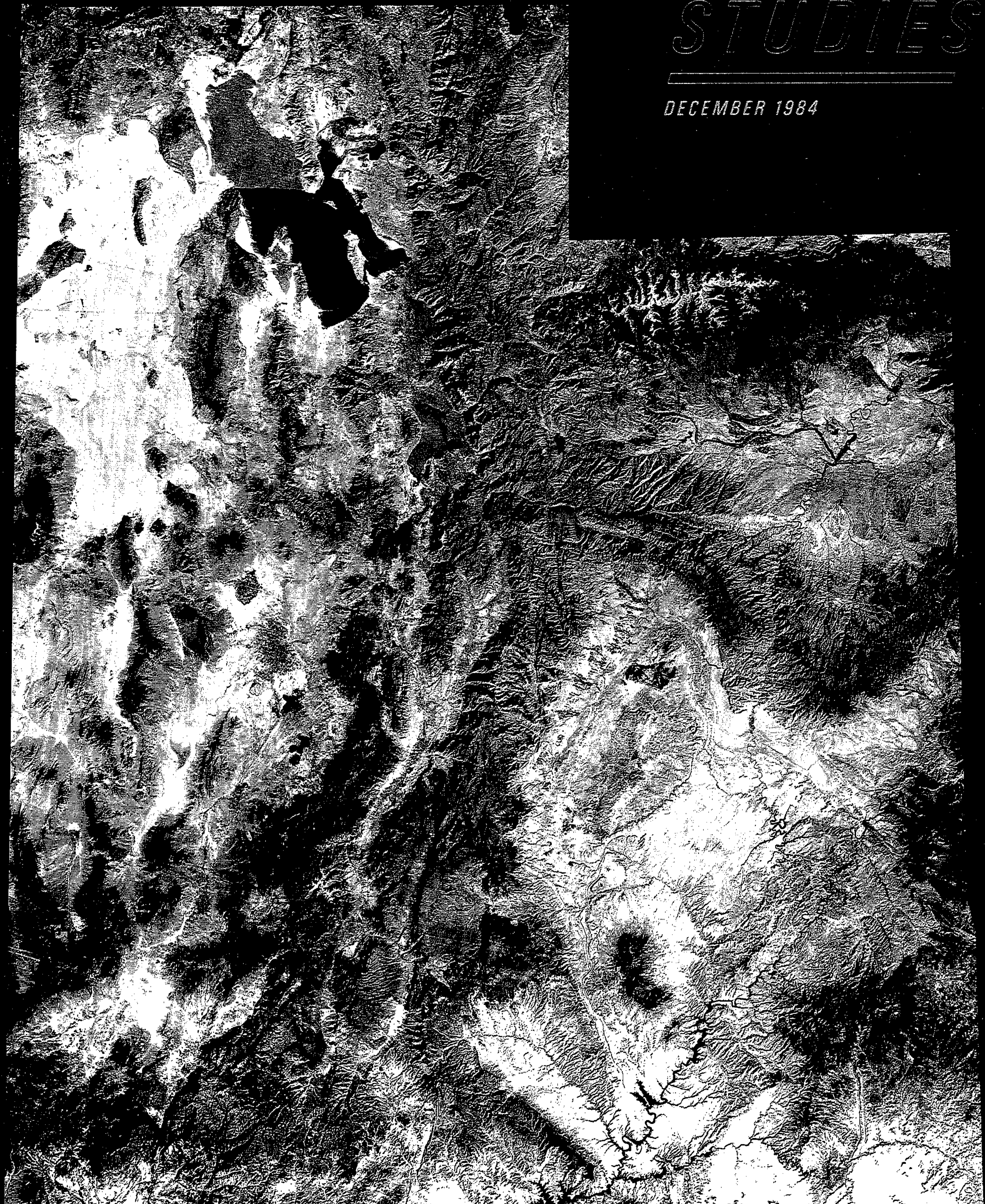
BRIGHAM YOUNG UNIVERSITY

GEOLOGY STUDIES

DECEMBER 1984



VOLUME 31, PART 1

BRIGHAM YOUNG UNIVERSITY GEOLOGY STUDIES

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CONTENTS

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Geology of the Mount Ellen Quadrangle, Henry Mountains, Garfield County, Utah*

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ABSTRACT

The Mount Ellen Quadrangle on the eastern flank of the Henry Mountains Basin includes Upper Jurassic and Cretaceous rocks that have been invaded and deformed by early Tertiary intrusions. Mapping of member subdivisions of the Morrison and Cedar Mountain Formations has clarified structural relationships near the laccolithic complex. Linear oblique normal faults display vertical displacements of up to 33 m over laccolithic intrusions. Low-angle reverse faults, and high-angle faults, both perpendicular to axes of intrusion, show displacements of up to 366 m and 274 m, respectively. The Pistol Ridge intrusion is now considered to be a bysmalith because of marginal faulting. Brittle deformation of country rocks suggests high rates of intrusion and minimal confining pressures at the time of emplacement. Available subsurface data confirm the presence of sill-like intrusions in the Triassic Chinle Formation at some distance from the probable source stock. The broad structural dome over the Mount Ellen complex may be a result of both a large magma chamber at depth and broad, multiple sill-like intrusions into Triassic and older formations.

Coal deposits of the Ferron Sandstone are limited to the southwestern part of the quadrangle. Coal occurs in a carbonaceous zone of 1–6 seams, each averaging 0.1–0.2 m (4–8 in) thick. Lenticularity of the coal is pronounced. Two directions of fault sets displace the coal, and dips of as much as 22° occur. Mining of the Ferron Sandstone coal is not economically feasible at present.

INTRODUCTION

It was in the Henry Mountains of southeastern Utah that Gilbert (1877) made his classical study of laccoliths. Seventy-five years later Hunt and others (1953) mapped the regional geology of the Henry Mountains but detailed mapping of member level units of Jurassic and Cretaceous strata has awaited this study (Morton in press). This study has identified a greater structural discordancy about the laccolithic complex than previously known and has predicted relationships of laccolithic intrusions at depth. Coal resources of the Ferron Sandstone have been studied and unconsolidated Quaternary deposits have been evaluated for their use as construction materials.

LOCATION AND ACCESSIBILITY

The Mount Ellen Quadrangle lies on the north end of the Henry Mountains. The highest point, Mount Ellen, stands 3,507 m above sea level and is 32 km southwest of Hanksville and 26 km east of Capitol Reef National Park (fig. 1).

Access to the quadrangle on improved dirt roads, shown on figure 1, is limited by weather conditions. Travel over the high passes in the quadrangle is not possible until early summer, after snow melt. Travel during the late summer months is commonly hampered by flash floods.

METHODS

Fieldwork was conducted from May through September of 1982. A Bausch and Lomb transfer scope was used to transfer field mapping on 1:31,680 aerial photographs to a 1:24,000 topographic base. Some structural attitudes have been added to my map, and contacts within the stock, shatter zone, and some of the shaly roof pendants

*A thesis submitted to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree of Master of Science, October 1983.

have been modified in the high areas, from a regional study by Hunt and others (1953, plate 7). Stratigraphic sections were measured with a Jacob's staff and Brunton compass. Eleven measured sections and ten channel samples of coal were made along the outcrop trace of the Ferron Sandstone. Coal samples were submitted to the Utah Geological and Mineral Survey for analysis.

ACKNOWLEDGMENTS

I appreciate the helpful advice and guidance of Dr. J. Keith Rigby, who served as thesis chairman, and Drs. L. F. Hintze and B. J. Kowallis, who served as committee members. Dr. M. Best assisted with the petrography. C. B. Hunt reviewed the geologic map (Morton in press). Thanks is also extended to the Utah Geological and Mineral Survey and the Exxon Company, USA, for financial support. Mr. C. W. Oliphant allowed use of facilities at King Ranch for a field base. Messrs. Golden and Keith Durfey shared their local expertise. My brothers, Jonathan and Dana, helped with the section measurement. Bill Whitlock and Curtis Smith provided welcome company during the field season. I give special thanks to my wife, Rachael, for constant support.

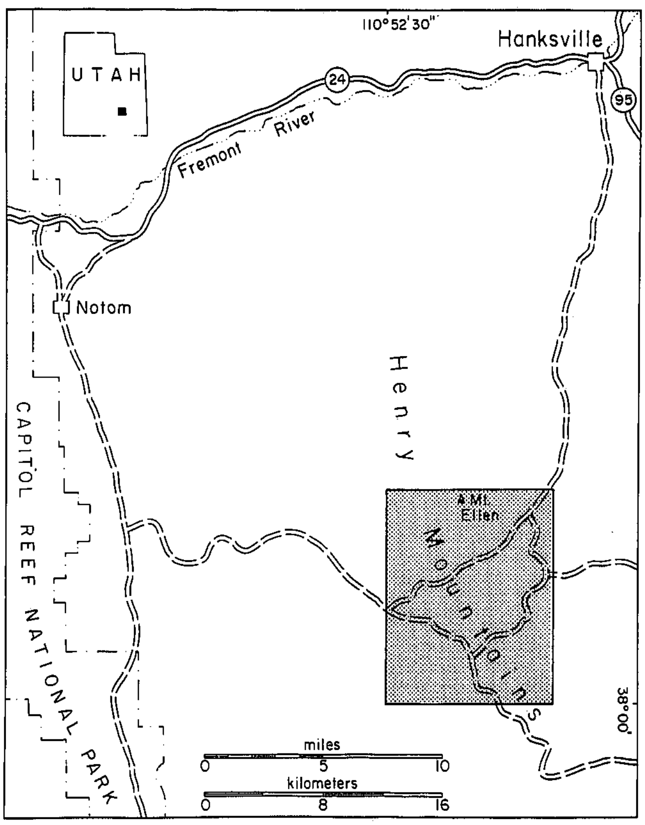

FIGURE 1.—*Index map of the Mount Ellen Quadrangle.*

PREVIOUS WORK

The Henry Mountains were first studied by Gilbert (1877), who described the intrusions and the general stratigraphy of the region. He proposed the concept of laccoliths on the basis of that study. Gilluly and Reeside (1928) named the Entrada, Curtis, and Summerville Formations from the San Rafael Swell, just north of the Henry Mountains Basin. Lupton (1914) named the Salt Wash Member of the Morrison Formation. Later Gregory (1938) named the Brushy Basin Member, but Craig (1955) first applied that terminology to the Morrison members in the Henry Mountains region. Stokes (1944) named the Cedar Mountain Formation, for Cretaceous rocks that had been included in the Morrison Formation.

Cross and Purington (1899) named the Mancos Shale, but Gilbert (1877) named the several shale and sandstone members in the Henry Mountains Basin. Later, Hunt (1946) renamed two of the members in the Henry Mountains Basin. Lessard (1973) conducted a regional micropaleontological and paleoecological study of the Tununk Shale. Maxfield (1976) studied the foraminiferal faunas of the entire Mancos Shale in five sections in eastern Utah, including one in the northern Henry Mountains Basin. Uresk (1979) and Hill (1982) studied the depositional environments of the Ferron Sandstone Member in the northern and western parts of the Henry Mountains Basin. Hill (1982) proposed the Notom delta to include Ferron Sandstone rocks of at least the western margin of the basin. Peterson and others (1980) described the depositional environments of the "Emery Sandstone," now termed the Muley Canyon Sandstone, and the Masuk Shale.

Doelling (1975) and Doelling and Graham (1972) described the coal deposits of the Dakota, Ferron, and Muley Canyon Sandstones. Law (1980) described the coals of the Muley Canyon Sandstone and their tectonic significance.

Hunt and others (1953) mapped and described the intrusions of the Henry Mountains. Armstrong (1969) later dated a laccolithic intrusion in the Henry Mountains. Johnson and Pollard (1973) described mechanics of the growth of some laccolithic intrusions in the Henry Mountains, and G. L. Hunt (in press) conducted an igneous petrology study of the Mt. Pennell stock, just south of the Mount Ellen complex. Hohl (1980) mapped the surficial deposits in the Bull Creek Basin, in the northeast corner of the quadrangle, on Mount Ellen.

STRATIGRAPHY

GENERAL STATEMENT

More than 1,200 m of Jurassic, Cretaceous, Tertiary, and Quaternary rocks are exposed in the Mount Ellen Quadrangle (fig. 2). Rocks of the Jurassic and Cretaceous

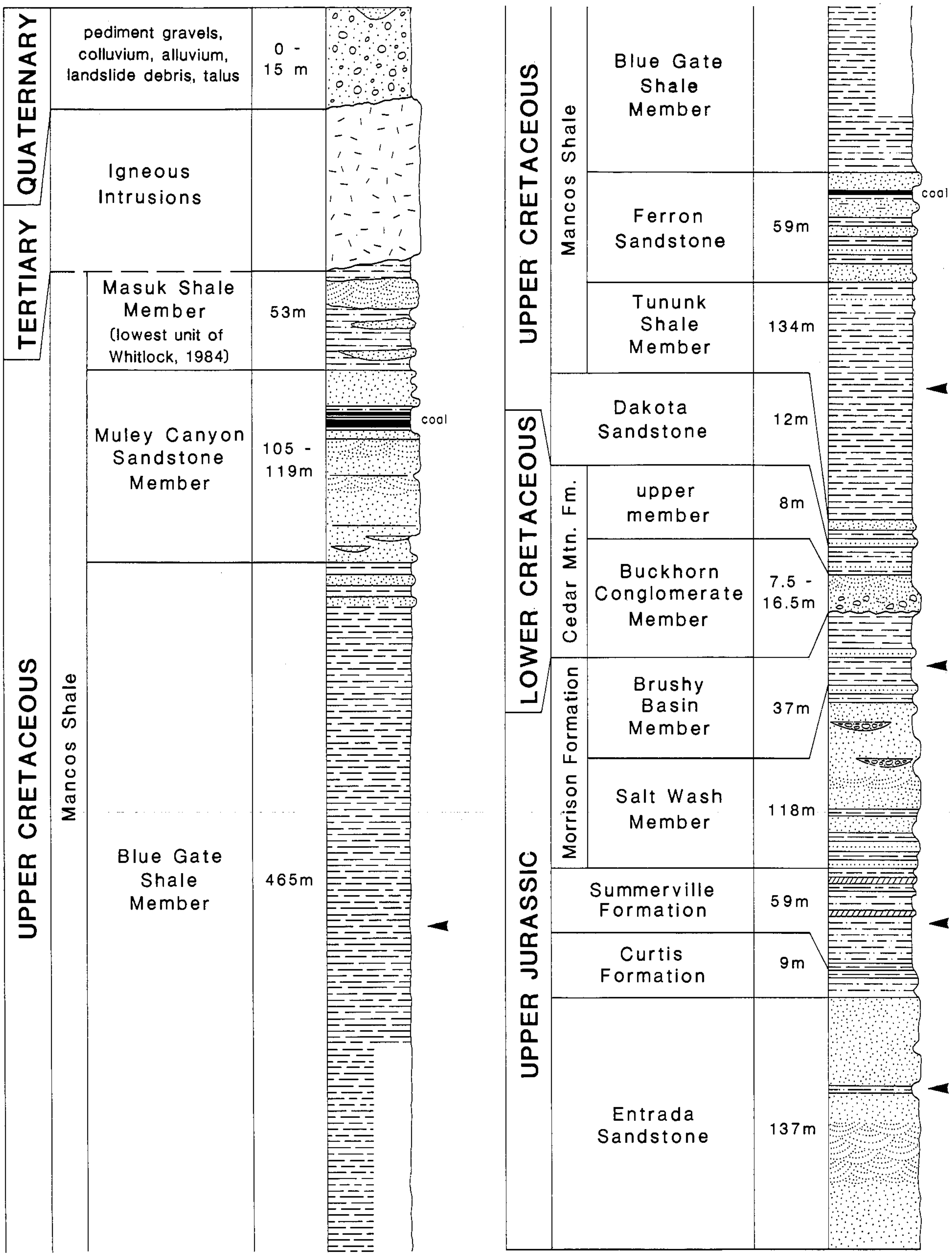

FIGURE 2.—*Stratigraphic column of rocks exposed in the quadrangle. Arrows indicate preferred levels of intrusion.*

systems have been upwarped and locally altered by Tertiary diorite porphyry intrusions (fig. 3). Unconsolidated Quaternary deposits are found throughout the quadrangle and consist of pediment gravels, colluvium, alluvium, landslide deposits, and talus.

JURASSIC SYSTEM

Entrada Sandstone

Hunt and others (1953, p. 70–72) reported that the Entrada Sandstone ranges from 91 m (300 ft), at the southern end of the San Rafael Swell, to 213 m (700 ft) in the southern end of the Henry Mountains. He also described a west-to-east facies variation. The western facies is a red, earthy, thin- to thick-bedded silty sandstone, and the eastern facies is a clean, massive, cliff-forming sandstone. Smith (1976, p. 140) interpreted units similar to Hunt's "earthy" facies as deposited in an interdeltaic-coastal environment.

The Entrada Sandstone is exposed in the northwestern corner of the quadrangle, where it has been ruptured by the Dugout Creek and Cedar Creek laccoliths. The best exposures, but the least accessible ones, are located in Slate Creek Canyon in the southeast corner of the map (fig. 3).

No complete section of Entrada Sandstone is exposed in the quadrangle. A partial section was measured south of Dugout Creek (fig. 3, and appendix, section 3). There the formation is a pale red to very pale orange, very fine grained sandstone with minor siltstone. The Entrada Sandstone is calcite cemented and contains minor gypsum. At this locality the formation is characteristic of Hunt's "earthy" facies. The exposed units are very thin to massively bedded. The formation weathers to ledges with minor slopes and low, resistant, rounded outcrops (fig. 4).

No fossils were found in the Entrada Sandstone. An Upper Jurassic age has been inferred by its stratigraphic position between the fossiliferous Carmel and Curtis Formations (Baker and others 1936, p. 58).

The basal contact of the formation is not exposed in the map area but is exposed in the quadrangle to the east. The upper contact with the greenish marine Curtis Formation is disconformable throughout most of the region (Hunt and others 1953, p. 71), although evidence of a disconformity was not seen in the locality where measured. This upper contact was mapped on a minor recessive zone that occurs at the boundary between the Entrada and Curtis Formations.

Curtis Formation

At the southern end of the San Rafael Swell the Curtis Formation is 53 m (175 ft) thick and thins southward to a depositional edge near the north side of Tarantula Mesa in the Steele Butte 7½-minute Quadrangle (Hunt and others 1953, p. 72). This same depositional wedgeout occurs, with an east-west trend, somewhere through the center of the study area. From exposures in the San Rafael Swell, Smith (1976, p. 154) interpreted the formation as being deposited in a shallow, warm, low-energy, marine environment.

Outcrops of Curtis beds are limited to the northwest corner of the quadrangle. The formation is 8.6 m of light greenish gray, glauconitic, calcareous siltstone with minor grayish purple shale, measured south of Dugout Creek (fig. 3, and appendix, section 2). It is thinly laminated to thinly bedded, and contains abundant oscillatory ripple marks. It forms a thin sharp ledge which contrasts with the thick rounded ledges of the underlying Entrada Sandstone, and the slopes of the overlying Summerville Formation (fig. 5).

Gilluly and Reeside (1928, p. 79) found marine fossils in the Curtis Formation in exposures in the San Rafael Swell. These date the unit as Middle Upper Jurassic age. The upper contact with the Summerville Formation is gradational and conformable.

Summerville Formation

Hunt and others (1953, p. 73) described the Summerville Formation in the Henry Mountains region as a reddish brown sandstone and shale with distinctive regular bedding. The formation thins in the Henry Mountains area from 76 m (250 ft) in the north, to 12 m (40 ft) near Halls Creek, approximately 30 km south of the quadrangle (Hunt and others 1953, p. 73). Petersen and Pack (1982, p. 21) interpreted the Summerville Formation on the east flank of the Teasdale Dome, some 25 km northeast of the map area, as being deposited in a broad, low-relief tidal-flat environment.

In the Mount Ellen Quadrangle the formation is best exposed in the northwest and southeast corners of the map area. Some of the best exposures are found in Slate Creek Canyon in the southeast corner of the quadrangle (fig. 3). Throughout the study area the formation is a frequent host for the Tertiary-age, diorite porphyry intrusions.

A complete section of the Summerville Formation was measured south of Dugout Creek (fig. 3, and appendix, section 2). At this locality the formation is 59 m of pale reddish brown to light brownish gray siltstone, mudstone, and shale interbedded with occasional hematitic gypsum. The clastic units in the formation contain abundant calcite as well as primary and secondary gypsum disseminated throughout.

Age of the Summerville Formation was determined by Gilluly and Reeside (1928, p. 80) to be Late Jurassic, on the basis of the formation's stratigraphic position above the fossiliferous Curtis Formation, and below the Morri-

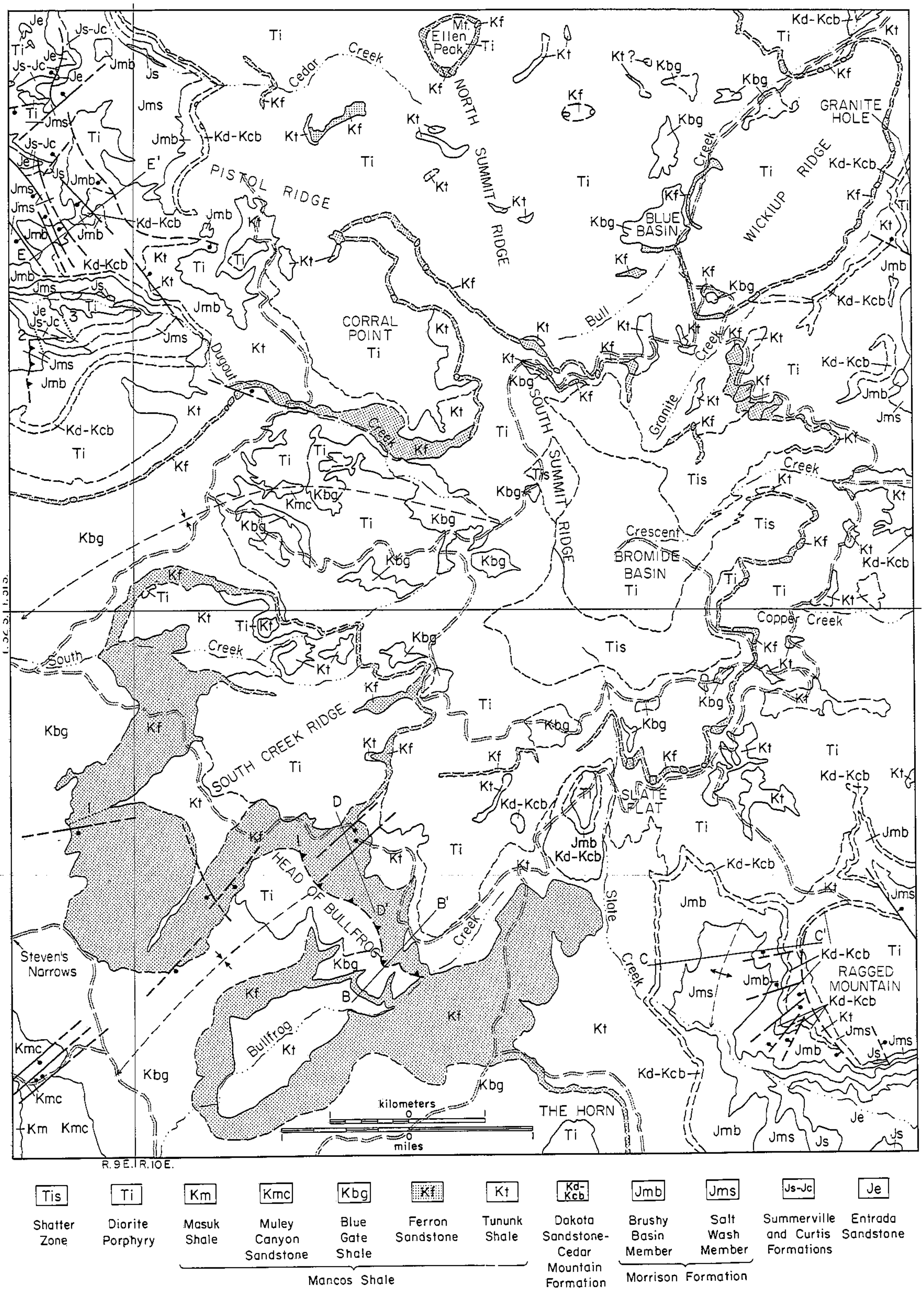

FIGURE 3.—*Bedrock geologic map of the Mount Ellen Quadrangle. Location of measured sections 1, 2, and 3, found in the appendix, indicated by dotted lines. Axes of plunging anticline and synclines inferred by series of arrows. Standard symbols used for faults.*

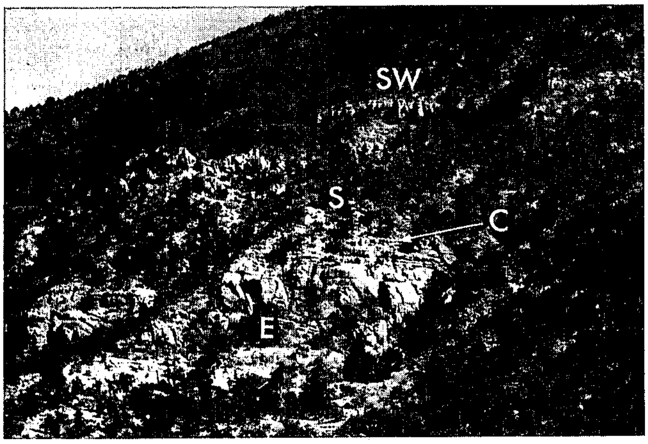

FIGURE 4.—*The Entrada (E), Curtis (C), Summerville (S) Formations, and Salt Wash Member (SW) of the Morrison Formation as viewed to the south on the north side of the Dugout Creek laccolith, a short distance east of measured section 2.*

son Formation. The basal contact with the Curtis Formation is gradational. The contact was mapped at the top of the ledge formed by the Curtis Formation (appendix, section 2, unit 4). A minor glauconitic siltstone, similar to those of the Curtis Formation appears 3.0 m from the basal contact of the Summerville Formation and may represent a "dying gasp" of the Curtis transgression (appendix, section 2, unit 7).

The upper contact with the Salt Wash Member of the Morrison Formation is a prominent disconformity in the northern Henry Mountains region but is reported to be less evident to the south (Hunt and others 1953, p. 73). A disconformable contact was not apparent in the measured section. The upper contact was mapped on top of a massive gypsum unit that forms a ledge.

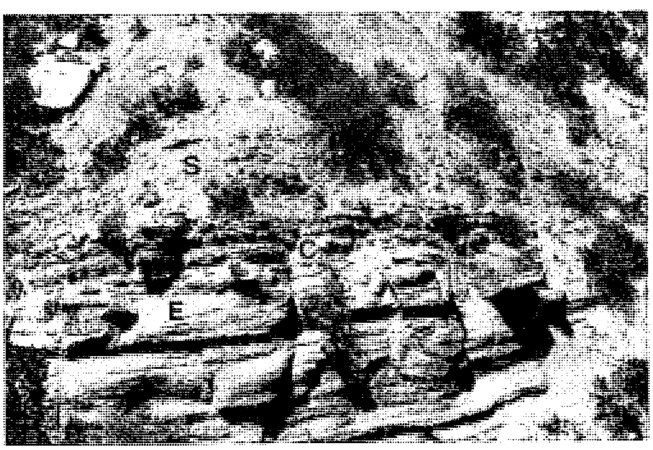

FIGURE 5.—*The Entrada (E), Curtis (C), and Summerville (S) Formations on the north side of the Dugout Creek laccolith. Location of measured section 2. View to the southwest.*

Morrison Formation

Baker and others (1936, p. 63) determined the age of the Morrison Formation as Upper Jurassic. Its depositional environment has been described by several authors (Baker and others 1936, p. 54; Craig 1955, p. 159–60; Stokes 1980, p. 120–21; and Petersen and Roylance 1982, p. 8–10) as one of fluvial and lacustrine sediments deposited on a broad, undissected plain, with frequent bentonitic clays derived from volcanic ash falls.

In the Henry Mountains region the Morrison Formation has been described as 152–183 m (500–600 ft) of conglomerate, sandstone, mudstone, shale, limestone, massive clay, and gypsum (Hunt and others 1953, p. 75–76). Hunt and others divided the formation into the lower Salt Wash Sandstone Member and an unnamed upper clayey member. This upper member had been previously defined elsewhere as the Brushy Basin Member (Gregory 1938, p. 59).

Salt Wash Member. Hunt and others reported that the Salt Wash Member in the Henry Mountains region is 46–145 m (150–475 ft) of lenticular claystone and shale with interfingering lenses of sandstone and conglomerate (1953, p. 75). Exposures in the Mount Ellen Quadrangle are best seen in the northwest and southeast and east central portions of the map area (fig. 3). In the northwest corner, west of Pistol Ridge, the Salt Wash Member has been disrupted by high-angle faults, creating seven sandstone cliffs, instead of the three seen in section 2, measured south of Dugout Creek (fig. 21). In the southeast corner of the quadrangle, south of Ragged Mountain, the Salt Wash Member is relatively undisturbed—the best exposure of the member in the map area.

West of Ragged Mountain the member has been folded into a southward-plunging anticline, which is likely a result of a laccolithic intrusion into the Summerville Formation at depth. South of Granite Hole the Salt Wash Member is the roof of a major laccolith and has been disrupted by a tear fault of substantial displacement. Throughout the quadrangle the Salt Wash Member is a frequent roof for the laccolithic complex.

A section measured south of Dugout Creek showed 118 m of very light gray to brownish gray sandstone and interbedded subordinate reddish and greenish bentonitic mudstone (fig. 3, and appendix, section 2). Sandstones of the upper 46 m are dominated by medium-grained to granular quartz sands; and in the lower part of the member fine to very fine quartz sands, with minor lenses of gravel, are predominant. This upward-coarsening trend in the member may be evidence for uplift of the source area, possibly caused by the eastward migration of Nevadian orogenic highlands. Rip-up clasts of greenish claystone are common throughout sandstones in the member. Both sandstones and mudstones contain minor calcite and iron oxide. The Salt Wash Member contains cliff-forming, thick-bedded to massive sandstones and laminated to thin-bedded sandstones, siltstones, and mudstones that form minor ledges and prominent slopes. Lenses of cross-bedded, gritty to pebbly sandstone occur in the massive cliff-forming units. The Salt Wash Member expresses itself as a series of cliffs and slopes. Approximately 40 m from the basal contact (appendix, section 2, unit 35), a lens of loose sand was encountered and sampled. The sample was searched by Dr. J. K. Rigby, Jr., of the University of Notre Dame, for mammal teeth. None were found although reptile teeth and turtle shell fragments occur.

Hunt and others described a distinct disconformity along the member's basal contact with the Summerville Formation, at several localities in the Henry Mountains region (1953, p. 75). However, no such disconformity was observed in the measured section.

Brushy Basin Member. Hunt and others (1953, p. 75–76, and plate 4) described this upper clayey member of the Morrison Formation as 38–114 m (125–374 ft) of section divided into two units; a lower variegated clay and an upper gray clay. Craig (1955, p. 155–56, fig. 29) included these clay units in the Brushy Basin Member in the Henry Mountains area.

The member is exposed in the northwest, southeast, and east central portions of the map area (fig. 3). In the northwest corner of the quadrangle the Brushy Basin Member has been deformed by intense folding and faulting caused by the Dugout Creek and Cedar Creek laccoliths and the Pistol Ridge bysmalith (fig. 6). West of Slate Flat the member is a host for a minor laccolith. In the southeast corner of the quadrangle the Brushy Basin Member has been folded and faulted by the Ragged Mountain bysmalith. The latter are the best but least accessible exposures of the member in the quadrangle. At Granite Hole the member is host for a major laccolith. The Brushy Basin Member is a frequent host for the Tertiary-age diorite porphyry laccoliths.

A section of the Brushy Basin Member was measured in the quadrangle to the west, in NE ¼, section 23, T. 31 S, R. 9 E (Whitlock 1984, appendix). There the member is 37 m of moderate red and pale greenish yellow mudstones and claystones. Minor, thin lenses of very fine grained sandstones and siltstones are present. The member is laminated to thinly bedded and has a high bentonitic clay content. The lower 15 m of the member is dominated by the moderate red mudstones, while the upper 22 m is predominantly pale greenish yellow mudstone. In this upper unit, approximately 17 m from the upper contact, a thin-bedded, very fine grained, pyritic, quartzose sandstone occurs. This and the overall color of the upper unit indicate a change in the paleoenvironment to one of a reducing nature.

The contact with the underlying Salt Wash Member is sharp, undulatory, and apparently conformable. This boundary was mapped at the break in slope formed by the rounded slopes of the Brushy Basin Member and the cliffs of the Salt Wash Member.

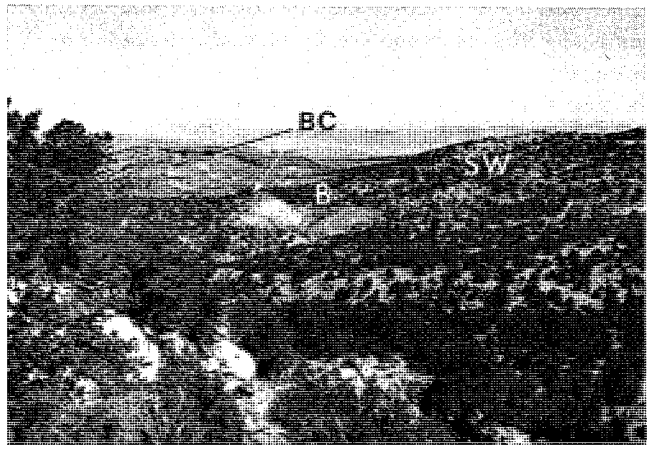

FIGURE 6.—*Salt Wash (SW) and Brushy Basin (B) Members of the Morrison Formation, and the Buckhorn Conglomerate (BC), west of the Pistol Ridge bysmalith. View to the northwest.*

CRETACEOUS SYSTEM

Cedar Mountain Formation

The Cedar Mountain Formation consists of two members: the Buckhorn Conglomerate, and an upper, unnamed shale member.

Buckhorn Conglomerate Member. Stokes (1944, p. 976–78) suggested that the Buckhorn Conglomerate Member was a pediment deposit, resulting from fluvial and eolian processes. Peterson and others (1980, p. 152), described the member as up to 22 m (73 ft) of cliff-forming conglomerate and conglomeratic sandstone. A diagnostic feature of the member is the presence of light gray to white quartzite pebbles.

Outcrops of the member in the Mount Ellen Quadrangle are small and rather isolated. They occur in three general localities: (1) west and north of Ragged Mountain, (2) southeast and north of Wickiup Ridge, and (3) west and southwest of Pistol Ridge. These outcrops are associated with those of the Jurassic system. The best exposures in the quadrangle occur between Slate Creek and Ragged Mountain, but the most accessible nearby exposures are found in the Steele Butte Quadrangle to the west.

A section of the member measured 0.3 km north of the road in SE ¼, NE ¼, section 23, T. 13 S, R. 9 E (Whitlock 1984, appendix) showed 16.5 m of brownish gray to yellowish brown sandstone and conglomerate. Sandstone occurs mainly in the upper 7.5 m of the section and is a thin-bedded, fine-grained, calcite-cemented, quartzose sandstone. This unit contains abundant iron oxide and is cross-laminated. The conglomerate, found in the lower 9.0 m of the section, is massively bedded and forms a cliff above the slopes of the Brushy Basin Member of the Morrison Formation (fig. 6). It is composed of chert and light gray quartzite pebbles in a medium-grained quartz sand matrix. The pebbles range from 3 to 85 mm in diameter but average 15–20 mm across. Minor lenses of medium-grained, calcareous, quartzose sandstone are present in the conglomerate (fig. 7).

Thickness and composition of the Buckhorn Conglomerate Member are extremely variable. A second section measured approximately 100 m to the southeast of that described above includes 7.5 m of very thin to laminated, fine-grained, calcareous, quartzose sandstone, with frequent hematitic horizons, that is equivalent to the conglomerate. Such variation may be attributed to a paleochannel running northeast–southwest, filled with a pebble lag gravel; and thin-bedded, finer-grained sandstones on either side represent ancient levee deposits.

Fossils are rare in the Buckhorn Conglomerate Member, and none were found in this study. Age of the formation is probably lower Albian (Peterson and others 1980, p. 152).

Throughout this part of the Colorado Plateau a disconformity is present at the base of the Buckhorn Conglomerate (Stokes 1944, p. 976), where channels have cut into the Brushy Basin Member. Contact with the overlying, upper unnamed shale member appears conformable.

Upper Unnamed Shale Member. Peterson and others (1980, p. 153) listed the depositional environments of the upper unnamed shale member as natural levee, flood-basin, and crevasse-splay deposits. Their conclusions were based on the lithology and stratigraphic position between fluvial sandstones. They described the member as up to 41 m (133 ft) of laminated to thin gray and greenish gray mudstone and shale, with some beds that are purple, brown, and red.

Exposures of this member are found in the same localities as the Buckhorn Conglomerate. The most accessible outcrops are found in the Steele Butte Quadrangle to the west.

A section measured 0.3 km north of the road in the SW ¼, NE ¼, section 23, T. 31 S, R. 9 E (Whitlock 1984, appendix) showed 8.0 m of interbedded, light gray to brownish gray carbonaceous shale and siltstone with minor laminated, fine-grained, quartzose sandstone. Carbonaceous shale in the lower 3.5 m is silty, and iron sulfate is found along bedding planes. The fine-grained sandstone is restricted to this same interval. The upper 4.5 m of the member is mainly a carbonaceous shale. Macerated wood and plant fragments were common. This upper unit also

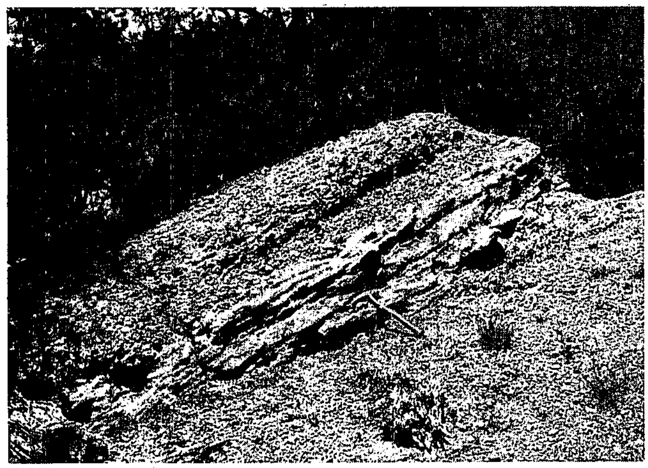

FIGURE 7.—*Upper part of Buckhorn Conglomerate 1 km west of the Pistol Ridge bysmalith in the SE ¼ of section 23, T. 31 S, R. 9 E. Note the coarse pebble gravel.*

shows a coarsening-upward sequence, for the section becomes predominantly a calcareous siltstone near the upper contact with the Dakota Sandstone. The entire member is thinly laminated to laminated and forms a slope.

Fossils have been collected at several localities in the upper unnamed member (Peterson and others 1980, p. 152, 153) although none were found in the measured section. Age of the member has been discussed by Peterson and others (1980, p. 152) and is considered to be middle to late Albian. The upper contact of this member with the Dakota Sandstone is reported to be disconformable in other areas (Peterson and others 1980, p. 153); however, no unconformity was observed in the measured section and nearby areas in the quadrangle.

Dakota Sandstone

Peterson and others (1980, p. 153) concluded that the Dakota Sandstone is separated by an unconformity from the Cedar Mountain Formation. Lawyer (1972) found, in a paleoenvironmental study of the Dakota Sandstone west of Hanksville, Utah, that the formation consists of a lower transgressive sequence of fluvial deposits, overlain by beach and shallow-marine deposits. In the Henry Mountains region the formation is interbedded gray sandstone, carbonaceous mudstone, and coal (Peterson and others 1980, p. 153–54). The Dakota Sandstone averages 11 m (35 ft) thick but ranges to as much as 28 m (Peterson and others 1980, p. 153). Hunt and others (1953, p. 78, fig. 19) noted the variable lithology and thickness of the Dakota Sandstone in the Henry Mountains area.

Exposures of the Dakota Sandstone are found in the same localities as the two members of the Cedar Mountain Formation. The Dakota Sandstone generally forms a minor ledge. The most accessible exposures are found in the quadrangle to the west, where a section was measured.

A complete section is exposed in the N ½ of section 23, T. 31 S, R. 9 E, 0.5 km west of exposures in the northwest part of the quadrangle (Whitlock 1984, appendix). In this locality the Dakota Sandstone is more than 12 m of pale orange to grayish yellow calcareous sandstone, with minor interbeds of siltstone in the lower 4.5 m. The sandstone is composed of very fine to medium-grained quartz sand, with minor kaolinite matrix and iron oxide cement. *Gryphaea* and *Ostrea* are abundant throughout the formation. Layers of *Ostrea* oriented parallel to bedding occur 0.8 and 4.5 m from the base. The uppermost 0.7 m of the formation includes up to 50%, by volume, of *Gryphaea* in the sandstone. The formation is thinly laminated to thin bedded, but bedding is commonly strongly bioturbated.

Peterson and others (1980, p. 154) reported that fossils found in the upper part of the Dakota Sandstone in the Henry Mountains area indicate that the formation is of late Cenomanian age. Upper contact of the formation with the overlying Tununk Shale Member of the Mancos Shale is sharp and conformable.

Mancos Shale

Gilbert (1877) divided the Mancos Shale into five members, in ascending order: Tununk Shale, Tununk Sandstone, Blue Gate Shale, Blue Gate Sandstone, and the Masuk Shale for exposures on the west flank of the Henry Mountains. Hunt (1946, p. 8) renamed the Tununk and Blue Gate Sandstones, the Ferron and Emery Sandstones, respectively, for exposures of similar beds on the Wasatch Plateau. On the basis of paleontological studies, Maxfield (1976) and Peterson and others (1980) both suggested that the members of the Mancos Shale in the Henry Mountains area are not entirely correlative with those of the Wasatch Plateau. The latter study indicated that both the Masuk Shale and Emery Sandstone of the Wasatch Plateau correlate with the Blue Gate Shale of the Henry Mountains region. As a result Smith (1983) renamed the "Emery Sandstone" of the Henry Mountains area the Muley Canyon Sandstone. The Masuk Shale Member retains its name since the type locality is in the Henry Mountains region.

Tununk Shale Member. Hunt and others (1953, p. 79–80) described the Tununk Shale Member in the Henry Mountains Region as 160–98 m (525–650 ft) of dark gray, fissile shale with minor bentonite and shaly sandstone. Lessard's (1973) micropaleontologic and paleoecologic study suggested that the Tununk Shale was deposited in shallow- to open-marine conditions. Peterson and others (1980, p. 155) described the member in the Henry Mountains area as 162–219 m (532–717 ft) of medium to dark gray bentonitic shale.

The Tununk Shale is widely exposed across the quadrangle and is a common host for Tertiary laccoliths. Outcrops are commonly roof pendants or exposures immediately adjacent to the intrusions. Where not involved in the laccolithic complex, the member weathers to incompetent slopes with frequent landslides and mudflows.

A section measured in the Steele Butte Quadrangle in sections 23, 14, and 15, T. 31 S, R. 9 E found Tununk beds to be 134 m thick. There and across the Mount Ellen Quadrangle, the member is medium bluish gray, thinly laminated to laminated, silty shale with minor thinly bedded yellowish orange, very fine grained, quartzose sandstone. The shale is calcareous and gypsiferous. Bentonite is a common constituent of the shale and causes the member to weather with a "popcorn" surface texture and badland topography. Septarian and melikarian nodules were frequently found in the upper 20 m of the member, some as large as 60 cm in diameter. This section appears thin compared to those measured by other authors. This discrepancy may be related to errors in section measurement because of pediment gravel cover.

Peterson and others (1980, p. 155) reported that fossils from the member in the Henry Mountains region indicate late Cenomanian to middle Turonian age. The contact with the overlying Ferron Sandstone Member is gradational and was mapped at a break in slope between the cliff-forming Ferron Sandstone and the slope of the Tununk Shale.

Ferron Sandstone Member. In the Henry Mountains region the Ferron Sandstone can be divided into three units (Hunt and others 1953, p. 83); a lower unit of interbedded sandstone and shale, a middle unit of massive sandstone, and an upper unit of lenticular carbonaceous shale, coal, and sandstone. Hunt and others (1953, p. 80) reported that the member is 91 m (300 ft) thick along the western edge of the basin and thins eastward to 46 m (150 ft) in the middle of the basin.

The Ferron Sandstone has been the focus of many studies in central Utah (Katich 1954, Hale 1972, Cotter 1975, Ryer 1981). Uresk (1979) and Hill (1982) studied the member on the flanks of the Henry Mountains Basin and concluded that the Ferron Sandstone was deposited by fluvial and deltaic processes. Peterson and others (1980, p. 155–59) subdivided the member into two units based on lithology and depositional environments: a lower unit of regressive near-shore marine and shoreline deposits and an upper unit deposited in a predominantly fluvial environment.

The Ferron Sandstone is widely exposed in bits and pieces in much of the quadrangle, but is best exposed in the southwest corner of the map area between South Creek and The Horn. It is a frequent roof for the laccoliths and in some localities has undergone extensive folding and faulting (fig. 8).

A measured section of Ferron Sandstone west of South Creek Ridge (fig. 3) shows 59 m of strata and consists of three units: a lower 14.7-m unit of interbedded sandstone, siltstone, and shale; a middle unit of 16.5 m of massive, cliff-forming, calcareous sandstone; and an upper unit of 16.1 m of interbedded carbonaceous shale, coal, and minor sandstone all capped by a calcareous, hematitic, fine-grained sandstone 2.5 m thick (appendix, section 1).

The lower unit is characterized by a coarsening-upward sequence, with siltstone interbeds confined to the lower part of the unit. Both siltstones and sandstones are very thin bedded, grayish orange, calcareous, and kaolinitic. Shale interbeds resemble those of the Tununk Shale. Trough cross-sets, climbing ripple marks, hummocky stratification; and ball-and-pillow structures are common (fig. 9).

The middle unit consists of a grayish orange, fine- to medium-grained, quartzose sandstone, with minor coaly and carbonaceous horizons. Cross-bed sets are common throughout, with platy, hematitic, laminations in the upper part of the unit. Petrified wood was found in this middle unit between Bullfrog Creek and Steven's Narrows in the NW ¼ of section 19, T. 32 S, R. 10 E.

The upper unit is dominated by coal and carbonaceous shale. Coals are described in greater detail in the section on economic geology later in this report. The carbonaceous interval is approximately 16 m thick and is interrupted twice by an olive gray shale of possible marine origin. The upper 2.5 m of this unit is a light gray, thin-bedded, fine-grained, quartzose sandstone with common hematitic concretions. This sandstone shows a coarsening-upward sequence and is gritty in the upper few centimeters. Northeast of Steven's Narrows, in the SE ¼ of section 12, T. 32 S, R. 9 E, pyritic concretions occur in this uppermost sandstone. These concretions are of the same size and texture as the hematitic concretions seen in the measured section and may be a product of hydrocarbon bleaching. Lower and middle units mentioned above correspond to the lower unit described by Peterson and others (1980, p. 155–59). Fossils indicate the member is middle to upper Turonian (Peterson and others 1980, p. 153, 157).

Hunt and others (1953, p. 83) reported that a disconformity is common at the contact with the overlying Blue Gate Shale. A conglomeratic sandstone at this upper contact in a section measured northeast of Steven's Narrows in the SE ¼ of section 12, T. 32 S, R. 9 E (Smith 1984, appendix, unit 1 of Blue Gate Shale) may well represent the disconformity described by Hunt and others. This conglomeratic sandstone contains approximately 10% subangular chert and quartz pebbles of 6–12 mm in diameter, 15% angular quartz granules, and is calcareous and well indurated. Peterson and others (1980, p. 159) suggested that this unconformity represents most of late Turonian and all of Coniacian time on the basis of the absence of six ammonoid faunal zones.

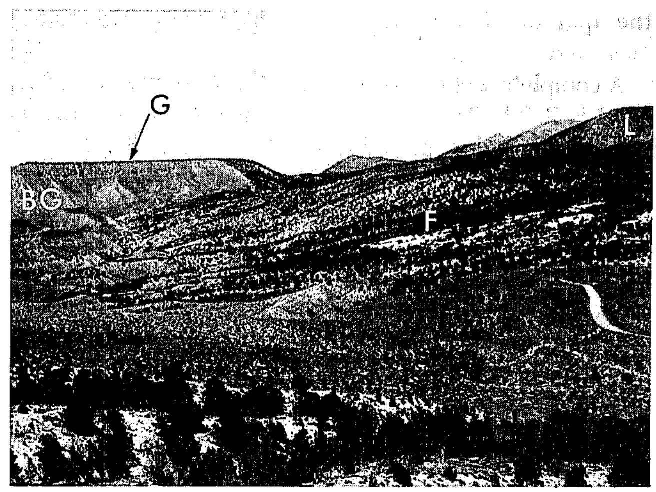

FIGURE 8.—*Ferron Sandstone (F) and the Blue Gate Shale (BG) in front of the South Creek laccolith (L) east of Steven's Narrows. Note the monoclinal flexure of Ferron Sandstone, possibly caused by an intrusion at depth. Beheaded pediments (G) on the left form an angular unconformity with the Blue Gate Shale.*

Blue Gate Shale Member. Hunt and others (1953, p. 83) described the Blue Gate Shale as 427 m (1,400 ft) of dark gray shale, subdivided into two units: a lower unit of homogenous shale, comprising two-thirds of the member, and an upper unit of interbedded shale and platy sandstone. Peterson and others (1980, p. 159) suggested that the member was deposited in normal marine waters 60–120 m (200–400 ft) deep.

The Blue Gate Shale forms strike valleys in the lower elevations along two belts: (1) from Bullfrog Creek across Steven's Narrows to South Creek, and (2) in the Blue Basin-Bull Creek area. In the higher areas of the quadrangle the member is a common host and is often exposed as roof pendants of the laccolithic complex, for example the outcrops west of South Summit Ridge.

A section measured northeast of Steven's Narrows in sections 12 and 14, T. 31 S, R. 9 E (Smith 1984, appendix), found 465 m of medium bluish gray to olive gray, calcareous, gypsiferous shale with minor interbeds of siltstone and very fine grained, calcareous, quartzose sandstone. Thickness of this section may be anomalously high because of difficulty in measurement and evaluation due to pediment gravel cover.

The lower 33 m is mainly a dark gray, calcareous shale that is very similar in appearance to the Tununk Shale Member. This resemblance makes for some difficulty in

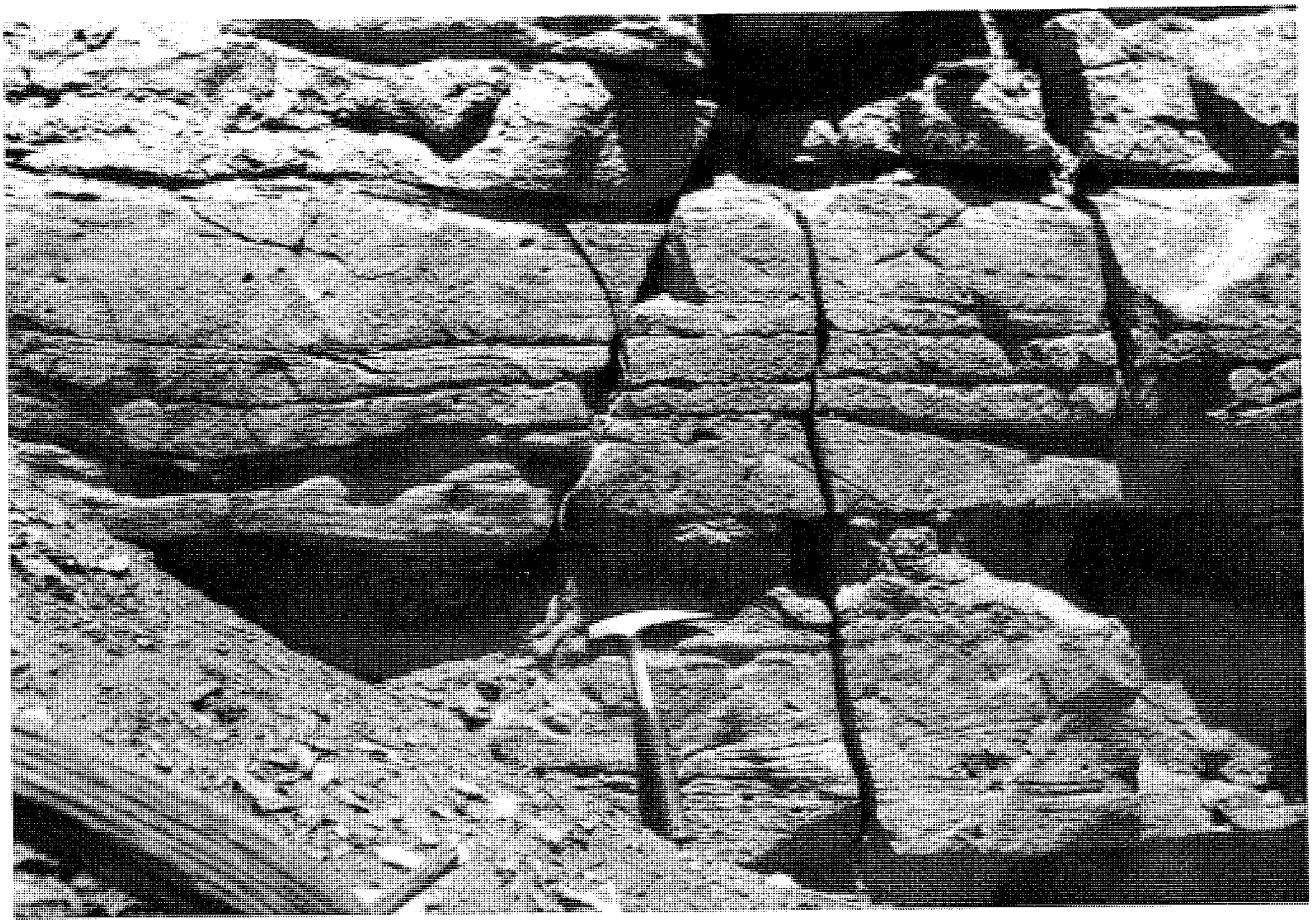

FIGURE 9.—*Hummocky stratification in the lower Ferron Sandstone, approximately 1 km north of The Horn.*

identifying the stratigraphic position of shaly roof pendants involved in the laccolithic complex. Higher in the section the shale is bentonitic and produces "popcorn"-textured soils and bandland topography. Minor interbeds of siltstone and sandstone generally form rounded shoulders, and gypsiferous shales produce thick, soft soils.

The upper 52 m of Blue Gate Shale is interbedded yellowish gray, very thin bedded to laminated, very fine grained, calcareous, quartzose sandstone and medium gray, gypsiferous shale. The sandstone produces steeper slopes and contains macerated plant and wood fragments, ripple marks and cross-beds. Shale of this upper level is bentonite poor and highly gypsiferous with selenite crystals a common constituent on weathered surfaces.

Faunas from the Blue Gate Shale in other areas (Peterson and others 1980, p. 159) indicate lower Santonian to lower Campanian age. The upper contact with the Muley Canyon Sandstone Member is gradational and was mapped at a break in slope at the base of the Muley Canyon Sandstone cliff.

Muley Canyon Sandstone Member. Hunt and others (1953, p. 84–85, 216–17) described the member in the Henry Mountains region as 76 m (250 ft) of sandstone, shale, and coal. Doelling and Graham (1972) and Doelling (1975) divided the member into three units: a lower unit of thick-bedded sandstone with minor shale; a middle cliff-forming sandstone unit; and an upper unit of coal and carbonaceous shale overlain by resistant sandstone.

Peterson and others (1980, p. 161) described the member as 91–136 m (298–446 ft) of sandstone, mudstone, and coal. They subdivided the member into two units: lower cliff-forming sandstone, and upper interbedded sandstone, mudstone, shale, and coal. Law (1980) divided the member into two units on the basis of lithology and depositional environments: a lower regressive, marginal-marine sandstone and an upper fluvial and tidally deposited sandstone, siltstone, carbonaceous mudstone, shale, and coal. These units correspond to those of Peterson and others (1980). The Muley Canyon Member occurs south of Steven's Narrows, where it forms a prominent cuesta.

The Muley Canyon Sandstone Member in the quadrangle is approximately 108 m thick and is similar to outcrops described by Whitlock (1984) in the Steven's Narrows area. Muley Canyon coals in the quadrangle south of

Steven's Narrows are discontinuous and the upper sandstone unit less massive.

Fossils found thus far in the member are not diagnostic of age. Peterson and others (1980, p. 159–62) concluded that rocks included here in the Muley Canyon Sandstone Member are early Campanian, on the basis of regional correlations and relationships to the overlying fossiliferous Masuk Shale.

The contact of Muley Canyon Sandstone with the overlying Masuk Shale is conformable and gradational. This upper boundary has been placed at different stratigraphic levels in different studies (Hunt and others 1953, Doelling and Graham 1972, Peterson and others 1980, Law 1980). I placed the contact at the top of a continuous sandstone that overlies the middle carbonaceous unit of Whitlock (1984), following his usage. Above this contact carbonaceous mudstone and shale interfinger with abundant but discontinuous sandstone lenses.

Masuk Shale Member. Hunt and others (1953, p. 85) described the Masuk Shale Member in the Henry Mountains region as 183–244 m (600–800 ft) of irregularly bedded sandy gray shale, sandy carbonaceous shale, and sandstone. Those thicknesses are greater than reported by subsequent authors because of differences in placement of the lower contact. Peterson and others (1980, p. 162) described the member as 183–201 m (601–660 ft) thick and placed the lower contact of the Masuk Shale stratigraphically higher than Hunt.

Exposures of Masuk Shale are limited in the quadrangle and occur only south of Steven's Narrows. Smith (1983) and Whitlock (1984) mapped subdivisions of the member in adjacent quadrangles. No such subdivisions were mapped here because only a part of the lowest unit is exposed in the quadrangle. In the quadrangle to the west, Whitlock (1984) separated three units, the lowest of which is partly exposed in the Mount Ellen Quadrangle and is similar to outcrops he described near Steele Butte, 3.5 km west of the quadrangle in sections 28 and 33, T. 31 S, R. 9 E.

Peterson and others (1980, p. 162) reported collections of gastropods, pelecypods, garpike scales, turtle shell fragments, and crocodilian teeth, which indicate a fresh- to brackish-water environment. Pollen collected from the overlying Tarantula Mesa Sandstone (Peterson and others 1980, p. 162) indicate an early to early late Campanian age for the Masuk Shale Member. The upper contact of the Masuk Shale-1 unit of Whitlock (1984) is gradational, placed along a horizon above which shales dominate over sandstones.

TERTIARY SYSTEM

Tertiary igneous intrusions and breccias are the most widespread rocks in the quadrangle. Diorite porphyry comprises both the Mount Ellen stock and its associated laccoliths. A shatter zone caused by and found at the periphery of the stock consists of a mixture of fragmented sedimentary rocks and diorite porphyry.

Diorite Porphyry

Hunt and others (1953, p. 152) described the diorite porphyry as light gray, uniformly speckled with abundant large white phenocrysts of feldspar 2–6 mm in diameter, and small inconspicuous phenocrysts of hornblende. Composition of a typical sample of diorite porphyry consists of 30% oligoclase, 15% hornblende, 5% magnetite, 4% apatite and titanite, and a 50% aphanitic groundmass which consists of predominantly quartz, orthoclase, and albite or oligoclase (Hunt and others 1953, p. 152; fig. 10). A quartz-bearing diorite porphyry has also been reported in the central and southeastern portions of the stock (Hunt and others 1953, p. 93), but relative ages of the diorite or quartz-bearing diorite porphyries have not been established. K/Ar dating of samples of hornblende from a laccolith in the Henry Mountains yielded dates of 48 and 44 m.y., respectively (Armstrong 1969, p. 2084).

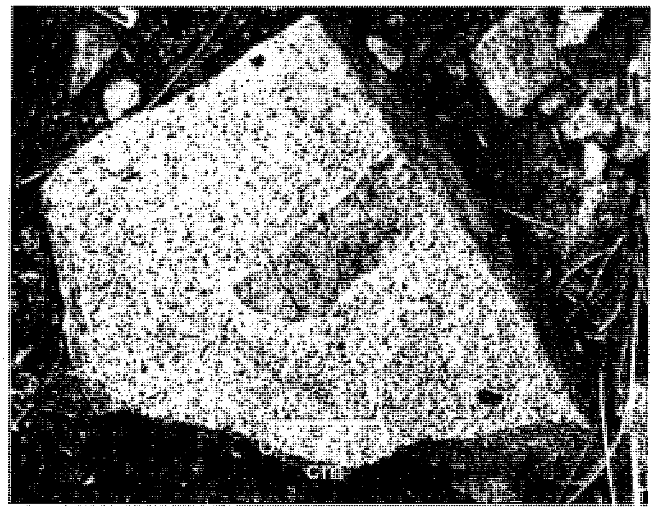

FIGURE 10.—*A quartzite xenolith in hornblende speckled diorite porphyry, south of Kimble-Turner Peak. Note sharp contact and lack of reaction rim.*

Hornblendite inclusions are common in the intrusive masses in the quadrangle, constitute approximately 1–2% of the igneous rocks, are generally coarsely crystalline and angular, have sharp boundaries with the intrusive (Hunt and others 1953, p. 160), and are believed to be relicts of a Precambrian basement complex at depth (G. Hunt personal communication 1983).

The diorite porphyry forms high ridges and peaks in the quadrangle. Diorite porphyry talus slopes on the flanks of intrusions make it difficult to distinguish outcrop from weathered debris. I considered the prominent ridges to be composed of predominantly in-place diorite porphyry with distal wedges of transported debris around their edges. Map contacts representing this relationship are shown with dashed lines (Morton in press).

Weathered outcrops of diorite porphyry display a variety of colors, ranging from red (iron oxide) to dark brown (desert varnish) to lighter shades of gray. The behavior of porphyry weathering is as unpredictable as the weathered color. In many areas the groundmass weathers first leaving a granular soil of phenocrysts; elsewhere the phenocrysts weather first. One thing is consistent about the porphyry: it produces a bumpy road.

A minor laccolith with an anomalous aureole of contact metamorphism, hosted by the Brushy Basin Member of the Morrison Formation, was mapped west of Slate Flat. Alteration of the country rock, though not intense, is of a greater magnitude than any seen elsewhere in the complex. The baked zone is 2–3 m wide instead of only a few centimeters. Samples of the diorite porphyry contain abundant phenocrysts that were determined to be plagioclase partially altered to sericite like other examples reported by Hunt and others (1953, p. 93). Embayed and rounded quartz phenocrysts and secondary calcite also occur in the same sample.

The extraordinary aureole of thermal alteration around this body may be related to geometry. The intrusion in question has arched the overlying members of the Cedar Mountain Formation and the Dakota Sandstone. Approximately 300 m north of the laccolith another intrusion has invaded the Tununk and Blue Gate Shales. These two intrusions may have "sandwiched" the Lower Cretaceous formations between them, increasing the amount of heat to which the sedimentary rocks were exposed and thus increasing the intensity of metamorphism.

Shatter Zone

A shatter zone caused by the Mount Ellen stock consists of a mixture of fragmented sedimentary rocks and diorite porphyry. The zone of brecciation occurs at the stock's periphery and is as wide as 1,067 m. Hunt and others (1953, p. 93) reported that the zone is predominantly diorite porphyry toward the stock and grades radially to a zone of predominantly sedimentary rocks. Thin basaltic sills and small irregular basaltic intrusions are associated with the diorite porphyry in the shatter zone and are apparently secondary (Hunt 1953, p. 152). Individual masses of sedimentary rocks are baked and irregularly oriented. Stratigraphic displacement of these sedimentary masses is not great (Hunt and others 1953, p. 93). The structure of the shatter zone is complex and was given only cursory attention in this study.

QUATERNARY SYSTEM

Five types of unconsolidated accumulations of Quaternary age have been mapped in the quadrangle (Morton in press). They are pediment gravels, colluvium, alluvium, landslide debris, and talus.

Pediment Gravels

Two distinct episodes of deposition of pediment gravels were distinguished in the quadrangle. The oldest pediment gravels, Qg-1, were deposited on surfaces that are only gently sloping, inclined away from the Mount Ellen complex. These older pediment-veneering gravels are found at relatively higher elevations than the younger series and have been dissected and beheaded by subsequent erosion (fig. 8).

Exposures of the older gravels are located west of Birch Spring and southeast of Steven's Narrows. These gravels consist of cobbles and boulders of diorite porphyry from the Mount Ellen complex that are somewhat rounded, and occur in a matrix of very fine to fine-grained, light brown sand (fig. 11). Thicknesses of the gravels vary. In the exposures west of Birch Spring the gravels are over 37 m thick, and those exposed southeast of Steven's Narrows are only up to 12 m thick. These older gravels, Qg-1, correspond to the pediment gravel of Whitlock (1984), where he has mapped them in lower more distal distributions.

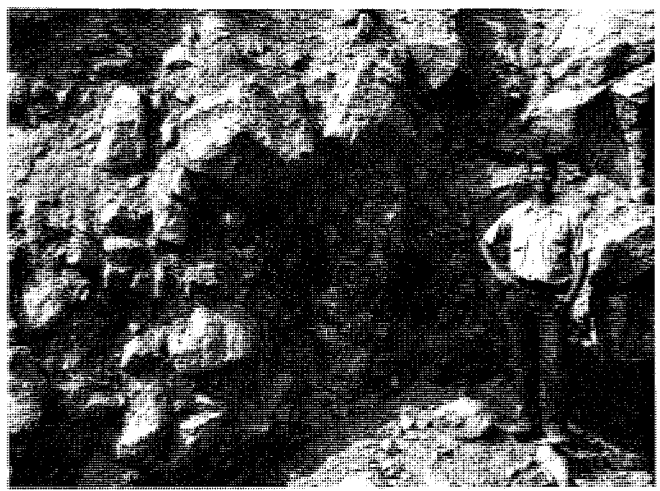

FIGURE 11.—*Quaternary pediment gravels (Qg-1 and 2) located 0.8 km west of the quadrangle in the NE ¼ of section 35, T. 31 S, R. 9 E. Note coarse texture, large blocks, and wide assortment of clast size.*

The younger pediment gravels, Qg-2, were deposited during a later episode, after pediments and deposits of the older gravels had been dissected and pediments beheaded. The younger lower gravel deposits have a composition similar to the older series and may well contain reworked materials of the older gravel. The younger gravels have been deposited on relatively lower surfaces that are inclined away from the Mount Ellen complex and tend to drape off the igneous rocks, to cover the Cretaceous and older sedimentary formations, and to surround the pinnaclelike exposures of the older pediments.

The younger gravels extend over a broad area of the quadrangle but are most evident in the southwest corner. There they form a belt that runs northwest–southeast, from west of McClellan Spring to Slate Creek. Another preserved remnant occurs at the head of a fanlike deposit at the eastern edge of the map, north of Crescent Creek. These gravels' veneered surfaces converge with other fans in the quadrangle to the east, and some of them contain gold placer deposits (Hunt and others 1953, p. 220).

Younger pediment gravels between Box Spring and Slate Flat are similar to those found on the west side of the mountain but are in a different drainage. Areas east of these limited deposits, along the base of Ragged Mountain and south into the lower reaches of Slate Creek, have no pediment gravel development. This distribution suggests that the eastward-draining of Slate Creek may have captured an earlier system, which may have flowed southwestward from the Slate Flat area, across Penellen Pass into Bullfrog Creek. These younger pediment gravels correspond to the alluvial terrace gravels of Whitlock (1984).

Colluvium

Colluvium consists of subangular cobbles and boulders of diorite porphyry in a sandy matrix. These materials have been transported short distances by gravity, solifluction, and frost action. Wedges of colluvium generally thicken distally from the igneous rock outcrops for a short distance then thin abruptly to distinct margins. The diorite porphyry-colluvium boundary was mapped along a break in slope formed at the transition from bedrock to transported debris. Colluvium-covered areas generally outline the perimeter of the intrusive complex.

Alluvium

Alluvium was deposited after the pediment gravels, contemporaneously with colluvium, landslide debris, and talus. Major streams in the quadrangle are margined with terraces and lined with sand and gravel of diorite porphyry clasts.

Landslide Debris

Landslides and associated debris were mapped near The Horn and north of Mount Ellen Creek. The landslide debris consists of angular blocks of diorite porphyry, some as large as 12+ m in diameter, floating in finer materials similar to colluvium. Surfaces of the debris slides are irregular and hummocky. The landslides may have been a product of the oversteepening of slopes by the downcutting of nearby streams, followed by the failure of shaly formations and subsequent debris flows. Such a pattern appears to be a reasonable explanation for the landslide seen near The Horn. More detailed work on the surficial deposits in the Bull Creek Basin area, in the northeastern corner of the quadrangle, has been done by Hohl (1980).

Talus

Talus occurs at the base of steep slopes throughout the quadrangle and is generally derived from the diorite porphyry. Talus usually consists of angular blocks from cobble to boulder size, with little finer matrix.

STRUCTURAL GEOLOGY

GENERAL STATEMENT

It was in the Henry Mountains that laccoliths were first identified and described by Gilbert (1877). Years later Hunt and others (1953) resurveyed the region, refining Gilbert's work. The present study, through increased detail in mapping, has provided additional data on deformation of the sedimentary rocks by the intrusions. Four intrusions are discussed in detail below. Structures found in mapping suggest other intrusions at depth.

HISTORY OF LACCOLITHIC CONCEPTS IN THE HENRY MOUNTAINS

Gilbert

Gilbert (1877) studied the geology of the Henry Mountains during an age when little was known about igneous rocks. His work clarified and helped resolve a lengthy debate over whether all igneous rocks were extrusive projections, over which blankets of sedimentary rocks were deposited; or whether some igneous rocks were intrusive bodies, having deformed the country rock. Gilbert (1877, p. 51–52) cited several lines of evidence gathered from exposures in the Henry Mountains to show that igneous bodies do intrude into older sedimentary strata.

Gilbert's work not only proved the existence of igneous intrusions, but also defined the concept of laccoliths, floored intrusions that had uplifted and folded the overlying strata. Gilbert (1877, p. 18–21; Hunt and others 1953, p. 87) described the laccoliths as mushroom intrusions, fed from below, with steep sides, convex shoulders, a gently rounded upper surface, and rounded in plan. Gilbert (Hunt and others 1953, p. 87) described some minor laccoliths as elongated bodies, such as The Horn (Gilbert's Sentinel Butte). Gilbert (1877, p. 72–80) speculated that the mechanism for intrusion was buoyancy due to differing densities between the fluid magma and the country rock.

Hunt, Averitt, and Miller

Hunt and others' (1953) study, some 75 years later, refined Gilbert's work through differentiation of the laccoliths, bysmaliths, and central stock of the Mount Ellen complex. Hunt and others (1953, p. 91–93) found the stock to be discordant with the country rock and mapped a shatter zone around its perimeter. They also found the degree of metamorphism and the occurrence of minor ore deposits to be greater in the stock than in the laccolithic satellites. Hunt and others (1953, p. 90–91) described the laccoliths as oriented in a radial fashion about the stock and composed of the same diorite porphyry. All these points lead to the conclusion that the Mount Ellen stock was the magmatic source for the laccoliths. Hunt and others (1953, p. 109) suggested that the laccoliths were fed laterally from the stock, rather than from below as Gilbert suspected.

Hunt and others (1953, p. 90–91) considered the lateral intrusions to be of two types: laccoliths with arch-raised roofs and bysmaliths with fault-raised roofs. Laccoliths were found to be ideally lobate in plan rather than circular, except where the intrusions are crowded and the forms complex. The laccoliths are concordant with the roof and floor formations and flat bottomed with rounded tops. Hunt and others (1953, p. 90) noted a degree of discordancy in that the laccoliths are not confined to one bedding plane but tend to climb stratigraphically in the host formations, carrying the intrusions to higher levels away from the stock. The distal ends of the laccoliths were found to be steepest with decreasing dips to the side. Anticlinal noses occur in the roof formations that are structurally open toward the stock.

Hunt and others (1953, p. 90–91) described bysmaliths in the region as similar to the laccoliths in that they were fed laterally and had maximum amounts of roof displacement at their distal ends, with decreasing displacement to the sides. Bysmaliths are ideally circular in plan and occur in a trap-door configuration, with the distal end structurally open because of high-angle faulting and the proximal end steeply folded and open to the stock.

Hunt and others (1953, p. 139) speculated that the mechanism for the intrusion of the stock was forceful injection. They (1953, p. 142) further suggested that the laccoliths were injected along bulges in the wall of the stock and assumed tonguelike forms as a result of the pressure caused by overlying strata.

INTRUSIONS

Mapping of members of the Cedar Mountain and Morrison Formations provided data on the nature of deformation of sedimentary rocks by laccoliths and bysmaliths. The stock and shatter zone, however, received only cursory attention in this study, but have been described by Hunt and others (1953, p. 91–93). Four laccoliths and bysmaliths located in the western and southern parts of the complex received greater attention. They include the South Creek and Dugout Creek laccoliths and the Ragged Mountain and Pistol Ridge bysmaliths. A short description of other minor intrusions follows. The remaining intrusions in the quadrangle have been described at length by Hunt and others (1953, p. 93–109).

Stocks

Hunt and others (1953, p. 91–93) described the Mount Ellen stock as a discordant, vertical, cylindrical mass composed of moderately homogeneous porphyry, rimmed by a shatter zone. An aerial magnetic survey (Affleck and Hunt 1980) of the Henry Mountains has confirmed this interpretation. On a residual total magnetic intensity map a circular 169 gamma anomaly exists over the Mount Ellen stock. From these data Affleck and Hunt suggested that the stock is cylindrical and steep sided and probably widens at depth.

Several other magnetic anomalies occur in the Mount Ellen complex suggesting that other stocklike bodies also exist. One anomaly, mapped under North Summit Ridge, is circular in map view and has a magnitude of 89 gammas. This information supports Hunt and others' (1953, p. 94) field evidence that the North Summit Ridge intrusions are the result of upward and outward injections. A third circular anomaly of approximately 100 gammas magnitude occurs in the quadrangle under the northwest side of Wickiup Ridge. Once again, magnetic information supports field data collected by Hunt and others (1953, p. 105; 1980, p. 111) and implies a stocklike body under Wickiup Ridge.

Laccoliths

South Creek Laccolith. The South Creek laccolith holds up a prominent ridge that runs east–west in the southwestern part of the quadrangle. South Creek laccolith is approximately 2,590 m long, and as wide as 2,440 m. It divides the drainages of the north-flowing South Creek and the south-flowing Bullfrog Creek.

Gilbert (1877, p. 41) recognized the South Creek laccolith ("E" laccolith) and suggested that the Blue Gate Shale hosted the intrusion. Hunt and others (1953, p. 97) renamed the laccolith and concluded that the Tununk Shale was the original host.

Four new features around the South Creek laccolith were identified during the present study. They are (1) linear oblique normal faults, (2) a low-angle reverse fault, (3) a minor tear fault, and (4) a dike in front of the South Creek laccolith. Traces of the linear oblique normal faults trend northeast–southwest and are located on the south flank of the South Creek laccolith. Displacement along these faults is minor, juxtaposing different blocks of Ferron Sandstone. A central graben has been formed on the flank of the South Creek laccolith (fig. 12). Horsts to either side of the graben are marked by uplift of the carbonaceous zone of the upper Ferron Sandstone. Vertical displacement is minor, some 9–12 m. Apparent horizontal displacement along the southernmost fault is some 210 m.

The oblique normal faults indicate tension over the laccolith and occur along the south flank of the intrusion. Faults occur in a reentrant, where Ferron Sandstone crops out between the South Creek laccolith and a laccolith to the southeast. This more southeastern laccolith trends northeast–southwest and will be referred to as the Bullfrog laccolith.

The oblique normal faults were likely produced as the Ferron Sandstone responded brittlely to roof raising. It is likely that other radial faults existed over the crests of the South Creek and Bullfrog laccoliths. In fact, this style of faulting may have been common over many of the laccoliths in the complex, but cover beds in which these faults would have formed have been eroded away.

The trace of a low-angle reverse fault trends north–south in front of the South Creek–Bullfrog laccoliths. The fault is best seen 365 m southwest of the Bullfrog laccolith. The Ferron Sandstone is overturned immediately in front of the laccolith, as much as 50° degrees, but 180 m to the southwest the Ferron Sandstone is almost horizontal (figs. 13, 14). Cross section B–B′ illustrates this relationship (fig. 15). The reverse fault is inclined toward the Bullfrog laccolith at a shallow angle and cuts the Tununk and Blue Gate Shales and the Ferron Sandstone. Toward the intrusion, the dip of the fault may be shallower than depicted in the cross section. Hunt (1953, p. 90) reported that many of the laccoliths climb in their hosts some 100 m (300 ft) in 1.6 km (1 mi). This type of discordance in the South Creek and Bullfrog laccoliths is much greater than previously recognized. The Ferron Sandstone roof has been ruptured and transported laterally as much as 380 m.

The low-angle reverse fault must have developed as the South Creek and Bullfrog laccoliths invaded the Tununk Shale and climbed gradually to higher stratigraphic levels as their roofs were raised. Continued intrusion, particularly of a lateral nature, overcame the internal strength of the Ferron Sandstone roof, rupturing it and carrying it and the intrusion to a higher interval in the Blue Gate Shale.

A minor tear fault with a northeast–southwest trend, occurs in the gully south of the overturned Ferron Sandstone outcrop approximately 365 m southwest of the Bullfrog laccolith. Here the Ferron beds are overturned 50° toward the east, while on the south side of the wash they dip to the west at 47°. Apparently the tear fault devel-

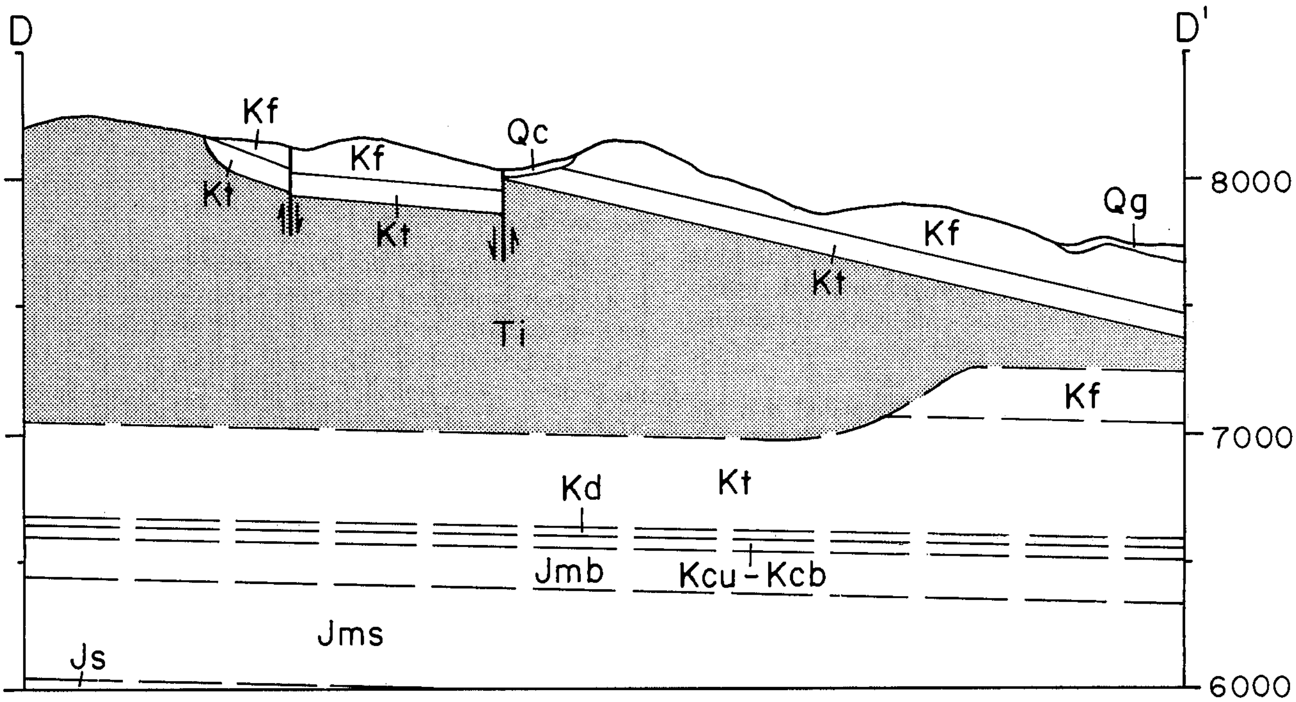

FIGURE 12.—*Cross section D–D′. Graben formed on south flank of South Creek laccolith by linear oblique normal faults. Horizontal and vertical scales are the same. Symbols are explained in legend of geologic map (fig. 3).*

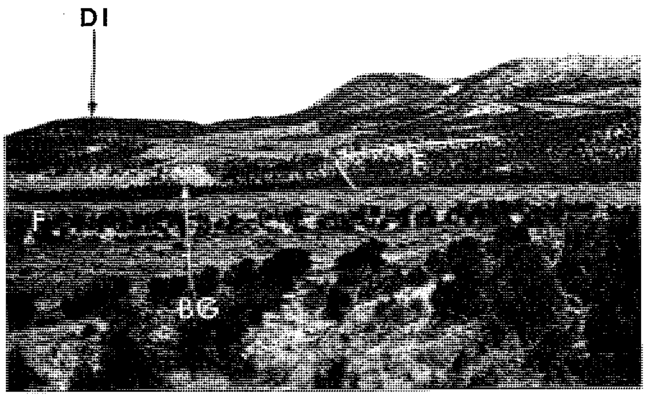

FIGURE 13.—*Low-angle reverse fault in front of South Creek–Bullfrog laccoliths. View to the north toward the Head of Bullfrog dike (DI). Note near horizontal Ferron Sandstone (F) on the left and overturned outcrop on the right. Blue Gate Shale (BG) outcrops left of center.*

oped during lateral intrusion of the South Creek–Bullfrog laccoliths.

Further evidence for the existence of the low-angle reverse fault is a dike of diorite porphyry that crops out at Head of Bullfrog. The trend of the dike roughly parallels the trace of the low-angle reverse fault and forms a series of low, rounded westward-facing hills (fig. 13). Previous surveys have mapped this feature as an outcrop of the Blue Gate Shale. During this study slates, slate breccias, and highly weathered outcrops of diorite porphyry were identified along Head of Bullfrog (fig. 16). A small outcrop of Blue Gate Shale trapped below the dike was mapped. This dike is here named the Head of Bullfrog dike. It is likely that the South Creek–Bullfrog laccoliths are the source for the Head of Bullfrog dike. They are both composed of diorite porphyry that bears hornblende inclusions.

The low-angle reverse fault in front of the South Creek–Bullfrog laccoliths is a possible plane of weakness that allowed a portion of the porphyry in the laccoliths to flow discordantly through the Ferron Sandstone roof into the Blue Gate Shale. This relationship is illustrated in cross section D–D′ (fig. 12).

The low-angle reverse fault may extend northward in front of South Creek Ridge. Two Ferron Sandstone outcrops suggest this extension on the west end of South Creek Ridge as the section is repeated approximately 400 m southeast of Birch Spring. The northern outcrop is a roof pendant to the intrusion and consists of the massive sandstone of the upper Ferron Sandstone. The southern outcrop is located at the floor of the intrusion and consists of carbonaceous shales and minor coal overlain by diorite porphyry.

Dugout Creek Laccolith. The Dugout Creek laccolith was first recognized by Gilbert (1877, p. 41, the Newberry Laccolith). Hunt and others (1953, p. 99–102) gave the

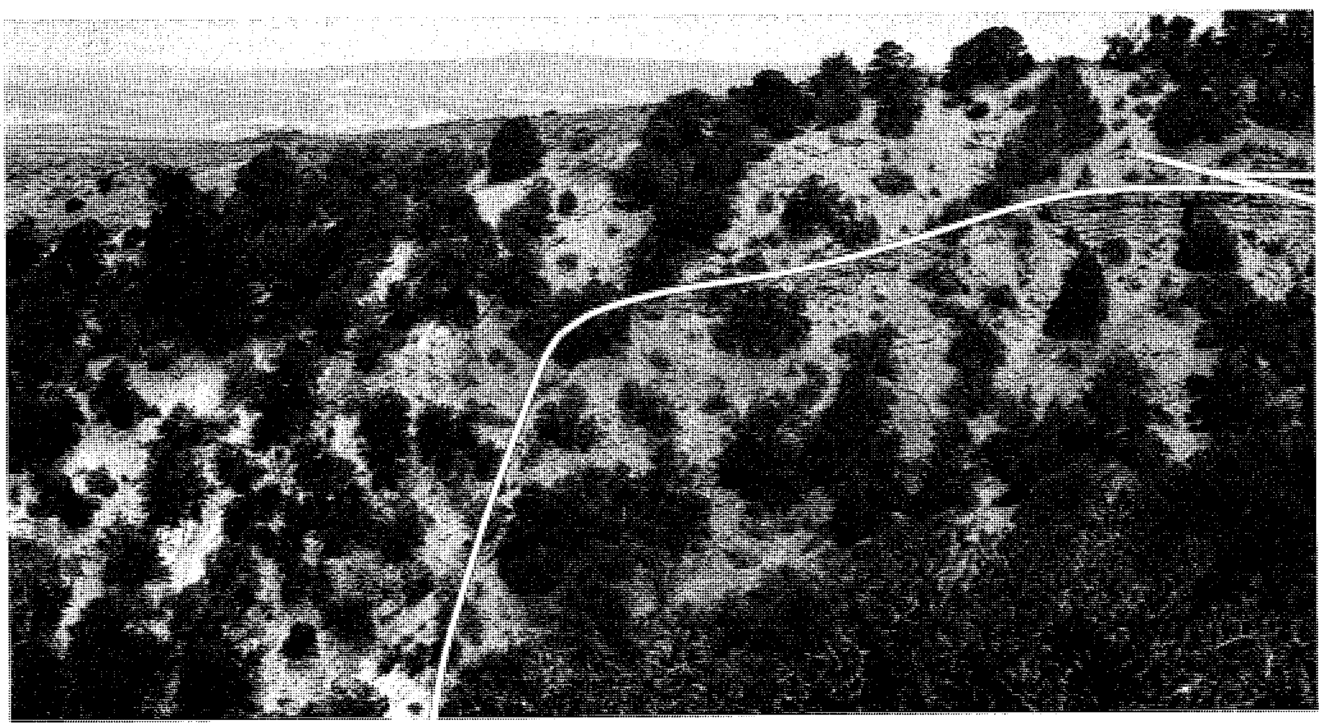

FIGURE 14.—*Closeup of overturned Ferron Sandstone west of Bullfrog laccolith. View to the northwest.*

laccolith its present name. The laccolith forms a prominent arch along the western margin of the quadrangle south of Dugout Creek. The Dugout Creek laccolith has invaded the Entrada Sandstone. Surface data, compared with the available subsurface data from the Exxon well, some 853 m to the north, indicate that the laccolith has raised its roof approximately 420 m.

The Dugout Creek laccolith underlies the Sarvis Ridge laccolith located to the south and east. The Sarvis Ridge intrusion has invaded the Tununk Shale. The two laccoliths have created a broad dome more than 2,590 m long and 2,740 m wide. Arched strata along the eastern side of the complex dip eastward as much as 22°. Dips are steepest along the western side, as much as 45°, like that considered as an ideal model of laccoliths by Hunt and others (1953).

An arch formed principally in the Salt Wash Member of the Morrison Formation occurs along the western margin of the Dugout Creek laccolith (fig. 17). A low-angle reverse fault was identified along this arch and another inferred near measured section 2. The reverse fault has truncated the Summerville Formation and caused an offset of sandstone cliffs in the overlying Salt Wash Member (fig. 18). Displacement along this fault is minor, some 40 m, but a distinct change in bed attitude occurs across the fault. Beds of the Salt Wash Member above the fault plane dip westward at 17°, and beds below dip at 25° to the west. The fault plane, easily seen in the escarpment south of Dugout Creek, was mapped to the south along

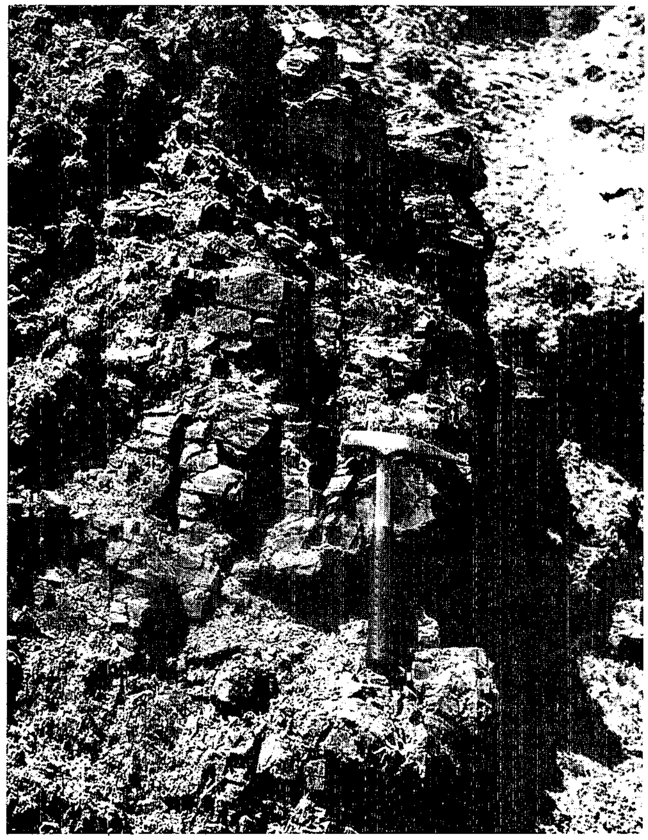

FIGURE 16.—*Slate and slate breccia of the Blue Gate Shale associated with the Head of Bullfrog dike. Located 0.8 km north of Bullfrog Creek in the NE ¼ of section 17, T. 32 S, R. 10 E.*

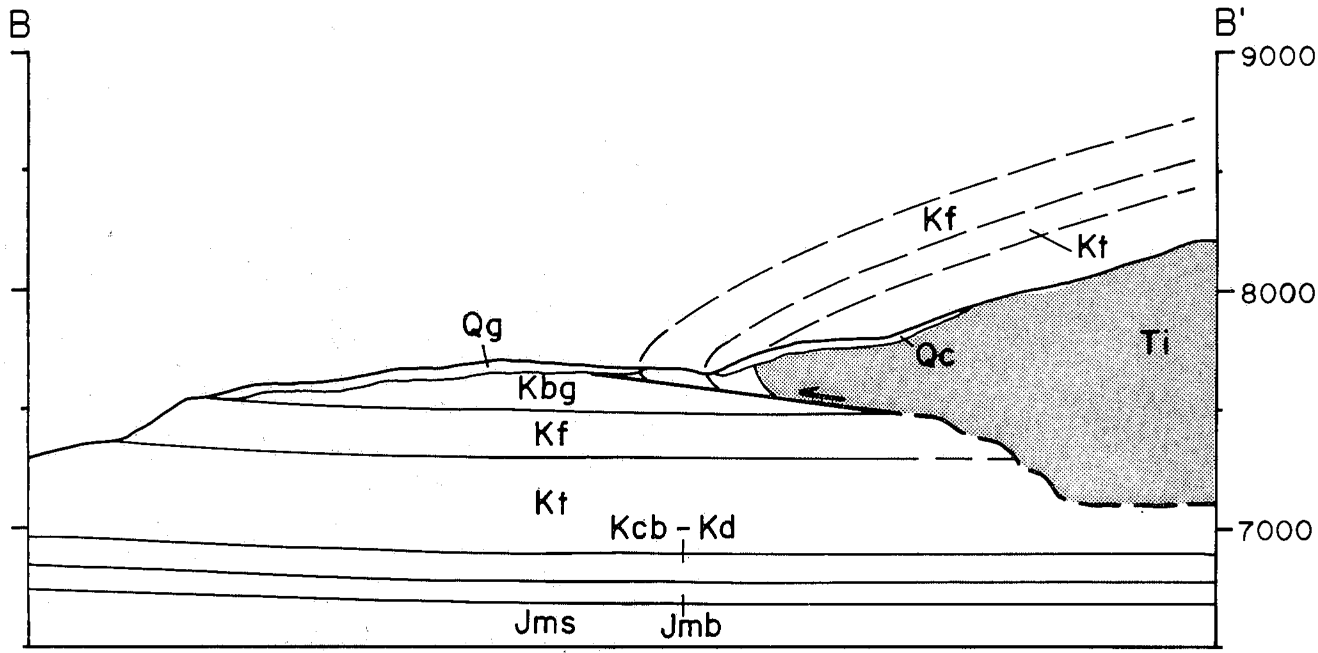

FIGURE 15.—*Cross section B–B'. Overturned Ferron Sandstone in front of South Creek–Bullfrog laccoliths. Horizontal and vertical scales are the same. Symbols are explained in legend of geologic map (fig. 3).*

the western margin of the laccolith. There the fault scarp forms a minor cliff in sandstones of the Salt Wash Member but is obscure where the fault cuts claystones of the Brushy Basin Member farther south.

An inferred reverse fault is located 305 m to the west. An abrupt change in dip is noticed across the projected fault trace where beds of the inferred hanging wall dip at 25° to the west, while those of the footwall dip 17° northwesterly. A minor cliff in the sandstones of the Salt Wash Member is seen to the south. Displacement along this fault must be less than that of its companion to the east. The inferred fault may extend quite a distance to the south, producing relationships like those in front of the South Creek laccolith, where a reverse fault has apparently provided a conduit for a dikelike arm of the porphyry to invade higher strata. If so, the diorite porphyry intrusion, hosted by the Tununk Shale, just west of the quadrangle, in the NE ¼ of section 26, T. 31 S, R. 9 E, may have been fed from the Dugout Creek laccolith.

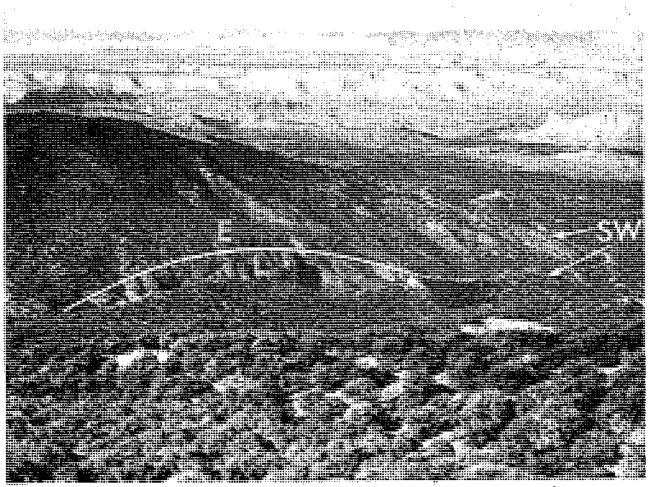

FIGURE 17.—*Dugout Creek laccolith (L) as viewed from Star Flat. Note the cuesta of Salt Wash Member (SW) of the Morrison Formation that outlines the intrusion. Laccolith (L) forms a cliff on the south side of Dugout Creek and is capped by Entrada Sandstone (E).*

Another discordant feature was mapped around the Dugout Creek laccolith, where part of the Entrada Sandstone has been juxtaposed against the Summerville Formation, along Dugout Creek near measured section 3. At this locality the Entrada Sandstone, on the south side of Dugout Creek, occurs immediately on the roof of the intrusion though the intrusion is hosted by the Summerville Formation on the north side of the creek (fig. 19). This discordance, which may have been a high-angle fault, may likely have extended vertically into higher roof units. This zone of weakness may be the reason Dugout Creek entrenched in the flank of the arched roof rocks rather than in the syncline to the north, between the Cedar Creek and Dugout Creek laccoliths.

The path of Dugout Creek is also controlled in two other localities by structures created by the Dugout Creek complex. Along the eastern side of the intrusions, the creek makes an abrupt change in course to the north as it encounters eastward-dipping strata. Dugout Creek makes a second path change to the northwest as a fault is encountered near the junction of Pistol and Dugout Creeks.

In conclusion, low-angle reverse faults, dikes, and oblique normal faults occur in roofs of both the Dugout Creek and South Creek–Bullfrog laccoliths and suggest a more brittle response of the roof than previously thought.

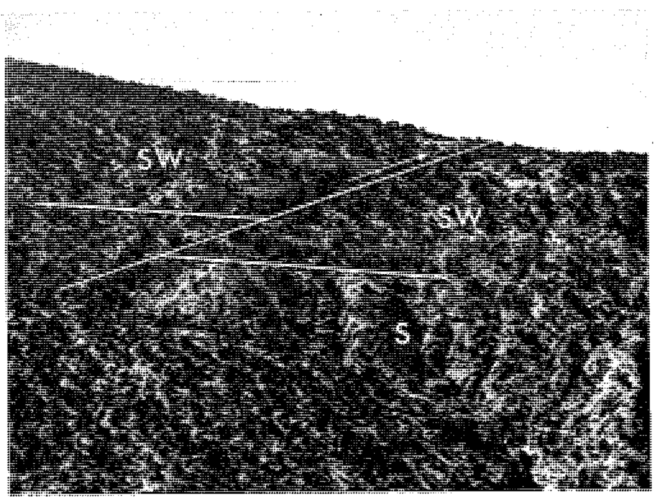

FIGURE 18.—*Low-angle reverse fault displaces cliffs of the Salt Wash Member (SW) of the Morrison Formation on the north side of Dugout Creek laccolith. Note the truncation of the Summerville Formation (S). Faulting is similar to that seen in front of the South Creek–Bullfrog laccoliths in figure 15. View to the south.*

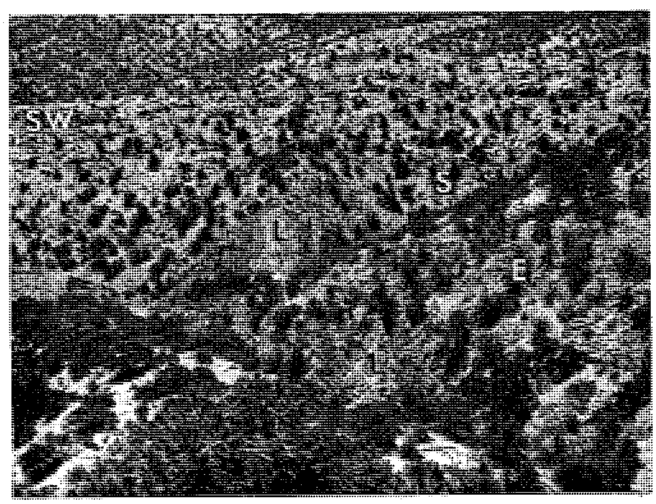

FIGURE 19.—*Dugout Creek laccolith (L). Foreground, roof of intrusion is Entrada Sandstone (E). Background, roof of same intrusion is the Summerville Formation (S). Northward-dipping cuesta is the Salt Wash Member (SW) of the Morrison Formation.*

These faults reflect brittle responses caused by both the horizontal and the vertical components of the intrusion process. Such a reaction of the roof strata must have been influenced by overburden pressure and the rate of intrusion. Either factor alone could have produced the type of deformation identified, but both likely contributed.

Bysmaliths

Ragged Mountain Bysmalith. Ragged Mountain is a prominent butte, approximately 1,829 m long, and 1,372 m wide, located in the southeastern corner of the quadrangle. Gilbert (1877, p. 47) first described Ragged Mountain (Scrope Butte) as a laccolith. Hunt and others (1953, p. 113–15) recognized the intrusion as a bysmalith after discovering that its roof had been raised by faulting.

Hunt and others (1953, p. 115) suggested that the Ragged Mountain bysmalith was fed laterally from the Mount Ellen stock and initially may have been a laccolith but ruptured its roof and then underwent vertical intrusion. The initial host and conduit from the stock must have been located no higher than the Summerville Formation (Hunt and others 1953, p. 115).

A rim syncline, five radial-type oblique normal faults that displaced the rim syncline, and a high-angle fault peripheral to the intrusion have been differentiated in this study. Exposures of both members of the Cedar Mountain Formation and the Dakota Sandstone outline the rim syncline on the west side of Ragged Mountain. The Buckhorn Conglomerate Member is a key unit for mapping the relationship. West of Ragged Mountain the conglomerate forms a ledge above the slopes of the Brushy Basin Member of the Morrison Formation and dips eastward as much as 30°. Farther east, upper Cedar Mountain beds and Dakota Sandstone dip westward at 50°–70°, forming an asymmetrical syncline that is steepest along its eastern limb (fig. 20). Dips decrease to the south, probably because the outcrops are closer to the axis of the rim syncline. The syncline plunges northward because the Tununk Shale crops out along the fold axis at the northwest corner of Ragged Mountain, while outcrops to the south expose progressively older rocks. Uplift of the southern part of the syncline supports the bysmalith model described by Hunt, for the greatest amount of uplift should occur along the distal end of the intrusion.

Radial oblique normal faults displace the rim syncline. The Buckhorn Conglomerate is a key horizon, for faults have offset these beds as much as 33 m vertically. The faults appear to have occurred as a brittle response during vertical intrusion. Evidence supporting this idea is seen in the radial faults themselves, for greatest displacements occur towards the southern end of the bysmalith, where the greatest amounts of uplift have occurred. Present-day topographic relief, combined with the radial disruption of the Dakota Sandstone, suggests that the intrusion may have invaded beds at least as high as the Tununk Shale, and perhaps higher.

Evidence for a high-angle fault peripheral to the intrusion is seen along the west side of Ragged Mountain. One of the best exposures of the relationship is found at the southernmost outcrop of Dakota Sandstone, where the nearly horizontal beds are only 122 horizontal m from the intrusion. Outcrop patterns indicate a high-angle fault runs north–south along the west side of Ragged Mountain.

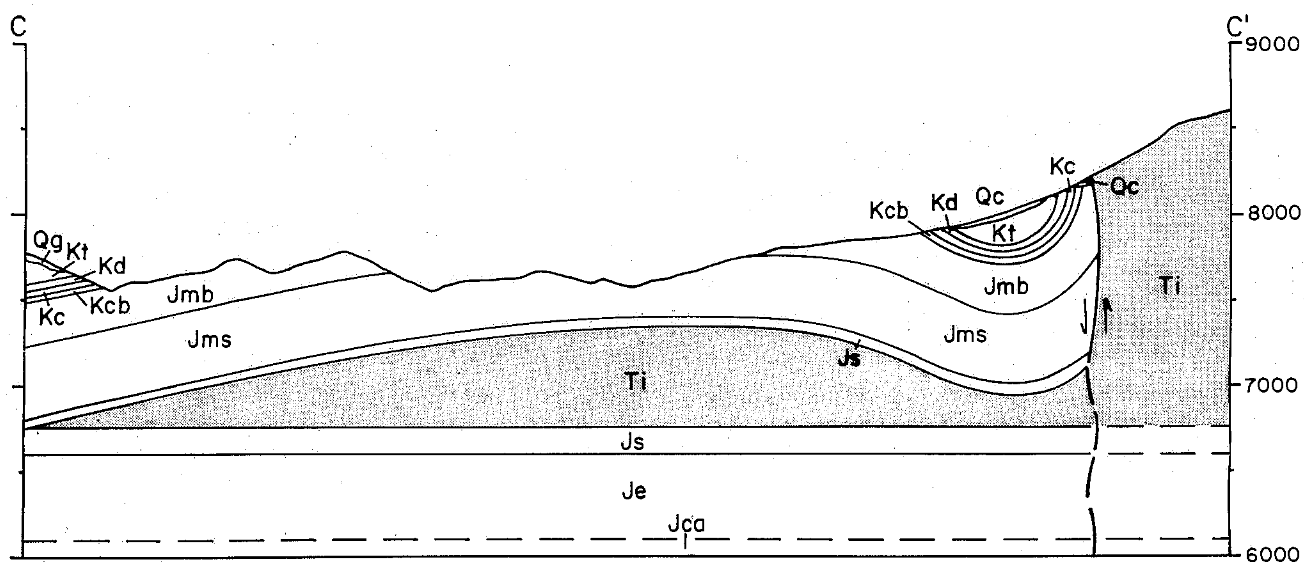

FIGURE 20.—*Cross section C–C′. Intrusions of Ragged Mountain bysmalith and associated rim syncline. Horizontal and vertical scales are the same. Symbols are explained in legend of geologic map (fig. 3).*

Trace of this same fault may turn east–west along the south side of Ragged Mountain. The trace is most likely located somewhere in the outcrop of the Brushy Basin Member. This member forms a banded outcrop between the horizontal outcrops to the south and the vertical outcrops to the north of the Salt Wash Member of the Morrison Formation.

Further study of the northern side of Ragged Mountain may locate another high-angle fault. If one is present, the Ragged Mountain bysmalith thus would be nearly circumscribed by high-angle faults. Such faulting and inferred faulting suggests that the Ragged Mountain bysmalith is more discordant than previously thought and that its bysmalithic behavior is well developed.

Genetically, the rim syncline, radial faults, and the peripheral high-angle fault are likely related. As the roof was lifted and folded, a rim syncline formed. Continued uplift initiated roof failure and radial normal faulting. Finally the disruption was consummated as a high-angle fault formed along the intrusion's perimeter as the magma moved upward into the overlying units.

Pistol Ridge Bysmalith. The western end of the Pistol Ridge bysmalith is shown in an escarpment approximately 2,042 m long, 457 m wide, and 152 m high in the northwest corner of the quadrangle. The bysmalith itself may extend eastward some 4 km. Gilbert (1877, p. 42) named the feature the Shoulder laccolith, but Hunt and others (1953, p. 102) renamed it the Pistol Ridge laccolith. The name *Pistol Ridge* on recent topographic maps differs from that used by Hunt and others (1953, plate 7). Hunt and others' Pistol Ridge is found in the same general locality as the modern-day Star Flat and has been located on the bedrock geologic map (fig. 3). The Pistol Ridge intrusion crops out approximately 800 m west of this locality.

The Pistol Ridge intrusion is a bysmalith, for its roof has been raised by a fault that runs along the western edge of the escarpment (fig. 3). Outcrops of Dakota Sandstone and both members of the Cedar Mountain Formation show beds inclined 39° to the west approximately 15 m from the intrusion. The Summerville Formation is exposed along the roof of the bysmalith 425 m to the north. This indicates that outcrops of the Salt Wash Member along the bysmalith's roof are basal exposures. If the intrusion were concordant, and had it invaded the Summerville Formation, as roof outcrops infer, then a room problem exists. These relationships are best explained by a fault that has displaced the roof strata some 274 m. See cross section E–E′ (fig. 21).

Hunt and others' (1953, p. 90–91) model of bysmaliths in the Henry Mountains suggests that greatest disruption of strata occurs near the axis of the intrusion at its distal end. Fault displacement diminishes laterally. This general fault model is exemplified by the Pistol Ridge bysmalith, for the distal fault dies out to the north. There Salt Wash beds are steeply folded over the edge of the intrusion (fig. 22). Displacement along the fault also decreases to the south, where Dakota Sandstone and the Brushy Basin Member of the Morrison Formation are apparently juxtaposed. Farther east the faulted contact is unclear where the Pistol

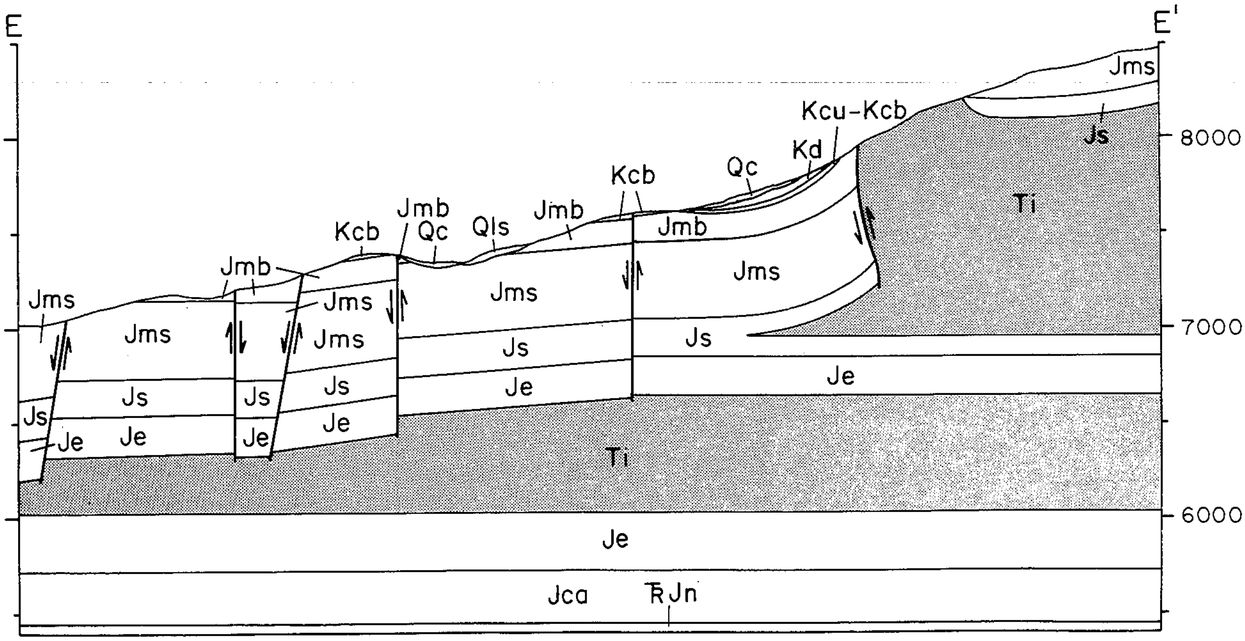

FIGURE 21.—*Cross section E–E′. Pistol Ridge bysmalith and the deeper Cedar Creek laccolith. Note numerous normal faults in roof of Cedar Creek laccolith. Horizontal and vertical scales are the same. Symbols are explained in legend of geologic map (fig. 3).*

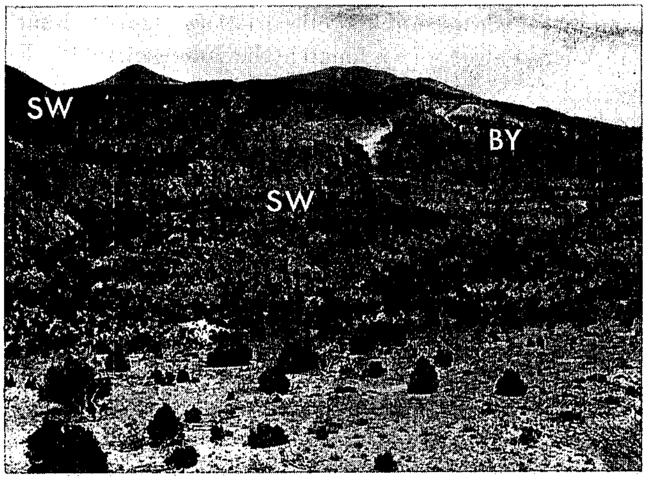

FIGURE 22.—*Pistol Ridge bysmalith (BY). Salt Wash Member (SW) is faulted in front of, and on the left extends up onto, the roof of the intrusion. View to the east.*

Ridge bysmalith is crowded by other intrusions, apparently at higher stratigraphic intervals.

The north–south orientation of the distal fault suggests that the axis of the intrusion is oriented more east–west than previously thought. Hunt (1953, p. 102) suggested that the bysmalith was injected in a northwesterly direction from the Mount Ellen stock, 5.8 km to the southeast. Magnetic studies of Mount Ellen (Affleck and Hunt 1980, p. 110–11) suggest that an additional stocklike body may exist under North Summit Ridge, only 4 km to the east. Both the closer proximity of the North Summit Ridge "stock" and the north–south orientation of the bysmalith's distal fault suggest that the bysmalith may well have been fed from a source to the east, rather than from the southeast.

Hunt and others (1953, p. 90) described bysmaliths in the region as circular in plan. The overall topographic expression of the Pistol Ridge bysmalith suggests that it is lobate in form. Bedded roof rocks dip away from the intrusion on the north side of Cedar Creek and delineate the northern edge of the bysmalith. The southern edge, though unclear, suggests an east–west lineation of the intrusion that is evidence for a lobate form.

Perhaps the lobate Pistol Ridge bysmalith is a transition between the rounded, distinctly discordant bysmaliths and lobate, dominantly concordant laccoliths. Pistol Ridge bysmalith, therefore, would be an incipient bysmalith, one that had begun to disrupt its roof by faulting the distal end. For some reason disruption by raising and faulting the lateral margins was never completed.

Other Intrusions

Laccolith West of Slate Flat. A minor laccolith west of Slate Flat has invaded the Brushy Basin Member of the Morrison Formation. The laccolith trends north–south and is approximately 1,220 m long and 610 m wide. The intrusion has created a dome in overlying strata that plunge to the south. The structure is well outlined by the Dakota Sandstone.

At the southern toe of the laccolith, rocks dip southward as much as 32°, but 152 m to the north dips decrease to 10°, as the same units occur on the roof of the laccolith. The Buckhorn Conglomerate is the immediate roof and has undergone some anomalous alteration, for it has been baked as much as 2–3 m away from the intrusion contact. However, 305 m farther north the Buckhorn Conglomerate is inclined some 27° southwest immediately in front of a step-like ridge of diorite porphyry. An outcrop of the Brushy Basin Member of the Morrison Formation occurs immediately adjacent to the steplike ridge suggesting that the Buckhorn Conglomerate was the roof of the intrusion before erosion.

The steplike effect in the top of the laccolith has caused multiple folding of overlying strata. Similar steplike structural terraces were identified at the Wickiup Ridge laccolith by Hunt (1953, p. 105) in the northeastern corner of the quadrangle. Such steplike development in the roof of laccoliths suggest that the original shape of the intrusion may have been wedgelike, later altered by bulging of the intrusion.

North Summit Ridge Intrusions. The North Summit Ridge intrusions occur in a north–south belt in the northern part of the quadrangle. The intrusions form a prominent ridge, including Mount Ellen Peak, which is 3,507 m above sea level. Hunt and others' (1953, p. 94) fieldwork suggested that the North Summit Ridge intrusions were injected upward and outward. Magnetic anomalies (Affleck and Hunt 1980) suggest that a stocklike body exists under the ridge. Because of the evidence presented by these previous studies, the synclinal folding of the Ferron Sandstone is suggested for isolated outcrops north and east of Corral Point (Morton in press). The western limb of the syncline may be a result of laccolithic type intrusion between Corral Point and Star Flat.

The sandstone roof pendants at the foot of Mount Ellen Peak, and those approximately 1,370 m northwest of Blue Basin were identified as beds now included in the Muley Canyon Sandstone (Hunt and others 1953, plate 7). Hunt and others (1953, p. 94) mentioned that the Mount Ellen Peak outcrops may well be relicts of the Ferron Sandstone. These outcrops are probably remnants of the Ferron Sandstone, as suggested by the structural contour map (Morton in press). Previous studies (Hunt and others 1953, Affleck and Hunt 1980) have shown that North Summit Ridge is underlain by a deep-seated pluton and has undergone substantial uplift, with isolated sandstone and shale outcrops now interpreted as Ferron Sandstone and Tununk Shale. Stratigraphic units rise progressively from the foot of the mountain to an apex near North Summit Ridge. Previous interpretations suggest that rocks rise toward the base of the ridge but then abruptly decline to form a basin in an area where plutonic uplift is now evident.

The North Summit Ridge intrusions may appear anomalously thick and bulging to some 885 m thick. In reality this thickness is quite reasonable. Surface mapping of the South Creek laccolith suggests that the lateral intrusion is over 610 m thick. Thickness of the North Summit Ridge intrusions is reasonable, particularly when they may have been fed directly from a local stocklike source.

STRUCTURES THAT IMPLY OTHER INTRUSIONS AT DEPTH

Faults West of the Pistol Ridge Bysmalith

Faults west of the Pistol Ridge bysmalith and north of Dugout Creek are apparently related to the Cedar Creek laccolith at depth. Hunt and others (1953, p. 102) described faulting around the southern exposures of the Cedar Creek laccolith in the NW ¼ of section 13 and the NE ¼ of section 14, T. 31 S, R. 9 E. Faults roughly perpendicular to the Cedar Creek laccolith were identified west of the Pistol Ridge bysmalith. One faulted outcrop of the Salt Wash Member has also been rotated against a high-angle fault in the NE ¼, NW ¼, section 13, T. 31 S, R. 9 E (fig. 23). All the faults mapped are of high angle. Most are near vertical, but two were found to be inclined to the west as much as 10°. See cross section E–E′ (fig. 21). The westward inclination suggests they are normal faults, possibly formed during roof raising.

Surface mapping west of the Pistol Ridge bysmalith indicates that the Brushy Basin and Salt Wash Members of the Morrison Formation are exposed at approximately 2,255 m above sea level. Subsurface data from a well drilled by Exxon USA, some 610 m southeast of the cross section E–E′, places the top of the Carmel Formation at approximately 1,744 m above sea level. Measured and average thicknesses for the intervening units make it apparent that nearly 122 m of section has been added at this locality.

The intrusion is likely hosted by the Entrada Sandstone, for the Entrada Sandstone is the host for the Cedar Creek laccolith in the extreme northwest corner of the quadrangle. There intrusion of the laccolith has caused several faults. Another line of evidence that the Entrada Sandstone is a host near cross section E–E′ is that the Summerville Formation is faulted and intrusions are absent in outcrops in the canyon, only 853 m northwest of the cross section.

This evidence suggests that the Cedar Creek laccolith extends southward underneath the area in question and has caused numerous faults in the overlying strata. The Cedar Creek laccolith probably wedges out farther southward toward the synclinal axis near Dugout Creek. Two explanations for the disruption of roof strata are offered: (1) if the Cedar Creek laccolith was emplaced first, then minimal overburden pressures and/or high rates of intrusion must have existed; (2) if the Pistol Ridge bysmalith was emplaced first, then the deformation may have been a response to reduced confining pressures as the Cedar Creek laccolith moved out from under the overlying bysmalith.

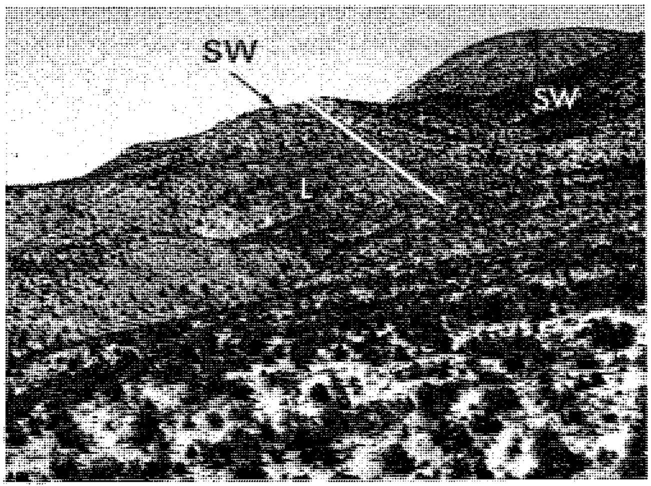

FIGURE 23.—*Block of Salt Wash Member (SW) of Morrison Formation, west of fault (white line), has been downdropped and rotated above the Cedar Creek laccolith (L). View to the northeast.*

Structures West of South Creek Ridge

A monoclinal flexure, linear and perpendicular faults, and a minor syncline occur west of South Creek Ridge and have been caused by an intrusion at depth. The monocline forms two prominent cuestas on the Muley Canyon and Ferron Sandstones near and east of Steven's Narrows (fig. 8). Surface mapping suggests that the monoclinal flexure of the Ferron Sandstone encloses a dome approximately 671 m high. Surface control suggests that the flexure-causing intrusion must be located at a moderate depth. Experience elsewhere in the quadrangle leads me to believe that a likely host for the intrusion is the Summerville Formation (cross section A–A′, Morton in press). If the Summerville Formation is used as a host, almost all structural closure can be accounted for.

Linear normal faults displace the monocline east, south, and northeast of Steven's Narrows. They are of minor displacement. Five faults mapped east and south of Steven's Narrows trend northeast–southwest away from the Mount Ellen Stock and appear to be aligned. A series of en echelon faults may occur along this trend. The faults east of

Steven's Narrows mark the boundary between the monocline and the plunging syncline. Both faults are downthrown to the south and may occur over the southern lateral margin of the intrusion at depth. The three faults mapped south of Steven's Narrows form a graben in the Muley Canyon Sandstone cuesta. Their traces are difficult to follow both northeast and southwest, but the system must die out within a short distance to the southwest because the overlying Tarantula Mesa Sandstone is not displaced. Such a loss of resolution in fault displacement and faulted strata passing horizontally into folded strata, are found in other parts of the Henry Mountains Basin (Hunt and others 1953, p. 89).

Trace of another linear normal fault northeast of Steven's Narrows trends east–west and has displaced the coal outcrops of the upper Ferron Sandstone. Displacement is only 12 m vertically, but the fault has buried the coal on the downdropped block to the south.

A normal fault perpendicular to the linear set previously described has a northwest–southeast trend east of Steven's Narrows. The fault is downthrown to the southwest and marks an abrupt change in attitudes in the Ferron Sandstone from nearly horizontal on the upthrown block to a dip of 8° southwest on the downthrown block. Minor perpendicular faulting was identified elsewhere on the monocline, but could not be mapped because of scale. These faults have displaced the coals of the upper Ferron Sandstone northeast of Steven's Narrows (fig. 24). All the faults mentioned above were likely produced in a manner similar to those associated with the Cedar Creek laccolith in the northwestern corner of the quadrangle.

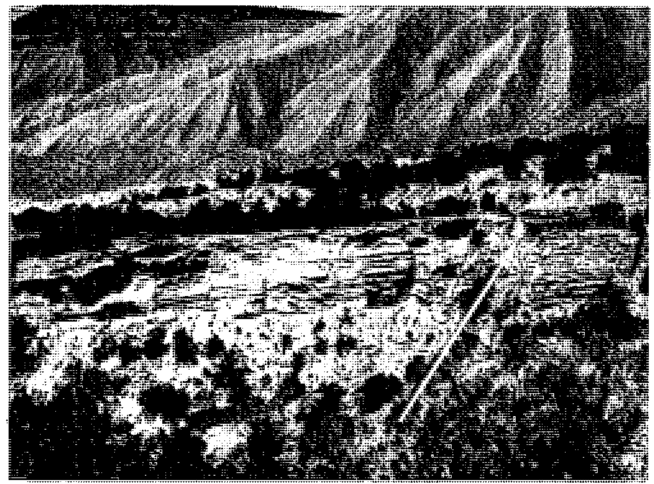

FIGURE 24.—*Perpendicular-type normal faults that displace the Ferron Sandstone and coal zone some 2–3 m northeast of Steven's Narrows. Blue Gate Shale in background to the northwest.*

Subsurface Information

Data collected from three wells drilled in and adjacent to the quadrangle suggest the existence of major laccolith and sill-like bodies in Triassic and older formations. A well drilled by Webb Resources in the NW ¼, NW ¼ of section 22, T. 31 S, R. 9 E, some 3,048 m from the western boundary of the quadrangle, drilled through an igneous sill-like body, presumably of diorite porphyry, hosted by the Triassic Chinle Formation. Gamma-ray logs indicate that the sill is 55 m thick, and has split the shales of the Chinle Formation, approximately 30 m above the basal contact with the Shinarump Conglomerate. The intraformational nature of the sill coincides with general occurrences of laccoliths seen at the surface. The sill is 10.6 km from the Mount Ellen stock and 9.6 km from the inferred stock under North Summit Ridge.

Information available from a well drilled by Exxon Company USA, west of the Pistol Ridge bysmalith and north of Dugout Creek, indicates that the top of the Navajo Sandstone is located at 1,661 m above sea level. This datum places the Navajo Sandstone 1,012 m higher there than in the Webb Resources well, some 4,345 m to the west. Such elevations of the Navajo Sandstone in the quadrangle produce a 13° regional dip to the west. Such a rise in the Navajo Sandstone is strong evidence for the occurrence of intrusions in the pre-Navajo Sandstone formations.

A well drilled by Jake Hamon in the adjacent quadrangle to the east, in the SE ¼, SE ¼ of section 17, T. 32 S, R. 11 E, was spudded into an outcrop of a diorite porphyry dike that had invaded the Navajo Sandstone. After 694 m were drilled, the hole had still not penetrated the bottom of the intrusion, and the site was abandoned. Gamma-ray logs indicate a "shaly" response between 1,518 and 1,420 m above sea level. This 98-m interval may well be a zone of pre-Navajo sedimentary rocks sandwiched between two intrusions. The dike seen at the surface may be a vertical expression of a laccolith at depth.

In conclusion, subsurface data available indicate the strong possibility of substantial, if not massive, intrusions in Triassic-age and possibly older formations. Data from wells on the west side of the quadrangle suggest that deep intrusions are sill-like and extend for several kilometers from known and inferred magma sources. The implication is that the broad structural dome over the Mount Ellen region may be not only the result of a broad magma chamber at depth, as proposed by Affleck and Hunt (1980, p. 112), but also may be a product of broad multiple sill-like intrusions into the Triassic and older formations.

INTERPRETATIONS

Genesis of Intrusions

The Henry Mountains Basin is a great sand-shale province. Surface and subsurface data suggest that the majority of the laccoliths and bysmaliths in the Henry Mountains are confined, at least initially, to shaly formations. The shales, thus, appear less competent and apparently have less internal strength. They could yield more readily to intrusive pressures. Also, water confined to particular layers would expand when in contact with an intrusion, and the resulting pore fluid pressures would be an effective aid in roof raising and subsequent sill and laccolithic intrusion. Shales also would be more likely to undergo bedding-plane shear, necessary for the development of the marginal monoclinal flexures and flat roofs, so commonly seen around the intrusions in the Henry Mountains (Pollard and Johnson 1973).

Clay-model experiments have shown that diapiric bodies tend to spread laterally when they encounter a strong overlying stratum (Ramberg 1981, p. 267). The sand-shale sequence in the Henry Mountains Basin may certainly exemplify this model. Perhaps diapiric movement of the Mount Ellen magmas was temporarily checked at each competent sandstone layer. Subsequent intrusion of sills and further laccolithic development could then have taken place in the immediately underlying incompetent or shaly formation. Increasing magmatic pressures would eventually overcome the internal strength of the roof, and diapiric movement would continue upward until the next competent stratum was encountered, where the process could be repeated.

Intrusive Forms

Deep laccoliths appear to be more sill-like than those mapped at the surface, probably because of two factors: higher confining pressures found at depth and less viscous magma due to higher temperatures. Higher confining pressures would have certainly been present at greater depths and could have effectively checked diapiric movement, transforming such action, for a short time, to lateral motion and resultant development of sills and laccoliths. Higher magmatic temperatures would have caused the margins of the lateral intrusions to remain hotter, allowing continued injection of magma. The prolonged presence of high pore fluid pressures may also have allowed more lateral-type intrusion causing a subsequent sill-like body. Higher magmatic temperatures, however, would have caused lower viscosities, apparently in contradiction to evidence presented by Hunt and others (1953, p. 145) that magmas of the Henry Mountains must have been exceedingly viscous, for they were able to float heavy hornblende inclusions. It is probable that the magmas, though viscous nearer the surface, were less viscous at depth.

The shallow intrusions are more bulging. This shape may be related to two factors: (1) decreased overburden pressures and (2) decreased magmatic temperatures. Decreased confining pressures would substantially reduce the amount of work necessary to lift and dome overlying strata. Hence, more lifting and deformation could be done for the same amount of magmatic energy, with resultant intrusive forms much more protruding than those seen at depth. Decreased magmatic temperatures would allow the margins of the intrusion to chill more rapidly. Chilled margins would reduce the effectiveness of pore fluid pressures and possibly inhibit the lateral invasion of strata. Lower temperatures of both the magma and shallower sediments would also cause viscosity to increase. It is likely that shapes of shallow intrusions may be a product of both reduced confining pressures and magmatic temperatures.

Brittle Deformation

Faulting identified around the laccoliths and bysmaliths may be the result of rapid rates of intrusion or minimal amounts of overburden pressure. Rapid rates of intrusion and high internal pressures are documented for the Mount Ellen stock by the occurrence of a peripheral shatter zone. Linear normal oblique faults and low-angle reverse faults mapped around the laccoliths, as well as radial normal oblique and high-angle peripheral faults mapped around the bysmaliths, could have also been caused by relatively high internal pressures and rapid rates of intrusion.

Minimal amounts of overburden pressure present over the complex may have allowed the roof rocks to respond brittlely as they were forced to enclose a greater volume. Brittle deformation around the laccoliths and bysmaliths is likely a product of both relatively rapid intrusion and decreased confining pressures.

Confining Pressures

From measured and average stratigraphic thicknesses, approximate lithostatic pressures can be calculated for each shaly interval in the Triassic to Cretaceous section, beginning with the Triassic Chinle Formation. The following assumptions were made: that the Tarantula Mesa Sandstone was the youngest stratum preserved in the Henry Mountains Basin; that lateral intrusions are intraformational and emplaced near the middle of the shaly formations; that average wet density for sandstones is 2.35 gm/m^3 (2,350 kg/m^3), and 2.40 gm/cm^3 (2,400 kg/m^3) for shales; that density remains constant with depth; and that sandstones and conglomerates have equal densities.

Thicknesses (m) of the overlying sandstones and shales were totaled separately and then multiplied by their assumed densities (kg/m^3). The total mass per unit area (kg/m^2) was then multiplied by the acceleration of gravity to produce the assumed pressures present (N/m^2). Pressures were then converted to bars (1 bar = 100,000 N/m^2).

On the basis of the assumptions listed above, the intrusion identified in the Webb Resources well, hosted by the Chinle Formation, would have experienced confining pressures of 451 bars. This sill-like intrusion lifted the eastern flank of the basin some 55 m at a distance of 10.6–9.6 km from a likely magma source. Intrusions in higher intervals may have experienced the following confining pressures: Carmel Formation—356 bars, Summerville Formation—304 bars, Brushy Basin Member of the Morrison Formation—265 bars, Tununk Shale—237 bars, Blue Gate Shale—153 bars, Masuk Shale—47 bars. These figures are probably best considered as minimum pressures present at the time of intrusion and may vary because of uncertainty on stratigraphic cover and rock density.

All of the common hosts, except for the Brushy Basin Member of the Morrison Formation, are overlain by a stronger roof of sandstone. Little is known about the deep intrusions hosted by the Chinle and Carmel Formations in the quadrangle, and intrusions that must have invaded the Masuk Shale have been eroded away. Of the intrusions exposed in the quadrangle, most were emplaced in the Blue Gate and Tununk Shales. The deep intrusions, particularly those hosted by the Chinle Formation, have experienced confining pressures of over 450 bars and illustrate sill-like forms, and those of higher intervals and less confining pressures are much more bulging. Perhaps these relationships are products of decreased confining pressures combined with the presence of stronger overlying roofs.

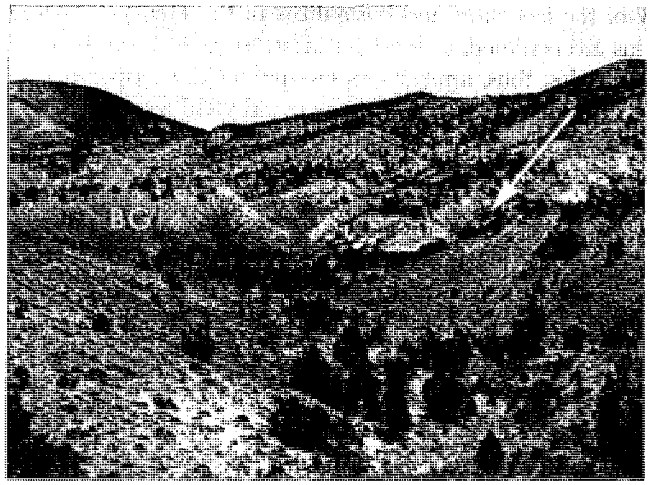

FIGURE 25.—*Ferron coal outcrop and overlying Blue Gate Shale (BG), east of Steven's Narrows. View is to the northeast. Arrow indicates coal zone.*

ECONOMIC GEOLOGY

COAL

Coal occurs in the Ferron and Muley Canyon Sandstones. Remnants of these units are mostly restricted to the southwest corner of the quadrangle. Other outcrops in the quadrangle are badly broken, having been sandwiched between intrusions, and no other coal exposures were observed. Ferron coal crops out on the monoclinal flexure east and northeast of Steven's Narrows (fig. 25). Coal at this locality is in lenticular beds and interfingers with carbonaceous shale. Thickness of the coal seams ranges up to 0.5 m (0–1.6 ft), with most outcrop sections only 0.1–0.2 m (4–8 in) thick. The coals are black, hard to moderately hard, cleated north–south to northwest–southeast in intervals of 2.5–5.0 cm (1–2 in). The cleats are coated with abundant iron sulfates and occasional gypsum. The coal is 70%–75% vitrain, and 25%–30% fusain. Near faults the coal shows abundant slickensides. Carbonaceous shale forms the floor and roof for most of the coal seams.

Beds above and below the coal zone of the upper Ferron Sandstone dip to the west and southwest 11°–22°. Faults of two sets displace the coal zone (see "Structures West of South Creek Ridge"). An east–west-trending normal fault has displaced one outcrop northeast of Steven's Narrows as much as 12 m. Numerous other north–south-trending faults occur along the monoclinal flexure, somewhat parallel to the fold axis, and have caused minor offsets in the coal zone, ranging from 1.5–3.0 m (fig. 24).

Stratigraphic and structural discontinuities make potential development of the coals of the Ferron Sandstone very unlikely. Though overburden is slight in the area east of Steven's Narrows, coal thickness does not warrant development. Multiple faulting of the coal seams further reduces the feasibility of development. Even in situ coal gasification appears likely to be hampered by the shallow burial and stratigraphic and structural complexities.

No coal outcrops were recognized in the Muley Canyon Sandstone. Law (1979) indicated that the coals are very lenticular south of Steven's Narrows. Just south of the quadrangle, in section 25, T. 32 S, R 9 E, Law (1979) reported that coal 0.7 m (2.4 ft) thick occurs in one zone. Whitlock (1984) reported the coal immediately south of Steven's Narrows occurs in two zones, is lenticular, and ranges from 0–2.1 m (0–7 ft) thick.

The Muley Canyon Sandstone dips to the west and southwest at 11°–17° and is offset by three normal faults, ranging from approximately 12–18 m in vertical displacement. Structure of the area is rather simple, but stratigraphic relations are much more complex, making possible coals of this part of the column unlikely prospects for future development.

PETROLEUM

Wells drilled in and adjacent to the quadrangle have all been dry and abandoned. Likely stratigraphic targets for production in the Henry Mountains Basin include Moenkopi, Kaibab, White Rim, Honaker Trail, and Paradox Formations. Oil shows in the Triassic and Permian beds are common, and several large tar sand deposits occur along the basin margin to the west and east. Petroleum potential for the basin has been described by Irwin and others (1980).

Faulting around the laccoliths, a shatter zone around the Mount Ellen stock, and other occurrences of brittle deformation suggest that the rate of intrusion was quite rapid. Hunt and others (1953, p. 165) reported that hornblende inclusions in the diorite porphyry suggest the magma was exceedingly viscous and that the temperature of the intrusion could not have exceeded 600° Celsius. Baking of the roof and floor rocks is slight. In many localities strata are altered only a few centimeters from the contact. Oil and gas could have been easily trapped updip in formations domed and subsequently ruptured by the stocks. Updip traps could be present along the wall of the stocks, similar to those found associated with salt diapirs in the Gulf Coast region.

METALS

Metal deposits were given only cursory attention in this study. About 75% of the gold, silver, and copper produced from the Henry Mountains has come from workings in Bromide Basin (Doelling 1980, p. 287). Doelling reported that since 1889 approximately 700 ounces of gold, 2,000 ounces of silver, and 17,500 pounds of copper have been extracted from ores of the Bromide Basin. Primary ore materials include chalcopyrite, pyrite, and specularite, and are generally found with quartz in breccia pipes and fissures of the Mount Ellen stock. The small and sporadic nature of the ore bodies makes potential future production appear limited.

The appearance of suspect hydrothermal alteration at the Wickiup Ridge laccolith is substantiated by the occurrence of sulfides, local bleaching, and a circular, 100-gamma magnetic anomaly on or under Wickiup Ridge (Affleck and Hunt 1980, p. 111).

No known placer gold deposits occur in the quadrangle, though some occur in the adjacent quadrangle to the east, apparently derived from the Bromide Basin area. Some potential for placer deposits may exist in the quadrangle along Crescent Creek. No known uranium-vanadium deposits occur in the quadrangle. However, substantial deposits occur in the Salt Wash Member of the Morrison Formation, some 4 km to the east, in the north–south-trending Henry Mountains mineral belt (Chenoweth 1980).

GRAVELS

Gravel deposits are abundant along the western and southern portions of the quadrangle. Thickness of the deposits is difficult to estimate but ranges up to 37 m. They consist of subangular to subrounded pebbles, cobbles, and boulders, some as large as 1.4 m in diameter, but most fragments fall into the 7–14-cm range (fig. 11). Pebbles and cobbles are of diorite porphyry, in a matrix of light brown, very fine to fine grained sand. They appear to be suitable for uses such as road base or concrete aggregates, but may need to be screened to remove oversized clasts. Such processing may be avoided by utilizing gravels in the alluvial fans found in the lower elevations east or west of the quadrangle. Deposits in the quadrangle that are readily accessible include gravels west of McClellan Spring, gravels in a beheaded pediment west of Birch Spring, and gravels in the Airplane Spring area.

Excessive removal of such gravels would destroy a major aquifer and could jeopardize the purity of local surface waters by exposing the mineral-rich Blue Gate Shale. Exhumation of this nature would activate stream-erosion processes. Erosion and leaching of the shales would pollute surface waters with added detritus and detrimental minerals such as gypsum.

WATER RESOURCES

Springs in the quadrangle generally occur near gravel/colluvium-shale contacts. Water stored in these highly permeable aquifers is derived from annual snow and rain. Yield as measured by Goode (1980, table 1) of the springs in the quadrangle varies from 11–454 liters per minute (3–120 gpm). For more information refer to Hunt and others (1953, p. 213), and Goode (1980).

No perennial streams are found in the quadrangle. Those of major importance—Bullfrog Creek, South Creek, Dugout Creek, Cedar Creek, Bull Creek, Granite Creek, Crescent Creek, Copper Creek, and Slate Creek—carry water most of the year but generally dry up during the summer months, except for periodic flash floods. Hunt and others (1953, p. 213) estimated the largest of these streams, Bull Creek and Dugout Creek, have annual discharge rates of a few thousand cubic meters (a few thousand acre ft). Copper, Crescent, and Granite Creeks may discharge a few hundred cubic meters (few hundred acre ft) annually, and the remaining streams even less.

SUMMARY

A thick section of Jurassic to Upper Cretaceous sedimentary rocks are exposed in the Mount Ellen Quadrangle. These strata represent environments that ranged from interdeltaic-coastal, shallow marine, and tidal flat of the San Rafael Group to fluvial, lacustrine, and floodplain of the Morrison and Cedar Mountain Formations. The Dakota Sandstone marks the beginning of a marine transgression that resulted in accumulations of the interfingering deltaic sandstones and marine shales of the Mancos Shale.

These rocks and others, now removed by erosion, were folded into the Henry Mountains basin by the early Tertiary Laramide orogeny. Subsequent to the folding, stocks of the Mount Ellen complex invaded strata along the eastern limb of the basin. During intrusion of the stocks, sill-like lateral intrusions invaded the incompetent strata, and overlying formations were lifted upward. As the stocks worked surfaceward, invading the shales and doming and rupturing the sandstones, the sill-like laccolithic intrusions became more bulging as magma temperatures dropped and confining pressures decreased.

Closer to the surface, a spectrum of intrusions developed. Some of the laccoliths remained concordant, folding the strata above them. Others developed linear normal faults in their roofs or low-angle reverse faults along their distal margins yet remained dominantly concordant. Still others became discordant. Roof rocks were displaced by high-angle faults along the distal margins of the intrusions. Some of the bysmaliths underwent continued intrusion, uplifting overlying strata, and resulting faults circumscribed the bysmaliths.

A great thickness of igneous material was inserted during development of the complex. A large dome formed, and erosion immediately began to carve into the highland. Erosion continues to date with streams carrying debris away from the peaks and depositing it on the flanks of the complex. Pediments document distinct periods of erosion.

Ferron Sandstone coals exposed in the southwestern corner of the quadrangle are thin and extremely lenticular. Subsequent structural deformation and their thinness have made mining of them not economical at present.

The appendix to this paper, manuscript pages 72–80 (single-spaced), is on file at the Department of Geology, Brigham Young University, where a copy may be obtained.

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