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PETROGRAPHY AND PETROLOGY
OF SMOKY BUTTE INTRUSIVES
GARFIELD COUNTY, MONTANA

by

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PETROGRAPHY AND PETROLOGY OF SMOKY BUTTE INTRUSIVES
GARFIELD COUNTY, MONTANA

Abstract

The Smoky Butte intrusives are located in T. 18 N., R. 36 E. Garfield County, Montana on the extreme eastern edge of the petrographic province of Central Montana. They consist of dikes and plugs arranged in linear, en-echelon pattern with a northeast trend and intrude the Tullock member (Paleocene age) of the Fort Union formation. Extrusive rocks are absent.

The rocks are potassium-rich volcanic types showing a disequilibrium mineral assemblage consisting of sanidine, leucite, biotite, olivine, pyroxene, magnetite plus ilmenite, apatite, calcite, quartz, and a yellowish to dark greenish glassy groundmass. Two chemical analyses of Smoky Butte rocks show high magnesium, potassium, titanium, and phosphorous and low aluminum and sodium content. The two norm calculations show that the rocks are oversaturated with 1.3 and 3.1 per-cent excess silica. Because of the peculiar nature of the Smoky Butte rocks, descriptive names have been applied to them. They are divided into six different types.

Three periods of intrusion are proposed for Smoky Butte quarry where three rock types crop out. Other evidence for multiple injection occurs in several multiple dikes. The upper contact of the intrusion is visible on a few plugs and dikes.

Smoky Butte rocks show some similarities to the undersaturated

potassium-rich rocks of the Highwood and Bearpaw Mountains of Montana, the rocks of the Leucite Hills of Wyoming, and the oversaturated rocks of the West Kimberly District of Australia.

INTRODUCTION

Location and Accessibility

The Smoky Butte intrusives are located 8 miles due west of Jordan, Montana in T. 18 N., R. 36 E., Garfield County, Montana. The intrusives extend from Section 1, southwest into Secions 12, 11, and 14 with a total length of 1.9 miles. They lie between Smoky Butte Creek to the north and the junction of Big Dry Creek and Lone Tree Creek to the south.

Smoky Butte is accessible from both its north and south extremities. The best route is to travel 6 miles towards Edwards along Highway 20 southwest from Jordan, turn right onto an improved ranch road for 4 miles, cross Big Dry Creek, and follow a trail for one more mile. A less accessible route is to take the Brusett road west from Jordan for 6 miles and then turn left onto a ranch road for another 4 miles.

The Smoky Butte intrusives lie on the extreme eastern edge of the petrographic province of Central Montana. The nearest intrusive rocks, which are dikes, occur 55 to 60 miles due south of Smoky Butte on Porcupine dome and near Ingomar dome. The nearest igneous rocks, which have been described in some detail (Ross, 1926), are located 10 miles west of Winnett, Montana, approximately 90 miles southwest of Smoky Butte (Figure 1).

Purpose

The purpose of this investigation was to determine the Smoky Butte rock types, to observe the metamorphic effects on the intruded

Tullock sediments, and to compare the rocks with those of the petrographic province of central Montana.

Previous Work

During the summers from 1902 to 1906, Barnum Brown collected vertebrate, invertebrate, and plant fossils from the Hell Creek formation in the Jordan area. He described Smoky Butte (then called Smoke Butte) as a highly vesicular andesite with calcite filling vertically oriented vesicles. He recognized the intruded sediments as Fort Union strata and mentioned that there was no displacement of the beds. He dated the intrusion as probably of latter Fort Union time (Brown, 1907, p. 232).

During the summers of 1957 and 1959, personnel of the Mineral Classification Branch, United States Geological Survey, prepared a geologic map and structure contour map of the Smoky Butte area as part of the Jordan-Lindsay coal field project. The purpose of the project was to classify government lands previously with-drawn for coal (unpublished report).

Field Work

The field work was completed during the summer of 1959, on weekends, while the author was employed as a geologic field assistant by the United States Geological Survey. Approximately 20 days were spent in the field making a plane table map* of the intrusives, collecting

*The plane table map was made to a scale of 1 inch equals 400 feet using Beaman Arc stadia methods for horizontal and vertical distances. Horizontal control was established from standard section and quarter-corner markers. Vertical control was established from a plane table traverse by G. E. Anderson and the author.

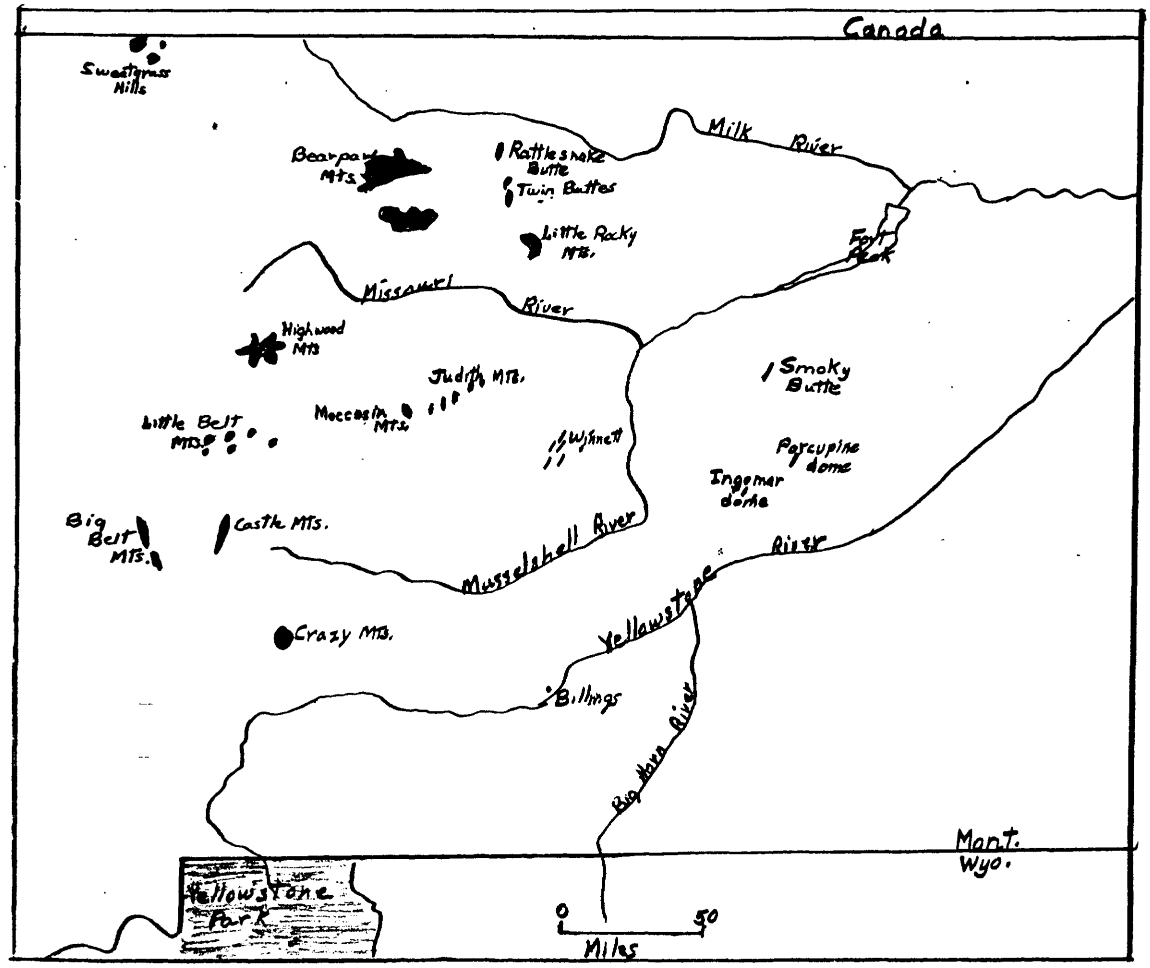


Figure 1: Sketch map of Central Montana showing the Tertiary igneous rocks.

hand specimens, and describing the intrusive relationships.

A stratigraphic section on the southeast side of the intrusive suite was measured and described by G. E. Anderson, assisted by the author, in conjunction with work in the Jordan-Lindsay coal field.

Acknowledgments

The author wishes to thank Mr. A. F. Bateman, Regional Geologist, Mineral Classification Branch, United States Geological Survey, Great Falls, Montana, for obtaining authorization for this work, and Mr. G. E. Anderson, Geologist of the same office, for his suggestions and assistance in plane table mapping. The author is also greatly indebted to Dr. John Hower for guidance and assistance. Thanks are also extended to Dr. J. P. Wehrenberg and to the rest of the staff of the Geology Department, Montana State University.

Thanks are due to W. T. Pecora, Chief, Geochemistry and Petrology Branch, and to W. G. Schlecht, Liason Officer, for authorization of two chemical analyses of Smoky Butte rocks, and to P. L. Elmore, S. P. Botts, I. H. Barlow, and G. Chlve, who analyzed the rocks.

SEDIMENTARY ROCKS

Introduction

An almost complete section of the Tullock member of the Fort Union formation of Paleocene age and the upper part of the Hell Creek formation of uppermost Cretaceous age is exposed on the southeast side of the Smoky Butte area (see Appendix I for measured section). Flaxville terrace gravel forms a thin mantle on the ridge top near the north end of the area near Half Sediment Butte (Plate II, Figure 3).

Upper Cretaceous

The upper part of the Hell Creek formation is exposed 1500 feet to the east of Ship Rock (Plate I, back pocket). It consists of light greenish-gray claystone with some thin, slightly carbonaceous shale beds. According to Thom and Dobbin (1924) the Hell Creek formation consists of somber colored clays, which probably accumulated in topset swamps of a great delta, and of fluviatile sandstone. Fossil remains of Triceratops are numerous in the lower zone and shells of Corbicula subelliptica plus shark remains occur in the upper zone.

Paleocene

The Tullock member of the Fort Union formation overlies the Hell Creek formation without a clear stratigraphic break. The base of the lowest coal is defined as the base of the Tullock member. On the southeast side of the intrusive suite this lowest coal is 1.2 feet thick. The Tullock member was named by Rogers and Lee (1923) after Tullock Creek, southwest of Forsyth, Montana. It consists of fine-grained, calcareous, yellow sandstone, or sandy shale, and contains numerous thin coal and carbonaceous beds. The scarp-forming character of the Tullock member is caused by a widespread thin-bedded, calcareous, ripple-marked sandstone. The numerous carbonaceous beds give a striped appearance to its outcrop. The characteristic yellow color of the beds was caused by thorough oxidation and leaching under conditions of flood plain deposition.

Miocene (?) or Pliocene

Large well-rounded quartzite pebbles up to 5 inches in length and 3 inches in diameter cap the ridge near the southern extremity of Half Sediment Butte (exposure (9), Plate I). These pebbles form a thin mantle above the Tullock sediments. According to Thom and Dobbin (1939, pp. 15-16) there are four major stages in the erosional history along the Missouri River just below the present mouth of the Milk River just below the present mouth of the Milk River (approximately 70 miles northeast of Smoky Butte). The oldest stage is represented by the Cypress surface of Oligocene age. The next lower surface, capped by gravel of Miocene or early Pliocene age, is called the Flaxville surface. According to Collier and Knechtel (1939, p. 13), the Flaxville gravel ranges in elevation from 2,500 to 2,800 feet or 500 to 800 feet below the Cypress Hills surface in T. 17 N., R. 49 E., McCone County, Montana. The gravel near Half Sediment Butte is at an elevation of 2,860. This gravel is presumed, by the author, to be of Flaxville age because it occurs on the terrace just below the highest erosional surface, and corresponds in elevation to the Flaxville gravel of McCone County.

REGIONAL GEOLOGY

Physiography and Geomorphology

Smoky Butte, with an elevation of 3065 feet, is the highest point in T. 18 N., R. 36 E. There is approximately 450 feet of relief between the top of Smoky Butte and the bed of Big Dry Creek (a mile and a half south) near the southeast corner of Section 13.

The Smoky Butte dike and plug suite intrudes the Paleocene Tullock member of the Fort Union formation. It is more resistant than the country rock and forms cone-shaped knobs and ridges of various sizes. The most prominent of these ridges is "Wall Rock" which is an exposed dike forming a wall 150 feet long and 23 feet high (Plate II, Figure 1).

The two intermittent streams, Smoky Butte Creek to the north and Big Dry Creek to the south of the intrusives, have a gradient of approximately 10 feet per mile. The divide between the two channels becomes broader and higher west of Smoky Butte and terminates eastward near the junction of the two streams. The ridge east of the intrusives is fairly flat with steep sides. The flat top and steep sides are caused by the presence of an indurated sandstone caprock at the top of the ridge.

Regional Structure

In the mapped portion of Garfield County, structure contours drawn on the base of the Tullock member indicate a very gentle southeast dip of the sediments with a synclinal axis passing through Sections 23, 24, and 25, of T. 18 N., R. 36 E. (Figure 2). This syncline is part of the Blood Creek-Sheep Mountain syncline shown on the structure contour map of the Montana plains by Dobbin and Erdmann (1955).

The syncline is about 250 miles long and extends westward to Fergus County and eastward to Fallon County, Montana. It is known in its western part as the "Blood Creek syncline" and in its eastern part as the "Sheep Mountain syncline".

The Smoky Butte dike and plug suite, located just north of the axis of the Blood Creek syncline, is separated into two parts that are offset slightly and have somewhat different orientations (Plate I). According to G. E. Anderson (personal communication) the projected north trend (N. 32°E.) appears to have been the locus of a gentle but positive monoclinal flexing which has resulted in a relative downwarping of the structure to the southeast. A similar structural effect is suspected along the south trend (N. 25°E.). The Tullock member is downwarped 10 feet on the southeast side. Anderson believes that these structural lineaments may have been produced prior to, but were more probably concurrent with the Tertiary folding of the Blood Creek syncline.

In the area surrounding Smoky Butte some trends paralleling those of the intrusives have been observed. Fractures in the resistant sandstone bed of the Tullock member that caps ridges and isolated knobs have an approximate N. 25°E. strike. A less well-defined complementary fracture set strikes approximately N. 80°W. A fault in Section 6, T. 18 N., R. 36 E. has a strike of N. 19°E.

These trends compare with some major regional trends east of Smoky Butte. On the geological map of Montana compiled by Ross, Andrews and Witkind (1955), it can be seen that the Weldon fault, northwest of Circle, McCone County, Montana has a northeast trend. Another striking northeast trend occurs along Redwater Creek near Circle.

A pre-Tertiary fault, which may be the same fault structure on which the Smoky Butte rocks were intruded, is presumed to extend northeast and southwest from Smoky Butte. It extends south and intersects the east-west trending faults near Bruneldo.

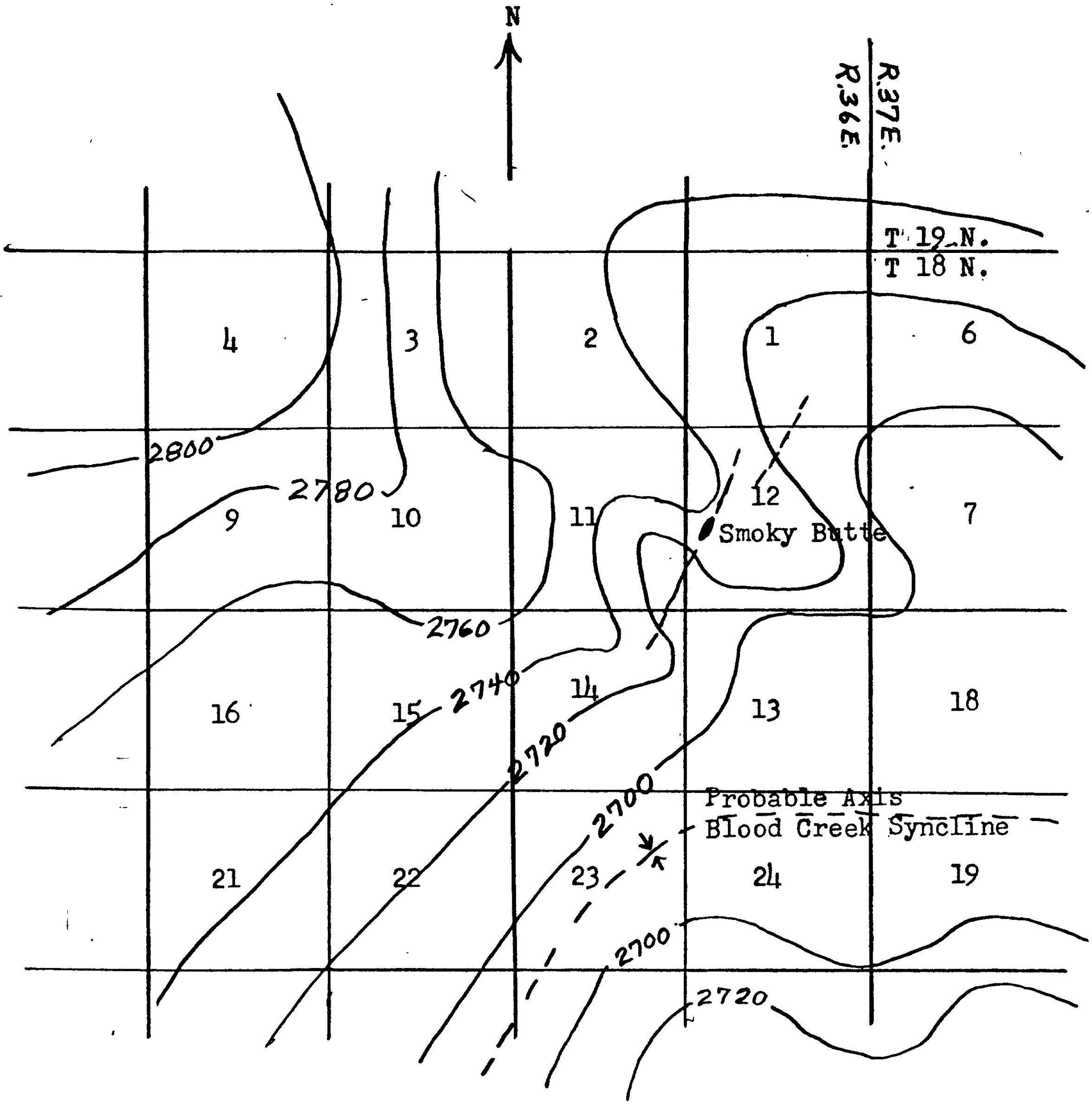


Figure 2: Structure Contours on base of Tullock member of Fort Union formation

0 1 2

Scale: 1 inch = 1 mile

Contour interval 20 ft.

Original map by G. E. Anderson

INTRUSIVE ROCKS

General Nature of the Plugs and Dikes

The Smoky Butte intrusives include both plugs and dikes arranged in a linear, en-echelon pattern for a distance of 1.9 miles. Extrusive rocks are absent. The northern one-third consists of plugs and short dikes trending N. 32°E. The southern two-thirds, with a trend of N. 25° E., is strikingly different because of the continuous nature of the dikes. A major offset separates the two trends at the southern extremity of the N. 32° E. trend and the northern end of the N. 25° E. trend. Other minor offsets occur on the north end of Smoky Butte and just north of Ship Rock. The dikes along the southern trend have a decidedly sinuous pattern (See Plate I).

The linear pattern of the plugs and dikes, the offsets, the sinuous-discontinuous dikes, and the parallel trend of the two short gulleys on the southeast side of the intrusive suite suggest fracture control.

Plugs

All of the plugs, except one, show similar characteristics. Smoky Butte, which is a relatively fresh, multiple dike-plug intrusion, is the exception. The other plugs are cone-shaped with talus covered sediments of the Tullock member held up along the sides. They contain similar indurated country rock xenoliths, ranging in size from microscopic to several feet in diameter as well as ubiquitous calcite vug fillings and inclusions which vary locally in abundance. All of the plugs exhibit flow banding next to the intrusive-sedimentary contact.

The light and dark bands create a laminated appearance.

In all the plugs, excluding Smoky Butte, the intrusive rocks are a light brown or gray color. Smoky Butte contains relatively fresh, dark colored rocks of three different types.

Smoky Butte

Smoky Butte, a multiple plug-dike intrusion located in the center of the intrusive complex, is the largest of the intrusions, being nearly 300 feet wide at its southern end near the quarry (Figure 3). In general appearance it is elongate with dikes extending both north and south.

The multiple nature of the intrusion is indicated in the Smoky Butte quarry where three rock types crop out (Plate III, Figures 1, 2, 3). The three rock types exposed in Smoky Butte quarry are: I. sanidine-biotite rock; dark, fine-grained, flared columnar jointed; biotite and sanidine are the principal minerals and they occur in the groundmass; (II) sanidine-leucite-biotite rock; greenish-gray, coarser grained than Type I with megascopically visible phenocrysts of biotite; (III) olivine-leucite-biotite rock; dark, weathers spheroidally, megascopically visible biotite and olivine phenocrysts.

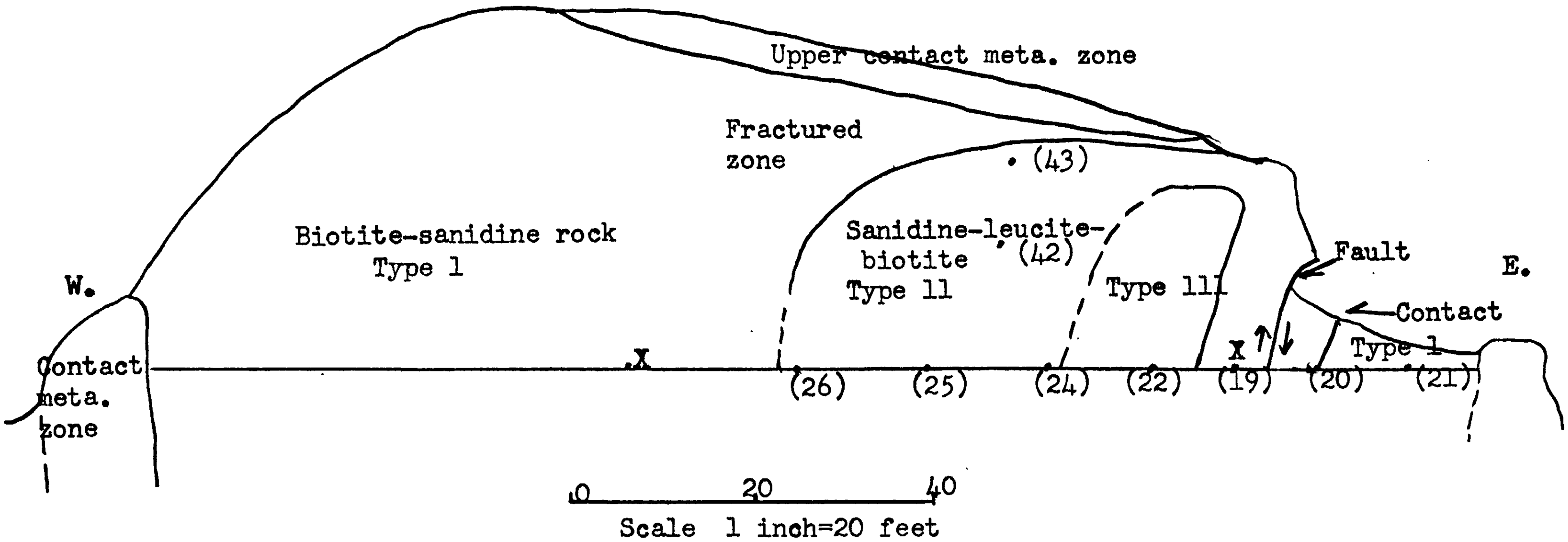
Type I rock is present on the extreme east and west sides, just inside the metamorphic-igneous contact. Type I rock has flared jointing which indicates the plug-like nature of this intrusion (See Plate III, Figure 1). Toward the center of the quarry, contact effects between this rock and a biotite rich, blocky fractures rock (Type II) are manifested in chilled zones with decreasing grain size of the Type II rock close to the contacts (Plate III, Figure 1 and 2). One of these contacts, exposed on the east side of the quarry, shows a very clear decrease in grain size of the porphyritic biotite rock with more marked lineation of the biotite laths next to the contact. A small amount of shearing is also present. Six feet west of this contact a fault occurs with a one-inch shear zone filled with quartz and chalcedony. This fault dips approximately 80°NW. with a N. 24°E. strike curving toward the east near the top of the outcrop (Plate III, Figure 2). On the west side of the quarry, the contact is more obscure. However, a more marked lineation of the biotite rock occurs with a small amount of shear.

The upper contact of Type II rock consists of a darkened zone making a sharp break from the rocks below and the metamorphosed, light gray, silt-sized, quartzitic sediments above.

Rock Type III crops out in the center of Smoky Butte quarry in a zone 16 feet wide. A darkened contact zone is visible on its eastern contact with Type II rock. Type III rock is a spheroidally weathered olivine-leucite-biotite rock of a darker color than the blocky sanidine-leucite-biotite rock (Type II) that it contacts. This same general rock type is found both north and south of Smoky Butte in its dike extensions.

Another outstanding feature visible in the quarry is the badly fractured zone present on the west upper side in the columnar jointed Type I rock. The fracturing is extreme near the contact of the columnar jointed Type I rock and the Type II rock and decreases westward away from the contact.

The bulk of Smoky Butte is composed of Type II rock containing the biotite phenocrysts. On the west side of the butte this rock is



(19) Index to sample position.
X Position of samples of which chem. analyses were made.

Figure 3: Sketch map of Smoky Butte quarry showing the intrusive rock types and their relationship.

jointed into elongated columns that dip approximately 60 degrees toward the center of the butte. On the northeast side the columns are nearly horizontal; however, the massive center part of the butte shows blocky fracturing.

The multiple nature of Smoky Butte is indicated in two other places besides the quarry. Approximately 150 feet north of the quarry, near the top of the butte, there is a sharp contact between the Type II rock on the north and the Type III rock which lies to the south. On the northern side of the butte, just south of index number (15) (Plate I). a dark, dense dike extension consisting of Type III rock continues south into the butte contacting the porphyritic biotite rock (Type II) on the west side. The dike at that point is 15 feet wide and the Type II rock outcrop is 23 feet thick, broadening to the south.

A short dike, 50 feet in length and 3.5 feet wide, occurs on the northwest side of the butte. It is a dark flow banded type with abundant light-colored, silt-sized xenoliths.

Exposure I

The northernmost exposure of the intrusive suite consists of light gray rock with megascopically visible biotite. The exposure is cone-shaped and has a dark contact zone 5 feet thick. The center of the exposure is massive.

The contact zone is inclined towards the center of the plug with dark contact rock present on the higher north end indicating near proximity to the upper contact.

A large, badly fractured xenolith that consists of highly indurated, bedded shale occurs on the northeast side of the plug.

Penetration up to one inch along the fractures of this xenolith by intrusive material has occurred. The xenolith is rimmed by a narrow, dark contact zone 4 inches wide.

Top Contact Butte

Top Contact Butte (index number (3), Plate I) is a small plug capped by 4.5 feet of indurated, yellowish sediments of the Tullock member. It clearly shows the upper sedimentary-intrusive contact zone in a 1.5 foot wide highly vesicular, dark zone. Vesicles and calcite inclusions and vug fillings near the contact make up 35 per cent by volume of the rock. These range in length from 2 to 30 mm with their long axes oriented horizontally. Away from the contact the vesicularity and dark hue diminishes gradually grading into the light brown rock below.

Radial Dike Butte

Radial Dike Butte (Plate I) is the largest of the light gray colored plugs. Two radial dikes occur on the west side. They show very pronounced flow banding with distorted, indurated sediments of the Tullock member present near their upper junction (See Plate II, Figure 3). On the north side, a small saddle separates the main higher part of the plug from its northern extension.

On the north side, the intrusive-sedimentary contact is well-exposed showing a dark chilled zone one foot thick. The zone has a rough currugated appearance that is caused by the great abundance of large vertically oriented vesicles. At the contact the intrusive rock has been sheared into narrow vertical plates which has created a zone of weakness resulting in a slight depression. Evidently, after consolidation by rapid chilling at the contact further upward movement of the partially molten center caused the shearing.

Exposure (6)

This exposure is more like a dike than a plug in that it is quite long in comparison with the width. The rock type is similar to that of Radial Dike Butte. On the east side, the dark contact zone varies from 6 inches to 2 feet in thickness. Generally the intrusion lacks the highly vesicular lineated nature common to the other plugs. Its only other peculiarity is the abundant hematite present along the fractures.

Bull Snake Knob

Bull Snake Knob (Plate I) is an oval shaped plug with a smooth rounded wall on the west side and a hackly, uneven surface with very abundant large xenoliths on the east side. Flow banding on the west side and the top indicate that the intrusion welled up vertically on the west side and was directed eastward horizontally, engulfing many large xenoliths. The abundant xenoliths plus the large amount of blocky talus on the east side also attest to this (See Plate II, Figure 3).

Instrument Butte (19)

This plug is the only one of any size occuring in the southern N. 25°E. trend of the complex (Plate III, Figure 3). In general, it is composed of light gray, flow banded rock that is similar to the other plugs. On its northern end, calcite is so abundant in the rock that it will effervesce with HCl.

Plate II

Figure 1: Looking southwest.

Wall Rock is seen on the right. The small ridge south of Wall Rock is exposure number (25).

Figure 2: Looking north.

This shows an abandoned shaft with 2 dikes visible. The easternmost dike has been blocked off by the resistant sandstone caprock. The western dike has penetrated the caprock, and has intimately penetrated fractures in a yellowish-green claystone of the Tullock member below the caprock.

Figure 3: This is a N. 32° E. view.

Half Sediment Butte is visible in the right foreground. Intrusive rocks are much darker colored than the sediments of the Tullock member. Bull Snake Knob is the next northernmost exposure. The large amount of blocky talus is clearly visible on the east side. The high butte in the background is Radial Dike Butte. Sediments of the Tullock member are visible between the dikes.

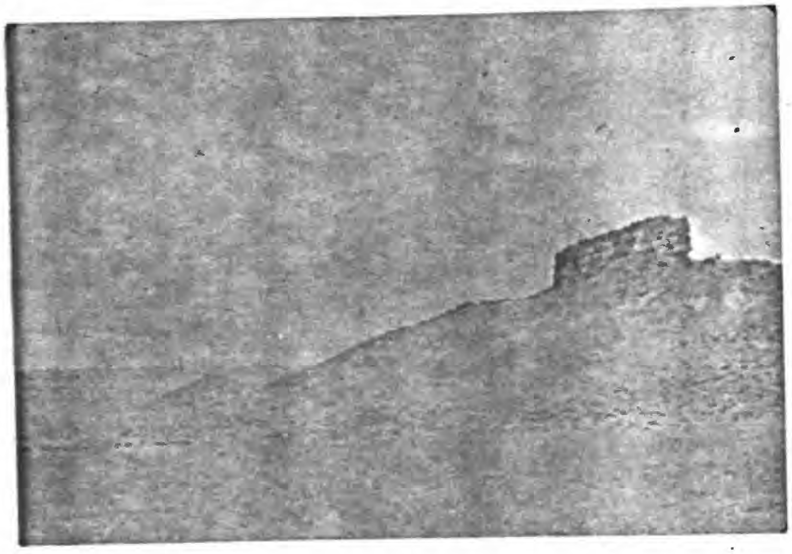


Figure 1

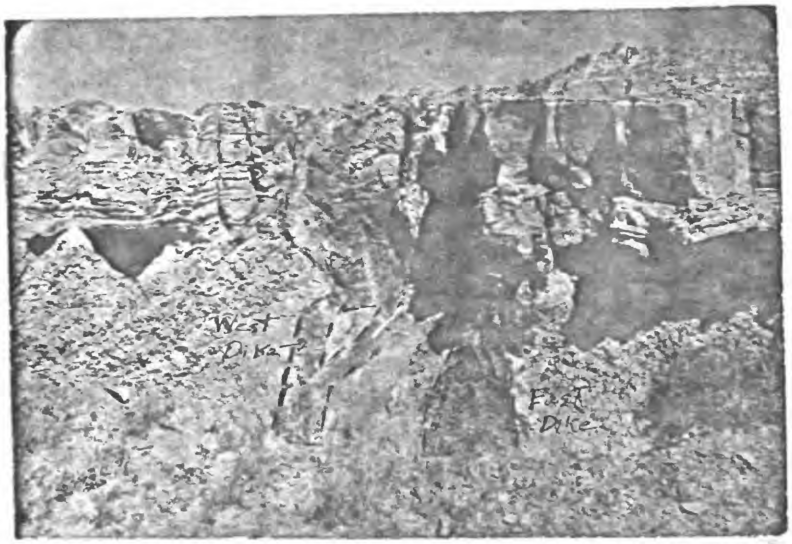


Figure 2

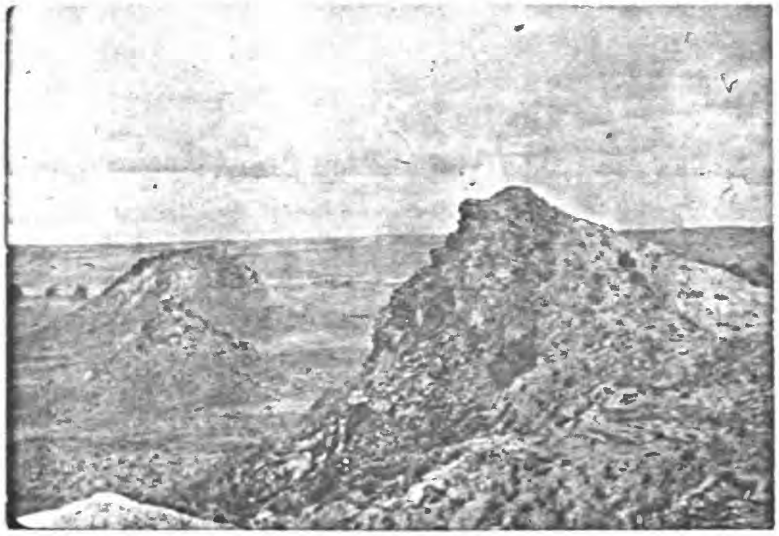


Figure 3

Plate III

Figure 1: View of Smoky Butte quarry looking north. The Type I rock occurs on the left. The flared columnar jointing is clearly visible. In the center of the picture the columnar jointed rock can be seen to be badly fractured. Type II rock is visible on the right side. It has a blocky type of fracture.

Figure 2: View of the east side of Smoky Butte quarry. It shows talus in foreground and a fault in the left upper corner in the Type II rock.

Figure 3: View looking north taken from the top of Ship Rock. Instrument Butte, a plug, can be seen just south of Smoky Butte. Smoky Butte quarry, located on the south side of Smoky Butte, is visible.

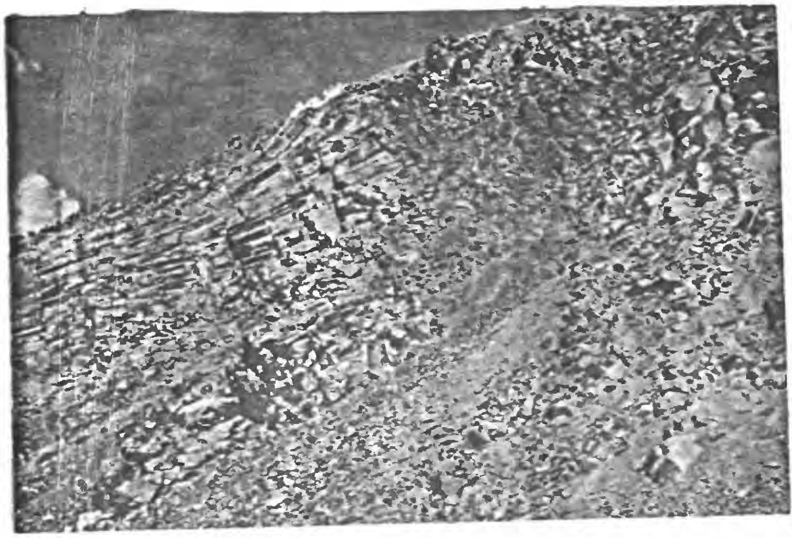


Figure 1

Figure 2

Figure 3

DIKES

General Considerations

The dikes make up the largest part of the intrusions. There are three general rock types found in the dikes. These are: (1) dark, dense dike rocks with no megascopically visible minerals, (2) light gray or brown dikes with abundant vertically oriented vesicles filled with calcite, and (3) glassy dikes with megascopically visible olivine and biotite phenocrysts. In the northern one-third of the suite (N. 32°E. trend), the dikes are short and discontinuous, not very different from the plugs in topographic features. Along the N. 25°E. trend in the southern two-thirds of the suite, the dikes are longer, more sinuous, and in places, much broader.

These are several multiple dikes, one of which shows five separate injections. In general, the dikes go around or through the light gray colored plugs, and show a varying strike and discontinuous pattern indicating fracture control.

Ship Rock

Ship Rock is the largest dike of the complex. It is about 60 feet wide at its widest point and forms the high, long, narrow ridge south of Smoky Butte. It has light-colored sediments of the Tullock member occurring near its top. The rock type is that of the first mentioned above, consisting of dark, dense rock, lacking megascopically visible minerals. Ship Rock has narrow dike extensions, both north and south. On the north, there are two parallel dikes. The easternmost dike is continuous and follows the northern slope to the top of the Ship Rock. The westernmost dike being discontinuous and more sinuous in nature, terminates at the foot of the slope. Two small plugs occur on the top of the ridge in contact with the fresh dike rocks. One plug occurs near the instrument station (index number (23)), and the other occurs near the north end of the ridge. These plug rocks are light gray and show megascopically visible, reddish-brown biotite in hand specimen. On the northernmost end of Ship Rock (near index number (22)), there is a dark vesicular zone indicating the upper contact of the dike.

Smoky Butte Dike Extensions

The Smoky Butte dike extensions, both north and south, are similar to the rock type of Ship Rock except that they are finer grained. The dike that extends south from Smoky Butte quarry is up to 6 feet in width. It has a fairly constant strike south from the quarry for 450 feet, and then is discontinuously offset to the west. The dike segments on the west side of Instrument Butte have a varying strike. This dike pattern suggests that Instrument Butte, a plug, was the first intruded and controlled the pattern of the dikes around it.

The northern dike extension, 15 feet wide near index number (15), decreases in width gradually north along the trend to 2.5 feet at its northern extremity near index number (14). It cuts through a flaggy, poorly exposed plug near index number (15).

Light Gray Dikes

The dike extending from index number (10) to (13) is a light gray dike under the second dike classification. It varies locally in thickness and has a discontinuous pattern on its northern end and forms low ridges. The southern extension of the dike is more continuous. It follows the western edge of the ridge south to index number (13) where a shaft was dug. The dike does continue south, but does not penetrate the resistant sandstone caprock occurring along the crest of the ridge.

Near index number (11), on the north end, the dike is 3 feet 4 inches wide. It has contact zones consisting of 2 inches of dark, vesicular rock and a 3-foot wide blocky, light brown center. The center zone has abundant vertically oriented country rock inclusions and calcite inclusions and vug fillings up to 2 cm in length.

On the ridge top south of index number (12), the dike cuts through the indurated sandstone caprock with only slight contact effects. The caprock is fractured in one-quarter inch intervals for 1 foot on either side of the dike.

The shaft, near index number (13), shows two interesting relationships. One is the barrier effect of the sandstone caprock, and the other is the penetration by the intrusive material of a yellowish claystone of the Tullock member. On both the north and south sides of the shaft, a dike is cut off above by the sandstone caprock. On the north side of the shaft, the westernmost dike penetrates the caprock and fills fractures in an indurated, yellowish claystone just below the caprock. This is shown on the photograph (Plate II, Figure 2).

Other dikes, similar in rock type, occur near index numbers (25) and (26). These dikes form low ridges on the extreme southern end of the suite.

Multiple Dikes

The dikes mentioned below have been classified as multiple dikes following the definition of Daly (1933, pp. 91-92).

> "Multiple dikes are intrusions of dike form, due to successive injections of one or more kind of magma into the same, intermittently widened fissures."

The dikes listed below all have two or more injections. The distinctive parts of the multiple dikes, intruded at different times as indicated by field observation, are defined as members of the multiple dike.

Wall Rock

Wall Rock is a multiple dike composed of 5 members, all intruded along the same fracture. The individual members of the dike range in width from 3 inches to 3.5 feet. The widest member, forming the 23 foot high wall, occurs on the western side. It contains abundant, large, indurated, light-colored siltstone inclusions and has chilled contact zones on both sides. The smaller members range in width from 3 to 6 inches, and have indurated sediments between them varying in thickness from one-half inch to 4 inches. The smaller members show very marked vertical lineation of the calcite-filled vesicles which increase in size and abundance near the contact zones.

Half Sediment Butte

Half Sediment Butte is a multiple dike with two members indicated by a chilled vesicular zone in the center and at the sedimentary-igneous contacts. (Plate II, Figure 3). It is located on the north end of the sandstone-capped ridge near index number (9) (Plate I), and supports siltstone of the Tullock member on its east side. The rock is light gray and flow banded with very abundant calcite vesicle fillings and inclusions. A simple dike extends south for a short distance from the multiple dike.

Half Sediment Butte penetrates the indurated sandstone caprock. Near the contact of the caprock and the dike, the sandstone has been fractures in narrow intervals. These intervals become wider spaced away from the contact and strike parallel to the trend of the dike (N. 32°E.).

Exposure (2)

This exposure also is a multiple dike, but it differs considerable from the two types just mentioned. It is composed of three members. The outer member is composed of a light gray, flow banded rock varying from 2 to 4 feet in thickness. Small vertically oriented inclusions of light-colored siltstone are abundant. Close to the contact with the inner member, this outer member rock is cleaved into plates less than one inch thick. The cleavage is inclined away from the center of the dike. A sharp contact exists between the rock of the outer member and the rock of the second member towards the center. There also is an abrupt change in color and texture. The second member rock is dark colored with megascopically visible biotite. This second member surrounds a glassy center zone and emerges from 12 feet, both north and south, in dikes showing normal characteristics.

The center member is composed of a black, friable, glassy rock with light-colored amygdules and olivine and biotite phenocrysts. Its friable nature causes a depression at the top of the intrusive. The contact between the center member and the surrounding middle member is sharp.

The dike is undoubtedly a multiple dike with the outer member intruded first, followed by the dark middle member and that in turn followed by the glassy center. After consolidation, further pressure from below caused the shearing of the light colored zone furthest from the center.

Rocks similar to those found on exposure (2) are located near index number (8) and (18). Near exposure (8), the rock is dark and amygdaloidal and is similar in hand specimen to the zone rimming the center of exposure (2). The dike is 24 feet long and 6.5 feet wide.

Near index number (18), the rock type is similar to the center zone of exposure (2) with abundant amygdules and a friable nature. It occurs in two dikes just north of Instrument Butte. The northern dike is 24 feet long and 9 feet wide. The southern dike is 38 feet long and 9 feet wide.

PETROLOGY

Introduction

The rock suite from the Smoky Butte area includes only fine-grained, porphyritic types. In general, the rocks can be divided by color into light gray, or brown types, and into dark colored types. The light colored types form all the plugs except Smoky Butte and are found in some of the dikes. The dark colored rocks compose Smoky Butte, its dike extensions, and Ship Rock plus some small minor dikes. The lighter colored rocks contain many more inclusions, a much greater percentage of calcite, and more marked flow banding than the darker rocks. Much of the color difference is probably the result of the greater abundance of these inclusions. The lighter colored plugs were intruded first because in places they are either cut by the dark dikes, or the dark dike pattern is controlled by the plugs.

All the rocks appear to have the same basic mineralogy and differ only in color, texture, and mode. Generally, they are composed of sanidine, biotite, pyroxene, leucite, olivine, serpentine, apatite, magnetite plus ilmenite with a groundmass of a light yellow, isotropic glass or a dark green slightly birefringent, fibrous glass.

Two chemical analyses were made of rocks from Smoky Butte quarry which show a close relationship indicating that they are comagmatic (Table IV, Analyses 1 & 2). The rock suite is rich in potassium, magnesium, phosphorous, and titanium, and poor in aluminum, sodium and calcium. According to Wade and Prider (1939, p. 50), in discussing similar rocks, the peculiar nature of the rocks has been caused by the low aluminum and the high potassium content. The Smoky Butte rocks are oversaturated and contain a disequilibrium mineral assemblage that indicates near surface conditions.

It appears that all the Smoky Butte intrusive rock types have the same chemical composition. Mineralogical and textural differences are accounted for by different rates of cooling and different conditions occurring during emplacement (the modes of 13 thin sections are given on Table I).

Because of the unusual nature of the Smoky Butte rocks, well-known established rock names cannot be applied to them. Rather than use little known rock names with modifiers, descriptive names are used instead. The Smoky Butte rocks have been divided into six different types which have been named with regard to the characteristic mineral components of ecah.

Type I: Sanidine-biotite rock; dark; fine grained; microlites of biotite and sanidine in the groundmass are the chief constituents.

Type II: Sanidine-leucite-biotite rock; dark; phenocrysts of biotite, sanidine, and serpentinized olivine with small leucite crystals.

Type III: Leucite-olivine-biotite rock; dark; phenocrysts of biotite and olivine; small leucite crystals; light green, glassy groundmass.

Type IV: Olivine (calcite)-biotite; light; phenocrysts of biotite and calcite pseudomorphs after olivine; glassy groundmass contains sanidine microlites but no leucite; calcite vug fillings and inclusions.

Type V: Olivine (serpentine)-biotite rock; dark; phenocrysts of biotite and serpentine pseudomorphs after olivine; sanidine microlites in groundmass glass; less calcite than Type IV.

Type VI: Sanidine-biotite-calcite rock; light; sanidine and biotite occur as microlites in groundmass; calcite inclusions and vug fillings.

Petrography

Type I: Sanidine-Biotite Rock

This rock type is exposed on the east and west sides of Smoky Butte quarry and consists of a dark, amygdaloidal, columnar jointed, sanidine-biotite rock. The jointing is flared, indicating the plug-like nature of this intrusion. Type I rock extends 150 feet north of the quarry where it contacts the sanidine-leucite-biotite (Type II) rock to be discussed next. A chemical analysis (Table IV, Number (2)) was made of this rock type.

Under the microscope, flow banding is very distinct (Plate IV, Figure 1) and oriented phenocrysts of sanidine and serpentine pseudomorphs after olivine are observed. The groundmass is indeterminable except for small opaque granules and euhedral crystals of magnetite and ilmenite. The rock is cut by fractures filled with calcite, euhedral quartz and epidote, clay minerals, and serpentine. These same minerals occur in vugs with minor amounts of hematite.

Although the bulk of this rock type is exposed on the west side of the quarry, a better insight of the actual mineralogy was obtained from the east side of the quarry. There, although the rock is similar in hand specimen, the groundmass is a little coarser grained. The petrographically identifiable minerals are: sanidine in phenocrysts, 5%; sanidine in groundmass, 30%; biotite, 12%; fresh olivine tr., serpentine, 3%; quartz in xenoliths, 2%; vug fillings of quartz, 1%; epidote, 1%; magnetite plus ilmenite, 14%; apatite, 5%; pyroxene, 2%; and unidentified, 26%. These are estimated percentages.

X-ray diffraction patterns of samples from both sides of the quarry show strong sanidine peaks indicating that sanidine is present in the microscopically indeterminable groundmass on the west side of the quarry.

Sanidine is the most common phenocryst and occurs in euhedral crystals in amounts up to 5%. It has a small 2V, negative sign, and indices less than balsam. Oligoclase is present in phenocrysts on the west side of the quarry in amounts up to 3%. It has a 2V of 60 degrees, extinction angle of 7 degrees on the albite twins, and a positive sign. A few of the crystals are zoned. Phenocrysts of pseudomorphs after olivine are present in amounts up to 1%. The pseudomorphs commonly carry a small amount of unaltered olivine in the centers. The bulk of the elongated euhedral crystal forms have been replaced by serpentine, quartz, epidote and calcite.

The rock has many vug and fracture fillings, containing eipdote and quartz in euhedral form, calcite, serpentine, clay minerals, and hematite. The epidote has high relief, slight pleochroism in a light yellow, birefringence of .013 to .015, high dispersion, and a 2V of about 75 degrees.

	TYPE II							TYPE III			TYPE IV	TYPE V	TYPE VI
Sample Number	1	19	24	25	26	42	43	22	3	49	7	5	8
Sanidine	40.6	33.2	35.3	35.2	31.4	33.0	32.8	—	—	2.6	7.5	11.5	17.5
Biotite	14.7	25.9	14.9	16.6	20.0	20.2	32.6	10.4	6.0	8.8	27.0	19.0	35.0
Pyroxene	10.6	8.6	8.6	7.0	9.8	5.0	5.0	7.3	9.0	13.6	—	2.0	—
Leucite	8.8	3.1	12.7	10.9	11.0	15.6	1.4	22.7	15.6	18.4	—	—	—
Olivine	1	1.5	tr.	tr.	tr.	tr.	0.4	9.2	4.6	4.0	pseud. 6.0	pseud. 8.5	pseud. 3.0
Serpentine	5.8	3.0	2.0	3.0	1.8	tr.	tr.	tr.	tr.	tr.	—	tr.	tr.
Ore	5.0	11.3	9.0	9.3	7.6	7.6	5.0	14.7	22.0	15.2	4.0	8.0	2.5
Apatite	4.5	4.4	4.5	4.3	4.5	4.2	2.4	8.6	5.0	7.4	4.0	4.0	3.5
Quartz	1	tr.	3.1	0.3	0.7	1.2	7.8	—	tr.	—	4.0	2.0	4.0
Calcite	—	—	—	tr.	0.1	0.4	tr.	—	—	—	7.0	1.0	11.5
Glass	9.1	9.1	8.8	13.2	13.1	11.0	12.0	26.7	20.8	22.0	38.5	44.0	8.0
Hematite	—	—	—	—	—	—	—	—	—	—	—	—	4.0
Unidentified	—	—	1.6	—	—	1.4	1.0	—	17.0	8.0	2.0	—	13.5

TABLE I

MODAL ANALYSES OF 13 THIN SECTIONS

Xenoliths make up from 5 to 15% of the rock and occur as elongated pod-shaped, quartzitic types oriented with respect to the flow banding. A narrow dark, glassy, band surrounds the xenoliths. Pleochroic yellow masses, consisting of highly birefringent crystal aggregates, occur throughout the groundmass and surround the quartzitic xenoliths. This mineral is presumed to be biotite since biotite was observed on the east side of the quarry in larger crystals of similar appearance.

Type II: Sanidine-Leucite-Biotite Rock

Type II rock occurs in Smoky Butte quarry, intruding the dark, sanidine-biotite columnar jointed type just described. It makes up the bulk of the butte and is exposed 150 feet north of the quarry, on top, and on the sides of the butte. It is greenish gray in color and has megascopically visible biotite phenocrysts up to 3 mm long.

In thin section, this rock can be seen to be a porphyry with phenocrysts of biotite, sanidine, pigeonite, augite, and olivine. The other minerals present include: leucite, apatite, serpentine, quartz, calcite, magnetite plus ilmenite, and a glassy groundmass. Model analyses 1, 19, 24, 25, 26, 42 and 43 are of this rock type (Table I). Chemical analysis (I) (Table IV) was made of this rock type. See also the photomicrographs (Plate V, Figure 1 & 2).

Sanidine is the most common mineral and composes 35% of the rock in the quarry and 41% on the top of the Butte and at the upper contact in the quarry. The sanidine occurs both as elongated phenocrysts and as small rod shaped microlites. It is optically negative and has a 2V of 25 degrees and indicies less than balsam.

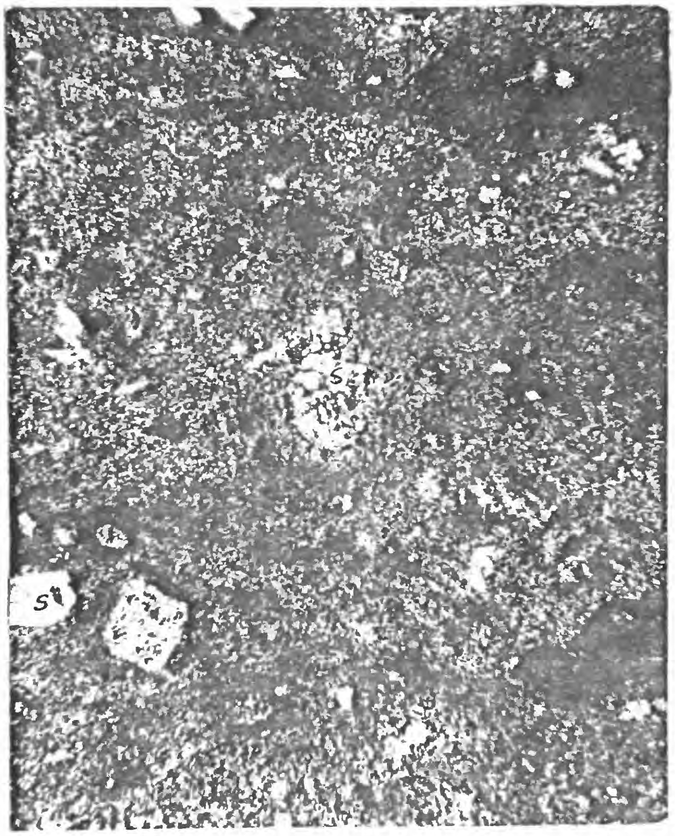


Figure 1: Type I rock: shows sanidine phenocrysts (s), indeterminable groundmass (west side of quarry), and flow banding. Plain light, x 50.

Plate IV

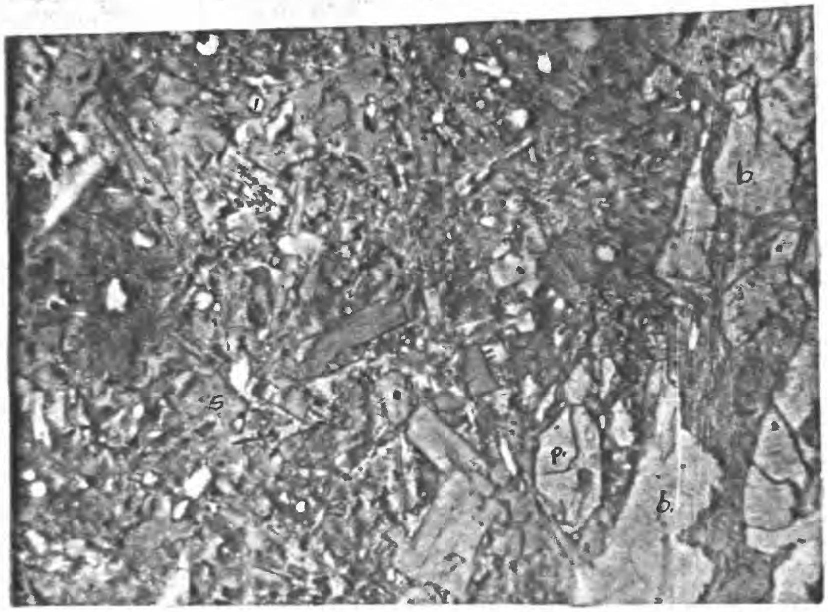


Figure 1: Type II rock; shows biotite (b), sanidine (s), leucite (l), pyroxene (p), magnetite and ilmenite (opaque), and apatite needles (clear). Plain light, x 50. West side of quarry.

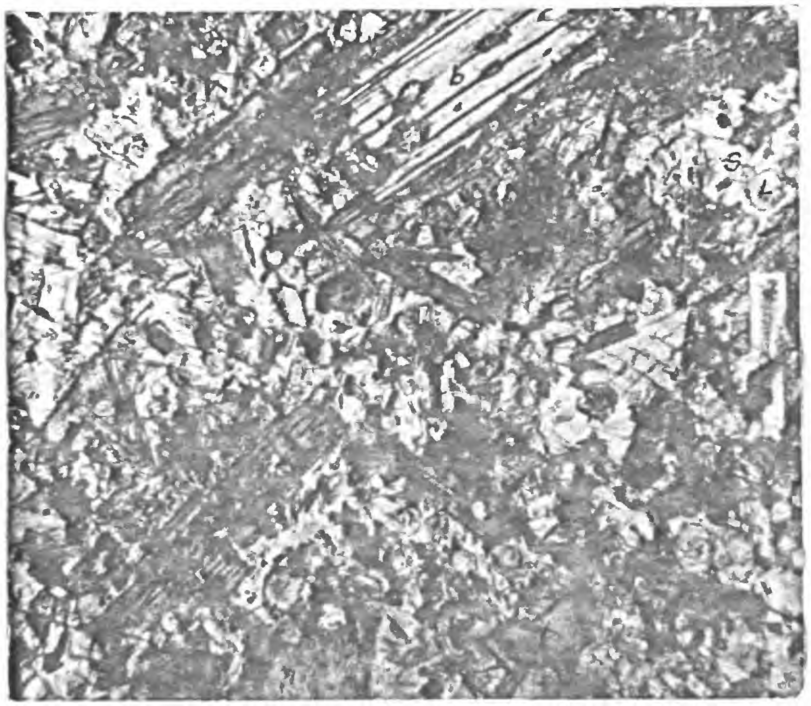


Figure 2: Type II rock; shows biotite (b), sanidine (s), leucite (l), pyroxene (p), magnetite & ilmenite (opague), and apatite needles (clear). Plain light, x 50. East side of quarry.

Plate V

Figure 1: Type III rock; shows leucite (l), olivine phenocyst (o), biotite phenocrysts (b), apatite needles (clear), magnetite & ilmenite (opaque grains), and glassy groundmass. Plain light, x 50.

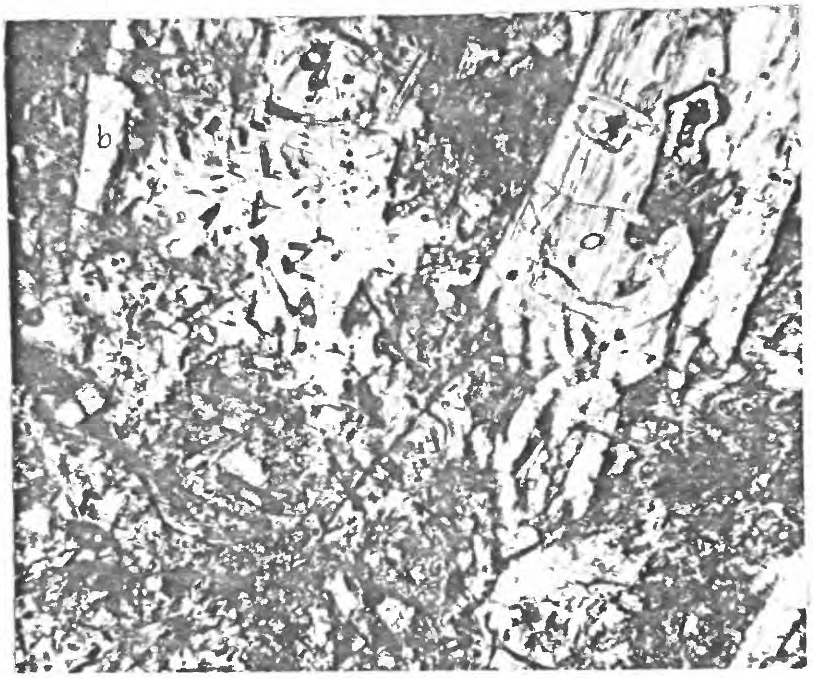


Figure 2: Type V rock; shows serpentine pseudomorph after olivine (o), magnetite & ilmenite (opague), apatite needles (clear), and both light and dark glassy groundmass. Plain light, x 50.

7

Plate VI

Biotite is the next most abundant mineral. It is present in amounts ranging from 15 to 33%. The smallest percentage occurs at the top of Smoky Butte, and the highest percentage occurs in the quarry next to the upper contact. The biotite is in euhedral plates and laths with the 2V varying from 5 to 40 degrees. It is pleochroic with X = light yellow, Y = light reddish brown, and Z = reddish brown. Extinction angles of 6 degrees with respect to the cleavages were observed on a few of the elongated laths. Many of the large plates have hornblende cleavage with the Mg rich center of the crystal a light yellow, and the Fe & Ti rich edges a darker yellow to reddish brown. All the biotite is poikilitic containing leucite, apatite, pyroxene, or smaller biotite laths. The refractive index of Y varies from 1.646 to 1.654. The type with the higher refractive index has a 2V close to 40 degrees, while the lower index type has a 2V ranging from 5 to 20 degrees. One anomalous biotite crystal 4 mm long has an extinction angle of 35 degrees. The pleochroism is the same as has been mentioned, and it has a 2V of 45 degrees. Its optic orientation is $Z \wedge C$ of 35 degrees. On the east side of the quarry, the biotite has greater absorption with the color of deep reddish brown, indicating a higher iron and titanium content.

Pigeonite and augite are present in both large and small euhedral crystals. The pyroxenes have an extinction angle of 45 degrees, and crystals with a 2V of 25 and 60 degrees are both present. The augite is predominant over the pigeonite by a ratio of 2:1. The maximum length of the largest pyroxene is 0.5 mm. The larger pyroxene crystals are located in the rocks on the west side of the quarry and on the top of the butte. On the east side of the quarry, the pyroxene crystals are much smaller with the only possible optical determination that of extinction angle.

Leucite occurs in subhedral to euhedral equant crystals surrounded by sanidine. A certain amount of recrystallization has taken place because the crystals are not wholly isotropic. The leucite crystals have a negative relief and a poorly defined contact with the sanidine. Some crystals show an equant, euhedral form in which sanidine is visible inside the leucite crystal outline while the rounded center remains completely isotropic.

Olivine is present in all the sections in amounts up to 2 percent. It occurs as unaltered portions of the original large phenocrysts which are up to 2 mm in length, and as small euhedral and anhedral crystals in the groundmass. The 2V is close to 90 degrees and the sign is negative. The Y index is 1.670, giving a composition of Fo_{78}. The majority of the stubby and club-shaped crystals have been altered to the highly birefringent serpentine bastite, which is light green in plane light. Serpentine of lower birefringence, pseudomorphic after olivine, is especially abundant at the top of the butte.

Magnetite and ilmenite occur in small euhedral equant and elongated crystals in amounts ranging from 5 to 11%. The lowest percentage of these minerals is present on top of Smoky Butte, and next to the upper contact in the quarry. The amount present, on the average, in the rest of the quarry rocks is 9%. Apatite occurs in very small needles and in large euhedral, elongated crystals. The apatite is fairly constantly present at 4.5%, but decreases at the upper contact in the quarry to 2.4%.

Quartz occurs in xenoliths surrounded by a narrow glassy zone, or intersticially. Calcite is present in minor amounts as a replacement of olivine. The groundmass averages about 11% of the rock and consists of glass which in plane light is dark greenish, and occurs between the sanidine laths. Under crossed prisms it polarizes light slightly.

In summary, the same minerals are present in all the thin sections of the sanidine-leucite-biotite rock. There are, however, some minor microscopic differences. The biotite in the rock on the east side of the quarry is much darker color, indicating a higher Fe and Ti content than the rest of the sanidine-leucite biotite rock. At the top of the quarry, near the upper contact, the leucite, magnetite plus ilmenite, and apatite content decreases.

Type III: Leucite-Olivine-Biotite Rock

This rock type is exposed in the center of Smoky Butte quarry and is readily identified in the field by its spheroidal weathering. It intrudes the sanidine-leucite-biotite rock type just described and is a much darker color with megascopically visible biotite and olivine phenocrysts. The rock composing the Smoky Butte dike extensions to the north and south, and the rock composing Ship Rock is related to this type. These rocks have the highest percentage of magnetite plus ilmenite. Modal analyses of these rocks are given on (Table I, samples 23, 3, 49). See also the photomicrograph of this rock type (Plate VI, Figure 1).

The petrographically identifiable minerals of sample 22, taken from Smoky Butte quarry are: leucite, 23%; olivine, 9%; pyroxene, 7%; serpentine tr., magnetite plus ilmenite, 15%; apatite, 8%; and a groundmass of yellowish glass, 27%. The rock is porphyritic with vertically oriented phenocrysts of olivine and biotite up to 3 mm in length.

The leucite is fresh, poikilitic, and contains microlites of apatite, magnetite, and ilmenite. It is present in small equant, euhedral crystals showing radially arranged inclusions and is up to 0.18 mm in diameter. The leucite has strong negative relief and is completely isotropic.

Olivine occurs in large, vertically oriented, euhedral skeletal and normal crystals up to 2 mm in length, and in small anhedral crystals in the groundmass. The refractive index of Y is 1.670, giving it the same composition as was present in Rock Type III (Fo_{78}).

The biotite is similar to that discussed previously in the sanidine-leucite-biotite type (Type II). It is present in plates and in elongated laths. The biotite is poikilitic containing magnetite and ilmenite, apatite, leucite, and pyroxene. Hornblende cleavage is visible in some of the plates.

Pyroxene occurs only in small microlites with the only possible optical test being the extinction angle of approximately 40 degrees.

A small veinlet traversing the thin section shows serpentinization of the groundmass glass and biotite. The light yellow glass has been altered to a darker green glass with a fibrous texture showing some polarization of light in first order interference colors. A biotite phenocryst 2 mm long has the center altered to serpentine while the outer part of the crystal has been unaltered.

Apatite occurs in both large and small euhedral elongated crystals. Magnetite and ilmenite occur in small euhedral equant and elongated crystals.

The groundmass consists of a light yellowish isotropic glass with a refractive index of 1.536. According to the classification given by Wahlstrom (1955, page 286), this glass falls in the leucite-tephrite range and has a silica content of approximately 58 per-cent by weight.

A variety of this rock type (leucite-olivine-biotite) is present in the Smoky Butte dike extensions and in Ship Rock. It differs from the variety just described in that it is much finer grained and has no megascopically visible minerals.

The petrographically identifiable minerals are the same as listed under sample 22, including: leucite, 15.6%; olivine, 4.6%; pyroxene, 9%; serpentine tr., magnetite plus ilmenite, 22%; apatite, 5%; quartz tr., a groundmass of yellowish glass, 20.8%; and unidentified, 17%. (For comparison of modes of Type III rocks see Table I). The grain size, however, is much finer. A few large unaltered olivine phenocrysts are visible and subhedral olivine microlites occur in the groundmass. The olivine is poikilitic containing opaque euhedral microlites of ilmenite and magnetite, and has a 2V close to 90 degrees and a positive sign. Pyroxene microlites were recognized by their extinction angle of 40 degrees. Poikilitic biotite containing euhedral opaque minerals, apatite, and leucite occurs in small irregular patches and euhedral elongated form with a pleochroism of X = light yellow, Y = light reddish brown, and Z = reddish brown. The biotite crystals are considerably smaller than the similar rock in the quarry (maximum length 0.2 mm). The leucite in the groundmass is present as euhedral, isotropic crystals with a maximum diameter of .04 mm. Apatite occurs in extremely small microlites dispersed throughout the groundmass.

Quartzitic xenoliths in this section have a rounded grain outline with a light yellowish glassy border. The grains are penetrated by a highly birefringent unknown mineral.

Sample 49, taken from Ship Rock, shows approximately the same mineralogy as sample 3, with one exception. Small sanidine crystallites occur in the groundmass. The grain size is larger than the dike rock just discussed with the biotite having a maximum length of 0.4 mm., and the leucite a maximum diameter of 0.09 mm. This rock has the greatest amount of pyroxene of all the rocks in the suite (see modal analysis, Table I, sample 49). The pyroxene occurs both in small crystallites and in large partially resorbed plates up to 0.5 mm. in length. 2 Vs of approximately 25 and 60 degrees were observed indicating the presence of both pigeonite and augite. The extinction angle is 45 degrees. Olivine occurs in euhedral phenocrysts and in small anhedral grains in the groundmass. The olivine is not serpentinized, but appears to have been broken up.

In summary, the rocks exposed in Smoky Butte quarry, the Smoky Butte dike extensions, and Ship Rock show the same mineral assemblage with minor exceptions. In general, the mineral size decreases according to the size of the intrusive. It appears that the rocks were intruded with olivine, leucite, biotite, and accessory minerals of apatite and opaque minerals. Ship Rock had also, when intruded, some large pyroxene phenocrysts.

Type IV: Olivine (Calcite)-Biotite Rock

This rock type forms the center of exposure (1) and shows a texture worthy of description in some detail. It differs from Type III, just described, in that there is complete absence of leucite, more glass is present in the groundmass, and sanidine occurs in oriented microlites.

In the hand specimen, the rock is light greenish gray in color. It has megascopically visible reddish-brown biotite, and abundant calcite vug fillings with inwardly terminated crystals. Calcite also occurs as inclusions.

The petrographically identifiable minerals are: biotite, 28%; sanidine, 7.5%; calcite pseudomorphs after olivine, 6%; calcite filling vugs, 4%; quartz, 4%; serpentine tr., magnetite plus ilmentite, 4%; apatite, 4%; and a glassy groundmass, 38.5%. The most striking aspects of this rock type are the light color, abundance of large euhedral phenocrysts, calcite pseudomorphs after olivine, and the very abundant glass.

Sanidine is confined entirely to the groundmass as elongated microlites. The microlites frequently occur as oriented aggregates with the dark greenish glass present between the individual crystals. In parts of the section a mesh structure is visible, composed of microlites of sanidine oriented perpendicular to one another with dark green isotropic glass between them. In some parts of the section, the sanidine is almost completely absent.

The biotite is the dark reddish-brown variety, and occurs as euhedral plates and laths up to 1 mm in length. It is poikilitic and encloses numerous needles of apatite, magnetite plus ilmenite, and calcite.

Calcite is very abundant as vug fillings, inclusions, and as pseudomorphs after olivine. The vugs are oval in shape and are up to 4 mm in diameter. The pseudomorphs average 1 mm in length and are in euhedral stubby and elongated crystal form. In some of the elongated pseudomorphs the skeletal olivine crystal structure, similar to the olivine in sample 22 from the quarry, is still visible. Euhedral quartz, some hematite, and a trace of serpentine around the outer edge of the crystal form occur with the calcite but are subordinate to it. Although much of the calcite occurs as vug fillings and in veinlets crossing the thin section, there is some evidence that it may occur as xenoliths also. Several of the large oval-shaped vugs actually appear to be calcite xenoliths because of the wide glassy zone around them.

Magnetite and ilmenite occur in euhedral elongated microlites in the groundmass. Apatite occurs in small, elongated needles. The groundmass is dark green in plane light and is isotropic.

Type V: Olivine (Serpentine)-Biotite Rock

This rock type forms the wall and center zone of exposure (2), the short dike at exposure (8), and the two dikes near index number (18), just north of Instrument Butte. In general, the dark, amygdaloidal rock in the center of exposure (2) is very similar to the outer dark, more resistant rock; except that it has more abundant fractures, a greater number of amygdules, and lacks sanidine.

Type V rock differs from Type IV in that serpentine instead of calcite occurs as pseudomorphs after olivine. The biotite is not as abundant, nor in as good crystal form, and pyroxene is present.

In hand specimen, Type V rock is a dark gray color with megascopically visible biotite, serpentine pseudomorphs after olivine, and calcite. Microscopically, the identifiable minerals are: sanidine, 10.5%; biotite, 19%; serpentine pseudomorphs after olivine, 8.5%; pyroxene, 3%; magnetite plus ilmenite, 8%; apatite, 4%; quartz, 2%; calcite tr., epidote tr., and a glassy groundmass, 44%. The modal analysis of types IV and V are given again on Table 1. See also the photomicrograph (Plate VI, Figure 2).

The biotite occurs in euhedral and subhedral plates and laths with a maximum length of 0.7 mm. It is pleochroic with Z = reddish-brown, Y = light reddish brown, and X = almost colorless to light yellow. The biotite is poikilitic containing magnetite plus ilmenite and apatite.

Sanidine occurs in the groundmass glass as microlites, and appears to have just begun to crystallize when it froze because in plane light few crystal outlines are visible. With crossed prisms, the sanidine microlites can be readily distinguished dispersed throughout the glass.

Most of the pseudomorphs after olivine are serpentine instead of calcite, which is the case in Type IV rock. Olivine is present as small unaltered portions of the original phenocrysts and in small partially serpentinized crystals in the groundmass. Some of the pseudomorphs after olivine are as long as 3 mm with a good euhedral crystal form; a few have skeletal form. The serpêntine is fibrous. In plane light it is light green and has a high apparent birefringence under crossed prisms. The 2V is about 25 degrees.

The pyroxene occurs in needle shaped crystals up to 2 mm in length with a 45 degree extinction angle the only possible optical determination. Magnetite, ilmenite, and apatite occur in small microlites dispersed throughout the groundmass. Calcite, quartz, and epidote occur as vesicular fillings.

The groundmass is slightly darker than that in Type IV rock. It ranges in color from a light yellow to brown in plane light. With crossed prisms, the light yellow glass can be seen to carry the abundant sanidine microlites while the darker, brown colored, almost isotropic glass occurs around areas containing abundant vesicles.

The center zone of exposure (2) differs but little from the outer more resistant zone. In hand specimen, the rock is dark colored, friable, contains abundant amygdules, and has megascopically visible olivine phenocrysts. The mineralogy is the same as in the outer zone with the same size range. There are some minor variations. Namely, unaltered olivine is more abundant, the groundmass glass has a turbid nature, there are more fractures that traverse the section in two directions, and sanidine is absent.

The biotite is the same as in the outer zone. Olivine occurs as unaltered parts of the original equant to elongated euhedral crystals. It also is found in small euhedral to anhedral grains in the groundmass. Many of the olivine crystals have the skeletal form previously described. The serpentine has replaced from one-half to all of the larger olivine crystals.

The groundmass glass is interesting because of its turbid nature. This type of turbid isotropic glass was not seen in any of the other rock types. The glass varies in color from clear to light yellow and shows no sanidine.

The abundant anygdules were studied by x-ray diffraction and found to be made up mostly of montmorillonite with a little quartz. The rock is cut by small irregular fractures filled by a highly birefringnent unknown mineral. Evidently the center zone of exposure (2) cooled more rapidly than the outer more resistant zone causing the close fracturing and inhibiting the development of sanidine in the groundmass.

Type VI: Sanidine-Biotite-Calcite Rock

This rock type makes up all the plugs, excluding Smoky Butte, and the dikes not mentioned under the previous rock descriptions. These include Top Contact Butte, Radial Dike Butte, exposure (6), Bull Snake Knob, Half Sediment Butte, the dike extending from exposure number (10), to (13), Instrument Butte, Wall Rock and exposure numbers (25) and (26).

In hand specimen, Type VI rocks are light gray or brown in color, have very abundant inclusions, and contain calcite as the only megascopically visible mineral. Generally, they are very fine-grained, flow banded types. X-ray diffraction determinations of the minerals supplemented the microscopic determinations. Correlation of some specimens by mode determined by x-ray diffraction was made to specimens in which the mode was determined petrographically. In all the rocks, moderate to strong sanidine peaks were present indicating their close relationship.

Except for their lighter color, these rocks do not differ greatly from the columnar jointed rocks of Type I. The same minerals can be identified microscopically, with microlites of sanidine and biotite making up the largest part of the rocks. The lighter color of Type VI rocks can probably be attributed, in large part, to the abundance of inclusions and calcite.

Sample (8), taken from Top Contact Butte, is fine-grained, light brown in color with vug fillings of calcite the only megascopically identifiable mineral.

The petrographically identifiable minerals are: sanidine, 17.5%; biotite, 35%; magnetite plus ilmenite, 2.5%; calcite pseudomorphs after olivine, 3%; calcite in vugs, 11.5%; quartz, 4%; menatite, 5%; apatite, 3.5%; and a groundmass glass, 8.0% with 17.5% unidentifiable material.

The sanidine and biotite occur as microlitic equal-sized crystals up to 0.2 mm in length in the groundmass. There are a few sanidine phenocrysts present as long as 0.5 mm. The average size of the sanidine and biotite is .02 mm. The biotite is the reddish-brown variety with pleochroism of X = colorless to light yellow, Y = light reddish brown, and Z = reddish brown. Hematite appears to be an alteration product of biotite with which it is associated throughout the section. In places the sanidine is well-developed with a low 2V and a negative sign. It occurs in both equant grains and elongated laths.

Calcite occurs as pseudomorphs after olivine in euhedral elongated crystals up to 2 mm. in length and in large oval shaped vugs up to 3 mm in diameter. Quartz occurs with the calcite, but is subordinate to it.

Magnetite and ilmenite occur in elongates needle shaped microlites. The apatite is present as exceedingly small needles in the groundmass. The groundmass glass, dark green in plane light, is isotropic and occurs between the sanidine microlites.

Samples taken from the dike at exposure (11) and Instrument Butte, show the same mineral assemblage as above except that they lack the pseudomorphs of calcite after olivine. The texture is the same except that the crystal size of the biotite and sanidine is slightly larger. Calcite occurs filling vugs and is very abundant. The ore minerals are more abundant than in sample (8).

Microscopically, a sample from one of the 6 inch wide dikes at Wall Rock, shows very marked vertical lineation, with the abundant ore and apatite needles vertically oriented. Calcite vesicle fillings are very abundant in lengths up to 6 mm. The groundmass polarizes light and was determined to contain sanidine by x-ray diffraction. No pseudomorphs after olivine are present.

PETROGENESIS

Introduction

The greatest amount of data available for petrogenetic interpretation exists for the rocks exposed in Smoky Butte itself. The rock types present in the Butte are the sanidine-biotite rock (Type I), the sanidine-leucite-biotite rock (Type II), and the leucite-olivine-biotite rock (Type III). The field relationships allow an interpretation of the intrusive sequence of these three rock types. The available chemical analyses are of rock Types I and II, sampled in Smoky Butte. Therefore, the petrogenesis of the rocks in Smoky Butte will be discussed first, and this discussion will be used as a basis for interpreting the other rock types present in the suite. The accessory minerals magnetite, ilmenite, and apatite which occur in all the rock types are not stressed in the following discussion.

Petrogenesis of the Rocks Present in Smoky Butte

The rock types present in Smoky Butte are shown in Figure 3, a sketch of the quarry where these rocks are well-exposed.

Field evidence shows that the sanidine-biotite rock (Type I) was the first intruded followed by the sanidine-leucite-biotite rock (Type II), and that in turn was followed by the leucite-olivine-biotite rock (Type III).

The sanidine-biotite rock (Type I) was intruded in plug form, as is indicated by the flared jointing of the columns. Later it was fractured on the west upper side and intruded by the blocky fractured sanidine-leucite-biotite rock (Type II). On the east side of the quarry the sanidine-leucite-biotite rock shows clearly the chilled contact effects with the columnar jointed rocks. The grain size decreases eastward to the contact and a more noticeable lineation is developed. Some shear occurs at the contact. Approximately 6 feet west from this contact, a fault with a one inch shear zone filled with quartz and chalcedony indicates movement of the Type II rock after solidification. The contact between the Type I rock and the sanidine-leucite-biotite rock (Type II) is not as well exposed at the west contact. It does, however, show a decrease in grain size and some shearing. The olivine-leucite-biotite rock (Type III) intrudes the sanidine-leucite-biotite rock (Type II) in a zone 16 feet wide. It is in sharp contact with the Type II rock.

Chemical analyses of Smoky Butte rock Types I and II are shown on Table IV, analyses (1) and (2). Analysis (1) is of the sanidine-leucite-biotite rock type and analysis (2) is of the sanidine-biotite rock. The norms of these rock types, the modes of the biotite-sanidine rock and the leucite-olivine rock, Type III, are given on Table II. No chemical analysis was obtained for the leucite-olivine-biotite rock (Type III). No mode for the sanidine-biotite rock was determined because of its fine-grained nature. However, x-ray diffraction shows it to be high in biotite and sanidine. The mode for the biotite- leucite sanidine rock (Type II) is a mean for all the thin sections of this rock type. Olivine and serpentine should be considered together as the total original olivine because most of the olivine has been altered to serpentine.

On the basis of the available data, the chemical analyses and the norms, it is evident that rock Types I and II are comagmatic. Although no chemical analysis was obtained for the olivine-leucite-biotite rock (Type III), it appears to have a similar composition. Evidence for this is the high percentage of silica rich glass present in the groundmass and the similarity of mineralogy which differs only in that the undersaturated minerals present in the olivine-leucite-biotite rock type failed to begin reacting with the melt to form saturated minerals, because of quenching. The differences in the rock types are accounted for by time of intrusion and rate of cooling. Table III shows the proposed intrusive scheme.

The columnar jointed Type I rock was the first intruded consisting of melt plus a few olivine crystals. In thin section, altered olivine phenocrysts make up less than 1 per cent of the rock with sanidine and biotite the predominant determinable minerals. Sanidine and biotite were determined petrographically on the east side of the quarry and their presence was confirmed on the west side of the quarry by x-ray diffraction. The small crystal size points to the conclusion that during intrusion the columnar jointed rock was completely molten, except for olivine phenocrysts, and that it crystallized rapidly in place.

The sanidine-leucite-biotite rock intrudes the Type I rock and was cooled relatively slowly, developing a much larger crystal size. The magma of this rock type contained crystals of olivine, leucite, and some biotite. The undersaturated minerals subsequently partially reacted with the melt to form saturated minerals during cooling. The reactions include leucite to sanidine and olivine to serpentine with pyroxene crystallizing from the melt. These relationships can be seen in thin sections. Most of the leucite has a poorly defined border with the surrounding sanidine. The olivine occurs only in small unaltered portions of the original euhedral crystals, the rest has been altered to serpentine. The pyroxene occurs in its largest crystal size away from the contact zones in the sanidine-leucite-biotite rock of the west side of Smoky Butte quarry. Many of the large biotite crystals have a pale Mg rich center and a dark Fe and Ti rich border indicating continued growth at the later stages of crystallization.

The olivine-leucite-biotite rock was the last type intruded. Its magma was intruded with leucite, olivine, and some biotite. Then it was quenched, prohibiting further reaction of the phenocrysts with the groundmass. Type III rock is a disequlibrium type in which crystallization progressed to the point where leucite had crystallized from the melt but was quenched before the leucite-orthoclase reaction could take place. The early crystallization must have occurred at some depth and at temperatures higher than the leucite-orthoclase reaction temperatures, after which the magma was intruded and the siliceous residue chilled quickly. This is evident in thin section as the minerals are unaltered except for a small veinlet traversing the section where the groundmass and a small amount of biotite were serpentinized.

The conclusion as to the sequence of events in the formation of the rocks in Smoky Butte is as follows. The amount of olivine originally present as phenocrysts follows the sequence of intrusion and allows an interpretation of the minerals present as phenocrysts when the magma intruded. Namely, there is an increasing amount of olivine in the sequence from the sanidine-biotite rock (Type I) to the sanidine-leucite-biotite rock (Type II) to the olivine-leucite-biotite

Modes

Rock Type	I	II	III
Sanidine	Major	34.5	- -
Biotite	Major	20.7	10.4
Pyroxene		7.8	7.3
Leucite		9.0	22.7
Olivine		1.3	9.2
Serpentine		3.1	Tr.
Ore		7.8	14.7
Apatite		4.2	8.6
Quartz		2.4	Tr.
Calcite		0.2	- -
Glass		10.9	26.7
Unidentified		1.5	- -

Norms

Apatite	4.5	4.8
Ilmenite	5.2	4.6
Rutile	0.7	1.4
Albite	8.0	10.5
Orthoclase	51.0	44.5
Anorthite	1.0	4.5
Hematite	1.5	1.9
Enstatite	21.0	22.8
Diopside	5.6	2.0
Quartz	1.4	3.1

Table II: Modes and Norms of Smoky Butte Quarry Rocks

Magma Chamber — Intrusive Rocks in Smoky Butte

Melt + few olivine xls
ore
apatite
— Intrusion with rapid cooling →
Sanidine-biotite (Type I)
Very fine grained with identifiable major minerals, biotite and sanidine.

Melt + 4% olivine
10% leucite
5% biotite
ore
apatite
? pyroxene
— Intrusion with slow cooling →

Reactions after intrusion
Olivine → serpentine
Leucite → sanidine
Melt → pyroxene +
Sanidine + more biotite

Sanidine-leucite-biotite (Type I)

Average Mode	
Sanidine	34.5
Biotite	20.7
Pyroxene	7.8
Leucite	9.0
Olivine	1.3
Serpentine	3.1
Ore	7.8
Apatite	4.2
Quartz	2.4
Calcite	0.2
Glass	10.9
Unidentified	1.5

Melt + 9.2% olivine
10.4% biotite
22.7% leucite
14.7 ore
8.6 apatite
7.3 pyroxene
— Intrusion and quenching →

Olivine-leucite-biotite (Type III)

Mode	
Biotite	10.4
Pyroxene	7.3
Leucite	22.7
Olivine	9.2
Ore	14.7
Apatite	8.6
Glass	26.7

TABLE III

PETROGENESIS OF SMOKY BUTTE QUARRY ROCKS rock (Type III). This is evident in thin section. Type I rock contains pseudomorphs of olivine in small amounts, not more than 1 per cent. Type II rock contains olivine and serpentine pseudomorphs after olivine averaging 4.4%. Type III rock contains the highest amount of olivine, 9.2%. This is the same sequence as that of the intrusions in Smoky Butte quarry. Leucite shows the same sequence because in the Type I rock it was not detected. In the Type II rock it averages 9% and in the Type II rock it makes up 22.7% by volume of the rock.

Relationships of the Other Intrusive Rocks to Those of Smoky Butte

The rocks exposed in the plugs and dikes, excluding Smoky Butte, are composed of 4 different rock types. Because Type VI rocks show close similarities to the biotite-sanidine rock (Type I) of Smoky Butte quarry, they will be considered first.

Generally, the Type VI rocks have sanidine and biotite occurring in the groundmass determined both optically and by x-ray diffraction. Olivine phenocrysts are absent except for Top Contact Butte where it occurs making up 3 per cent of the rock. In these respects the light colored plug and dike rocks resemble closely the Smoky Butte columnar jointed Type I rock. The light colored dike and plug rocks contain a much greater percentage of inclusions consisting of fine-grained, light-colored, indurated sediments and calcite, which account in large part for the lighter color.

The northern and southern Smoky Butte dike extensions and Ship Rock are composed of the dark, dense leucite-olivine-biotite rock (Type III). The southern Smoky Butte dike extension by-passes several small light colored plugs and as can be seen on Plate I, its outcrop pattern appears to be controlled by Instrument Butte, where it is offset to the west. The northern Smoky Butte dike extension cuts through a small light colored plug at exposure (15) (Plate I).

From the relationships pointed out above, the light-colored plugs and dikes composed of rocks similar to the sanidine-biotite rock (Type I) of Smoky Butte were intruded contemporaneously to the columnar jointed, Type I rock. The Smoky Butte dike extensions and Ship

TABLE IV

CHEMICAL ANALYSES MODES AND NORMS OF SMOKY BUTTE AND RELATED ROCK TYPES

	1	2	3	4	5	6	7	8
SiO_2	51.2	53.1	51.19	51.07	50.23	39.19	49.26	46.51
TiO_2	5.0	4.6	4.89	2.13	2.27	0.40	1.11	0.83
Al_2O_3	11.0	10.9	8.53	9.93	11.22	8.41	13.64	11.86
Fe_2O_3	2.6	2.1	6.12	2.72	3.34	3.47	1.72	7.59
FeO	2.7	3.4	1.38	1.19	1.84	5.51	7.76	4.39
MnO	0.13	0.1	0.06	0.04	0.05	0.24	0.12	0.22
MgO	8.0	8.4	7.15	10.31	7.09	22.78	8.31	4.73
CaO	4.2	4.3	5.82	4.87	5.99	8.90	8.42	7.41
Na_2O	1.1	0.9	0.58	0.82	1.37	3.23	1.90	2.39
K_2O	7.1	8.4	9.02	9.92	9.81	2.14	5.02	8.71
H_2O	4.1	1.5	3.25	4.23	2.65	4.22	1.53	3.55
P_2O_5	2.2	2.1	0.79	1.53	1.89	0.53	0.75	0.80
CO_2	0.09	<0.05	nil	- -	- -	- -	- -	- -
Others			.93	.90	2.87	1.44	.02	0.70
TOTAL	99.0	100.0	99.71	99.66	100.4	100.53	99.56	99.72

1. Smoky Butte Type II rock. At station 124 in Smoky Butte quarry. Rapid rock analysis by the U.S.G.S.
2. Smoky Butte Type I rock. 74 feet west of station 124 in Smoky Butte quarry. Rapid rock analysis by the U.S.G.S.
3. Cedricite (Leucite, diopside, phlogopite, K, Na, Mg amphibole, groundmass). (Wade and Prider, 1939, p. 75). West Kimberly, Australia.
4. Orendite (Pholognite, leucite, sanidine). Leucite Hills, Wyo. (Washington 1917, p. 592).
5. Wyomingite (Phologopite, leucite, diopside). (Cross 1897, p. 130).
6. Nephelene Hauynite Alnoite. Winnett, Montana. (Ross, 1926, p. 221).
7. Augite mafic phonolite. Highwood Mountains (Buie, 1941, p. 1768).
8. Leucitite. Bearpaw Mountains (Weed & Pirsson, 1896a, Vol. 2, p. 147).

Table IV (continued)

Modes

	1	2	22	3	4	5	6	7	8
Sanidine	Major	34.5			Major			50.0	
Plagioclase								7.0	
Biotite	Major	20.7	10.4	2.0	Minor	Minor	16.0	5.0	Minor
Pyroxene	Minor	7.8	7.3	10.0	Minor	Minor	5.0	25.0	31.1
Leucite		9.0	22.7	60.0	Major	Major			57.1
Olivine	Minor	1.3	9.2	5.0			35.0	10.0	
Serpentine	Minor	3.1	tr.						
Ore	Minor	7.8	14.7			Minor	6.0	3.0	11.8
Apatite	Minor	4.2	8.6		Minor		1.0		
Quartz	Minor	2.4	tr.						
Calcite	Minor	0.2							
Rutile				4.0					
Amphibole				5.0	Minor				
Hauynite							11.0		
Melilite							17.0		
Nepheline							4.0		
Glass		10.9	26.7			Minor			Minor
Unidentified		1.5		14.0			5.0		
Norms									
Apatite	4.5	4.8		1.6	3.5	4.0	1.1	2.4	1.6
Ilmenite	5.2	4.6		2.6	2.0	3.0	0.6	2.0	1.2
Rutile	0.7	1.4		2.3	0.5	0.2	--	--	--
Albite	8.0	10.5		5.5	8.0	7.5	--	10.5	--
Orthoclase	51.0	44.5		44.0	48.5	51.0	--	29.5	34.8
Anorthite	1.0	4.5		--	--	--	2.8	10.5	--
Hematite	1.5	1.9		4.6	2.0	2.4	0.4	--	4.5
Enstatite	21.0	22.8		10.8	4.0	--	--	--	--
Diopside	5.6	2.0		20.8	11.6	14.8	30.4	17.5	26.8
Quartz	1.4	3.1		2.2	--	--	--	--	--
K_2SiO_3				5.6	5.4	3.8	--	--	3.0
Nepheline					--	3.3	16.8	3.1	13.5
Olivine					14.7	9.9	36.5	14.7	2.5
Magnetite							4.0	2.6	3.0
Leucite							4.0		9.4
Kaliophillite							4.5		

Rock, composed of rocks similar to the leucite-olivine-biotite rock (Type III), were intruded later as was the Type III rock in the Smoky Butte quarry.

An anomalous situation occurs in exposure (1) and (2) in rock Types IV and V. These rocks contain a high percentage of biotite and calcite or serpentine pseudomorphs after olivine, sanidine microlites in the groundmass, but no leucite. Other rock types with this much olivine and biotite occurring as phenocrysts also contain leucite. Rock types IV and V were intruded with phenocrysts of biotite and olivine plus magnetite, ilmenite, and apatite and quenched as sanidine began to crystallize. These rocks were intruded after olivine and biotite had crystallized, but before leucite had crystallized. If these rock types were under higher P_{H_2O} then Type II and III rocks mentioned previously, there would be a smaller leucite range according to the system albite-orthoclase and the crystallization temperature would be lower. This would account for the absence of leucite and abundant biotite. After intrusion, a small amount of sanidine crystallized before the groundmass was frozen. The high percentage of initial olivine suggests that these types were intruded later, contemporaneous to Type III rock of Smoky Butte quarry. The lack of leucite, however, makes this a questionable conclusion.

Magma Type

The chemical characteristics of Smoky Butte rocks are unusual. Chemical analysis (1) (Table IV) is of the sanidine-leucite-biotite rock (Type II) and analysis (2) is of the sanidine-biotite rock (Type I). The other analyses given on Table IV are of rocks showing affinities or province relationships to the Smoky Butte intrusives.

As we have seen, rock Types I and II differ considerably in texture and structure but they have a similar chemical composition. Rock Type III also appears to have a similar composition.

The most striking features of the chemical analysis of Smoky Butte are the high potassium, phosphorous, titanium, and magnesium content, and the low aluminum and sodium content. The rocks are potassium-rich volcanic types and are related to the more potassium-rich subprovinces of the petrographic province of Central Montana: the potassium-rich subprovinces of the Highwood and Bearpaw Mountains. The Smoky Butte rocks differ from these types, however, in that they are oversaturated. The norm calculations show that there is more than a sufficient amount of silica to have formed all saturated minerals with 3.1 per cent excess silica in the sanidine-leucite-biotite rock type and 1.3 per cent excess silica in the sanidine-biotite rock. In this respect the Smoky Butte rocks are closely related to the West Kimberly, Australia rocks which have excess silica in the norm calculations and similar compositions. The Smoky Butte rocks are related also to the potassium-rich volcanic rocks of the Leucite Hills of Wyoming.

Analysis number (3) (Table IV) is of cedricite from the West Kimberly District of Australia. In general, the Smoky Butte rocks have less ferric iron, potassium, and calcium and more aluminum, phosphorous, and magnesium than the cedricite. The mineralogy of cedricite differs from the Smoky Butte rocks in that there is much less biotite and no sanidine associated with leucite, which is the predominant constituent (see Table IV for mode and norm) (Wade and Prider, 1939, pp. 65-66).

This feature is shown by the leucite-olivine-biotite rock (mode given on Table IV, sample 22) which occurs in the center of the Smoky Butte quarry and which has a similar composition to the sanidine-biotite rock (Type I) and the sanidine-leucite-biotite rock (Type II). The olivine-leucite-biotite rock (Type III), as can be seen in the mode has a higher biotite, olivine, ore, apatite, and glass content and a lower leucite content than the cedricite. Some of these differences can be explained in light of differences in water and oxygen pressure present during crystallization (Turner and Verhoogen, 1960, pp. 135-139). If the P_{H_2O} was higher and the P_{O_2} lower in the Smoky Butte rocks as compared to the cedricite, this would account for the higher biotite and ore content. The chemical analysis of cedricite (Table IV, analysis (4)) shows a greater ferric iron content when compared to the Smoky Butte analyses indicating higher oxygen pressure oxidized the ferrous iron to ferric iron. In the norm calculations the cedricite has an excess of silica. The greatest difference between the norm calculation of cedricite and the Smoky Butte rocks lies in the larger calculated diopside content. The greater amount of diopside in the norm of cedricite is caused by slightly more calcium and less phosphorous and aluminum present in the composition of the cedricite, which left more calcium to be used in making wollastonite and finally, more diopside. The potassium is in excess of the aluminum and was combined with silica to form K_2SiO_3.

Analyses (4) and (5) are of orendite and wyomingite from the Leucite Hills of Wyoming. According to Cross (1894, pp. 120-126) leucite and sanidine are the predominant minerals in orendite with subordinate phlogopite, amphibole, and diopside. Apatite and rutile are accessory minerals, but no magnetite, ilmenite, or pyrite occur. Wyomingite contains phlogopite, leucite, diopside, apatite, and a glassy groundmass. The phlogopite shows similarities to the Smoky Butte biotite in its high 2V (up to 35 degrees). The chemical analyses of the Leucite Hills rocks compare to the Smoky Butte rocks closely in most respects. The major differences are that they have more ferric iron and more potassium. The norm calculations, however, show that they are considerable undersaturated, because olivine and nepheline appear. Orendite and wyomingite, like the cedricite, have excess potassium over aluminum which was combined with silica to form K_2SiO_3. They have more calcium left from the apatite construction giving a higher calculated diopside content similar to cedricite.

As has been previously stated, the Smoky Butte intrusives lie on the extreme eastern edge of the petrographic province of central Montana. The nearest rocks that may be similar to Smoky Butte rocks are located 55 to 60 miles due south of Smoky Butte intrusives. Bowen (1915, p. 66) described a dike (9 feet wide and one-half mile long) on Porcupine dome in T. 10 N., R. 38 E., Rosebud County, Montana. The dike is composed of reddish brown vesicular rock containing small flakes of biotite, a considerable proportion of calcite, and some black shale inclusions. Only biotite and calcite could be determined petrographically.

Other small intrusives in the vicinity of Smoky Butte occur in T. 8 N., R. 36 E., Rosebud County, Montana, near the Ingomar dome. The dikes seem similar in occurrence and mineralogy to some of the Smoky Butte rock types. Heald (1926, pp. 26-27) described the dikes as intruding late Cretaceous sediments, varying in width from a few inches to several feet, and having strikes of from N. 68 E., to N. 80 E. They are composed of extremely altered light to dark greenish-brown material. A microscopic study of the rock shows it to be porphyritic; containing biotite, calcite, serpentine, and apatite. Inclusions are numerous consisting of crystalline light brownish-gray limestone, reddish quartzite, and light-gray shale. In some small limestone inclusions, carboniferous fossils were found indicating that this limestone was brought up from the Madison Limestone formation, probably more than 5,000 feet below the surface.

The nearest intrusive rocks to Smoky Butte that have been described in some detail are located 10 miles west of Winnett, Montana. As can be seen from the chemical analysis, the norm, and the mode (Table IV), the nepheline hauynite alnoite described by Ross (1926, p. 218-227) differs greatly from the Smoky Butte rocks and is highly undersaturated.

When the Smoky Butte rocks are compared to the most potash-rich rocks of the petrographic province of Central Montana, it can be seen that they are quite different (Table IV, analysis (7)). Buie's analysis (1941, p. 1767-1768) of augite mafic phonolite was used because it shows the closest approximate chemical composition to the Smoky Butte rocks. From the chemical analysis, the norms, and the mode (Table IV) the differences are apparent. The augite mafic phonolite is undersaturated with more anorthite present in the norm.

The leucitite from the Bearpaw Mountains described by Weed and Pirsson (1896a, p. 145-146) approaches the Smoky Butte rocka in alumina and potash content (Table IV). It differs, however, in being highly undersaturated. The most important features of the leucitite analysis are the low aluminum and silica, and the high potash content which sufficiently explain the presence of the leucite. In the mineralogy of the leucitite, the biotite shows similarities to that of Smoky Butte rocks. It occurs as large (5-10 mm), partially reabsorbed crystals which have a 2V of 38 degrees and are pleochoic from nearly colorless to dark reddish-brown.

CONCLUSIONS

The Smoky Butte rocks are shallow intrusives with a disequilibrium mineral assemblage. No extrusive rocks occur. Evidence of the upper contact is clearly visible for some of the intrusives: Top Contact Butte has 4½ feet of light yellowish Tullock sediments capping it; exposure (1) has a contact zone rock on its highest surface; Ship Rock, on its north end, has a darkened contact zone; Bull Snake knob with its flow banding shows evidence of deflection to the east.

The Smoky Butte plugs and dikes, arranged in a linear, *en echelon* pattern, intrude the Hell Creek formation and the Tullock member of the Fort Union formation. From the structural relationships, the intrusives appear to be related to the Tertiary folding of the Blood Creek-Sheep Mountain syncline of late Eocene time. The Flaxville gravel capping the ridge near Half Sediment Butte, of Miocene (?) or Pliocene time, was deposited after erosion had already exposed the intrusives.

The Smoky Butte rocks have been divided into 6 types. Because of their unusual nature they have been given descriptive names. The differences in the Smoky Butte rocks are accountable by time of intrusion and conditions existing during emplacement. Three different periods of intrusion have been proposed as indicated in Smoky Butte quarry (Table III shows the proposed scheme of intrusion). Other rocks, occurring in dikes and plugs, are related to the quarry types. The light-colored plugs and dikes were intruded contemporaneously to the Type I rock of Smoky Butte quarry. The dark dike rocks that have cut through the smaller plugs, or where their outcrop pattern appears to be controlled by the plugs, were intruded at the same time as Type III rock of the quarry. Because of the similarities in the chemical composition of the rock Types I and II, it is believed that Type III rock also has a similar composition. This rock has much more silica-rich glass in the groundmass. The difference in mineralogy and texture of the Smoky Butte rocks is accounted for by the minerals present when the magma was intruded and rate of cooling. The first intruded rock in Smoky Butte quarry contained the least amount of olivine and no identified leucite. The later intrusions contained progressively more olivine and leucite because crystallization was occurring in the magma chamber.

The high biotite and ore content of the rocks points to the conclusion that these rocks were subjected to high P_{H_2O}. The low ferric iron content indicated low P_{O_2}.

The high calcite content of the earlier intruded plugs and dikes cause the lighter color. This calcite occurs both as inclusions and vug fillings. About the dike rocks exposed near Ingomar dome, Head (1926, pp. 37) has said: "It is of considerable interest that the magma that formed these dikes was both sufficiently liquid to travel a mile or more and so cool that it did not appreciably alter the small limestone fragments that it contained." The calcite inclusions in the Smoky Butte rocks were probably brought up from the Madison formation.

METAMORPHISM

The metamorphic effects of the dikes and plugs vary with the size of the intrusive as well as the rock type. High induration of the sediments occurs only within a few inches of the contact of the light-colored gray dikes, dark fresh dikes, and the cone-shaped plugs. The degree of induration decreases away from the contact with unmetamorphosed sediments present 6 inches to 3 feet away from the contact, depending on the size of the intrusive. The widest contact metamorphic zone is at Smoky Butte, consisting of a highly indurated and fractured zone 10.5 feet wide. This zone makes a sharp contact with the slightly indurated sediments of the Tullock member on the west side of the quarry.

Xenoliths, both large and small, are most abundant in the light-colored dikes and plugs. They show a high degree of induration generally with a highly vesicular, darkened zone around them. In thin section, it can be seen that the smaller oriented siltsized quartzitic xenoliths have darkened glassy borders. In many cases rounded grain shapes making up the xenolith can be distinguished. The larger xenoliths are indurated, very light-colored types consisting of silt to clay-sized material.

The contact metamorphic rock above the quarry is very light gray in hand specimen and consists of indurated, silt-sized, rounded to subangular quartz and plagioclase feldspar grains. About 25 per cent of the rock is made up of the larger sized grains (0.3 mm). The groundmass is much finer grained, composed of silt-sized particles of quartz and feldspar with abundant calcite filled small fractures and voids.

A xenolith sampled in Smoky Butte quarry shows some of the features of the upper contact-metamorphic zone. It differs in that the grain size is smaller, there is less calcite present, and hornblende occurs. In hand specimen the xenolith is gray colored, badly fractured, and surrounded by intensified flow banding of the sanidine-biotite rock (Type I) which contains it.

The microscopically identifiable minerals in the xenolith mentioned above are: quartz and plagioclase making up approximately 30% of the rock; hornblende, 2%; biotite tr., opaque ore minerals tr. hematite tr, and unidentified highly birefringent mineral, 3%; and a groundmass, 63%. The larger quartz and feldspar grains are subangular to angular with a maximum length of 0.015 mm. The feldspar varies in optical properties indicating presence of both sodic and calcic types.

Hornblende occurs in elongated euhedral plates up to 0.47 mm in length with an extinction angle of 16 degrees and pleochroism from clear to light green. Biotite, pleochroic from colorless to dark brown has a small optic angle. The groundmass is composed of undetermined microlites. Highly birefringent microlites, which are clear in plain light, occur throughout the groundmass.

REFERENCES CITED

Anderson, G. E., 1960, Personal Communication.

Bowen, C. F., 1915, Possibilities of Oil in the Porcupine Dome, Rosebud County, Montana, U. S. Geol. Survey Bull. 621.

Brown, Barnum, 1907, The Hell Creek Beds of Montana: Am. Mus. Nat. Hist. Bull., Vol. 23, pp. 823-845.

Collier, A. J. and Knechtel, M. M., 1939, The Coal Resources of McCone County, Montana, U. S. Geol. Survey Bull. 905.

Daly, R. A., 1933, Igneous Rocks and the Depths of the Earth: McGraw-Hill Book Co., Inc., New York and London, pp. 598.

Dobbin, C. E., and Erdmann, C. E., 1955, Structure Contour Map of the Montana Plains: U. S. Geol. Survey, Map OM 178B.

Cross, W., 1897, Igneous Rocks of the Leucite Hills and Pilot Butte, Wyoming. Am. Jour. Sci. 4th Series, Vol. 4, pp. 115-141.

l
Head, K. C., 1926, The Geology of the Ingomar Anticline, Treasure and Rosebud Counties, Montana: U. S. Geol. Survey Bull. 786, pp. 1-37.

Larsen, E. S., 1940, Petrographic Province of Central Montana: Geol. Soc. America, Bull. V. 51, pp. 887-948.

- - - - - - - - -, Hurlbut, C. S., Burgess, C. H. and Buie, B. F., 1941, Igneous Rocks of the Highwood Mountains, Parts II-VII: Geol. Soc. America Bull., V. 52, pp. 1733-1868.

Rogers, G. S. and Lee, W., 1923, The Tullock Creek Coal Field: U. S. Geol. Survey Bull. 749.

Ross, C. S., 1926, Nepheline-Hauynite Alnoite from Winnett, Montana: Am. Jour. Sci., 5th Series, V. 11, pp. 218-227.

Ross, C. P., Andrews, D. A., and Witkind, J. J., 1955, Geologic Map of Montana: Montana Bur. of Mines and Geology, J. R. Van Pelt, Director.

Thom, W. T., Jr., and Dobbin, C. E., 1924, Stratigraphy of Cretaceous-Eocene Transition Beds in Eastern Montana and the Dakotas: Geol. Soc. America Bull., V. 35, pp. 481-506.

Turner, F. J. and Verhoogen, J., 1960, Igneous and Metamorphic Petrology: McGraw-Hill Book Co., Inc., New York, 672 pp.

USGS is [illegible] geologic [illegible] map of [illegible] H + V.

Wade, A. and Prider, R. T., 1940, The Leucite-Bearing Rocks of the West Kimberley Area, Western Australia: Geol. Soc. London Quart. Jour., V. 96, pp. 39-98.

Wahlstrom, E. E., 1955, Petrographic Mineralogy: John Wiley and Sons, Inc., New York, 407 pp.

Washington, H. S., 1917, Igneous Rock Analyses, U. S. Geol. Survey Prof. Paper 99.

Weed, W. H. and Pirsson, L. V., 1896a, The Bearpaw Mountains, Montana: Am. Jour. Sci., 4th Ser., V. 1, pp. 283-301, 351, 362; V. 2, pp. 136-148, 188-199.

ADDITIONAL REFERENCES

Chayes, F., 1949, A Simple Point Counter for Thin Section Analysis: Am. Min., V. 34, pp. 1-11.

Hurlbut, C. S. and Griggs, D., 1939, Igneous Rocks of the Highwood Mountains, Montana: Part 1, The Laccoliths'. Geol. Soc. America Bull., V. 50, pp. 1043-1112.

Kemp, J. F. and Knight, 1903, The Leucite Hills of Wyoming: Geol. Soc. America Bull., V. 14, pp. 305.

Knopf, A., 1936, Igneous Geology of the Spanish Peaks Region, Colorado: Geol. Soc. America Bull., V. 47, pp. 1727-1784.

Larsen, E. S. and Buie, B. F., 1938, Potash Analcime and Pseudoleucite from the Highwood Mountains of Montana: Am. Mineralogist, V. 23, pp. 837-849.

Pirsson, L. V., 1905a, Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana: U. S. Geol. Survey Bull. 237.

- - - - - - - - , 1905b, The Petrographic Province of Central Montana, Am. Jour. Sci., 3rd Series, V. 20, pp. 35-49.

Reeves, F., 1927, Geology of the Cat Creek and Devil's Basin Oil Fields and Adjacent Areas in Montana: U. S. Geol. Survey, Bull. 786, pp. 39-95.

Schultz, A. R. and Cross, W., 1912, The Potash-Bearing Rocks of the Leucite Hills, Sweetwater Co., Wyoming: U. S. Geol. Survey Bull. 512.

Tuttle, O. F., and Bowen, W. L., 1958, Origin of Granite in the Light of Experimental Studies in the System $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O: Geol. Soc. of America, Memoir 74.

Weed, W. H. and Pirsson, L. V., 1896b, The Geology of the Little Rocky Mountains, Montana: Jour. Geol., V. 4, pp. 399-428.

- - - - - - - - - - - - - - - -, 1896, Missourite, a New Leucite Rock from the Highwood Mountains, Montana: Am. Jour. Sci., 4th Ser., Vol. 2, pp. 315-323.

Williams, H., 1936, Pliocene Volcanoes of the Navajo-Hopi Country: Geol. Soc. America Bull., V. 47, pp. 111-172.

APPENDIX

COMPOSITE MEASURED SECTION

Upper Part of Hell Creek Formation

and Tullock Member of the Fort Union Formation

Location: Southeast side of Smoky Butte intrusives. Sec. 12, 13, 14, T. 18 N., R. 36 E. From the top to bottom; colors refer to weathered rock. See Plate I for location.

Unit Number	Lithology	Unit Thickness	
		Feet	Inches
47	Sandstone, buff-tan, very fine-grained	Over 75	0
46	Bone, dark-brown-black, very silty, numerous rusty partings	3	2
45	Mudstone, buff-tan and sandy at base, gray and clayey at top	8	2
44	Bone, shaly to silty, coaly at base, concretionary	4	7
43	Mudstone, gray and clayey at base, buff and silty at top, flaky	5	6
42	Shale, gray-black, boney at base	1	0
41	Mudstone, buff-gray, sandy	4	10
40	Sandstone, buff-gray, very fine-grained, clayey at base, contains concretions and channel sands	7	3
39	Bone, silty	0	7
38	Mudstone, buff and sandy at base, gray, carbonaceous and clayey at top	3	0
37	Shale, orange-brown, clayey, subfissile	3	0
36	Sandstone, buff-tan, very fine-grained clayey	3	4
35	Sandstone, buff-tan, very fine-grained, somewhat limey, indurated to a flaggy bench	5	0

Unit Number		Unit Thickness Feet	Inches
34	Mudstone, buff-tan, shale and sandy at intervals	12	7
33	Coal, silty, powdery, varies in thickness	1	6
32	Sandstone, buff-tan, very fine-grained, somewhat clayey at top	11	5
31	Mudstone, buff, sandy and carbonaceous at top	10	9
30	Limestone, tan, very silty, hackly	1	3
29	Shale, black and coaly at base, gray and clayey at top	2	10
28	Mudstone, yellow-gray, very sandy at base, shaly at top	4	8
27	Claystone, buff-tan, contains ironstone and channel sands	3	6
26	Claystone, buff-tan	1	3
25	Coal, very bony at base, thin papery shale at top	1	10
24	Mudstone, medium-light gray, silty to clayey, carbonaceous	6	9
23	Coal, platy, clear, contains yellow dust and selenite	0	10
22	Mudstone, light-gray, silty, subfissile	2	0
21	Mudstone, buff-tan, silty, with interlayered chert and ironstone	6	6
20	Shale, dark-brown, papery, carbonaceous	0	8
19	Bone, shaly to sandy, somewhat coaly top and base	1	6
18	Mudstone, gray-buff, sandy at base, clayey at top	9	6
17	Sandstone, buff-tan, medium-grained, friable, salt-and-pepper, with a two-foot zone of indurated, tan, channel sands at the top	12	4

Unit Number		Unit Thickness	
		Feet	Inches
16	Coal, platy, clear	0	7
15	Shale, dark-brown, papery, very carbonaceous	0	6
14	Siltstone, buff-tan, friable	3	5
13	Mudstone, gray-buff, clayey to sandy, with interlayered ironstone and channel sands	13	7
12	Mudstone, gray-buff, silty, with interlayered ironstone	5	2
11	Shale, brown-black, papery, somewhat coaly	2	0
10	Claystone, gray-brown, carbonaceous, subfissile	3	3
9	Shale, dark-brown, fissile	0	4
8	Coal, platy, somewhat bony at base	2	2
7	Claystone, light-gray, carbonaceous at top	2	4
6	Mudstone, yellow-gray to buff, sandy except at base	3	9
5	Coal, platy, clear	1	2
4	Mudstone, yellow-gray, sandy	1	7
3	Claystone, light-green-gray, slightly carbonaceous at base	7	4
2	Claystone, light-green-gray	5	8
1	Mudstone, buff-gray, and clayey at base, buff-tan and sandy at top	Over 7	2
		276	1