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Geology and petrology of the Devils Tower, Missouri Buttes, and Barlow Canyon area, Crook County, Wyoming

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GEOLOGY AND PETROLOGY OF THE DEVILS TOWER, MISSOURI BUTTES, AND BARLOW CANYON AREA, CROOK COUNTY, WYOMING

by
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This dissertation submitted by Don L. Halvorson in partial fulfillment of the requirements for the Degree of Doctor of Philosophy from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

(chairman)

This dissertation meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

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ABSTRACT

Field and laboratory investigations were employed to determine the mode of emplacement and a petrogenetic model for three igneous localities in Crook County, Wyoming: the Devils Tower, the Missouri Buttes, and the Barlow Canyon area.

X-ray fluorescence, microprobe data, and optical analyses identify the Missouri Buttes rock as foid-bearing alkali trachyte and analcime phonolite and the Devils Tower and Barlow Canyon rocks as analcime phonolite.

Associated alloclastic breccia with a crystal-charged volcanic glass matrix, surrounding depressions representing collapse of igneous material back into the vent, striking similarity to known volcanic necks, and the occurrence of other extrusive volcanism in the vicinity lead to the conclusion that the Devils Tower and the Missouri Buttes are the erosional remnants of volcanic necks.

The Barlow Canyon intrusion is a small laccolith which caused additional folding of an Early Cretaceous dome.

Analcime constitutes 10% to 30% of the phonolite in Devils Tower and the Missouri Buttes, and up to 70% of the Barlow Canyon phonolite. Calculated analcime unit cell dimensions are $a_o = 13.736 \pm .003$Å, and reflect a silica-undersaturated composition. Analcime microphenocrysts and some groundmass analcime are interpreted as primary igneous phases. The remainder of the analcime was magmatically derived from hydrous, sodium-rich fluids. The analcime-liquid stability field indicates a

crystallization depth of 18 km to 43 km and a temperature of 600° - 640°C.

Microprobe and x-ray fluorescence data plot along the trachyte-phonolite trend and show a differentiation pattern from Missouri Buttes trachyte to Missouri Buttes and Devils Tower phonolite to Barlow Canyon phonolite. Differentiation occurred by fractional crystallization through the mechanisms of flotation and flow differentiation.

The rocks in all three localities are intratelluric material which in the Missouri Buttes and Devils Tower has been rapidly propelled to the surface by H_2O and CO_2 pressure.

INTRODUCTION

Purpose and Scope

In 1974 and 1975, I was president of Devils Tower Natural History Association. At that time, the association decided to produce a publication on the geology of Devils Tower National Monument, Wyoming, to replace the out-of-print USGS Bulletin 1021-I (Robinson 1956). It was assumed that this could be done by piecing together the existing literature. A literature search, however, pointed up several problems: first, most of the articles are quite old (1874-1909) and somewhat contradictory; second, there was a lack of chemical and petrologic data; third, the mode of emplacement of Devils Tower was very much in question; and finally, because of the lack of analytical data, no modern petrogenetic model had been proposed.

These concerns were brought with me to the University of North Dakota, where further literature search showed that similar problems exist throughout the northern Black Hills. Consequently, a group of faculty and students organized a Northern Black Hills Igneous Province study group for the purpose of sampling, mapping, and updating chemical and petrologic data for the province.

A detailed geologic map for the area of study, the 126 km^2 including and immediately surrounding Devils Tower and the Missouri Buttes, was constructed on a sale of 1:20 000 (Plate 1). Individual igneous intrusions were also mapped on appropriate scales to reflect their particular features (Plates 2, 3, and 4). Mapping was useful for determination of structural relationships between the igneous and sedimentary rocks and in deciphering the deformational history of the area.

Two hundred and fifty-five rock samples were collected from the three igneous intrusions in the study area (appendix I), plus ninety-two from the surrounding Mesozoic and Cenozoic sediments (appendix II). The sedimentary samples were collected from measured sections and described from hand specimens. Colors of sedimentary rocks were determined from the Revised Standard Soil Color Charts.

Igneous rocks were classified and characterized chemically and petrographically by x-ray diffraction, optical microscopy, x-ray fluorescence, and electron microprobe analysis. Early in the research, it was discovered that the analcime content ranged from 10% to 70% and played an important role in the crystallization history of the rock. X-ray diffractograms were used to calculate unit cell dimensions of the analcime (Coombs and Whetton 1967), structural states of the feldspars (Wright 1968), and basic mineral compositions. Normative minerals were calculated from chemical analyses for use in rock classification and studies of compositional variation. Individual mineral grains were analyzed using electron microprobe techniques.

The cooling history of the rocks and the mode of emplacement were interpreted from field data and oriented thin-sections. Field work included observation of the structural relationship between the igneous and sedimentary rocks, the types of igneous rocks exposed in the area, and the spacial relationship of jointing due to cooling.

Chemical and petrographic data were used to develop a petrogenetic model. This model includes a possible source rock, the differentiation of rock types, their movement and path to the surface, and their emplacement at or near the surface.

Finally, consideration has been given to local tectonism and its relationship to the tectonic development of the western United States.

Geographic Location of the Study Area

Devils Tower is located in northeastern Wyoming, approximately 45 km northwest of the town of Sundance and 16 km southwest of the town of Hulett. The map area for this study is approximately 126 km^2, located between latitude 44°34'17"N and 44°40'24"N, and between longitude 104"40' 45"W and 104°49'18"W. This lies within portions of Townships 53 and 54 N. and Ranges 65 and 66 W. in Crook County, Wyoming.

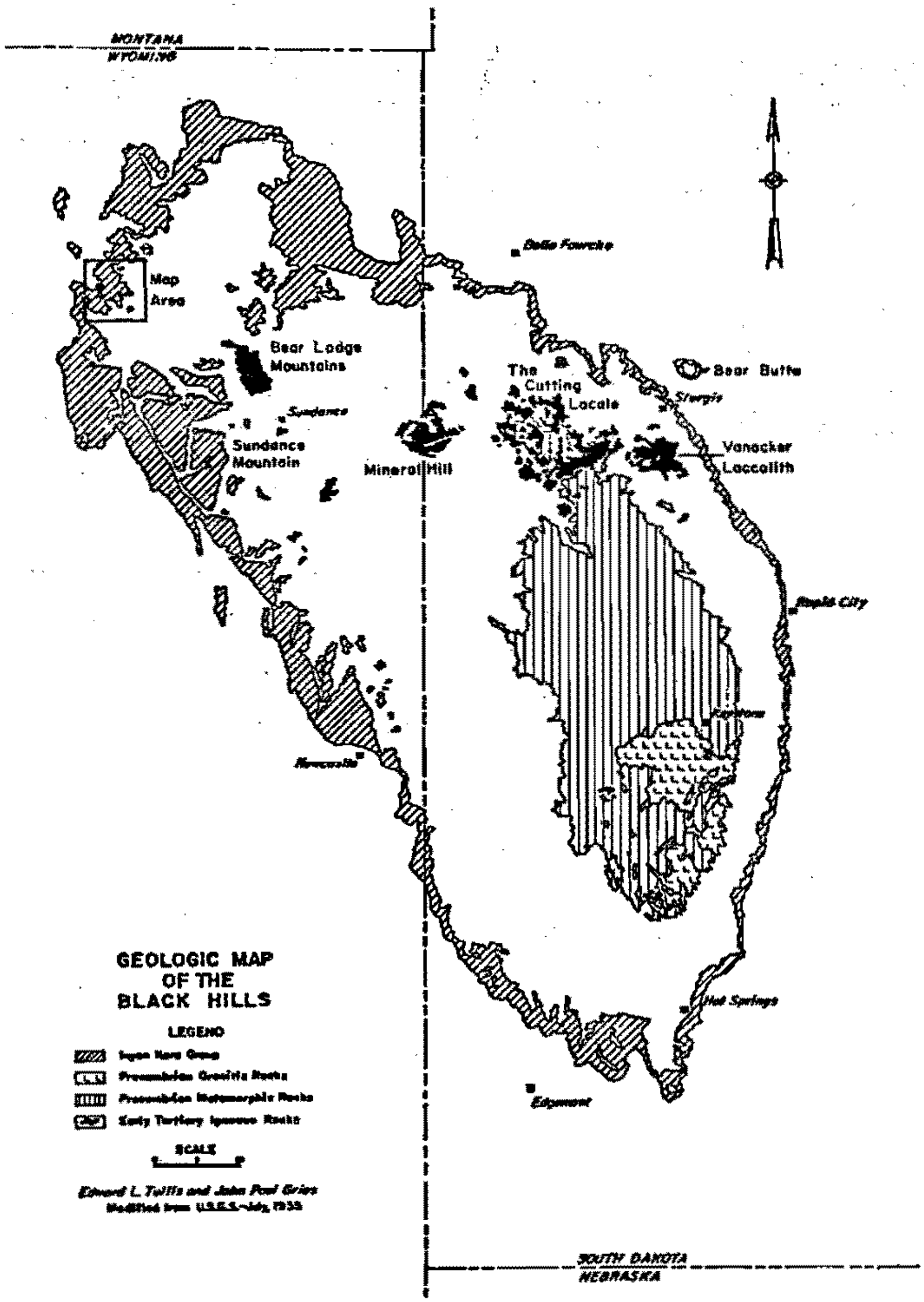
The geologic map was based on air photos, pace and compass traverses, and measured stratigraphic sections at known elevations. The map area (Plate 5) includes Mesozoic and Cenozoic sedimentary rocks intruded by three separate igneous bodies. These intrusions were individually mapped, Devils Tower on a scale of 1:2 400 (Plate 2), Missouri Buttes on a scale of 1:5 000 (Plate 3), and the Barlow Canyon dome on a scale of 1:1 500 (Plate 4).

Relationship to Northern Black Hills Igneous Province

The study area comprises the westernmost extension of the Northern Black Hills Igneous Province which extends approximately 105 km in an east-west direction from Bear Butte, South Dakota, in the east to Missouri Buttes, Wyoming, in the west. Along this east-west line, igneous activity occurred at four principal eruptive centers: the Vanocker laccolith, the Cutting locale, Mineral Hill, and the Bear Lodge Mountains (Figure 1). In addition to these major centers, many other smaller locales are recognized throughout the province.

Most of the rocks of the province are porphyritic, and vary from rhyolite, latite, syenite, and diorite to more alkaline rocks commonly classified as phonolites. With the exception of a few basic lamprophyres scattered throughout the province, more felsic rock types predominate. Petrographically and structurally, the rocks of the area mapped are most closely related to the phonolites surrounding the Bear Lodge Mountains which lie 18 km to the southeast (Fashbaugh 1979, and White 1979, oral communication).

Fig. 1. Location of study area. Base map taken from Gries and Tullis (1955) in Geologic History of the Black Hills, p. 32.


MONTANA
WYOMING
Belle Fourche
Map Area
Bear Lodge Mountains
Sundance
Sundance Mountain
Mineral Hill
The Cutting
Locale
Bear Butte
Sturgis
Vanocker Laccolith
Rapid City
Newcastle
Hot Springs
Edgemont
SOUTH DAKOTA
NEBRASKA
GEOLOGIC MAP OF THE BLACK HILLS
LEGEND
SCALE

ANALYTICAL METHODS AND PROCEDURES

Modal Analysis

Modal analyses were computed from thin-section point counts, using 750 counts per thin-section. Counts were made using a Brinkmann electronic point counter with the grid spacing set at one-half the average grain size, as outlined by Chayes (1956). Five hundred of these counts were made at 35X, and were used to determine percentages of phenocrysts and groundmass. Phenocrysts were individually identified. The remaining 250 counts were made at 100X to determine the mineralogy of the groundmass. Results were tabulated in three categories: (1) phenocrysts; (2) groundmass; and (3) veins, pore-fillings, and alteration products.

Reliability of a given mode varies directly with the relative percentage of each phase. With 750 counts, a maximum confidence level of 96% is attained. Modal percentages of 22 to 78% vary ± 3%; from 2 to 8% vary ± 2%; and from 1 to 2% vary ± 1% (Van der Plas and Tobi 1965).

Sample Preparation

Samples were ground and split by the following procedure:

1. 40 g sample crushed to <2-3 mm
2. sample split to 20 g
3. 20 g sample ground in Spex mixermill (large steel vial) for 5 minutes to <20 mesh

4. successive splits made to obtain 1 g samples for electron microprobe and x-ray diffraction, and a 6 g sample for x-ray fluorescence
5. samples ground in Spex mixermill (vial 5004) for 5 minutes

X-ray Diffraction

X-ray diffraction samples were prepared with 0.8 g of finely ground sample and 0.2 g of silicon as an internal standard. The mixture was then backloaded using method B (Hutchison 1974, p. 145). A quartz standard was run before each analysis, and its intensity used to standardize successive runs. All peak positions were measured from the Si_{111} peak $2\theta = 28.44°$. A Philips high-angle x-ray diffractometer was used, with CuK radiation and nickel filter.

For mineral identification, samples were scanned from 2° to 60° 2θ at a rate of 1° 2θ/minute at 37 KV and 18 mA. For analcime unit cell calculations, the samples were scanned from 2° to 88° 2θ at ¼°/minute at 45 KV and 20 mA. For feldspar structural states, samples were scanned on oscillatory mode between 20° and 51° 2θ four times, and the values averaged; machine conditions were set at 45 KV and 20 mA.

X-ray Fluorescence

Fused pellets for x-ray fluorescence were prepared by the following procedure modified from Welday and others (1964, pp. 889-903):

1. 6 g finely ground sample dried in a vacuum at >20" vacuum, at 100°C for 10-15 minutes
2. sample cooled in vacuum desiccator
3. weighed in porcelain crucible

4. heated in a muffle furnace at 850°C for 10 minutes

5. cooled in vacuum desiccator

6. reweighed to determine fusion loss

7. 5.2 g of lithium tetraborate added to 2.8 g of specimen powder and mixed thoroughly

8. specimen fused at 1050°C for 20 minutes

9. air-cooled fusion beads reweighed to check error due to flux loss

10. fusion bead crushed and broken into ¼" chips

11. reground in Spex mixermill (vial 5004) for 5 minutes

12. final powder pressed into an aluminum Spex cap at 15000 psi (10 MPa) by a Spex C-30 hydraulic press, using the method outlined by Hutchison (1974, pp. 265-268)

Instrument parameters for the chemical analyses are given in table 1. USGS rock standards GSP-1, G-2, AGV-1, DST-1, PCC-1, W-1, and BCR-1 were used. The average weight percent oxides outlined by Fleisher (1969) and Flanagan (1969) were plotted against counts per second and fitted to a line generated by a least squares best fit program. Oxide percentages of unknown samples were determined by comparison with the standards curve.

CIPW norms, differentiation indices, and ratios for triangular plots were calculated from weight percentage oxides using General Rock Norms Program M0016 (Bowen 1970).

Electron Microprobe Analysis

Finely ground sample powder was backloaded into an eighth inch hole in a bakelite disk (10 samples per disk). These samples were

TABLE 1

INSTRUMENT PARAMETERS FOR X-RAY FLUORESCENCE

Element	Mg	Al	Si	P	K	Ca	Ti	Mn	Fe	Na
Analytical Line	1K	1K	1K	1K	1K	K	K	1K	1K	Sodium determined by electron microprobe
Tube Anode	Cr	Cr	Cr	Cr	Cr	Cr	Cr	W	W	
Crystal	ADP	EDdT	EDdT	EDdT	LiF	LiF	LiF	LiF	LiF	
Detector Voltage (Kv)	1.793	1.815	1.815	1.782	1.865	1.755	1.785	1.780	1.780	
Volts (Kv)	50	50	50	50	35	35	35	50	35	
Current (mA)	25	25	25	25	10	8	10	40	30	
Window	16	24.5	27	16	49.3	28	30	40	40	
Lower Level	7	5.5	7.5	9	12.5	7	15	11	14	
Collimator	crs.	crs.	crs.	crs.	crs.	crs.	crs.	fine	fine	
Path	vac.	vac.	vac.	vac.	vac.	vac.	vac.	air	air	
Counter	gas-f	gas-f	gas-f	gas-f	gas-f	gas-f	gas-f	scnt.	scnt.	
Counting Interval (Sec)	100	100	100	100	100	10	20	100	10	
Goniometer Reading °2θ	106.8	112.8	78.08	58.55	136.85	113.16	86.07	62.7	57.6	
Backround Reading °2θ	108.5	108.0	79.75	56.50	133.50	110.00	84.00	66.0	56.0	
Crystal Position	2	2	2	2	1	1	1	1	1	

analyzed at 39X magnification for 200 seconds, permitting analysis of 1 mm^2. Analyses were made of two areas in the upper and lower halves of each sample, and the results averaged. Polished thin-sections were also utilized for microprobe analysis of individual mineral grains.

Matrix corrections and standardization of chemical analyses were done by Dr. Frank Karner using a Tracor Northern XML fitting program and a Bence-Albee analytical program. Samples were analyzed using a JEOL 35U scanning electron microscope with a KEVEX energy dispersive detector. Iron was reported as Fe_2O_3 and re-calculated to FeO and Fe_2O_3 by the method of Irving and Baragar (1971, p. 526).

PREVIOUS WORK

Early explorations in the Devils Tower area were made by army expeditions in the late 1850's. Both the Warren expedition and the Raynolds expedition, which Hutton accompanied as topographer, visited the area but did not write descriptions of it. In 1875, Newton served as geological assistant to a United States Geological Survey party to the Black Hills, and it is he who first described the Tower and its rock. In his published report (Newton 1880), he gave this description of Devils Tower: "It is a great rectangular obelisk of trachyte, with a columnar structure, giving it a vertically striated appearance, and it rises 625 feet, almost perpendicular, from its base."

Newton also examined the Missouri Buttes, identifying the rock there also as trachyte and the agglomerate as volcanic tuff. His samples were examined microscopically by Caswell (1880), who concluded that the Tower rocks were sanidine trachyte and the agglomerates rhyolite breccia.

Theories on the mode of emplacement of the Tower soon began to develop. Carpenter (1888) proposed that it was the neck of an extinct volcano.

Pirsson (1894) did further thin-section studies of the Tower rock, and first classified it as phonolite. He also gave the only published chemical analysis of the rock.

Jagger (1901) worked out a rather complete general geology of the Devils Tower area, proposing that the Devils Tower and the Missouri

Buttes were originally both part of a large tabular igneous body thickened in the center, with a relatively flat floor, and vented under the Missouri Buttes. Jagger also first discovered agglomerates in the Devils Tower vicinity.

In 1907, Darton and O'Harra published the information available on this area, including some new petrographic studies made by Johannsen, and prepared the first detailed geologic map. For the Devils Tower rocks, Johannsen proposed the name aegerite-syenite porphyry or phonolite porphyry. The term phonolite porphyry was accepted and used by Darton; the Missouri Buttes rocks were also classified by this name.

Darton and O'Harra described two igneous intrusions not previously mapped, and these rocks were subsequently examined and named by Johannsen. A small outcrop one-half mile west of the Missouri Buttes was classified as monzonite. A larger area in Barlow Canyon, northeast of the Missouri Buttes, was classified as aegerite-syenite porphyry or phonolite. Darton and Johannsen agreed that the agglomerates at both Missouri Buttes and Devils Tower were igneous in origin.

Darton (1909) offered a third theory of origin. He proposed that the Missouri Buttes and Devils Tower represented two separate laccoliths with individual vents. His idea was obviously influenced by the observations of other geologists, as this statement reflects:

> The vertical columns have been supposed to indicate that the tower is not the stock of a flow or intrusion at higher levels, but recent observations by Johnson in the Mount Taylor region of New Mexico and by C. A. Fisher in central Montana show that vertical columns may exist in stocks (Darton 1909, p. 69).

Dutton and Schwartz (1936), in an article on jointing in the Devils Tower, supported Carpenter's theory that the Tower is the neck of an extinct volcano.

The next significant contribution to the geology of the Devils Tower area was made by Robinson in 1956. He constructed a detailed map of the Devils Tower National Monument area, and presented (1956, p. 13) a fourth theory of origin:

> The evidence gathered during the present investigation . . . suggests that Devils Tower is a body of intrusive igneous rock, which was never much larger in diameter than the present base of the Tower, and which at depth (1000 feet or more) is connected to a sill or laccolith type body.

Three different Eocene dates have been presented for the Devils Tower and Missouri Buttes. A K-Ar age determination on alkali feldspar from Devils Tower (Bassett 1961) indicated a date of 40.5 ± 1.6 m.y.; K-Ar dates on aegirine from the Missouri Buttes (McDowell 1971) indicated 49.6 ± 1.7 m.y.; and fission track ages of sphenes (Hill, Izett, and Naeser 1975) placed Devils Tower at 53.3 ± 6.8 m.y. and Missouri Buttes at 55.5 ± 7.1 m.y.

FIELD RELATIONSHIPS

Stratigraphy

The sedimentary rocks exposed in the map area have a combined thickness of approximately 290 m and range in age from Triassic to Quaternary. Except for the fossiliferous limestone of the Redwater Member of the Sundance Formation, which are commonly slumped, the beds throughout the map area are nearly parallel throughout. They do not, however, necessarily reflect continuous deposition, as there are disconformities at the base of the Gypsum Spring, Sundance, and Fall River Formations. Two cycles of marine transgression and regression are evident in this sedimentary sequence, resulting in about equal amounts of marine and non-marine sediments. The sedimentary rocks in the area represent ten formations, exclusive of surficial deposits (Plate 1).

Permian and Triassic Systems

Spearfish Formation

The oldest rocks mapped in the study area are the red sandstones of the Spearfish Formation. They are exposed along the Belle Fourche River and in Sawmill Gulch. The best exposures are east of Devils Tower, where 45.8 m of reddish-brown interbedded sandstone, siltstone, and claystone are present. Gypsum occurs throughout this sequence as thin stringers along bedding planes and in fractures. This section represents the largest exposure of Spearfish in the map area.

The thickest measurement for the Spearfish Formation was made by Petroleum Incorporated in the Holmes No. 1 well, sec. 13, T. 54 N., R. 66 W., where 251.5 m were encountered. The 45.8 m section measured in the map area represents only the upper 20 percent of the total thickness and correlates in stratigraphic position and lithology with the Triassic Red Peak Member of the Chugwater Formation in southeastern and central Wyoming (Robinson and others 1964, p. 9). Therefore, all of the Spearfish in the area mapped is probably Triassic in age.

Jurassic System

Gypsum Spring Formation

The Gypsum Spring Formation is exposed only along the Belle Fourche River and for a short distance along Barlow Creek. Unexpectedly, it does not appear in Sawmill Gulch, and apparently has been removed by erosion.

The formation varies in thickness from 4.5 to 10.5 m. The lower part consists of white gypsum interbedded with dull reddish-brown mudstones, and the upper part of similar colored siltstone. This division in the formation is consistent throughout the map area. Strike and dip measurements within the Gypsum Springs are usually unreliable because erosion of underlying material has caused slumping and collapse of the gypsum layers.

An abrupt contact is apparent between the Gypsum Spring and the Spearfish Formation below it, but regional correlations indicate that the contact is actually an unconformity with a hiatus representing most of the early Jurassic time (Imlay 1952, p. 1747-1749).

Stockade Beaver Shale Member

Poor to fair exposures of the Stockade Beaver Member occur along the Belle Fourche River and Barlow Creek, varying in thickness from 18 m to 31 m. They consist mostly of olive gray to grayish-red shale, interbedded with light gray sandstone. The contact between the Stockade Beaver and the underlying Canyon Springs is gradational, but where the Canyon Springs is missing, the Stockade Beaver rests unconformably on the underlying Gypsum Spring or Spearfish Formations.

Hulett Member

Sandstone of the Hulett Member forms prominent cliffs along the Belle Fourche River, Barlow Creek, Sawmill Gulch, and Barnard Canyon. It is a dull yellow, resistant member, ranging from 18 m to 27 m in thickness. The lower 3 to 4 m of sandstone are interbedded with greenish-gray shales as the Stockade Beaver Member grades upward into the Hulett. The contact is placed approximately where sandstone predominates over shale.

Lak Member

The Lak Member of the Sundance Formation forms covered slopes and is consequently poorly exposed in the map area. The only measurable sections are encountered just east of Devils Tower and near the Storm Hill Road in Barlow Canyon. The Lak consists of 12 m to 18 m of pale yellow to dull orange, very fine-grained, poorly cemented sandstone and siltstone, with a few thin greenish-gray shale partings. The gradational contact with the underlying Hulett is marked

Sundance Formation

The Sundance Formation, which is upper Jurassic in age, crops out along the Belle Fourche River and along Barlow Canyon, resting unconformably on the Gypsum Spring Formation. At the entrance to Sawmill Gulch, where the Gypsum Spring is missing, the Sundance rests unconformably on the Spearfish Formation.

Imlay (1947) named five members of the Sundance Formation: Canyon Springs, Stockade Beaver, Hulett, Lak, and Redwater, listed from oldest to youngest. The contacts between the members appear to be conformable within the study area. Imlay (1952) suggested that the Lak-Redwater contact may be disconformable, but because of poor exposure this could not be confirmed.

Canyon Springs Member

Canyon Springs, the basal member of the Sundance Formation, appears in the map area only in Sawmill Gulch. At the mouth of the creek, a thickness of 3.1 m of massive, extremely calcareous sandstone is exposed, yellow at the base and grading upward to pink and yellow brown. Near the base, a 0.1 m layer of reddish-brown sandy shales and siltstones occurs. About 1 km farther north, the Canyon Springs thins to 2.4 m of massive, light, yellow-gray sandstone.

Elsewhere throughout the map area where the basal unit of the Sundance Formation is exposed, a thin layer of coarse-grained sand and chert pebbles is encountered. This conglomeratic layer may represent a very thinned version of the Canyon Springs Member.

where the sandstones become more poorly cemented and finer grained, and can only be approximated.

Redwater Shale Member

The Redwater Shale Member occurs as grass-covered slopes throughout most of the central and western part of the map area, and is also exposed in a small dome 1 km north of the Missouri Buttes. This member consists mainly of greenish-gray shale, interbedded with numerous layers of fossiliferous limestone and fine- to medium-grained sandstone, and varies in thickness from 12 m to 51 m. In spite of its poor exposure, upper and lower contacts can be located. Throughout the area mapped the lower contact of the Redwater underlies a dull yellow-orange glauconitic sandstone about 0.8 m thick; this contact is gradational with the underlying Lak Member. The upper contact is at the top of a resistant ledge of grayish-yellow cancareous sandstone 0.8 m to 2.5 m thick.

Morrison Formation

The Morrison Formation crops out in grass- and debris-covered slopes along the base of a plateau capped by rocks of the Inyan Kara Group in the western and northern parts of the map area, and in the center of the small dome 1 km north of the Missouri Buttes. It varies in thickness from 0 to 66 m, and consists largely of grayish-red and greenish-gray claystone.

The basal portion of the Morrison Formation is interbedded light gray sandstone and discontinuous beds of marl and limestone. It is calcareous, weathers to a greenish gray or gray red, and rests conformably on the underlying Sundance Formation. The contact is represented by a thin transitional zone which separates the non-marine beds above from those of marine environment below. This unit varies in thickness from about 8.5 m to 15 m. The upper Morrison is mostly claystone, non-calcareous, and weathers to shades of green. The contact between this upper unit and the calcareous beds below is sharp and can be designated within 1 m.

In two structurally high areas, the Barlow Canyon dome and the east-facing edge of the Inyan Kara Group plateau, erosion completely removed the Morrison Formation prior to deposition of the overlying beds. East of the Barlow Canyon dome, typical Morrison claystone, marl, and limestone has been replaced by about 18 m of very fine-grained light gray sandstone.

Cretaceous System

Lakota Formation

The Lakota Formation forms moderately steep slopes and ledges along the Inyan Kara group plateau, ranging from 34 m to 64 m in thickness. It is similarly exposed in two domes in the map area, the one located 1 km north of the Missouri Buttes, and the other, called the Basin, 1.5 km southwest of the Buttes.

The beds of the Lakota display considerable lateral and vertical variation. The formation is comprised of resistant, ledge-forming, dull orange sandstones, interbedded with less resistant claystones and containing lenses of siltstone and sandstone conglomerate. Cross bedding and ripple marks are observed. Some of the sandstone is highly silicified, particularly north of the Missouri Buttes. Considerable carbonaceous material is found in the lower part of the formation. Its lower contact with the Morrison is generally unconformable. Where the Morrison has been removed in Barlow Canyon, the Lakota lies unconformably on the erosional surface of the Sundance Formation.

Fall River Formation

The Fall River Formation forms a broad, westward-dipping plateau in the western and northern parts of the mapped area. The upper portion consists of non-resistant light gray siltstone a few meters thick, which has been mostly removed by erosion. Below this lies a series of very resistant sandstones, light gray to yellow orange in color, which caps the divides. These beds contain numerous ferruginous concretions and sandstone concretions cemented with calcite or silica. Many beds are ripple marked and cross laminated.

The lower Fall River contains mostly dark gray shales and siltstones with some sandstone layers and carbonaceous shales which locally are sufficiently abundant to form small coal seams. The lower 6 m are interbedded carbonaceous siltstone and white sandstone encrusted with carnotite.

The Fall River ranges in thickness from 39 m to 54 m. The lower contact is unconformable and easily located by the noticeable change which occurs between the variegated claystones and the carbonaceous siltstones. This contact marks the change from fluvial sedimentation below to fluviomarine above (Waage 1959).

Skull Creek Shale

The Skull Creek Shale is exposed only in the extreme northwest corner of the map area and in seven small locales around the Missouri

Buttes. These exposures are an erosional remnant; outcrops are usually sagebrush-covered, black, "gumbo" soils. The maximum thickness measured was 12 m of brownish-gray to black noncalcareous shale with thin beds of bentonite and ferruginous siltstone. The contact with the underlying Fall River is gradational.

Newcastle Sandstone

Two small outcrops of the Newcastle Sandstone are exposed within the talus of the Missouri Buttes, with a maximum observed thickness of 6 m. The Newcastle is massive and forms slabby ledges. It is a light gray sandstone colorfully streaked in some places with yellow, orange, and red iron stains. The Newcastle-Skull Creek contact is difficult to observe, but is apparently gradational.

Mowry Shale

The Mowry is exposed in three small areas within the Missouri Buttes talus with maximum measured thickness of 9 m. It is a dark gray shale, very thinly bedded, containing numerous fish scales and interbedded with bentonite layers, 10 to 15 cm thick. No lower contact was observed, but it is reported to be gradational (Izett 1963).

Oligocene Series

White River Formation

The youngest formation exposed in the map area is the White River, which caps large areas of the broad divides north and west of the Missouri Buttes. About 9 m of light gray, coarse- to very coarse-grained, feldspathic sandstone form the resistant lower unit. At least part of this unit is visible wherever the formation is exposed.

In one area approximately 1 to 2 km northwest of the Buttes, the sandstone is capped by 15 m of grayish-white calcareous claystone.

The White River Formation lies with angular unconformity on the Fall River and Skull Creek Formations, and possibly nonconformably on some of the Missouri Buttes talus. The outer edges of the talus sheet are extremely weathered, so this relationship can only be inferred.

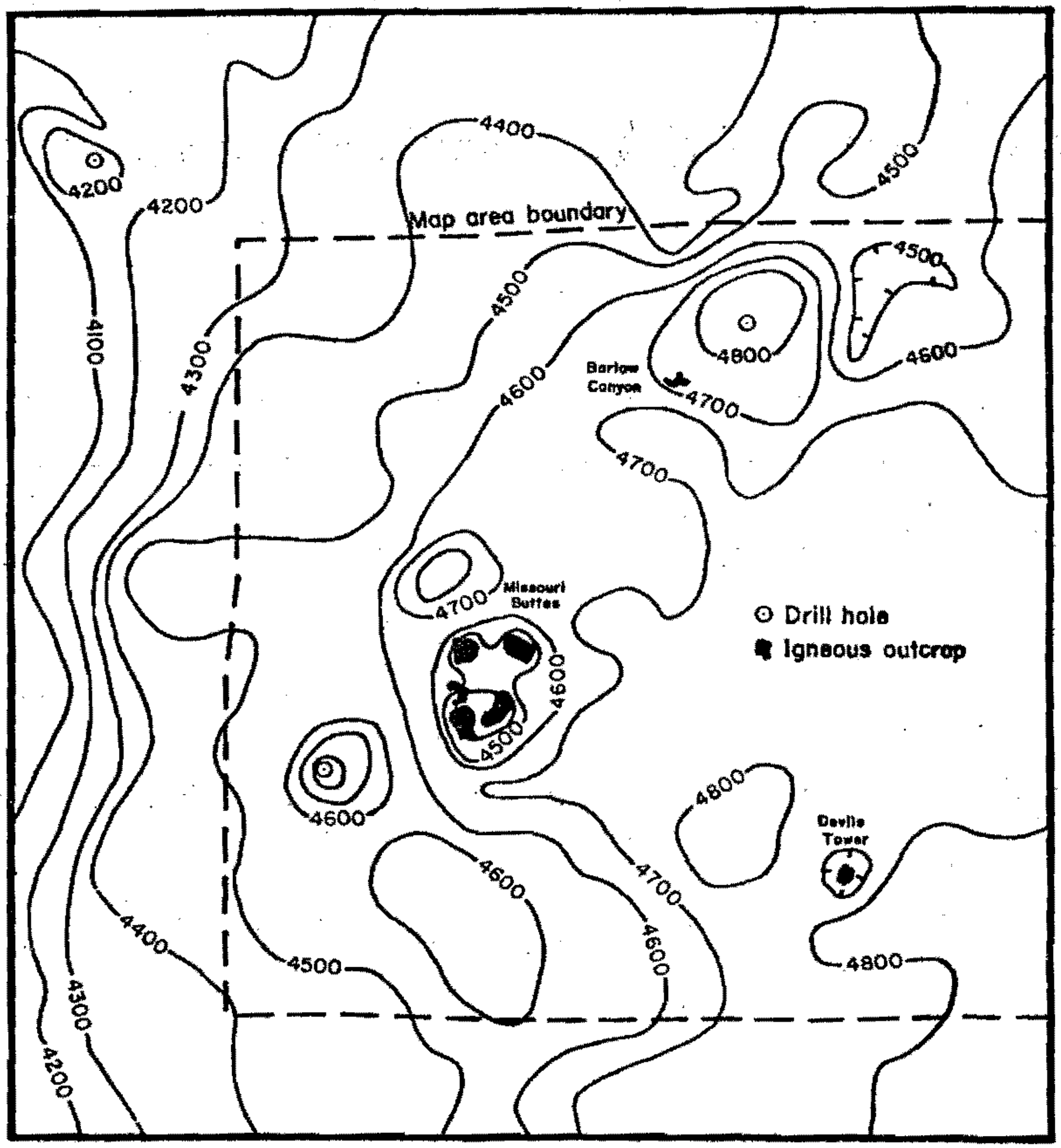
Structural Deformation

The Devils Tower-Missouri Buttes area is situated about 10 km east of the Black Hills monocline. Using structural contours drawn with the top of the Fall River Formation as the mapped surface (Robinson and others 1964), the studied area is on a structural high over 1200 m above the eastern edge of the Powder River Basin. The sedimentary beds in the area have a gentle westward dip of approximately 9 m/km.

Three major structural domes interrupt the gentle dip: the Barlow Canyon dome with 61 m (200 feet) of closure, the Basin with 91 m (300 feet) of closure, and the dome 1 km north of the Missouri Buttes with 61 m (200 feet) of closure. Two smaller domes, one 2-3 km south of the Buttes, and another 1 km west of Devils Tower, each have about 30 m (100 feet) of closure. Two major depressions also exist in the area, one surrounding the Missouri Buttes with 91 m (300 feet) of closure, and one surrounding the Devils Tower with 30 m (100 feet) of closure (Figure 2).

The structural history of this area can be approximately deduced from field observations. After deposition of the Morrison Formation of late Jurassic age, an area of about 10 km^2 in Sawmill

Fig. 2. Structure contour map of the Devils Tower, Missouri Buttes, and Barlow Canyon area. Contours are drawn on the top of the Fall River Formation (from Robinson and others 1964).



SCALE 1:96000

1 0 1 2 3 4 km

CONTOUR INTERVAL 100 FEET

DATUM IS MEAN SEA LEVEL

Gulch was uplifted. Evidence of this late Jurassic or early Cretaceous uplift is seen in the truncation of the Morrison Formation and the upper 40 m of the Redwater Member of the Sundance Formation under an angular unconformity which dies out laterally in the lower Lakota Formation (Izett and others 1961). This unconformity can be traced in the Lakota by the presence of polished chert and quartzite pebbles and nodules of shale containing belemnites from the Redwater.

Robinson and others (1964) have suggested that the absence of the Gypsum Spring Formation may indicate that earlier uplift occurred in this area during the Jurassic Period. The fact that the Gypsum Spring appears to be removed only in the area of the dome supports this suggestion. It seems reasonable to conclude that uplift occurred in the area prior to the late Cretaceous major uplift in the Black Hills (Izett and others 1961).

Similarity of size and shape and proximity to domes of confirmed igneous origin indicate that the Barlow Canyon dome is also the result of igneous activity.

The Holmes No. 1 well penetrated 335 m of rocks in the center of the dome and bottomed in the Minnelusa Formation, contacting no igneous rock. However, many igneous intrusions in the Black Hills are known to be emplaced in beds below the Minnelusa, so igneous origin for the dome cannot be excluded. A small sill of analcime phonolite was intruded directly below the Hulett Member of the Sundance in the southwest flank of the Barlow Canyon dome and caused some additional folding; but because of its limited lateral extent, this intrusion could not have caused the major folding.

A transition from marine to terrestrial sediments between the Sundance and Morrison Formations indicates that crustal uplift occurred during late Jurassic time. This uplift coincides with and is probably related to the Nevadan orogeny farther west. Such an eastward expression of the Nevadan orogeny can be observed in Colorado where cherts and "dinosaur bone" conglomerate were deposited from material shed eastward from the Wet Mountains (Gerhard, oral communication).

This early uplift may have initiated magma generation by causing local melting in the lower crust, thus providing a mechanism for the formation of the Barlow Canyon dome and also the Oil Creek dome 80 km to the southeast (T. 47 N., R. 62 W.). Both are early Cretaceous in age.

Deposition of terrestrial sediments during the Cretaceous was followed by marine deposition, so crustal movements continued throughout most of the Cretaceous Period.

Toward the end of the Cretaceous, after the Fox Hills Formation was deposited, uplift probably related to the Laramide occurred in this area. Its expression in the Black Hills is the basement-cored uplift of two large blocks (Black and Roller 1961). The western edge of the northern block is the Black Hills monocline just west of the area mapped. The uplift of this northern block is significant because it probably produced deep fractures in the crust which provided a route for magma to reach the surface. Before the emplacement of the Missouri Buttes and Devils Tower, probably in late Cretaceous or Paleocene time, movement of magma resulted in the formation of the other four domes in the map area and the Poison Creek dome 2 km to the northwest. Drilling encountered igneous rock at 467.3 m in The Basin and at 617.2 m in Poison Creek dome, both within the Minnelusa Formation of Pennsylvanian and Permian age.

Uplift from the Laramide orogeny continued until Oligocene time and drained the seas from the region. At about the time of the Paleocene-Eocene boundary (54 m.y. ago; Berggren 1972, p. 201), magma in the vicinity of the domes approached or perhaps reached the surface. Remnants of this volcanism are the Missouri Buttes and Devils Tower. These volcanic intrusions are considered younger than the adjacent domes because some of the oldest talus on the Missouri Buttes extends out over the surface of the erosionally truncated dome to the north.

A maximum of approximately 1960 m of sedimentary material could have been deposited on top of the present Fall River erosional surface prior to the major Laramide uplift. This estimate is based on thickness of a vertical section from the Skull Creek Shale to the Fox Hills Formation in the Black Hills monocline about 10 km west of the map area. With the uplift, deposition virtually ceased and erosion began. By late Oligocene time, most of the present surface was exposed, as is shown by the unconformable contact of the late Oligocene White River Formation with the underlying Fall River and Skull Creek Formations (dating of White River based on Brown 1952, and Robinson and others 1964).

If the approximate date of the major Laramide uplift in the area is assumed at 65 m.y. ago, and the beginning of deposition of the White River formation at 38 m.y., this leaves approximately 27 m.y. to remove the 1960 m, and results in a denudation rate of about 6.7 cm/1000 years. This figure is slightly above the United States average of 6 cm/1000 years (U.S. denudation rate calculated by Judson and Ritter 1964). Applying McDowell's (1971) date of 49.6 ± 1.7 m.y., or Hill and others' (1975) date of 55.5 ± 7.1 m.y. to the 6.7 cm/1000 years denudation rate, indicates that 780 m to 1170 m of material lay above the top of the Missouri Buttes at the time of their emplacement. Using Bassett's (1961) date of 40.5 ± 1.6 m.y., and Hill and others' (1975) date of 53.3 ± 6.8 m.y., the cover above the present top of Devils Tower would have been 170 m to 1025 m at emplacement.

Both of these igneous bodies lie within a depression in otherwise nearly horizontal strata. These depressions are probably due to collapse of the igneous masses back into partially evacuated magma conduits. The collapse around Devils Tower is uniform, but at the Missouri Buttes irregularities are caused by the dome to the north. The Buttes depression is deepest at the southern end where it reaches 91 m in depth, and shallowest at the northern end where it overrides the dome. The Skull Creek, Newcastle, and Mowry Formations appear to have been pulled into the depression at the southern end where beds dip as much as 48°.

Faults in the area of Devils Tower and the Missouri Buttes (Plate 1) show vertical displacement and are apparently related to this collapse around the igneous bodies. The collapse would also reduce the calculated amount of sedimentary cover at the time of emplacement by as much as 100 m.

DEVILS TOWER

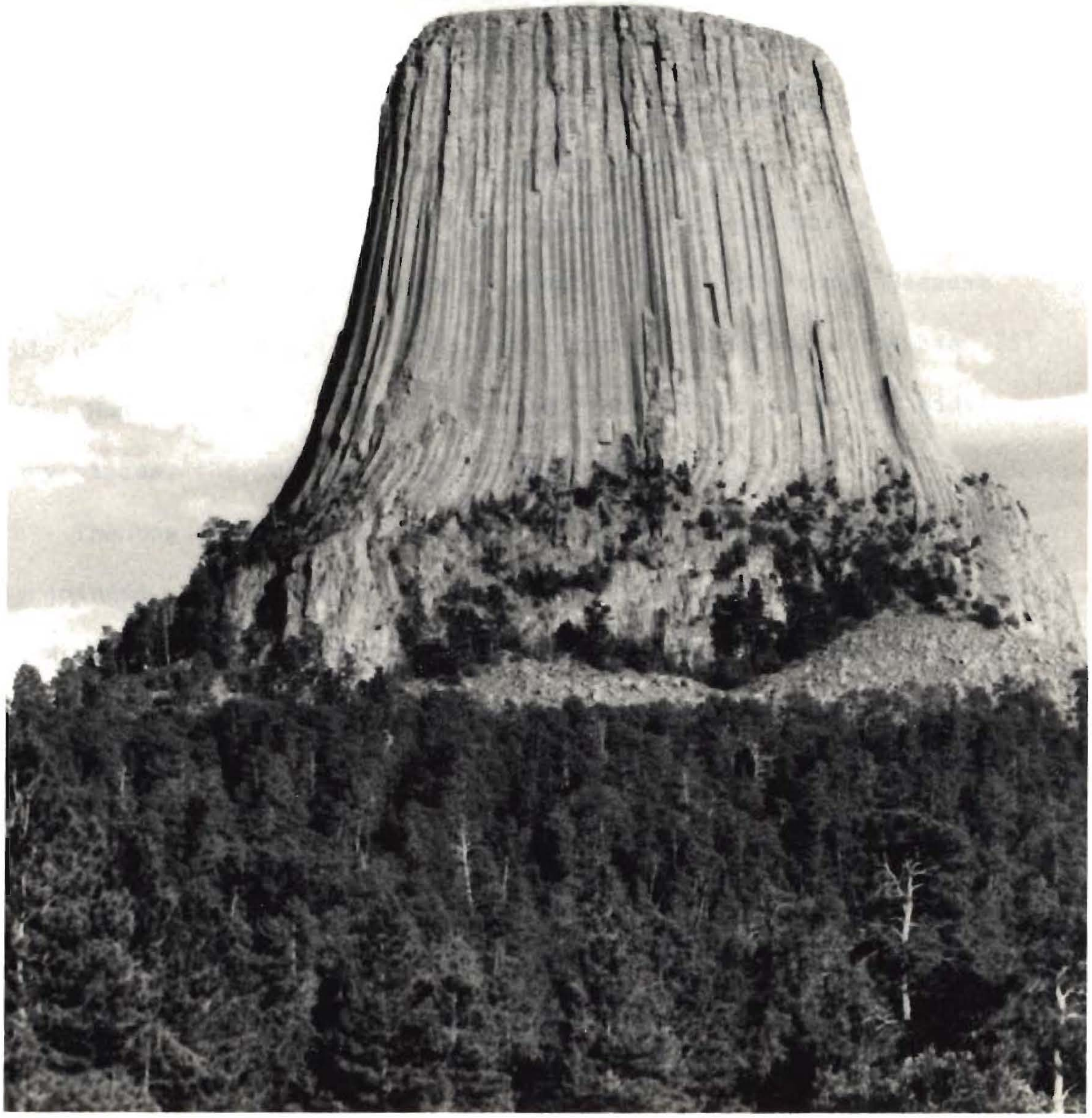
General Geology

Devils Tower is one of the most prominent and striking features in the Black Hills (Figure 3). This steep-sided igneous body rises abruptly 386 m above the Belle Fourche River, to a maximum elevation of 1560 m. It is intruded through and appears to rest upon a "platform" of the Sundance Formation which dips gently inward toward the Tower 3° to 7°. This platform stands as a resistant hill surrounded on all sides by streams and capped by igneous talus which has impeded further erosion.

The entire section of the Sundance Formation is represented in the platform. Quartzite crops out in several places in the talus sheet at elevations up to 1330 m and very probably represents the upper sandstone unit of the Redwater Member which has been silicified and metamorphosed. Robinson (1954) placed the contact between the Redwater and Lak Members at about 1280 m. This makes the Redwater Member in the platform 50 to 53 m thick, which is consistent with its thickness elsewhere.

The Tower itself rises almost vertically 229 m above the Jurassic platform. Distinctive columnar jointing characterizes the upper 180 m. The lower section varies in height from a few meters up to about 38 m and forms the more massive base of the Tower. The base has a slightly elliptical perimeter measuring 228 m by 304 m; the

Fig. 3. Northwest side of Devils Tower, showing columnar jointing and the massive base. (Unless otherwise noted, all photographs were taken by the author.)



larger measurement was taken in a N.15°E. direction.

Dutton and Schwartz (1936) made a detailed study of the joint systems in the base. They described one set of vertical radial joints and another peripheral joint set, both related to the cooling of the perimeter of the igneous shaft. The top of the base, known as the shoulder, is defined by outward-flaring columns which dip about 15° toward the perimeter and merge with the block jointing of the base. These gently-dipping columns show very pronounced ridges and swells perpendicular to the columnar jointing (Figure 4). These ridges and swells are faintly visible in the columns above and, under certain light conditions, give the Tower a layered appearance.

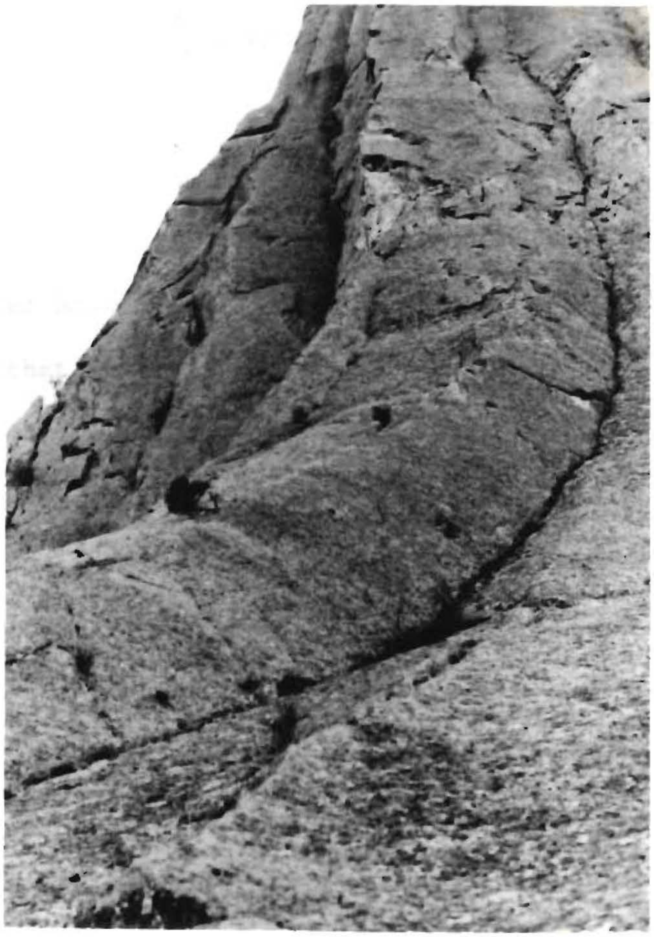
Above the shoulder stand huge columns which measure 2 m to 3 m in diameter at the base and taper to about 1.5 m at the top. Because of this upward tapering, the whole mass dips outward toward the base 75° to 85°. Most of the columns are 5-sided; some have four or six sides. In many places, the columns merge or split (Figure 5).

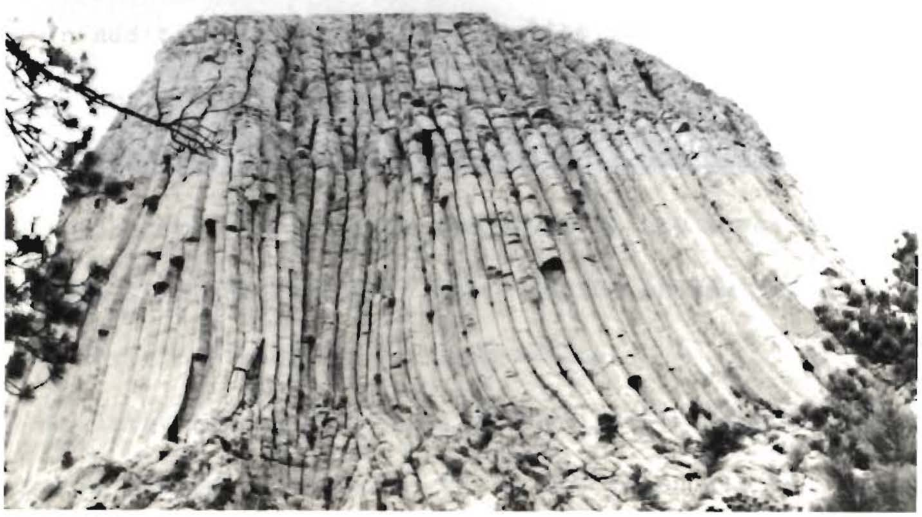
The top section (approximately 45 m) of the columns is horizontally jointed. Rocks weathering out of this area are small joint blocks which show the beginning of spheroidal weathering. The lower limit of the horizontal jointing approximates the former upper level of the Fall River Formation. These resistant beds impeded erosion and exposed only the top section to weathering. When these resistant beds were finally removed, the rest of the Tower was rapidly exposed by erosion.

The top of the Tower measures 55 m by 90 m. From a distance, it appears to be flat but it is actually rounded, especially on the southeast side.

Fig. 4. Outward-flaring columns on the northeast shoulder of Devils Tower, showing horizontal ridges and swells (striations).

Fig. 5. Southwest view of Devils Tower showing merging and splitting columns. The base has been removed by erosion in the central region, exposing nearly vertical interior columns.





Devils Tower is surrounded by a talus sheet, about 47 m thick near the base, that thins rapidly outward. Maximum outward extent averages about 350 m. Dutton and Schwartz (1936) conjectured that most of the talus had fallen from the upper part of the Tower and that the present base is indicative of the Tower's original size. It is obvious that most of the present talus is from the upper columns, but it does not necessarily follow that the Tower's original size is limited by the present base. At Hulett, 16 m to the northeast, old stream terraces of the Belle Fourche River are littered with rock from Devils Tower, which indicates Quaternary removel of considerable amounts of Devils Tower talus material. Also, three possible outcrops of phonolite were noted within the talus sheet: one 9 m south of the Tower, another about 90 m south-southeast, and a third about 160 m north-northeast of the Tower. The closest outcrop stands out as a ledge and is obviously in place. The other two are relatively large areas of jointed material which also appear to be in place. These outcrops could be radiating dikes or part of the original shaft.

In addition to the three phonolite outcrops in the talus, an elliptical knoll of alloclastic breccia, 50 m in maximum dimension, is located 240 m N.72°W. of the Tower. This breccia may at one time have been plastered against the phonolite of the Tower much like the volcanic necks in the Taylor Mountain region of New Mexico which are phonolite interiors sheathed in agglomerate.

No large blocks are known to have fallen from the Tower during the recorded history. Lichen cover on the talus blocks near the base indicates that it has been some time since any significant fall.

Going outward from the Tower, at least four stages of talus alteration are encountered. The first talus sheet contains columnar sections and angular blocks with a heavy lichen cover. The second consists of talus blocks mixed with soil. The third sheet is mostly soil covered and has a thin A horizon over a C horizon. The A horizon of the fourth sheet is underlain by a dense clay horizon about 30 cm thick; the C horizon is talus. These stages probably coincide with climatic changes occurring during the Pleistocene Epoch.

These periods of talus development and removal, together with the possible outliers of phonolite and the presence of related alloclastic breccia, imply that the original igneous body may have been somewhat larger and of a different shape than the presently exposed Tower.

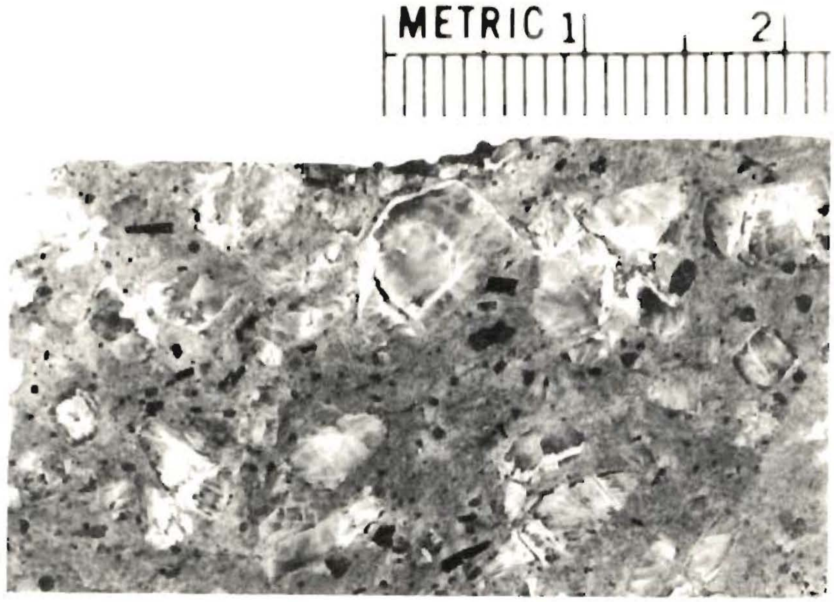
Mineralogy and Petrography

Analcime Phonolite

The Devils Tower phonolite is holocrystalline and coarsely porphyritic with a gray to olive gray aphanitic groundmass (Figure 6). Phenocrysts consist of anorthoclase, aegirine-augite zoned to aegirine, and sphene, set in a well developed trachytic groundmass composed of low albite, microcline, analcime, aegirine, nepheline, and nosean. Groundmass percentages range from 40% to 62%. Common alteration or replacement products are calcite, zeolite, hematite, clay, and analcime (table 2).

Fig. 6. Hand specimen of Devils Tower analcime phonolite showing large anorthoclase phenocrysts and small dark crystals of aegirine-augite in an aphanitic groundmass. Section was treated with HCl and stained with malachite green to bring out the analcime. Analcime appears in the groundmass and in the anorthoclase phenocrysts as dark gray areas. (Photograph by Howard Okland)

Fig. 7. Photomicrograph of Devils Tower analcime phonolite, 35X, showing a large anorthoclase phenocryst and euhedral aegirine-augite crystals zoned to aegirine in a trachytic groundmass of dark acicular aegirine, albite laths, and analcime. Careful examination reveals several hexagonal microphenocrysts of nosean and nepheline.


METRIC 1
2

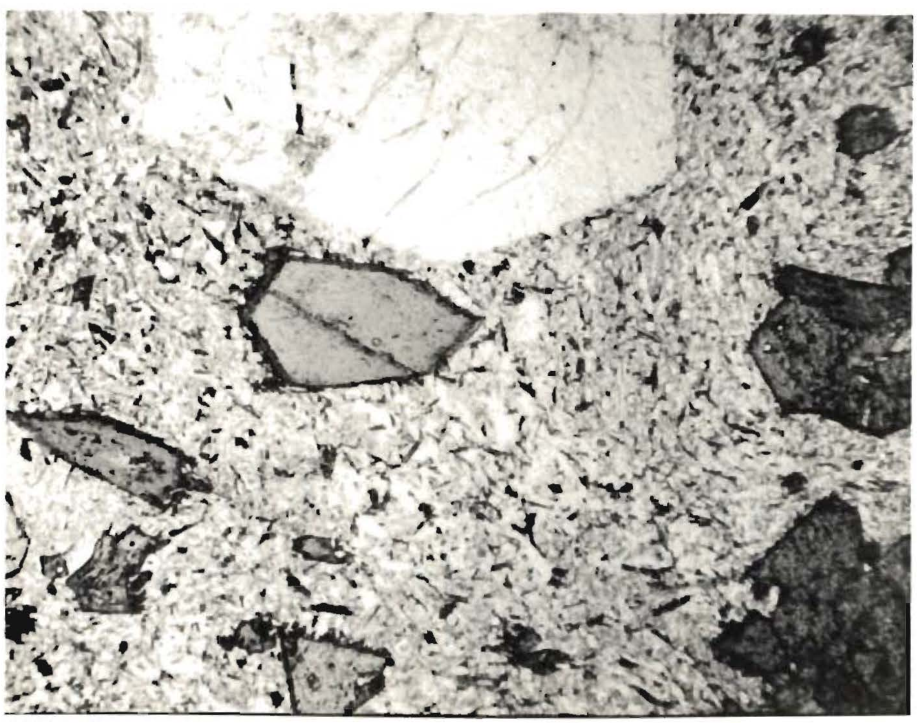


TABLE 2

MODAL ANALYSES OF DEVILS TOWER PHONOLITE

Sample Number	T16	T31	T32	T26	T14	T122	T112	T101	T23	T115	T11	T12	T13
Phenocrysts													
Anorthoclase	31.2	23.4	24.4	37.2	36.0	17.5	29.3	33.6	32.4	21.6	34.9	26.9	28.5
Aegirine-augite	5.4	7.0	5.2	2.8	6.6	4.2	9.2	8.0	6.4	7.1	5.6	6.5	7.4
Sphene	0.6	0.2	1.2	X	X	0.8	0.4	X	0.4	X	X	X	0.3
Nepheline	0.5	X	X	X	X	X	X	X	X	X	X	X	X
Nosean	0.8	X	X	X	X	X	X	X	X	X	X	X	X
Groundmass and microphenocrysts	49.9	50.0	62.4	45.6	49.6	56.7	39.5	44.4	42.4	62.5	47.5	59.8	52.4
Albite and microcline	17.4	X	X	X	X	X	X	X	X	X	X	X	X
Analcime	19.7	X	X	X	X	X	X	X	X	X	X	X	X
Aegirine	12.8	X	X	X	X	X	X	X	X	X	X	X	X
Veins, pore-filling, and replacement													
Analcime	9.2	10.0	4.0	12.0	5.8	11.2	14.8	8.0	12.8	7.2	10.2	6.0	6.9
Calcite	2.2	0.6	X		0.6	3.2	0.8	0.4	4.0	0.4	1.0	X	4.3
Zeolite		4.4	X	0.8		1.6	0.4	2.4		0.6	0.6	0.8	X
Hematite	0.2	0.6	2.0		1.4		X	X	0.4	0.6	0.2		0.2
Clay		3.4	0.8	1.0		4.8	5.6	3.2	1.2				

X present but not point-counted.

Feldspars

Phenocrysts

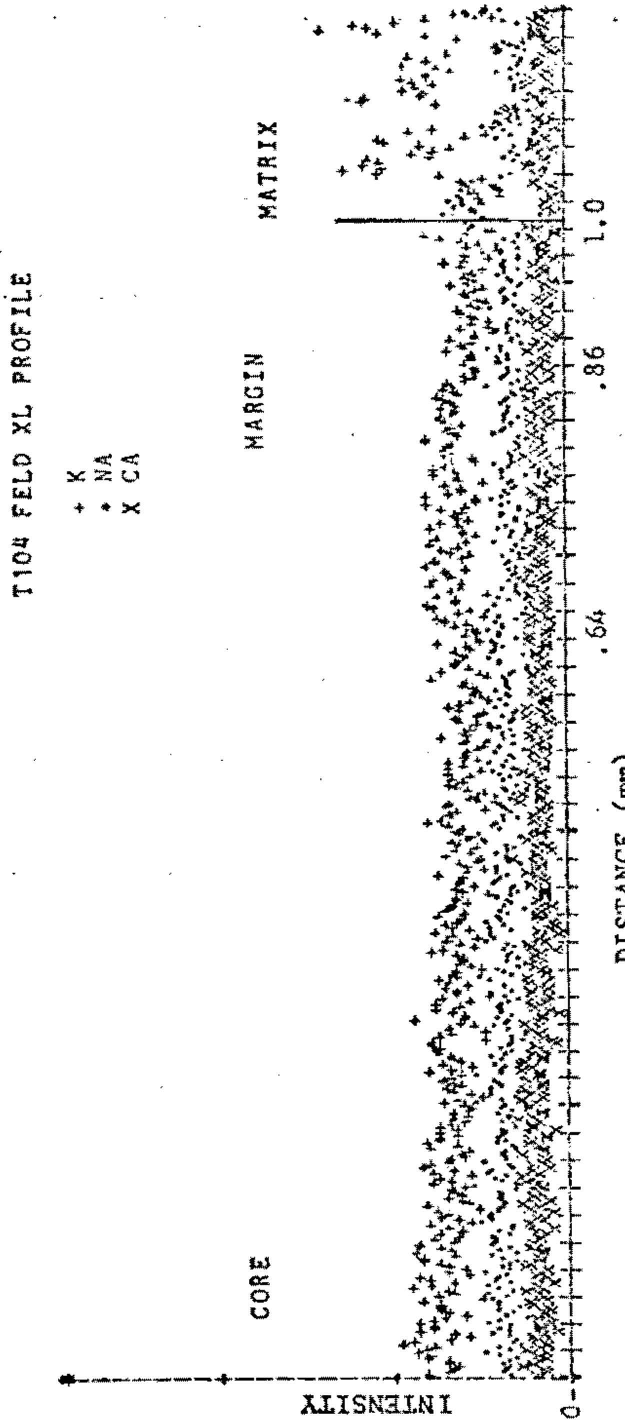
The most abundant phenocrysts are anorthoclase. They range in shape from euhedral crystals to anhedral fragments and in size from 1 mm to 16 mm (Figure 7). These phenocrysts display degrees of alteration: some are clear in thin-section, others pale brown. Many are poikilitic, enclosing small euhedral grains of sphene and acicular aegirine.

Some of the anorthoclase is strongly zoned. This is most noticeable in sections cut perpendicular to 'b' using crossed polars with the grains near extinction. Zoning is shown by variation of 2V and no change in extinction angle. An average of several measurements indicates that 2V increases outward from about 45° at the core to 55° in the margin. Although these measurements are only estimated, a change in chemical composition from the core outward is indicated.

A microprobe core-to-margin profile of a zoned feldspar, sample T104 (Figure 8), shows an oscillatory-zoned phenocryst. Potassium content decreases slightly from the core outward for 0.64 mm, then shows a sharp increase for 0.22 mm, and drops decidedly to the margin. The Na/K ratio changes inversely with the rise and fall of potassium. The contacts between zones appear rather sharp in thin-section; this observation is confirmed by the abrupt changes on the microprobe profile.

Some phenocrysts produce an off-centered BXA figure in which 'a' is nearly perpendicular to the stage. These are large, straight-sided, tabular forms in which characteristic anorthoclase gridiron twinning is well developed. In other samples where the twinning

Fig. 8. Microprobe profile from core to margin of Devils Tower anorthoclase sample T104. Oscillatory zoning is noted by the variation in potassium intensity.


T104 FELD XL PROFILE
+ K
• NA
X CA
CORE
MARGIN
MATRIX
INTENSITY
0
.64
.86
1.0
DISTANCE (mm)

lamellae are too fine to be observed, uneven extinction (moiré effect) is noted.

Microperthite is present as intergrowths of low albite and K-feldspar along cracks and in patches. The feldspar x-ray diffraction peaks are very complex. Several peaks that could not be characterized by Wright's (1968) method may represent cryptoperthitic albite and sanidine. The perthites may not be formed by exsolution, but intergrowths that have grown directly from the melt. Lofgren and Gooley (1977) demonstrated that in fast crystal growth within a reduced pressure environment, potassium is pushed ahead of the crystallizing interface until it reaches supersaturation. At this point, nucleation and growth of a K-rich zone occur. This process can be repeated many times, producing a psuedo-perthitic intergrowth.

A second and more traditional explanation is that the perthitic lamellae represent limited exsolution of the anorthoclase. Subsolvus exsolution would be greatly influenced by the composition of interstitial fluids which are most likely responsible for the perthite along margins and in fractures. The patch perthites may have grown directly from the melt.

These alternative explanations could be tested by microprobe analysis. Feldspars grown from the melt show a higher degree of solid solution, plagioclase becomes more An- or Or-rich, sanidine becomes more Ab-rich, and the intergrowths develop zoning which is incompatible with an exsolution origin (Lofgren and Gooley 1977).

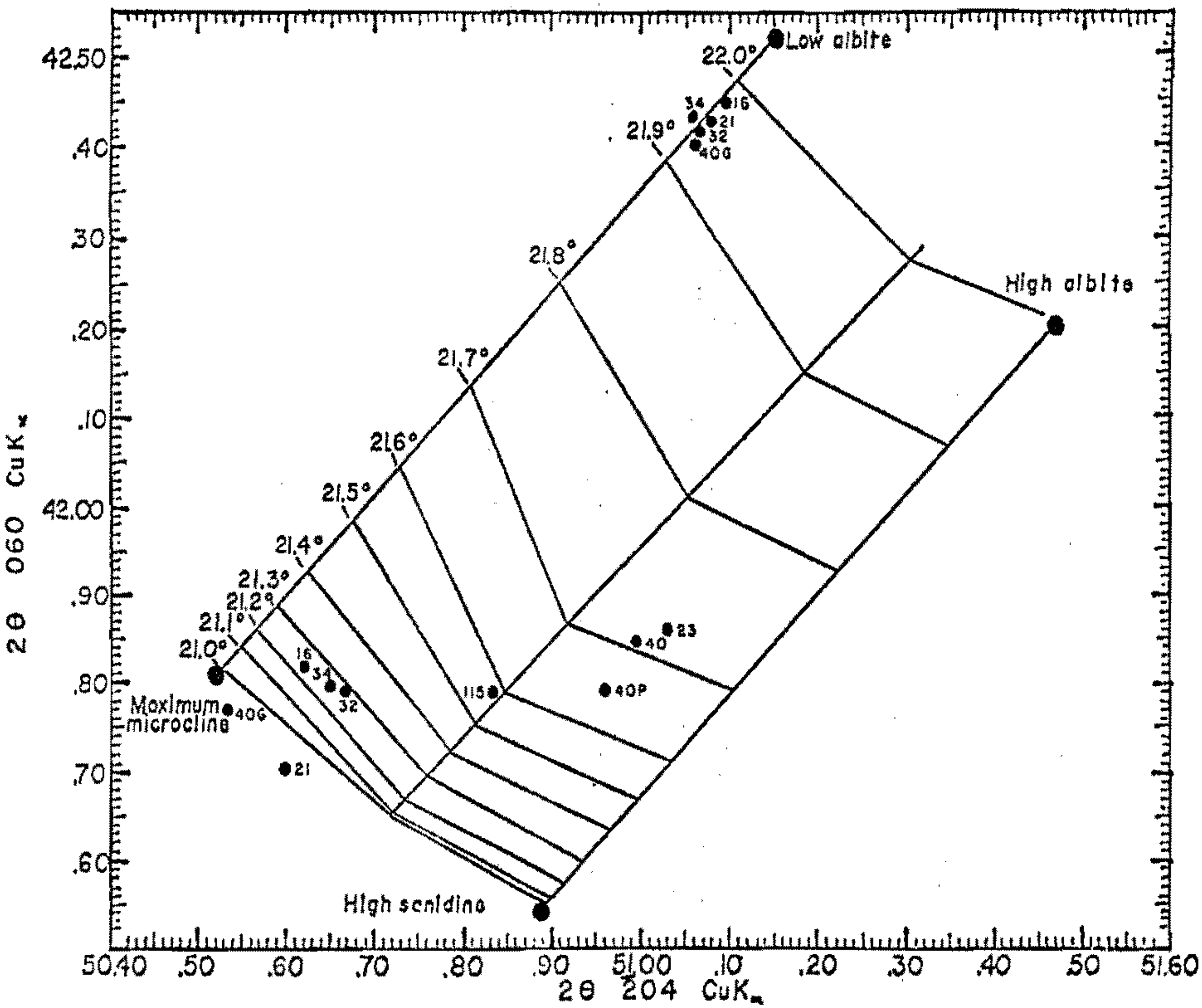
Analcime replacement in the anorthoclase phenocrysts occurs along both walls of fractures and in rims and patches. In many instances, both the phenocryst and the analcime have been altered to calcite, hematite, or anisotropic zeolite, indicating that the zeolite metamorphism post-dates the analcime replacement. Kaolinite is also a common replacement product of the feldspars.

Johannsen (in Darton and O'Harra, 1907) described the anorthoclase in the Devils Tower rocks as Na-rich orthoclase. Diffraction patterns of feldspar phenocrysts were examined by Wright's (1968) three-peak method. Only non-anomalous feldspars which occur in major amounts were plotted. Results are shown in Figure 9. Feldspar phenocrysts in the Tower phonolite are recognizable as anorthoclase, Or_{24}-Or_{30}, containing detectable amounts of high albite and sanidine which were not plotted. This paper will use MacKenzie and Smith's (1956) definition of anorthoclase as a high temperature alkali feldspar more Na-rich than Or_{37}.

The abundance of feldspar phenocrysts in the Tower rocks ranges between 28.7% and 49.2% (table 2), including the analcime reported as replacement. Although these figures show considerable range, the actual vertical distribution is quite uniform. For example, sample T16, which was collected near the top of the Tower, has 40.4% feldspar phenocrysts; and T101, near the base, has 41.6%. Wider differences in percentage seem to be related to alignment of phenocryst grains and location of the point-count trace.

Assuming that all feldspar phenocrysts in the Tower rock are anorthoclase poses some contradictions. Samples T16, T32, and T34, collected at intervals from 1485 m to the top of the Tower, show no discernable anorthoclase (Figure 9). Instead, the phenocrysts plot closer to maximum microcline. Very little difference can be observed, however, except for a slight increase in estimated 2V. Optically,

Fig. 9. Ordering of feldspars in the Devils Tower phonolite determined from Wright's (1968) 3-peak method.


Low albite
High albite
High sanidine
Maximum microcline
22.0°
21.9°
21.8°
21.7°
21.6°
21.5°
21.4°
21.3°
21.2°
21.1°
21.0°
34
16
21
32
40G
23
40
40P
115
2θ 060 CuKα
2θ 204 CuKα
42.50
.40
.30
.20
.10
42.00
.90
.80
.70
.60
50.40
.50
.60
.70
.80
.90
51.00
.10
.20
.30
.40
.50
51.60

anorthoclase can be considered to form a series with microcline (Heinrich 1965); according to MacKenzie and Smith (1956), anorthoclase forms a series with low sanidine. In either case, a change in structural state is indicated. The Devils Tower feldspars change from high temperature, disordered forms at the base to lower temperature, more ordered forms at the top.

Electron microprobe data on the feldspars in sample T104, shown in table 3, compare well with anorthoclase data published by Deer and others (1969). The only significant variation is in the potassium content, but this is within the limits of other anorthoclase analyses in the same publication. Analyses were made on the phenocrysts shown in Figure 7.

Groundmass

Feldspars occur in the Devils Tower rock as subparallel laths and anhedral patches. Optic axis and field angle methods estimate 2V to be greater than 70°, suggesting a composition close to low albite. Some of the feldspar grains display distinct Carlsbad twinning and faint albite twinning. Michel-Levy's method (Heinrich 1965) was applied with limited success to several albite twins; results are approximately An_3 to An_6.

Groundmass feldspar laths were identified by Johannsen (Darton and O'Harra 1907) as orthoclase, but x-ray diffraction patterns calculated by Wright's method (1968) indicate that they are low albite with minor amounts of microcline (Figure 9). An electron microprobe analysis of a feldspar lath from sample T104 compares reasonably well with a microcline analysis by Deer and others (1969) (table 3).

TABLE 3

MICROPROBE ANALYSES OF DEVILS TOWER FELDSPARS

	Sample					
	A	B	C	D	E	F
SiO_2	66.85	63.70	66.49	66.97	67.55	65.58
Al_2O_3	20.18	21.83	19.99	18.75	18.40	19.58
FeO	0.19	0.18	0.33	0.88	0.75	0.21
MgO	–	0.14	–	–	–	0.12
CaO	0.73	2.75	0.63	0.36	0.19	0.49
Na_2O	7.93	7.55	7.88	7.88	6.82	5.90
K_2O	3.84	3.75	4.57	5.39	6.23	7.88
TiO_2	0.13	–	0.06	0.04	–	–
P_2O_5	–		–		–	
MnO	0.09		–		–	

NOTE: Comparison analyses from electron microprobe (Frank R. Karner, analyst).

NOTE: Comparison analyses from Deer and others 1969.

– below detectable limits

Sample key: (A) Anorthoclase phenocryst, T104, point half way between margin and core; (B) Anorthoclase, inclusions in augites, Euganean Hills, Italy; (C) Anorthoclase phenocryst, T104, average line analysis; (D) Anorthoclase, Grande Caldeira, Azores; (E) Microcline subhedral grain, T104, groundmass, (F) Microcline perthite, nepheline syenite, Korea.

Further microprobe analysis is necessary to define the relative amounts and compositions of the feldspars.

Devils Tower feldspars point-count at about 30% of the groundmass (table 2). This percentage is low because analcime replacement of feldspars has been recorded with interstitial analcime. SEM photographs clearly indicate a considerably higher feldspar percentage.

Pyroxenes

Phenocrysts

The principal mafic mineral in the Devils Tower rock is a green aegirine-augite, often found with a dark rim of aegirine. Phenocrysts are usually stubby, euhedral prisms up to 3 mm long, and octagonal cross sections showing distinctive pyroxene cleavage. Point-count percentages average about 6% (table 2). No consistent vertical variation in pyroxene content was noted.

In plane-polarized light, phenocrysts are slightly pleochroic: α = green, β = yellow, γ = pale green. Many crystals are strongly zoned; those with most pronounced zoning show maximum interference colors near the edge of second-order orange. Extinction angles measured near the cores range from 23° to 28°, and cross sections show symmetrical extinction. Optical evidence indicates that the cores are aegirine-augite.

The dark rims show extinction angles between 6° and 9° and a high third-order interference color. No pleochroism is observed because the outer layer is dark in plane-polarized light. The low extinction angle and high interference colors indicate that the rim is aegirine.

Microprobe analyses of Devils Tower pyroxenes with published analyses for comparison (Deer and others 1969) are shown in table 4. Of the three core-to-margin analyses made, one shows distinctive zoning (Figures 10 and 11). An increase in Fe and Na from core to margin and a decrease in Ca and Mg is apparent. This sample analysis indicates an aegirine-augite core and an aegirine rim.

Probe analyses of cores show some variation in Fe content but basically agree with published aegirine-augite analyses (Deer and others 1963). One phenocryst analyzed shows little change from core to margin, even though in thin-section it appears to have an aegirine rim. The margin analysis may not have been within the aegirine zone.

Microprobe data from the margins indicate a clear trend toward Na and Fe enrichment which in some samples has progressed to form aegirine rims. In most cases, however, the rim is still aegirine-augite or some intermediate composition.

Groundmass

The only mafic mineral present in the groundmass is aegirine. It comprises about 12.8% of the whole rock or 25% of the groundmass and forms small needles with no preferred orientation. A few grains are subhedral. The crystals are light green in plane-polarized light, and in cross polars display high third-order interference colors. Extinction angle is very low, 2° to 3°. Pleochroism is moderate: α = bluish green, β = green, γ = light yellow. Because the crystals are so small, 2V could not be determined. Aegirine accounts for the characteristic green tint in much of the Devils Tower phonolite.

TABLE 4

MICROPROBE ANALYSES OF DEVILS TOWER PYROXENES

	Sample							
	A	B	C	D	E	F	G	H
SiO_2	50.24	51.68	48.98	48.69	50.44	49.65	49.57	48.63
Al_2O_3	1.01	1.28	2.52	2.05	2.20	2.88	2.54	2.35
FeO	27.33	24.27	21.36	23.54	21.48	18.79	16.71	22.44
MgO	2.34	4.29	4.99	4.04	5.31	6.48	7.65	4.70
CaO	9.33	9.56	16.08	15.21	13.40	17.33	18.89	16.09
Na_2O	7.96	7.25	4.14	4.58	5.34	3.60	2.82	4.26
K_2O	0.15	–	–	0.05	0.39	0.08	0.21	0.06
TiO_2	0.66	1.59	0.38	0.58	0.38	0.40	0.72	0.37
P_2O_5	0.14		–	0.08		–	–	–
MnO	0.79	0.45	1.37	1.11	0.61	0.73	0.77	0.93
S	–		0.11	–		–	0.66	0.12
Na	37.95		24.37	26.31		22.20	18.42	24.85
Ma	8.60		22.61	17.81		30.78	38.49	21.08
Fe^{+2}+Mn	53.45		53.03	55.88		37.02	43.09	54.07

NOTE: Comparison analyses from electron microprobe (Frank R. Karner, analyst).

NOTE: Comparison analyses from Deer and others 1963.

– below detectable limit.

Sample key: (A) Aegirine-augite, T104, rim; (B) Aegirine-augite, aegirine granulite, Aberdeenshire; (C) Aegirine-augite, T104, rim; (D) Aegirine-augite, T104, margin point; (E) Aegirine-augite, syenite pegmatite, Ilmen Mountains, U.S.S.R.; (F) Aegirine-augite, T104, core; (G) Aegirine-augite, T104, core point; (H) Aegirine-augite, T104.

Fig. 10. Microprobe profile across a zoned pyroxene phenocryst, showing a decrease in Ca and Mg and an increase in Fe from core to margin, sample T104.

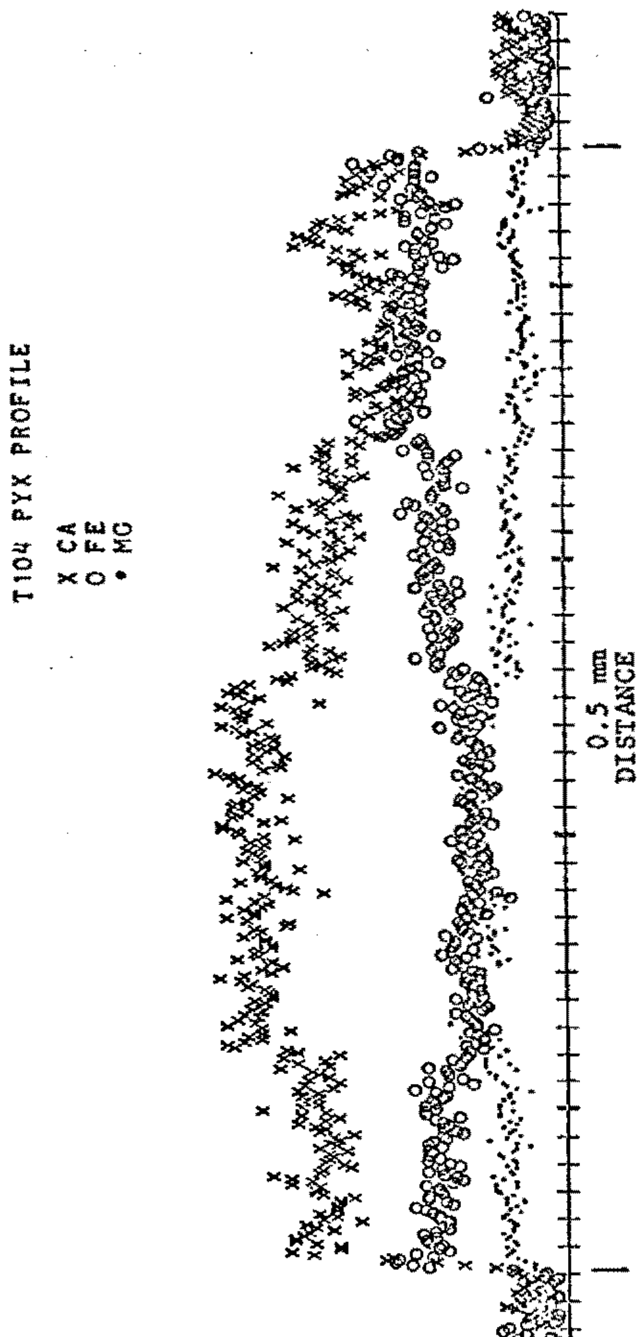
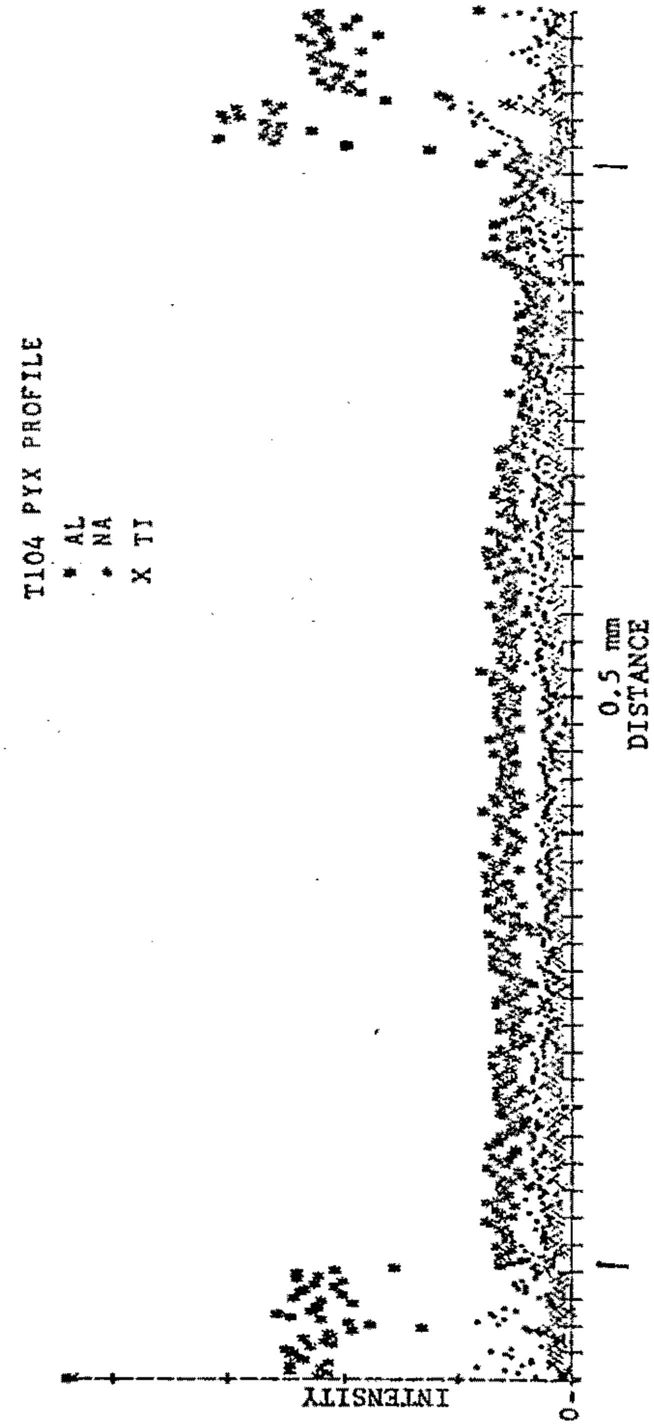

T104 PYX PROFILE
X CA
O FE
• MG
INTENSITY
0
0.5 mm
DISTANCE

Fig. 11. Microprobe profile across a zoned pyroxene phenocryst, showing a Na increase from core to margin, sample T104.


T104 PYX PROFILE
* AL
. NA
X TI
0.5 mm
DISTANCE
INTENSITY
0

Analcime

As has been stated, analcime has replaced feldspar along margins, in fractures, and in large irregular patches. This analcime replacement predates the zeolite metamorphism. Analcime is also one of the major constituents of the groundmass (up to 40%) and comprises 10% to 20% of the whole rock (table 2). Groundmass analcime is anhedral and fills spaces between other grains. In plane-polarized light, it appears as cloudy gray patches; with crossed polars, it is isotropic or nearly so. Patches are too small and irregular to provide good optical data.

X-ray diffractograms reveal that analcime is a major phase in the Devils Tower phonolite, and not merely a minor alteration product, as previously reported (Johannsen, in Darton and O'Harra 1907). The origin of this analcime will be discussed in a later section.

Both nosean and nepheline occur as microphenocrysts. Pirsson (1894) described some fresh nepheline and an altered mineral of the sodalite group. Johannsen (Darton and O'Harra 1907) reported neither of these in the material he examined.

Nosean appears as very small euhedral to subhedral grains, usually in hexagonal cross sections. They range in color from pale bluish gray to brown in plane-polarized light, and are isotropic with crossed polars. All of the crystals observed contain minute white inclusions which were identified by electron microprobe as barite. These barite inclusions facilitate identification of nosean in thin-section. The percentage of nosean is small, less than 1%.

Nepheline occurs as short colorless prisms and hexagonal cross sections in plane-polarized light. With crossed polars, hexagonal sections are isotropic; prisms show parallel extinction and are length-fast. Nepheline composition is less than 1% (table 2).

Accessory Minerals

Accessory minerals include magnetite in small cubes and irregular grains, and sphene in euhedral rhombic sections and irregular grains. The sphene is non-pleochroic, shows prominent parting, and does not go to complete extinction. Percentages of sphene range up to 1.2% in some samples (table 2).

Alloclastic Breccia

The alloclastic breccia near Devils Tower was first described by Jaggar (1901) under the term agglomerate. According to his report, "the matrix appears to be a decomposed porphyry, and the rocks included comprise irregular fragments of granite, limestone, sandstone, quartzite, purplish rhyolite, slate or schist, black shale, flint, and coarse pegmatite" (Darton and O'Harra 1907, p. 6). Examples of all of the rocks mentioned were found; nearly all of them were weathered out of the matrix.

Because the mass is extremely weathered, good matrix samples are difficult to find. One finally laminated matrix sample collected shows depressions in the laminations where pebbles have landed and subsequently been covered. Within the laminations are flattened blebs of pumice and scoriaceous material.

Darton (1909) reported finding within the agglomerate large boulders of Pahasapa Limestone containing Mississippian spirifers and other unidentified fossils. Some of the shales found are coaly and possibly of early Cretaceous age.

Brown (1954) reported that the agglomerate in the Devils Tower area and near the Missouri Buttes is sedimentary in origin, but did not indicate an adequate source for the variety of materials found. Robinson (1954) mapped the outcrop as the Redwater Member of the Sundance Formation. Considering the number of rock types represented in this small outcrop--from Precambrian granites and schists to Mississippian limestones and even early Cretaceous(?) coals--and noting the fact that these outcrops are found only in the immediate vicinities of Devils Tower and the Missouri Buttes, it is very unlikely that they are sedimentary deposits.

These pyroclastic rocks have traditionally been called agglomerate, but this term seldom appears in contemporary literature. The name alloclastic breccia has been chosen because it most accurately describes the rock unit.

MISSOURI BUTTES

General Geology

The Missouri Buttes are situated about 5 km northwest of Devils Tower (Plate 1). Five peaks rise above the Fall River Formation plateau to a maximum height of 241 m (Figure 12). They are arranged in a roughly rectangular pattern which tapers southward, with three buttes along the western edge and two along the eastern edge (Plate 3). The highest is the northwest butte, reaching a maximum elevation of 1637 m. The northeast butte is 1590 m, and the southern buttes 1530 m. The west-central butte is the lowest in elevation, 1493 m. Differences in relief are partly due to the irregularity of the depression that surrounds the buttes.

The two northern buttes are separated from the southern three by a deep gully cut by the Right Fork of Lake Creek. Gullying has removed much of the talus material and exposed two large outcrops of alloclastic breccia south of the northwest butte, one on each side of the creek. A saddle between the two northern buttes is also filled with breccia.

The three southern buttes form a triangle which encloses a grass-covered plateau. One of the breccia outcrops is situated on the northern slope of this plateau. Jaggar (1901) mapped the breccias as agglomerates and suggested that they extend throughout the entire central area of the buttes. This extent was not confirmed

Fig. 12. View of the Missouri Buttes from the northwest. Photograph shows the extensive talus cover around the northern buttes.

in the field. Only the three outcrops shown in Plate 3 could be found near the buttes.

The other two breccia outcrops shown on the map, situated about 0.7 km west of the buttes, have not been previously mapped or reported. Figure 13 shows the top 3.5 m of one of these outcrops. The other outcrop is a grass-covered knoll similar in shape to the brecciated area near Devils Tower.

Darton (1909) reported that a small mass of monzonite crops out about a half mile from the western edge of the buttes. No monzonite outcrop, as such, was found; Darton very probably was referring to the two breccia locales just described. Large boulders of granite and quartz monzonite are plentiful at these locations.

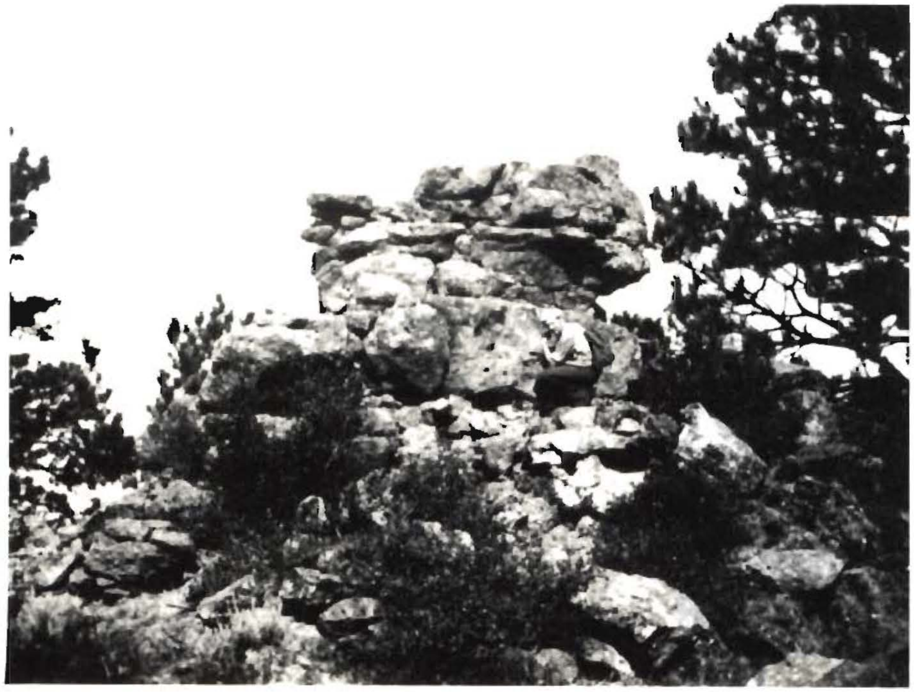
Several springs located along the western and eastern edges of the buttes seem to delineate the boundaries of the igneous masses. The springs have probably formed at the surface of the contact between the sedimentary and igneous rocks.

The Missouri Buttes are surrounded by a massive talus sheet about 6 km^2 in area. On the north, the talus extends about 1 km from the base of the igneous bodies and narrows to as little as 0.2 km along the southern margin, where much of it has been removed by streams. Thickness of the talus sheet is difficult to determine because of the doming on the north flank and the deepening of the Missouri Buttes depression to the south. Field estimates place its maximum thickness at about 60 m.

An observation easily made on air photos is that the Missouri Buttes seem to be separated into large sheets or plates dipping at very steep angles to the south or southeast. These sheets strike N.75°E. on all except the northeast butte, where the strike is N.40°E. Although

Fig. 13. Outcrop of alloclastic breccia 0.7 km west of the Missouri Buttes. Photograph shows distinctive horizontal joint set. (Photograph by Frank R. Karner)

Fig. 14. Close-up view of the alloclastic breccia pictured in Figure 13; clasts of sedimentary, igneous, and metamorphic rocks in a matrix of glass and crystal fragments. (Photograph by Frank R. Karner)



the sheets are many meters thick, they are much less discernable in the field because they are broken up by columnar and block jointing.

Columnar jointing appears in all except the west-central butte. Although not as spectacular as in the Devils Tower, many of the columns are quite impressive, particularly in the northeast and southwest buttes. In the northwest butte, some columns are nearly vertical for most of their extent, but curve abruptly to become horizontal near their base. None of the columns extends to the top of the buttes, but are all overlain by block-jointed material for a distance of as much as 90 m. The horizontal columnar sections are not exposed at the edge of the buttes, but inward from the margin. This indicates that they were at one time surrounded by more massive rock, much the same as the curved columns in the shoulder of Devils Tower which merge into the more massive base.

Field observations in the Missouri Buttes area indicate that the igneous masses were emplaced through gently dipping sediments with very little disruption of the sedimentary layers. There are no upturned beds. Angles of dip are consistent with regional measurements, except for the sharp inward dip along the perimeter of the collapse basin surrounding the Missouri Buttes.

These observations, plus the presence of large amounts of alloclastic breccia, make a laccolithic origin (Jaggar 1901; Darton 1909) for the Missouri Buttes improbable.

Mineralogy and Petrography

Analcime Phonolite and Alkali Trachyte

The Missouri Buttes rocks are light gray to olive gray trachyte and phonolite. They are holocrystalline and in some areas seriate porphyritic. Phenocrysts compose 57% to 71% of the rock. The phenocrysts are sanidine, anorthoclase, aegirine-augite zoned to aegirine, sphene, nepheline, and extremely altered nosean(?) in an aphanitic groundmass of acicular aegirine and sanidine laths mixed with cloudy brown areas of isotropic analcime. The groundmass varies from a randomly oriented to trachytic texture. Calcite, hematite, and anisotropic zeolite are present as alteration products.

Feldspars

Phenocrysts

Phenocrysts in the Missouri Buttes rocks are primarily sanidine, and range in size from 0.5 mm to about 8 mm (Figure 15). In thin-section, most grains are 6-sided or square; some are elongated parallel to 'a'; many are zoned. They are clear to light brown in plane-polarized light and first-order gray with crossed polars. Estimates of 2V range between 42° and 60°. High 2V indicates that the optic plane is parallel to the (010) face (Heinrich 1965). A higher crystallization temperature is expected than when the optic plane is normal to the (010) face. Extinction angles range from parallel to about 8°.

Many sanidine grains appear dark in all orientations and can be easily confused with grains which have been replaced by isotropic analcime. These dark-colored grains are square or slightly elongated in outline and have a much lower 2V (between 0° and 20°). Some produce an interference figure much like a uniaxial cross. Johannsen (Darton and O'Harra 1907) reported that nepheline phenocrysts were approximately equal in abundance to feldspares in the Missouri Buttes phonolite.

Fig. 15. Zoned sanidine phenocrysts in trachytic groundmass, Missouri Buttes Sample MB167, showing analcime replacement and poikilitic aegirine.

Fig. 16. Glomeroporphyritic aegirine-augite with poikilitic sphene. A large area in the groundmass has been altered to zeolite and calcite.

In twenty-three x-ray diffraction patterns made from all five areas of the buttes, no nepheline was detected. It is possible that some of the feldspars with small axial angles could have been interpreted as nepheline.

The structural state of seven feldspars was determined by Wright's (1968) 3-peak method and plotted in Figure 17. Five samples are identified as high temperature, disordered sanidine, Or_{95} to Or_{100}; two are anorthoclase, Or_{26} to Or_{29}. In x-ray diffraction patterns, much of the sanidine appears to be quite Na-rich. High temperature sanidines can contain more Na than low temperature varieties, provided exsolution of albite has not occurred (Heinrich 1965). No albite appears in the diffraction patterns, indicating limited exsolution.

Microprobe analyses were made of four feldspar grains, two anorthoclase and two sanidine, and compared with published analyses (table 5).

The feldspar phenocrysts display considerable analcime replacement along cracks and in patches, and some alteration to calcite, zeolite, and kaolinite. Aegirine needles are occasionally poikilitically enclosed in regular patterns.

Groundmass

Small laths and anhedral patches of sanidine comprise the groundmass. No zoning or twinning was observed. Most x-ray diffraction patterns of Missouri Buttes rocks have only one sharp sanidine peak. Groundmass feldspars of other composition were not detected.

Fig. 17. Ordering of feldspars in Missouri Buttes phonolites and trachytes determined by Wright's (1968) 3-peak method. All feldspars plot as sanidine or anorthoclase.

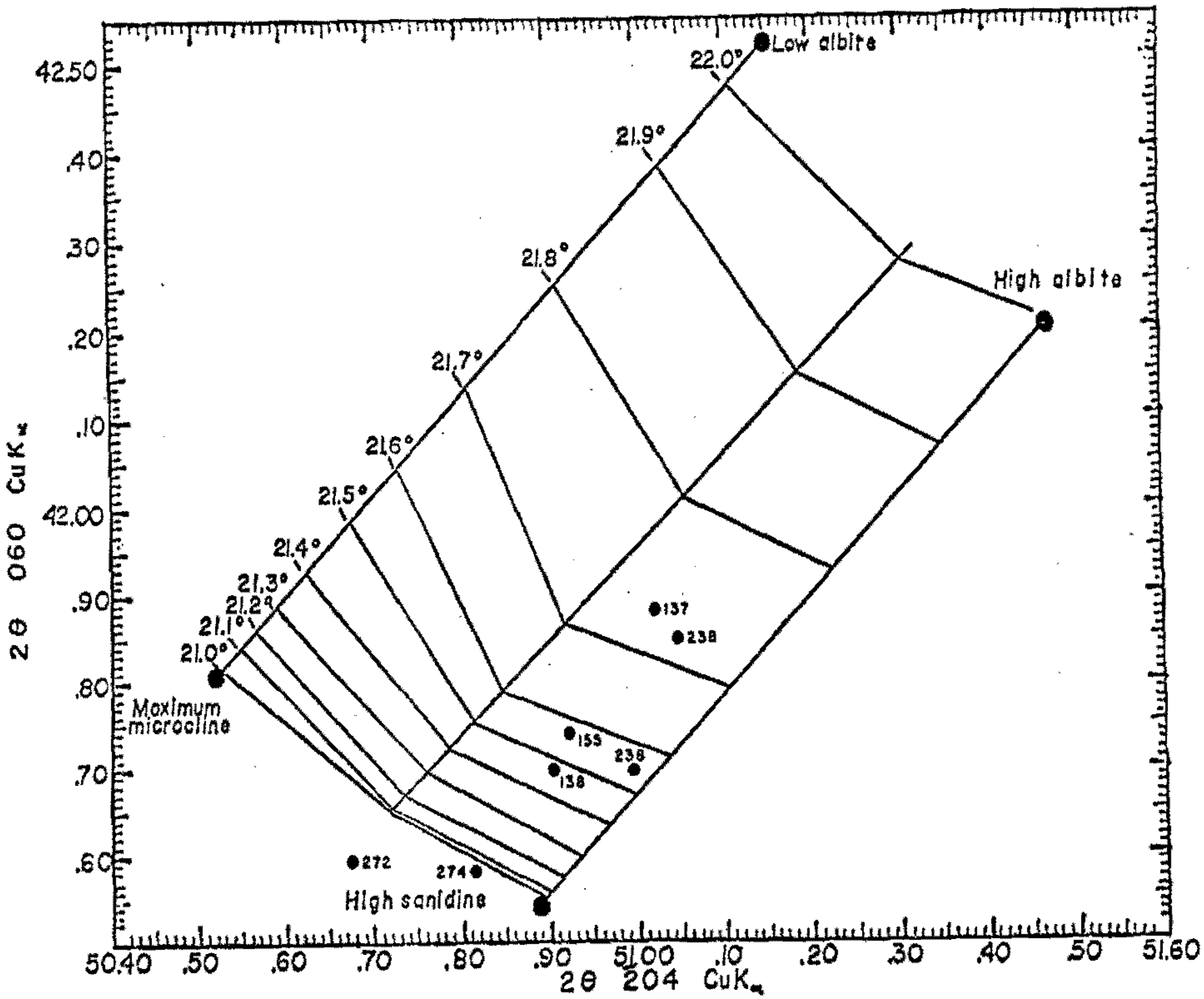

Low albite
High albite
Maximum microcline
High sanidine
22.0°
21.9°
21.8°
21.7°
21.6°
21.5°
21.4°
21.3°
21.2°
21.1°
21.0°
137
238
155
238
138
272
274
2θ 060 CuKα
42.50
.40
.30
.20
.10
42.00
.90
.80
.70
.60
2θ 204 CuKα
50.40
.50
.60
.70
.80
.90
51.00
.10
.20
.30
.40
.50
51.60

TABLE 5

MICROPROBE ANALYSES OF MISSOURI BUTTES FELDSPARS

	Sample						
	A	B	C	D	E	F	G
SiO_2	66.47	67.27	66.64	66.64	66.97	66.88	63.70
Al_2O_3	17.59	18.35	17.99	19.72	18.75	20.11	21.83
FeO	1.74	0.92	0.39	0.15	0.88	0.22	0.18
MgO	–	–	–	–	–	–	0.14
CaO	0.06	0.15	–	0.60	0.36	0.86	2.75
Na_2O	6.01	6.45	5.03	7.06	7.88	7.96	7.55
K_2O	8.07	7.05	9.81	5.53	5.39	3.75	3.75
TiO_2	–		–	0.09	0.04	0.17	–
P_2O_5	–		–	–		–	
MnO	–		0.09	0.15		–	

NOTE: Comparison analyses from electron microprobe (Frank R. Karner, analyst).

NOTE: Comparison analyses from Deer and others 1969.

- below detectable limit.

Sample key: (A) Sanidine phenocryst, MB123, rim inclusion; (B) Sanidine, rhyolite, Mitchell Mesa, Texas; (C) Sanidine phenocryst, MB167; (D) Anorthoclase phenocryst, MB167 core; (E) Anorthoclase, Grande Caldeira, Azores; (F) Anorthoclase phenocryst, MB167 core; (G) Anorthoclase, inclusions in augite, Euganean Hills, Italy.

Point-count analysis of the groundmass was attempted, but small grain size, analcime replacement, and alteration prevent definitive analysis. A feldspar percentage of approximately 50% is estimated.

Pyroxenes

Phenocrysts

The mafic phenocrysts of the Missouri Buttes rocks are primarily aegirine-augite. Some are zoned to aegirine. Point counts indicate that percentages of aegirine-augite phenocrysts range from 4% in the phonolite to 12% in the trachyte (table 6).

The phenocrysts are usually euhedral prisms or octagonal cross sections with distinct pyroxene cleavage. All are pheochroic: α = emerald green; β = yellow to yellowish red; γ = pale green. Maximum interference colors are low third-order. Nearly all crystals are strongly zoned. Extinction angles for the cores range from 15° to 32°. Cross sections show symmetrical extinction. Estimated 2V is greater than 60°. Optical evidence confirms that the phenocrysts are intermediate between augite and aegirine.

Margins of phenocrysts appear black in plane-polarized light and have a much lower extinction angle (6° to 9°). Pleochroism (where visible) is somewhat higher than in the cores. The rims are assumed to be aegirine because it is the only pyroxene with such a low extinction angle.

The rims, which appear so dark under microscope, assume a completely different appearance in scanning electron microscope photographs. A clear region of aegirine is revealed, poikilitically enclosing small feldspar crystals. This poses a question concerning

TABLE 6

MODAL ANALYSES OF MISSOURI BUTTES PHONOLITE AND TRACHYTE

	Sample						
	MB123	MB155*	MB170	MB190	MB128	MB125	MB160*
Phenocrysts							
Sanidine	31.2	32.0	27.1	28.3	20.8	32.6	26.6
Anorthoclase	14.4	11.6	6.1	8.9	4.8	9.4	6.9
Aegirine-augite	2.8	10.1	6.4	6.5	4.8	4.4	11.8
Nepheline	X	0.9	X	X	X	X	1.6
Sphene	0.8	X	0.4	0.9	1.2	0.4	0.4
Nosean	X	X	X	X	X	X	X
Analcime	X	X	X	X	X	X	X
Groundmass	32.0	29.2	42.8	23.4	38.0	42.9	43.2
Veins, pore-filling, and replacement							
Analcime	15.6	12.8	15.2	14.8	27.2	8.0	8.0
Hematite		0.5	0.4	0.8	1.2	0.8	0.8
Calcite	1.6	2.4	1.2	4.1	1.6	1.5	0.4
Zeolite	1.2	0.5	0.4		X	X	0.3
Clay	0.4	X		12.0	0.4		
Nepheline				0.3			

X present but not point-counted

*alkali trachyte

the relative age of the aegirine and the feldspar. Consideration of crystallization and nucleation rates offers a possible answer.

Crystal nucleation rate is inversely proportional to $(\Delta S_m)^2$ and $(\Delta T)^2$; crystal growth rate is proportional to ΔS_m and either ΔT or $(\Delta T)^2$ (Carmichael and others 1974). Entropy of fusion, ΔS_m, for alkali feldspars is low, 0.75-0.77 entropy units per atom in gram-formula-weight, and for pyroxene between 1.88 and 2.83 entropy units. Winkler (in Carmichael and others 1974) has shown that nucleation rate curves peak at a lower temperature than crystallization rate curves. More nuclei develop under rapid cooling conditions than with slow cooling. With low entropy of fusion, feldspar would produce many more nuclei than aegirine, but the growth rate for aegirine would be much faster, and the poikilitic texture would result. Rapid cooling would account for the abundance of enclosed feldspars.

The distribution of pyroxene phenocrysts varies considerably throughout the five Missouri Butte units. Lowest percentages are from the northwest butte, about 3% to 5%, increasing slightly upward. Vertical variation is observed only in this butte. The northeast and southeast buttes are intermediate, about 6.5%. Highest percentages are in the trachytes of the west-central and southwest buttes, where values range from about 10% to 12% (table 6). A possible explanation for this variation is that everywhere except in the northwest butte the pyroxene becomes glomeroporphyritic (Figure 16). This texture suggests eruptions of material from levels of the magma chamber where ferromagnesian minerals had accumulated by gravity settling.

Microprobe analyses confirm the optical studies. Three pyroxene cores and two margins were analyzed (table 7). Essentially the

TABLE 7

MICROPROBE ANALYSES OF MISSOURI BUTTES PYROXENES

	Sample								
	A	B	C	D	E	F	G	H	I
SiO_3	48.08	46.61	48.71	50.44	49.12	49.66	51.68	51.44	51.92
Al_2O_3	3.79	3.47	1.95	2.20	2.03	1.94	1.28	0.70	1.85
FeO	16.69	21.08	24.47	21.48	24.54	26.21	24.87	29.59	32.19
MgO	7.30	7.27	3.18	5.31	3.78	2.90	4.29	1.06	–
CaO	20.19	17.84	11.92	13.40	11.86	10.00	9.56	3.61	–
Na_2O	2.13	1.04	6.21	5.34	6.73	7.57	7.25	11.28	12.86
K_2O	0.13	0.27	0.16	0.39	0.16	0.09	–	0.14	0.19
T_iO_2	1.21	1.18	1.74	0.38	0.56	0.71	1.59	1.36	0.77
P_2O_5	–		0.27		0.08	–		0.24	
MnO	0.33	1.11	1.34	0.61	1.09	0.86	0.45	0.52	–
SO_3	0.08		–		–	–		–	
Na	15.27		33.71		34.00	36.87		47.27	
Mg	40.36		13.29		14.67	10.85		3.43	
Fe^{+2}+Mn	44.37		53.01		51.33	52.29		49.30	

NOTE: Analyses from electron microprobe (Frank R. Karner, analyst).

NOTE: Comparison analyses from Deer and others 1963, 1969.

– below detectable limit.

Sample key: (A) Ferroaugite, MB167, core; (B) Ferroaugite, syenite, Southwest Africa; (C) Aegirine-augite, MB104, rim; (D) Aegirine-augite, syenite pegmatite, Ilmen Mountains, U.S.S.R.; (E) Aegirine-augite, MB104, core; (F) Aegirine-augite, MB123, core; (G) Aegirine-augite, aegirine granolite, Aberdeenshire; (H) Aegirine, MB123, rim; (I) Aegirine, riebeckite-albite granite, Nigeria.

same trends are observed as in the Devils Tower rocks: an increase in Fe and Na and a decrease in Ca and Mg toward the margin.

One of the phenocrysts analyzed has no aegirine rim but displays the typical compositional trends in the aegirine-augite. One of the cores shows a lower Fe and a higher Ca content than most standard analyses for aegirine-augite, and compares favorably with ferro-augite (Deer and others 1969). The third analysis is very similar to Devils Tower rocks--an aegirine-augite core with a margin of aegirine.

The only ferromagnesian mineral detected by x-ray diffractograms is aegirine-augite.

Groundmass

Groundmass pyroxenes in the Missouri Buttes phonolite and trachyte consist entirely of acicular prisms and anhedral patches of aegirine, optically identical to those of the Devils Tower.

Mineralogically and texturally, all of the Missouri Buttes rocks are very consistent; the most noticeable difference is in color. The lightest-colored rocks are the trachytes from the west-central and southwest buttes. These rocks contain the greatest abundance of pyroxene phenocrysts, but the lowest percentage of groundmass pyroxene. As at Devils Tower, the amount of aegirine in the groundmass apparently determines the color of the rock.

A notable example is found at the top of the southeast butte where the light gray phonolite is interlayered with olive green bands up to 1 cm thick and several centimeters long, and contains angular clasts about 2 cm in diameter of the same green material. Microscope examination identifies these green areas as aegirine needles and a few subhedral sanidine crystals surrounded by isotropic analcime. The clasts and blebs are themselves surrounded by analcime and are highly altered to calcite and zeolite. They closely resemble the rocks in the Barlow Canyon laccolith which will be discussed later, and probably represent movement of late-stage Na-rich fluids.

Analcime

Analcime occurs as small phenocrysts in rounded, hexagonal, and trapezoidal forms. In plane-polarized light they are cloudy brown; with crossed polars they are isotropic or weakly anisotropic.

Microprobe analysis of an analcime phenocryst is shown in table 8. Total concentration percentage in this analysis is only 91.53%. The remaining 8.47% is arbitrarily assigned to oxygen. The values reported correspond almost exactly with standard analyses for analcime, if the 8.47% were assigned to H_2O. Samples of Barlow Canyon analcime appeared to boil in the electron beam, indicating a loss of H_2O. This was not observed in the Missouri Buttes analysis. The weak birefringence noted may be related to changes in structure following water loss (Heinrich 1965). The sample analyzed may represent analcime which has undergone a loss of water.

In addition to the phenocrysts, much analcime occurs as replacement of sanidine along margins and fractures and in patches. This analcime, in turn, has been effected by zeolite metamorphism and altered to calcite. Replacement analcime comprises from 8% to 22% of the rock. Most noticeable replacement is seen in samples from the top of the northwest butte.

TABLE 8

MICROPROBE ANALYSES OF MISSOURI BUTTES ANALCIME

	Sample A	Sample B
SiO_2	55.95	52.89
Al_2O_3	22.73	24.63
FeO	0.09	
MgO	-	-
CaO	-	0.19
Na_2O	12.97	13.31
K_2O	0.27	9.73
TiO_2	-	
P_2O_5	-	
MnO	-	
H_2O	8.47	7.95

NOTE: Comparison analyses from electron microprobe (Frank R. Karner, analyst).

NOTE: Comparison analyses from Deer and others 1979.

- below detectable limit.

Sample key: (A) Analcime microphenocryst (MB160); (b) Analcite pegmatite patch in borolanite, Assynt, Scotland.

Analcime is a major phase of the groundmass of Missouri Buttes phonolite and in some areas may comprise 50%. It forms cloudy gray to brown anhedral patches and fills the spaces between other grains. No systematic variation in analcime was observed, either throughout the Missouri Buttes or within individual units.

Accessory Minerals

The most frequently encountered accessory mineral in the Missouri Buttes phonolite and trachyte is sphene, which comprises about 1% of the whole rock. Grains are euhedral rhombic sections and long prisms that show high relief and characteristic parting.

The only nepheline found occurs as small euhedral hexagonal cross sections and square prisms about the same size as the groundmass material. Very small amounts of nepheline are seen in most thin-sections, but a sufficient amount to point count appears only in the trachyte of the west-central and southwest buttes (table 6). The grains are uniaxially negative, clear and colorless in plane-polarized light, go to extinction in cross section, and show parallel extinction in the square sections. These small grains have not been analyzed by electron microprobe, but are probably nepheline.

A few small, rounded partly resorbed, isotropic grains are brown in plane-polarized light and contain numerous inclusions. These grains are assumed to be nosean because of their resemblance to identified nosean crystals in the Devils Tower phonolite.

Magnetite occurs as very rare, irregularly-shaped grains in the aegirine-augite.

Alloclastic Breccia

In surface exposure, a great variety of rock clasts are observed, similar to those in the Devils Tower breccia. At the Missouri Buttes, however, the matrix material has been preserved (Figure 14). In thin-section, the matrix consists of angular crystal fragments (up to 3 mm) of quartz microcline, sanidine, hornblende, aegirine-augite, and oligoclase, An_{22}-An_{26}. Small zenoliths of sandstone, shale, carbonatite, limestone, granite, trachytic phonolite, and schist are set in an earthy brown groundmass. Most of the groundmass is isotropic and spotted with brown iron oxide.

In thin-section, groundmass material is either colorless or gray to red, massive, sometimes vesicular, and it has no birefringence. Partial or complete devitrification is shown by the presence of feldspar spherulites and acicular crystallites. The material is obviously glass. The alloclastic breccias of the Missouri Buttes are unquestionably igneous in origin.

BARLOW CANYON LACCOLITH

General Geology

An exposure of analcime phonolite occurs as a small cliff on the north side of Barlow Creek, N.E.¼ sec. 23, T. 54 N., R. 66 W., and extends for 310 m (Plate 1). This igneous material was intruded directly below the Hulett Member of the Sundance Formation on the southwest flank of the Barlow Canyon dome, and forms an irregularly shaped exposure rising about 33 m above the road at the base of the canyon (Plate 4).

The dip on all flanks of the Barlow Canyon dome ranges between 6° and 9°. Just west of the intrusion, however, the dip is 16°W., and at the northeast corner it is 3°E., indicating that additional folding was caused by the intrusion.

This igneous body has been exposed on the west by a north-south trending gully, and on the south by Barlow Creek. Its total extent can only be estimated. Observations imply that the western and southern extension roughly coincides with the boundary of the surface exposure. The size of the intrusion is limited on the north and east by Sawmill Gulch, where no igneous exposures are found. Consequently, the horizontal cross section of the body appears to be an ellipse with the major axis trending north-northeast and maximum dimensions of 300 m by 650 m. The intrusion is concordant with the overlying Hulett. The lower contact of the intrusion cannot be observed.

The thickness of the intrusion increases from the western edge to the center. The form of the exposure implies that it is a small laccolithic structure. Darton and O'Harra (1907) considered this intrusion to be a laccolith; Izett (1963) classified it as a sill. Hereafter in this paper, the term Barlow Canyon laccolith will be used.

The main unit of this phonolite laccolith is overlain by a contact zone of lighter-colored, highly altered rock which contains inclusions of shale and sandstone from the Stockade Beaver or lower Hulett Member of the Sundance Formation which it intruded. The contact zone is from 0.5 m to 8 m thick and has an abrupt contact with the lower unit. This contact zone has not been previously described. Izett (1963) mapped it either as Stockade Beaver or as part of the main unit.

Mineralogy and Petrography

Analcime Phonolite

The main rock unit of the Barlow Canyon laccolith is 10 m to 25 m thick and composed of resistant, dull-brown to dark olive-gray, slightly porphyritic phonolite with an aphanitic groundmass. Phenocrysts comprise about 15% to 17% of the rock, and consist of sanidine, anorthoclase, aegirine-augite zoned to aegirine, analcime, and nosean(?) (table 9). The other 83% to 85% of the rock is groundmass consisting mainly of subhedral analcime, randomly oriented sanidine laths, and numerous star bursts of acicular aegirine. Small patches of calcite are found throughout the groundmass and in fractures of the feldspar phenocrysts. Hematite, chlorite, and limonite also occur as alteration products.

TABLE 9

MODAL ANALYSES OF THE BARLOW CANYON PHONOLITE

	Sample	
	BC110	BC134
Phenocrysts		
Sanidine	4.0	2.0
Aegirine-augite	X	X
Sphene		0.4
Nosean	2.4	2.0
Analcime	2.8	2.0
Groundmass	82.8	84.8
Veins, pore-filling, and replacement		
Calcite	7.2	8.8
Zeolite	0.8	X
Analcime	X	X
Hematite	X	X

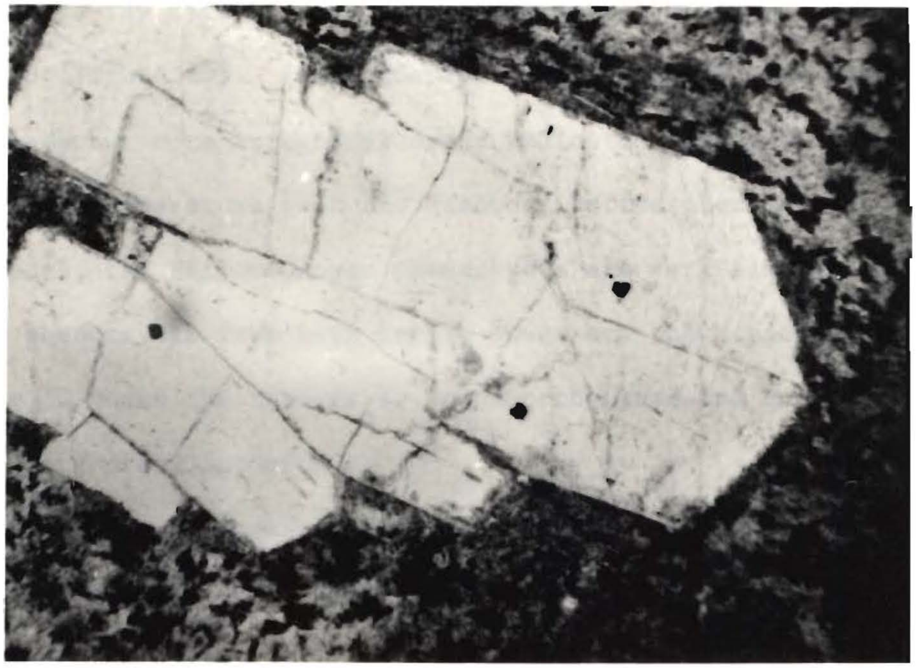
X present but not point-counted.

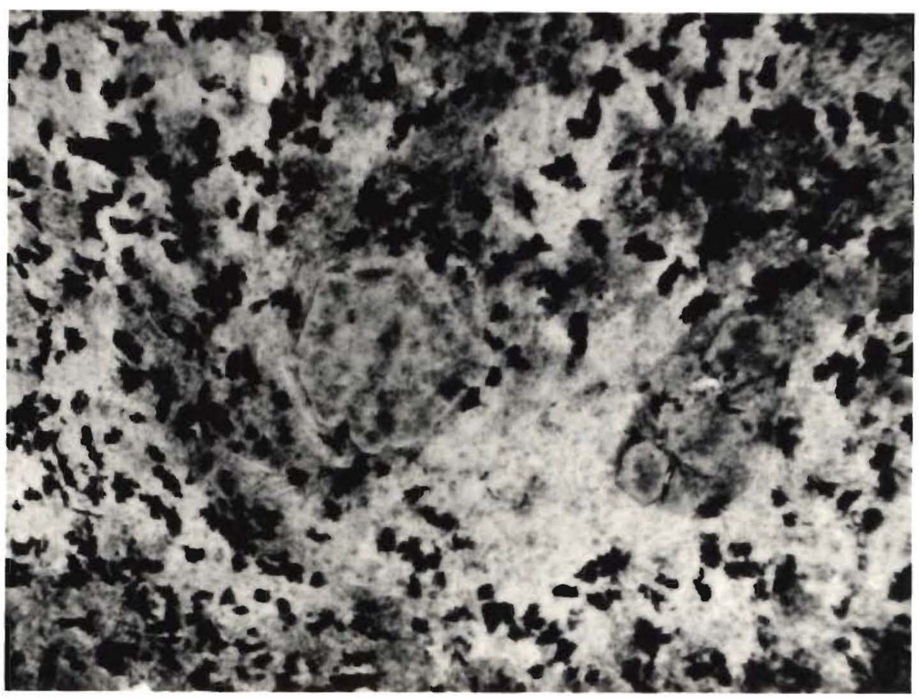
Phenocrysts

Thin-sections consistently contain approximately 2% to 4% euhedral to subhedral sanidine and anorthoclase phenocrysts ranging up to 3 mm (table 9). These feldspars are clear and colorless in plane-polarized light and show very little replacement by analcime (Figure 18). Small aegirine needles are often poikilitically enclosed in the feldspar.

Fig. 18. Zoned euhedral sanidine phenocryst, showing no resolution along margin and little analcime replacement. Sample BC110, 35X.

Fig. 19. Euhedral analcime phenocrysts with patterned inclusions set in a groundmass of aegirine star bursts, sanidine laths, and interstitial analcime, Barlow Canyon. Sample BC110, 100X.





X-ray diffraction data were analyzed by Wright's (1968) 3-peak method (Figure 20). All feldspars plot as sanidine or anorthoclase, but somewhat more structural order indicates a slightly lower crystallization temperature than the Missouri Buttes phenocrysts. In other respects, the Barlow Canyon phenocrysts are very similar to the feldspar phenocrysts from both Devils Tower and the Missouri Buttes. Table 10 shows the results of one anorthoclase and two sanidine electron microprobe analyses.

Aegirine-augite occurs only rarely as small, slightly altered euhedral grains, surrounded by dense black rims of minute aegirine needles. It is optically and chemically the same as the aegirine-augite in the Missouri Buttes and Devils Tower. Chemical data from a microprobe analysis is shown in table 10.

A few very highly altered grains with circular or hexagonal outlines are observed. These phenocrysts are a little lighter in color than the groundmass and closely resemble the nosean found in sample T104 from Devils Tower. They are isotropic with crossed polars and contain the same small white barite(?) inclusions.

Microprobe analysis verified the presence of analcime (table 10). The analyzed sample appeared to boil under the electron beam; this indicates a high volatile content consistent with analcime which characteristically contains at least 8% H_2O. The analcime occurs as individual euhedral to subhedral grains about 0.5 mm in diameter and small clusters with no intervening groundmass. The clustered grains may have accumulated by flotation. They are rounded to trapezoidal in outline, light brown in plane-polarized light, and contain many inclusions

Fig. 20. Ordering of feldspars in Barlow Canyon phonolite determined from Wright's (1968) 3-peak method.

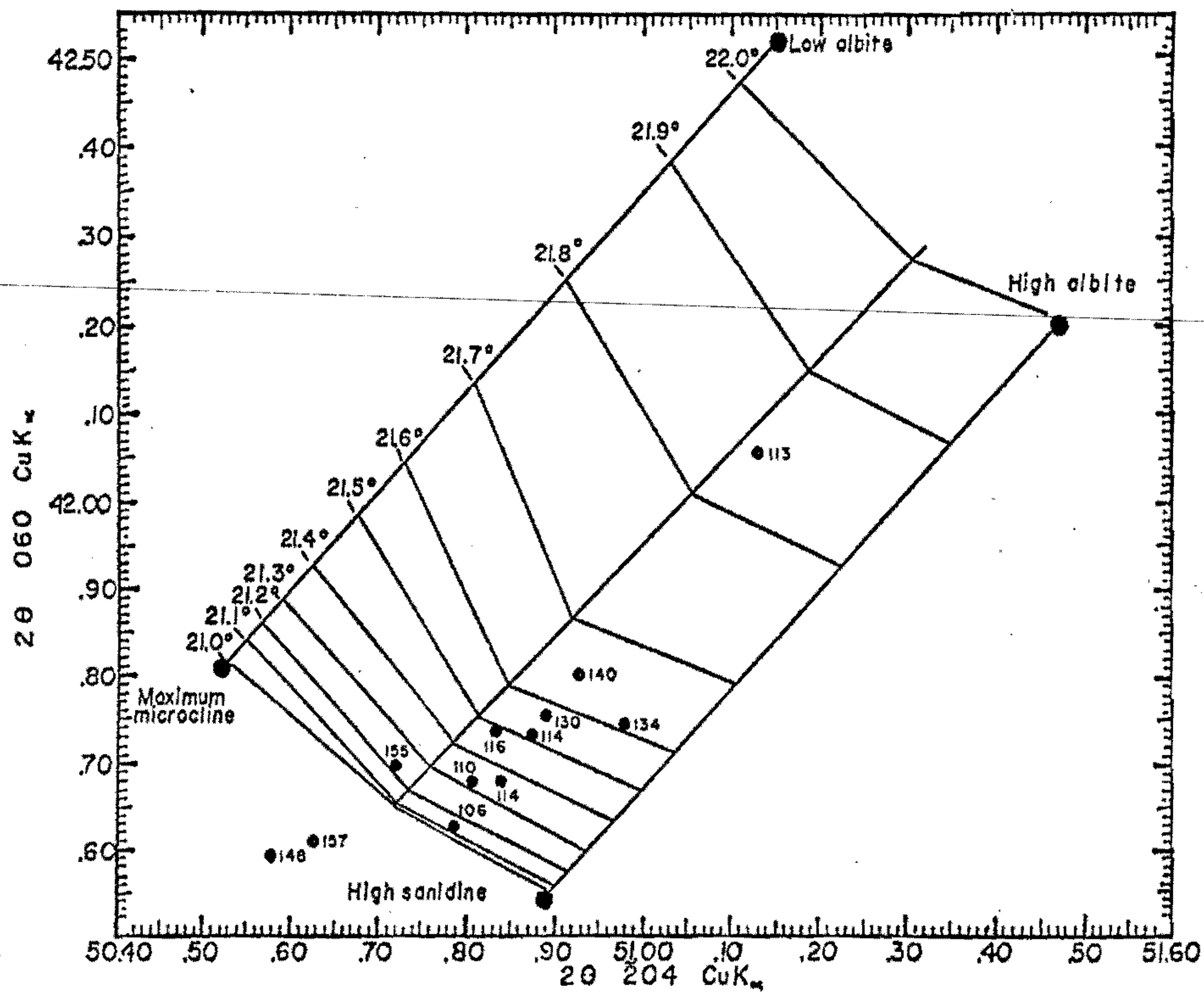

Low albite
High albite
Maximum microcline
High sanidine
22.0°
21.9°
21.8°
21.7°
21.6°
21.5°
21.4°
21.3°
21.2°
21.1°
21.0°
113
140
130
134
114
116
155
110
114
106
157
148
42.50
.40
.30
.20
.10
42.00
.90
.80
.70
.60
2θ 060 CuKα
50.40
.50
.60
.70
.80
.90
51.00
.10
.20
.30
.40
.50
51.60
2θ 204 CuKα

TABLE 10

MICROPROBE ANALYSES OF BARLOW CANYON MINERALS

	Sample										
	A	B	C	D	E	F	G	H	I	J	K
SiO_2	50.11	52.89	68.04	66.97	50.62	50.44	49.96	51.72	66.15	66.71	67.27
Al_2O_3	28.64	24.63	18.80	18.75	1.71	2.20	9.30	1.56	17.35	18.66	18.35
FeO	0.52		0.22	0.88	19.95	21.48	21.97	28.52	1.78	0.33	0.92
MgO	0.32	-	-	-	6.22	5.31	2.72	1.41	0.15	-	-
CaO	0.94	0.19	0.14	0.36	15.77	13.40	1.50	2.56	0.11	-	0.15
Na_2O	9.76	13.31	7.29	7.88	4.48	5.34	10.16	11.28	5.08	5.31	6.45
K_2O	0.59	9.78	5.34	5.39	0.17	0.39	0.96	0.34	9.20	8.86	7.05
TiO_2	0.06		0.11	0.04	0.46	0.38	2.71	1.32	-	0.07	-
P_2O_5	-		-		-		0.12		0.08	-	
MnO	0.07		-		0.55	0.61	0.54	0.21	-	-	
SO_3	0.25										
H_2O	8.73	7.95		0.03		0.47		0.50			0.08
Cl									0.04		

TABLE 10--Continued

	Sample										
	A	B	C	D	E	F	G	H	I	J	K
Na					25.95	50.43					
Mg					27.71	10.37					
Fe^{+2}+Mn					46.34	37.20					

NOTE: Comparison analyses from electron microprobe (Frank R. Karner, analyst).

NOTE: Comparison analysis from Deer and others 1963, 1969.

- below detectable limit.

Sample key: (A) Analcime, BC110, microphenocryst; (B) Analcite, pegmatite in borolanite, Assynt, Scotland; (C) Anorthoclase, BC110, phenocryst; (D) Anorthoclase, Grande Caldeira, Azores; (E) Aegirine-augite, BC110, phenocryst; (F) Aegirine-augite, syenite pegmatite, Ilmen Mountains, U.S.S.R.; (G) Aegirine, BC110, needle; (H) Fibrous aegirine, pegmatite dike in shonkinite, Bearpaw Mountains, Montana; (I) Sanidine, BC110, phenocryst; (J) Sanidine, BC110, phenocryst; (K) Sanidine, rhyolite, Mitchell Mesa, Texas.

arranged in circular patterns (Figure 19). Point counts indicate that about 2% to 3% of the rock consists of analcime phenocrysts.

Groundmass

Analcime consistently appears in x-ray diffractograms as the principal felsic mineral in the Barlow Canyon phonolite. In thin-section, most of the groundmass is isotropic analcime. Very small laths of sanidine and detectable amounts of albite, which could not be characterized by Wright's (1968) method, are scattered throughout the analcime. In some sections, the groundmass has a trachytic texture.

The most striking feature of the groundmass is the presence of star-burst clusters of acicular aegirine (Figure 19). They appear black in plane-polarized light, but where they extend into clear areas of the groundmass some optical properties can be observed. They are highly pleochroic: α = green; β = green; γ = yellow, and show strong birefringence (possibly third-order). The needles are length fast and have small extinction angles, less than 6°.

Electron microprobe analysis of an aegirine needle situated next to a pyroxene phenocryst is shown in table 10. The analysis matches standard aegirine except for the slightly higher Al_2O_3, MgO_4, and TiO_2 values. The presence of small amounts of ilmenite and chlorite could account for these differences. Chlorite was seen in thin-section and identified by probe analysis.

Natrolite was found only in sample BC101. It was identified from x-ray diffraction patterns and observed in thin-section as non-radiating fibrous material, length slow, and displaying a maximum interference color of first-order yellow. Other anisotropic zeolites and calcite are common alteration products of the Barlow Canyon groundmass.

Contact Zone

The upper unit of the Barlow Canyon laccolith is interpreted as a contact zone. This rock has a turbulent groundmass of randomly oriented K-feldspar laths, a few aegirine needles, and a number of irregular patches, most of which appear to be very fine-grained shale. Flakes of shale from the Stockade Beaver or Hulett Members of the Sundance Formation up to 2 cm in length were observed in hand specimens collected throughout the contact zone.

A few large sanidine phenocrysts are relatively unaltered, but most phenocrysts remain as mere grain outlines with completely altered cores. Some grains can be identified as aegirine-augite by their shape and pale green color. Others are round or hexagonal and isotropic, and appear to have been feldspathoids.

X-ray diffractograms of upper unit rock display strong peaks for sanidine, smectite, kaolinite, and chlorite, which account for the difficulty of description in thin-section.

PETROCHEMISTRY

Bulk rock chemical analyses were made of 47 samples of Devils Tower, Missouri Buttes, and Barlow Canyon igneous rocks, 39 by electron microprobe and 8 by x-ray fluorescence (appendix III). Chemical analyses were normalized for comparison of microprobe and x-ray fluorescence data. This procedure did not effect the Devils Tower and Missouri Buttes rocks which have a low water content (USGS analysis in Darton and O'Harra 1907). Because Barlow Canyon rock contains 6% H_2O (Izett 1963), it was necessary to consider unnormalized analyses, in which the SiO_2 content ranges from 55% to 56% and Al_2O_3 content from 19% to 20%. These percentages compare well with Izett's analysis of Barlow Canyon rock and match the average phonolite analysis given by Nockolds (1954). Modal analyses of Barlow Canyon rock also plot as phonolite (Streckeisen 1979). The modifier "analcime" is added to the name to characterize the major feldspathoidal constituent of the rock. Hence, the name analcime phonolite is given to the rock of the lower Barlow Canyon unit.

The Al_2O_3 content of the Missouri Buttes and Devils Tower rocks is about 1% to 2% lower than the Barlow Canyon phonolite. SiO_2 content, however, is considerably higher, averaging about 61.5%. This percentage of silica saturation is characteristic of trachytes (Carmichael and others 1974) and, except for a higher Na content, these rocks match an average alkali trachyte analysis presented by Nockolds (1954).

Because the Missouri Buttes and Devils Tower rocks are fine-grained, they are difficult to point-count. Therefore, both chemical and modal analyses must be considered. Normative nepheline percentages vary from 1% to 14%, which indicates a considerable range in feldspathoidal content. This is confirmed by modal point counts.

The southwest and west-central buttes plot as alkali trachyte (Streckeisen 1979), and should be given the name foid-bearing alkali trachyte to indicate the small amount of included feldspathoids. Rocks from the other three buttes and Devils Tower fall very near the alkali trachyte-phonolite boundary or well within the phonolite range (Streckeisen 1979), and are called analcime phonolite to indicate their mode and feldspathoidal content.

Little chemical variation is noted throughout the lower unit of the Barlow Canyon laccolith. The only exception is BC105 which was collected just below the contact zone and shows an increase in K and a decrease in Na in relation to the average compositions of the lower unit, which is continued in the contact zone above. Definite chemical differences are noted between the upper and lower units. Na content decreases from about 8.5% to 1%, and K content increases from 5% to 7.5% between the two units. Percentage of Fe content is noticeably less in the upper unit.

Sample SEDX is a shale xenolith from the Stockade Beaver or lower Hulett Member, which was collected from the contact zone. Almost no chemical difference is seen between the analysis of the xenolith and the average analyses of the enclosing rock (appendix III). This implies that large quantities of Stockade Beaver shale were assimilated in a very fluid melt.

Devils Tower rocks are chemically very homogeneous, except for a slight upward decrease in Na content. This decrease is verified in point-count and is apparently related to the vertical decrease in analcime.

The only notable chemical variation among the Missouri Buttes rocks is the lower Na content in the trachytes from the southwest and west-central buttes. The phonolite buttes reflect the slight vertical decrease in Na noted in Devils Tower, and are chemically very comparable to the Tower rock. Perfect fractionation curves are drawn on a portion of a Ne-Ks-Q diagram (Figure 21). All of the curves shown begin in the 2-feldspar region and extend to the nepheline-feldspar field boundary (Hamilton and MacKenzie 1965). One curve appears as a straight line from "m," the minimum of the system Ab-Or-Q-H_2O at 100 MPa, to 'N' on the nepheline-feldspar field boundary. This line represents a thermal

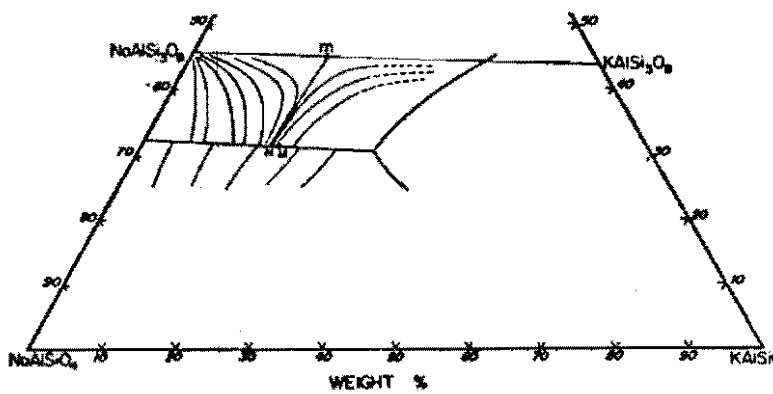


Fig. 21. Fractionation curves in part of the $NaAlSiO_4$-$KAlSiO_4$-SiO_2-H_2O system at P_{H_2O} = 1 kbar (100MPa) projected onto the anhydrous base. The line m-N is the unique fractionation curve or thermal valley.

m = 3-phase boundary

N = intersection of Ne-Kf field boundary and 3-phase boundary from m

M = minimum for the system Ab-Or-Ne-Ks

minimum on the liquidus surface. Any liquid whose composition falls on this line must remain there until it reaches the nepheline-feldspar field boundary. As seen in Figure 21, any liquid composition near the m-N curve will, under perfect fractionation, nearly parallel the thermal valley. This valley may also act as a thermal barrier that can prevent a fractionating liquid from crossing it. This means that a liquid rich in Na could not have been derived from a previous K-rich liquid (Hamilton and MacKenzie 1965).

In Figure 22, bulk compositions of the Devils Tower, Missouri Buttes, and Barlow Canyon rocks are plotted on a Ne-Ks-Q diagram. Most rock compositions fall either on the unique fractionation curve or on the Na-rich side of the curve. The few rock compositions that appear on the K-rich side of the curve may plot there because of modifications in the curve caused by other components in the natural melt. The plot shows the sodic character of the rocks and suggests that leucite was never a stable phase. The average compositions of rocks from all three igneous bodies follow almost exactly the trachyte-phonolite trend plotted by Hamilton and MacKenzie (1965).

Electron microprobe analyses of 13 pyroxenes have been plotted on a Na-Mg-Fe^{+2} + Mn diagram along with their trend, line 1 (Figure 23). Early Fe enrichment was followed by Na enrichment. The rocks appear similar to other alkaline suites with sodic differentiation trends.

Na enrichment is also observed from core to margin in the pyroxene phenocrysts and even more (a 3 percent increase) in the aegirine needles in the groundmass. Once again, a clear sodic differentiation trend is indicated.

Fig. 22. Plot of Devils Tower, Missouri Buttes, and Barlow Canyon bulk rock composition on a Ne-Ks-Q diagram. Plots of all rocks except those from the Barlow Canyon contact zone fall on or near the unique fractionation curve. Barlow Canyon contact zone bulk rock composition and xenolith of sedimentary rock are plotted for comparison.

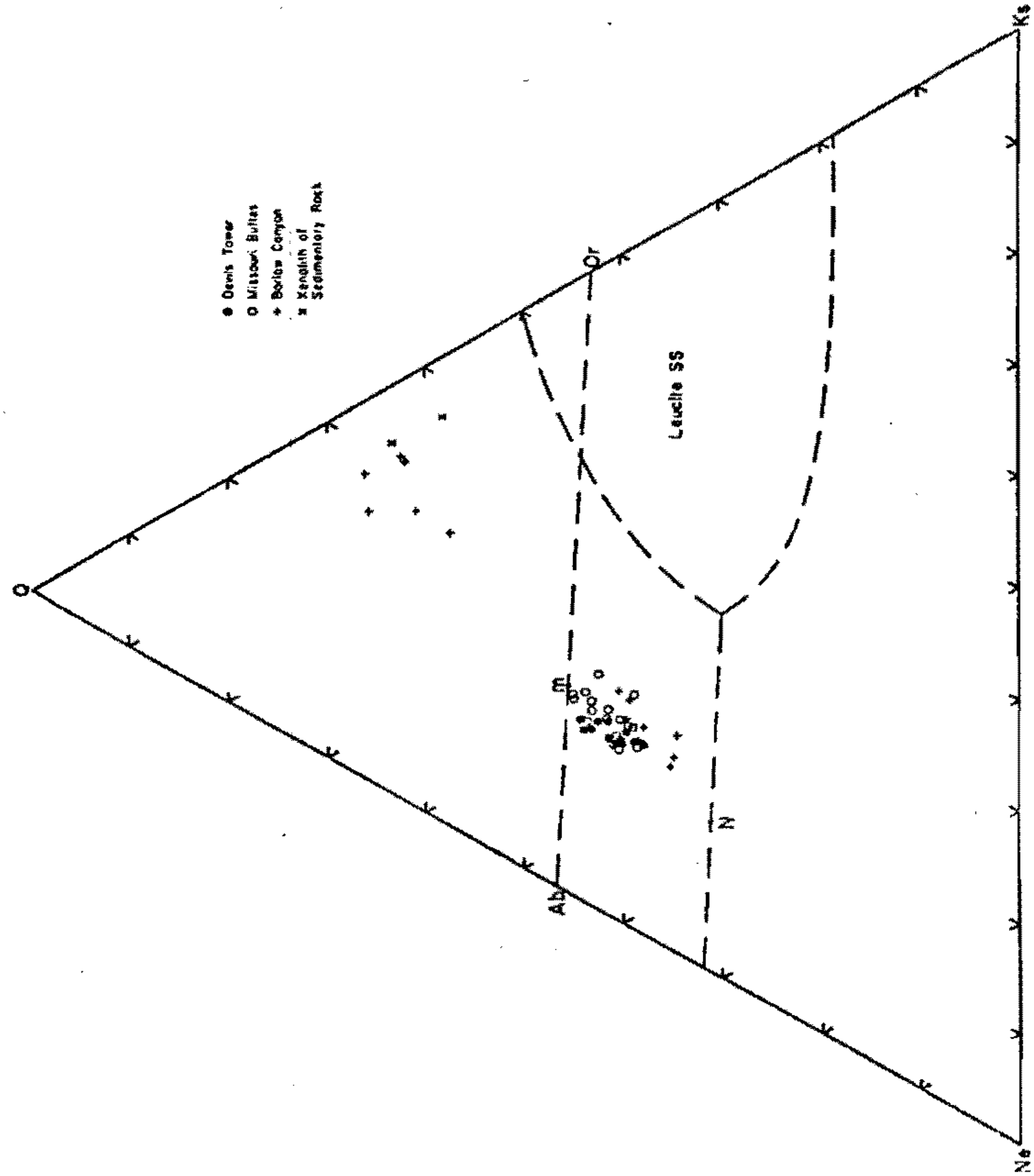

● Devils Tower
○ Missouri Buttes
+ Barlow Canyon
x Xenolith of Sedimentary Rock
Q
Or
Ks
Ab
Ne
N
Leucite SS

Fig. 23. Pyroxene composition trends diagram. (1) the Devils Tower, Missouri Buttes, and Barlow Canyon suite relative to pyroxene composition trends in other areas of alkaline rocks, plotted on a Na-Mg-Fe+Mn diagram.

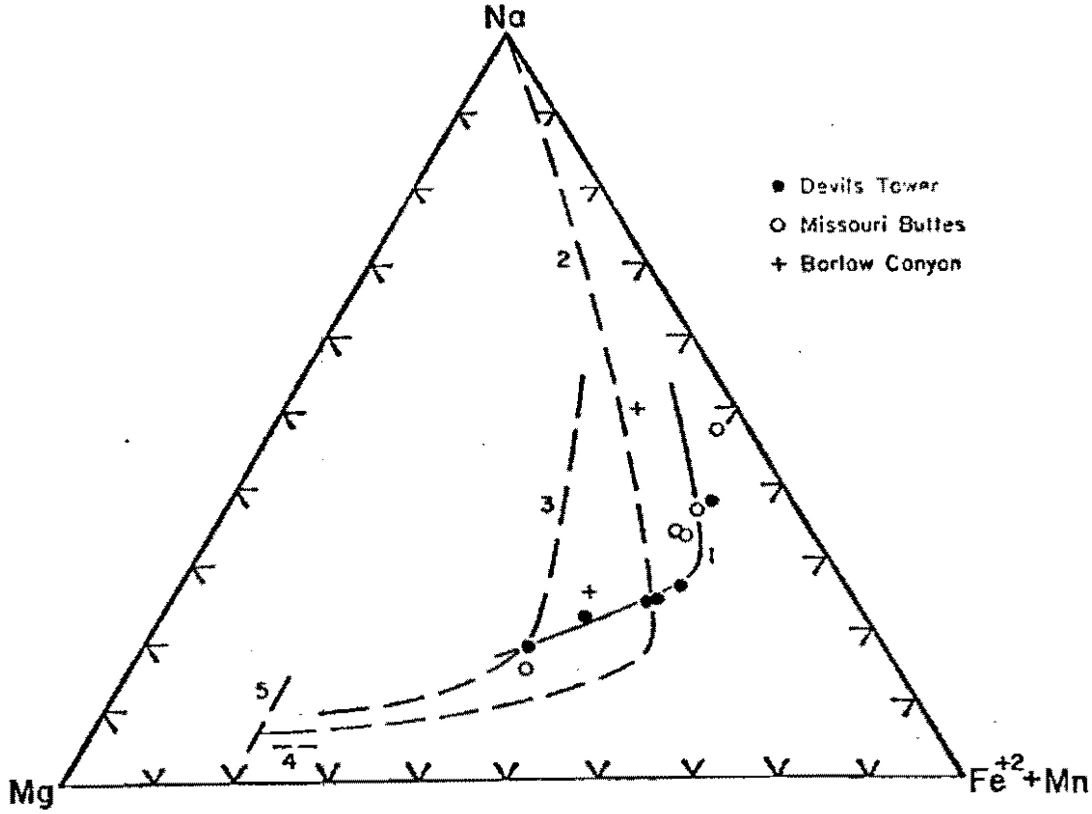
(2) South Qoroq Centre (Stephenson 1972)

(3) Crowsnest suite (Ferguson and Edgar 1978)

(4) Roman Province (Cundari 1975)

(5) Square Top Intrusion (Wilkinson 1966)

Curve 4 is from a province showing potassic differentiation.

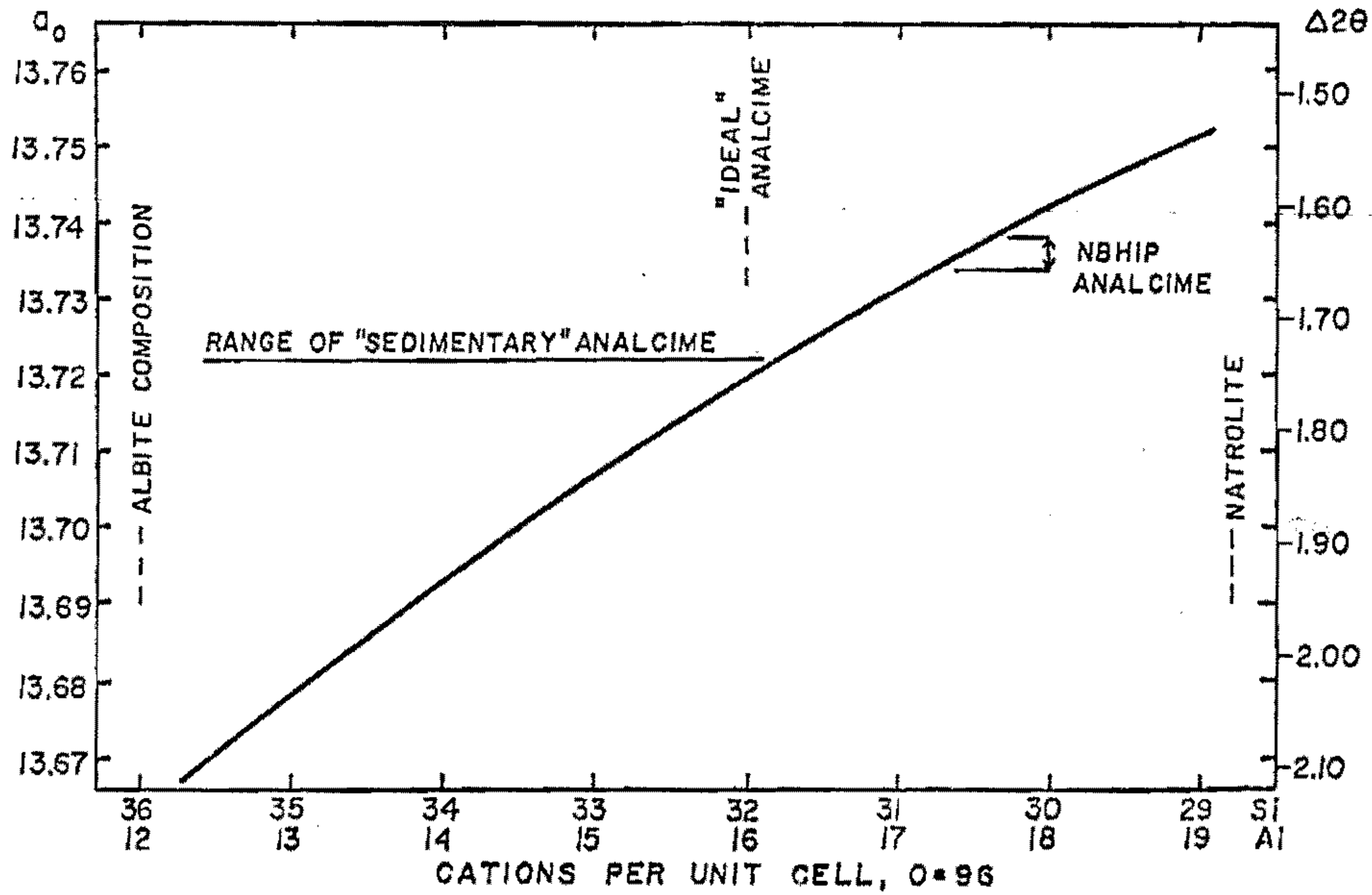

Na
Mg
Fe+2+Mn
● Devils Tower
o Missouri Buttes
+ Barlow Canyon
1
2
3
4
5

FORMATION OF ANALCIME

Cubic cell dimensions of analcime from the Missouri Buttes, Devils Tower, and Barlow Canyon were calculated from x-ray diffraction peaks, using the formula $a_o = d\sqrt{h^2 + k^2 + l^2}$, where a_o = length of the unit cell edge, d = the 'd' spacing, and hkl = the x-ray diffraction indices (Bloss 1971). Each peak, as well as the average a_o value for each analyzed sample was calculated. All peak positions were measured from Si_{111} = 28.44 2θ. Standard deviation ranged from 0.012 to 0.025, indicating that samples were within detectable limits. Analcime unit cell dimensions were determined to be: $a_o = 13.736 \pm .003Å$ (Halvorson and others 1977). Representative data is shown in appendix IV. Figure 24 shows the range in composition of the northern Black Hills igneous province analcimes.

Saha (1959, 1961) showed that the cell edge of analcime solid solution changes with chemical composition. Peters and others (1966) proposed a simple but sensitive method of evaluating the chemical composition by measuring the displacement of the $CuK_{\alpha 1}$ peak of the (639) reflection against the $CuK_{\alpha 1}$ peak of the (331) reflection of the silicon standard, $\Delta 2\theta = 2\theta_{anl(639)} - 2\theta_{Si(331)}$. Values calculated for the analcimes found throughout the study area average 2θ = 1.65. This is equivalent to a cell dimension of a_o = 13.735, as shown in Figure 24 (Coombs and Whetten 1967). In spite of the uncertainty contributed by low peak heights, this figure is almost exactly the same as the figure

Fig. 24. Plot of analcime unit cell dimensions. Relating a_o (analcime unit cell dimension) and $\Delta 2\theta - (2\theta_{anl(639)} - 2\theta_{Si(331)}$ to analcime composition (after Coombs and Whetten 1967). The range of the undersaturated analcimes of the northern Black Hills igneous province has been plotted to show their compositions.



a_0
13.76
13.75
13.74
13.73
13.72
13.71
13.70
13.69
13.68
13.67
Δ2θ
1.50
1.60
1.70
1.80
1.90
2.00
2.10
ALBITE COMPOSITION
"IDEAL" ANALCIME
NBHIP ANALCIME
RANGE OF "SEDIMENTARY" ANALCIME
NATROLITE
36 12
35 13
34 14
33 15
32 16
31 17
30 18
29 19
Si Al
CATIONS PER UNIT CELL, O=96

derived from unit cell dimension calculations. Peters and others (1966) determined that analcime with a $\Delta 2\theta$ equalling 1.65 has an approximate composition of $Ab_{53}Ne_{47}$. The calculated analcime composition implies more silica undersaturation and a higher degree of thermal stability (Roux and Hamilton, 1976) than most natural (stoichiometric) analcimes, which cluster around $Ab_{65}Ne_{35}$. High temperature synthetic analcimes are near $Ab_{50}Ne_{50}$.

The stoichiometric formula for ideal analcime is $NaAlSi_2O_6 \cdot H_2O$ or, based on 96 oxygen, $Na_{16}Al_{16}Si_{32}O_{96}$. Using Figure 24, the average composition of Devils Tower area analcimes (unit cell values a_o = 13.735 - 13.739) is $Na_{17.6}Al_{17.6}Si_{30.4}O_{96}$, which has a $SiO_2 : Na_2O$ ratio of 3.455. It is apparent from Figure 25 that a 2θ value of 1.65 corresponds to a $SiO_2 : Na_2O$ ratio of 3.5. The data, therefore, is consistent and indicates that the analcime examined is substantially undersaturated with respect to silica. All analcimes of authigenic or burial

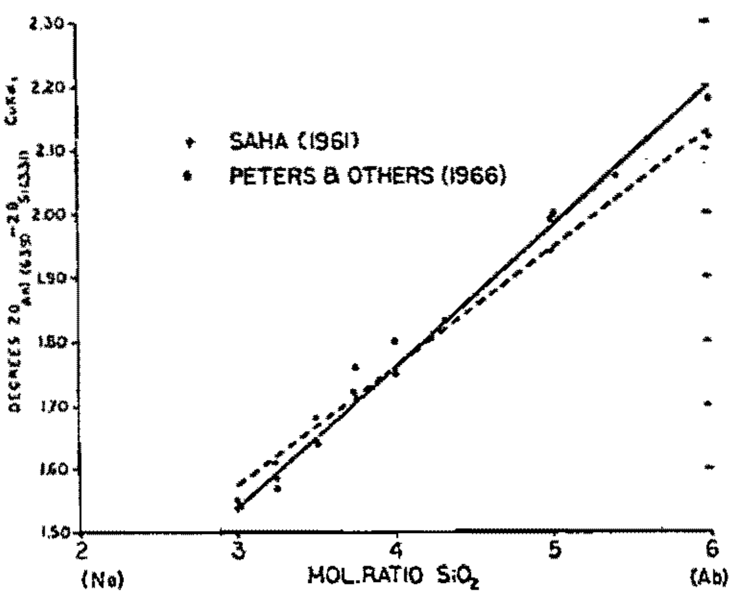


Fig. 25. Analcime determinative curve. Mol. ratio SiO_2 = molecular ratio $SiO_2:Na_2O$.

metamorphic origin have silica-rich compositions (Coombs and Whetten 1967). The silica-undersaturated analcimes from the Missouri Buttes, Devils Tower, and Barlow Canyon fall well within the range of documented primary igneous analcime (Ferguson and Edgar 1978).

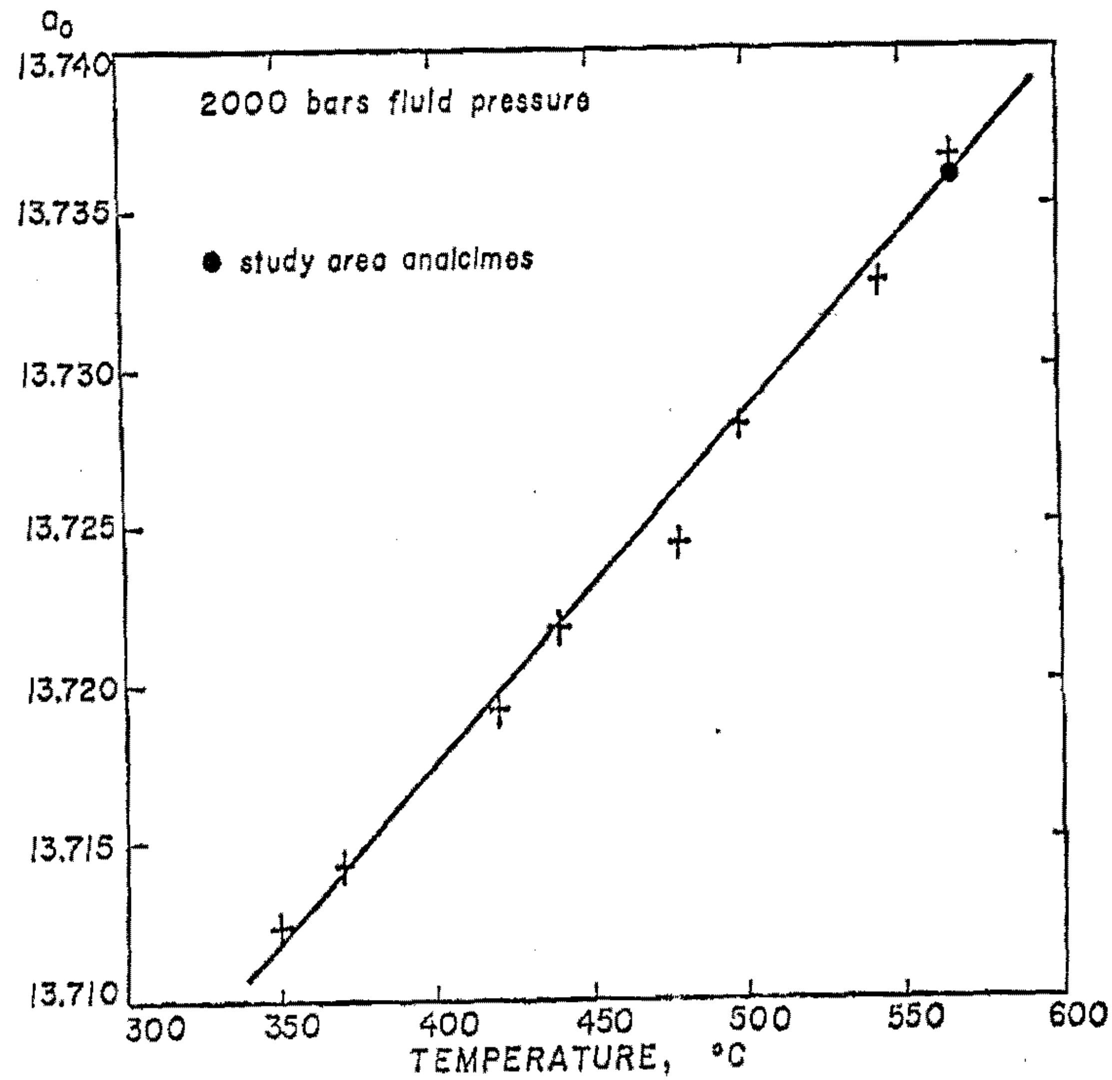
Liou (1971) experimentally investigated several analcime reactions and confirmed what had been predicted from field evidence, that the silica content of analcime decreases as temperature increases (Figure 26). The precise composition of analcime formed in any environment depends upon other factors, i.e., bulk rock chemistry, the nature of interstitial fluids, and mineral association, in addition to temperature. No attempt is made here to use the temperature to composition relationship as a geothermometer. The presence of analcime with unit cell dimensions of 13.736, however, supports the hypothesis that this analcime formed late in the crystallization sequence of a H_2O- and Na-rich, silica undersaturated magma, but at relatively high temperature.

Small euhedral phenocrysts of analcime have been identified in the Barlow Canyon rock, and tentatively in the Missouri Buttes rock. Additional probe work on Devils Tower phonolite may also reveal it there. The presence of euhedral analcime grains is consistent with the supposition that the mineral has crystallized from a liquid.

The perimeters of many analcime phenocrysts are relatively intact, even though some cores show considerable secondary alteration. This may indicate a degree of equilibrium with the liquid from which they crystallized.

The patterned inclusions within the phenocrysts present another area for future study. Analysis of their composition should give

Fig. 26. Temperature of crystallization diagram for analcimes of study area, based on unit cell dimensions (after Liou 1971).



a_0
13.740
13.735
13.730
13.725
13.720
13.715
13.710
2000 bars fluid pressure
● study area analcimes
300
350
400
450
500
550
600
TEMPERATURE, °C

valuable information about the coexisting phases at the time of crystallization.

An alternative method for the formation of the analcime phenocrysts is alteration from leucite (Gupta and Fyfe 1975). As already stated, all the rocks examined are sodic. On a Na-Mg-Fe+Mn diagram, the pyroxenes plot along a differentiation path similar to that of other sodic alkaline rocks. When bulk rock chemistry is plotted on a Ne-Ks-Q diagram, all the rocks except those from the alteration zone of Barlow Canyon plot along the thermal valley of the liquidus surface and will follow this line during fractionation. It is unlikely that the liquid was ever the right composition for the crystallization of leucite.

Because electron microprobe profiles have not been made across the analcime phenocrysts, it is not known whether chemical zoning with potassium is present. The K_2O weight percent, however, is very low, from 0.29 to 0.55%, considerably less than the maximum of 2 weight percent K_2O reported for igneous analcime from experimental studies (Roux and Hamilton 1976).

Analcime replacement of feldspar grains is apparently deuteric and not related to secondary alteration. It is late-stage replacement related to the consolidation of the igneous mass.

The origin of the groundmass analcime is more problematic. The analcime microphenocrysts in this rock cannot be physically separated from the groundmass analcime and therefore they appear together in x-ray diffraction patterns. Consequently, the groundmass may not be as silica undersaturated as diffraction patterns indicate. Until more precise data on the groundmass analcime is available, it is only possible to speculate on its origin.

One possible origin is from late-stage, hydrous, magmatically derived fluids under subsolvus conditions. There is evidence in the Missouri Buttes that late-stage magmatic fluids entered the cooling rocks. Near the top of the southeast butte, horizontal flow banding is distinct. In thin-section, these bands are seen to be alternating layers of gray phonolite and green, fine-grained material consisting of minute aegirine needles and analcime. The composition of this green material may be very similar to the bulk composition of the magmatic fluids. This flow-banded rock probably formed near the margin of the intrusion where the magma was partly congealed.

Throughout the vertical extent of the southeast butte, consistently high normative nepheline values are noted. The two northern phonolite buttes show a decrease in normative nepheline from 13.9% to 4.1% vertically upward; in Devils Tower the decrease is from 13.4% at the bottom to 2.9% at the top. Nepheline content appears to be directly related to the analcime content of the groundmass. Obviously, other feldspathoids contribute to this, but modal analysis shows that they are very evenly distributed throughout both the Missouri Buttes and Devils Tower. Comparison of analcime x-ray peak intensities to calculated normative nepheline values confirms the idea that analcime is a major contributor to the normative nepheline percentage. The two trachyte bodies in the Missouri Buttes do not display this vertical variation in nepheline content. They probably had already cooled sufficiently to prevent the entrance of magmatically derived fluids.

These observations strongly support the hypothesis that upward-moving, magmatically derived, hydrous fluids were the source of the groundmass analcime.

A hydrothermal origin for the groundmass analcime is a second possibility. This analcime is mostly interstitial and represents a late-stage mineral that crystallizes after emplacement. The rocks of the Devils Tower area were emplaced into a thick sequence of late Cretaceous marine sediments which could have provided a ready source of sodium-rich fluids. In a normal period of diagenesis, 10^5 to 10^7 years (Ferguson and Edgar 1978), the analcime could have formed from some pre-existing phase.

Finally, the groundmass analcime could be primary, as the x-ray diffraction patterns indicate, and crystallized directly from the liquid.

Several factors support this hypothesis. For example, rapid transport and cooling are indicated by the presence of volcanic breccias and the lack of extended subsolvus history. Also, final crystallization produced a very undersaturated analcime, near natrolite in composition. This type of analcime has a slightly extended stability range (Wilkinson 1965). Experimental calculations of the precipitation of analcime from a melt are based on a 3-component system. It is not known what effect additional components might have on this system. The possibility remains that the quenching of the sodium-rich melt could have produced analcime.

The difficulty with this theory is that the necessary pressure for an analcime-melt assemblage to exist is between 5 and 14 Kb (Roux and Hamilton 1976). With maximum possible cover for this area, the pressure would have been only about 0.3 Kb, far less than that required for the formation of primary analcime.

Without further data, origin of the analcime remains in question.

MODE OF EMPLACEMENT

Missouri Buttes

In the discussion of the geologic history of the area, it was noted that movement of igneous rock at depth had formed several domes prior to the emplacement of the Barlow Canyon laccolith, Devils Tower, and the Missouri Buttes. Fractures caused by this doming and by the Laramide basement-cored uplift provided access for magma to reach the surface. By the end of the Paleocene Epoch, pyroclastic eruptions had occurred just east of the Basin dome. These eruptions are speculative, but necessary to enlarge passageways without substantially disrupting the surrounding sediments. The presence of large quantities of allo-clastic breccia attest to the volatile content of the magmatic fluids.

The emplacement of the alkali trachytes of the southwest and west-central buttes followed these pyroclastic eruptions. Much of the pyroclastic material, and perhaps part of the southwest butte itself, has undoubtedly been removed by stream action along the southern and western boundaries. Field evidence already mentioned indicates that the plateau at the northeast edge of the butte may be underlain by pyroclastic breccia.

The west-central butte is much smaller than the other four buttes and probably represents a dike related to the main conduit below the southwest butte. This whole trachyte mass must have cooled substantially before the eruption of the other three buttes. The low analcime content of the groundmass indicates that the trachyte had sufficiently solidified to prevent the entrance of magmatically derived hydrous fluids.

With the original vent blocked, consequent eruptions occurred to the north and east. These eruptions apparently were quite similar to the first one, involving pyroclastic ejections and eventual emplacement of more fluid material similar in composition to the trachytes.

This emplacement was closely followed by the infiltration of magmatically derived hydrous fluids from below. This was apparently a very fluid and volatile phase. Evidence for this fluid phase is observed in the high analcime content throughout the extent of the southeast butte and in the flow-banded rocks at the top, which must have resulted from the mixing of fluids with layers of partly congealed material. In the northern buttes, the analcime content gradually decreases vertically upward, indicating that the fluids were less able to enter the cooler rocks at the top of the igneous masses. These fluids contributed sodium to the bulk chemistry of the trachyte and a higher aegirine and interstitial analcime content to the groundmass. Consequently, these rocks are classified as phonolite.

An alternative hypothesis is that all the buttes erupted at approximately the same time, but from at least two different levels of the same magma chamber. The phonolitic rocks would have derived from a higher level of the chamber where the fractionated trachyte melt was more volatile and Na-rich. The abundance of alloclastic breccias around the vents might support this hypothesis. The similarity of chemical compositions between the trachytes and phonolites however, is inconsistent with a fractionation model.

Devils Tower

The emplacement history of the Devils Tower is very similar to that of the Missouri Buttes in terms of pyroclastic eruptions through horizontal strata, magma emplacement, and activity of hydrous fluids. The Tower, in fact, might be considered a flank eruption of the Missouri Buttes. And because the chemistry of Tower and Buttes phonolites is so similar, the same arguments against major fractionization apply. They are essentially trachytic rocks which have undergone analcimization.

Cooling History

Both the Missouri Buttes and Devils Tower originally vented to the surface through several hundred meters of sediments. Most of the pyroclastic material was blown out through these vents; some remained as lining for the vent walls. Remnants of this wall lining still surround some of the present buttes and Devils Tower.

After emplacement of the more fluid phases of the eruption, cooling began from the surface downward and from the periphery inward. Peripheral cooling and shrinkage first caused the series of joints roughly parallel to the circumference of the igneous mass and the set of vertical radial cracks normal to the peripheral joint set. These joint sets are well-developed in the base of Devils Tower and are also observed in the northeast Missouri Butte.

Continued marginal cooling formed the horizontal columnar joints (Figure 4). The jointed columns almost immediately turned upward because temperature gradients from the surface were greater than horizontal temperature gradients. Rapid cooling probably also caused extensive block jointing at the surface. Much of the block-jointed material still overlies the columns in the Missouri Buttes, but has been removed by erosion from Devils Tower.

As cooling continued, columns developed downward from the surface and met the upward-curving columns simultaneously forming below. At these junctions, two or three columns often merged into one. On the southeast side of Devils Tower where erosion has exposed an interior section, the columns can be seen to extend vertically downward into the base; these columns were obviously uneffected by temperature gradient from the margin (Figure 5).

In studies of columnar jointing in Hawaiian lava flows, Ryan and Sammis (1978) found that striation distances and column width are both proportional to the size of the cooling body, suggesting a relationship to temperature gradients. Seismic evidence indicates that thermal fracture is a discreet event involving a sudden period of crack advance. The distance between striations represents the material involved in a particular fracturing event. These phenomena are observable in Devils Tower columns where both column width and distance between striations (the horizontal swells and ridges shown in Figure 4) increase downward. The size of the Devils Tower columns is directly related to the size of the igneous mass. Since the mass was insulated on the margin by sedimentary cover, perpheral cooling was slowed and the unusually large columns were allowed to form.

All the features described for Devils Tower are observable in various areas of the Missouri Buttes. A similar cooling history is therefore implied.

Laccoliths and Volcanic Necks

As stated earlier, the Barlow Canyon intrusion seems to be a small laccolithic structure. Some details of its mode of emplacement have already been mentioned.

The Missouri Buttes and Devils Tower, however, are necks of extinct volcanoes which have been exposed by erosion. This theory was first proposed by Carpenter (1888) and later expanded by Dutton and Schwartz (1936). The material which fed these volcanoes came from a minimum depth of 18 km. Evidence for this conclusion is listed in the following statements:

1. The alloclastic breccia in the vicinity of Devils Tower and the Missouri Buttes is definitely igneous in origin and probably represents periods of violent eruption.

2. A very definite similarity exists between these two features and the volcanic necks in the Taylor Mountain area of New Mexico.

3. The distinctive columns with basal flare are also found in the volcanic necks of the Taylor Mountains (Dutton and Schwartz 1936), but have not been reported in columnar-jointed laccoliths.

4. The Missouri Buttes and Devils Tower were intruded directly through horizontal sediments without disrupting them, even in the immediate vicinity of the igneous bodies.

5. Recent research indicates that many of the laccolithic intrusions in the Black Hills region may have been less passive than previously considered. Sundance Mountain may be a mixed volcanic cone consisting of welded ash fall, massive quartz latite, and ash flow tuffs. Nearby Sugarloaf Mountain is composed of layered tuffs (Fashbaugh 1979).

6. Collapse of materials into partly evacuated reservoir chambers accounts for the depressions surrounding the Missouri Buttes and Devils Tower. The 90 m of depression at the southern end of the Buttes is difficult to explain with a laccolithic model.

7. Flow directions deduced from oriented thin-sections and field observations indicate mostly vertical flow. It must be noted that in both igneous bodies orientation of some grains is horizontal; this could, however, simply indicate turbulent flow.

8. The stability field for the analcime-liquid system is 5 kbar minimum (Roux and Hamilton 1976), which indicates that the original melt of Devils Tower and Missouri Buttes rock had to originate at a minimum depth of 18 km.

9. It is unlikely that magma which had ascended from great depths and had just penetrated the resistant Hulett Member of the Sundance Formation, as well as the Lakota and Fall River Formations, would be stopped abruptly by the less resistant shales above. When the magma reached the shale beds, the weight of the column of igneous rock could have exceeded the strength of the shale, causing the magma to flow horizontally. No indication of horizontal spread, however, is observed. The continuously cylindrical shape of the intrusions indicates that the magma moved steadily upward and probably reached the surface.

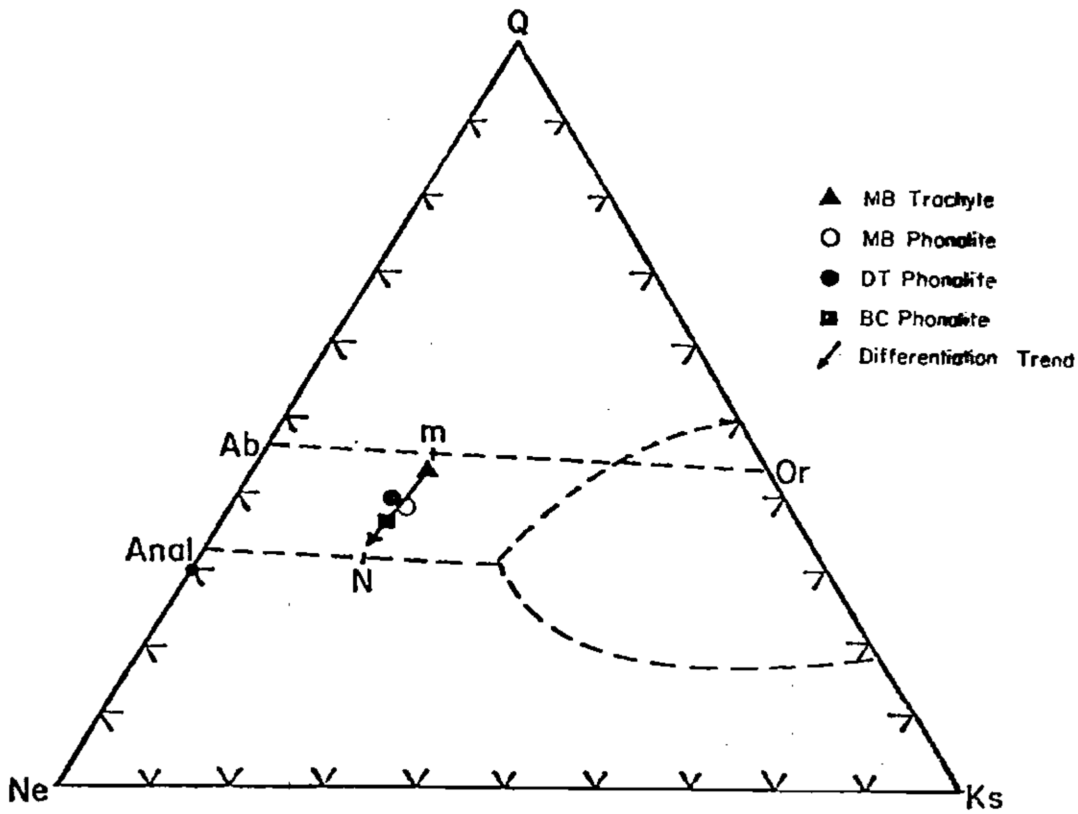
10. Carbonatites have been found, although not formally reported, in the nearby Bear Lodge Mountains, and also as fragments in the alloclastic breccias of the Missouri Buttes. Their presence suggests a high volatile content for the magma and the possibility of explosive volcanism.

PETROGENETIC MODEL AND SUMMARY

Bulk rock chemistry and pyroxene analyses indicate that the Devils Tower, Missouri Buttes, and Barlow Canyon rocks differentiated from a sodic trachytic magma. The differentiation trend is illustrated by a bulk rock chemical series from the Missouri Buttes trachytes to the analcime phonolites from Devils Tower and the Missouri Buttes, to the Barlow Canyon analcime phonolite (Figure 27). The close alignment of the chemical series to a perfect fractionation curve, line m-N (Figure 27), strongly indicates that differentiation by fractional crystallization of a trachytic liquid is peralkaline rhyolite, but an alternative product is phonolite with a molecular excess of Na_2O and Al_2O_3 (Hamilton and MacKenzie 1965). The presence of acmite in many of the rocks (appendix III) confirms this molecular excess of Na_2O and Al_2O_3.

Differentiation of the Devils Tower, Missouri Buttes, Barlow Canyon phonolites probably occurred by the mechanism of fractional crystallization of a trachytic melt. With the early crystallization of potassic sanidine, the K/Na ratio of the residual liquid decreased. Later, the crystallization of analcime caused the removal of Na from the residual liquid because of analcime's restricted composition, and the K/Na ratio increased again. This change in K/Na ratio is clearly demonstrated in the zonation of sanidine phenocrysts. The effect of the early crystallization of pyroxene on the original melt is not clearly known, so its role will not be considered in the following discussion.

Fig. 27. Proposed differentiation trend of Devils Tower, Missouri Buttes, and Barlow Canyon Suite. The average bulk rock composition of each igneous rock unit is plotted on a Ne-Ks-Q diagram. 'N' and 'm' mark the end points of the the thermal valley. The trend exactly follows the thermal valley and is characteristic of a typical trachyte-phonolite trend (Hamilton and MacKenzie 1965). Average compositions were calculated from data given in appendix III


Q
Ab
m
Or
Anal
N
Ne
Ks
MB Trachyte
MB Phonolite
DT Phonolite
BC Phonolite
Differentiation Trend

Crystal fractionation may have resulted from gravity settling and the tapping of magma from the crystal accumulation zone. This method was proposed by Ferguson and Edgar (1978) for differentiation of similar rocks from the Crowsnest Suite. The difficulty with this hypothesis is that s specific gravity difference of only 0.1 (Ferguson and Edgar 1978) exists between sanidine phenocrysts and groundmass. It is unlikely that significant gravity settling could result from such a small difference. An alternative mechanism is flowage differentiation in which suspended particles migrate toward the high velocity region, probably where magma is moving toward the surface.

A trachytic crystal mush consisting of sanidine, pyroxene, analcime, and liquid separate from the phonolitic residual melt, possibly by flowage differentiation, moved toward the surface, and was emplaced at the present site of the southwest and west central Missouri Buttes.

The phonolites of the Missouri Buttes appear to represent a natural liquid line of descent, as shown in Figure 27, having crystallized directly from the Na-rich residual melt. Bulk chemical analyses tend to support this model. Chemically, the trachytes and phonolites are very similar; the major difference is the decrease in the K/Na ratio observed in the phonolites.

An alternative model is that all five of the Missouri Buttes were originally trachyte. The southwest and west central buttes were emplaced first and had completely crystallized before the others were emplaced. When the three more recent buttes were partially crystallized from the surface downward, magmatically derived Na-rich hydrous fluids were introduced from below. These fluids crystallized as groundmass analcime and aegirine. This model would explain the unusually high SiO_2 content of the phonolites, near 62%, a percentage more typical of trachyte. The upward decrease in normative nepheline, previously shown to be related to analcime content, would also be consistent with this model.

The Devils Tower phonolite displays the same high SiO_2 content and the upward decrease in groundmass analcime observed in the Missouri Buttes. This implies that it also was originally trachyte. In this paper, the Devils Tower rock is termed phonolite because of the high percentage of groundmass analcime.

The phase assemblage K-feldspar-nepheline-analcime characterizes the rocks of the Missouri Buttes. Plagioclase is not present, although small amounts of albite were detected by x-ray diffraction. The albite was probably formed by exsolution during cooling; it occurs along the margins and fractures of the sanidine phenocrysts.

The pressure at which the phenocrysts crystallized within the magma chamber can be estimated. Figure 28 is a sequence of liquidus diagrams that shows the stability field of analcime and the mineral assemblages that can coexist at four different P_{H_2O} conditions (Roux and Hamilton 1976). A K-feldspar-nepheline-analcime-melt assemblage is stable at pressures greater than 8 kb (800 MPa) (Figure 28c and d), which is equivalent to a confining pressure produced by an overburden about 28 km thick. This establishes a minimum depth of 28 km for the crystallization of the phenocrysts of Missouri Buttes rocks.

The phase assemblage for the Devils Tower phonolites is K-feldspar-albite-nepheline-analcime(?). Analcime microphenocrysts have not been positively identified by microprobe analysis, but are

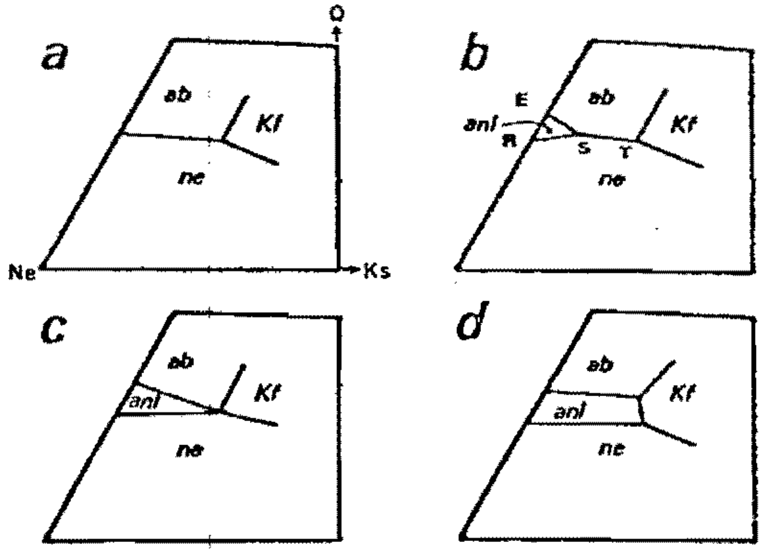


Fig. 28. Isobaric, Polythermal Liquidus Diagrams. Diagrams for part of the residua system for a Ne-Ks-Q diagram T = ternary eutectic; ERS = analcime liquid field (Roux and Hamilton 1976).

a) P_{H_2O} less than 5 kbar
b) P_{H_2O} between 5 kbar and 8 kbar at 610°C.
c) P_{H_2O} 8 kbar
d) P_{H_2O} greater than 8 kbar at 610°C.

seen in thin-section. Assuming the presence of analcime, the melt assemblage of these minerals would be stable at P_{H_2O} greater than 500 MPa but less than 800 MPa, at which point the analcime field breaks the tie line between nepheline and albite (Figure 28c). If the Missouri Buttes magma began to crystallize at a P_{H_2O} greater than 800 MPa, and the Devils Tower magma at P_{H_2O} greater than 500 MPa, crystallization in different magma chambers, separated vertically by about 10 km, would be indicated.

The presence of alloclastic breccias around both the Missouri Buttes and Devils Tower, and the proximity of extrusive volcanism and carbonatites indicate that the magma may have had a high volatile content. In this case, P_{H_2O} could have been greater than $P_{lithostatic}$.

With the removal of liquid to form the Missouri Buttes, P_{H_2O} could have decreased enough to draw the analcime field away from the ternary eutectic point, t (Figure 28), and to allow the mineral assemblage found in the Devils Tower phonolites to crystallize cotectically from the liquid.

The striking similarity in bulk rock composition between the Missouri Buttes and Devils Tower rocks implies that they differentiated from the same magma. Hill and others (1975) arrived at the same conclusion on the basis of fission track dating. Present data does not distinguish whether the Missouri Buttes and Devils Tower rocks crystallized in the same magma chamber through a reduction in P_{H_2O}, or whether the Devils Tower rocks were formed in an auxiliary magma chamber nearer the surface.

Several factors indicate that the Barlow Canyon phonolite was differentiated from the same magma that produced the Devils Tower and Missouri Buttes phonolites by the mechanism of flotation. First, the Barlow Canyon rocks are composed primarily of finely trachytic groundmass with a few scattered phenocrysts closely resembling those in the other two igneous bodies; second, the presence of many partly corroded analcime phenocrysts indicates disequilibrium with the melt; third, the analcime phenocrysts are grouped together with no intervening groundmass, suggesting flotation; and finally, the absence of nepheline in the Barlow Canyon rock indicated that crystallization of K-feldspar and analcime had kept the remaining residual liquid from reaching the feldspar-nepheline cotectic (Ferguson and Edgar 1978). Since the specific gravity of analcime is approximately 2.25 and that of the phonolite groundmass about 2.5 (Ferguson and Edgar 1978), flotation is a feasible mechanism.

The Barlow Canyon mineral assemblage is characterized by sanidine and analcime. No nepheline or albite has been identified. A melt assemblage of this composition is stable only at pressures greater than 800 MPa. Barlow Canyon phonolites probably differentiated from the same magma as the Missouri Buttes and Devils Tower, by flotation and removal of the very fluid phase at the top of the magma chamber.

Studies of the stability field of analcime crystallizing in the presence of a liquid (Peters and others 1966; Roux and Hamilton 1976) indicate a pressure of formation for the analcime phonolites from Barlow Canyon and the Missouri Buttes greater than 8 kbar (or 28 km) and a temperature of about 600°C, and for the Devils Tower a pressure greater than 5 kbar (or 18 km) and a temperature between 610°C (Figure 27). At a depth of 12 to 14 kbar, the jadeite + vapor $\rightleftharpoons$ analcime transformation occurs (Roux and Hamilton 1976). The lack of jadeite components fixes the maximum depth at 43 to 50 km.

All of the rocks examined are intratelluric and, in the Missouri Buttes and Devils Tower, have been rapidly brought to the surface by H_2O and CO_2 pressure. The present outcrops are plugs, the erosional remnants of volcanic and pyroclastic materials filling conduits which once reached the surface. In Barlow Canyon, magma was trapped below the Hulett Member of the Sundance Formation enroute to the surface, and bulged up the overlying beds to form a small laccolith.

The relationship of the trachyte to the parental magma is speculative. Carmichael and others (1974) have attributed trachyte origin to the partial differentiation of alkali olivine basalt, Wright (1969) to melting of the upper mantle, and Bailey (1974) to the melting of deep crust. The northern Black Hills are essentially devoid of basic igneous rocks that might offer a clue to the parental magma.

A maximum depth of formation for the Devils Tower, Missouri Buttes, Barlow Canyon suite is about 43 km. This is at or near the base of the Laramide foreland crust which has an average thickness of 45 to 50 km (Gilluly 1963). The data available at this time implies the melting of lower crustal material and the rise of magma along fractures related to the monocline 10 km to the west. This monocline may mark the western boundary of a large basement-cored block that was uplifted during the Laramide orogeny.

APPENDICES

APPENDIX I

IGNEOUS ROCK DESCRIPTIONS

TABLE 11

IGNEOUS ROCK DESCRIPTION - DEVILS TOWER PHONOLITE

Sample No.	Rock Type	Color	Texture	Phenocrysts	Groundmass
T11-T40 T100-T128	analcime phonolite	gray to olive gray	holocrystalline aphanitic trachytic coarsely por- phyritic	anorthoclase aegirine- augite nepheline analcime nosean	albite microcline aegirine analcime calcite zeolite hematite clay

NOTE: Sample locations shown on Plate 2.

TABLE 12

IGNEOUS ROCK DESCRIPTION - DEVILS TOWER ALLOCLASTIC BRECCIA

Sample No.	Rock Type	Matrix Color	Texture	Matrix	Clasts
T129	alloclastic breccia	yellow brown, and red	scoriaceous banded	decomposed devitrified glass(?)	sandstone limestone shale granite schist phonolite pumice scoria

NOTE: Sample locations shown on Plate 2.

TABLE 13

IGNEOUS ROCK DESCRIPTION - MISSOURI BUTTES TRACHYTE

Sample No.	Rock Type	Color	Texture	Phenocrysts	Groundmass
MB138-MB155	foid-bearing alkali trachyte	light gray	holocrystalline seriate porphyritic trachytic glomeroporphyritic aphanitic	sanidine aegirine-augite anorthoclase sphene nepheline nosean	sanidine analcime aegirine calcite hematite zeolite
MB156-MB165	foid-bearing alkali trachyte	light gray	holocrystalline porphyritic trachytic aphanitic	sanidine aegirine-augite anorthoclase sphene nepheline nosean	sanidine analcime aegirine zeolite clay

NOTE: Samples MB138-MB155 are from the southwest butte.
Samples MB156-MB165 are from the west central butte.
All sample locations are shown on Plate 3.

TABLE 14

IGNEOUS ROCK DESCRIPTION - MISSOURI BUTTES PHONOLITE

Sample No.	Rock Type	Color	Texture	Phenocrysts	Groundmass
MB190-MB212	analcime phonolite	olive gray	holocrystalline trachytic aphanitic coarsely porphyritic	sanidine aegirine-augite anorthoclase nepheline analcime nosean	sanidine aegirine analcime calcite zeolite
MB100-MB102, MB166-MB189	analcime phonolite	olive gray	holocrystalline trachytic porphyritic aphanitic	sanidine aegirine-augite nepheline analcime	sanidine aegirine analcime zeolite clay
MB104-MB105, MB122-MB139, MB237-MB242	analcime phonolite	olive gray	holocrystalline trachytic porphyritic aphanitic	sanidine anorthoclase aegirine-augite nepheline analcime nosean	sanidine aegirine analcime zeolite magnetite hematite

NOTE: Samples MB190-MB212 are from the southeast butte.
Samples MB100-MB102 are from talus of the northeast butte.
Samples MB166-MB189 are from the northeast butte.
Samples MB104 and MB105 are from talus of the northwest butte.
Samples MB122-MB139, MB237-MB242 are from the northwest butte.
All sample locations are shown on Plate 3.

TABLE 15

IGNEOUS ROCK DESCRIPTION - MISSOURI BUTTES ALLOCLASTIC BRECCIA

Sample No.	Rock Type	Matrix Color	Texture	Matrix	Clasts
MB106-MB121, MB213-MB222, MB223-MB236, MB243-MB257, MB258-MB271, MB272-MB278	alloclastic breccia	yellow, brown, and red	scoriaceous vesicular some massive	partly devitrified glass crystal fragments of: quartz K-feldspar biotite hornblende microcline aegirine-augite oligoclase	limestone sandstone shale granite quartz monzonite schist phonolite carbonatite

NOTE: Samples MB106-MB121 and MB272-MB278 are from the saddle between the northeast and northwest buttes.
Samples MB213-MB222 and MB223-MB236 are from two outcrops 0.5 km east of the northwest butte.
Samples MB243-MB257 are from the southern flank of the northwest butte.
Samples MB258-MB271 are from the northern flank of the buttes' central plateau.
All sample locations are shown on Plate 3.

TABLE 16

IGNEOUS ROCK DESCRIPTION - BARLOW CANYON ALTERED ZONE

Sample No.	Rock Type	Color	Texture	Phenocrysts	Groundmass	Zenoliths
BC106, BC113-BC116, BC118, BC136-BC139, BC143-BC146, BC160-BC171	alteration zone	white to light brown	turbulent	sanidine anorthoclase aegirine-augite feldspathoids(?)	sanidine chlorite smectite kaolinite	shale sandstone

NOTE: Sample locations shown on Plate 4.

TABLE 17

IGNEOUS ROCK DESCRIPTION - BARLOW CANYON LOWER UNIT

Sample No.	Rock Type	Color	Texture	Phenocrysts	Groundmass
BC100-BC105, BC107-BC112, BC117, BC119-BC135, BC140-BC142	analcime phonolite	dull brown to dark olive gray	holocrystalline aphanitic trachytic slightly porphyritic glomeroporphyritic	sanidine anorthoclase aegirine-augite analcime nosean	analcime sanidine aegirine calcite hematite limonite

NOTE: Sample locations shown on Plate 4.

APPENDIX II

SEDIMENTARY ROCK DESCRIPTIONS

TABLE 18

SEDIMENTARY ROCK DESCRIPTIONS

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S2	Gypsum Spring	gypsum	N-9 white	crystalline	massive
S3	Gypsum Spring	gypsum	N-9 white	crystalline	nonresistant
S4	Gypsum Spring	claystone	2.5YR 4/3 dull reddish brown	silt/clay	nonresistant mottled with gray
S5	Sundance Jssb	shale	2.5Y 6/2 grayish red	very fine/ fine	angular fragments noncalcareous
S6	Sundance Jssb	sandstone	5Y 7/2 light gray	fine	resistant calcareous
S7	Sundance Jssb	shale	5GY 6/1 olive gray	very fine/ fine	nonresistant slightly calcareous
S8	Sundance Jssb	sandstone	2.5Y 7/3 light yellow	very fine	resistant calcareous
S9	Spearfish	siltstone	2.5YR 5/6	silt/clay	resistant $CaSO_4$ coating
S10	Spearfish	sandstone	2.5Y 7/2 grayish yellow	very fine	resistant noncalcareous
S11	Spearfish	siltstone	5YR 6/6 orange	silt/clay	nonresistant noncalcareous

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S12	Sundance Jsl	sandstone	7.5YR 7/4 dull orange	very fine	nonresistant calcareous
S13	Sundance Jsl	siltstone	7.5YR 6/4 dull orange	silt/clay	nonresistant calcareous
S14	Sundance Jsl	sandstone	2.5Y 8/4 pale yellow	fine	resistant calcareous
S15	Sundance Jsr	shale	5Y 7/2 light gray	silt/clay	calcareous
S16	Sundance Jsr	limestone	5Y 7/2 light gray	fine	slabby, very fossiliferous
S17	Lakota	sandstone	10YR 7/4 dull yellow orange	fine	cross bedded iron stained
S18	Sundance Jsr	sandstone	10YR 7/3 dull yellow orange	medium	glauconitic slightly calcareous
S19	Sundance Jsr	sandstone	2.5Y 7/2 grayish yellow	medium	calcareous veins of calcite
S20	Morrison	sandstone	10YR 8/1 light gray	very fine	nonresistant noncalcareous
S21	Lakota	sandstone	10YR 8/2 light gray	fine	noncalcareous

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S22	Lakota	claystone	7.5YR 7/2 light brownish gray	silt/clay	highly altered iron concretions
S23	Lakota	claystone	5YR 6/6 orange	silt/clay	highly altered iron concretions
S24	Fall River	sandstone	10YR 6/6 bright yellowish brown	very fine	noncalcareous iron concretions
S25	Fall River	sandstone	10YR 8/3 light yellow orange	fine	noncalcareous iron concretions
S26	Fall River	shale	5Y 8/1 light gray	fine	noncalcareous
S27	Fall River	sandstone	10YR 8/3 light yellow orange	fine/med.	spherical siderite inclusions
S28	Morrison	sandstone	7.5Y 8/2 light gray	fine	noncalcareous
S29	Sundance Jsr	sandstone	5Y 7/1 light gray	fine	resistant calcareous
S31	Sundance Jsh	sandstone	10YR 7/3 dull yellow orange	fine	ripple marked iron inclusions
S37	Sundance Jsr	sandstone	10YR 7/3 dull yellow orange	fine/med.	resistant calcareous

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S38	Morrison	limestone	2.5Y 7/2 grayish yellow	fine	sandy
S39	Morrison	shale	5Y 6/1 gray	very fine/ fine	poorly cemented
S40	Morrison	sandstone	5Y 7/1 light gray	fine	lenticular very calcareous
S41	Morrison	claystone	2.5YR 5/2 grayish red	silt/clay	nonresistant calcareous
S42	Sundance Jsl	shale	10YR 7/6 bright yellowish brown	fine	many small iron concretions
S43	Sundance Jsh	sandstone	10YR 7/4 dull yellow orange	fine	calcareous
S44	Lakota	conglomeratic sandstone	7.5YR 5/6 bright brown	fine to coarse	silica cement granules and pebbles
S45	Lakota	quartzite	7.5YR 6/1 brownish gray	fine	very resistant
S46	Lakota	sandstone	7.5YR 5/6 bright brown	medium to 3 mm	sorted
S48	Sundance Jsh	sandstone	2.5Y 8/4	fine	massive slightly calcareous

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S49	Spearfish	siltstone	2.5YR 5/6 bright brown	silt/clay	nonresistant
S50	Sundance Jscs	sandstone	5YR 6/4 dull orange	very fine/ fine	light yellow orange layers
S51	Sundance Jscs	sandstone	10YR 8/2 light gray	fine	resistant calcareous
S52	Sundance Jsr	sandstone	5Y 7/2 light gray	fine	very resistant calcareous
S55	Lakota	sandstone	2.5Y 7/3 light yellow	fine	spherulitic calcite segregations
S56	Lakota	sandstone	2.5Y 8/2 light gray	fine	calcareous
S57	Lakota	sandstone	10YR 6/1 brownish gray	fine	light gray layers
S58	Lakota	sandstone	7.5YR 6/6 orange	fine/med.	spherical calcite cemented concretions
S59	Fall River	carbonaceous sandstone	10YR 7/2 dull yellow orange	fine	interbedded coals carnotite
S60	Fall River	sandstone	10YR 8/1 light gray	very fine	carnotite

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S61	Fall River	sandstone	2.5Y 7/2 grayish yellow	fine	flat, polygonal joints at top
S62	Fall River	sandstone	10YR 8/1 light gray	fine	carnotite
S63	Fall River	sandstone	2.5Y 7/2 grayish yellow	fine/med.	siltstone nodules and streaks
S64	Fall River	sandstone	2.5Y 8/2 light gray	medium	iron segregations friable
S65	Fall River	sandstone	10YR 6/1 brownish gray	medium	local cross laminations
S66	Fall River	clayey sand-stone	10YR 7/1 light gray	fine	carbonaceous
S67	Fall River	sandstone	10YR 7/4 dull yellow orange	fine	worm borings, concre-tions, red iron layers
S69	White River	sandstone	2.5Y 7/2 grayish yellow	medium/ coarse	quartz, feldspar, mica, & clay p llets
S70	White River (?)	sandstone & conglomerate	5Y 7/2 light gray	coarse/very coarse	pellets & fragments terrace deposit(?)
S71	White River	sandstone & conglomerate	5Y 7/1 light gray	coarse/very coarse	mostly quartz, igneous fragments

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S72	Skull Creek	shale	10YR 4/1 brownish gray	fine	nonresistant poorly exposed
S73	White River	sandstone	10YR 6/2 grayish yellow brown	med./ coarse	quartz & feldspar fragments
S75	Newcastle	sandstone	10YR 8/1 light gray	fine	streaked with multi-colored iron stains
S76	Morrison	sandstone	5Y 8/1 light gray	very fine	irregularly bedded ripple marked
S78	Skull Creek	shale	10YR 4/1 brownish gray	fine	nonresistant poorly exposed
S79	Mowry	shale	10YR 6/1 brownish gray	fine	fish scales good exposure
S80	Newcastle	chert	2.5Y 7/3 light yellow	crystalline	resistant nodules
S81	Newcastle	sandstone	2.5Y 8/2 light gray	fine	moderately resistant
S82	Sundance Jsh	sandstone	10YR 7/3 dull yellow orange	fine	contact between Jsh and phonolite

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S83	Sundance Jsh	sandstone	2.5Y 8/3 pale yellow	fine	contact of Jsh and altered phonolite zone
S84	Sundance Jsh	sandstone	10YR 7/3 dull yellow orange	fine	contact of Jsh and altered phonolite zone
S85	Sundance Jsh	sandstone	2.5Y 7/3 grayish yellow	fine	calcareous, massive, 10cm above contact
S86	Sundance Jsh	sandstone	10YR 7/8 yellow orange	fine	20cm above contact
S87	Sundance Jsh	sandstone	10YR 6/3 dull yellow orange	fine	contact between Jsh and phonolite
S88	Sundance Jsh	sandstone	N3/0 black	fine	iron stained
S89	Redwater Jsr	sandstone	10R 3/4 dull red	fine/med.	ferrugenous, calcareous
S90	Redwater Jsr	quartzite	2.5Y 7/2 grayish yellow	med.	metamorphosed ss
S91	Redwater Jsr	sandstone	10YR 8/3 light yellow orange	fine/med.	calcareous, slabby

TABLE 18--Continued

Sample No.	Formation	Rock Type	Color	Grain Size	Remarks
S92	Redwater Jsr	sandstone	2.5Y 8/8 pale yellow	fine/med.	calcareous, thin bedded
S93	Redwater Jsr	sandstone	2.5YR 7/3 pale reddish orange	fine/med.	calcareous, slabby
S94	Sundance Jsh	sandstone	7.5YR 6/3 dull brown	very fine	thin lens
S95	Sundance Jsh	sandstone	7.5YR 5/4 dull brown	med.	altered, clays present
S96	Sundance Jsh	sandstone	10YR 8/3 dull yellow orange	med.	massive
S97	Sundance Jsh	conglomerate	5YR 6/6 orange	coarse/ very coarse	nonresistant

APPENDIX III

X-RAY FLUORESCENCE AND MICROPROBE CHEMICAL AND NORMATIVE ANALYSES

TABLE 19

CHEMICAL COMPOSITION AND NORMATIVE MINERALOGY OF DEVILS TOWER PHONOLITE

Sample No.	T114*	T115*	T114	T103	T32	T110	T26	T31	T16	T113	T100	T115	T40	T40G
SiO_2	61.58	62.42	61.72	61.86	62.58	62.06	62.31	61.85	62.23	62.20	61.00	60.37	61.70	60.04
Al_2O_3	19.43	18.79	19.02	19.16	19.30	19.04	19.89	19.76	19.49	19.16	19.38	19.16	19.30	19.08
Fe_2O_3	1.73	1.73	2.04	1.91	2.06	1.92	1.94	1.96	1.92	2.01	1.82	1.94	1.92	2.08
FeO	1.25	1.23	1.09	1.34	1.10	1.17	1.64	1.56	1.13	1.21	1.36	2.10	0.95	1.72
MgO	0.22	0.30	0.22	0.28	0.34	0.31	0.26	0.28	0.66	0.24	0.22	0.51	0.26	0.76
CaO	1.41	1.54	1.40	1.12	1.12	1.24	0.92	1.20	1.72	1.00	1.22	1.34	1.36	1.62
Na_2O	8.61	8.16	8.88	8.68	7.88	8.64	7.64	7.82	7.74	8.54	9.10	8.67	8.73	8.12
K_2O	5.14	5.18	4.71	4.86	4.58	4.79	4.76	4.96	4.58	4.86	4.96	4.92	4.90	5.16
TiO_2	0.23	0.23	0.54	0.41	0.56	0.42	0.44	0.46	0.42	0.51	0.32	0.44	0.42	0.58
P_2O_5	0.10	0.12	0.06	--	--	--	0.08	--	--	--	--	0.06	0.04	0.04
MnO	0.28	0.30	0.20	0.18	0.22	0.34	0.06	0.08	--	0.13	0.32	0.32	0.22	0.18
S	--	--	0.04	0.14	0.21	--	--	--	0.04	0.09	0.22	0.12	0.14	0.59
CIPW Norms														
C							0.69							
Or	30.38	30.61	27.86	27.72	27.08	28.32	28.14	29.33	27.08	28.73	29.33	29.09	28.97	30.57
Ab	49.18	52.29	51.65	54.82	59.63	53.12	59.30	54.54	56.58	55.54	45.35	46.43	51.91	47.25
An					3.77		4.04	4.17	4.91					0.37
Ne	12.00	8.41	10.84	9.67	3.83	9.86	2.92	6.33	4.86	8.66	14.50	13.42	10.90	11.72
Ac	1.35	1.09	3.11	0.84		1.62				0.68	4.35	1.94	1.66	
Wo	2.65	2.86	2.74	2.33	0.75	2.57		0.75	1.51	2.07	2.53	2.61	2.71	3.21
En	0.55	0.75	0.55	0.70	0.65	0.77		0.38	1.31	0.60	0.55	0.92	0.65	1.90
Fs	1.39	1.32	0.60	0.49		0.96		0.35			1.85	1.76	0.06	
Fo					0.14		0.45	0.22	0.24			0.25		
Fa							0.61	0.22				0.52		
Mt	1.83	1.96	1.40	2.36	1.88	1.97	2.81	2.84	2.28	2.52	0.46	1.84	1.96	1.74
Il	0.44	0.44	1.03	0.78	1.06	0.80	0.84	0.87	0.80	0.97	0.61	0.84	0.80	1.10
Ap	0.24	0.28	0.14									0.14	0.10	
Pr			0.08	0.26	0.39				0.08	0.17	0.41	0.22	0.26	1.11

TABLE 19--Continued

Sample No.	T114*	T115*	T114	T103	T32	T110	T26	T31	T16	T113	T110	T115	T40	T40G
Triangular Plot Data														
Q	39.69	41.51	40.22	40.93	43.84	40.78	44.31	42.54	43.26	41.47	38.22	38.77	40.28	39.70
Ne	43.04	41.03	43.76	43.46	40.63	43.09	39.50	40.54	40.83	42.46	44.67	44.21	43.31	42.52
Ks	17.27	17.46	16.02	15.61	15.53	16.13	16.19	16.92	15.90	16.07	17.11	17.02	16.41	17.78

NOTE--Below detectable limits.

*X-ray fluorescence analyses (Don L. Halvorson, analyst).

Na in x-ray fluorescence analyses done by microprobe.

Microprobe analyses made by Frank R. Karner.

Constituents normalized to 100%.

TABLE 20

CHEMICAL COMPOSITION AND NORMATIVE MINERALOGY OF MISSOURI BUTTES PHONOLITE

Sample No.	MB191*	MB186*	MB127*	MB174*	MB186	MB193	MB174	MB191	MB127	MB167	MB196	MB173	MB128	MB203	HB123
$Si9_2$	60.92	60.96	61.82	61.22	60.08	61.33	60.92	60.98	61.78	61.46	60.90	61.73	61.73	60.84	61.33
Al_2O_3	18.88	20.00	19.40	20.06	20.49	19.53	20.60	19.64	19.64	20.08	18.95	20.14	19.84	19.40	19.02
Fe_2O_3	1.74	1.73	1.70	1.71	1.92	2.08	1.87	2.06	1.86	1.89	1.96	1.83	1.89	1.92	1.88
FeO	1.87	1.58	1.21	1.48	1.82	0.82	1.33	1.34	1.26	1.54	1.36	1.48	1.56	1.44	1.82
MgO	0.39	0.36	0.24	0.49	0.48	0.48	0.58	0.28	0.09	0.48	0.36	0.68	0.42	0.92	1.17
CaO	1.52	1.01	0.88	1.00	1.04	1.86	0.90	1.26	0.70	1.26	2.30	0.73	0.80	1.08	1.06
Na_2O	8.02	8.40	8.46	8.44	8.72	7.61	8.58	8.19	8.66	7.44	8.00	7.70	7.94	8.28	8.38
K_2O	6.02	5.44	5.42	5.02	4.84	5.32	4.57	5.38	5.06	5.01	5.31	4.79	5.17	5.39	4.64
TiO_2	0.24	0.23	0.20	0.21	0.42	0.58	0.37	0.56	0.36	0.39	0.46	0.33	0.39	0.42	0.38
P_2O_5	0.10	0.08	0.08	0.08	--	0.12	0.06	--	0.08	--	--	0.12	--	0.06	0.05
MnO	0.28	0.21	0.58	0.30	0.16	0.22	0.16	0.23	0.44	0.34	0.18	0.41	0.21	0.15	0.20
S					--	--	--	--	--	0.04	0.06	--	--	0.06	--
CIPW Norms															
C							0.05			0.13		1.25			
Or	35.58	32.15	32.03	29.66	28.61	31.45	27.02	31.82	29.92	29.63	31.43	28.32	30.57	31.86	27.44
Ab	39.52	47.37	48.73	50.79	48.12	50.80	53.43	48.97	52.96	53.58	47.85	57.67	53.19	47.29	53.38
An		0.80		2.02	2.47	3.42	4.08	0.94		6.26	0.12	2.84	3.23		0.58
Ne	13.05	12.84	11.32	11.17	13.92	7.77	10.41	11.04	10.80	5.10	10.81	4.08	7.60	12.20	9.52
Ac	3.76		1.74						0.38					0.25	
Wo	2.88	1.54	1.60	1.01	1.12	2.10		2.22	1.23		4.72		0.31	2.07	1.82
En	0.71	0.59	0.38	0.45	0.52	1.20		0.70	0.22		0.90		0.15	1.50	1.12
Fs	2.33	0.98	1.32	0.56	0.59			0.26	1.11		0.33		0.15	0.39	0.59
Fo	0.18	0.22	0.15	0.54	0.47		1.01			0.84		1.19	0.63	0.56	1.26
Fa	0.66	0.39	0.57	0.74	0.59		0.45		0.01	0.91		1.10	0.69	0.16	0.73
Mt	0.64	2.51	1.59	2.48	2.78	1.68	2.71	2.99	2.51	2.74	2.85	2.66	2.74	2.66	2.73
Il	0.46	0.44	0.38	0.40	0.80	1.10	0.70	1.06	0.68	0.74	0.88	0.63	0.74	0.80	0.72
Ap	0.24	0.19	0.19	0.19		0.28	0.14		0.19			0.28		0.14	0.12
Pr										0.08	0.11			0.11	

TABLE 20--Continued

Sample No.	MB191*	MB186*	MB127*	MB174*	MB186	MB193	MB174	MB191	MB127	MB167	MB196	MB173	MB128	MB203	MB123
Triangular Plot Data															
Q	38.88	39.31	40.08	40.13	38.65	41.75	40.48	40.19	40.43	43.12	40.21	43.71	41.94	39.58	40.90
Ne	40.03	42.55	41.80	43.03	44.93	39.90	44.07	41.76	42.95	39.42	41.62	39.94	40.65	42.25	43.32
Ks	21.09	18.13	18.12	16.84	16.42	18.35	15.45	18.05	16.62	17.46	18.17	16.35	17.41	18.17	15.78

NOTE--Below detectable limits.

*X-ray fluorescence analyses (Don L. Halvorson, analyst).

Na in x-ray fluorescence analyses done by microprobe.

Microprobe analyses made by Frank R. Karner.

Constituents normalized to 100%.

TABLE 21

CHEMICAL COMPOSITION AND NORMATIVE MINERALOGY OF MISSOURI BUTTES TRACHYTE

Sample No.	MB159*	MB159	MB142	MB150	MB155
SiO_2	61.73	61.71	61.06	61.14	61.64
Al_2O_3	18.00	19.47	19.81	19.90	19.41
Fe_2O_3	1.80	2.12	1.86	1.98	2.06
FeO	2.38	1.40	1.38	1.82	1.86
MgO	0.65	0.69	0.72	0.88	0.78
CaO	1.88	1.37	2.00	1.54	1.44
Na_2O	6.83	7.00	7.12	6.71	6.88
K_2O	6.02	5.43	5.20	5.02	5.02
TiO_2	0.30	0.62	0.36	0.48	0.56
P_2O_5	0.11	--	0.28	0.06	0.12
MnO	0.30	0.14	0.12	0.34	0.16
S		--	0.04	0.04	--
CIPW Norms					
C				0.77	0.33
Or	35.57	32.10	30.74	29.69	29.68
Ab	46.77	52.43	50.97	54.16	55.71
An	0.68	5.67	6.74	7.25	6.36
Ne	5.97	3.70	5.04	1.44	1.38
Ac					
Wo	3.31	0.47	0.57		
En	1.20	0.40	0.40		
Fs	2.18	0.01	0.12		
Fo	0.29	0.93	0.98	1.54	1.36
Fa	0.59	0.03	0.33	1.13	0.84
Mt	2.61	3.08	2.70	2.87	2.99
Il	0.57	1.18	0.68	0.91	1.06
Ap	0.26		0.66	0.14	0.28
Pr			0.08	0.08	
Triangular Plot Data					
Q	42.65	43.85	43.10	45.03	45.07
Ne	36.30	37.17	38.43	36.83	37.11
Ks	21.05	18.97	18.47	18.14	17.81

Note--Below detectable limits.

*X-ray fluorescence analyses (Don L. Halvorson, analyst).

Na in x-ray fluorecence analyses done by microprobe.

Microprobe analyses made by Frank R. Karner.

Constituents normalized to 100%.

TABLE 22

CHEMICAL COMPOSITION AND NORMATIVE MINERALOGY OF BARLOW CANYON PHONOLITE

Sample No.	BC134*	BC134	BC140	BC101	BC130	BC105	BC110
SiO_2	58.59	59.18	58.40	57.69	57.91	58.44	58.32
Al_2O_3	22.47	21.58	21.55	20.68	21.13	21.90	21.26
Fe_2O_3	1.71	1.84	1.78	1.76	1.86	1.76	1.85
FeO	1.56	1.82	2.04	1.36	1.68	1.64	1.77
MgO	0.57	0.66	0.18	2.50	1.14	0.54	1.82
CaO	0.98	0.99	0.57	0.52	1.52	3.00	0.99
Na_2O	7.55	7.88	9.45	8.80	9.06	6.64	8.23
K_2O	5.80	5.18	5.22	5.77	4.78	5.34	4.76
TiO_2	0.21	0.34	0.28	0.26	0.36	0.26	0.35
P_2O_5	0.06	--	--	--	--	0.05	0.04
MnO	0.48	0.29	0.40	0.42	0.29	0.20	0.38
S		0.16	0.05	0.17	0.21	0.16	0.17
CIPW Norms							
C	2.13	1.21					0.86
Or	34.28	30.64	30.87	34.12	28.26	31.58	28.14
Ab	41.35	46.14	40.16	33.95	39.75	39.77	44.63
An	4.47	4.92	0.97		2.87	14.19	4.65
Ne	12.22	11.15	21.60	21.86	20.02	8.91	13.57
Ac				0.19			
Wo			0.78	1.08	1.95	0.16	
En			0.13	0.82	1.31	0.08	
Fs			0.71	0.14	0.49	0.07	
Fo	1.00	1.15	0.22	3.79	1.07	0.89	3.18
Fa	1.54	1.14	1.35	0.74	0.44	0.85	1.16
Mt	2.48	2.67	2.58	2.46	2.70	2.55	2.68
Il	0.40	0.65	0.53	0.49	0.68	0.49	0.66
Ap	0.14					0.12	0.10
Pr		0.30	0.09	0.32	0.39	0.30	0.32
Triangular Plot Data							
Q	39.30	39.89	34.93	34.44	35.20	40.62	38.48
Ne	40.32	41.96	47.73	45.76	48.10	38.83	44.56
Ks	20.38	18.15	17.35	19.80	16.70	20.55	16.96

NOTE--Below detectable limits.

*X-ray fluorescence analyses (Don L. Halvorson, analyst).

Na in x-ray fluorescence analyses done by microprobe.
Microprobe analyses made by Frank R. Karner.

Constituents normalized to 100%.

TABLE 23

CHEMICAL COMPOSITION AND NORMATIVE MINERALOGY OF BARLOW CANYON CONTACT ZONE AND SEDIMENTARY ROCKS

Sample No.	BC144	BC106	BC113	BC114	BC116	SEDX	S7
SiO_2	62.88	63.50	62.67	63.18	63.39	61.35	56.79
Al_2O_3	22.70	24.72	22.88	22.94	24.76	18.94	18.16
Fe_2O_3	--	--	1.94	--	--	2.78	2.31
FeO	1.82	0.88	0.93	1.77	1.66	2.16	5.81
MgO	1.20	1.28	0.81	1.43	1.24	2.04	5.86
CaO	1.57	0.98	1.01	0.52	0.69	0.88	4.56
Na_2O	2.66	1.06	1.24	2.08	1.63	0.86	0.50
K_2O	6.53	6.66	7.66	6.78	5.88	8.92	4.69
TiO_2	0.42	0.45	0.44	0.41	0.48	1.28	0.81
P_2O_5	--	--	--	--	--	--	0.13
MnO	0.04	--	0.07	--	--	--	0.18
S	0.10	0.42	0.28	0.84	0.19	0.75	0.16
CIPW Norms							
Q	15.13	27.85	22.79	21.52	27.52	17.29	14.42
C	8.41	13.99	10.72	11.24	14.47	6.27	4.28
Or	38.62	39.38	45.30	40.08	34.77	52.73	27.73
Ab	22.53	8.97	10.50	17.61	13.80	7.28	4.23
An	7.80	4.86	5.01	2.58	3.43	4.37	21.78
En	2.99	3.19	2.02	3.56	3.09	5.08	14.60
Fs	2.52			0.85	1.87		7.43
Mt			0.94			0.54	3.35
Il	0.80	0.86	0.84	0.78	0.91	2.43	1.54
Ap							0.31
Pr	0.19	0.79	0.52	1.57	0.36	1.40	0.30
Triangular Plot Data							
Q	57.46	66.23	62.07	60.98	65.82	58.44	63.28
Ne	16.27	6.57	7.49	12.41	10.13	5.31	5.12
Ks	26.27	27.19	30.44	26.61	24.04	36.26	31.61

NOTE--Below detectable limits.

Microprobe analyses made by Frank R. Karner.

Constituents normalized to 100%.

Sample SEDX is a sedimentary rock xenolith from the contact zone.

Sample S7 is from the Stockade Beaver Shale Member of the Sundance Formation.

APPENDIX IV

X-RAY DIFFRACTION DATA FOR ANALCIME UNIT

CELL CALCULATIONS

TABLE 24

X-RAY DIFFRACTION DATA FOR ANALCIME UNIT CELL CALCULATIONS

Sample	T40			T21			BC155			MB103		
(hkl)	°2Θ	dÅ	a_o	°2Θ	dÅ	a_o	°2Θ	dÅ		°2Θ	dÅ	a_o
211	15.78	5.616	13.76	15.78	5.616	13.76	15.78	5.61	13.742	15.80	5.609	13.739
220	18.25	4.861	13.75	18.27	4.856	13.73	18.24	4.86	13.746	18.16	4.885	13.817
321	24.20	3.678	13.76	24.24	3.672	13.74	24.22	3.67	13.732			
400	25.95	3.434	13.74	25.94	3.435	13.74	25.95	3.43	13.720	25.95	3.433	13.732
332	30.54	2.927	13.73	30.53	2.928	13.73	30.52	2.93	13.743	30.55	2.926	13.724
422										31.95	2.801	13.722
431	33.24	2.695	13.74	33.24	2.695	13.74	33.23	2.70	13.767	33.28	2.692	13.726
521				35.85	2.505	13.72	35.81	2.50	13.693	35.85	2.505	13.720
611	40.48	2.228	13.73				40.48	2.23	13.747	40.52	2.23	13.746
640										47.78	1.904	13.729
721										48.75	1.868	13.726
651	52.50	1.743	13.72	52.50	1.743	13.72	52.48	1.74	13.701	52.28	1.744	13.732
800										53.37	1.717	13.736
831	57.72	1.597	13.74	57.72	1.597	13.74	57.73	1.60	13.764			
1121	78.10	1.224	13.74	78.09	1.224	13.74						
average value		13.739			13.736			13.735			13.737	
standard deviation		0.017			0.012			0.025			0.026	

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REFERENCES CITED

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Geologic Map of the Devils Tower, Missouri Buttes, and Barlow Canyon Area

Base map by Topographic Division, U.S. Geological Survey, 1955 and 1957

EXPLANATION

QUATERNARY

Qal — Alluvium
Silt, sand, and gravel

Qt — Stream terrace deposits
Silt, sand, and gravel

Qtl — Talus
Locally derived igneous material

TERTIARY

Twr — White River Formation
Light-gray coarse-grained feldspathic sandstone overlain by grayish-white calcareous claystone

UNCONFORMITY

Tap, **Tab**

Tap, Analcime phonolite: *gray to olive gray, holocrystalline, porphyritic. Phenocrysts of sanidine, anorthoclase, aegirine-augite zoned to aegirine, nepheline, analcime, and nosean in a trachytic groundmass of acicular aegirine, sanidine, albite, microcline, and anhedral analcime. Calcite and zeolite are common alteration products.*

Tab, Alloclastic breccia: *consists of angular clasts of limestone, sandstone, shale, granite, quartz monzonite, schist, and phonolite. Matrix is partly devitrified, colorless to red glass containing many crystal fragments of quartz, feldspar, and various ferromagnesian minerals. Matrix looks brown in hand specimens.*

Tat — Foid-bearing alkali trachyte
Light gray, holocrystalline, seriate porphyritic. Phenocrysts of sanidine, anorthoclase, aegirine-augite zoned to aegirine, sphene, nepheline, and nosean in a groundmass of acicular aegirine, sanidine laths, and anhedral analcime. Groundmass varies from random orientation to trachytic texture.

CRETACEOUS

Km — Mowry Shale
Dark-gray shale with numerous fish scales, interbedded with bentonite

Knc — Newcastle Sandstone
Light-gray massive sandstone

Ksc — Skull Creek Shale
Brownish-gray to black shale interbedded with bentonite

Kfr — Fall River Formation
Fine- to medium-grained light-gray to yellow-orange sandstone interbedded with light-gray siltstones and dark-gray carbonaceous shales

UNCONFORMITY

Kla — Lakota Formation
Fine- to coarse-grained dull-orange sandstones and conglomeratic sandstones, interbedded with variegated claystones

JURASSIC

UNCONFORMITY

Jm — Morrison Formation
Variegated fine-grained claystones with discontinuous beds of gray sandstone and limestone

Jsr, **Jsl**, **Jsh**, **Jssb**, **Jssc** — Sundance Formation

Jsr, *Redwater Shale Member is fine- to medium-grained greenish-gray shale interbedded with fossiliferous limestone and glauconitic sandstone*

Jsl, *Lak Member is very fine-grained pale-yellow to dull-orange friable sandstone interbedded with siltstones and greenish-gray shale*

Jsh, *Hulett Member is fine- to medium-grained dull-yellow sandstone underlain by greenish-gray shales*

Jssb, *Stockade Beaver Shale Member is olive-gray to grayish-red shale interbedded with light-gray sandstone*

Jssc, *Stockade Beaver Shale and Canyon Springs Sandstone Members undifferentiated*

UNCONFORMITY

Jgs — Gypsum Spring Formation
Massive white gypsum overlain by reddish-brown claystone and mudstone

UNCONFORMITY

TRIASSIC

Ʀs — Spearfish Formation
Reddish-brown interbedded sandstones, siltstones, and claystones

---

Contact
Dashed where approximately located; dotted where concealed

Fault
Dashed where approximately located. U, upthrown side; D, downthrown side

Linear trend, doubtful fault

Strike and dip of beds

Horizontal beds

Drill hole

by
Don L. Halvorson
1979

TRUE NORTH · MAGNETIC NORTH

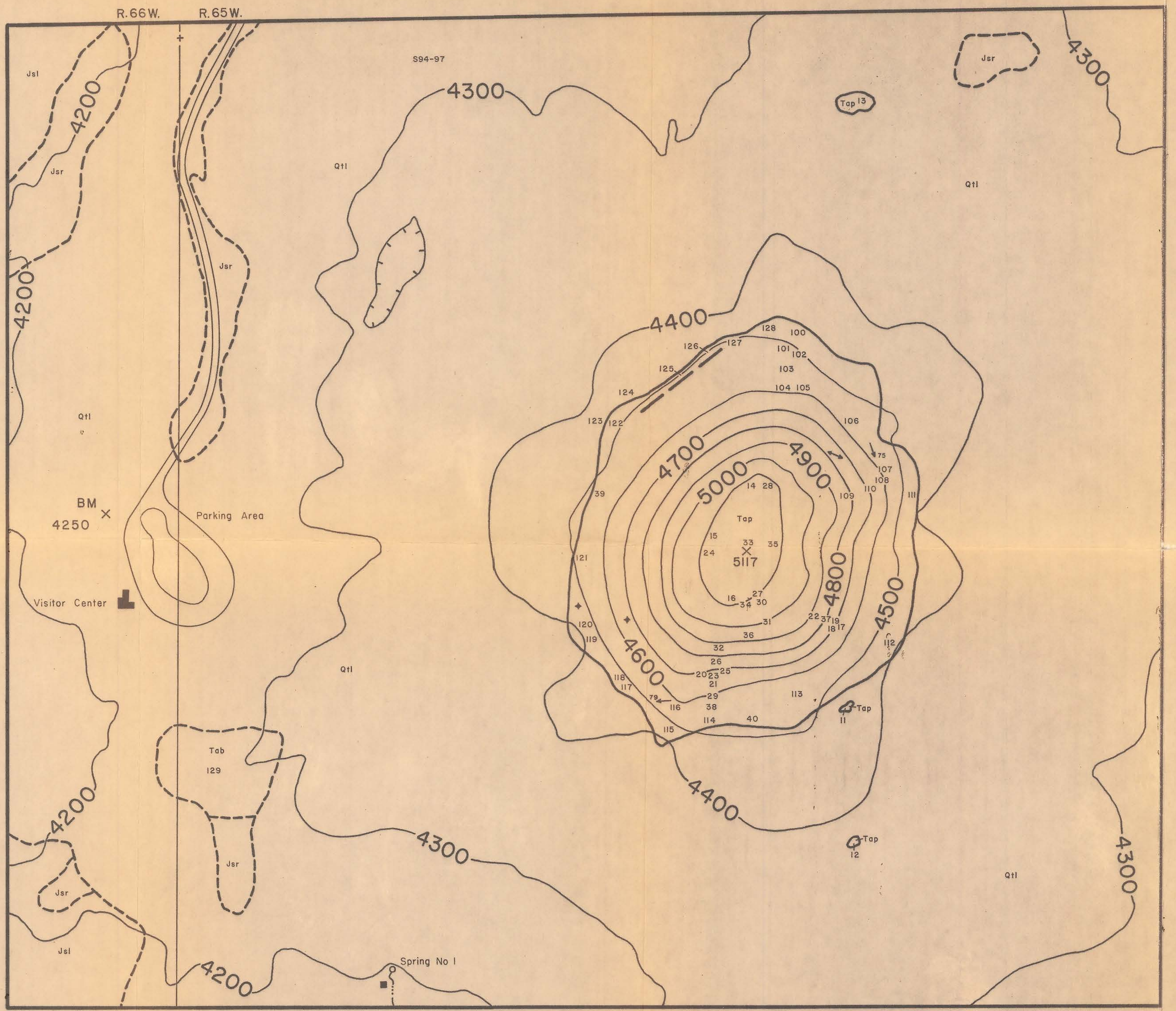
SCALE 1:20 000

DATUM IS MEAN SEA LEVEL

Geologic Map of the Devils Tower Area

Halvorson Dissertation

PLATE 2



Base from U.S. Geological Survey special topographic map, 1949

SCALE 1:2400

50 0 100 200m

CONTOUR INTERVAL 100 FEET

DATUM IS MEAN SEA LEVEL

TRUE NORTH 14° MAGNETIC NORTH

EXPLANATION

QUATERNARY

Qtl — Talus

TERTIARY

Tap Tab

Tap, Analcime phonolite: *gray to olive gray, holocrystalline, coarsely porphyritic. Phenocrysts of anorthoclase, aegirine-augite zoned to aegirine, nepheline, analcime, and nosean in a trachytic groundmass of acicular aegirine, albite, microcline, and anhedral analcime. Calcite and zeolite are common alteration products.*

Tab, Alloclastic breccia: *consists of angular clasts of limestone, sandstone, shale, granite, schist, and phonolite in a badly decomposed matrix. Matrix is partly laminated and contains flattened clasts of pumice and scoriaceous material.*

JURASSIC

Jsr / Jsl

Sundance Formation

Jsr, *Redwater Shale Member*

Jsl, *Lak Member*

Contact
Dashed where approximately located

Fault
Dashed where approximately located

80 — Bearing and plunge of flow lineation

Horizontal flow lineation

Vertical flow lineation

100 — Igneous rock sample number

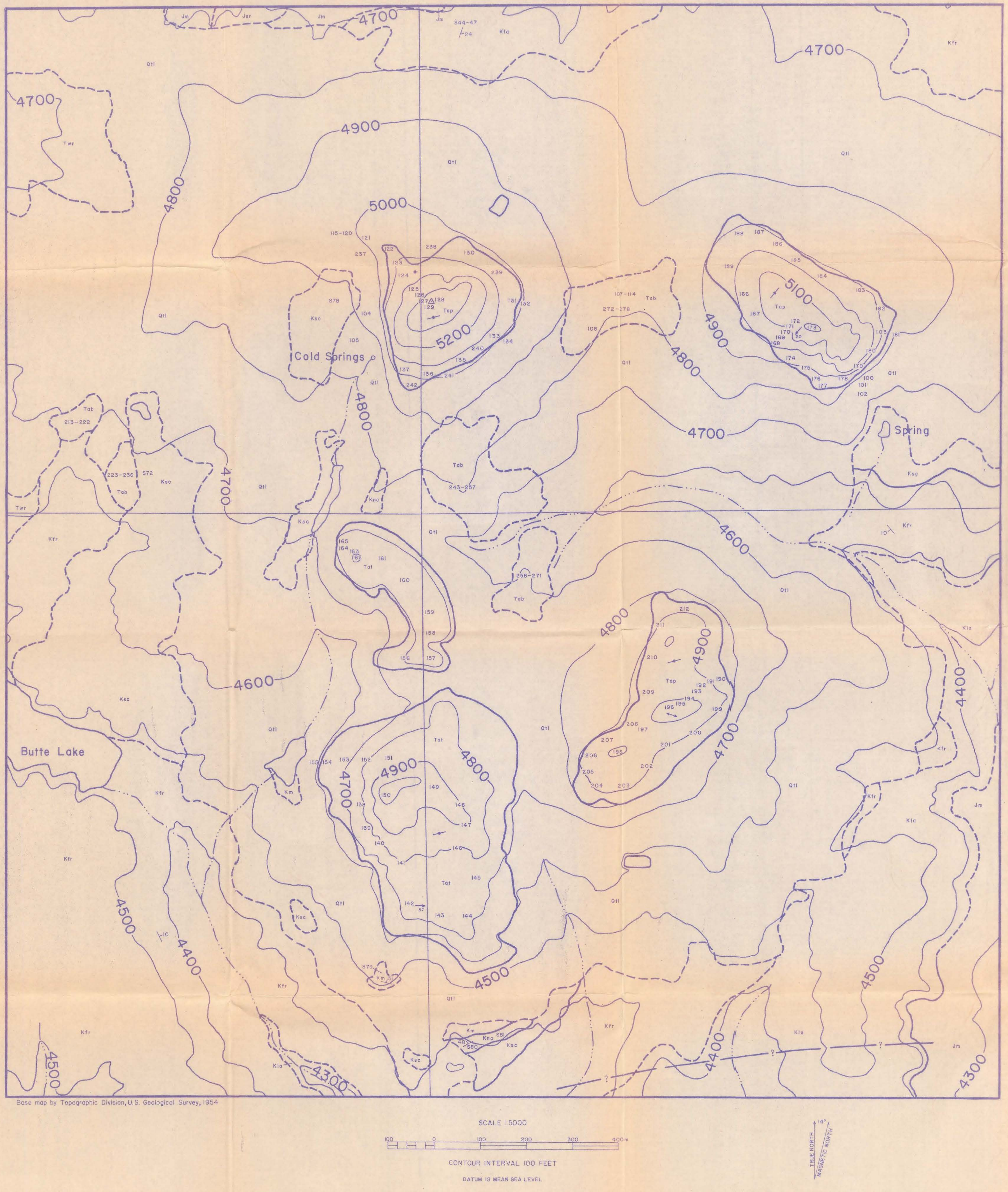
S50 — Sedimentary rock sample number

by
Don L. Halvorson
1979

Geologic Map of the Missouri Buttes Area

Halvorson Dissertation

PLATE 3



EXPLANATION

QUATERNARY

Qtl

Talus

TERTIARY

Twr

White River Formation

UNCONFORMITY

Tap Tab

Tap, Analcime phonolite: *gray to olive gray, holocrystalline, porphyritic. Phenocrysts of sanidine, anorthoclase, aegirine-augite zoned to aegirine, nepheline, analcime, and nosean in a trachytic groundmass of acicular aegirine, sanidine, and anhedral analcime. Calcite and zeolite are common alteration products.*

Tab, Alloclastic breccia: *consists of angular clasts of limestone, sandstone, shale, granite, quartz monzonite, schist, and phonolite. Matrix is partly devitrified, colorless to red glass containing many crystal fragments of quartz, feldspar, and various ferromagnesian minerals. Matrix looks brown in hand specimens.*

Tat

Foid-bearing alkali trachyte

Light gray, holocrystaline, seriate porphyritic. Phenocrysts of sanidine, anorthoclase, aeririne-augite zoned to aegirine, sphene, nepheline, and nosean in a groundmass of acicular aegirine, sanidine laths, and anhedral analcime. Groundmass varies from random orientation to trachytic texture.

CRETACEOUS

Km

Mowry Shale

Knc

Newcastle Sandstone

Ksc

Skull Creek Shale

Kfr

Fall River Formation

UNCONFORMITY

Kla

Lakota Formation

UNCONFORMITY

JURASSIC

Jm

Morrison Formation

Jsr

Sundance Formation

Jsr, Redwater Shale Member

Contact

Dashed where approximately located

Linear trend, doubtful fault

Strike and dip of beds

Bearing and plunge of flow lineation

Horizontal flow lineation

Vertical flow lineation

Strike of vertical planar joints

100 Igneous rock sample number

550 Sedimentary rock sample number

by

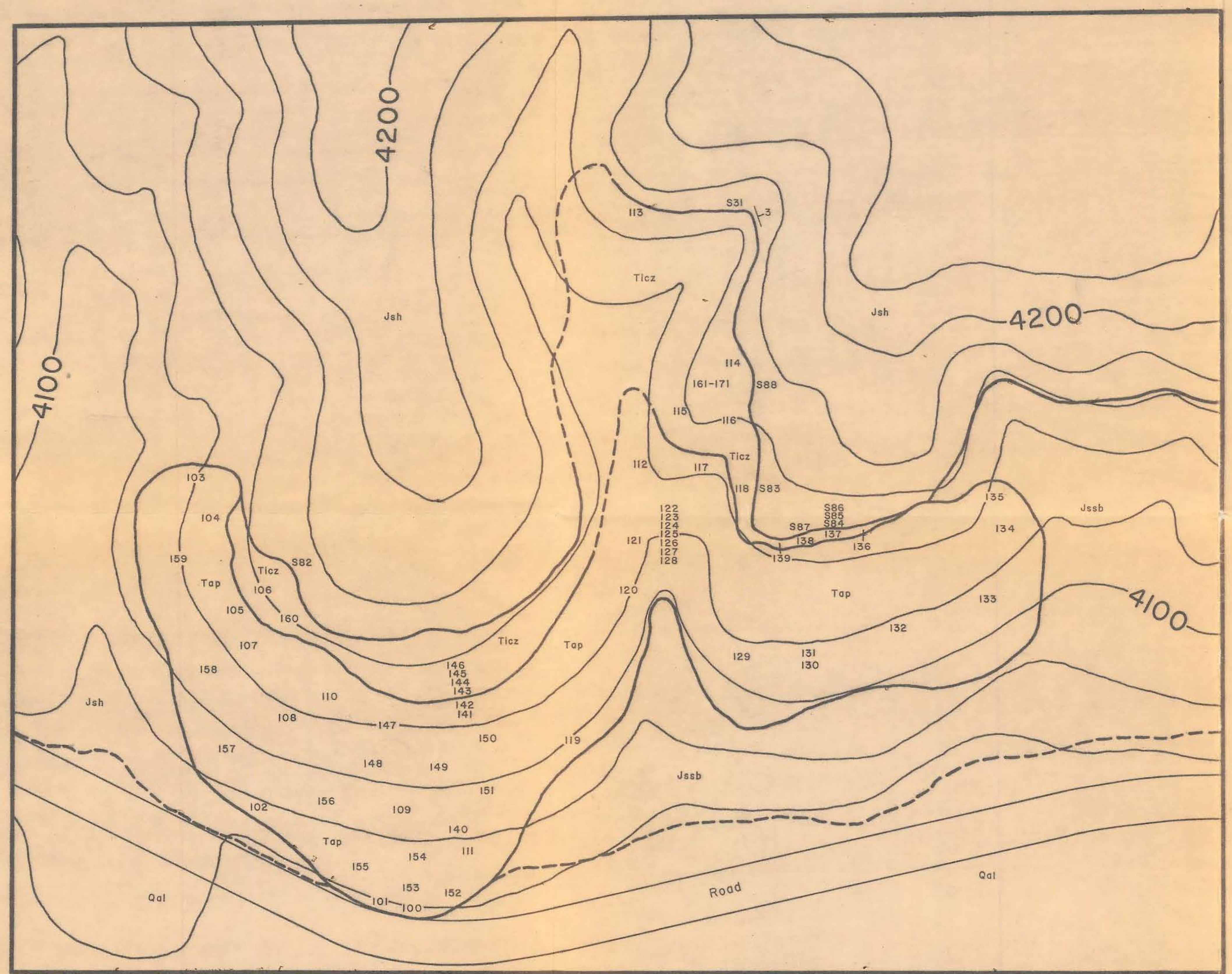
Don L. Halvorson

1979

Geologic Map of the Barlow Canyon Area

Halvorson Dissertation

PLATE 4



Base map by Topographic Division, U.S. Geological Survey, 1954

SCALE 1:1500

50 0 100 m

CONTOUR INTERVAL 20 FEET

DATUM IS MEAN SEA LEVEL

14°
TRUE NORTH
MAGNETIC NORTH

EXPLANATION

QUATERNARY

Qal
Alluvium

TERTIARY

Tap | Ticz

Tap, Analcime phonolite: *dull brown to dark olive gray, holocrystalline, slightly porphyritic. Phenocrysts of sanidine, anorthoclase, aegirine-augite zoned to aegirine, analcime, and nosean in a trachytic groundmass of anhedral analcime, sanidine laths, and star bursts of acicular aegirine. Calcite is common alteration product.*

Ticz, Igneous contact zone: *white to light brown highly altered rock containing many shale fragments. A few phenocrysts of sanidine and an altered feldspathoid in a groundmass of clay, chlorite, and randomly oriented feldspar laths.*

JURASSIC

Jsh / Jssb

Sundance Formation
Jsh, *Hulett Member*
Jssb, *Stockade Beaver Shale Member*

Contact
Dashed where approximately located

3
Strike and dip of beds

100
Igneous rock sample number

S50
Sedimentary rock sample number

by
Don L. Halvorson
1979

Location Map

Sedimentary Rock Samples and Geologic Map Plates

EXPLANATION

QUATERNARY

Qal — Alluvium

Qt — Stream terrace deposits

Qtl — Talus

TERTIARY

Twr — White River Formation

UNCONFORMITY

Tap — Analcime phonolite
Tab — Alloclastic breccia

Tat — Alkali trachyte

CRETACEOUS

Km — Mowry Shale

Kns — Newcastle Sandstone

Ksc — Skull Creek Shale

Kfr — Fall River Formation

UNCONFORMITY

Kla — Lakota Formation

UNCONFORMITY

JURASSIC

Jm — Morrison Formation

Jsr, Jsl, Jsh, Jssb, Jssc — Sundance Formation
Jsr, Redwater Shale Member
Jsl, Lak Member
Jsh, Hulett Member
Jssb, Stockade Beaver Shale Member
Jssc, Stockade Beaver Shale and Canyon Springs Sandstone Members undifferentiated

UNCONFORMITY

Jgs — Gypsum Spring Formation

UNCONFORMITY

TRIASSIC

Ts — Spearfish Formation

Contact
Dashed where approximately located; dotted where concealed

Fault
Dashed where approximately located.
U, upthrown side; D, downthrown side

Linear trend, doubtful fault

Drill hole

550
Sedimentary rock sample number

TRUE NORTH
MAGNETIC NORTH

by
Don L. Halvorson
1979

SCALE 1:20 000

DATUM IS MEAN SEA LEVEL