fault zone.
0.6	181.8	Purple Haze outside dance pavilion, its best days behind it, on the right. Most rocks we will see in the western part of Kingston Canyon are blocks of volcanic mudflow breccia of the Mount Dutton Formation, tilted by an intersecting series of parallel and en echelon normal faults of the Sevier fault zone. South of Kingston Canyon, most faults strike north-northeast, whereas north of Kingston Canyon, most strike north-northwest (Rowley, 1968). On the hill towering above the Purple Haze, two petrologically identical medium-brown, densely welded, crystal-poor, local ash-flow tuff cooling units filled a stream channel draining the stratovolcano that deposited the breccia. Although in most places these lenticular cooling units are in contact, they have a small wedge of breccia separating them in the center of the channel. This is the only place we have seen these cooling units, which probably differed in age by only a few minutes or a few years. We will get a better view of these rocks on our way back.
1.6	183.4	Osiris Tuff, a densely welded ash-flow unit, on the right. A north-northeast-striking fault passes across our path and displaces this tuff up on the east; it forms the caprock of the large hills at 1:00 and 10:00.
0.9	184.3	**STOP NO. 10**, KINGSTON CANYON MUDFLOWS. PULL OVER TO THE RIGHT. Look at volcanic mudflow breccias, the most voluminous rock type in the Maryvale volcanic field. We classify most breccias as alluvial facies, as opposed to near-source vent facies. A basaltic feeder dike stands up in bold relief on our left. RETURN TO THE VEHICLES AND CONTINUE

		EAST. In about 200 meters, we will pass over another north-northeast-striking fault, also upthrown to the east, into pink rocks of the Three Creeks Tuff Member (Rowley, 1968).
1.4	185.7	**STOP NO. 11**, CRYSTAL-RICH TUFF. PULL OVER TO THE RIGHT. On our right, spectacular exposures on the northern wall of Kingston Canyon of, from base to top, 15 meters of resistant bedded sedimentary rocks that can be assigned to the Claron Formation; 15 meters of pink, crystal-rich ash-flow tuff of the 30-Ma Wah Wah Springs Formation of the Needles Range Group; 20 meters of bedded sedimentary rocks; and 200 meters of crystal-rich ash-flow tuff of the 27-Ma Three Creeks Member of the Bullion Canyon Volcanics. Cross the road to the north for a quick look at float samples of the Wah Wah and Three Creeks. RETURN TO THE VEHICLES AND CONTINUE EAST.
1.1	186.8	The hill at 10:00 is Phonolite Hill, mostly a rhyolite dome but with a tuff ring at its base. Observe the different geomorphology of the canyon exposures to our right versus those to our left: a classic function of erosion (notably freeze-thaw cycles) on south-facing versus north-facing slopes.
0.3	187.1	**STOP NO. 12**, PHONOLITE HILL. PULL OVER TO THE LEFT. The rhyolite of Phonolite Hill erupted at 5 Ma in the base of Kingston Canyon, which was cut following the main phase of basin-range faulting. This date, when combined with the east-dipping 8-Ma rhyolite flow that caps the Sevier Plateau north of us, provides one of the best constraints on basin-range faulting—between 8 and 5 Ma—yet reported (Rowley and others, 1981). Examine outcrops of tuff-ring sediments on the northern side of the road. The vertical contact of the dome with these sediments, containing a 1-meter thick vertical vitrophyre, is exposed on the slope above us, but we do not have the time to go there so will examine rhyolite float instead. RETURN TO THE VEHICLES AND CONTINUE EAST.
1.3	188.4	Several other domes are to the right. All of them are on a line with a northwest strike, probably erupted along a fracture.
1.4	189.8	On left and right, the gentle eastward dip (here it has steepened from its average of about 3^{o}) of the Sevier Plateau is obvious. The Plateau rim to the left and right is held up by the Osiris Tuff and, locally, also by basalt lava flows. The next plateau to the east, the Awapa Plateau, is similarly uplifted along a fault zone (Paunsaugunt fault zone in Grass Valley to the east) and tilted eastward.
1.2	191.0	**STOP NO. 13**, OSIRIS TUFF. PULL OVER. Examine two densely welded ash-flow tuffs. The eastern (upper) of the two tuffs is the Osiris Tuff, derived from the Monroe Peak caldera at about 23 Ma. Three zones are clearly seen in its 20 meter stratigraphic section: a basal glass, the red devitrified stony zone, and the upper gray vapor-phase zone. The lower tuff is the 26-Ma Antimony Member of the Mount Dutton Formation, an even more densely welded ash-flow tuff and here about the same thickness as the Osiris (Rowley and others, 1994). Its

source is not known but probably is beneath the Sevier River Valley in the Joseph area, based on other cooling units in that area. It has the same zones as the Osiris. The type area of the Antimony is here, not far from the town of Antimony to the southeast (Anderson and Rowley, 1975); the type area of Osiris is near the ghost town of Osiris, south of Antimony (Williams and Hackman, 1971). At this stop, the Osiris rests directly on Antimony, but several kilometers to the east, about 300 meters of Mount Dutton mudflow deposits separate them. East of Antimony, the Mount Dutton Formation thins rapidly, at the flanks of the clustered stratovolcanoes and other volcanoes. Before they pinch out, however, the clasts become rounded and grain supported and instead of mudflow deposits, they have become reworked into conglomerate. A basalt flow overlies Osiris about 100 meters east of this stop; Rowley and others (1981) dated it at about 8 Ma. RETURN TO VEHICLES AND CONTINUE EAST.

0.3	191.3	SR-22 on the left intersects SR-62. We are in Grass Valley, north of the town of Antimony. The earthen dam of Otter Creek Reservoir is a few hundred meters to the east of us. TURN AROUND AND RETURN TO US-89.
12.3	203.6	Intersection with US-89. TURN LEFT (SOUTH) ON US-89. The rounded hills to the left and right are mostly faulted blocks of volcanic mudflow breccia of the Mount Dutton Formation, but some white conglomerate and sandstone of the Sevier River Formation are present. Enter Circle Valley.
2.1	205.7	Abandoned potato warehouse on the left. The Sevier fault zone on the left is complicated, so lots of small horst blocks can be seen sticking out of the basin fill. The large Tushar fault zone on the right exposes little more than volcanic mudflow breccia, with some lava flows, from the base to the top of the scarp. However, the scarp here creates a spectacular cross section through a stratovolcano, with a north-dipping northern flank and a south-dipping southern flank. The south faces of the highest peaks contain spectacular glacial cirques. These peaks are underlain by lava flows of the potassium-rich mafic volcanic rocks erupted about 23 to 22 Ma (Anderson and others, 1990b). This is the same south-facing scarp seen before, separating the Tushar Mountains from the Markagunt Plateau and largely controlled by the Blue Ribbon transverse zone.
1.4	207.1	Cross the Sevier River and enter Circleville.
1.5	208.6	Leave Circleville.
0.7	209.3	Spectacular outcrops of volcanic mudflow breccia adjacent to the highway on the right.
1.1	210.4	On the right, against the cottonwood trees, is the boyhood home of the infamous outlaw LeRoy Parker, better known as Butch Cassidy. Butch frequented the gold camp of Kimberly, but apparently he avoided trouble there and in other places when he was near home (Herring, 1989). Soon we will enter Circleville

		Canyon, exposing mostly vent facies of the Mount Dutton Formation (Anderson and others, 1990b). Assigning vent versus alluvial facies is not a cut and dried procedure: we use vent facies when dikes, lava flows, and flow breccia are abundant, when initial dips are seen, and when the clasts in volcanic mudflow breccia masses are monolithologic.
1.1	211.5	**STOP NO. 14**, CIRCLEVILLE CANYON STRATOVOLCANO DEPOSITS. PULL OVER TO THE RIGHT JUST BEYOND THE VERTICAL ROADCUT ON A SHARP RIGHT CURVE. This roadcut on the right probably represents the throat of a stratovolcano, as suggested by the presence of dikes, a probable fault, lava flows, and volcanic mudflow breccia. CONTINUE SOUTH. Farther south, some of the breccias are well bedded, a feature that is more indicative of alluvial facies. Many of the breccias are tilted, but interpreting whether these are initial dips or fault tilt blocks is problematic.
2.4	213.9	**OPTIONAL STOP**, CIRCLEVILLE CANYON STRATOVOLCANO DEPOSITS. TIME PERMITTING, PULL OVER ON THE RIGHT JUST BEYOND THE ROADCUT, ALSO ON A RIGHT CURVE. This roadcut is best classified as vent facies, suggested by mostly flow breccia, lava flows, and volcanic mudflow breccia. CONTINUE SOUTH.
0.6	214.5	**OPTIONAL STOP**, CIRCLEVILLE CANYON STRATOVOLCANO DEPOSITS. TIME PERMITTING, PULL OVER ON THE LEFT, ACROSS THE ROAD FROM A VERTICAL ROADCUT. This is a possible throat or vent area, consisting of breccia dikes on top of each other as well as lava flows. CONTINUE SOUTH.
1.9	216.4	The outcrops to the left, across the Sevier River, consist mostly of scores of dikes emplaced into each other. Some of them are breccia dikes. The landform that was built up above them is assumed to have been a stratovolcano.
1.0	217.4	Roadcut on the right consists of basin-fill deposits plastered on the wall of this canyon.
1.5	218.9	**OPTIONAL STOP**, SPRY INTRUSION. PULL OVER ON THE RIGHT, TIME PERMITTING. The Spry Intrusion is a well exposed quartz monzonite porphyry laccolith of batholithic dimensions (Anderson, 1965, 1993; Anderson and Rowley, 1975). Furthermore, gravity and aeromagnetic data indicate that it extends in the subsurface at least 50 km south of these exposures (Blank and Kucks, 1989; Anderson, 1993; Rowley and others, 1998). It vented a local series of lava flows, dikes, and volcanic mudflow breccias, known collectively as the volcanic rocks of Bull Rush Creek (Anderson and others, 1990b) and it vented an ash-flow tuff called the Buckskin Breccia (Anderson, 1965; Anderson and Rowley, 1975). The Buckskin Breccia spread widely over the northern Markagunt Plateau and is distinctive because it contains abundant lithic clasts of the Spry Intrusion. All these volcanic and intrusive rocks have the same age, 26-25 Ma (Anderson and others, 1990b). The

Buckskin Breccia filled a series of grabens in the northern Markagunt Plateau, thereby partly providing proof of an early episode of west-northwest striking faults (Anderson, 2001). CONTINUE SOUTH. Note, as we continue along U.S.-89, that the Spry outcrops ahead and to the right have a flat top that is about 130 meters above road level; this surface is overlain by pediment deposits (Anderson and others, 1990b). This clearly represents an upper-level erosion surface. In addition, the top of Circleville Canyon north of us has subhorizontal to gently rolling topography at about 300 meters above the canyon bottom, further proof of older erosion surfaces at the same level as above Marysvale Canyon, noted above.

0.7 219.6 Cliffs of the Spry Intrusion on the right. Then, beyond this, we break out into the Sevier River valley, defined by the Sevier fault zone on the east and the generally east-tilted (but locally faulted) Markagunt Plateau on the west. Far to the south and the left, the red rocks on the lower part of the scarp of the Sevier Plateau are Claron Formation. This red member of the Claron is overlain by white sedimentary rocks, formerly considered the white member of the Claron (Rowley, 1968) but now perhaps part of the Brian Head Formation (Sable and Maldonado, 1997); the white rocks are in turn overlain by the southward thinning volcanic mudflow breccia (alluvial facies) of the Mount Dutton Formation.

5.1 224.7 Bear Valley Junction, where SR-20 intersects on the right with US-89. TURN RIGHT ON SR-20. As we make the turn, one of two crosses on the right is a tribute to Highway Patrolman Lynn Pierson.

1.3 226.0 North-dipping volcanic rocks on the hill to the right form the northern part of the Orton structural dome, which is probably caused by an underlying laccolith (Anderson, 1965; Anderson and Rowley, 1975, 1987). The oldest exposed rocks in the interior of the dome belong to the Claron Formation. The Claron is overlain by a local assemblage of volcanic rocks exposed to the left and low on the hill to the right. These volcanic rocks have a date of 32 Ma (Fleck and others, 1975) and predate ash-flow tuffs of the 30-Ma Wah Wah Springs Formation, which caps the hill to the right. The Wah Wah Springs is overlain by the 27-Ma Isom Formation, just north of the hill to the right, and in turn by the 26-25 Ma Bear Valley Formation (Anderson, 1971), a widespread eolian sandstone and intertongued local ash-flow tuffs.

1.3 227.3 Outcrops of gray, green, and yellow eolian sandstone of the Bear Valley Formation on both sides of the road. The Bear Valley accumulated to thicknesses of as much as 300 meters in parts of the northern Markagunt Plateau. Like the Buckskin Breccia, it is thickest along fault scarps and in grabens of west-northwest faults (Anderson, 1971, 2001). The Bear Valley is overlain by great thicknesses of volcanic mudflow breccia of the Mount Dutton Formation.

3.5 230.8 **STOP NO. 15**, BUCKSKIN BRECCIA. At the base of the ledge on the right, Wah Wah Springs Formation is overlain by Isom

Formation and in turn by Buckskin Breccia. Look at the unique ash-flow tuff of the Buckskin Breccia, which contains lithic clasts of the Spry Intrusion. These ash-flow tuffs, all 50 meters or less thick, are in turn overlain by thick masses of volcanic mudflow breccia of the Mount Dutton Formation (Anderson and Rowley, 1987). Then enter Bear Valley, a north-northeast trending graben. CONTINUE WEST ON SR-20.

3.6	234.4	**OPTIONAL STOP**, BEAR VALLEY. PULL OVER ON RIGHT, THEN WALK BACK TO AN OVERLOOK OF BEAR VALLEY. Discuss the origin of the northern Markagunt Plateau. CONTINUE WEST ON SR-20. From here, most of the outcrops are of the Mount Dutton Formation.
2.7	237.1	Enter Buckskin Valley, another north-northeast-trending graben (Anderson, 1965).
1.0	238.1	In the middle of Buckskin Valley, look right to see the high Tushar Mountains on the horizon; the white peaks are rhyolite intracaldera fill in the Mount Belknap caldera. The generally south-facing scarp between this range and the lower northern Markagunt Plateau is apparent.
6.9	245.0	In Parowan Valley, TURN LEFT (SOUTH) ONTO ENTRANCE RAMP TO I-15. RETRACE OUR ROUTE TO THE MIDDLE CEDAR CITY EXIT (EXIT 59), THEN TO THE PARKING LOT WEST OF ECCLES COLISEUM.
36.5	281.5	TURN INTO PARKING LOT WEST OF ECCLES COLISEUM. END OF FIELD TRIP.

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View to the west southwest into the Mount Belknap caldera from a point on its eastern topographic wall. Mount Belknap (elev. 12,139 ft) is the peak on the right. The smooth slopes and cliffs reflect the eruptve sequence of ash flow tuffs and cliff forming rhyolite lava flows.