GEOLOGY OF THE RED HILLS AREA, IRON COUNTY, UTAH

by

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ABSTRACT

The Red Hills area comprises a small basin range block which is aligned with the northerly-trending Hurricane Cliffs but which lies immediately west of the Markagunt Plateau margin in southwestern Utah. The area is of considerable geologic interest because it lies in the Colorado Plateaus-Basin and Range transition zone and serves as a key to the geologic relationship of the plateaus and basin ranges.

The stratigraphic section of the area is similar to that of the plateaus and includes 6,000 to 8,000 feet of sedimentary and volcanic rocks which range in age from Jurassic to Quaternary. Rock units include the Navajo sandstone, Carmel limestone, Entrada, Curtis, and Winsor formations of Jurassic age; the Iron Springs sandstone of Upper Cretaceous age; the Claron (Pink Cliffs Wasatch) formation and a sequence of volcanic-derived sediments and acidic welded tuffs and lavas of early to middle Tertiary age; old pediment gravels of late Tertiary-early Quaternary age; and olivine basalts of Quaternary age.

In late Cretaceous time, the Iron Springs sandstone and older rocks were uplifted in an isolated welt, with northerly trend along the site of the Red Hills and Hurricane Cliffs, and thrust eastward toward the site of the plateaus. The Laramide fold complex was bevelled and covered by hundreds of feet of early to middle Tertiary rocks which accumulated in intermontane basins flanking the uplifted belt and which ultimately buried deeply-eroded remnants of the old welt.

In middle Tertiary time, the present arrangement of plateau and basin and range structural elements largely came into existence; the Hurricane fault zone, which was developed approximately coincident with the old buried fold axis south of the Red Hills area, is replaced northward by the easterly-trending Summit monocline which transfers the plateau margin abruptly eastward to the Paragonah fault zone at the margin of the Markagunt Plateau. Because of this Cenozoic monoclinal warping, transverse to the Laramide axis, abrupt plunge of the Laramide fold was imposed long after the fold had been formed, bevelled, and buried under hundreds of feet of Tertiary rocks. As a result of the eastward shift of the plateau margin, the Red Hills area and its segment of the Laramide fold lie several miles west of the plateau margin.

During mid-Tertiary faulting and warping along the plateau margin, the Red Hills area was broadly upwarped and bevelled at its southern end as plateau drainage was extended westward to the Great Basin. In late Tertiary-early Quaternary time, the Red Hills area was upfaulted between subsiding blocks of Parowan and Cedar City Valleys along the curving plateau margin. Quaternary basalts were locally erupted onto lower flanks of the rising range block of the Red Hills area, and the basalt sheets were broken by latest phases of uplift of the range block.

In consequence of uplift of the range block athwart the westward-flowing drainage from the high plateaus, Winn Creek, favored by only slight rise of the range block, and Parowan Creek, favored by relatively large discharge, maintained their antecedent positions and cut transverse gaps through the rising range block. Latest phases of uplift of the range block defeated Parowan Creek, causing abandonment of the gap and development of the Little Salt Lake playa in the Parowan Valley graben.

STRUCTURAL ELEMENTS OF THE PLATEAU-BASIN RANGE TRANSITION ZONE IN SW UTAH—NW ARIZONA

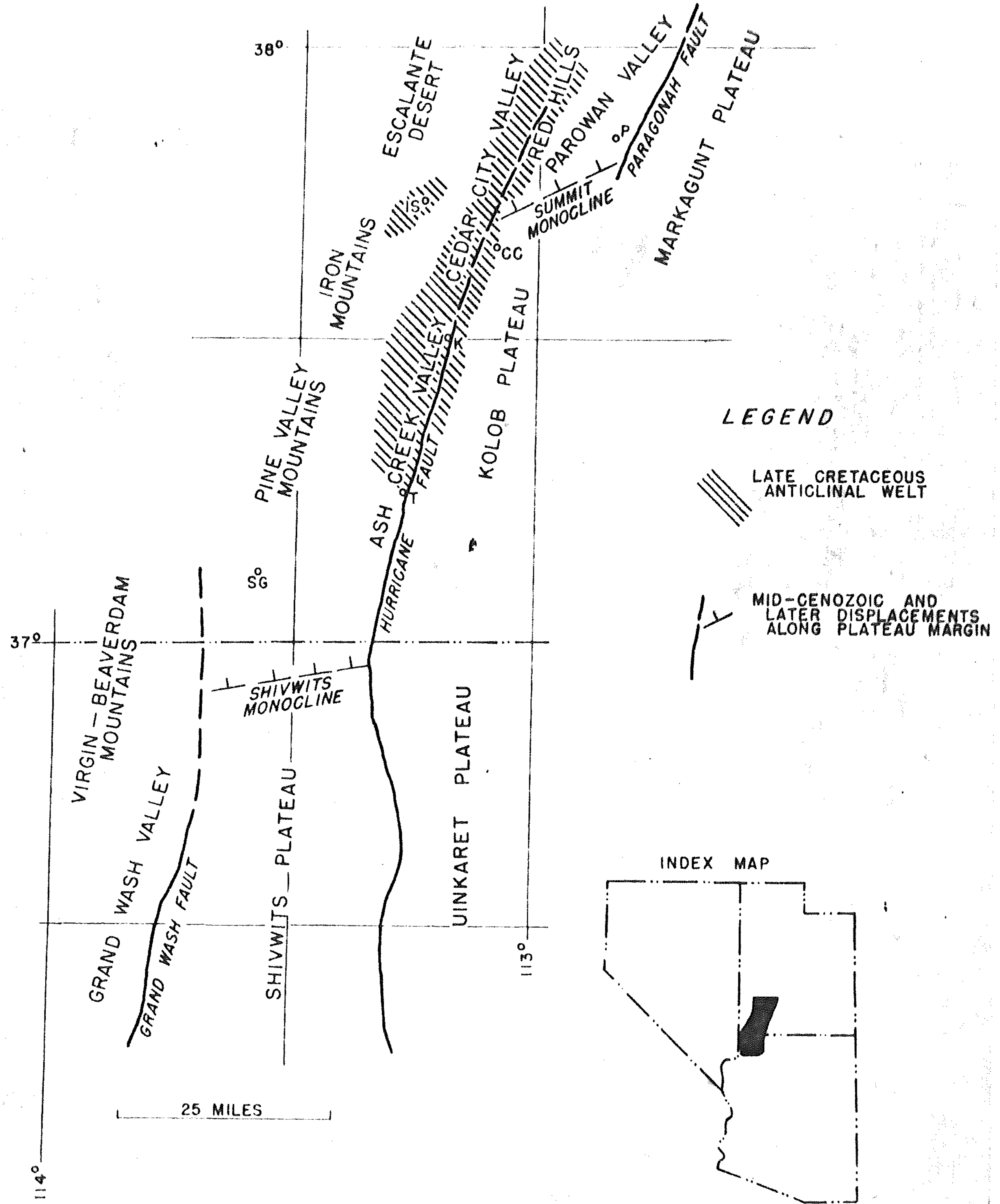


Fig. 1. SG, T, K, CC, IS, and P indicate St. George, Toquerville, Kanarraville, Cedar City, Iron Springs, and Parowan, Utah, respectively.

shifts abruptly eastward and continues northward from Paragonah along a fault scarp at the west margin of the Markagunt Plateau (Thomas and Taylor, 1946).

This repeated shifting of the plateau margin causes eastern portions of the Basin and Range province to have marked alignment and essential continuity with one segment of the Colorado Plateaus margin and to lie west of a more northerly segment of the plateau margin. These areas in the plateau-basin range transition zone can be expected to closely resemble the plateaus in their pre-block faulting geology and the basin ranges in their post-block faulting geology.

The Red Hills area lies in such a zone, aligned with and nearly continuous with the Hurricane Cliffs segment of the plateau margin but lying several miles west of the Markagunt Plateau margin. The study by the present writer was undertaken to determine the nature of the plateau-basin range transition zone in the Red Hills area and to determine to what extent the structure, stratigraphy, and geomorphology of the transition zone can be related to that of the plateaus and nearby basin ranges.

The only previous geologic investigation of the Red Hills area was of a reconnaissance nature in connection with hydrologic studies of Cedar City and Parowan Valleys (Thomas and Taylor, 1946). Thomas and Taylor mapped major Cenozoic faults which outline the Red Hills area and separate it from flanking basins, but the nature of their work prevented them from making a detailed study of regional geologic relationships. In the plateaus immediately east and south of the Red Hills (Gregory, 1949, 1950) and in the ranges of the Iron Springs district southwest of the Red Hills area (Mackin, 1947, and personal communication) detailed geologic studies have been made recently, and these studies have been referred to extensively by the present writer during preparation of this paper.

Generalized geology and physiography of the Red Hills area

The stratigraphic section includes 6,000 to 8,000 feet of sedimentary and volcanic rocks which range in age from Jurassic to Quaternary. Following essentially conformable deposition of Jurassic and Cretaceous formations, the rocks were folded and thrust faulted, bevelled, and covered by bouldery late Cretaceous-early Tertiary red beds and overlying pyroclastic and volcanic-derived sediments. With no appreciable hiatus, there followed an epoch of vast accumulation of early to middle Tertiary acidic volcanics of lava flow and *nuees ardentes* origin, similar in lithology and sequence to Tertiary volcanics which blanket thousands of square miles in southwestern Utah. In middle to late Tertiary time and continuing into Quaternary time, broad warping and block faulting, accompanied by local extrusion of basaltic lava, separated the range block of the Red Hills area from the rising plateau blocks and the subsiding Cedar City and Parowan Valleys, ultimately defeating drainage which formerly flowed westward in a canyon cut through the rising Red Hills.

Figure 2 is modified slightly from the only topographic map which is available for the Red Hills area (Kanab and St. George, Utah, reconnaissance topographic sheets of the Powell survey). Despite a very small scale of 1 inch to 4 miles and a contour interval of 250 feet, the map serves as a guide to major topographic features of the area.

geology.

The summers of 1950-51 were spent in the field, and geologic mapping was done directly on 9" x 9" contact prints of the SCS aerial photographs. Rocks are excellently exposed in the area, and tracing of geologic boundaries on the photographs is generally limited only by the alluvium of the basins.

Contacts and structural features were transferred, by inspection, from the contact prints to a controlled mosaic base map, from which the geologic boundaries and culture were traced. Drainage was traced from a Soil Conservation Service planimetric map and superimposed on the tracing of the photomap base. For simplification of discussion of locations in the text of this paper, the writer also superimposed the General Land Office grid, adjusted to the few section corners which were found during the course of the field work.

For purposes of construction of structure sections, a limited number of elevations was determined by aneroid and stereometer.

Acknowledgments

The writer has benefitted greatly from discussion of problems with Professor J. Hoover Mackin, who suggested the thesis area and supervised preparation of this paper. Special thanks are due one of Mackin's field assistants, Dr. Robert Christman of the U. S. Geological Survey, for comments on problems concerning the volcanic rocks of the area. Professors H. E. Wheeler, H. A. Coombs, and J. D. Barksdale have been especially helpful in problems of stratigraphy, petrology, and structure, respectively. The other staff members of the Department of Geology, University of Washington, have also given generously of their

time. The writer extends thanks to his wife, Dorothy, for very able assistance in the field and in preparation of the manuscript.

TABLE OF FORMATIONS

Red Hills area, southwestern Utah

	Formation	Thickness	Description
QUATERNARY	Alluvium	0-600'+	Unconsolidated sediments found locally in small valleys but chiefly as basin fill; deep wells indicate at least several hundred feet of thickness (Thomas and Taylor, 1946)
	Unconformity		
	Basalt	5-200'	Gray to black olivine basalt derived from local vents which are still marked by unmodified cinder cones
	Unconformity?		
—?—	Older alluvium	0-100'	Fanglomerate material, including fragments of acidic volcanic rocks and Tertiary and older sedimentary rocks; caps elevated terraces near south end of area
	Unconformity		
	*Purple Patch	0-50'	Purple dacitic welded tuff containing abundant biotite and hornblende; generally lies on gravels which are conspicuous as a red soil belt
	Unconformity		
	*Little Black Mountain	0-200'+	Black basalt and dolerite, chiefly agglomerate and breccia with minor flows; covers dozens of square miles in Black Mountains, north of Red Hills area, where bedded breccias are hundreds of feet in thickness
	Unconformity?		
	*Cane Spring	100-500'	Olive-drab tuff and cross-bedded and laminated tuffaceous sandstone, with minor amounts of volcanic mudflow(?) breccia
TERTIARY	*Giant City	100-200'	Salmon-pink quartz latitic welded tuff containing numerous red felsite fragments; characterized by massiveness, cavernous weathering
	*Gray Mountains	100-300'	Chocolate-brown to red andesite flows of highly variable texture
	Unconformity?		
	*South	0-150'	Salmon-pink dacitic welded crystal tuff containing abundant biotite and hornblende; platy

STRATIGRAPHY

The stratigraphic section of the Red Hills area includes 6,000 to 8,000 feet of sedimentary and volcanic rocks which range in age from Jurassic to Quaternary. The rocks are similar in lithology and sequence to rocks of the Markagunt and Kolob Plateaus (Thomas and Taylor, 1946; Gregory, 1950) and the Iron Springs district (Mackin, personal communication), but fossils are generally lacking for establishment of biostratigraphic correlations. Inasmuch as the Red Hills area is isolated by alluviated basins, physical correlations with sections of surrounding areas must be based on lithologic similarity, similarity of sequence, and similarity of structural relations.

The rock units described in the following pages are those which the present writer recognized as mappable lithologic units and represented on the geologic map (Plate I). Proposed correlations with rock units in surrounding areas and problems of temporal correlations will be discussed in descriptions of the individual formations.

Jurassic sequence

General statement

Thomas and Taylor (1946) recognized Navajo sandstone in Hieroglyph Canyon at the west end of Parowan Gap. In fault contact with the Navajo sandstone, they found blue-gray limestone and red beds which they tentatively designated as Wasatch. The present writer found Upper Jurassic fossils in the blue-gray limestone, and it now appears that the Navajo sandstone, the fossiliferous limestone, and the red beds constitute an essentially conformable sequence in west-central Parowan Gap and correspond in general to the Jurassic rocks of the Kolob Plateau (Gregory, 1950). Because of late Mesozoic folding and thrust faulting and limited exposure of the rocks in the Red Hills area, stratigraphic relations are not entirely clear, but the Red Hills Jurassic section differs in detail from that of surrounding areas. The following is a composite measured section of these rocks in Parowan Gap. The manner in which the individual units and the sequence vary from those of surrounding areas will be treated in a discussion of the individual formations.

Jurassic rocks — W½, Sec. 27; T33S-R10W; Iron Co., Utah

South wall of Parowan Gap

Iron Springs formation (Cretaceous) — sandstone, conglomeratic; greenish-gray to buff; limestone and quartzite pebbles in a calcareous sand matrix; thin-bedded to massive.

Unconformity?

Upper Jurassic rocks (undifferentiated)	Thickness in feet
11. Shale; gray	5
10. Sandstone, medium-grained; white; calcareous, moderately friable; massive, with a few thin lenses of buff medium-grained sandstone; silica sand prospect in this unit . .	70
9. Partly covered; chiefly thin-bedded silty sandstone . . .	35
8. Sandstone, medium-grained; white; massive; moderately friable; calcareous and somewhat arkosic; stained with limonite; a few thin-bedded sandstone partings	10
7. Poorly exposed; chiefly sandstone, fine-grained and friable; calcareous; greenish-gray, but stained with limonite; contains bits of coaly material locally; in beds a few inches to 1 foot thick	25

Unconformity?

6. Limestone; pale greenish-gray; silty, with clay partings, weathers into plates and chips $\frac{1}{2}$ to 1 inch thick; edgewise conglomerate of limestone plates and lenses in greenish sand matrix, near top	20
5. Sandstone, fine- to medium-grained; white to pale green; stained with limonite; calcareous, but soft and friable; in beds up to 1 foot thick	45
4. Sandstone, fine- to medium-grained; white to gray, but mottled dark red; extremely soft and calcareous; gypsiferous; interbedded with maroon silty shales and earthy sandstone; poorly exposed	140
3. Limestone; light gray; dense and massive, with a few thin intercalated sandstones; weathers into plates 1-6 inches thick; upper few feet extremely platy and breaks into wafer-thin chips that are highly ripple marked	50
Fault contact with Claron (Tertiary) formation	
Offset to north wall of Parowan Gap and measured west	
Fault contact with Iron Springs (Cretaceous) sandstone	
2. Limestone; pale blue-gray; massive; numerous joints that simulate bedding, but which are unreliable in determination of attitudes; rare bands of fossil shells only reliable guide to attitudes—thickness difficultly determinable; N80E 45W (overturned) . . .	400
1. Limestone; gray; silty; richly fossiliferous and oolitic; in thin beds that become silty toward base .	25
Unconformity?	
Navajo formation — sandstone, fine- to medium-grained; buff weathering; massive and cross-bedded, but slabby at top; poorly exposed here, but approximately 1,000 feet thick at Hieroglyph Canyon	1,000
Total thickness of Jurassic rocks	1,800

Navajo sandstone

Thomas and Taylor (1946) designated a massive, cross-bedded sandstone in Hieroglyph Canyon as Navajo sandstone on the basis of lithologic similarity to the well-known Navajo sandstone of the Colorado Plateaus.

The present writer has confirmed the correlation by noting that an identical sandstone which crops out in a dry gulch one-half mile east of Hieroglyph Canyon is overlain disconformably(?) by Upper Jurassic limestone that is identical with Upper Jurassic Carmel limestone which overlies the Navajo sandstone in the Kolob Plateau (Gregory, 1950). Exposure of the supposed top of the Navajo formation in the Red Hills area is limited to the single locality noted above, and the base of the Navajo is not exposed in the area. In the hogback through which Hieroglyph Canyon is cut, the maximum thickness of Navajo exposed is approximately 1,000 feet. This may represent nearly the entire unit, on the basis of comparison with a thickness of 1,100 feet reported by Gregory (1950) in the Cedar City area.

Because of strong deformation the Navajo sandstone of the Red Hills area is intensely jointed or shattered, but its over-all characteristics of uniform massiveness and complex cross-bedding are generally recognizable. In detail, the rock making up the bulk of the formation is a clean, fine- to medium-grained white sandstone, composed chiefly of well-sorted, rounded to sub-angular quartz grains (some of which are frosted), weakly cemented by lime. In contrast to the moderately friable, limy phases, parts of the Navajo are quartzitic; quartzite pebbles and cobbles of Navajo(?) lithology occur in the Claron (Tertiary) conglomerates. Iron-oxide imparts an over-all buff color to weathered sandstone surfaces, and limonite is concentrated along joint planes (Fig. 3).

Immediately north of Hieroglyph Canyon, where tilted and bevelled Navajo is overlain unconformably by Tertiary acidic volcanic rocks, the sandstone exhibits brilliant red, yellow, and purple staining, probably

Fig. 3. Indian petroglyphs chipped into limonite varnish on joint surfaces of Navajo sandstone at Hieroglyph Canyon, along Utah state highway #127.

due to baking and oxidation or recrystallization of ferruginous cement. On the other hand, bright red strata in the Navajo sandstone along the west margin of the Hieroglyph Canyon hogback about a mile south of Parowan Gap probably owe their red color to primary depositional environment rather than to baking at a contact with volcanics because the red color is not limited to a Navajo-Quaternary basalt contact at the crest of the hogback. In fact the red color is most strongly developed in the stratigraphically lowest portion of Navajo exposed in the Red Hills area.

Like most of the Navajo sandstone of the plateaus, where Gregory has assigned it a probable Middle Jurassic age, the formation of the Red Hills area has yielded no fossils. Because of very limited exposure of the Navajo in the Red Hills area, the present writer will not attempt any extended discussion of age or depositional history of the formation.

Carmel formation

The blue and gray limestones in the measured section of Jurassic rocks (units #1-3) which contain abundant Upper Jurassic fossils in their basal portion, and are in other respects similar to the Carmel formation of the Kolob Plateau (Gregory, 1950) are here designated as Carmel. The formation is exposed only in the western portion of Parowan Gap where it is in fault contact with Navajo sandstone at the east end of Hieroglyph Canyon and in questionable disconformable contact with Navajo sandstone in a small gulch (SE$\frac{1}{4}$, NE$\frac{1}{4}$, NW$\frac{1}{4}$; Sec. 27; T33S-R10W) one-half mile east of Hieroglyph Canyon. Most of the Carmel formation of the Red Hills area consists of massive limestone. The difficulty of determination of attitudes, coupled with intense folding and shearing of the limestone, casts some doubt on the validity of thickness measurements. Certainly the Carmel is no less than 300 feet thick; it may be as much as 500 feet thick.

Complete sections of the Carmel formation of the Kolob Plateau (Gregory, 1950) and of the Iron Springs district and Pine Valley Mountains (Mackin, personal communication) typically consist of three members: (1) basal thin-bedded limestones, with some gypsum; (2) intermediate shales or thin-bedded limestones; and (3) upper massive limestones, with a richly fossiliferous thin-bedded zone in the lower part and "ribbon beds" of rippled limestones in the upper part. In the Red Hills area, only the upper massive member is present, and exposures of the Navajo-Carmel contact are not clear enough to indicate certainly whether the lower thin-bedded and gypsiferous members have been eliminated by shearing or whether their absence is explained by a Navajo-Carmel disconformity.

Fig. 4. Rippled platy limestone at top of Carmel formation along south wall of west-central Parowan Gap (SW$\frac{1}{4}$; Sec. 27; T33S-R10W).

Most of the Carmel formation in the Red Hills area consists of dense and massive limestone almost barren of fossils. The lowermost exposed strata of the formation, however, are thin-bedded and highly fossiliferous. Some of the shaly limestones are essentially accumulations of fragmentary and abraded gastropod and pelecypod shells, crinoid columnals, and tiny oolites (0.1 to 0.5 mm. diameter). These basal limestones have yielded numerous fossils: *Pentacrinus asteriscus* Meek and Hayden, *Trigonia quadrangularis* Hall and Whitfield and *T. montanensis* Meek, *Camptonectes bellistriatus* Meek, *Ostrea* n. sp., and *Lima* N. sp. These genera and species are represented in a more complete fauna from the type locality of the Carmel formation (Gregory, 1950, p. 40) and collectively indicate an Upper Jurassic age. The abundance of tightly-packed and fragmentary marine fossils suggests that basal Carmel of the Red Hills area was deposited in a near-shore environment; the ripple-marked top of the Carmel and its apparently conformable succession by gypsiferous strata strongly suggest that shallow water conditions prevailed during deposition of most of the Carmel formation.

Entrada formation

The ripple-marked limestone at the top of the Carmel formation is succeeded abruptly by maroon and white, gypsiferous and limy sandstones and shales which are so weak that they crop out only in fresh stream cuts, on both walls of Parowan Gap, about 3/4 mile east of Hieroglyph Canyon. These weak beds, however, form a distinctive red soil belt between the bluish-gray beds of the Carmel below and the greenish-gray sandstones and limestones above. The red beds grade upward into somewhat more resistant bedded sandstones which are included with the red beds to constitute a mappable lithologic unit about 185 feet thick (units #4 and 5 of the measured section). Because of close similarity of these rocks to the friable Entrada sandstones resting on the Carmel limestone in the

Kolob Plateau (Gregory, 1950), these beds are here referred to as Entrada.

No fossils were found, and the entire formation is so poorly exposed that the writer will not attempt a discussion of depositional history. The presence of evaporites suggests a restriction of post-Carmel seas.

Curtis formation

On the south wall of Parowan Gap the Entrada sandstone is succeeded by greenish-gray argillaceous limestone which has been generally eliminated by thrust faulting on the north wall of the gap. This limestone resembles limestones of the Curtis formation of the Kolob Plateau (Gregory, 1950). On the basis of lithologic similarity, as well as stratigraphic position above probable Entrada, 20 feet of limestone (unit #6 of the measured section) are here assigned to the Curtis formation. The Curtis formation of the Red Hills area does not contain thick gypsum beds which characterize the Curtis formation of the Kolob Plateau, but a disconformity at the top of the formation in Parowan Gap, suggested by the presence of an edgewise conglomerate of limestone chips in a sandy matrix, may explain poor development of the Curtis formation in the Red Hills area.

The Curtis limestone of the Red Hills area has not yielded fossils, but its age is almost certainly Upper Jurassic, by comparison with fossiliferous and dated Curtis of the Kolob Plateau (Gregory, 1950).

Winsor formation

Above the distinctive greenish thin-bedded limestone of the Curtis formation are bedded and friable greenish sandstones (units #7-11 of the measured section) which strongly resemble Cretaceous sandstones that form most of the lower walls of Parowan Gap. With respect to their stratigraphic position between probable Curtis limestone and a conglomeratic sandstone near the base of the Cretaceous sequence, these friable sandstones most closely correspond to the Winsor (Morrison equivalent?) formation of the Kolob Plateau and Zion National Park area (Gregory, 1950). Most of Gregory's detailed work on definition and regional studies of the Winsor formation is still awaiting publication, and it is difficult to make anything more than a tentative assignment of the friable, greenish sandstones to the Winsor formation of Upper Jurassic or Lower Cretaceous age.

Cretaceous sequence

General statement

In the lower walls of Parowan Gap and in the southern Red Hills there is exposed a thick sequence of coal-bearing and marine fossiliferous sandstones which are grossly similar to drab Cretaceous rocks that form a series of rough benches and slopes between the colorful Pink Cliffs (Wasatch) and the brilliant White Cliffs (Navajo) of the Colorado Plateaus. Similar rocks are also present in the same stratigraphic position in the Pine Valley Mountains west of the Hurricane Cliffs (Gardner, 1941) and northward into the Iron Springs district (Mackin, 1947).

Gregory and Moore (1933) subdivided the Cretaceous rocks of the Kaiparowits Plateau into Dakota conglomeratic sandstone, Tropic shale, Straight Cliffs and Wahweap sandstones, and the Kaiparowits formation — a more or less standard section for south-central Utah. As Gregory traced the Cretaceous rocks westward to the Hurricane Cliffs and the western Markagunt Plateau, however,

> strata . . . characteristic of the Dakota, the Tropic, the Straight Cliffs, and the Wahweap formations occupy no persistent position. Laterally they intergrade and in vertical section they are duplicated. Furthermore, brackish water and marine deposits seem to be capriciously related and many fossils, including those most common, appear in the lowest and highest beds. In this assemblage of strata, so widely variable in composition, texture, bedding, and origin, attempts to establish tenable subdivisions proved futile. Reluctantly, the decision was reached to class them as undifferentiated Cretaceous deposits. (Gregory, 1950, p. 50)

It is noteworthy that Mackin (personal communication) had similar difficulties in establishing subdivisions of the Cretaceous Iron Springs sandstone in the basin ranges immediately west of the Hurricane Cliffs. The present writer was unable to subdivide the Cretaceous sequence in the Red Hills area.

Iron Springs formation

Rather than designate the undifferentiated Cretaceous rocks of the Red Hills area simply as "undifferentiated Cretaceous," the present writer has tentatively correlated them with the Iron Springs formation (Mackin, 1947) on the basis of similarity of lithology, sequence, and structural relations, and has adopted that formational name.

Section of Iron Springs formation — Sec. 26, 27; T33S-R10W; Iron Co., Utah

North wall of Parowan Gap

Claron formation — conglomerate; pebbles and cobbles of varicolored quartzite and dark limestone, up to 2 feet in diameter, in a fine to coarse, arkosic sand matrix; buff in lower part, pink in upper part; calcareous; lower part often weathers into conical pinnacles 10-50 feet high and 5-30 feet broad at base.

Unconformity (discordance slight at east end of Gap; 90° in central Gap)

Iron Springs formation	Thickness in feet
27. Sandstone, fine- to coarse-grained, with interbedded shales and thin impure limestones; gray to buff; calcareous; arkosic; in massive but non-persistent beds 1-25 feet thick, abundant leaf impressions locally and tubular limonite concretions that may represent fossil wood. (beds with gentle eastward dip)	500+
Fault contact with older Iron Springs rocks with attitude N30E 70W (overturned)	
26. Sandstone, medium-grained; gray to buff; calcareous; in beds 1-5 feet thick, interbedded with gray, calcareous shales and thin-bedded sandstones	135
25. Shale; gray; calcareous; contains abundant shell fragments.	5
24. Sandstone, medium-grained; gray to buff; calcareous; massive; abundant oyster shells in upper part, with interiors of shells filled with sand and occasional small quartzite pebbles; basal beds ripple-marked	15
23. Shale; like No. 25	10
22. Sandstone; like No. 24; in single massive bed	2
21. Shale; like No. 25	6
20. Sandstone; like No. 24	15
19. Sandstone; like No. 26, but with interbedded limestones composed essentially of broken oyster shells	270
18. Sandstone, medium-grained; white; massive, with some cross-lamination; calcareous; forms first rib east of coal prospect	20
17. Shale; gray to black; gypsiferous and carbonaceous, with thin stringers of bone and coal (coal reportedly 16-18 inches thick where mined many years ago in spur on north wall of Parowan Gap)	10
16. Limestone, sandy; gray to buff; thin-bedded	1
15. Shale; gray; calcareous, with thin beds of shaly limestone containing numerous but poorly-preserved gastropods	10

14. Sandstone, fine- to medium-grained; white; strongly calcareous and resistant; pitted weathered surfaces; moderate cross-lamination; occasional oyster shell fragments; forms first prominent rib west of coal prospect visible north of road through Parowan Gap . . 20

13. Limestone, shaly, gray; composed chiefly of shell fragments in a chalky matrix; grades upward into thin-bedded siltstones and chalky sandstone 10

12. Sandstone; gray to brown; strongly calcareous; in single massive bed 5

11. Shale; gray; calcareous; grades upward through thin-bedded sandstone into sandy limestone, shaly limestone, and calcareous shales; limestones are dirty and composed chiefly of shell fragments and bits of coaly material 30

10. Sandstone; like No. 23; forms second prominent rib west of coal prospect 15

9. Sandstone, fine- to medium-grained; gray to buff; strongly limonitic and interbedded with maroon shales and thin yellow sandstones; forms a broad belt on both walls of Parowan Gap, with ribs of brown sandstone alternating with maroon soil slopes on the shales 420

8. Sandstone, fine- to medium-grained; white, but somewhat stained with limonite; forms a massive ridge with narrow covered intervals on sandy shale 60

7. Sandstone, medium-grained; gray to buff; calcareous, in limonite-stained beds 1-20 feet thick, with minor amounts of thin-bedded fine-grained sandstone and maroon shales 520

6. Sandstone, medium-grained; gray to buff; calcareous; local concentrations of limonite along joint planes; in single massive bed 35

5. Sandstone; like No. 6, but in beds 1-2 feet thick, with thin siltstone partings 15

4. Poorly exposed; chiefly maroon shales and thin interbedded fine-grained sandstones; grades upward into buff, thin-bedded sandstone 30

3. Sandstone, fine- to medium-grained; white to buff; strongly stained with limonite; calcareous; forms massive rib; some cross-lamination 10

2. Sandstone, fine- to medium-grained; gray, but mottled purple; thin-bedded and interbedded with purple shales, grading upward into gray and maroon-mottled calcareous shales; sandstone is locally quartzitic . . . 25

Offset to south side of Gap

1. Sandstone, medium- to coarse-grained; white; extremely friable except where locally tightly cemented with limonite; differential weathering of cement gives rise to honeycombed cavernous ledges; in beds 1-5 feet thick, with some cross-lamination; numerous lenses and beds of pebble conglomerate up to 20 feet thick; pebbles of quartzite, limestone, and black and brown chert up to 3 inches, average 1 inch in diameter 35

Total thickness of Iron Springs fm. 2,250 +

Unconformity?

Winsor formation -- sandstone, fine- to medium-grained; white to greenish-gray; bedded to massive.

The formation has yielded only a few poorly-preserved and non-diagnostic fossil leaves at the type locality (Mackin, personal communication), and its age is in question, although its position between Upper Jurassic and Tertiary(?) rocks suggests a Cretaceous age. In the Red Hills, fossils are rare in the formation, but sandstones and shales intercalated with thin coal beds near the middle of the sequence have yielded a few poorly-preserved gastropods (*Glauconia coalvillensis* Meek and *Cyrodes depressa* Meek) and oysters. Thin oyster shell biostromes, identical with those described by Gregory from fossiliferous strata of Coloradoan age in the Markagunt Plateau, are also found interbedded with the fossiliferous sandstones and shales of the Red Hills area. The uppermost beds in the formation in the southern Red Hills have yielded poorly-preserved leaf impressions and limonitized wood fragments like uppermost undifferentiated Cretaceous (Coloradoan?)

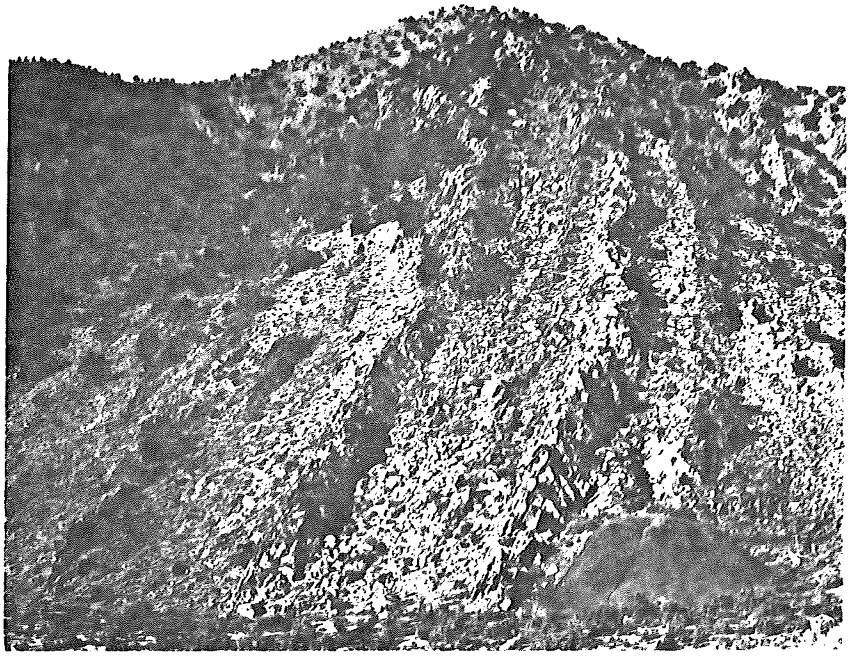


Fig. 5. Coal-bearing and marine fossiliferous sandstones, shales, and limestones of the Upper Cretaceous Iron Springs formation in central Parowan Gap (units #9-19 of measured section).

rocks of the Markagunt Plateau. On the basis of this meager faunal evidence, the Iron Springs formation of the Red Hills area appears to be largely Upper Cretaceous, probably chiefly Coloradoan, in age.

The lower half of the Iron Springs formation in the Red Hills area has yielded no fossils, but it may be basal Upper Cretaceous or Lower Cretaceous in age. Although Lower Cretaceous rocks are generally regarded as absent in southwestern Utah (Gregory, 1950), the evidence is of a negative character — no fossils found in strata between Coloradoan faunal zones a few hundred feet above the base of the Cretaceous sequence and Argovian faunal zones several hundred feet below the top of the Jurassic sequence. Although the Iron Springs formation at its type locality and in the Red Hills area is conglomeratic and rests with unconformity on Upper (but not uppermost) Jurassic rocks, the time value of the unconformity is indeterminable in the absence of fossils.

No statement of areal stratigraphic variation will be attempted here because exposure of the lower four-fifths of the Iron Springs formation in the Red Hills area is limited to the walls of Parowan Gap and to a small area about one mile south of the Gap. These lower Iron Springs strata are vertical or overturned and highly faulted; measured thicknesses are only approximate.

Late Cretaceous-early Tertiary sequence

General statement

In the Red Hills area, Iron Springs sandstone and older rocks were overturned and thrust eastward over nearly flat-lying upper Iron Springs strata. The entire sequence was bevelled and covered discordantly by bouldery conglomerate, about 200 feet thick, which grades upward into red beds that are almost identical with Wasatch (Eocene) strata of the Pink Cliffs of the Markagunt and Paunsaugunt Plateaus. Similar structural and stratigraphic relations are exposed in other basin ranges immediately west of the Hurricane Cliffs — in the Iron Springs district (Mackin, 1947) and along the east flank of the Pine Valley Mountains (Gardner, 1941). Except along isolated Laramide welts of the Kanarra fold, Waterpocket flexure, and East Kaibab monocline, the pre-Tertiary rocks of the plateaus of southwestern Utah are generally concordant with overlying Tertiary rocks (Gregory, 1950).

In the extreme western portion of the Markagunt Plateau, bouldery conglomerate at the base of Pink Cliffs Wasatch red beds rests disconformably on Kaiparowits sandstone of late Cretaceous age (Gregory, 1950,

p. 56). The Kaiparowits formation includes thick lenses of bouldery conglomerate that is similar in texture and composition to the overlying Wasatch basal conglomerate, and an important question arises regarding the relationship of the two conglomerate units of the Markagunt Plateau to the single conglomerate unit of the basin ranges.

Problem of physical correlations and age relations

Where the Kaiparowits formation is exposed around the margins of the Markagunt Plateau and eastward into the Paunsaugunt Plateau, it is disconformable on Cretaceous rocks equivalent to the Iron Springs formation, and there is an abrupt change from generally marine Coloradoan faunas of the Iron Springs equivalents to terrestrial Laramie or latest Cretaceous floras and fresh-water faunas of the Kaiparowits formation (Gregory, 1950, 1951). Thus, an hiatus which involves all of Montanan and perhaps part of Coloradoan time is indicated. Inasmuch as the Kaiparowits and older Cretaceous rocks are sensibly concordant in the Markagunt Plateau, any diastrophism responsible for the hiatus was clearly of epeirogenic nature in the plateaus.

In central Parowan Gap a conglomerate unit beneath Eocene(?) red beds rests with 90° angular unconformity on Iron Springs sandstone and older rocks. On the basis of position immediately beneath Eocene(?) red beds, the conglomerate would be regarded *a priori* as equivalent to the basal conglomerate of the Wasatch formation of the Markagunt and Paunsaugunt Plateaus (Gregory, 1951). On the other hand, the lower half of the conglomerate unit of the Red Hills area very closely resembles Kaiparowits conglomerate of the Markagunt Plateau with respect to lithology, style of weathering into conical pinnacles, and expression as barren white areas on aerial photographs. If the basal portion of the conglomerate unit of the Red Hills area is equivalent to the Kaiparowits formation, orogenic movements of late Coloradoan or Montanan age are indicated in the Red Hills.

On the bases discussed above, it appears that the single conglomerate unit of the Red Hills area is equivalent to the Kaiparowits formation and the basal conglomerate of the Wasatch formation of the Markagunt Plateau. The following interpretation of geologic events seems in best accord with late Cretaceous-early Tertiary stratigraphic and structural relations exposed at scattered localities in eastern Iron County, Utah — as a northerly-trending fold rose near the site of the Red Hills during late Cretaceous time, marine or brackish water environments were replaced by a terrestrial piedmont environment; streams were established across tilted strata, which are now exposed in Parowan Gap, bevelling them and depositing coarse and angular gravels on the eroded surface; these gravel deposits overlapped westward on bevelled flanks of the late Cretaceous fold and interfingered eastward with floodplain sands and silts of the Kaiparowits formation of the plateaus. Lenticular conglomerates in the Kaiparowits formation of the western Markagunt Plateau represent local channel gravels of shifting streams.

By latest Cretaceous or early Eocene time, streams flowing eastward away from the mountain belt had spread gravels over vast areas, blanketing Kaiparowits deposits with bouldery gravels which constitute the upper part of the late Cretaceous-early Tertiary conglomerate unit of the Red Hills and the Wasatch basal conglomerate of the Markagunt Plateau.

Stratigraphic nomenclature

From evidence presented previously, it is suggested that Eocene(?) red beds and the underlying conglomerate unit of the Red Hills area may be collectively equivalent to the Wasatch and Kaiparowits formations of the Markagunt Plateau. In the Red Hills area, it would be questionable procedure to designate the red beds as Wasatch and the underlying conglomerate as Kaiparowits, for the conglomerate may be equivalent to both the Kaiparowits formation and the basal conglomerate of the Wasatch formation of the Markagunt Plateau. Furthermore, the Wasatch of southern Utah can be referred to the Wasatch type locality in northern Utah and southwestern Wyoming only by way of rough comparison but not direct tracing with "Wasatch" of central Utah. Recently, "Wasatch" of central Utah has been shown to have a far greater stratigraphic range than type Wasatch, and the name has been abandoned (Spieker, 1946). With stratigraphic terminology of dubious validity and with probable lack of equivalence between late Cretaceous-early Tertiary rock units of the Markagunt Plateau and the Red Hills area, it is necessary to adopt a new formational name or to make use of one that is already in use for equivalent rock units, outside the plateaus.

In the Iron Springs district several miles southwest of the Red Hills area, folded Iron Springs sandstone and older rocks are bevelled and overlain unconformably by conglomerate and Eocene(?) red beds which are collectively designated as the Claron formation (Leith and Harder, 1908; Mackin, 1947). These rocks of the Claron formation are identical with the conglomerate unit and overlying red beds which lie with angular unconformity on bevelled Iron Springs sandstone and older rocks in Parowan Gap. The present writer has, therefore, adopted the name Claron

Unconformity
Claron formation

	Thickness in feet
28. Poorly exposed; chiefly silty limestone; gray, but mottled red; many coarse calcite veinlets; interbedded with red shales and siltstones	45
27. Limestone; pink; earthy and nodular; veined with coarsely crystalline calcite; upper part bleached white	25
26. Poorly exposed; chiefly silty limestone; mottled yellow, purple, and red; siltstones and shales intercalated with limestones; minor non-persistent ledges on the mottled limestones and covered slopes on siltstones and shales	160
25. Limestone, somewhat silty; mottled pink; massive; abundant small geodes and veinlets filled with coarse calcite	10
24. Siltstone; calcareous; red; interbedded with red shales and thin gray platy sandstone	25
23. Limestone; gray to white; somewhat silty; roughly bedded in beds 5-10 feet thick; grayish algal or concretionary structures locally abundant; veined with coarse calcite; the upper of two conspicuous white limestones in hills north of Winn Gap	25
22. Sandstone, fine to medium; gray, but washed red; in beds 1-3 feet thick, interbedded with red platy sandstones, siltstones, and shales	55
21. Covered; red soil belt; chiefly red siltstones and shales	30
20. Limestone, somewhat silty; white; intricately veined, with gray matrix enclosing white fragments; occasional tiny blue chalcedony veinlets; no algal structures readily apparent, but rock is highly brecciated like many reported algal limestones; faintly mottled pink and purple; nodular weathering; the lower of two conspicuous white limestones in hills north of Winn Gap; forms massive caprock of White Butte west of Summit	35
19. Sandstone, fine to medium; gray, but washed red; strongly calcareous grading upward into silty red limestone which grades upward into pink and purple silty limestone and siltstones	25

18.	Partly covered; chiefly thin silty red limestones and interbedded gray and red shales and siltstones	105
17.	Sandstone, fine; gray, but washed pink; in single massive bed	5
16.	Sandstone, fine; red; thin-bedded and platy	15
15.	Sandstone, medium; gray; friable; weakly calcareous; grades upward into mottled yellow, purple, and greenish silty algal limestone	15
14.	Partly covered; chiefly mottled purple and red silty limestones	55
13.	Sandstones, medium- to coarse-grained; locally conglomeratic; calcareous; gray, but washed red; massive, locally cross-laminated; prominent ledge maker	55
12.	Partly covered; chiefly red platy fine-grained sandstones and calcareous siltstones; a few thin nonpersistent ledge-making sandstones	45
11.	Sandstone, medium- to coarse-grained; gray, but washed red; calcareous; platy in lower part; massive and conglomeratic in upper part, with quartzite and limestone pebbles up to 6 inches, 2 inches average diameter	25
10.	Limestone, somewhat silty; gray, but washed red; nodular; numerous "algal biscuits" or marl balls up to 1 inch in diameter; forms prominent ledge	5
9.	Siltstone; calcareous; forms deep-red soil slope	20
8.	Conglomerate; quartzite and black limestone pebbles up to 1 inch diameter, with lenses of fine- to medium-grained gray calcareous sandstone up to 5 feet thick; forms conspicuous ledge	25
7.	Covered red soil belt; chiefly red siltstones and red silty limestones; some thin non-persistent pebble conglomerate lenses; forms low rolling hills, with small subdued cuestas on more resistant limestone and sandstone lenses	250
6.	Sandstone; like No. 15	15
5.	Limestone, silty; mottled yellow, purple, and red; in beds up to 2 feet thick; forms rough slopes	30
4.	Poorly exposed; chiefly red silty limestones and siltstones	35

3. Sandstone; like No. 15	5
2. Partly covered; chiefly red silty limestones and calcareous siltstones	60
1. Conglomerate; with pebbles and cobbles of white, purple, pink, yellow, and brown quartzite up to 10 inches; pebbles and cobbles of gray, black, and brown limestone and chert up to 6 inches in diameter; in a gritty arkosic sand matrix weakly cemented with lime; grades upward into pebble conglomerate in a pinkish matrix of fine- to medium-grained sand tightly cemented with lime; minor interbedded medium- to coarse-grained sandstones	150
Total thickness of Claron formation	1,350

Unconformity
Iron Springs formation — gritty arkosic buff-weathering sandstones, locally containing numerous leaf impressions; locally mottled and stained purple.

Section of Claron formation in northern Red Hills, Iron County, Utah

Section measured north of Parowan Gap, along east side of Red Hills

Jackrabbit formation — extremely poorly exposed; chiefly volcanic ash and tuff; pale green to white.

Unconformity(?) Claron formation	Thickness in feet
22. Poorly exposed; chiefly thin conglomeratic sandstones, platy red sandstones and siltstones, and purple-mottled limestones; thickness estimated because of difficulty of placing contact with overlying formation	100
21. Sandstone, conglomeratic; vari-colored limestone and quartzite pebbles in about equal amounts, some chert pebbles, and occasional pebbles of pink-and-purple-mottled limestone that very closely resembles that of the underlying Claron red beds; pebbles loosely packed in a medium- to coarse-grained arkosic matrix that is highly calcareous; in beds 2-10 feet thick	65

20.	Sandstone; medium- to coarse-grained; calcareous; gray, but washed light pink to red; interbedded with thin earthy limestones and red calcareous siltstones; this unit forms rough benches and slopes with non-persistent ledges throughout; becomes more calcareous toward the top and terminates in a purple earthy limestone with sandstone lenses	35
19.	Sandstone; silty and extremely platy; gray, but washed red; weak and forms slope	15
18.	Conglomerate; abundant gray and black limestone pebbles and cobbles up to 6 inches in diameter, and some white quartzite pebbles; occasional pebbles of limestone that closely resembles some of the Claron limestones below; all in a purple-mottled fine- to medium-grained sand matrix that is highly calcareous and resistant to weathering; forms cap of prominent cuesta near north end of Red Hills, along temporary road that leads off into Jackrabbit	50
17.	Sandstone; like No. 20	350
16.	Limestone; earthy; massive; nodular weathering; interbedded with platy calcareous sandstones; limestones are yellow and washed red; sandstones are gray, but washed red	40
15.	Sandstone, gritty and arkosic; calcareous; gray, but washed light pink; somewhat friable	35
14.	Partly covered; chiefly silty, mottled limestone with a few pebble conglomerate lenses	50
13.	Sandstone, conglomeratic; gray to buff; quite friable; weakly calcareous; some pebble lenses up to 15 feet thick, but these are non-persistent and form discontinuous but prominent light-colored blotches among the red limestone slopes	40
12.	Limestone, silty; mottled purple and red, with occasional thin lenses of gray friable sandstone and pebbly conglomeratic sandstone; earthy members make slopes and sandy members make ledges about 1 foot thick	50
11.	Conglomerate; black limestone and quartzite pebbles in about equal quantities; with lenses of medium- to coarse-grained, calcareous sandstone	40
10.	Limestone, silty; nodular; mottled purple and red; light pink where not overlain by red beds; hard and forms bench	80

9. Partly covered; chiefly thin-bedded calcareous sandstone and nodular sandy limestone	35
8. Sandstone, conglomeratic; quartzite and black limestone pebbles up to 4 inches (about 1/3 of pebbles are limestone) in medium- to coarse-grained sand matrix; gray toward the top, but grades downward through highly calcareous sandstone into red- and purple-mottled sandy and silty limestone	75
7. Sandstone, conglomeratic; quartzite and black limestone pebbles (about 1/3 of the pebbles are limestone) in medium to coarse arkosic sand matrix; gray, but washed red; upper part is highly calcareous and grades upward into yellowish sandy limestone	15
6. Limestone, silty; mottled purple and yellow; nodular weathering, but surfaces of more massive blocks are extremely pitted and rough; thin red arkosic sandstone parting in the middle of this unit; upper part of the unit is yellow limestone; numerous algal balls and colonies up to 6 inches in diameter throughout most of the unit; forms resistant but highly variable ledge throughout much of northern Red Hills	70
5. Sandstone, conglomeratic; chiefly quartzite pebbles up to 1 inch, in a medium-to coarse-grained sand matrix; gray, but washed red	15
4. Partly covered; chiefly thin pebble conglomerates and interbedded red platy sandstones	50
3. Conglomerate; quartzite and black limestone pebbles (in ratio of 10:1) up to 6 inches, in fine- to medium-grained sand matrix; highly calcareous; interbedded with thin red sandstones and nodular yellow and purple-mottled limestones that are non-persistent; upper few feet of the unit become less conglomeratic and grade upward into a pink- and purple-mottled limestone which caps a fairly persistent bench of variable thickness; the limestones contain numerous greenish algal balls up to 1 foot in diameter, and the conglomerate locally contains numerous calcite geodes up to 2 inches in diameter	40
2. Poorly exposed; chiefly thin sandstones and mottled limestones	40
1. Conglomerate; vari-colored quartzite pebbles, cobbles, and boulders up to 2 feet in diameter, and some black limestone pebbles and cobbles up to 6 inches,	

in fine- to coarse-grained sand matrix; minor gritty sandstone lenses; lower half of this unit has a buff-weathering medium- to coarse-grained arkosic sand matrix, and weathers into distinctive cones and pinnacles 30 to 50 feet high and 10 to 30 feet broad at the base; upper part is pale pink to red and has a fine- to medium-grained sand matrix tightly cemented with lime. In the upper part of this unit, limestone pebbles increase in relative abundance up to 10% of pebble fraction; the uppermost few feet are very highly calcareous and grade laterally and vertically through highly calcareous conglomerate and silty sandstones into red- and purple-mottled silty limestone chiefly of algal origin; this thick unit of conglomerate forms the upper part of an impressive cliff north of state highway #127 near the east end of Parowan Gap	210
Total thickness of Claron formation	1,500

Unconformity

Iron Springs formation — gritty arkosic sandstones with interbedded gray shales and thin, impure limestones.

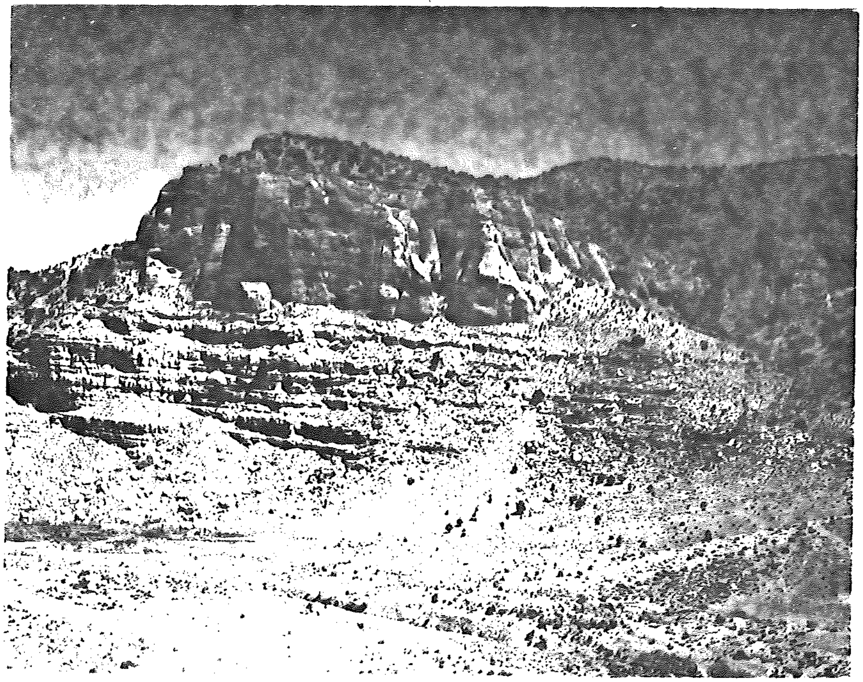


Fig. 6. North wall of Parowan Gap along Utah state highway #127, immediately west of Little Salt Lake, showing bedded Iron Springs sandstones, massive basal conglomerate member of Claron formation, and lower part of red beds member of the Claron.

Fig. 7. Typical texture of Claron basal conglomerate; quartzite and limestone pebbles, cobbles, and boulders in a limy, arkosic sand matrix.

The basal conglomerate member is well-developed throughout the area, and although lenticular pebbly conglomerates occur in middle and upper portions of the formation, they are never confused with the massive, persistent, coarse conglomerate at the base of the formation. In the west-central part of the area, the basal conglomerate member rests on bevelled edges of folded and faulted Mesozoic strata. Even though the conglomerate contains some fragments apparently derived from the underlying Navajo sandstone and Carmel limestone, most of the fragments are exotic quartzites, dense limestones, and Paleozoic fossiliferous limestones, unlike any rocks now known to be exposed in eastern Iron County, Utah (Gregory, 1950). The source of these rocks is not known to the present writer, although Mackin (personal communication) has noted possible source rocks in ranges near the Utah-Nevada state line, west of the Iron Springs district. Probably the dense limestones were derived, in large part, from Kaibab limestone which is now downfaulted beneath Cedar City Valley but which is known (Gregory, 1950) to have participated in Laramide folding in southwestern Utah.

The surface on which the basal conglomerate was deposited appears to have less than 10 feet of local relief, when it is viewed in vertical section on distant canyon walls, but careful tracing on the walls of Parowan Gap shows local relief of at least 30 feet on the surface of unconformity. About a mile north of Parowan Gap (W½, W½; Sec. 23; T33S-R10W) Claron basal conglomerate and overlying red beds apparently overlap an ancient hill of Navajo sandstone, and the surface of unconformity has local relief of about 100 feet. In the extreme western portion of the Red Hills area (SE¼, SE¼; Sec. 21; T33S-R10W and SW¼, NE¼; Sec. 28; T33S-R10W) immediately east of Hieroglyph Canyon, nearly flat-lying upper Claron limestones and sandstones and overlying acidic volcanics are in apparent depositional contact with steeply-dipping Navajo sandstone and Carmel limestone. Although the contact is obscure, it does not seem to be a fault. If the contact is a depositional contact, local relief of at least 1,000 feet is indicated for the eroded surface on which Tertiary rocks were deposited. In view of resistance of the massive Navajo sandstone to erosion and probable nearness of the western Red Hills area to a piedmont portion of Laramide uplift in central Iron County, 1,000 feet of local relief is not surprising. The Navajo sandstone erosion remnant which was overlapped by upper Claron and acidic volcanic rocks probably extended as a more or less continuous, north-northeasterly trending ridge along the old piedmont surface.

The basal conglomerate member passes rather abruptly upward into red earthy limestones, siltstones, feldspathic sandstones, and limestone pebble conglomerates of the middle Claron red beds member. This member is the most extensively exposed unit in the area, and it is responsible for brilliant hues of the Red Hills. Although local vertical sections show well-defined subdivisions of this red beds sequence, sandstones and limestone-pebble conglomerates grade laterally, through limy sandstones and siltstones into impure limestones, usually within distances of 100 feet.

The red beds member is characterized by extreme irregularity of bedding, with many diastems. Such irregularities of bedding, textures, and composition are characteristic of fluviatile sediments but incompatible with classical ideas of lacustrine origin of the Pink Cliffs Wasatch and its equivalents (Dutton, 1880).

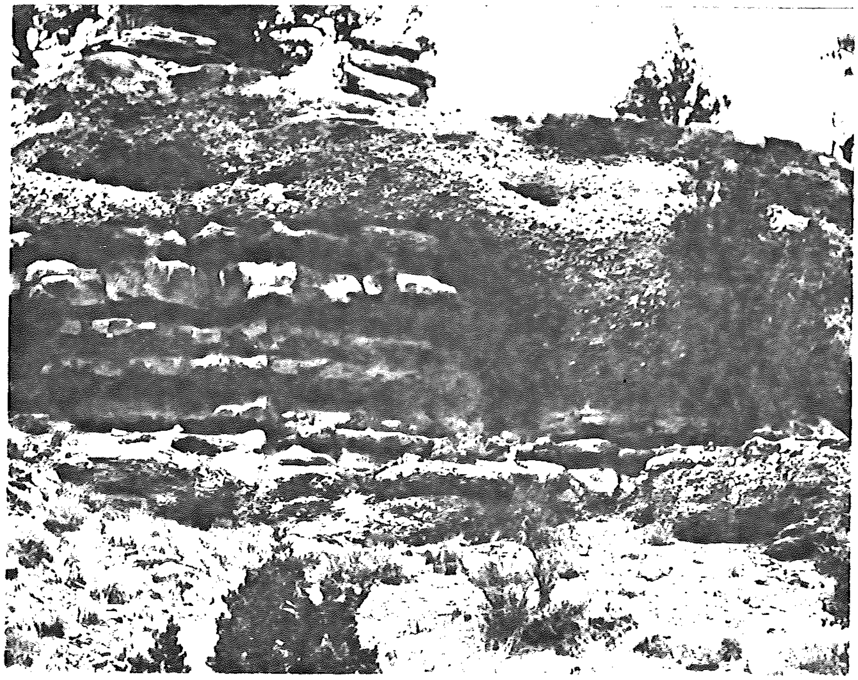


Fig. 8. Typical, irregular conglomerate unit in fluviatile, middle Claron rocks in east fork of Whitney Canyon, south of Parowan Gap.

On the other hand, great quantities of marlstone and concentrically-laminated spheroidal "marl balls" up to 1 foot in diameter, similar to those commonly associated with fresh-water lake deposits, occur in the limy siltstones and silty limestones and present a special problem. Mawson (1929) has described "algal balls" from intermittently flooded depressions in southwestern Australia; the "balls" reportedly range up to 8 inches in diameter and locally form "algal ball" pavements. The supposed algal structures which are locally developed in the red beds member of the Claron formation probably were formed in this manner in intermittent floodplain lakes. Brecciated structures in the associated limestones may represent intermittent desiccation and shrinkage fracturing of algal marls.

Although the red beds member appears to consist entirely of red and orange rocks, only the finer-grained, earthy sediments are red, and their brilliant colors are washed over drab gray sandstones and conglomerates. A major problem of the red beds member is the origin of alternating red and drab beds. Much has been written on the subject of origin of red beds, but a recent summary which is of particular significance in the present problem is found in a paper by Van Houten (1948) in which color-banded Cenozoic deposits of the Rocky Mountain region are interpreted as deposits in a seasonally humid savannah environment in intermontane basins associated with rising mountains of late Cretaceous-early Tertiary time. The color is due to hematite in various concentrations or states of aggregation, and Van Houten concludes that ferruginous clastics were derived from red rocks or red soils of well-drained humid uplands at the margins of the basins. The initially red sediments retained their red color, if they were deposited in open country, and lost their red color, by reduction of ferric iron and partial leaching of the resulting ferrous iron, if deposited in a forest environment. Shifting environments of sedimentation and vegetation caused lateral and vertical variations in colors of the sediments, largely independent of grain size of the sediments.

In the Red Hills area, no lignites or other indexes of swampy and forest environments are present in the red beds member of the Claron, and it is likely that the basin of deposition of the Claron red beds had a very sparse vegetative cover. Initially red fine-grained sediments derived from red fine-grained rocks and/or red soils of uplands flanking the basin were locally deposited on floodplains at the site of the Red Hills area and suffered little reduction of ferric pigments. Coarse clastics deposited in channels of shifting streams were apparently derived from non-red rocks, because they are free of organic debris which could have reduced them and are red only where they grade into the silty and marly portions of the Claron.

In the northern Red Hills, deposition of fluviatile sediments continued on into the upper part of the Claron, but in the southern Red Hills the fluviatile environment was temporarily modified by intermittent development of a shallow lake, in which two pure, white limestone beds were deposited. Evidence for a lacustrine environment is not conclusive, but the writer believes that the following features of white limestones of the upper member of the Claron formation point to a lacustrine origin. The limestones are persistent beds of nearly pure limestone, each about 30 feet thick, without interbedded clastic material. Probable algal structures, in the form of limy granules and concentrically-laminated limestone "balls" up to 3 inches in diameter, are abundant, especially in the upper bed of white limestone. Both limestones are now compact but show clear evidence of brecciation of porous structures followed by recrystallization and filling of fractures with secondary calcite and minor amounts of chalcedony. Older fine-grained concretionary structures are crushed or broken, and vugs are filled by coarsely crystalline calcite. It is likely that the limestones originated as spongy algal deposits which suffered compaction and recrystallization under load of overlying rocks. All of the features described above are similar to features present in lacustrine algal limestone of the Wasatch formation of north-central Utah (Eardley, 1931) and the Flagstaff (Paleocene) lacustrine limestone of central Utah (Spieker, 1946).

Persistence, purity, and probable algal origin of these white limestones in the upper part of the Claron formation of the southern Red Hills indicate that the limestones accumulated in a lake. The lake was probably shallow for it was abruptly replaced by a fluviatile environment following deposition of each pure, white limestone bed. Furthermore, limestone is not likely to form in deep lakes (Eardley, 1931) because cold bottom waters, rich in CO_2, hold accumulating calcium carbonate in solution.

The lower of the two white limestones of the upper Claron is identical, in lithology and position in sequence, with a white limestone near the museum at Cedar Breaks National Monument, even to the extent of development of distinctive, rainbow-hued marlstones immediately beneath the massive limestone ledge. Similar white limestones extend along the south rims of the Markagunt and Paunsaugunt Plateaus and probably record the existence of a vast, early Tertiary lake which covered thousands of square miles in southwestern Utah. The postulated

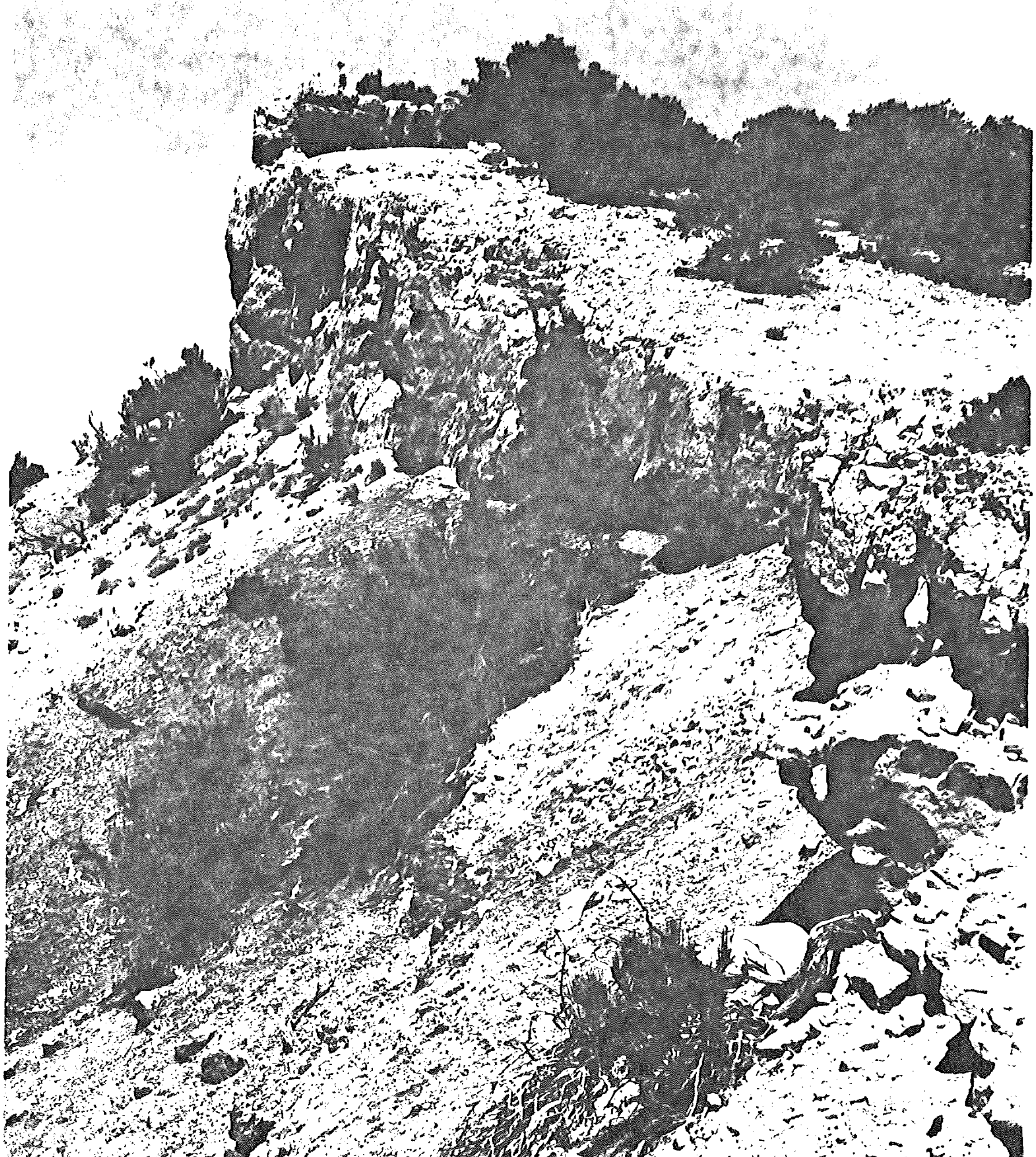


Fig. 9. Massive white algal limestone in upper part of Claron formation (unit #20 of measured section in southern Red Hills), capping White Butte west of Summit, Utah.

lake extended at least as far southwestward as the Iron Springs district, where similar white limestones are extensively developed in the upper part of the Claron formation (Mackin, personal communication). It extended into only the southern part of the Red Hills area, for upper Claron rocks of the northern Red Hills are pebbly conglomerates.

In the southern Red Hills, upper Claron limestones are generally overlain disconformably by Tertiary acidic volcanic rocks, and geologic record of the postulated Eocene lake of early Tertiary age is absent. In the Iron Springs district (Mackin, personal communication) and eastward into the southern High Plateaus (Gregory, 1950), upper Claron or Wasatch limestones grade upward into beds of chalcedony and volcanic ash which immediately underlie Tertiary acidic volcanics. These extensive beds of chalcedony may indicate abundance of diatoms which flourished in the postulated Eocene lake with increasing availability of silica during beginning phases of extensive Tertiary volcanism.

Jackrabbit formation

In the northern Red Hills and southern Gray Mountains, non-pyroclastic upper Claron red beds grade upward into a thick sequence of white volcanic ash and green volcanic-derived sediments. The entire sequence generally conformably underlies thick sheets of resistant acidic volcanics. The volcanic-derived sediments are weak and very poorly exposed in a dissected pediment, locally known as Jackrabbit, along the west flank of the Gray Mountains. Although the actual contact between upper Claron red beds and the pale green sediments is not sharply defined, the sequence of volcanic sediments constitutes a distinctive unit for which the name Jackrabbit formation is proposed. The basal boundary of the formation must be drawn arbitrarily along the top of stratigraphically highest exposed non-pyroclastic Claron sediments, for lack of good exposures and because of possible interfingering relationships between the Claron and Jackrabbit formations. The upper boundary may be generally drawn at the base of the stratigraphically lowest, resistant felsite unit of the Tertiary acidic volcanic sequence, a dacitic welded crystal tuff. The Jackrabbit formation is at least 550 feet thick at the type locality on the western flank of the Gray Mountains and consists chiefly of poorly-consolidated gritty and conglomeratic sediments derived from a volcanic terrain.

North of Cedar Breaks National Monument, at the base of Brian Head peak, white limestones of the Claron or Wasatch formation are overlain by approximately 500 feet of volcanic ash, siliceous limestone, chalcedony, tuffaceous sandstone, vitrophyric lavas, and andesitic agglomerate which Gregory (1950) collectively designated as the Brian Head formation. Despite extreme variation in composition, texture, and thickness, lower members of the Brian Head formation generally constitute a distinctive unit lying between the marlstones of the Wasatch formation below and the thick sheets of resistant volcanic rocks above, throughout great areas of the southern Markagunt Plateau. It seems unfortunate, however, that Gregory chose Brian Head peak as the type locality for the formation, for the present writer observed that andesite agglomerate upper members of the Brian Head formation grade laterally into thick andesite flows which are elsewhere regarded as part of the supposedly overlying acidic volcanic units of flows and welded tuffs.

Mackin (personal communication) and the writer studied many exposures of Gregory's Brian Head formation and acidic volcanics in the

Piute Highlands and in the Markagunt Plateau north of Brian Head peak, and independently came to the conclusion that so much confusion of stratigraphic relations is encountered in use of the term Brian Head formation that it is no longer appropriate. Figure 10 shows interpretations by the present writer concerning stratigraphic relationships of volcanic-derived sediments which generally lie between Claron or Wasatch marlstones and Tertiary acidic lavas and welded tuffs in eastern Iron County, Utah. It appears that the Jackrabbit formation of the Red Hills area is approximately equivalent to only the lower portion of the type Brian Head formation of the southern Markagunt Plateau.

Gregory (1945) noted that as the Brian Head and Wasatch formations are traced from the southern Markagunt, northward into volcanic source areas of the Tushar and Sevier Plateaus of central Utah, the Brian Head formation is rather consistently overlain by andesite lavas. At the type locality, however, the Brian Head formation is overlain by rhyolite "lava" or welded tuff, perhaps because of confusion of the upper part of type Brian Head formation with agglomerate phases of andesite lavas which ordinarily overlie the Brian Head formation. If this should be the case, only the lower portion of type Brian Head formation, equivalent to the Jackrabbit formation of Red Hills area, is the "Brian Head formation" which Gregory has mapped throughout large areas of the eastern and northern Markagunt Plateau (Gregory, 1949). Only detailed tracing of units will supply decisive information for this problem, but on the basis of reconnaissance in the southern Markagunt Plateau and in upper Sevier Valley, the present writer believes that the term Brian Head formation should be restricted or abandoned.

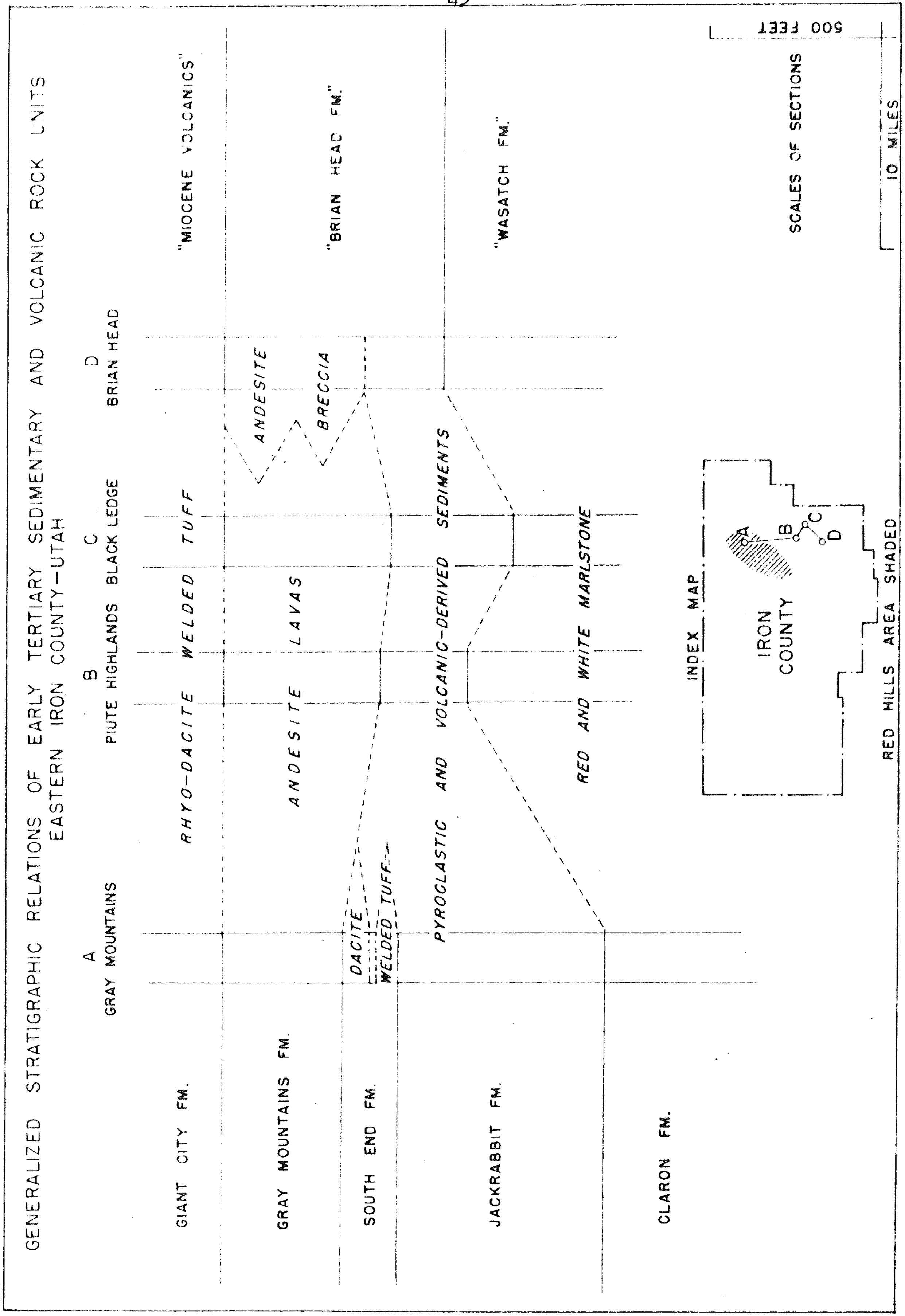

GENERALIZED STRATIGRAPHIC RELATIONS OF EARLY TERTIARY SEDIMENTARY AND VOLCANIC ROCK UNITS
EASTERN IRON COUNTY—UTAH
A
GRAY MOUNTAINS
B
PIUTE HIGHLANDS
C
BLACK LEDGE
D
BRIAN HEAD
GIANT CITY FM.
GRAY MOUNTAINS FM.
SOUTH END FM.
JACKRABBIT FM.
CLARON FM.
"MIOCENE VOLCANICS"
"BRIAN HEAD FM."
"WASATCH FM."
RHYO-DACITE WELDED TUFF
ANDESITE LAVAS
ANDESITE
BRECCIA
DACITE
WELDED TUFF
PYROCLASTIC AND VOLCANIC-DERIVED SEDIMENTS
RED AND WHITE MARLSTONE
INDEX MAP
IRON COUNTY
A
B
C
D
RED HILLS AREA SHADED
SCALES OF SECTIONS
500 FEET
10 MILES

Fig. 10

The following is a measured section of the Jackrabbit formation at its type locality. Because of generally poor exposures of these weak sediments in the Red Hills area, the measured section will serve as a general description of the rock types present.

Measured section of Jackrabbit formation — Sec. 8; T33S-R9W Iron County, Utah

South End formation — salmon-pink, biotite- and hornblende-rich felsite with abundant feldspar phenocrysts and some red felsite fragments.

Jackrabbit formation	Thickness in feet
6. Conglomerate; well-rounded cobbles of gray felsite up to 1 foot in diameter, in a red sandy matrix; occasional lenses of hard shales and siltstones	75
5. Sandstone; conglomeratic; felsite fragments and pebbles up to 1 inch in diameter, with an occasional well-rounded quartzite pebble; in regular beds about 1 foot thick; color varies from pale to bright green	85
4. Altered tuff(?); poorly exposed, but makes a conspicuous red-orange soil slope	15
3. Sandstone; conglomeratic; felsite pebbles and cobbles up to 1 foot in diameter, in gritty sand matrix; alternating sandstone and conglomerate beds up to 5 feet thick, with bright green (chloritic clay) partings and films around constituent rock and mineral fragments	125
2. Sandstone, tuffaceous, medium- to coarse-grained, many biotite flakes; in massive to paper-thin beds, with conglomerate lenses up to 20 feet thick; pebbles and cobbles are exclusively andesitic, perfectly rounded and nearly spherical	150
1. Poorly exposed; chiefly white to pale green ashy tuff and tuffaceous sediments that make light-colored soil slopes between outcrops of uppermost Claron limestones and upper members of Jackrabbit formation	100
Total thickness of Jackrabbit formation	550

Unconformity(?)

Claron formation — thin conglomeratic sandstones, platy sandstones and siltstones, and purple-and-white mottled marlstones.

Fig. 11. Typical volcanic conglomerate of upper part of Jackrabbit formation. Well-rounded and nearly spherical pebbles and cobbles of andesite in a tuffaceous sand matrix; rather poorly indurated and strongly contrasted with resistant welded tuff of overlying South End formation.

No fossils were found in the Jackrabbit formation, but because it conformably succeeds the Eocene(?) Claron formation, the Jackrabbit formation is probably Eocene or Oligocene in age. Gregory (1950) states that the Brian Head formation of the Markagunt Plateau is probably Miocene in age, because it overlies the Eocene(?) Wasatch formation and underlies the thick acidic volcanic sequence which unconformably underlies the Pliocene-Pleistocene Sevier River formation of central Utah. The dating is very crude, and the Brian Head formation may range in age from Eocene to Pliocene.

Petrographically typical specimens from the various rock types represented in the formation show a wide variety of textures and composition. Most of the fine-grained sediments contain abundant andesine, with minor amounts of quartz and chloritized biotite, imbedded in a chloritic clay matrix. Potash feldspar is remarkably rare, which suggests that these fine-grained sediments were derived from andesites or related rocks, rather than from more acidic rocks. Most of the coarse-grained sediments, especially common in the upper part of the formation, contain andesite fragments almost exclusively, although occasional quartzite and limestone fragments are present. In the coarse-grained sediments, fragments are generally surrounded by films of chloritic material and imbedded in a sandy and clayey matrix.

Abundance of coarse clastics indicates that any lakes which may have been present in the Red Hills and surrounding areas during deposition of upper Claron limestones were rapidly filled by volcanic debris and converted to fluviatile plains over which were spread extensive sheets of acidic volcanics.

The dominance of andesite debris in rocks of the Jackrabbit formation is puzzling, for no older felsite sources are known in the immediate area of eastern Iron County (Gregory, 1950). Apparently this andesite debris was derived from early Tertiary or older felsites in areas to the west or north.

Tertiary acidic volcanic sequence

General statement

Interfingering with the uppermost portion of the Jackrabbit formation in the Gray Mountains and resting disconformably on upper Claron limestones in western Parowan Gap and in the southern Red Hills are extensive sheets of rhyo-dacite welded tuffs, andesite flows, volcanic-derived arkosic sandstone, and dolerite flows and agglomerate. This sequence has a total thickness of at least 1,500 feet; the youngest units are not completely exposed in the Red Hills area.

Similar volcanic sequences of comparable thickness are present in the Iron Springs district (Mackin, personal communication) and in the southern Markagunt Plateau (Gregory, 1949, 1950). On the basis of extensive field and petrographic study by Mackin and Nelson (1950) and Christman (1951) in the Iron Springs district and by the present writer in the Red Hills area, as well as reconnaissance by Mackin and the present writer in the southwestern Markagunt Plateau, the following volcanic sequence was found to be remarkably consistent throughout hundreds of square miles in southwestern Utah:

(4) pink welded tuff of rhyo-dacitic composition (the resistant cap of Brian Head Peak, north of Cedar Breaks National Monument)
(3) chocolate-brown andesite flows and agglomerate (the Black Ledge of the Markagunt Plateau)
(2) pink welded crystal tuff of quartz latitic or dacitic composition (absent in Markagunt Plateau and southern Red Hills)
(1) white and pale green volcanic-derived sediments of the Jackrabbit and lower Brian Head formations

Volcanic units above the rhyo-dacitic welded tuff are variable — red and black vitreous welded tuff of quartz latitic and rhyolitic composition in the Iron Springs district; black andesite flows and agglomerates in the southern Markagunt Plateau; tuffaceous arkose and doleritic flows and agglomerate in the Red Hills area.

It is noteworthy that the volcanic sequence of southwestern Utah is widely different from that of central Utah (Callaghan, 1945) which includes early Tertiary latitic tuffs and breccias, overlain unconformably by late Tertiary rhyolite and tuffs. This sequence of simple groups of chemically related rocks is markedly different from the sequence of rocks of mixed composition in southwestern Utah. Perhaps the differences between the volcanic sequences of central Utah and southwestern Utah are a reflection of the proximity to volcanic centers in the Tushar, Sevier, and Fish Lake Plateaus of central Utah (Dutton, 1880); more likely, however, these differences in volcanic sequence are related to mixing or interfingering, in southwestern Utah, of volcanics from central Utah sources with volcanics from more westerly or southwesterly sources. Recently, as Callaghan extended his reconnaissance southward and westward from the Marysvale area, he found that tremendous quantities of basaltic breccias, in the Black Mountains north of the Red Hills area, interfinger with almost the entire volcanic sequence of the Marysvale area (Christman, personal communication).

In the Red Hills area, the present study of the volcanic rocks was primarily to determine the volcanic sequence and its stratigraphic relations with volcanic sequences of neighboring areas. The sequence has been subdivided on bases of color, texture, style of weathering, and other properties that are useful for field mapping purposes; each map unit does not necessarily represent the deposit of a single process. All of the formations described below and represented on the geologic map (Plate I), except the massive rhyo-dacitic welded tuff, show local textural variations, both laterally and vertically, which suggest multiple volcanic outbursts, but field exposures are too limited for differentiation of members within the map units.

The rocks of the volcanic sequence, including intercalated sediments, are entirely unfossiliferous and may range in age from early to middle Tertiary, because they overlie late Cretaceous-early Tertiary sedimentary rocks, with essential conformity, and underlie late Tertiary(?) gravels and Quaternary(?) basalt sheets, with marked angular unconformity. The Tertiary acidic volcanic units are concordant and probably represent a conformable sequence.

General petrography

With the exception of sandy sediments and dolerite flows and agglomerate in the upper part of the volcanic sequence of the Red Hills area, the Tertiary volcanic rocks are extremely fine-grained or glassy, with minor amounts of felsitic rock and mineral fragments. Matrices which were formerly glassy have been devitrified to porcellaneous textures.

Petrographically, the rocks are simple; feldspars, quartz, biotite, hornblende, augite, and olivine constitute the bulk of the mineral fraction. Magnetite, hematite, zircon, and sphene are common accessory minerals. Undevitrified portions of the matrix of most of the rocks is dominantly glass which has an index of refraction slightly below balsam, indicating an intermediate composition. In most of the rocks, however, the glassy matrix has been devitrified to fine-grained aggregates of tridymite and feldspar or to feathery and plumose aggregates of tridymite and feldspar or chalcedony.

Feldspars are present in thin sections of all the rocks, and plagioclase is, by far, the most abundant. Sanidine is present in sections of the rhyo-dacitic welded tuff unit, but orthoclase is very rare. The abundant plagioclase usually shows some crystal faces, but many of the crystals are broken and shattered. Although a few plagioclase crystals show extremely complex twinning and zoning, albite twinning or combination Carlsbad-albite twinning is most common and indicates a composition of An_{40-60}. Christman (personal communication) found that index oils indicate a composition of An_{30-50}.

Quartz occurs in small amounts in all but the most basic rocks. Silica also occurs in the form of chalcedony and opal(?) and as fine-grained tridymite — alteration or devitrification products of the generally vitreous matrix of the rocks. Quartz, when present as a primary mineral, usually occurs as crystals, 1-3 mm. in diameter, with corroded and embayed faces.

Biotite occurs sparingly in most of the rocks, but it is so abundant in the quartz latitic-dacitic welded crystal tuffs, that they were designated as "biotite tuffs" in the field. The biotite is usually iron-rich and strongly pleochroic; it frequently contains inclusions of magnetite and zircon. The biotite crystals are usually euhedral, but they are occasionally bent and broken, especially in the rhyo-dacitic welded tuff.

Hornblende occurs primarily as euhedra in the "biotite tuffs." Soda-rich augite and rare olivine occur chiefly in the dolerite lavas and basalt breccia at the top of the volcanic sequence.

South End formation

Immediately overlying the Jackrabbit formation and underlying andesite lavas at the south end of the Gray Mountains are two salmon-pink felsite units, each approximately 50 feet thick, which the writer has designated, collectively, as the South End formation. Around the east flank of Flat Top peak the formation distinctly consists of two identical massive and resistant felsites, separated stratigraphically by about 30 feet of weak volcanic-derived sediments that are identical with Jackrabbit sediments which immediately underlie the lower felsite member. An interfingering relationship with the uppermost portion of the Jackrabbit formation is suggested, but areal exposure of the Jackrabbit-South End contact is too limited for decisive information.

In the vicinity of Parowan Gap only one of the felsite members is developed, and it rests with angular unconformity on Navajo sandstone. In the southern Red Hills and eastward into the Markagunt Plateau, the South End formation is absent, although its equivalent (Mackin, personal communication) occurs extensively in the northern part of the Iron Springs district, a few miles west of the southern Red Hills. Southward and eastward thinning and disappearance of the formation suggests depositional thinning with increasing distance from a westerly or northwesterly source of the felsites, because the Brian Head formation, roughly equivalent to the Jackrabbit formation, of the Markagunt Plateau seems to grade upward into and interfinger with andesite lavas which normally conformably overlie the South End formation and its equivalent in the Gray Mountains and in the Iron Springs district. No additional information concerning location of the source of the South End formation was discovered.

Megascopically, the rock might be mistaken for a fine-grained biotite granite porphyry; generally, however, an abundance of felsite and pumice(?) inclusions betrays the volcanic character. There are no flow structures, columnar jointing, or tubular vesicles of a typical lava; a high degree of consolidation and complete lack of bedding indicate that the rock unit is not an ordinary tuff. Although ledges of the felsite appear tabular from a distance, close examination shows no textural or mineralogical sorting or stratification, other than a crude sheeting, which is reliable for determination of attitudes.

In thin section, the rock has a composition of about 50% glassy or very fine-grained matrix, 25% calcic andesine, about 5% quartz, 10% hornblende, 10% biotite, and occasional felsite fragments. Petrographically, the rock is a dacite, but a wholly fragmental character of the glassy matrix and included mineral grains indicates that the rock is pyroclastic in origin. In spite of widespread growth

Fig. 12. Crescentic and cuspate forms resulting from competitive growth of spherulites in glassy matrix of South End felsite. If spherulites were less well-developed or less obvious, the cuspate interstices might be confused with glass shards. Spherulites in this case apparently have no relationship to shard boundaries and are not, therefore, examples of axiolitic structure.

of spherulites and granular aggregates of devitrification products in the formerly glassy groundmass, vague cuspate relicts show that glass shards once constituted a rather large part of the matrix. Clearly, the rock is either a tuff which was welded by its own heat of deposition (nuee ardente deposit) or an air-fall tuff which was consolidated by post-depositional devitrification of its glassy matrix or by cementation.

There is no evidence of sorting or textural grading throughout the entire thickness, 50 feet, of either felsite unit; and although the intercalated sediments are well-bedded, there is no bedding within either unit. Both units are highly indurated, in contrast to the weakly consolidated pyroclastic sediments separating them, and their superior hardness surely came about through internal processes rather than through general cementation.

Inasmuch as field relations and thin sections fail to provide a basis for distinction between a turbulent, hot ash fall which was consolidated by devitrification of its heated glassy constituents and a turbulent, hot ash fall which was consolidated by welding of its glassy constituents, and, in which, the forms of the compacted and welded glass shards have been largely effaced by later devitrification, the writer was unable to definitely establish the mode of origin of the indurated tuffs of the South End formation. In the Iron Springs district (Christman, 1951, unpublished manuscript) relicts of compacted and welded glass shards are sufficiently preserved in the equivalent of the South End formation to indicate that the unit is a welded tuff or nuee ardente deposit.

Gray Mountains formation

In the central Gray Mountains massive, chocolate-brown andesite flows, which have an aggregate thickness of 100-300 feet, essentially conformably overlie the upper indurated tuff member of the South End formation and underlie a massive rhyo-dacitic welded tuff. The sequence of andesite flows is here designated as the Gray Mountains formation. In the southern Red Hills, where the South End formation is absent, the Gray Mountains lavas rest disconformably on upper Claron limestones, separated from the limestones by a few feet of gritty and weakly consolidated tuffaceous sediments.

The formation is broadly divisible into a lower chippy or platy chocolate-brown member which ranges up to 50 feet in thickness and contains abundant tubular vesicles filled with chalcedony and calcite, and an upper massive red member, 50-250 feet thick, with rude columnar jointing. Local occurrence of slaggy zones between the two members indicates the presence of at least two flow units, but exposures are so poor that the writer was unable to map the flows separately.

Megascopically, the rock is dark red to brown, with a uniformly porcellaneous texture; phenocrysts are rare. The basal member of the formation is commonly amygdaloidal. The rock appears homogeneous, and although the basal member and local portions of the upper member are chippy or platy, the remainder of the formation is blocky.

In thin sections, phenocrysts of calcic andesine are sparingly developed; the crystals are unbroken and unaltered but highly resorbed at the margins. Quartz is not present, except as a fine-grained filling of vesicles; augite is rarely present. The matrix is partly-devitrified glass with uniformly disseminated hematite and magnetite which apparently control the color of the rock in hand specimen. The glassy matrix contains numerous spherical vesicles about 0.1 mm. in diameter, with marginal alteration and quartz filling, but the matrix contains no glass shards or rock fragments. The rocks of the formation are clearly flow rocks, and although the thin sections supply little information about composition, these flow rocks probably are andesitic, on the basis of rare phenocrysts of andesine.

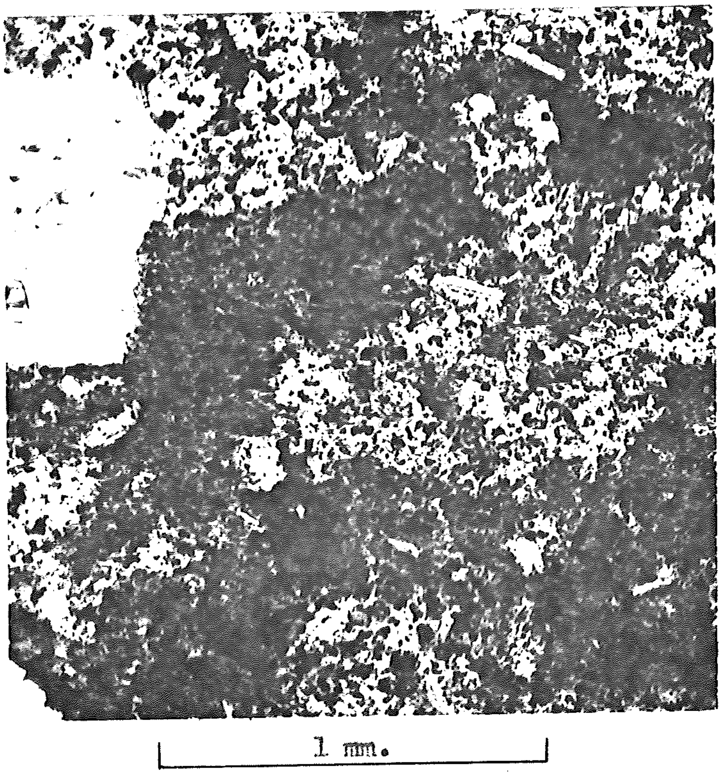


Fig. 13. Gray Mountains andesite flow. Note complete lack of shards and fragments, although the matrix is composed entirely of glass with uniformly disseminated magnetite.

In the Red Hills, only flow rocks were noted in the Gray Mountains formation, but along the Black Ledge which extends northward from Brian Head Peak just beneath the rim of the Markagunt Plateau, andesite flows which occupy the same stratigraphic position as the Gray Mountains formation grade laterally into andesite flow breccias and agglomerates.

The Gray Mountains formation and equivalent flows and agglomerates are found throughout the southern Gray Mountains, central and southern Red Hills, Markagunt Plateau, and the Iron Springs district; no sources for the andesite have been found, although local accumulation of agglomerate and flow breccia, with no obvious volcanic vent or cone, suggests local derivation from numerous fissures which are probably concealed beneath the vast sheets of lava.

Giant City formation

In the northern half of the Gray Mountains, and in scattered exposures at the south end of the Red Hills, a pink, massive felsite unit, which is here designated as the Giant City formation, overlies the andesite lavas and is generally separated from the lavas by a few feet of olive-drab sandstone. At the type locality in the northern Gray Mountains, this massive unit is about 200 feet thick and weathers into tremendous prismatic joint blocks which resemble skyscrapers of a giant city, hence the name.

The formation consists of a single unit, presumably the deposit of a single volcanic outburst, which is characterized by a uniform thickness of about 200 feet throughout several square miles of outcrop. As far as the writer could determine, the surface on which the felsite was deposited was one of low relief — essentially the initial surface of the uppermost flow of the Gray Mountains formation, locally covered thinly with tuffaceous arkose. The actual contact between the Giant City felsite and the Gray Mountains lavas is not exposed, but the contact

Fig. 14. Massive joint blocks of Giant City formation in north-central Gray Mountains; figure in circle gives scale. Note the complete lack of bedding and lack of flow structures or well-developed columnar jointing.

of intervening arkosic sediments and the Giant City felsite is sharp and without mingling of the two rock types or development of a slaggy zone at the base of the felsite. The most significant feature of the sediment-felsite contact is a complete lack of baking effects or reddening of the greenish sediments.

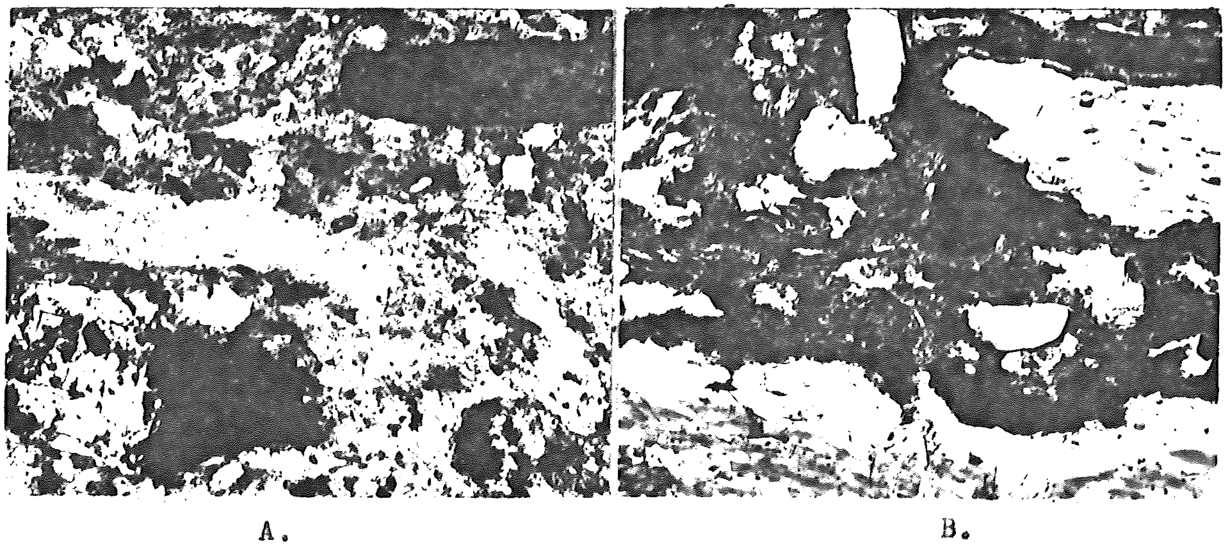
Megascopically, the rock consists of numerous red and brown felsite fragments, large quartz grains, and scattered feldspar, biotite, and hornblende grains in an indurated porcellaneous matrix. The rock varies little in appearance from exposure to exposure, or from top to bottom of the unit, with the exception of red and black vitrophyres, up to 30 feet thick, developed locally at the base. Despite the presence of numerous rock fragments, the rock would probably be designated as a rhyolite lava, in hand specimen. At the outcrop, however, the unit shows no flow structures or other features of lavas; large numbers of sub-parallel, lenticular cavities (up to a few inches in length) due to weathering out of glassy or pumiceous inclusions might be mistaken for flow structures. On the other hand, despite the numerous rock fragments, one would hesitate to designate the rock as a tuff, because of the high degree of induration and a complete lack of sorting or bedding throughout the entire 200-foot thickness.

In thin sections a fragmental character is expressed throughout the unit, and the formation is clearly not a lava flow. In addition to numerous rock fragments, there are broken grains of sanidine, sodic andesine, quartz, and hornblende and bent flakes of biotite scattered throughout a matrix which consists largely of cuspate glass shards and glassy volcanic dust(?) which is extensively devitrified. Sanidine is usually less abundant than plagioclase in thin sections; the composition is that of a quartz latite, although correlative rocks in surrounding areas have been described as rhyolite (Christman, 1951) and dacite (Gregory, 1950, p. 104). The rock is obviously of pyroclastic origin, but the reason for its high degree of consolidation is not readily apparent in thin sections of devitrified portions of the unit.

In thin sections of basal vitrophyres of the formation, the original glassy matrix is not devitrified and clearly consists of elongate crescentic shards which are highly contorted but generally aligned parallel to the base of the formation. The shards show evidence of intense deformation — warping around mineral grains, packing into embayments of corroded mineral grains, interpenetration and coalescence with adjoining shards — with no fracturing or shattering, indicating that they were deformed while in a highly plastic state. These intensely compacted and welded shards clearly indicate a nuee ardente origin for the unit.

The basal vitrophyres give way rather abruptly to the upper portion of the unit, in which devitrification of the glassy portion is so complete that any welded or compacted shard structures which may have been present have been obscured. In some exposures, especially in the southern Red Hills and eastward in the mouth of Summit Canyon at the margin of the Markagunt Plateau, the transition between undevitrified basal vitrophyres and devitrified upper portions of the Giant City formation is marked by a zone of devitrified rock which includes lenses of undevitrified black vitrophyre. These lenses of vitrophyre are several inches in diameter but generally less than an inch thick, and their long dimensions are parallel to the base of the formation. In thin section, the lenses are seen to contain numerous welded and compacted glass shards which are elongated parallel to the margins of the lenses, hence also aligned parallel to the base of the formation like the welded shards in the basal vitrophyres. Such remarkable parallel orientation of the lenses and constituent glass shards with glass shards in the basal vitrophyres, as well as restriction of the glass lenses to a zone intermediate between undevitrified basal vitrophyres and devitrified upper portions of the unit, could hardly be expected if the lenses represent accidental inclusions. Surely these lenses represent locally fused masses of initially discrete glass shards whose shard outlines have been preserved as dusty films or optical discontinuities. The masses of fused shards probably escaped devitrification because of a reduction of reactive surface area by coalescence. Inasmuch as the zone of glassy lenses grades downward into continuous sheets of glasses at the base of the unit, the basal vitrophyres probably represent widespread fusion or coalescence (Fig. 15) of glass shards under high pressures and/or temperatures at or near the base of the unit. The preceding statement implies that, for a given welded tuff unit, basal glasses are most likely to form only under thicker portions of the deposit or under hotter or less viscous portions of the unit. The former hypothesis accords with observations by Gilbert (1938); the latter hypothesis is partly supported by negative evidence, a lack of baking effects where non-vitreous basal portions of the Giant City welded tuff rest directly on tuffaceous arkose, discussed in the second paragraph of this section on the Giant City formation.

A problem which is of even greater importance than origin of the basal vitrophyres is the mechanism of distribution of this _nuee ardente_ deposit over large areas. Of closely similar lithology and position in the volcanic sequence, this welded tuff unit is found throughout the northern Gray Mountains, the southern Red Hills, the Iron Springs district, and the southern Markagunt Plateau; it is literally everywhere. There are no conspicuous textural variations which would suggest local derivation from numerous vents or fissures, except for pseudo-dikes of tabular, opalized fault zones in the formation in Sec. 23; T32S-R9W; yet it is difficult to conceive of this remarkable uniformity of lithology and position in stratigraphic sequence over



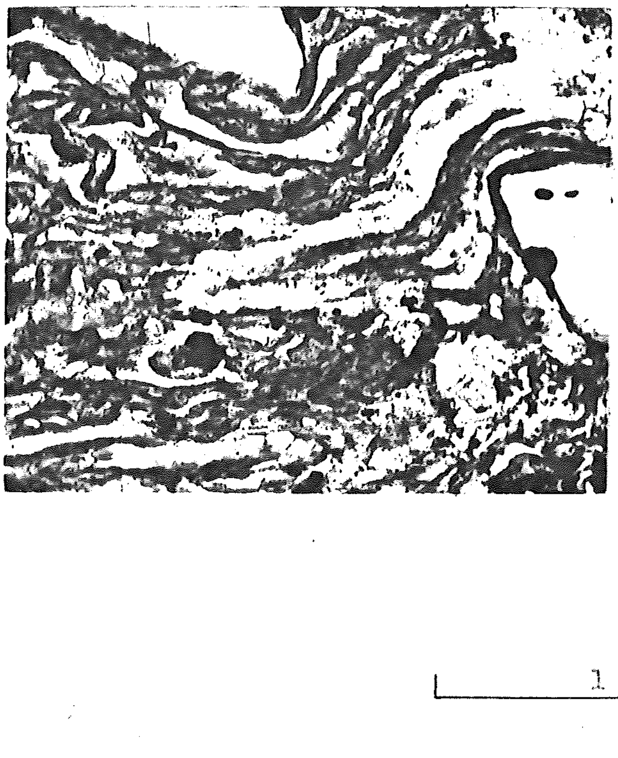


Fig. 15. Thin sections of various portions of the Giant City tuff, showing degrees of devitrification. A—completely devitrified matrix of upper portions of the unit; B—lenses of glass (light) in devitrified matrix of intermediate portions of the unit; C—undevitrified welded and compacted glass shards of basal portions of the unit.

hundreds of square miles as due to a single blast of nuees ardentes which accumulated deposits at least 200 feet thick. Certainly we do not yet have sufficient experience or information about mechanisms of nuees ardentes of the past, which seem to have been far more extensive than modern nuees ardentes which leave deposits only on volcanic slopes and nearby lowlands. Perhaps a knowledge of heat transfer or of the role of exothermic reactions in supplying heat to rapidly expanding clouds of incandescent material (Gilbert, 1938) would offer an avenue of attack on the problem, although intense heat is apparently not necessary in the formation of some portions of welded tuffs, as shown by lack of baking effects on tuffaceous arkose immediately beneath the Giant City welded tuff.

Cane Spring formation

South and east of Cane Spring, at the northern tip of the Gray Mountains, are extensive exposures of a drab green, well-laminated, cross-bedded sandstone which Thomas and Taylor (1946, geologic map in pocket) mapped as "undifferentiated Cretaceous." The present writer traced the sandstone southward and eastward from Cane Spring and found that, despite lateral and vertical intergradation with greenish tuffs, these sandstones and related tuffs constitute a distinctive mappable unit that lies conformably between the Giant City formation and doleritic agglomerate and flow rocks which crop out discontinuously along the east flank of the Gray Mountains. These distinctive greenish rocks are here designated as the Cane Spring formation.

There is no corresponding unit in the volcanic sequence of the Iron Springs district (Mackin, personal communication) and there apparently

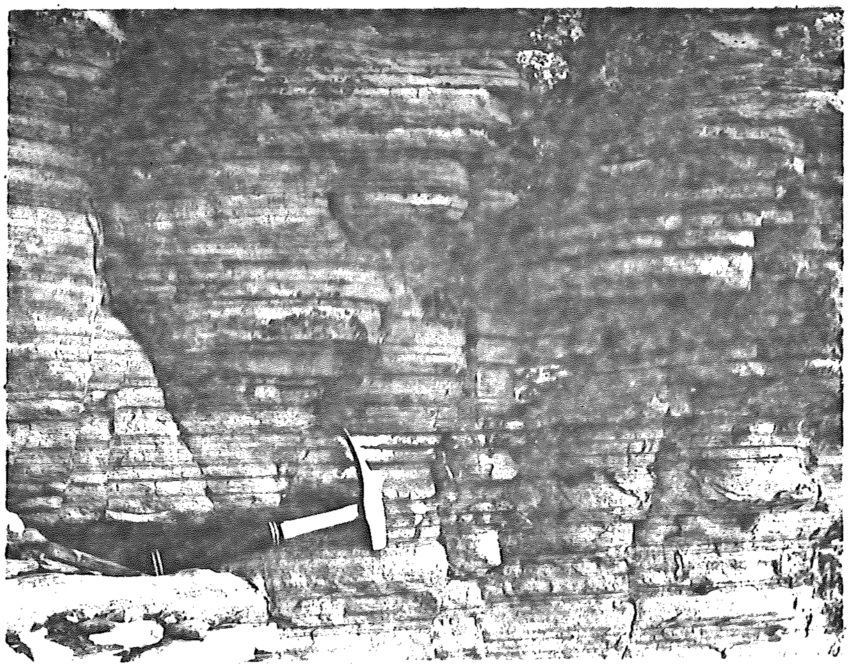


Fig. 16. Uniformly-laminated tuffaceous sandstone of the lower part of the Cane Spring formation, near sheep corral along road from Parowan to Cane Spring.

is no corresponding unit in the volcanic sequence of the southern Markagunt Plateau, on the basis of reconnaissance by the present writer. This formation of sandstones and/or tuffs may extend northward into the largely unexplored Black Mountains north of the Red Hills area, but the laminated sandstones which are well-developed in the vicinity of Cane Spring probably represent accumulation in a local basin of standing water related to drainage obstruction by accumulating volcanic rocks in surrounding areas.

The greenish laminated sandstones at Cane Spring grade laterally, southeastward, into an olive-drab tuff which closely resembles the sandstone, except for lack of lamination or other stratification. The tuff is visibly granular and only moderately consolidated; it is wholly different from the porcellaneous and highly consolidated welded tuffs elsewhere in the volcanic sequence of the Red Hills area. The sandstone and intergrading tuff have similar composition and contain well-sorted, rounded and angular grains, 0.1 - 1 mm. in diameter, of feldspar, quartz, augite, hornblende, quartzite, red felsite, and black obsidian. The ferromagnesian minerals are responsible for the greenish color of the rocks, especially where they are concentrated in finer-grained laminae of the sandstone.

In thin section, the writer was unable to identify positively the cementing material of the sandstone and tuff, but he believes that it is opaline silica because of its extremely low birefringence in thin section and glassy luster on fresh surfaces of hand specimens. The most striking feature of the sandstone and tuff in thin section is a close packing of mineral and rock grains and a complete lack of glass shards or dust -- features which suggest considerable air or water sorting of volcanic material, with deposition of the finer fragments elsewhere, in contrast with poor sorting of pyroclastic material in turbulent *nuees ardentes*.

Although the previously described sandstone and tuff comprise the bulk of the formation, greenish, thin, highly consolidated tuffs and drab, hydrothermally altered rocks which appear to be volcanic mudflow breccias are interbedded with the sandstone and tuff near the top of the formation along the northeast margin of the Gray Mountains. Exposures of these exotic rock types are too limited to indicate their stratigraphic significance.

Little Black Mountain formation

At Little Black Mountain and also extending along the east side of the northern Gray Mountains into foothills of the Black Mountains north of the Red Hills area (Thomas and Taylor, 1946), there are discontinuous and rather poor exposures of doleritic and basaltic flows(?) and breccia which generally rest conformably on the drab rocks of the Cane Spring formation. At the type locality, agglomerate and thin flows aggregate at least 200 feet thick, and the top of the unit is not exposed; apparently equivalent agglomerates which are exposed in bold escarpments of the Black Mountains immediately north of the Red Hills area have a thickness of several hundred feet.

Fig. 17. Basaltic agglomerate at type locality of the Little Black Mountain formation near Parowan—Cane Spring road.

At Little Black Mountain the beds of agglomerate show a southwesterly dip of 25°, strikingly discordant with an easterly dip of 10° in nearby exposures of Cane Spring sandstones. Since there is no apparent fault contact between the two units and since they are ordinarily concordant elsewhere, these locally high dips of the agglomerate, as well as tremendous sizes of blocks in the agglomerate, probably represent proximity to a volcanic source. Little Black Mountain is roughly conical in form and might be mistaken for a volcanic cone or remnant of a cone, but the northwesterly strike of the beds of agglomerate is consistent throughout the mountain; there are no radial dips as one might expect on the flanks of a volcanic cone. The lack of radial dips suggests a linear (fissure) source rather than a point (vent) source for the agglomerate.

Away from the type locality, only massive dolerite is exposed on a pediment which flanks the eastern side of the northern Gray Mountains and only basalt breccia is exposed in low rolling hills west of the northern Gray Mountains and northward into the foothills of the Black Mountains. Exposures are so poor that the writer was unable to relate the massive dolerite to the basaltic breccias; the dolerite may represent dike feeder(s) for the agglomerate and associated basaltic flows.

Megascopically, the rocks of the Little Black Mountain formation are dolerite and basalt which contain phenocrysts of augite up to 2 mm. in diameter. The dolerite is dark gray and massive, but basaltic blocks in agglomerate phases of the formation are glossy black and vesicular. Blocks in the agglomerate are imbedded in a weakly-consolidated, white tuffaceous matrix.

In thin section, the rocks of the formation are similar mineralogically, differing only in texture and structure. Soda-rich augite and laboradorite phenocrysts 0.1 - 0.5 mm. in diameter are imbedded in a matrix of euhedral plagioclase (Fig. 18). Magnetite is scattered sparingly throughout the rock. Incipient hydrothermal alteration has converted the margins of augite crystals to chlorite and feldspar crystals to epidote.

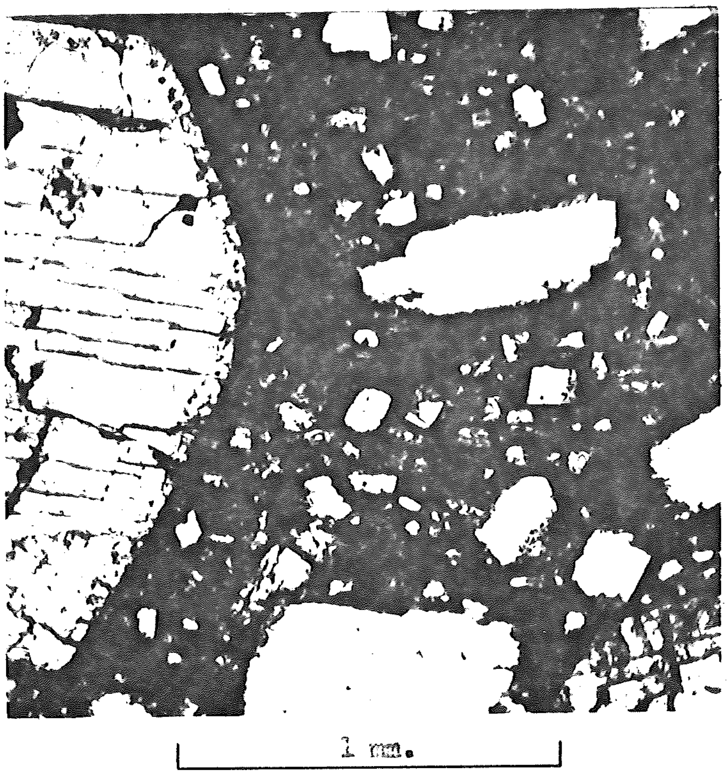


Fig. 18. Massive dolerite phase of Little Black Mountain formation. Typical texture of augite and sodic lab~~ø~~radorite phenocrysts in plagioclase matrix.

Petrographically, the rocks of the Little Black Mountain formation are basaltic. Agglomerates which lie on the Giant City welded tuff at the rim of the Markagunt Plateau, at the Parowan Canyon lookout constructed by the U. S. Forest Service on the Sydney Valley-Yankee Reservoir road, are stratigraphically equivalent to the Little Black basalts. The gravels are poorly sorted and contain angular pebbles, cobbles, and boulders up to several feet in diameter.

These fanglomerate gravels are here designated simply as "older alluvium," although Gregory (1950, pp. 68-69) believes that these gravels are equivalent to the Parunuweap formation of the Zion Park region, on the basis of similarity in structural and geomorphic relations. Gregory (1945) has also tentatively correlated the Parunuweap formation with the fossiliferous upper Pliocene-lower Pleistocene Sevier River formation of central Utah on the same basis. However, until more detailed regional geomorphology has been studied in the southern plateaus, the present writer prefers to call the deposits "older alluvium," of probable Pliocene-Pleistocene age.

Because this unit serves as a datum in recognition of late Tertiary-early Quaternary diastrophism which is partly responsible for present form of the upland block of the Red Hills area, this older alluvium will be discussed in connection with structure and geomorphology of the Red Hills area.

Quaternary(?) basalts

Areal extent and dating of the basalts

In strong contrast with the very extensive Tertiary acidic volcanics with their apparent lack of vent sources, the youngest volcanics in the Red Hills area occur as localized basalt flows which are associated with obvious vents marked by lava domes and cinder cones. The basalt has only a poorly-developed soil on its surface and still retains little-modified scoriaceous surfaces, pressure domes and ridges, and associated cinder cones. Traditionally (Gregory, 1950, pp. 97-101), these young basalts throughout the southwestern Colorado Plateaus and adjoining areas are regarded as Quaternary in age. Their freshness in the Red Hills area suggests a middle to late Quaternary age.

The Quaternary(?) basalts of the Red Hills area are confined to the southern Red Hills, where they occur in two isolated areas of several square miles extent, one east of Rush Lake and the other west of Summit in the vicinity of Winn Gap. The Rush Lake basalt area, although somewhat faulted, is apparently little modified from its original extent and obviously originated from centrally-located cinder cones and a lava dome east of Rush Lake. At least two successive flows can be differentiated in some vertical sections, but it is not possible to map the flows separately. The present margins of the outcrop area probably represent essentially the initial margins of the flows at the north and east margins of the outcrop area, but the flows extend an unknown distance southward under valley alluvium north of Enoch and at least a mile west of Rush Lake (Thomas and Taylor, 1946).

The Winn Gap basalt area is not associated with an obvious vent or source in the Red Hills, a fact which caused Thomas and Taylor (1946) and Gregory (1950) much concern. The present writer noted the apparent source in a little-modified cinder cone near where Winn Creek issues from the Markagunt Plateau. The conical form and variegated cinder beds are visible from nearby U. S. highway #91, and the radially-dipping layers of cinders are strikingly shown in a fresh stream cut by Winn Creek. The cinder cone is the only one in the vicinity and is definitely the source of nearby small areas of basalt along the plateau margin. Although the basalt sheets associated with the cinder cone are downwarped or downfaulted and covered by a mile-broad strip of alluvium which intervenes between the plateau margin and Winn Gap through the southern Red Hills, the cone surely marks the source of the Winn Gap basalt.

The basalts from both the Rush Lake and Winn Gap areas are equally fresh, and the two basalt sheets were probably essentially contemporaneous, on the basis of similar sequence and structural relations. Both lie on Tertiary-Quaternary alluvium which Gregory (1950, p. 68) regarded as equivalent to the Parunuweap (Pliocene?) formation of the Zion National Park region; both sheets are broken by late Quaternary(?) movements on faults in the Red Hills area. Significance of these age relations will be discussed in the chapter on geomorphology.

Petrography of the basalts

The rock is gray to black and ranges in texture from aphanitic to intermediate or doleritic, with conspicuous phenocrysts of olivine up to 2 mm. in diameter. In thin section, the matrix is a felted mass of labradorite microlites with phenocrysts of olivine and some augite. Magnetite is present as an accessory mineral. The writer did not note any glassy material in the matrix.

No volcanic pipes or dike feeders are exposed, but they probably underlie the associated small cinder cones, about 200-500 feet high, which are built up of red and black cinders, blocks, and occasional ropy bombs.

STRUCTURAL GEOLOGY

General considerations

In late Cretaceous time, the Iron Springs sandstone and older rocks were uplifted in a north-northeasterly trending anticlinal or monoclinal welt, along the site of the Red Hills and the Hurricane Cliffs, and thrust eastward toward the site of the plateaus (Gregory, 1950). The fold was subsequently bevelled and buried beneath hundreds of feet of early Tertiary sedimentary and volcanic rocks. In a general way, the orogenic movement may be designated as Laramide, in the sense that it was approximately coeval with late Cretaceous-early Tertiary (Laramide) orogenic pulses reported from the Colorado Plateaus and Rocky Mountain region.

In middle Tertiary and Quaternary time, the present plateau margin and adjacent basins and ranges were being developed by broad warping and block faulting. In general, the fault zone margin of the plateaus was developed parallel to the axis of the old Laramide fold, but repeated easterly shift of the plateau margin caused some segments of the Laramide fold to lie west of the plateaus.

In northern Arizona (Fig. 1), the Grand Wash fault scarp forms the west boundary of the Shivwits Plateau, westernmost of the Colorado Plateaus. Near the Arizona-Utah boundary, the north end of the Shivwits Plateau block is sharply downwarped (Gardner, 1941) and the plateau margin is shifted abruptly eastward to the Hurricane fault along the west margin of the Kolob Plateau (Fenneman, 1931). In southwestern Utah, the Hurricane fault zone was superimposed on the zone of the old Laramide fold, but immediately north of Cedar City, near the south end of the Red Hills area, the plateau margin shifts abruptly eastward for several miles, and a segment of the Laramide fold lies several miles west of the Markagunt Plateau margin, in the Red Hills area.

Since the days of Dutton (Gregory, 1950) the Markagunt Plateau margin north of Cedar City has been generally regarded as due to continuation of the great Hurricane fault zone; eastward shift of the plateau margin has been regarded simply as a change in trend of the Hurricane fault zone. On the other hand, the present writer noted that precisely where the plateau margin shifts abruptly eastward, the Laramide fold along the base of the Hurricane Cliffs plunges abruptly northward beneath alluvium of Cedar City Valley. This remarkable coincidence of abrupt shift of the plateau margin and abrupt plunge of the Laramide fold suggests a major problem of the nature and relation of old Laramide structures and more recent structures of the plateau margin and the Red Hills area.

For convenience of presentation of structural interpretations, the following topics will be discussed separately: (1) Laramide structure of the Red Hills area, (2) Cenozoic structures responsible for eastward shift of the plateau margin and warping or fragmentation of the old Laramide folded structures, (3) Cenozoic structures of the Red Hills area, and (4) structural interrelations of the Hurricane fault zone, Summit monocline, Red Hills range block, and Cedar City and Parowan basin blocks.

Laramide structure of the Red Hills area

In the central part of Parowan Gap (Plate II), the Iron Springs sandstone and older rocks are overlain in marked angular unconformity by the Claron basal conglomerate. The present study of continuous exposures along the walls of the Gap shows that the Iron Springs formation and older rocks were overturned and thrust westward over nearly flat-lying upper Iron Springs rocks; basal Iron Springs rocks were locally overridden by the massive Carmel limestone. This entire structural complex was bevelled by erosion and mantled by boulder conglomerates of the Claron formation.

Fig. 19. South wall of central Parowan Gap, showing overturned Upper Cretaceous Iron Springs sandstones in thrust fault contact (center) with flat-lying, upper Iron Springs sandstones. The structure is bevelled and overlain unconformably by Claron basal conglomerate (late Cretaceous-early Tertiary).

Barren slope in upper center is essentially the stripped sole of the thrust; tree-covered slopes to the right are overturned beds in upthrown block.

Orogeny which produced the folded and thrust faulted structure clearly post-dates the youngest portion of the Iron Springs formation exposed in the folded complex and pre-dates the Claron basal conglomerate which overlies the folded rocks with angular unconformity. As indicated in previous discussion of stratigraphy, only the middle portion of the Iron Springs formation is definitely dated as Coloradoan; the upper portion of the formation may be Coloradoan also, on the basis of similarity to Coloradoan "undifferentiated Cretaceous" rocks of the Markagunt Plateau. Only the upper part of the Claron formation is dated as Eocene, on the basis of equivalence with fossiliferous limestones in the Pink Cliffs Wasatch of the southern High Plateaus; the basal conglomerate of the Claron may be as old as the Kaiparowits (Laramie) formation of the Markagunt Plateau. Therefore, orogeny which produced the folded and faulted structure in the Red Hills area is probably of Montanan, post-Coloradoan—pre-Laramie, age; it may range from Coloradoan to Eocene in age. Although the orogeny can not be dated precisely, it clearly is included in the plexus of late Cretaceous-early Tertiary orogenic pulses which have generally been recognized in the Rocky Mountain and Colorado Plateau regions (cf. Spieker, 1946, pp. 142-156, for review and criticism of use of the term Laramide).

The Laramide folded structure which is well exposed on the walls of Parowan Gap is here designated as the Parowan Gap fold; the structure is represented elsewhere in the Red Hills area by two small exposures about a mile north of the Gap and by a square mile of continuous exposures about one mile south of the Gap. The fold axis trends approximately N20°E, and a southward projection of this trend almost exactly coincides with the axis of the Laramide Kanarra fold (Gregory,

1950) along the base of the Hurricane Cliffs south of Cedar City. As Thomas and Taylor (1946) pointed out, several miles of exposure of downwarped Cenozoic rocks intervene between Cedar City and the Parowan Gap area, and it is not possible to show that the Parowan Gap fold and the Kanarra fold were continuous. Certainly, the remarkable near-coincidence of axial trends strongly suggests continuity or an <u>en echelon</u> relationship of the Parowan Gap fold and Kanarra fold.

In both the Parowan Gap fold and Kanarra fold, only the eastern half of the structure is exposed; the western half of each has been downfaulted beneath Cedar City Valley. The writer concurs with Gregory (1950) in belief that the Kanarra-Parowan Gap fold may be restored as a monocline or asymmetrical anticline overturned eastward. Plate III shows a structure section through Parowan Gap and a suggested restoration of the Laramide structure, based on observed attitudes corrected for Cenozoic tilting and faulting, as a somewhat faulted, overturned anticline or monocline modified to a double-S form by a subsidiary fold.

One might inquire as to whether the folded structure is one of a series of Appalachian-type folds or an isolated welt. Near the west end of Parowan Gap, the structure is largely obscured by younger rocks; west of Hieroglyph Canyon, the structure is downfaulted and buried beneath alluvium of Cedar City Valley. In the Iron Springs district southwest of the Red Hills, however (Mackin, personal communication), the Claron formation and older rocks are concordant throughout tens of square miles west of a southerly projection of trend of the Parowan Gap fold. The Claron and older rocks are concordant (Fig. 6) in the eastern part of Parowan Gap and in the Markagunt Plateau to the east. Although the plateau is separated from the Parowan Gap area by the alluviated

Parowan Valley, the plateau margin curves westward along the south end of Parowan Valley, effectively giving a transverse structure section of the valley. A study of exposures of concordant Cretaceous and Tertiary rocks along the curving plateau margin shows that Laramide folds probably do not underlie Parowan Valley. Thus, it appears that the Parowan Gap fold and its probable southward continuation, the Kanarra fold, constitute an isolated welt, similar in tectonics and in age to tightly-folded welts along the plateau margin in central Utah (Spieker, 1949).

Cenozoic structures responsible for eastward shift of the plateau margin and warping or fragmentation of Laramide folded structures

Although areal geologic maps and accompanying texts by Thomas and Taylor (1946), Gregory and Williams (1947), and Gregory (1950) clearly indicate that the axis of the Kanarra fold is essentially horizontal for at least 20 miles south of Cedar City (Fig. 1), none of the authors made reference to the remarkably abrupt plunge of the Kanarra fold axis, shown by outcrop patterns on the geologic maps by Gregory and Thomas. The plunge is about 45°, in a northerly direction, and is shown on the geologic maps by half of a blunt anticlinal nose or an abrupt westward shift in strike of the east flank of the fold.

An abrupt plunge of 45° of a fold axis which is otherwise horizontal for a distance of at least 20 miles is hardly expectable in primary development of a simple fold like the Kanarra fold. Evidence will be presented in subsequent paragraphs which demonstrates that abrupt northward plunge of the Laramide Kararra fold is due to subsequent development of an easterly-trending mid-Cenozoic monocline along the plateau margin north of Cedar City, downthrown to the north, transverse to the north-northeasterly trend of the Kanarra fold.

Abrupt plunge of the late Cretaceous Kanarra fold takes place precisely where the plateau margin departs from the mid-Tertiary Hurricane fault zone and shifts abruptly eastward along the south end of Parowan Valley. It appears, therefore, that plunge of the Laramide fold is related to a much later structural feature which is responsible for abrupt shift of trend of the plateau margin. Gregory (1950, p. 115) figured "Cretaceous deposits at the mouth of Fiddler Canyon curved downward to their contact with the Hurricane fault" near this point of shift in trend of the plateau margin. Maps and sections by Gregory, as well as the map by Thomas, show consistent attitudes of approximately N50°E 45°NW in concordant Tertiary and Cretaceous rocks exposed discontinuously along the northwestern margin of the Piute Highlands section of the Markagunt Plateau, although neither author apparently regarded these unusual attitudes as anything more than drag effects in the vicinity of a supposed Hurricane fault zone along the plateau margin. The dips are consistently high nearly a mile back of the plateau margin and are clearly not a matter of simple drag along a fault zone; the attitudes represent an easterly-trending monocline.

Neither the map by Gregory nor the map by Thomas actually shows the Hurricane fault or any other continuous fault zone along the plateau margin; in fact, the numerous faults of the Piute Highlands transect the plateau margin, which is fundamentally a monoclinal scarp between Parowan and Cedar City. It is this northeasterly-trending Cenozoic monocline, essentially contemporaneous with but transverse to the north-northeasterly-trend of the Hurricane fault, which is responsible for shift in trend of the plateau margin. Likewise, the monocline is transverse to the old Laramide fold axis, and downthrow on the monocline is responsible for abrupt plunge of the Laramide fold. This is rather clearly a case in which the plunge of a fold was developed by an independent transverse warping, long after the fold had been produced, bevelled, and buried under hundreds of feet of younger rocks.

The monocline, hereafter referred to as the Summit monocline because of excellent exposures south of Summit, Utah, is obviously younger than andunrelated to development of the Laramide Kanarra fold, because the monocline involves Tertiary and Quaternary rocks. A Quaternary(?) basalt sheet which originated from a cone at the mouth of Winn Canyon, south of Summit, and flowed eastward is now tilted 10-20° westward by geologically recent displacements on the Summit monocline. Major development of the monocline, however, took place in mid-Tertiary(?) time, post-Tertiary acidic volcanics--pre-Quaternary basalt, essentially contemporaneous with the first major movements in the Hurricane fault zone (Gregory, 1950). Strongly tilted (30°-45° dips) Cretaceous and Tertiary sedimentary rocks and Tertiary acidic volcanics in the monoclinal zone are bevelled and overlain, in angular unconformity, by the Quaternary basalt which participated in late Quaternary folding on the monocline; strong tilting of the older rocks beneath the basalt was surely due to mid-Tertiary development of the monocline. On the shoulder of the monocline, 4 miles northeast of Cedar City, the geologic map and sections by Gregory (1950) show Tertiary acidic volcanic rocks resting with angular unconformity on Cretaceous rocks, suggesting to the present writer that slight initial folding of the monocline, with local stripping away of the Wasatch, began in post-Wasatch--pre-Tertiary acidic volcanics time.

The following diagrams (Fig. 20) summarize the sequence of events along the Summit monocline in the vicinity of Summit and Winn Creek, as interpreted by the present writer. A nearly identical and contemporaneous sequence of events along the Hurricane fault zone has been reported by Gardner (1941), although faulting rather than flexing was responsible for major displacements. The erosion surface developed at the base of the monocline in Stage 1 roughly corresponds to the "Mohave peneplain" of Gardner.

Early movement on the Summit monocline probably occurred somewhat earlier than most of the late Cenozoic faults of the Piute Highlands, because the monoclinal structure is largely transected and fragmented by the faults. Gregory (1950) regarded most of the faults of the Piute Highlands as Quaternary in age because they record much less displacement than master faults like the Hurricane fault and are probably related to ultimate development of the present Parowan Valley block.

Cenozoic structures of the Red Hills area

Nature of the structures

In the central and northern Red Hills and in the Gray Mountains, early Tertiary sedimentary and acidic volcanic rocks have a regional easterly dip of about 10° and are broken by numerous high-angle faults. The generally uniform dip was produced by broad warping rather than by tilting of fault blocks because attitudes of the Tertiary rocks in unfaulted portions of the northwestern Red Hills area, indicate that the eastward dip in the Red Hills and Gray Mountains was developed on the east flank of a broad anticlinal structure whose axis parallels

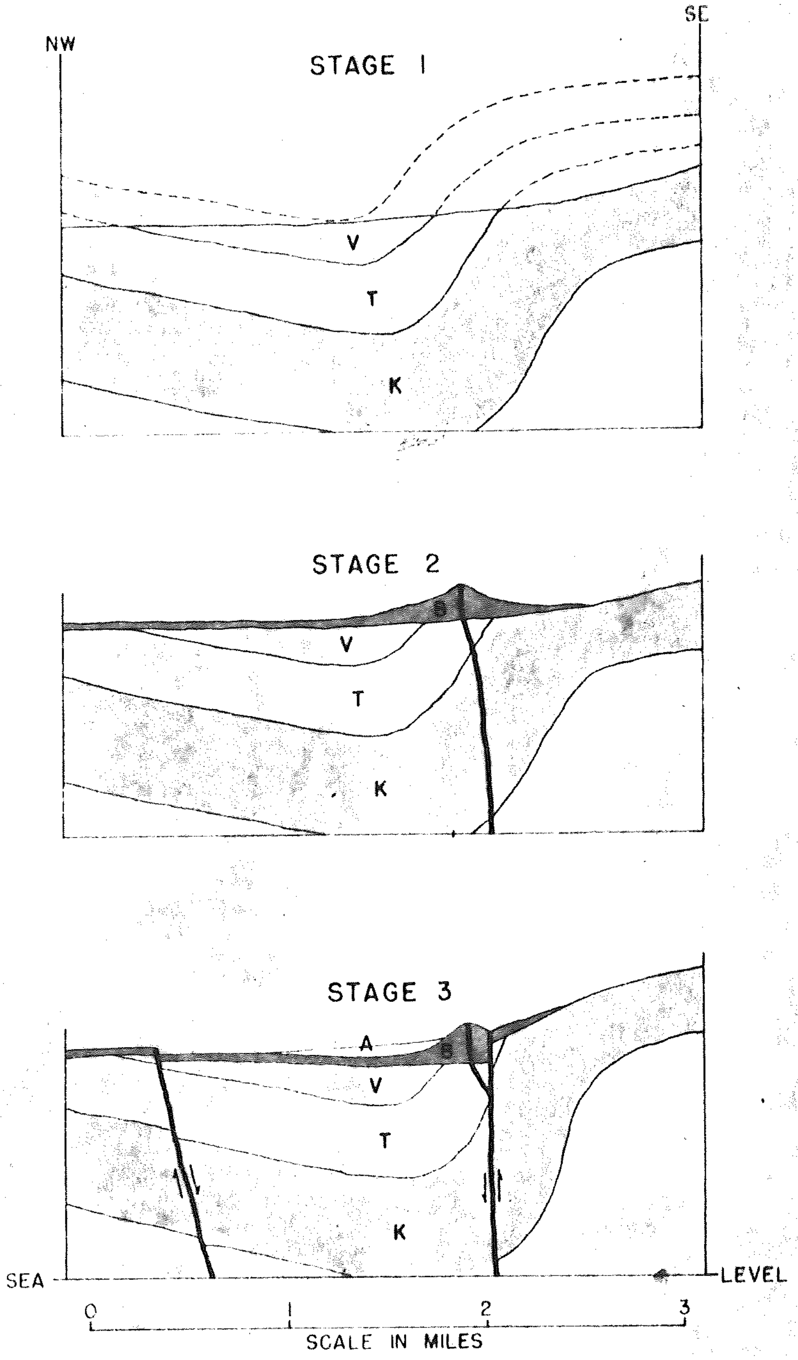


Fig. 20. Sequence of events along Summit monocline in the vicinity of Summit and Winn Creeks at the west margin of the Markagunt Plateau.

Stage 1—Mid-Tertiary downwarping, followed by pedimentation of flank and toe of fold during late Tertiary-early Quaternary time.

Stage 2—Burial of pediment by Quaternary(?) basalt which originated from vent at mouth of Winn Canyon.

Stage 3—Further tilting and minor faulting in late-Quaternary(?) time.

A—recent alluvium
B—Quaternary(?) basalt
V—early to middle Tertiary acidic volcanics
T—Claron or Wasatch formation
K—Iron Springs formation

and lies near the western edge of the range block approximately coincident with the old Laramide axis. Furthermore, as will be shown later, most of the faulting of the Red Hills area appears to have been post-Quaternary(?) basalt, and little or no tilting of the basalt sheets accompanied the faulting.

Southward toward Parowan Gap, the anticlinal structure becomes more and more obscured in numerous fault blocks immediately east of Hieroglyph Canyon, although the general reversal of dip is recognizable. South of Parowan Gap, the faulted anticline is buried beneath the extensive area of Quaternary(?) basalt which lies immediately east of Rush Lake. The anticlinal warping, accompanied by only minor faulting, took place prior to or during early Quaternary time, because the warped Tertiary strata are bevelled and overlain by flat-lying Quaternary(?) basalt.

The Quaternary(?) basalt sheets and tilted Tertiary strata are broken by numerous high-angle faults which have a north-northeasterly trend, parallel to the old Laramide trend. In the Gray Mountains a few minor faults have a northeasterly trend. Most of the fault planes seem to dip nearly vertically, as shown by straight and simple traces, independent of topography; the few planes for which reliable dips were obtained suggest that the tendency is toward normal rather than reverse faults. The range boundary fault zone, south of the east end of Parowan Gap, is exposed in a shallow prospect pit (NW$\frac{1}{4}$, NW$\frac{1}{4}$; Sec. 23; T34S-R10W), and shear planes dip 70° easterly, toward the downthrown side of the fault. South of central Parowan Gap (W$\frac{1}{2}$, SW$\frac{1}{4}$; Sec. 34; T33S-R10W), a high-angle fault trace shows faint westward displacement where the fault line crosses streams and lowlands. On the basis of equally fresh and continues a straight course to the south end of the Gray Mountains. Because of downwarp of the south end of the Gray Mountains beneath Parowan Valley and Little Salt Lake, the range block margin jogs sharply eastward and continues northward along one or more fault scarps at the east margin of the Gray Mountains. For the most part, the faulted east margin of the Gray Mountains is much less well-defined and much more deeply eroded than the simple east margin of the Red Hills, suggesting that elevation of the Red Hills segment of the eastern portion of the range block has taken place somewhat more recently than elevation of the Gray Mountains portion.

Faults which break the Rush Lake basalt sheet along the west margin of the range block and at the lateral margins of the Enoch graben appear to have been developed very recently, perhaps no more than a few thousand years ago. Talus from the scarps is extremely limited, and margins of the upthrown block are barely notched by stream erosion and weathering. Along the east side of the Enoch graben the fault scarp is a simple and straight scarp about 150 feet high; along the west side of the Enoch graben, the scarp is about the same height but is complex and irregular because of widespread development of fault splinters and small hinge blocks. Along the west margin of the range block, the fault pattern is strikingly _en echelon_, but the individual fault scarps are straight and simple, with little development of talus or erosional re-entrants.

Because of the freshness and general lack of erosional modification of the fault scarps which bound the range, and the horst-graben-horst elements within the range, the writer believes that major development of the range block occurred in middle to late Quaternary time. This limitation of faulting essentially to the Quaternary Period in the Red Hills area strikingly contrasts with the record of dominantly mid-Tertiary displacement along the Hurricane fault zone of the Kolob Plateau margin (Gardner, 1941; Gregory, 1950).

Structural interrelations of the Hurricane fault zone, Summit monocline, Red Hills range block, and Cedar City and Parowan basin blocks (Fig. 22)

Although Cenozoic faults of the Red Hills area are aligned with the north-northeasterly trend of the Hurricane fault zone south of Cedar City, the Red Hills faults can hardly be regarded as an extension of the Hurricane fault zone. Although downthrow on most of the faults in both areas is to the west, small displacements of a few tens or hundreds of feet in the Red Hills area are, by no means, comparable to thousands of feet of displacement reported from the Hurricane fault zone (Gregory, 1950). The faults of the Red Hills area represent a rapid dying out of the Hurricane fault zone northward, as the zone of displacement is shifted eastward to the Markagunt Plateau margin.

Although it has been generally thought, since the days of Dutton (1880), that the Hurricane fault shifts abruptly eastward, north of Cedar City, and continues northward along a bold escarpment at the west margin of the Markagunt Plateau, Thomas and Taylor (1946) and Gregory (1950) noted that the Hurricane fault, as a narrow zone of fracture, might be said to end at Kanarraville several miles south of Cedar City. The present writer noted that the Summit monocline, rather than the Hurricane fault, extends along the plateau margin north of Cedar City. It appears that most of the displacement in the Hurricane fault zone south of Cedar City is taken up by the Summit monocline which transfers

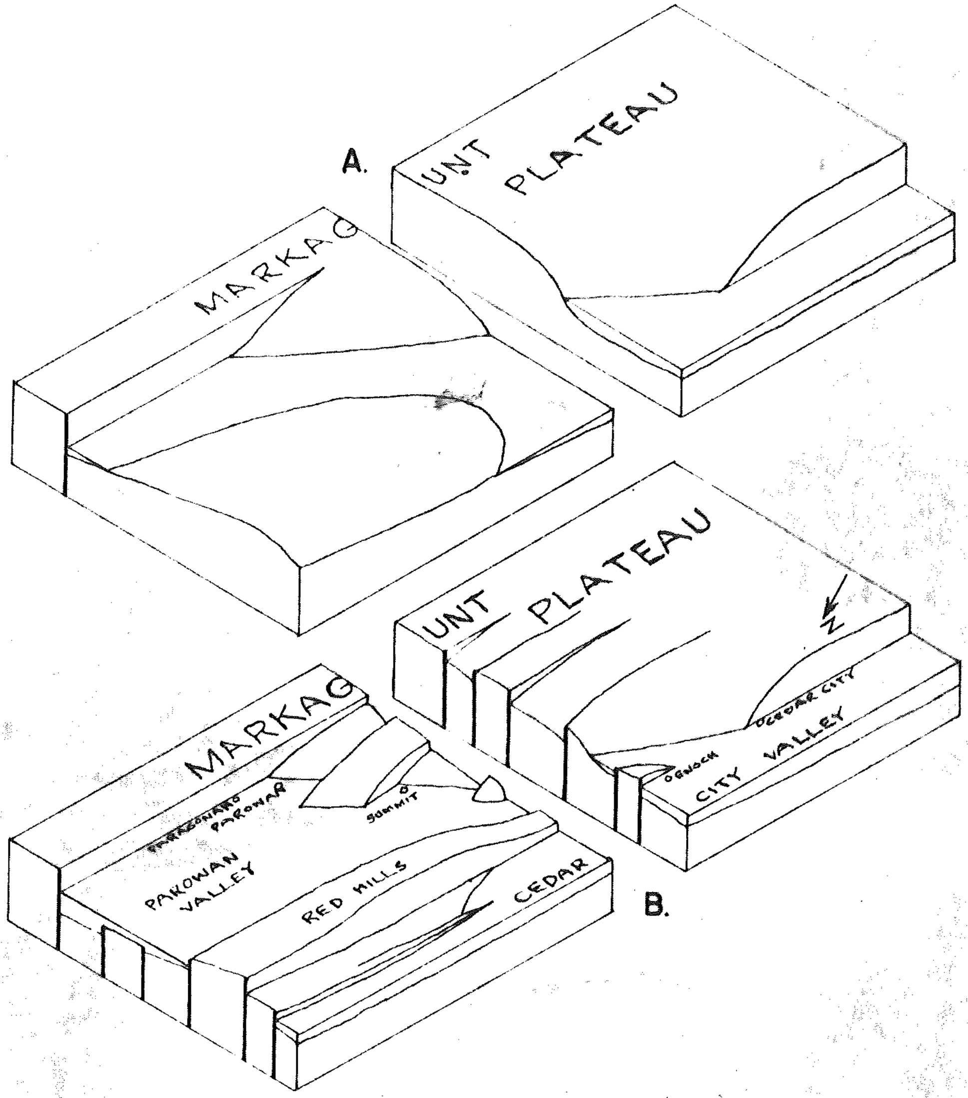


Fig. 22. Diagrammatic representation of fundamental Cenozoic structural elements of eastern Iron County, Utah. The deformed surface is arbitrary but corresponds approximately to the top of the Tertiary acidic volcanic sequence. Blocks are shown as unmodified by erosion; blocks are split and hypothetical basin fill is added for clarity.

A—mid-Tertiary(?) deformation: chiefly post-acidic volcanics—pre-Quaternary(?) basalt.

B—late Tertiary-Quaternary deformation: dominantly post-Quaternary(?) basalt.

the zone of downthrow eastward to the master fault that forms the west margin of the Markagunt Plateau north of Paragonah (Thomas and Taylor, 1946). This fault, which is here designated as the Paragonah fault, bears an en echelon relationship to the Hurricane fault, and the Summit monocline serves as the structural bridge between the two master faults. The Red Hills area bears little more than incidental relationship to the great zone of downthrow along the plateau margin during Cenozoic time; the Red Hills area represents a locally upwarped portion of the otherwise uniformly depressed basin block immediately west of the uplifted plateau block.

GEOMORPHOLOGY

General considerations

The most outstanding geomorphic problems of the Red Hills area are concerned with the role of Cenozoic displacements in delineation of the range block from flanking basins, coupled with development of Parowan Gap through the rising range block ~~and~~ ultimate defeat of the stream which cut the gap.

The first attack on geomorphic problems of the Red Hills area was made by Douglas Johnson (1918, pp. 232-234) who stated:

> In the summer of 1906 I passed through the Parowan Valley at the western base of the high plateaus of Utah. This depression . . . is well shown on the Kanab topographic quadrangle, and was interpreted as a graben. . . . The great fault which bounds the valley on the southeast is abundantly attested by both physiographic and stratigraphic evidence, as I proved by several traverses across the fault southeast of Summit, Parowan, Paragoonah, and elsewhere. On the northwest the valley floor terminates abruptly at the base of a pronounced scarp, which is more or less dissected, but which shows occasional well-marked triangular facets such as characterize the fault faces of certain block mountains. The topography strongly suggests that Parowan Valley is a down-dropped block, bounded on the southeast by a fault-block plateau and on the northwest by a fault-block mountain whose more gentle backslope is toward the northwest.
>
> Cutting transversely through the block mountain just mentioned is a remarkable gorge directly in line with the extended lower course of a stream which rises in the block plateau and flows northwest through the town of Parowan. According to the map, however, the stream does not continue through the gorge at the present time, but terminates in a salt lake at the base of the fault scarp. The topographic relations suggested the possibility that a recent upfaulting of the block mountain had obstructed the Parowan stream and left the antecedent gorge deserted. . . . the deserted valley has not yet been raised much above its former level, and the lake initiated by the rising obstruction has found no new outlet. It is possible that heavy rains might so raise the lake-level as to cause it to spill out through the gorge itself before another outlet was found. Unfortunately, I was not able

stereometric measurements on the aerial photos, the fault plane has a westerly dip of about 60°, toward the downthrown block. Similar relationships are shown north of Parowan Gap ($SE\frac{1}{4}$, $SE\frac{1}{4}$, $SE\frac{1}{4}$; Sec. 22; T33S-R10W).

Displacements along individual faults within the range block are relatively slight and range from a few feet to a few hundred feet. Displacements on the master faults which outline the range block and separate it from flanking valleys generally can not be accurately determined because of extensive alluviation of downthrown blocks. Immediately northwest of White Butte along the east margin of the range block, throw of the range boundary fault is at least 1,000 feet because middle Claron limestone on the downthrown block abuts against upper Iron Springs sandstones about 800 feet below the base of the Claron formation. Along the west margin of the range at Rush Lake, a Quaternary(?) basalt sheet, at the base of a little-modified fault scarp, lies about 300 feet below a portion of the same basalt sheet on the upthrown block. It appears, therefore, that the range boundary faults generally record major displacement of several hundred feet.

As shown by Thomas and Taylor (1946) the range block (Red Hills area of the present paper) which separates Parowan and Cedar City Valleys owes its form to Cenozoic block faulting. Studies by the present writer indicate that at least two cycles of displacement, (1) post-acidic volcanics—pre-Quaternary basalt and (2) post-Quaternary basalt, have been important in shaping of the range block, but much of the outlining and separating of the range from flanking basin blocks was accomplished by the more recent cycle of faulting. Evidence supporting these statements will be presented subsequently, but the statements have been introduced here to help clarify the following discussion of structural elements of the Red Hills area.

Structural elements

Thomas and Taylor (1946) described the range block as a horst with an internal graben. The high eastern half of the range block, the Red Hills and Gray Mountains of the present paper, was designated as the Red Hills horst. The long strip of upland, Hieroglyph Canyon hogback, along the west margin of the south part of the range block was designated as an extension of the Hamilton's Fort horst of the Cedar City area. The lowland, Enoch Valley and its northward extension into the range block, between the two horsts was designated as the Enoch graben.

When the area is mapped in detail (Plate I) and analyzed (Plate IV), the simple concept of horst-graben-horst is adequate for only the southern part of the area, and then chiefly with respect to the most recent movement along faults. In fact, identity of the Enoch graben is largely lost north of the extensive area of Quaternary(?) basalt because the east boundary fault of the Enoch graben branches into several faults and the east boundary fault of the Hieroglyph horst dies out rapidly toward the east end of Hieroglyph Canyon.

For the southern one-third of the range block separating Cedar City and Parowan Valleys, the names of Red Hills horst and Enoch graben are retained in a restricted sense (Plate IV). Inasmuch as Thomas and Taylor inferred the positions of boundary faults of the narrow Hamilton's Fort horst beneath 7 miles of alluvium of Cedar City Valley and into the Red Hills area, the present writer prefers to substitute a local name, Hieroglyph horst, for the horst which is situated along the west side of the southern Red Hills area. In the northern two-thirds of the range block which separates Cedar City and Parowan Valleys, fault block distribution and fault patterns are so complex that the writer has not attempted to assign names to the various structural elements.

Dating of Cenozoic displacements in the Red Hills area

As indicated previously, early movement on the Hurricane fault-Summit monocline zone may have begun in late Eocene time, but major displacement did not occur along the zone until Miocene(?) time, post-acidic volcanics—pre-Quaternary basalt; initial anticlinal warping in the Red Hills area accompanied this major displacement along the forming plateau margin.

Apparently only limited faulting occurred in the southern Red Hills area prior to extrusion of Quaternary basalts, because most of the faults of the southern Red Hills area break the basalt sheets or are continuous with faults which break the basalt sheets, and total displacement on a given fault is approximately equal to displacement of an initial surface of a basalt sheet along that fault. In the northern part of the Red Hills area the basalt sheet datum is absent, and the writer can date movement on the various faults no more closely than post-acidic volcanics. As will be shown subsequently, early stages of upfaulting of the central part of the Red Hills area began in late Pliocene-early Pleistocene(?) time, immediately prior to extrusion of Quaternary basalts and continued after extrusion of the basalts; the poorly-dated faults along the margin of and within the northern part of the Red Hills area probably had a similar history. .

The writer noted only two faults which definitely had pre-basalt movement, although as indicated above, the faults of the northern part of the Red Hills area can not be dated precisely. A fault (W$\frac{1}{2}$, Sec. 27; T33S-R10W) which abruptly terminates exposure of folded Mesozoic rocks in west-central Parowan Gap, by downthrow of middle and upper Claron red beds against the Carmel limestone, had displacement of at least 500 feet; all of the movement was pre-basalt because the fault passes beneath the Rush Lake basalt sheet without displacement of the basalt. This fault was the major mid-Tertiary(?) fault associated with anticlinal warping of the Red Hills area, and it broke the anticline approximately along the crest. The fault extends only about one mile north of Parowan Gap, but it presumably extends for several miles southward beneath the basalt and may have later served as the avenue of ascent for the Rush Lake basalt flows.

A fault which extends southward from Whitney Canyon (W$\frac{1}{2}$, W$\frac{1}{2}$; Sec. 35; T33S-R10W) has a total throw of about 1,000 feet, but only 200-300 feet can be ascribed to post-basalt faulting; the difference of 700-800 feet is a measure of displacement along the fault prior to extrusion of the Rush Lake basalt. A short segment of fault line (W$\frac{1}{2}$; Sec. 21; T34S-R10W) emerging from beneath the southeast edge of the basalt sheet records only pre-basalt movement and may represent the southern terminus of pre-basalt displacement on the Whitney Canyon fault.

It is noteworthy that linear extent of the Whitney Canyon fault is roughly limited to the structurally highest portion of the Red Hills horst (Plates I, IV) suggesting that displacement along the Whitney Canyon fault accompanied upward bulging of the Red Hills horst. This bulging or upwarping of the central part of the Red Hills horst took place entirely in pre-basalt time, because post-basalt movement on the

Whitney Canyon fault produced no appreciable upward bulge in the portion of the basalt sheet on the upthrown block. A complementary fault along the east margin of the Red Hills horst, the east boundary fault of the range block of the Red Hills area, probably also had early movement prior to Quaternary(?) basalt outpouring, to facilitate uplift of the Red Hills horst above the subsiding block of Parowan Valley. The entire eastern portion of the range block probably began to rise above the subsiding Parowan Valley block in late Tertiary-early Quaternary time, but the writer was unable to find conclusive evidence for precise dating of faults beyond the margins of Quaternary basalt sheets.

For the most part, the fault scarps which bound the range block and the horst-graben-horst structural elements are remarkably fresh and unmodified by erosion. A little-eroded fault scarp which rises as much as a thousand feet above Parowan Valley, from Parowan Gap to Winn Gap, at the east margin of the range block, shows large faceted spurs and an extremely straight base line which is independent of internal structure of the range block. Northward from Parowan Gap, a fault scarp, which bears an en echelon relationship to the previously mentioned scarp, is

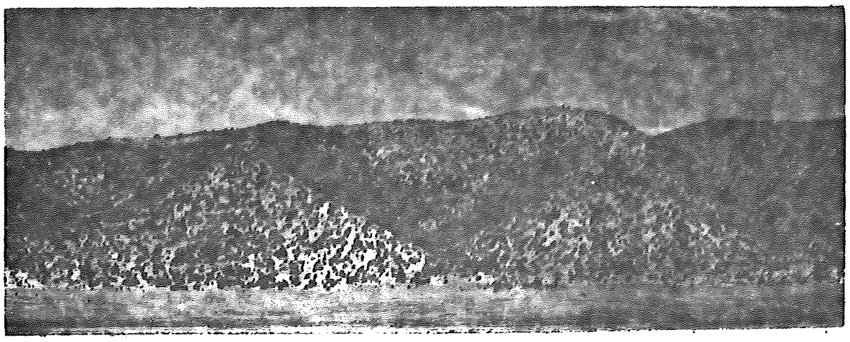


Fig. 11. Triangular-faceted spurs due to late Quaternary(?) faulting along the east margin of the Red Hills due west of Parowan, near the Boxheads.

> to visit the entrance to the gorge, nor otherwise to test the validity of my tentative interpretation. Observations based on a reconnaissance map with contour interval of 250 feet, supplemented by visual inspection from a distance of four or five miles, must not be accorded too high a value.

While the above observations attest Johnson's skill in map interpretation, the highly simplified concepts based on reconnaissance neglect certain outstanding geomorphic problems — complexity in history of uplift of the range block of the Red Hills area and origin of the transverse stream which was defeated by "recent upfaulting of the block mountain."

Tertiary geomorphic events in the Red Hills area (Fig. 23)

One of the significant facts discovered in detailed study of the Quaternary(?) basalt sheets is that these lavas, which are broken by geologically recent faults, lie on bevelled edges of tilted Tertiary strata throughout extensive areas of the southern Red Hills. As suggested in previous discussion of Cenozoic structure of the Red Hills area, these tilted Tertiary strata of the southern Red Hills probably represent the east flank of a broad anticline which was rising at the site of the Red Hills area while the plateau margin and major basins to the west were developing in mid-Tertiary time. Presumably, this anticline served as an effective drainage barrier between subsiding Parowan and Cedar City basins, at least until the anticline had been bevelled by drainage which was consequent on its flanks and/or until the anticline had been overwhelmed by alluvium which was being deposited in Parowan basin, thereby effecting drainage integration and extension of plateau drainage across the site of the Red Hills area.

In the southern Red Hills, there is no doubt that pre-basalt drainage integration took place, because extensive pediment remnants, mantled by coarse gravels of late Tertiary(?) age, ("fanglomerate terraces" of Thomas and Taylor, 1946) define a broad erosion surface which bevelled tilted Tertiary rocks at the toe of the Summit monocline and westward to Cedar City Valley. These remnants of the old pediment, locally covered by Quaternary(?) basalt in the vicinity of Winn Gap, extend northward to the south end of the Whitney Canyon fault zone and westward beneath the Rush Lake basalt sheets. A similar erosion surface on tilted Tertiary and older rocks is exposed beneath the eroded northern edge of the Rush Lake basalt sheet, two miles south of Parowan Gap, and seems to represent the extensive pediment of the southern Red Hills. Because of recent dissection of weak Tertiary strata north of the area of Rush Lake basalt, the writer was unable to determine the northern limit of the pediment.

The prominent upwarped portion of the Red Hills horst flanks these pediment remnants on the north and east, and one is led to wonder how the upwarped block fits into the development or restriction of the extensive late Tertiary pediment of the southern Red Hills. As indicated in the discussion of dating of Cenozoic displacements in the Red Hills area, initial upwarp of the structurally highest portion of the Red Hills horst took place entirely in pre-Quaternary(?) basalt time; however, as the pediment of the southern Red Hills is traced toward the upwarped portion of the Red Hills horst and the Whitney Canyon fault zone, the pediment ends abruptly and seems to bear no genetic relation to the Red Hills horst. Near the south end of the Whitney Canyon fault zone, the pediment gravels are well preserved on the downthrown block immediately adjacent to the fault line, but the gravels are totally absent from the slightly upthrown block. Furthermore, immediately north of Winn Gap on the south flank of the up-bulged portion of the Red Hills horst, the Quaternary(?) basalt, which elsewhere lies on the late Tertiary pediment gravels, lies directly on an irregular surface developed on the upper Claron limestones and early Tertiary acidic volcanic rocks.

All of these relations suggest that, by late Tertiary time, the mid-Tertiary anticline was extensively pedimented and traversed by plateau drainage in the entire southern Red Hills area; only in late Tertiary or early Quaternary time, immediately prior to extrusion of Quaternary(?) basalt, did the central and northern(?) portion of the present Red Hills horst begin to rise above the pedimented basin west of the plateaus, with consequent stripping of the late Tertiary gravels from the upthrown block. Shortly after uplift and stripping of the gravels, Quaternary basalts poured across uneroded, relatively down-thrown portions of the old pediment and overlapped the flanks of the newly uplifted portion of the Red Hills.

In the central and northern Red Hills area, the writer was unable to find remnants of the late Tertiary pediment, or its capping gravels, which extended from the Markagunt Plateau to Cedar City Valley, across the site of at least the southern Red Hills area. Instead, in the Jack-rabbit area west of the Gray Mountains, accordant summits of low, rolling hills define an extensive pediment which is continuous westward with Cedar City Valley and is continuous eastward with the foot of a retreating escarpment of resistant acidic volcanic rocks which cap the Gray Mountains. This erosion surface is obviously independent of Markagunt Plateau drainage and is clearly due to bevelling of the mid-Tertiary anticline of the Red Hills area, by drainage on the west flank of the rising anticline.

It might be argued that the site of the northern Red Hills area was once part of a vast pediment, continuous with the one preserved in the southern Red Hills, which extended from the plateaus to Cedar City Valley, and that the present local erosion surface of the Jackrabbit area was developed during and since late Tertiary(?) upfaulting of the range block and destruction of the late Tertiary pediment. The writer believes, however, that in view of the general limitation of erosional modification of fault blocks associated with late Tertiary-Quaternary upfaulting of the range block, the extensive pediment of the Jackrabbit area can be explained best by continued erosion since initial anticlinal upwarping of the Red Hills area in mid-Tertiary(?) time. In the northern Red Hills area, therefore, drainage from the Markagunt Plateau probably never proceeded across the site of the area but was forced to fill a broad basin which intervened between the Red Hills anticline and the Paragonah fault scarp. Farther south, because of a convergence of trends of the Red Hills anticline and the Summit monocline, the subsiding intervening basin was narrow and was filled rapidly, causing burial of the Red Hills anticline and establishment of through-flowing drainage to Cedar City Valley, as recorded by remnants of a late Tertiary pediment. At some indeterminable point, intermediate between the site of the northern and southern Red Hills area, on the Red Hills axis and extending eastward to the base of the rising plateau, there probably was a drainage divide, probably the alluvial fan of Parowan Creek discharging from the Markagunt Plateau, between the through-flowing drainage which was bevelling the southern part of the Red Hills anticline

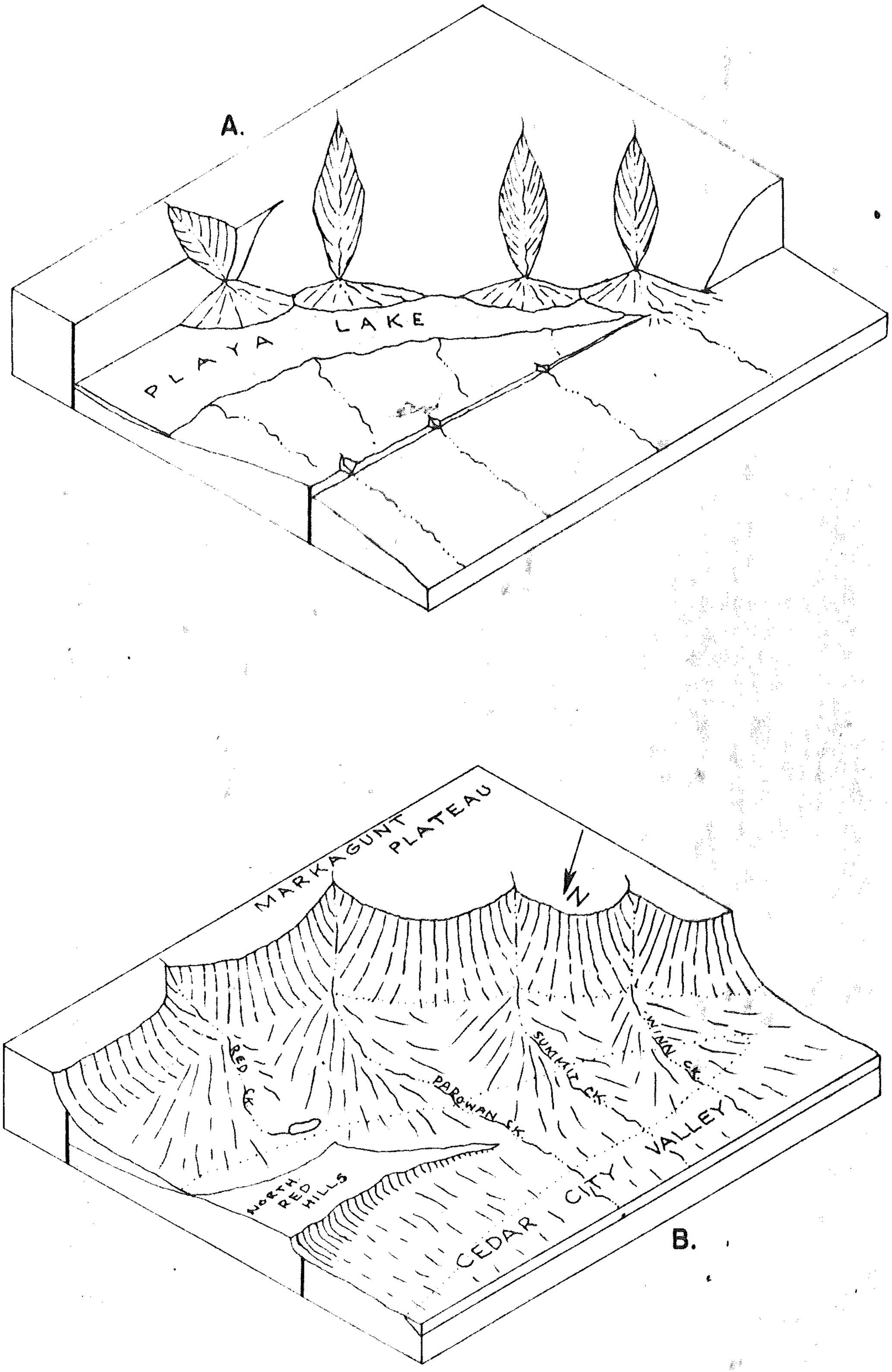


Fig. 23. Diagrammatic representation of Tertiary geomorphology of eastern Iron County. A—Immediately following mid-Tertiary(?) displacements. B—Integration of drainage and bevelling of southern Red Hills during late Tertiary time. Dots outline areas with thin alluvial cover as opposed to areas with thick basin fill.

and interior drainage which was burying the east flank of the northern part of the Red Hills anticline.

Quaternary geomorphic events in the Red Hills area

With initiation of upfaulting of the range block of the Red Hills area in late Tertiary-early Quaternary time, immediately prior to and continuing after extrusion of Quaternary(?) basalt sheets, development of the range proceeded rapidly until ~~the~~ present form was attained. Numerous recent fault scarps in the alluvium of Cedar City and Parowan Valleys near the margins of the range suggest that faulting is still in progress.

Although uplift of the central and northern(?) Red Hills area probably began immediately prior to extrusion of Quaternary(?) basalts, development of the Parowan Valley graben-Red Hills horst-Enoch graben-Hieroglyph horst-Cedar City Valley graben structural elements of the southern Red Hills area did not take place until some time after emplacement of the basalt sheets. As indicated earlier, all of the fault scarps in the basalt sheets are remarkably fresh and unmodified by erosion of the upthrown block or deposition of talus at the base of the scarp.

At the extreme southern end of the Red Hills, the east boundary fault of the range block dies out and the range merges eastward with the alluvium of Parowan Valley. This limited development of the range block and upfaulting above the Parowan Valley basin block took place entirely in post-basalt time, because Tertiary rocks beneath the basalt are essentially continuous, stratigraphically, and record no pre-basalt upfaulting of the range block; as indicated earlier, north of Winn Gap, upfaulting of the range block was immediately pre-basalt.

The record of faulting described in preceding paragraphs indicates a progressive southward growth or extension of the range block during late Tertiary-Quaternary time. As a result, the northern portions of the range are maturely eroded; the southern portions are youthful. The clear-cut development of Winn Gap through the southern Red Hills, by superposition from late Tertiary-Quaternary gravels and basalt sheets and by maintenance of an antecedent position to cut the shallow gap

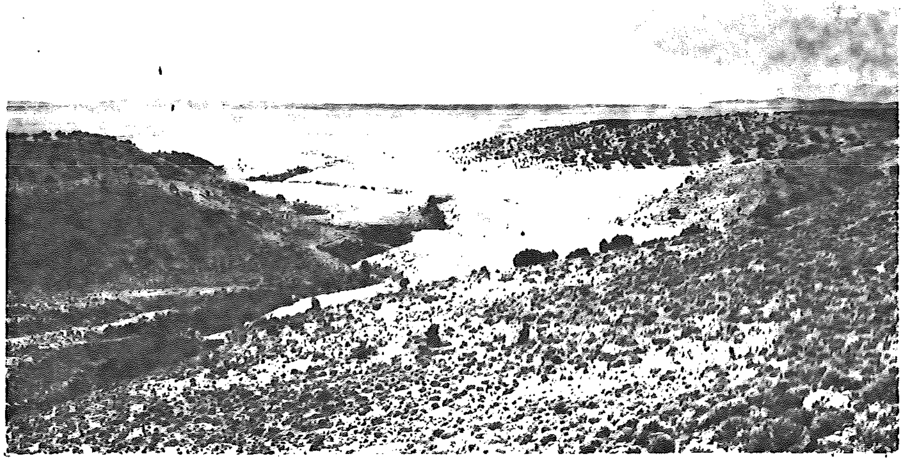


Fig. 24. Winn Gap through the southern Red Hills—Cedar City Valley and ranges of Escalante Desert beyond.

Winn Creek, which heads in the Markagunt Plateau, was superimposed from Quaternary(?) basalt (preserved near east end of gap) and late Tertiary-early Quaternary(?) gravels (pre-basalt) which cap the flat-topped uplands flanking the gap. In addition, Winn Creek maintained its antecedent position, cutting Winn Gap, as the southern Red Hills relatively rose about 50 feet above Parowan Valley and about 250 feet above Cedar City Valley in post-basalt time. Incision of "inner valley" in alluvium is related to post-1860 arroyo cutting which is common in arid regions of southwestern United States.

with slight rise of the range block above flanking basins, should provide an understanding of development of the deep Parowan Gap through the structurally-higher and slightly older central Red Hills.

Parowan Gap is strikingly aligned with the extended lower course of Parowan Creek; the gap was surely cut by the antecedent Parowan Creek during upfaulting of the range block. As suggested earlier, prior to upfaulting of the central and southern Red Hills area, the site of Parowan Gap was part of a vast alluvial plain or pediment, across which Parowan, Summit, and Winn Creeks flowed westward to Cedar City Valley. Winn Creek has been able to maintain its antecedent position to the present time because of only slight rise of the range block above southern Parowan Valley; Parowan Creek was able to maintain its antecedent position, at least until geologically recent time, because it is the major stream which discharges from the Markagunt Plateau north of Cedar City; Summit Creek is one of the minor streams of the plateau and also encountered the greatest degree of upthrow of the range block, resulting in early defeat of Summit Creek and the building of an alluvial fan divide across the subsiding Parowan Valley between Winn Creek and Parowan Creek (Thomas and Taylor, 1946).

The narrow floor of Parowan Gap, which is very flat in longitudinal profile, lies only a few feet above the flat floor of Little Salt Lake, and defeat of Parowan Creek has obviously taken place very recently. It is a moot question whether defeat was by continued uplift of the range block or by the generally-recognized increasing aridity during recent millenia; either factor could have caused abandonment of the Gap and development of the Little Salt Lake playa.

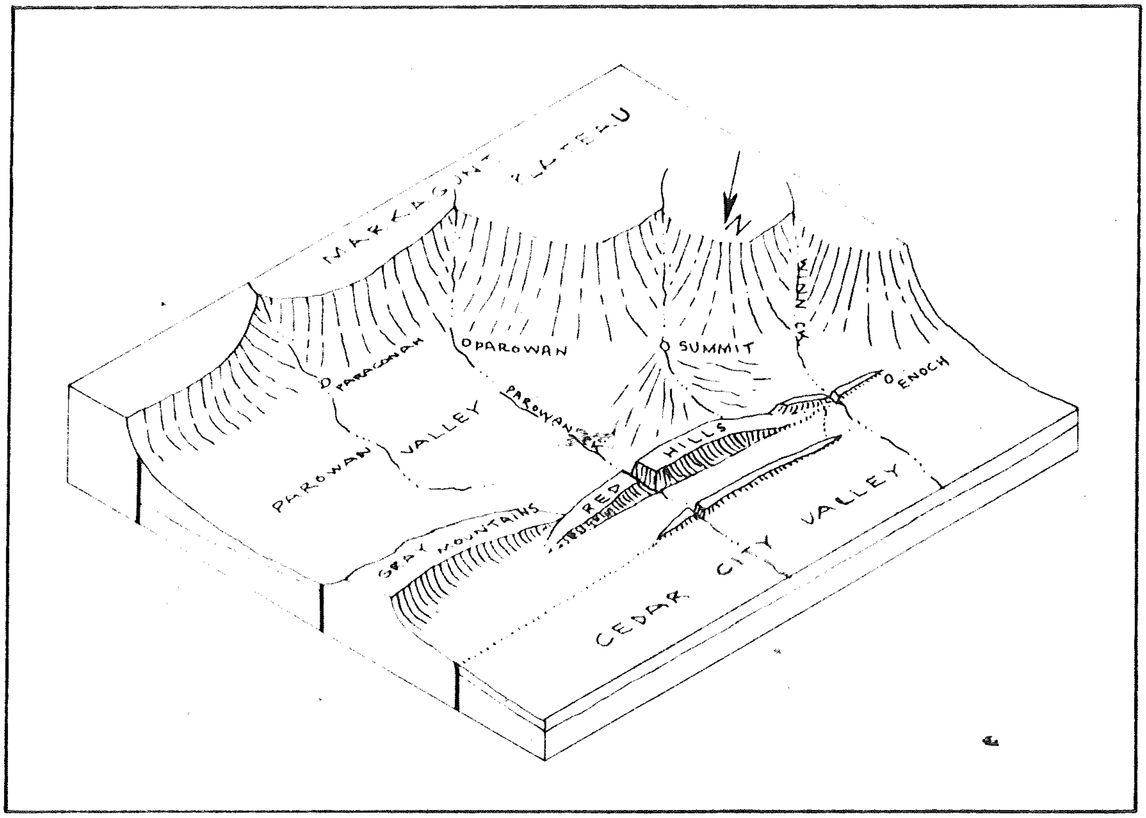


Fig. 25. Quaternary geomorphology of Red Hills area. Development of transverse gaps through rising range block of Red Hills area by antecedent Parowan and Winn Creeks; defeat of Summit Creek. Latest uplift of range block ultimately defeated Parowan Creek and left Parowan Gap abandoned.

Because of near coincidence of the lake floor and the flat longitudinal profile of the Gap, it is suggested that Little Salt Lake may have discharged intermittently through the Gap during more humid climatic phases of late Quaternary time; it is doubtful that an expanded Little Salt Lake existed for long enough periods of time to develop shoreline features, as did the major Pleistocene pluvial lakes of the Great Basin. Fremont (1844, p. 271) found Little Salt Lake to be "about seven miles long and one broad," but because of subsequent use of water of Parowan Creek for irrigation of the farms of Mormon settlers, the Wheeler survey

(1889, vol. 1, p. 48) found that the lake had evaporated to alkaline flats. Thomas and Taylor (1946, p. 30) described an "indistinct strand line" about 12 feet above the present floor of Little Salt Lake, but the present writer was unable to locate the supposed shoreline feature. The writer did note that some poorly-preserved terrace remnants a few feet above the present floor of Parowan Gap (Sec. 27, 28; T33S-R10W) suggest that the upfaulted floor of Parowan Gap has been lowered several feet, to its present near-equality of elevation with the floor of Little Salt Lake, by expansion of the lake and spilling out through the Gap to Cedar City Valley.

Thomas and Taylor (1946, p. 13) describe a "delta formed at the mouth of the small canyon just south of Parowan Gap". The present writer examined the supposed delta and found that its flat upper surface merges southward with one of the numerous stream terraces, called Rush Lake Benches by local inhabitants, in Cedar City Valley north of Rush Lake. The supposed delta is probably a lobate remnant of one of the terraces which are related to southward-flowing parallel drainage of northern Cedar City Valley. The "delta" was used as evidence, by Thomas and Taylor, that Rush Lake had once expanded widely to a level of about 5,520 feet, attaining a depth of at least 130 feet. Such a lake would have covered nearly the entire Cedar City Valley and should have left distinct shoreline features, in addition to the "delta" south of Parowan Gap. Mackin (personal communication) has not noted evidence of the inferred vast lake, in Cedar City Valley east of the Iron Springs district; the present writer has not noted evidence of the inferred lake, in Cedar City Valley south and west of the Red Hills area. Although no detailed study of the geomorphology of Cedar City

Valley was made, it appears that the supposed shoreline features described by Thomas and Taylor can be related to dissection of Cedar City Valley alluvium following Quaternary basin capture and extension of Cedar City Valley drainage westward to the Escalante Desert.

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VITA

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After receiving an honorable discharge from the armed services in August, 1946, he re-entered the University of Illinois and received a B.S. in chemistry in February, 1947, an A.B. in geology in June, 1947, and an M.A. in geology in August, 1949.

In September, 1949, he entered the University of Washington and began work on a doctorate in geology. After finishing all formal course work and while completing work on the thesis, he accepted an instructorship in geology at the University of Nebraska during the 1951-52 academic year.

Plate III

GENERALIZED WEST-EAST STRUCTURE SECTION THROUGH PAROWAN GAP UTAH WITH SUGGESTED RESTORATION OF PRE-CLARON STRUCTURE

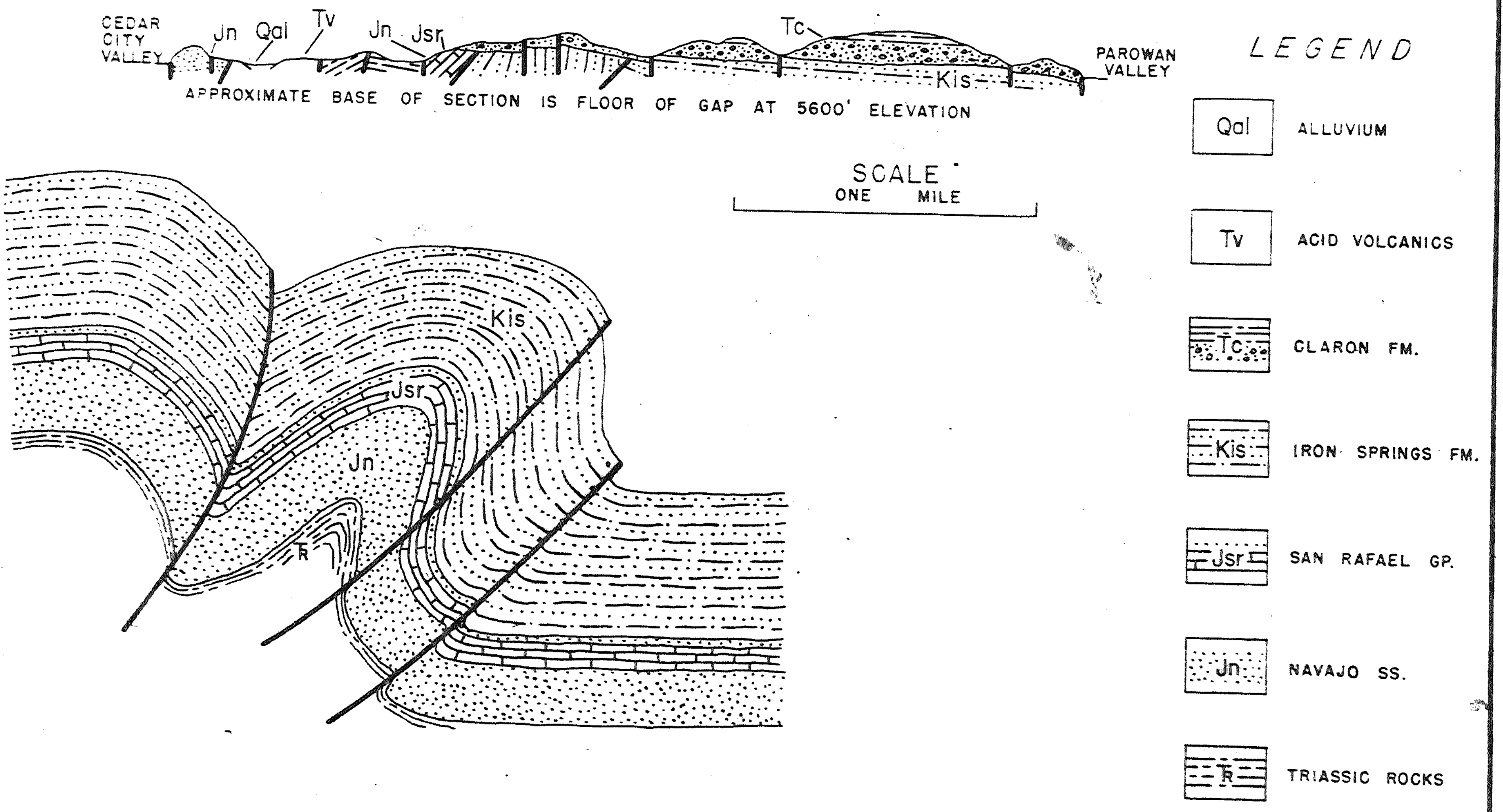
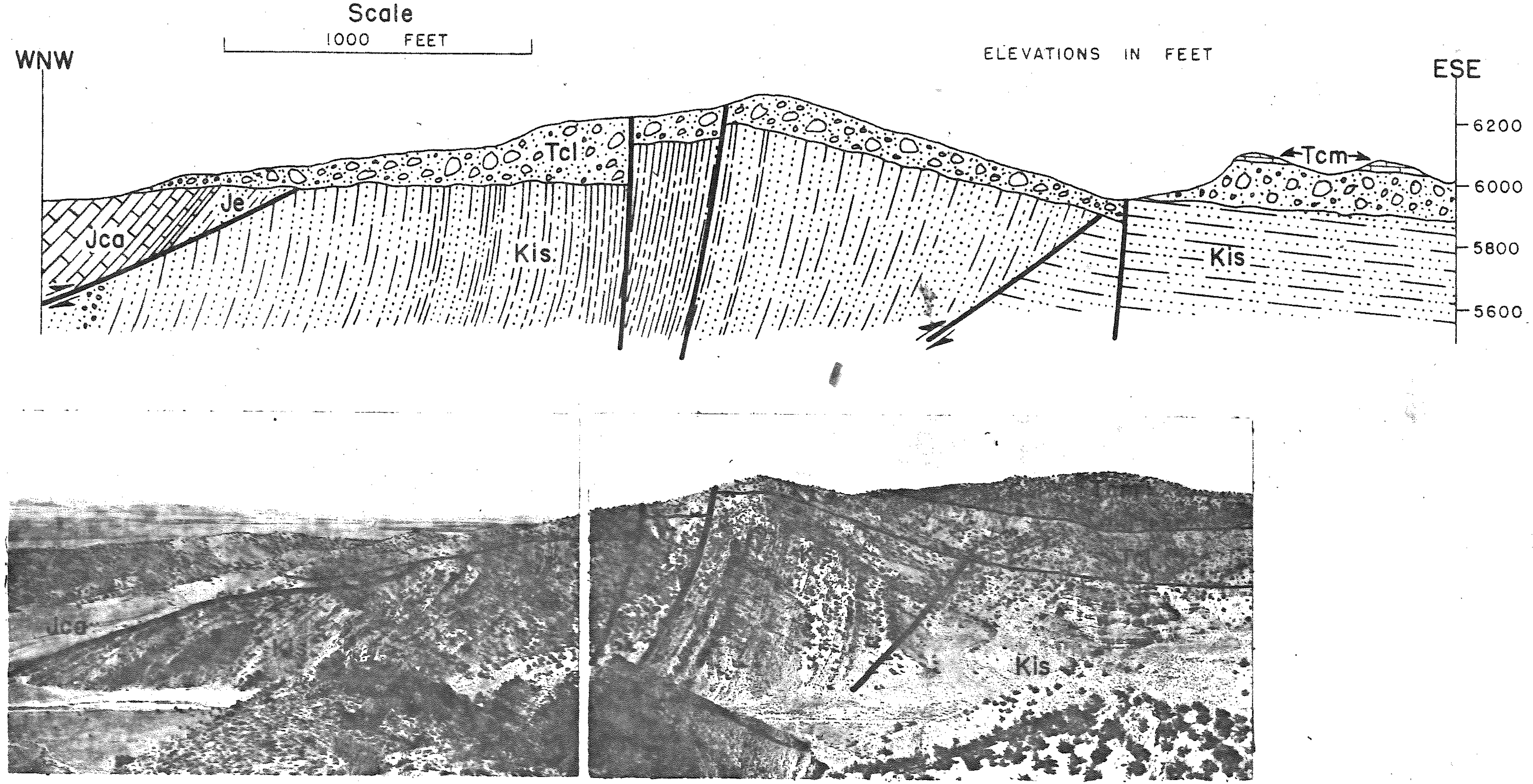


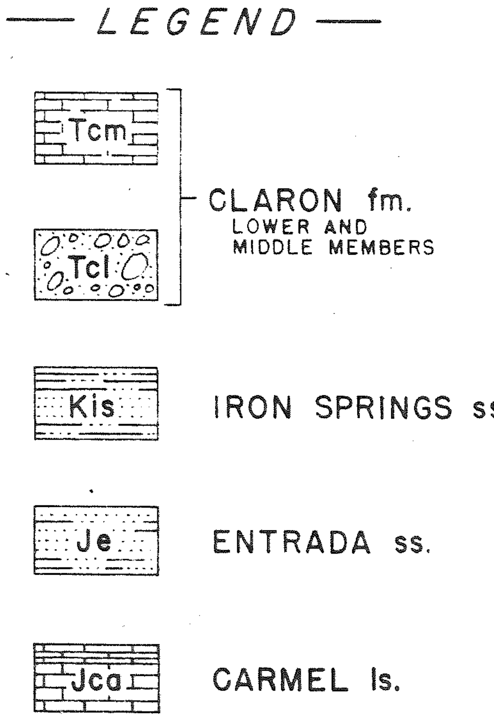
Plate II

Section and photograph do not match because of
perspective effects in photograph.

STRUCTURE SECTION AND PHOTOGRAPH OF NORTH WALL OF CENTRAL PAROWAN GAP
UTAH

FLOOR OF GAP IS BASE OF SECTION





R.L. THREET — 1951