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Petrology of the Cenozoic phonolites and related rocks of the Houston Creek area, Bear Lodge Mountains, Wyoming

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PETROLOGY OF THE CENOZOIC PHONOLITES AND RELATED ROCKS OF THE HOUSTON CREEK AREA, BEAR LODGE MOUNTAINS, WYOMING

by
Frederick S. O'Toole

Bachelor of Science, University of North Dakota, 1978

A Thesis

Submitted to the Graduate Faculty

of the

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in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

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This thesis submitted by Frederick S. O'Toole in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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(Chairman)

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F. D. Holland Jr.

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

Dean of the Graduate School

Permission

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Date 4/21/81

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VITA

Mr. Frederick Simon O'Toole was born November 13, 1954, at Cavalier, North Dakota. Mr. O'Toole was graduated from Valley High School of Crystal-Hoople, North Dakota, in May, 1972, and received his Bachelor of Science in geology from the University of North Dakota in August, 1978.

Mr. O'Toole is a junior member of the American Association of Petroleum Geologists, a student member of the American Institute of Mining, Metallurgical, and Petroleum Engineers, a member of Sigma Gamma Epsilon, a National Honorary Society for the Earth Sciences, and is to be employed by Gulf Oil Exploration and Production Company.

ABSTRACT

The purpose of this study was to map and study the characteristics and origin of the Cenozoic phonolites and related rocks of the Houston Creek area, located on the southwestern flank of the Bear Lodge Mountains, 10 km northwest of Sundance, Wyoming. Mapping was conducted on a 1:10,000 scale over a 16 km^2 area. Microprobe, optical, and x-ray diffraction procedures were employed to observe and describe petrographic and chemical characteristics of the rocks.

The Cenozoic igneous rocks of the Houston Creek area are classified as phonolite, phonolite porphyry, trachyte porphyry, sodalite-bearing phonolite, and altered felsite. These hypabyssal rock types are characterized by porphyritic volcanic textures and trachytic to pilotaxitic fabrics. They contain phenocrysts of sanidine, aegirine-augite, hauyne, sodalite, orthoclase, sphene, and melanite, with analcime, natrolite, calcite, and clays(?) occurring as major alteration products. Field relationships indicate that phonolite and trachyte porphyry were emplaced as sills within the Minnelusa Formation and phonolite porphyry was emplaced as a sill at the Deadwood-Whitewood Formation contact. Sodalite-bearing phonolite appears to have been injected as dikes along fracture zones developed in altered felsite, which comprises the intrusive core of the Bear Lodge Mountains.

Major element chemistry shows that the phonolites are sodic in character and are higher in total alkalis and lower in SiO_2 than trachyte porphyry. Chemical and petrographic trends indicate that these rocks resemble those of a typical alkali olivine basalt series and that the primary magma was phonolitic in composition. Granitic xenoliths, present in slightly SiO_2-enriched phonolites, suggest that granitic crustal contamination may have been a major cause of igneous variation in the Houston Creek area.

The magma was partly crystallized at the time of emplacement and is interpreted to have had a temperature of somewhat less than 715° C. Present evidence indicates the possibility that the phonolitic magma was generated by partial melting of alkali olivine basaltic material in the lower crust. The partial melting may have been initiated by Laramide-induced uplift and relief of pressure at depth, which produced an influx of alkali-rich volatiles from the underlying mantle. These volatiles served to focus heat, reduce crustal melting temperatures, and provide the magma with its alkaline character.

INTRODUCTION

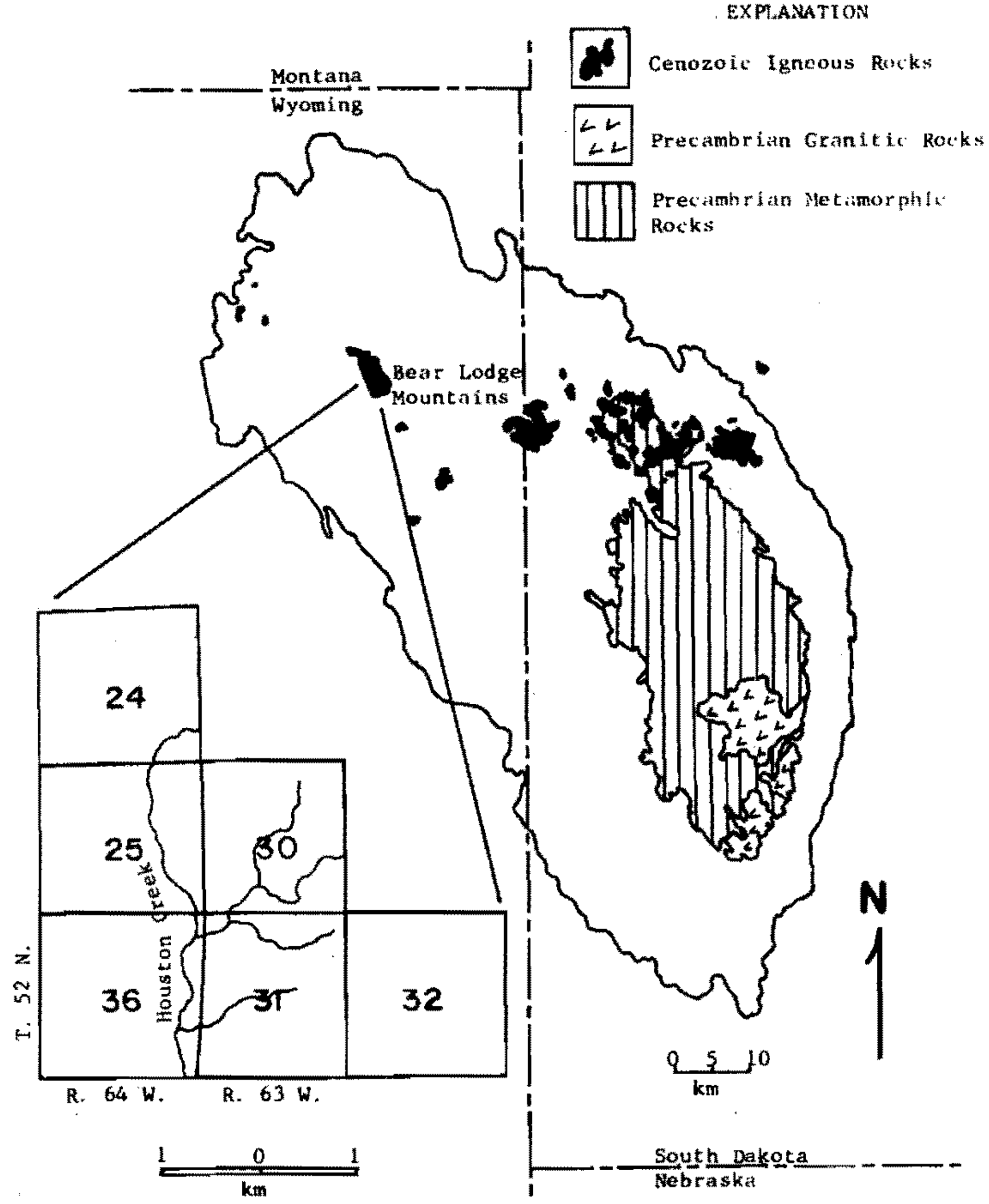
Location and Geologic Setting

The Houston Creek area is located on the southwestern flank of the Bear Lodge Mountains of northeastern Wyoming (Figure 1). A geological map was constructed on a topographical base at a scale of 1:10,000 (Plate 1). The area mapped includes the following sections: sec. 30, 31, and 32 of T. 52 N., R. 63 W., and sec. 24, 25, and 36 of T. 52 N., R. 64 W.

The Bear Lodge Mountains of Wyoming are a northwestern extension of the Black Hills of South Dakota, an asymmetrical arcuate dome essentially defined by the outcrop pattern of the Cretaceous Fall River Sandstone (Figure 1). The areal extent of the Black Hills is approximately 190 km north-south and 95 km east-west. Physiographically, the Bear Lodge Mountains are separated from the Black Hills by a strike valley developed largely on the red beds of the Triassic Spearfish Formation.

Geologically, the Black Hills region is closely related to the central Rocky Mountains and contains large exposures of uplifted Precambrian rocks (King, 1977). The oldest rocks exposed are granitic gneisses, assigned an age of approximately 2500 m.y. (Zartman and others, 1964). These rocks are unconformably overlain by a sequence of Precambrian metasedimentary and metaigneous rocks. The entire sequence of Precambrian metamorphic rocks is intruded by the Harney Peak Granite, assigned an age of about 1700 m.y. (Peterman and Hedge, 1972).

Figure 1. Location map showing the Houston Creek area and outcrop locations of Precambrian rocks and Cenozoic igneous rocks of the Black Hills region. Areal extent of the Black Hills region defined by the top of the Fall River Sandstone. Base map taken from Gries and Tullis (1955, p. 32).


EXPLANATION
Cenozoic Igneous Rocks
Precambrian Granitic Rocks
Precambrian Metamorphic Rocks
Montana
Wyoming
Bear Lodge Mountains
South Dakota
Nebraska
N
0 5 10
km
24
25
30
36
31
32
Houston Creek
T. 52 N.
R. 64 W.
R. 63 W.
1 0 1
km

Resting unconformably on the Precambrian crystalline core rocks of the Black Hills is a sequence of Paleozoic and Mesozoic sedimentary deposits. These units dip radially from the core; the dip is fairly steep on the eastern flank and is more gentle on the western flank.

Igneous rocks of Cenozoic age have intruded the northern half of the Black Hills province in the form of dikes, sills, laccoliths, and stocks (Shapiro, 1971). These igneous bodies are concentrated in an east-west line, extending approximately 105 km from Bear Butte, South Dakota to the Missouri Buttes of Wyoming. Compositionally, the rock types vary from rhyolites to phonolites. Absolute ages of the igneous bodies, as determined by potassium-argon techniques by McDowell (1966), range from 38.8±2.1 m.y. to 49.4±1.7 m.y.

Previous Work

Darton (1905) first mapped the geology of the Bear Lodge Mountains at a scale of 1:125,000. Igneous rocks include Cenozoic porphyritic varieties of trachyte, syenite, monzonite, and phonolite, as well as Precambrian granite. His map shows a concentration of phonolite porphyry bodies to the southwest of Warren Peaks. It is these phonolite porphyry bodies, cropping out in the Houston Creed area, that form the focus of this thesis.

Following Darton's (1905) work, no studies were carried out in the Bear Lodge Mountains until Brown (1952) studied igneous rocks exposed in the vicinity of Warren Peaks, located to the northeast of the Houston Creek area. He interpreted the Bear Lodge Mountains to be a laccolithic structure formed by the injection of trachytic magma along planes of stratigraphic weakness. He proposed that the phonolites and related rocks of the periphery are products of a secondary magma injected into fracture zones created by the trachyte emplacement. Causes for igneous variation were unexplained.

Chenoweth (1955) examined the igneous assemblages of the southern and central Bear Lodge Mountains. He proposed that relative age relationships could be distinguished on the basis of alteration and mineralization of preexisting igneous rocks by younger intrusives.

Fashbaugh (1979) studied certain phonolitic rocks of the southeastern Bear Lodge Mountains and the quartz latites of nearby Sundance Mountain and Sugarloaf Mountain. He interpreted the quartz latites as having been explosively extruded, while the Bear Lodge Mountains rocks were passively emplaced as dikes and sills.

A detailed petrologic examination of phonolites and trachytes from the Missouri Buttes-Devils Tower-Barlow Canyon igneous center was conducted by Halvorson (1980). This Cenozoic eruptive center is located about 35 km northwest of the Houston Creek area. Halvorson (1980) proposed that the phonolites probably originated by fractionation involving both gravity settling and crystal flotation processes. He stated that the relationship of the trachytic melt to a parental magma is problematic, as no mafic igneous rocks are found in the area.

White (1980) mapped and studied the igneous rocks exposed in a 33 km^2 area immediately north of the Houston Creek area. White determined the Cenozoic intrusives in that area to be dominantly phonolites and trachytes, emplaced as laccoliths and sills. He showed evidence that the igneous rocks in the area may be related to potassic alkali olivine basalt series rocks.

Purpose and Approach

Detailed petrographic description and petrologic interpretation of the Bear Lodge Mountains igneous rocks have not been attempted until recent years. This project is part of a coordinated effort by students and faculty of the University of North Dakota Geology Department to study the Cenozoic igneous activity of the northern Black Hills area. In addition to this thesis, related work has been done by the following University of North Dakota geologists: Don L. Halvorson (Devils Tower area, Ph.D. dissertation, 1980), John T. Ray (Tinton district, M.S. thesis, 1979), Earl F. Fashbaugh (Sundance Mountain area, M.S. thesis, 1979), Stanley F. White (central and western Bear Lodge Mountains, M.S. thesis, 1980), and Michael Wilkinson (central Bear Lodge Mountains, M.S. thesis, in preparation).

The principal objectives of this specific investigation are: (a) to map the geology of the Houston Creek area at a larger scale than previous work by Darton (1905) and Brown (1952), (b) to study carefully the contact relations of the igneous bodies to the intruded rocks to aid in deciphering structural controls of emplacement, (c) to describe in detail the petrography of the igneous rocks cropping out in the study area, with particular emphasis on the phonolites, (d) to interpret the character of the phonolitic magma and its crystallization history, and (e) to discuss the origin of the phonolites and related rocks in light of chemical and petrologic trends.

Mapping of the geology of the Houston Creek area was carried out during the summers of 1979 and 1980. Pace and compass procedures were followed, using aerial photographs for additional control. A workable scale of 1:10,000 was used, with the USGS 15 minute Sundance Quadrangle map serving as a topographic base. Information compiled on the final geologic map (Plate 1) includes rock-stratigraphic units, contacts, bedding attitudes, sample locations, and igneous outcrops.

METHODS AND PROCEDURES

Sampling Procedure

Mapping of the Houston Creek area included sampling and field description of rock types exposed in the area. A suite of 132 Cenozoic igneous rocks was collected for subsequent petrographic examination, with sampling done on the basis of outcrop availability and lithologic variability. Paleozoic and Mesozoic sedimentary rocks were macroscopically described and differentiated into rock-stratigraphic units.

Sampling locations in the Houston Creek area were numbered serially and are plotted on Plate 1. Specimens collected were coded to the sampling site number, with all sample number prefixed by "BL-" (denoting Bear Lodge Mountains origin). For example, BL-35 is the sample collected from sampling location 35.

Modal Analysis

Igneous rocks of the Houston Creek area were modally analyzed using polished petrographic thin sections. Modes were based on 500 point counts per thin section and are expressed in volume percentages. The grid spacing chosen for the point counting was one half the average grain size of the phenocrysts, as all samples were to some degree porphyritic. Undetermined cryptocrystalline and microcrystalline materials were recorded as "groundmass". The accuracy of the given mode varies with the relative percentage of each phase; a modal percentage of 28-80% varies ±4%, 13-28% varies ±3%, 5-13% varies ±2%, and 1-5% varies ±1%

(Van der Plas and Tobi, 1965). Identification of major mineral phases was verified by x-ray diffraction and optical determination of refractive indices. In addition, phenocrysts were examined by electron microprobe methods to determine compositions.

X-ray Diffraction

The procedure for the preparation of samples for analysis by x-ray diffraction followed a procedure outlined by David Brekke (oral communication):

1. sample was crushed in a porcelain mortar to fragments less than 1 cm in diameter
2. sample was split in half and crushed to less than about 2-3 mm in diameter
3. about 20 grams of sample were ground for five minutes to less than 20 mesh (0.84 mm) in a Spex Mixer Mill (vial 8004)
4. two grams of sample were ground to less than 325 mesh (44 microns) in a Spex Mixer Mill (vial 5004).

Approximately one gram of sample was backloaded into an aluminum specimen holder. Silicon powder was used as an internal standard for the proper adjustment of peak positions. X-ray diffraction analysis was conducted with a Philips-Norelco high-angle diffractometer and Cu K-alpha radiation.

For whole-rock qualitative recognition of mineral phases, samples were scanned from 2° to 60° 2θ at 1° 2θ per minute with machine conditions set at 37 KV and 18 mA. For the determination of alkali feldspar structural states, samples were scanned from 20° to 52° at $\frac{1}{4}^\circ$ 2θ per minute with machine conditions set at 45 KV and 19 mA.

Electron Microprobe Analysis

Whole-rock sample splits of about one gram retained from step 4 above were ground for an additional 3 to 5 minutes in the Spex mixer mill (vial 5004) for electron microprobe analysis. The samples were back-loaded into 3 mm-diameter holes drilled into carbon discs and analyzed for 200 seconds over a 1 mm^2 area. A JEOL 35C scanning electron microscope with a Kevex energy dispersive detector was utilized. The x-ray spectra were processed by a Tracor Northern XML fitting program and the matrix correction program of Bence and Albee (1968). Polished thin sections were also used for microprobe analysis of individual phenocrysts and for positive identification of phases present in the groundmass. All chemical analyses presented in this study were determined by using electron beam techniques developed for rock powders and polished thin sections (Karner, oral communication), and are expressed in oxide weight percentages. Total iron oxide was reported as Fe_2O_3 and converted to FeO and Fe_2O_3 by the method of Irving and Baragar (1971, p. 526).

Igneous Rock Classification

The Houston Creek Cenozoic igneous rocks are characterized by porphyritic textures with aphanitic groundmasses. The rocks are best categorized as hypabyssal (or subvolcanic) as they appear to have been emplaced as shallow intrusives. The classification system followed in this study is that of Streckeisen (1967), the classification recommended by the International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Igneous Rocks. However this scheme, which is based on modal mineral percentages, considers hypabyssal rocks as textural varieties related to plutonic rocks and names them accordingly. Because of the predominance of volcanic textures in the hypabyssal rocks of the Houston Creek area, volcanic rock names have been chosen in place of the recommended plutonic equivalents. Feldspathoid mineral names are used as modifiers for phonolites characterized by constituent feldspathoids other than nepheline and/or hauyne, as specified by Streckeisen (1979, p. 332). Rocks containing greater than 20 percent phenocrysts are designated as porphyritic varieties (e.g. phonolite porphyry).

PRE-CENOZOIC STRATIGRAPHY

The stratigraphic units exposed in the Houston Creek area range in age from Precambrian to Cenozoic. The complete stratigraphic section of the Black Hills region is shown in Figure 2. The descriptions that follow are intended to provide a necessary background for reference to the accompanying geologic map of the Houston Creek area (Plate 1). Only the units which are present in the mapped area are described.

Precambrian

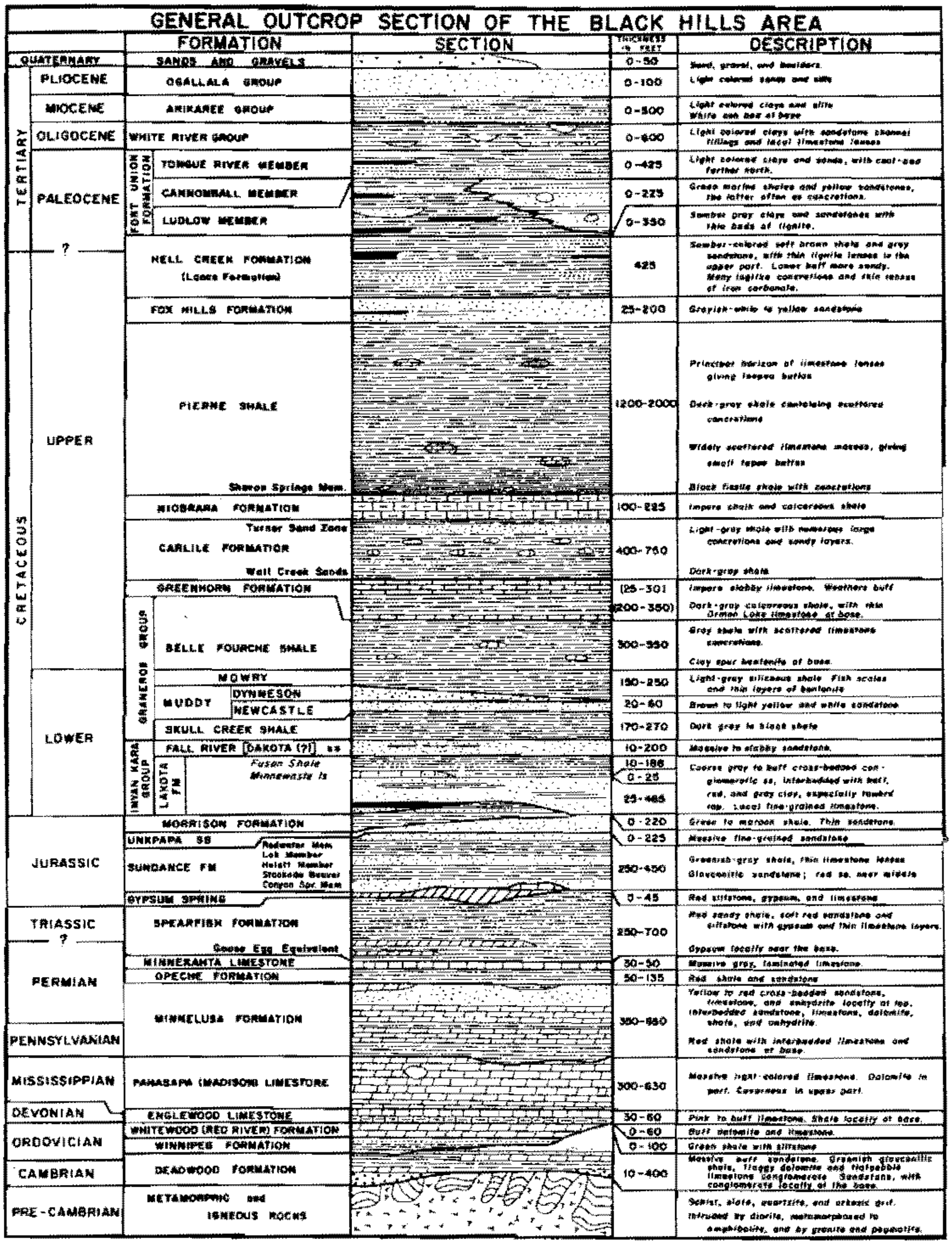
Granitic Gneiss

The oldest rock in the study area is Precambrian granitic gneiss, which crops out in the NE ¼ of section 32 (Plate 1). Darton (1905) mapped the rock as "granite" and assigned it a Precambrian age based on stratigraphic position. The Precambrian rocks of the Bear Lodge Mountains have not been correlated with Precambrian rocks of the Black Hills proper. However, the granitic gneiss exposed in section 32 bears a strong resemblance to granitic gneiss found at Little Elk Creek Canyon, located about 24 km northwest of Rapid City, South Dakota. Zartman and others (1964) dated the Little Elk Creek Canyon gneiss at 2500 m.y. This date is similar to an age determination of the Bear Lodge Mountains granitic gneiss, which indicates a minimum age of 2600 m.y. (Staatz, written communication, 1980).

Granitic gneiss in the study area occurs as extensive float material associated with highly altered felsite. This field relationship suggests

Figure 2. Stratigraphic section of the Black Hills region (from Wyoming Geological Association Guidebook, 1968, p. 5).

GENERAL OUTCROP SECTION OF THE BLACK HILLS AREA



		FORMATION	SECTION	THICKNESS IN FEET	DESCRIPTION
QUATERNARY		SANDS AND GRAVELS		0-50	Sand, gravel, and boulders.
TERTIARY	PLIOCENE	OGALLALA GROUP		0-100	Light colored sands and silts
	MIOCENE	ARIKAREE GROUP		0-500	Light colored clays and silts White ash bed at base
	OLIGOCENE	WHITE RIVER GROUP		0-600	Light colored clays with sandstone channel fillings and local limestone lenses
	PALEOCENE	FORT UNION FORMATION: TONGUE RIVER MEMBER		0-425	Light colored clays and sands, with coal beds farther north.
		FORT UNION FORMATION: CANNONBALL MEMBER		0-225	Green marine shales and yellow sandstones, the latter often as concretions.
		FORT UNION FORMATION: LUDLOW MEMBER		0-350	Somber gray clays and sandstones with thin beds of lignite.
	?				
CRETACEOUS	UPPER	HELL CREEK FORMATION (Lance Formation)		425	Somber-colored soft brown shale and gray sandstone, with thin lignite lenses in the upper part. Lower half more sandy. Many loglike concretions and thin lenses of iron carbonate.
		FOX HILLS FORMATION		25-200	Grayish-white to yellow sandstone
		PIERRE SHALE		1200-2000	Principal horizon of limestone lenses giving teepee buttes Dark-gray shale containing scattered concretions Widely scattered limestone masses, giving small tepee buttes
		Sharon Springs Mem.			Black fissile shale with concretions
		NIOBRARA FORMATION		100-225	Impure chalk and calcareous shale
		CARLILE FORMATION Turner Sand Zone Wall Creek Sands		400-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale
		GREENHORN FORMATION		(25-30)	Impure slabby limestone. Weathers buff
		GRANEROS GROUP		(200-350)	Dark-gray calcareous shale, with thin Orman Lake limestone at base.
		GRANEROS GROUP: BELLE FOURCHE SHALE		300-350	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
	LOWER	GRANEROS GROUP: MOWRY		150-250	Light-gray siliceous shale. Fish scales and thin layers of bentonite
		GRANEROS GROUP: MUDDY: DYNNESON NEWCASTLE		20-60	Brown to light yellow and white sandstone
		GRANEROS GROUP: SKULL CREEK SHALE		170-270	Dark gray to black shale
		INYAN KARA GROUP: FALL RIVER [DAKOTA (?)] ss		10-200	Massive to slabby sandstone.
		INYAN KARA GROUP: LAKOTA FM Fuson Shale Minnewaste ls		10-188 0-25 25-485	Coarse gray to buff cross-bedded conglomeratic ss, interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone.
JURASSIC		MORRISON FORMATION		0-220	Green to maroon shale. Thin sandstone.
		UNKPAPA SS		0-225	Massive fine-grained sandstone
		SUNDANCE FM Redwater Mem. Lak Member Hulett Member Stockade Beaver Canyon Spr. Mem.		250-450	Greenish-gray shale, thin limestone lenses Glauconitic sandstone; red ss. near middle
		GYPSUM SPRING		0-45	Red siltstone, gypsum, and limestone
TRIASSIC		SPEARFISH FORMATION		250-700	Red sandy shale, soft red sandstone and siltstone with gypsum and thin limestone layers.
?		Goose Egg Equivalent			Gypsum locally near the base.
PERMIAN		MINNEKAHTA LIMESTONE		30-50	Massive gray, laminated limestone.
		OPECHE FORMATION		50-135	Red shale and sandstone
		MINNELUSA FORMATION		350-850	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite.
PENNSYLVANIAN					Red shale with interbedded limestone and sandstone at base.
MISSISSIPPIAN		PAHASAPA (MADISON) LIMESTONE		300-630	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
DEVONIAN		ENGLEWOOD LIMESTONE		30-60	Pink to buff limestone. Shale locally at base.
ORDOVICIAN		WHITEWOOD (RED RIVER) FORMATION		0-60	Buff dolomite and limestone.
		WINNIPEG FORMATION		0-100	Green shale with siltstone
CAMBRIAN		DEADWOOD FORMATION		10-400	Massive buff sandstone. Greenish glauconitic shale, flaggy dolomite and flatpebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRE-CAMBRIAN		METAMORPHIC and IGNEOUS ROCKS			Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

that the gneiss may represent a large block of Precambrian basement material brought up during emplacement of the felsite.

Samples of the granitic gneiss are pink on fresh surfaces and dull yellowish-brown on weathered surfaces. The gneiss is consistently fine- to medium-grained with a moderately to well-developed gneissic foliation. The foliation is defined by the parallel orientation of biotite in thin lenses separated by a fractured matrix of quartz and feldspar. The rock displays an allotriomorphic granular fabric in its more massive parts, but a cataclastic fabric is prevalent.

Anhedral microcline microperthite is the predominant mineral present, marked by combined albite-pericline twinning and perthitic exsolution laminae. Quartz occurs as highly strained and fractured grains, relatively unaltered and free of inclusions (Figure 3). Polysynthetically twinned, anhedral to subhedral oligoclase (An_{10-15}) occurs as grains highly altered to epidote and fine-grained muscovite. Both the alkali feldspar and oligoclase crystals exhibit resorbed margins and are commonly separated by a microcrystalline felsic matrix. Biotite, altered to chlorite along margins and fractures, contains inclusions of magnetite(?), zircon and apatite.

Paleozoic

Deadwood Formation

The Deadwood Formation includes rocks ranging in age from Late Cambrian to Early Ordovician. The Deadwood is generally divided into three major rock units, each of which is exposed in the Houston Creek area. The lower unit is a massive, well-indurated, brown quartzitic sandstone with conglomerate locally at the base. The middle unit con-

Figure 3. Photomicrograph of Precambrian granitic gneiss sample BL-42. Note combined albite-pericline twinning in microcline and relatively clear, unaltered quartz. Crossed polars, 45X.

sists of thin beds of gray-green shale alternating with flaggy, dolomitic limestone, glauconitic sandstone, and limestone-pebble conglomerate. These are overlain by a massive, well-indurated sandstone unit, marked by an abundance of Skolithos and related trace fossils.

The lower and upper units of the Deadwood are highly resistant, frequently forming prominent ledges in sections 30 and 32 (Plate 1). The middle unit is generally poorly exposed along slopes. In section 32 the upper Deadwood is separated from the lower and middle Deadwood by a considerable thickness of igneous rock of Cenozoic age. Occasional baked, somewhat slaty samples of Deadwood rock types were found, but contact metamorphic effects resulting from the emplacement of the igneous rock appear to be minimal.

Whitewood Formation

The Whitewood Formation appears to overlie the Deadwood disconformably in the Bear Lodge Mountains. The Winnipeg Formation, which generally underlies the Whitewood Formation in the Black Hills region, appears to be missing from the stratigraphic section in the Houston Creek area. Darton (1905) and Brown (1952) did not map the Winnipeg Formation, and field mapping during this study revealed no evidence of Winnipeg Formation in the Houston Creek area.

The Whitewood Formation is a massive, mottled, grayish-brown dolomite of Late Ordovician age. Exposures in sections 30 and 32 are usually in the form of benches (Plate 1).

Englewood Limestone

The Englewood Limestone, consisting of pink to lavender, slabby, argillaceous limestone, rests disconformably on the Whitewood Formation.

Darton (1905) thought that the Englewood is probably represented in the Bear Lodge Mountains by a silty layer at the base of the Pahasapa Limestone. Based on the identification of corals and brachiopods, Darton considered the entire Englewood to be Lower Mississippian in age, but Klapper and Furnish (1962) have noted that the basal portion contains conodonts regarded as Late Devonian.

The only exposure of the Englewood in the Houston Creek area is on an isolated knoll in section 32, forming a rubbly slope between outcrops of the Whitewood Formation and Pahasapa Limestone (Plate 1). In this study the Englewood and Pahasapa Limestones are mapped as a single unit.

Pahasapa Limestone

The most prominent sedimentary unit in the study area is the Pahasapa Limestone. It is a massive, gray to grayish-brown crystalline carbonate, ranging in composition from pure limestone to pure dolomite with various combinations of the two. The lower contact of the Pahasapa is conformable with the underlying Englewood Limestone (Robinson and others, 1964). Marine fossils consisting mostly of brachiopods and corals indicate the formation is Early Mississippian in age (Darton, 1909). Steep resistant cliffs of this unit occur along Houston Creek and its tributaries in sections 30, 31, and 32 (Plate 1).

Minnelusa Formation

The Minnelusa Formation rests disconformably on the Pahasapa Limestone. Yellow, red, and brown sandstone make up the bulk of the formation, with the exception of some red shale interbedded at the base, and some flaggy limestone near the middle. Darton (1901) assigned the Minnelusa a Pennsylvanian age, but later work by Foster (1958) has shown that the Pennsylvanian-Permian boundary should be placed within the formation. Exposures of the Minnelusa Formation within the Houston Creek area are restricted to sections 24, 30, and 31, where numerous outcrops of Minnelusa sandstones exist along streams and drainages (Plate 1).

Opeche Formation

The Permian Opeche Formation disconformably overlies the Minnelusa Formation (Robinson and others, 1964). The Opeche consists of reddish-brown to maroon, poorly lithified siltstones and shales with local thin beds of gypsum. Although no fossils have been reported from the Opeche Formation, a Permian age has been assigned to it, as both underlying and overlying rocks have been demonstrated to be Permian (Robinson and others, 1964). The Opeche is typically a slope-former throughout the Houston Creek area, except where exposed beneath resistant beds of the overlying Minnekahta Limestone along ridges in sections 25 and 30 (Plate 1).

Minnekahta Limestone

The Permian Minnekahta Limestone is an excellent stratigraphic marker. It lies conformably on the Opeche Formation (Robinson and others, 1964) and is composed of gray to lavender flaggy limestone with a red silty shale at the base. Darton (1909) reported marine invertebrate fossils from the Minnekahta that suggest a Permian age. The Minnekahta typically forms dip slopes almost barren of soil and vegetation within the Houston Creek area. Good exposures occur in sections 24, 25, and 36 as ledges along streams and drainages (Plate 1). These outcrops generally provide excellent bedding surfaces for the determination of structural attitudes.

Mesozoic

Spearfish Formation

The Spearfish Formation of Permian and Triassic age consists of red, weakly lithified shale, siltstone, and sandstone, and thick beds of white gypsum near the base. According to Robinson and others (1964) the Spearfish rests with sharp contact but with no apparent unconformity on the underlying Minnekahta Limestone. In most parts of the Black Hills region the Spearfish is overlain by the Jurassic Gypsum Springs Formation. However, Robinson and others (1964) report that the Gypsum Springs is absent in T.52N., R.64W., and that the Spearfish is disconformably overlain by the Jurassic Sundance Formation. Field studies for this thesis confirm that the Gypsum Springs Formation is not present in the Houston Creek area.

A Permian-Triassic age has been demonstrated for the Spearfish Formation in northeastern Wyoming (Robinson and others, 1964). The upper part of the Spearfish has the same stratigraphic position and lithology as the Red Peak Member of the Triassic Chugwater Formation of central and southeastern Wyoming (Robinson and others, 1964). The lower gypsiferous sequence correlates with a red shale unit of Permian age in the Hartville uplift to the south (Denson and Botinelly, 1949) and in the Bighorn Mountains to the west (Hose, 1954).

The Spearfish Formation occurs in the western portions of sections 24, 25, and 36 as scattered, gypsum-capped, gently sloping knolls of variegated sandstone (Plate 1).

Sundance Formation

In the Houston Creek area, the Jurassic Sundance Formation lies disconformably on the Spearfish Formation. The Sundance contains five members which were named by Imlay (1947). These members are, from oldest to youngest, the Canyon Springs Sandstone, Stockade Beaver Shale, Hulett Sandstone, Lak Shale, and Redwater Shale. Imlay (1947) and Schmitt (1953) demonstrated a Jurassic age for the Sundance Formation by use of contained fossils and regional correlation.

Exposures of only the lowermost member, the Canyon Springs Sandstone, were found in the Houston Creek area. They consist of a light yellowish-gray, fine-grained, friable sandstone that is generally a nonresistant unit. Outcrops of the Canyon Springs are located in cutbanks of Miller Creek in sections 25 and 36 (Plate 1).

CENOZOIC IGNEOUS ROCKS

Phonolite Porphyry

General

A prominent igneous rock type of the Houston Creek area is classified as phonolite porphyry on the basis of its composition and texture. Good exposures are found in the SE ¼ of section 32 (Plate 1). These outcrops commonly exhibit well-defined columnar joint patterns (Figure 4).

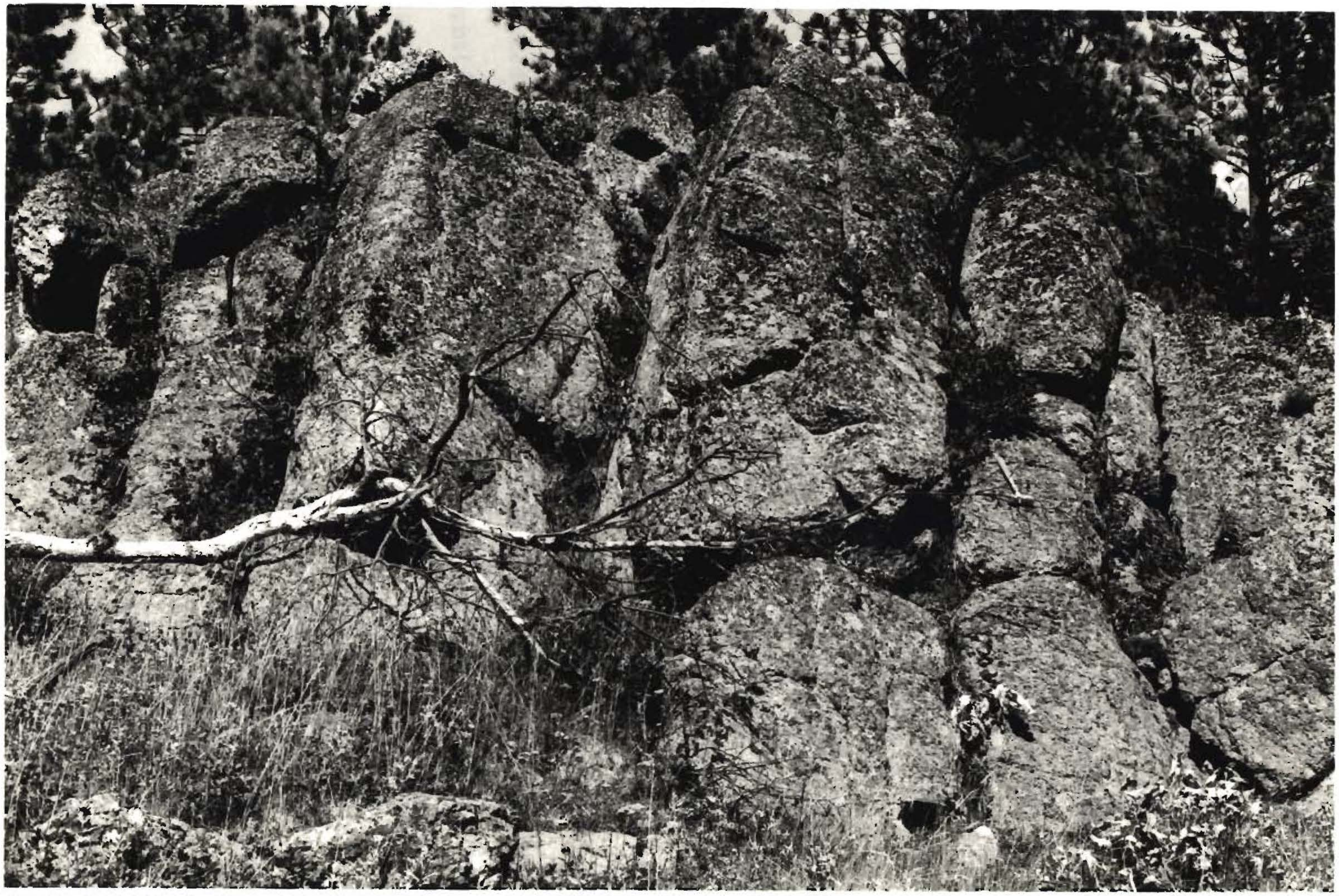
Stratigraphically, the phonolite porphyry occurs between the Cambrian-Ordovician Deadwood Formation and the Ordovician Whitewood Formation. A foliation, produced by the alignment of tabular alkali feldspar phenocrysts, conforms to the regional strike of the intruded rocks. The phenocrysts typically dip 30 to 45 degrees SW, which is comparable to the dips of the country rocks. Since the intruded rocks have the same structural attitudes, the phonolite porphyry body is interpreted as being a sill.

Contact metamorphism of the country rocks is limited to slight silicification and iron-oxide staining at the base of the Whitewood Formation. There is no apparent alteration of the Deadwood Formation.

Petrography and Mineral Chemistry

The phonolite porphyry is a gray to olive gray, holocrystalline, aphanitic rock with a pronounced porphyritic texture. Sanidine, aegirine-augite, hauyne, and sphene are the dominant phenocrysts, and

Figure 4. Exposure of Houston Creek phonolite porphyry showing well-developed columnar jointing. This exposure is found at location 10 in section 32 (Plate 1).



are set in a well-developed trachytic groundmass composed predominantly of orthoclase and smaller amounts of aegirine and magnetite(?). Biotite occurs as phenocrysts in some samples. Common alteration products are analcime, natrolite, calcite, and hematite.

The modes of six representative samples of phonolite porphyry are given in Table 1. The groundmass is 58 to 70 percent of these rocks and appears to be predominantly composed of lath-shaped orthoclase interstitially dispersed with isolated to clustered acicular aegirine crystals. Aegirine accounts for the characteristic green tint of the phonolite porphyry. Scattered ovoid to irregularly shaped patches of secondary alteration disrupt the dominant trachytic character of the matrix.

Subhedral to euhedral phenocrysts of sanidine range in grain size from less than 1 mm to 25 mm (Figure 5). They comprise from 14 to 30 percent of the rock (Table 1) and are typically flow-oriented in subparallel arrangement with the trachytic matrix. Grains commonly poikilitically enclose small crystals of sphene, apatite, and aegirine. Rounded and embayed crystals are common and are probably the result of magmatic corrosion following crystallization. Alteration of sanidine to clays(?) and replacement by analcime and natrolite along fractures are widespread.

Alkali feldspar structural states were determined for several sanidine phenocrysts using Wright's (1968) x-ray diffraction three-peak method. The results are shown in Figure 6. The phenocrysts (samples BL-5, BL-10, and BL-11) plot as highly disordered sanidine. Similarly, the three-peak method was applied to feldspars from the groundmass (samples BL-4D, BL-5A, and BL-11A). These feldspars plot as intermediate ordered orthoclase. Using Wright's (1968, p. 93) plot of Or content

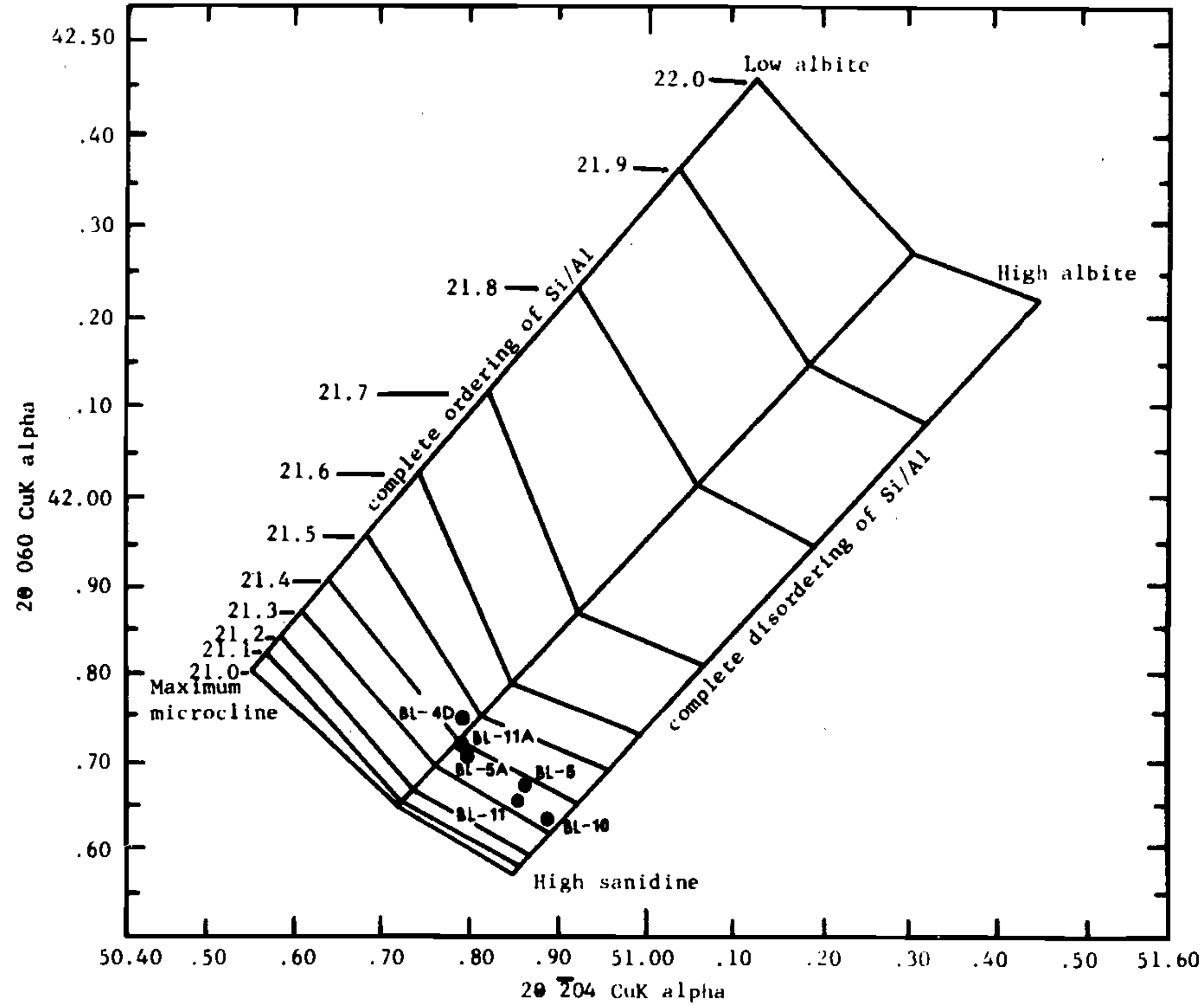
TABLE 1

MODAL ANALYSES OF THE HOUSTON CREEK PHONOLITE PORPHYRY IN VOLUME PERCENTAGES

Sample Number	BL-5	Bl-5A	BL-8	BL-8-6	BL-10	BL-11
Groundmass	57.4	59.6	57.6	70.2	58.2	67.6
Sanidine	22.6	23.0	24.0	14.0	30.2	17.8
Aegirine-augite	11.0	11.0	11.6	9.8	8.0	9.2
Aegirine	pr	pr	pr	pr	pr	pr
Olivine	0.0	0.0	pr	pr	0.0	0.0
Hauyne	pr	0.4	pr	0.6	0.2	0.2
Analcime	2.2	2.8	3.6	2.6	1.6	2.6
Natrolite	pr	0.4	0.8	pr	0.2	1.0
Biotite	0.0	0.0	0.0	pr	pr	pr
Sphene	1.2	1.4	1.2	1.4	0.8	1.0
Magnetite(?)	0.4	0.8	1.0	0.6	0.4	0.6
Calcite	1.6	0.4	pr	0.8	pr	pr
Hematite	pr	pr	0.2	pr	0.0	pr
Apatite	pr	0.2	0.0	pr	0.4	0.0

pr = present; noted optically but not point counted

Figure 6. Ordering of Si/Al in alkali feldspars from the Houston Creek phonolite porphyry as determined by the three-peak method of Wright (1968). Sanidine phenocrysts (samples BL-5, BL-10, and BL-11) are highly disordered. Groundmass orthoclase (samples BL-4D, BL-5A, and BL-11A) show intermediate ordering.


42.50
.40
.30
.20
.10
42.00
.90
.80
.70
.60
2θ 060 CuK alpha
50.40
.50
.60
.70
.80
.90
51.00
.10
.20
.30
.40
.50
51.60
2θ 2̄04 CuK alpha
Low albite
22.0
21.9
21.8
21.7
21.6
21.5
21.4
21.3
21.2
21.1
21.0
High albite
complete ordering of Si/Al
complete disordering of Si/Al
Maximum microcline
High sanidine
BL-4D
BL-11A
BL-5A
BL-6
BL-11
BL-10

against $2\theta(\bar{2}01)$, sanidine phenocrysts were determined to be Or_{61} (±3%). A composition of Or_{82} (±4%) was obtained for orthoclase from the groundmass.

Electron microprobe analyses of phonolite porphyry feldspars are shown in Table 2 (columns A and B). The variation in sodium and potassium between orthoclase from the groundmass and the sanidine phenocryst is slight, as is the variation in silicon-aluminum substitution.

Aegirine-augite, comprising from 8 to 12 percent of the rock (Table 1), is the major mafic mineral. Phenocrysts are typically stubby, subhedral to euhedral prisms up to 4 mm in length, and often display distinctive pyroxene cleavage (Figure 7). Grains are generally strongly pleochroic with X=emerald green, Y=yellowish-green, and Z=brownish-green. Some crystals have colorless cores and bright green margins; however, most grains appear to lack zoning. Simple twinning with (100) as the twin plane is quite common. Indices of refraction obtained from sample BL-8 are: alpha=1.710, beta=1.722, gamma=1.743. Poikilitic fabrics are common among the larger aegirine-augite grains with inclusions consisting of sphene, apatite, and magnetite(?). Magnetite(?) has replaced aegirine-augite crystals along margins and fractures.

Microprobe analyses of two aegirine-augite phenocrysts are shown in Table 2 (columns C and D). These grains show very little chemical variation and are similar to aegirine-augite analyses listed in Deer and others (1963A).

Hauyne occurs as relatively fresh microphenocrysts and as pseudomorphs almost entirely replaced by secondary alteration products, and appears to be the only feldspathoid present in the phonolite porphyry.

TABLE 2

CHEMICAL ANALYSES OF HOUSTON CREEK PHONOLITE PORPHYRY MINERALS IN OXIDE WEIGHT PERCENTAGES

	A	B	C	D	E
SiO_2	66.50	61.99	49.70	51.66	32.06
Al_2O_3	19.28	20.53	4.56	3.31	26.36
FeO	0.00	0.00	9.12	11.60	0.00
Fe_2O_3	0.18	0.81	2.82	1.77	0.25
MgO	0.00	0.00	10.72	10.02	0.33
CaO	0.00	0.43	21.88	20.25	3.32
Na_2O	3.39	4.97	1.23	2.35	18.51
K_2O	11.95	10.32	0.10	0.06	1.02
TiO_2	0.00	0.22	1.32	0.27	0.00
MnO	0.00	0.00	0.24	0.55	0.00
P_2O_5	0.00	0.00	0.00	0.00	0.00
ClO	0.00	0.00	0.00	0.00	0.39
SO_3	0.00	0.12	0.00	0.00	11.51
Total	101.30	99.39	101.70	101.85	94.76

Explanation of Column Headings

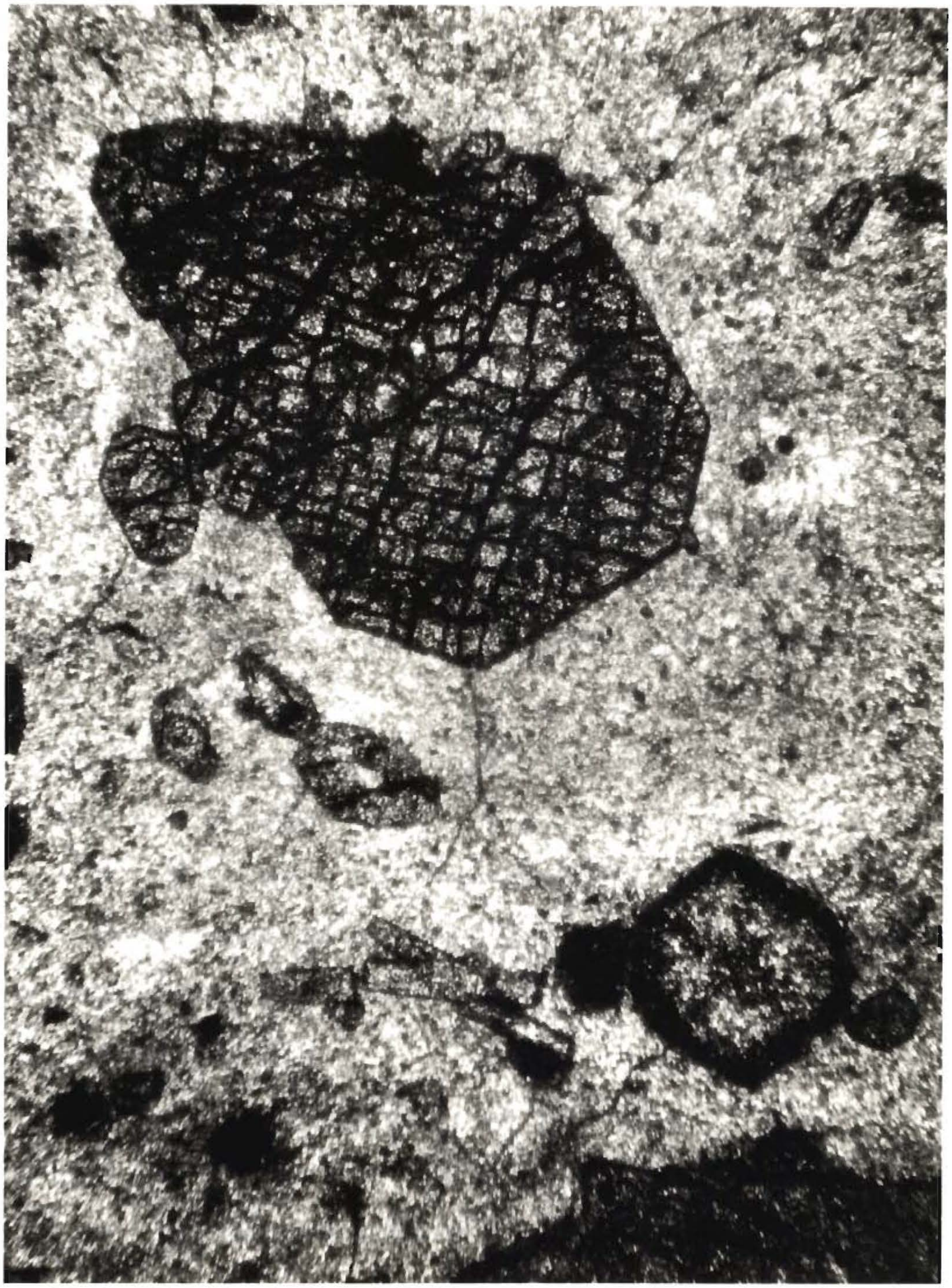
A = Sanidine, sample BL-11, phenocryst

B = Orthoclase, sample BL-11, groundmass

C = Aegirine-augite, BL-5, phenocryst

D = Aegirine-augite, BL-5A, phenocryst

E = Hauyne, BL-10, phenocryst



The hauyne crystals generally have hexagonal outlines (Figure 7). Grain sizes range up to 1 mm, with unaltered surfaces displaying a bluish-gray color that may be irregularly distributed. Crystals with embayments lined by tiny needles of aegirine occur locally. A microprobe analysis of hauyne is given in Table 2 (column E). The relatively poor closure (total oxide weight = 94.76%) may indicate alteration by volatile-rich phases such as zeolites, clays, and calcite. Otherwise, major cation and sulfate ion percentages appear to be similar to published compositions of hauyne listed in Deer and others (1963B).

Sphene occurs as phenocrysts up to 1.5 mm in length and as inclusions in pyroxenes and feldspars. Abundances range from 1 to 2 percent (Table 1). Crystals are typically euhedral and have rhombic cross sections (Figure 8). Twinned cross sections are bisected along the long diagonal by the (100) twin plane. Sphene has a pale gray-brown color and lacks pleochroism.

Olivine crystals, outlined by reaction rims of aegirine-augite and magnetite(?), are present in some of the phonolite porphyry samples (Figure 9). Also present are accessory amounts of apatite, both as poikilitic inclusions and as grains scattered within the groundmass. Magnetite(?) may be of the titaniferous variety, especially where closely associated with sphene.

Analcime, natrolite, calcite, and hematite are present as secondary alteration products in all phonolite porphyry samples modally analyzed (Table 1). Analcime occurs as cloudy, slightly anisotropic material replacing sanidine and as irregular patches throughout the groundmass. Natrolite is often associated with analcime as fine-grained, radially

Figure 8. Photomicrograph of rhombic and lath-shaped crystals of sphene from phonolite porphyry sample BL-5. Note twinning along the (100) plane exhibited by grain at the right. Maximum dimension of crystal at the right approximately 1.5 mm. Crossed polars, 194X.

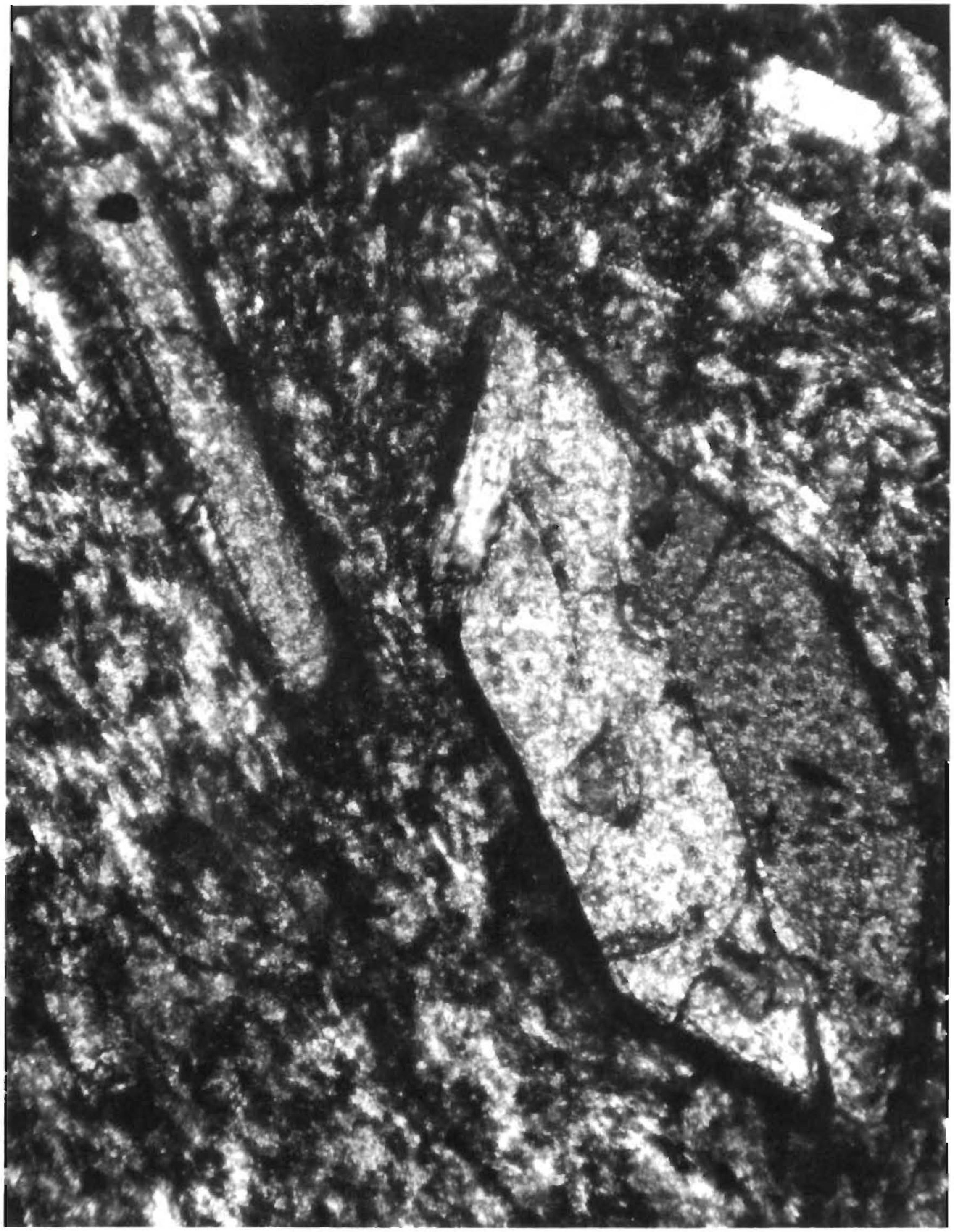


Figure 9. Photomicrograph of olivine crystal from phonolite porphyry sample BL-8. Olivine enclosed by large reaction rim of aegirine-augite and magnetite(?). Plane polarized light, 78X.

arranged fibers replacing sanidine. Calcite occurs as fine-grained to microcrystalline aggregates replacing sanidine, hauyne, and matrix materials. Hematite is found as secondary rims enclosing magnetite(?).

Rock Chemistry

The bulk rock chemistry and CIPW mineralogy of seven samples of Houston Creek phonolite porphyry are listed in Table 3. All samples are undersaturated with respect to SiO_2 as indicated by the persistence of normative nepheline. Normative nepheline ranges from 4 to 15 percent with a mean of approximately 9 percent. The rocks have SiO_2 contents which fall within a narrow range from 59.5 to 60.5 percent. These values are slightly higher than the SiO_2 content given for the average phonolite composition of Nockolds (1954, p. 1024), but are similar to published phonolite analyses from Sorensen (1974, p. 324). On the basis of Shand's (1947) concept of alumina saturation, the phonolite porphyry is peraluminous as Al_2O_3 exceeds ($CaO + Na_2O + K_2O$) in all analyses. Total alkalis ($Na_2O + K_2O$) plotted against SiO_2 fall in the phonolite field of Cox and others (1979, p. 14) for all seven samples. The mean Na_2O/K_2O ratio of these rocks is 1.00 with values ranging from 0.76 to 1.15 (Table 3).

Phonolite

General

An extensive body of phonolite forms a resistant promontory northwest of Houston Creek in section 24 (Plate 1). The phonolite occurs as float material at the top of the promontory and is exposed in roadcuts in the southern half of section 24 (sample locations 63, 64, and 65; Plate 1).

TABLE 3

NORMALIZED CHEMICAL ANALYSES, CIPW NORMATIVE MINERALOGY, AND Na_2O/K_2O RATIOS OF THE HOUSTON CREEK PHONOLITE PORPHYRY

Sample	BL-4D	BL-5	BL-5A	BL-8-6	BL-10	BL-11	BL-11A
SiO_2	60.09	60.36	59.77	59.27	59.28	60.47	59.56
Al_2O_3	19.54	19.37	19.04	18.99	18.62	19.22	19.57
Fe_2O_3	2.13	1.99	2.16	2.05	1.84	1.90	2.04
FeO	0.84	1.06	1.06	1.57	1.77	1.85	1.08
MgO	0.41	1.01	1.20	0.66	0.77	1.32	1.27
CaO	2.17	2.81	2.78	2.30	2.86	1.96	2.52
Na_2O	7.28	6.12	6.25	7.36	7.30	5.41	6.23
K_2O	6.50	6.34	6.44	6.40	6.58	7.14	6.61
TiO_2	0.63	0.49	0.66	0.55	0.34	0.40	0.54
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MnO	0.00	0.23	0.31	0.00	0.00	0.25	0.24
SO_3	0.32	0.00	0.28	0.72	0.46	0.00	0.31
quartz	0.00	0.00	0.00	0.00	0.00	0.00	0.00
corundum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
orthoclase	38.44	37.54	38.07	37.86	39.06	42.22	39.07
albite	39.51	39.97	38.06	38.23	32.34	37.97	36.88
anorthite	2.55	6.67	5.85	2.38	0.00	7.07	6.99
nepheline	10.85	6.46	7.05	10.51	14.68	4.24	7.48
diopside	2.20	5.43	6.18	4.08	7.24	2.14	4.29
hypersthene	0.00	0.00	0.00	0.00	0.00	0.00	0.00
olivine	0.00	0.00	0.09	0.00	0.00	2.81	0.82
magnetite	0.88	2.75	2.51	2.97	1.86	2.75	2.70
ilmenite	1.19	0.03	1.25	1.04	0.65	0.76	1.02
apatite	0.00	0.00	0.00	0.00	0.00	0.00	0.00
acmite	0.00	0.00	0.00	0.00	1.63	0.00	0.00
Na_2O/K_2O ratio	1.12	0.97	0.97	1.15	1.11	0.76	0.94

Although contact relations are somewhat unclear, the igneous body appears to have been intruded along a plane of stratigraphic weakness within the Pennsylvanian-Permian Minnelusa Formation. A thin, nonresistant shale unit, which separates massive units of sandstone and carbonate, may have provided a passageway for the emplacement of phonolite as a sill or small laccolith. An inferred contact between the phonolite and a trachyte porphyry body has been placed near the boundary of sections 24 and 25 (Plate 1), although the possibility exists that these two rock types are gradational.

Outcrops of phonolite typically display well developed subhorizontal jointing that is interpreted as being a product of exfoliation. Contact metamorphism or metasomatism of the country rocks is demonstrated by an abundance of silicified boulders of Minnelusa sandstone at or near the contacts.

Petrography and Mineral Chemistry

Samples of phonolite are typically medium to dark gray with aphanitic groundmasses and slightly porphyritic textures. Phenocrysts include aegirine-augite, sanidine, hauyne, and melanite garnet. The groundmass is strongly trachytic to randomly oriented and is composed predominantly of orthoclase and aegirine-augite. Accessory minerals include sphene, apatite, and magnetite(?), with analcime, natrolite, calcite, and hematite present as secondary alteration products. Granitic and pyroxene-rich xenoliths, up to 7 cm in maximum dimension, occur locally.

The modes of six samples of phonolite are given in Table 4. The groundmass is 75 to 81 percent of the rock and is composed largely of rectangular, Carlsbad twinned orthoclase microlites containing tiny

TABLE 4

MODAL ANALYSES OF THE HOUSTON CREEK PHONOLITE IN VOLUME PERCENTAGES

Sample number	BL-52	BL-55	BL-55A	BL-63	BL-79	BL-80
Groundmass	78.4	77.8	75.2	80.4	81.2	79.4
Sanidine	0.6	0.2	2.2	0.8	pr	0.8
Plagioclase	0.0	0.0	0.0	pr	0.0	0.0
Aegirine-augite	13.2	13.8	17.2	12.2	14.4	13.6
Aegirine	pr	pr	pr	pr	pr	pr
Melanite	0.8	0.6	0.0	0.6	0.2	1.2
Hauyne	2.2	2.2	1.4	0.2	0.2	0.8
Analcime	2.4	1.8	1.4	1.8	1.4	2.2
Natrolite	1.0	1.8	0.8	2.2	1.8	1.6
Sphene	0.2	pr	0.4	0.2	pr	0.0
Magnetite(?)	0.6	0.4	0.4	0.6	0.2	pr
Calcite	pr	0.2	0.4	pr	pr	0.2
Hematite	pr	0.6	pr	0.4	0.2	pr
Apatite	pr	0.8	0.6	0.6	0.4	0.2

pr = present; noted optically but not point counted

aegirine-augite crystals and patches of isotropic analcime. Alteration of the groundmass by calcite and clays(?) is widespread and appears to be most pronounced in the vicinity of localized microfractures.

Aegirine-augite is distributed throughout the rock as microphenocrysts less than 0.1 mm and as phenocrysts up to 1.5 mm in length. The grains are typically subhedral and compose from 12 to 17 percent of the phonolite (Table 4). Aegirine-augite crystals are highly pleochroic with X=green, Y=green, and Z=yellowish-green, and show strong birefringence. Larger phenocrysts are commonly zoned with colorless or pale green cores and deep green margins. Aegirine-augite phenocrysts frequently contain poikilitic inclusions of sphene and apatite. Minor replacement by magnetite(?) is also evident.

Microprobe analyses of a zoned aegirine-augite phenocryst are given in columns C and D of Table 5. The pale green core of the phenocryst (Column C) shows enrichment of CaO and MgO, whereas the deep green margin (Column D) is enriched in Na_2O and FeO. Both analyses are similar to published aegirine-augite analyses listed in Deer and others (1963A).

Subhedral to anhedral sanidine phenocrysts comprise less than 3 percent of the phonolite (Table 4). The phenocrysts range up to 2 mm in length and frequently poikilitically enclose minute aegirine needles. Replacement of sanidine by clear, isotropic analcime and radially fibrous natrolite is extensive. A microprobe analysis of an unaltered sanidine phenocryst is given in Table 5 (Column A). The analysis is very similar to an analysis of sanidine from the Houston Creek phonolite porphyry that is described in the previous section and presented in Table 2.

A microprobe analysis of orthoclase from the groundmass is presented in Table 5 (Column B). The orthoclase is shown to be slightly more sodic

TABLE 5

CHEMICAL ANALYSES OF HOUSTON CREEK PHONOLITE MINERALS IN OXIDE WEIGHT PERCENTAGES

	A	B	C	D	E	F
SiO_2	65.11	61.62	47.85	55.29	34.91	37.56
Al_2O_3	18.96	22.31	3.20	1.79	3.48	29.67
FeO	0.00	0.00	17.56	21.05	19.06	0.00
Fe_2O_3	0.31	0.79	2.01	1.80	5.08	0.11
MgO	0.00	0.00	5.64	1.79	0.00	0.00
CaO	0.00	0.00	18.91	5.19	31.49	6.65
Na_2O	4.05	9.30	2.65	11.19	0.00	11.39
K_2O	10.46	6.09	0.08	0.12	0.00	3.19
TiO_2	0.00	0.00	0.51	0.30	3.58	0.00
MnO	0.12	0.00	0.94	1.79	1.41	0.00
P_2O_5	0.00	0.00	0.00	0.16	0.26	0.00
BaO	0.00	0.12	0.00	0.00	0.00	0.00
SO_3	0.00	0.00	0.00	0.00	0.00	6.58
Total	99.00	100.23	99.34	100.46	99.26	96.16

Explanation of Column Headings

A = Sanidine, BL-55, phenocryst

B = Orthoclase, BL-55, groundmass

C = Aegirine-augite, BL-52, zoned phenocryst, core

D = Aegirine-augite, BL-52, zoned phenocryst, margin

E = Melanite, BL-52, phenocryst

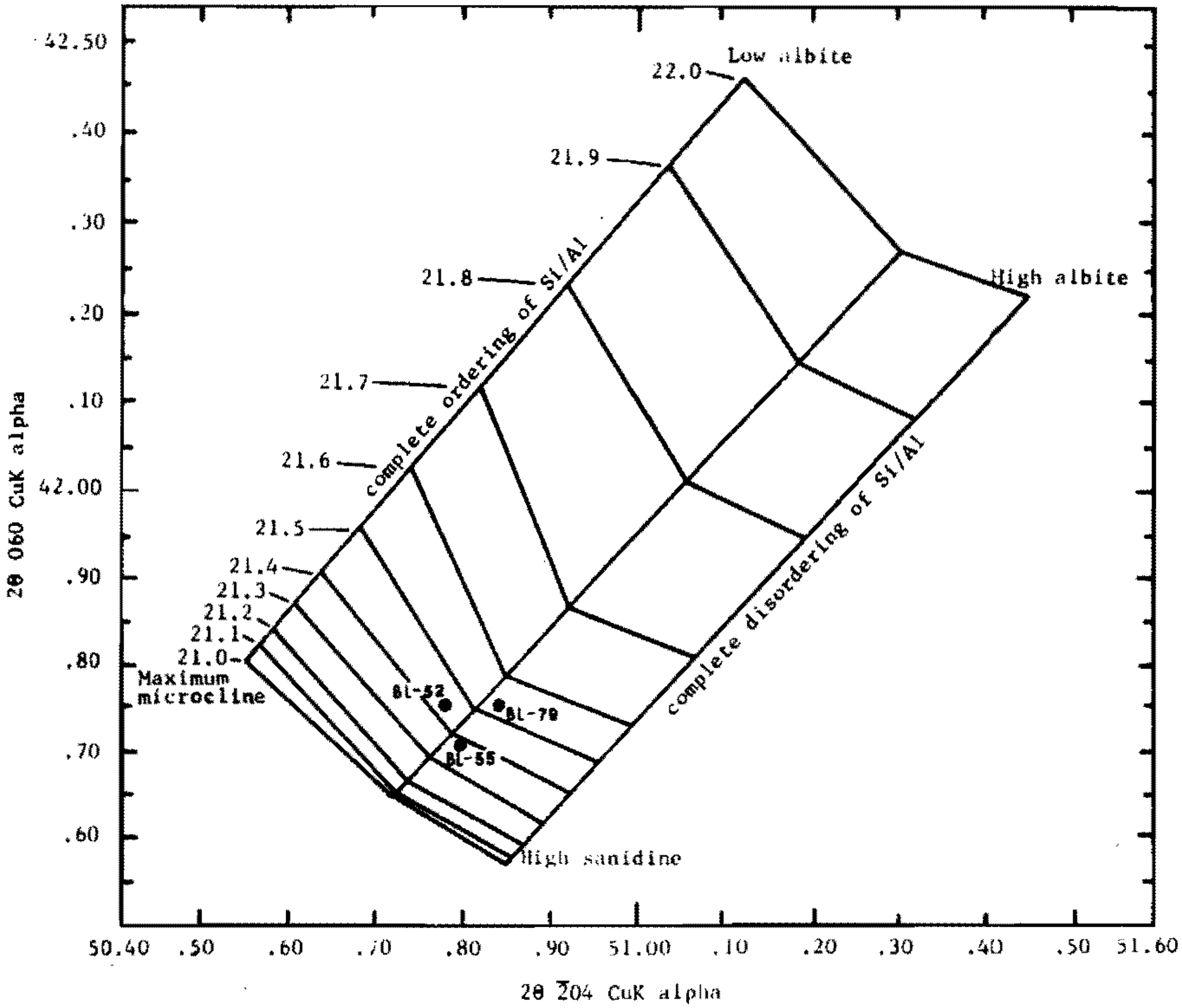
F = Hauyne, BL-52, phenocryst

and less potassic than the phenocryst of sanidine, but is similar to several published analyses presented in Deer and others (1963B). Structural states of the groundmass feldspars were determined by Wright's (1968) x-ray diffraction three-peak method. The results are given in Figure 10. All groundmass feldspars plot as orthoclase with intermediate ordering. Compositions range from Or_{69} to Or_{76} as determined by Wright's (1968, p. 93) plot of Or content against $2\theta(\bar{2}01)$.

Hauyne is present as phenocrysts with hexagonal outlines. The grains range up to 1 mm in their maximum dimension and are 1 to 2 percent of the rock (Table 4). Alteration of hauyne by analcime, calcite, and clays(?) is typically concentrated in the cores. Crystal margins are relatively unaltered and commonly rimmed by tangential aegirine needles and magnetite(?). A microprobe analysis taken near the margin of a hauyne crystal is given in Table 5 (Column F). Slight alteration by volatile-rich phases is indicated by the relatively poor closure (total oxide weight = 96.16%). However, the composition is very similar to chemical analyses of hauyne crystals presented in Deer and others (1963B).

Melanite garnet (a titaniferous variety of andradite) occurs as dark brown phenocrysts that comprise approximately 1 percent of the phonolite (Table 4). Grains of melanite are subhedral with six-sided cross sections and are typically glomerophyrically arranged with phenocrysts of aegirine-augite and hauyne. Grain size ranges up to 1 mm. The refractive index of melanite from phonolite sample BL-80 is 1.880. Poikilitic inclusions include sphene, apatite, aegirine-augite, and magnetite(?). Melanite is partially replaced by analcime along fractures and by aegirine-augite and magnetite(?) along crystal margins. The chemical analysis of a melanite phenocryst is presented in Table 5

Figure 10. Ordering of Si/Al in groundmass feldspars from the Houston Creek phonolite as determined by the three-peak method of Wright (1968). All three samples plot as orthoclase with intermediate ordering.



42.50
.40
.30
.20
.10
42.00
.90
.80
.70
.60
2θ 060 CuK alpha
50.40
.50
.60
.70
.80
.90
51.00
.10
.20
.30
.40
.50
51.60
2θ $\bar{2}$04 CuK alpha
Low albite
High albite
High sanidine
Maximum microcline
22.0
21.9
21.8
21.7
21.6
21.5
21.4
21.3
21.2
21.1
21.0
complete ordering of Si/Al
complete disordering of Si/Al
BL-52
BL-79
BL-55

(column E). The composition is similar to analyses of melanite published in Deer and others (1962). The TiO_2 content of 3.58 percent complies with the distinction by Deer and others (1969, p. 25) that the melanite variety of andradite contains between 1 and 5 percent TiO_2.

Phonolite samples contain accessory amounts of sphene, apatite, and magnetite(?) (Table 4). Natrolite occurs as large patches of intergrown crystals or as radial masses replacing feldspar phenocrysts and groundmass. Analcime and calcite replacement is widespread among phenocrysts and groundmass. Pyrite has replaced magnetite(?) in samples BL-52 and BL-63.

Xenoliths

Localized exposures of phonolite contain xenoliths of two distinct types: relatively abundant granitic varieties and less common pyroxene-rich mafic varieties. These xenoliths vary from angular to subrounded and range in size from several millimetres to 7 cm.

The granitic inclusions consist of quartz, microcline, calcic oligoclase, and lenses or pockets of chloritic biotite. Accessory minerals include zircon, apatite, and magnetite(?). The granitic inclusions typically have hypidiomorphic granular areas with interstitial microcrystalline material. Crystal boundaries are generally extensively corroded. Lenses of biotite, strained plagioclase, and quartz grains with extreme undulose extinction suggest that the xenoliths are fragments of granitic gneiss.

The mafic xenoliths are typically composed of 70 to 80 percent augite or aegirine-augite, lesser amounts of biotite and magnetite(?), and secondary clays(?) and analcime. Textures vary from hypidiomorphic to panidiomorphic granular. The xenoliths are typically characterized by fine-grained pyroxene-rich reaction rims that resemble staining in hand samples (Figure 11). However, some mafic xenoliths exhibit less distinctive, gradational contacts with the host material. Secondary clays(?) occur as cloudy aggregates interstitial to subhedral to euhedral grains of pyroxene. Clear, isotropic analcime is randomly dispersed throughout the inclusions (Figure 11). Brown biotite commonly forms replacement rims around pyroxene crystals.

Rock Chemistry

The bulk rock chemistry and CIPW mineralogy of seven samples of Houston Creek phonolite are listed in Table 6. Undersaturation of SiO_2 is indicated by the presence of normative nepheline in all samples. Normative nepheline varies from 7 to 15 percent with a mean percentage of approximately 12. The phonolites are slightly more silicic and less alkalic than the Houston Creek phonolite porphyry (Table 3), but closely resemble phonolite analyses published in Sorensen (1974, p. 324). SiO_2 contents of all seven samples are tightly grouped between 61 and 62 percent with a mean of approximately 61.3. On the basis of Shand's (1947) alumina saturation index, the phonolite is strongly peraluminous as the molecular proportion of Al_2O_3 exceeds $CaO + Na_2O + K_2O$ in all analyses. Total alkalis plotted against SiO_2 fall within the phonolite field of Cox and others (1979, p. 14) for all seven samples. The mean Na_2O/K_2O ratio of the phonolite is 1.30 with values ranging from 1.16 to 1.49 (Table 6).

Figure 11. Photomicrograph of mafic xenolith from phonolite sample BL-55A. Xenolith marked by dark pyroxene-rich reaction rim and colorless analcime in the core area. Note the phenocrysts of hauyne at the lower left. Plane polarized light, 10X.

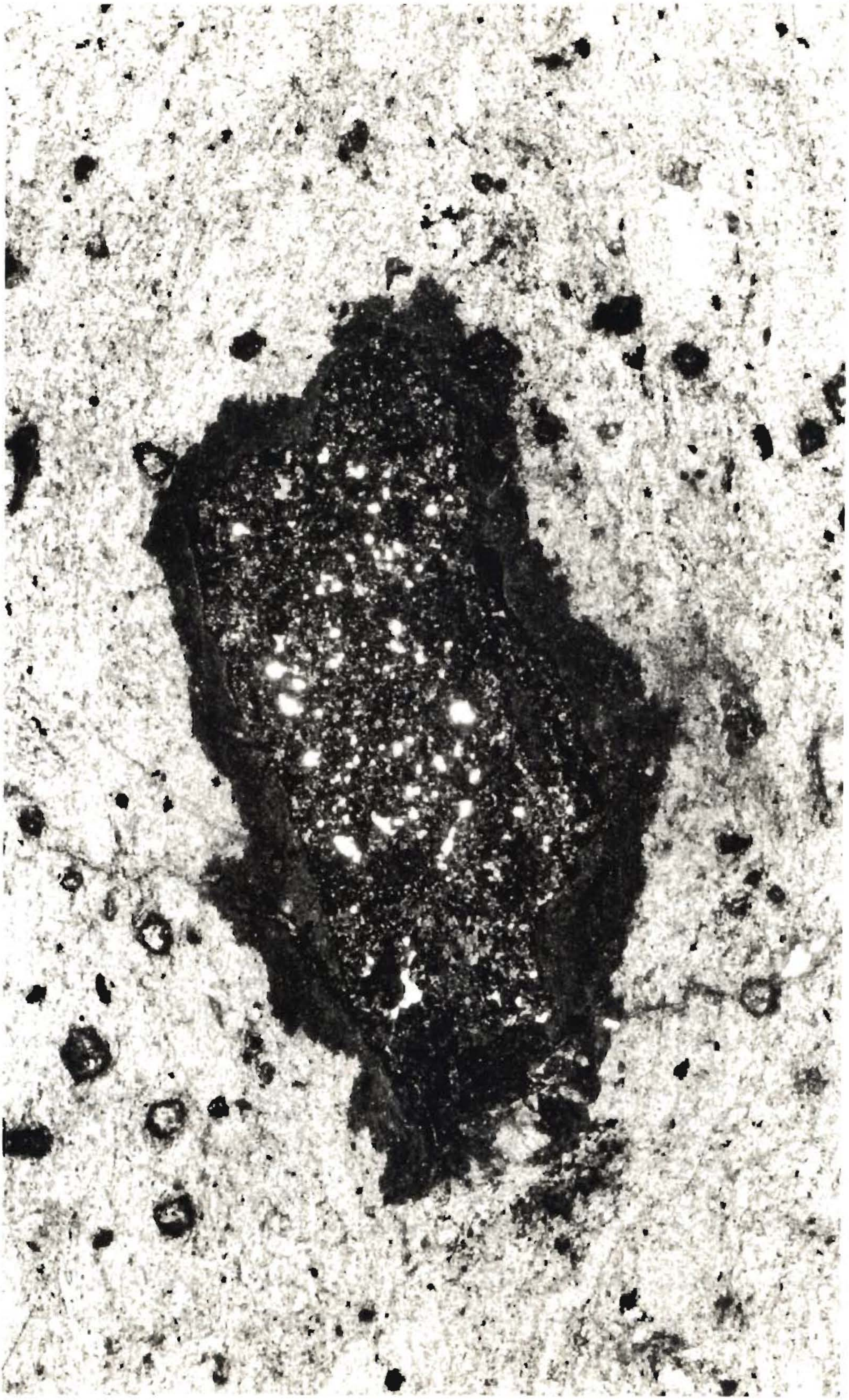


TABLE 6

NORMALIZED CHEMICAL ANALYSES, CIPW NORMATIVE MINERALOGY, AND Na_2O/K_2O RATIOS OF THE HOUSTON CREEK PHONOLITE

Sample	BL-55	BL-52	BL-79	BL-80	BL-55A	BL-65	BL-69
SiO_2	62.38	60.99	60.84	61.20	61.04	60.98	61.38
Al_2O_3	19.40	19.76	19.44	20.21	20.18	20.09	20.25
Fe_2O_3	1.69	1.50	1.74	1.60	1.67	1.64	1.70
FeO	1.40	1.83	1.77	0.76	0.42	1.17	0.78
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.25
CaO	0.92	0.83	1.05	1.08	0.88	0.96	1.78
Na_2O	7.71	8.70	8.41	7.74	7.90	8.16	7.49
K_2O	6.08	5.83	5.85	6.65	6.83	6.25	6.03
TiO_2	0.19	0.00	0.24	0.10	0.17	0.14	0.20
P_2O_5	0.00	0.00	0.00	0.00	0.18	0.00	0.00
MnO	0.00	0.26	0.28	0.16	0.00	0.33	0.13
SO_3	0.24	0.21	0.24	0.35	0.43	0.18	0.00
quartz	0.00	0.00	0.00	0.00	0.00	0.00	0.00
corundum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
orthoclase	35.92	34.48	34.61	39.35	40.48	36.97	35.63
albite	49.93	42.20	43.17	42.81	42.33	43.40	45.12
anorthite	1.20	0.00	0.00	1.98	0.92	0.35	3.82
nepheline	7.43	14.64	13.18	11.09	11.85	13.29	9.89
diopside	1.61	3.67	4.65	0.38	0.00	2.21	1.34
hypersthene	0.00	0.00	0.00	0.00	0.00	0.00	0.00
olivine	0.00	1.09	0.01	0.00	0.00	0.00	0.00
magnetite	2.45	0.82	1.56	2.32	0.86	2.38	2.35
ilmenite	0.36	0.00	0.45	0.19	0.32	0.26	0.38
apatite	0.00	0.00	0.00	0.00	0.42	0.00	0.00
acmite	0.00	2.69	1.91	0.00	0.00	0.00	0.00
Na_2O/K_2O ratio	1.27	1.49	1.44	1.16	1.16	1.31	1.24

Trachyte Porphyry

General

A body of trachyte prophyry is exposed along a north-south trending ridge in sections 24, 25, and 30 (Plate 1). Extensive jagged outcrops line the top of the ridge and overlook Houston Creek to the west.

Contact relations appear to be similar to those of the Houston Creek phonolite to the north; the trachyte appears to have been emplaced concordantly as a sill or small laccolith along planes of weakness within the Minnelusa Formation. The trachyte porphyry may possibly be a compositional variant of the Houston Creek phonolite, as field relations between the two rock types are relatively obscure. Field evidence at the southern extremity of the body suggests that the trachyte porphyry is in fault contact with the Minnekahta Limestone (Plate 1).

Exposed contacts of the trachyte porphyry with the country rock are at the northwest and southern extensions of the igneous body. Sandstones of the Minnelusa Formation are typically metamorphosed to highly silicified quartzites at the contacts of this formation with the body, but the effects appear to be limited to several meters. Tabular phenocrysts of alkali feldspar within the trachyte porphyry are aligned subparallel to contacts with the intruded rock. The contact with the Minnekahta, here interpreted as a fault, is marked by brecciation and slight recrystallization of the limestone.

Petrography and Mineral Chemistry

The trachyte porphyry is a light to medium gray, holocrystalline, aphanitic rock with a distinct porphyritic texture. Major phenocrysts are orthoclase, aegirine-augite, melanite, and sphene, arranged in a well-developed trachytic groundmass of orthoclase microlites and minor aegirine. Accessory minerals include magnetite(?) and apatite, with analcime, natrolite, hematite, and calcite occurring as the major alteration products. Small mafic inclusions, generally less than 5 mm in diameter, are present in several samples, but are highly replaced by iron oxides.

Modal analyses of six samples of trachyte porphyry are given in Table 7. The table shows that the groundmass is 52 to 61 percent of these rocks. Lath-shaped microlites of orthoclase combine with acicular aegirine crystals to produce a very pronounced trachytic groundmass. Phenocryst orientations vary from flow-oriented to random, with flow-oriented samples found at or near contacts with the country rock. Scattered, irregularly shaped patches of secondary or deuteric alteration products commonly disrupt the trachytic character of the groundmass.

Orthoclase is the major mineral that occurs as phenocrysts. The phenocrysts are 1 mm to 15 mm long and comprise 21 to 29 percent of the rock (Table 7). Individual orthoclase phenocrysts frequently show concentrically zoned patterns of clay(?) alteration and are often partially replaced by analcime and natrolite. Poikilitic inclusions include aegirine needles and fine-grained muscovite. Many of the orthoclase grains have embayed and irregular crystal boundaries.

Alkali feldspar structural state results, as determined by Wright's (1968) three-peak method, are presented in Figure 12. Orthoclase phenocrysts (samples BL-83 and BL-85) show intermediate ordering of Si/Al. Ordering in orthoclase from the groundmass (samples BL-88 and BL-90) is shown to be slightly higher than ordering in the phenocrysts. Using

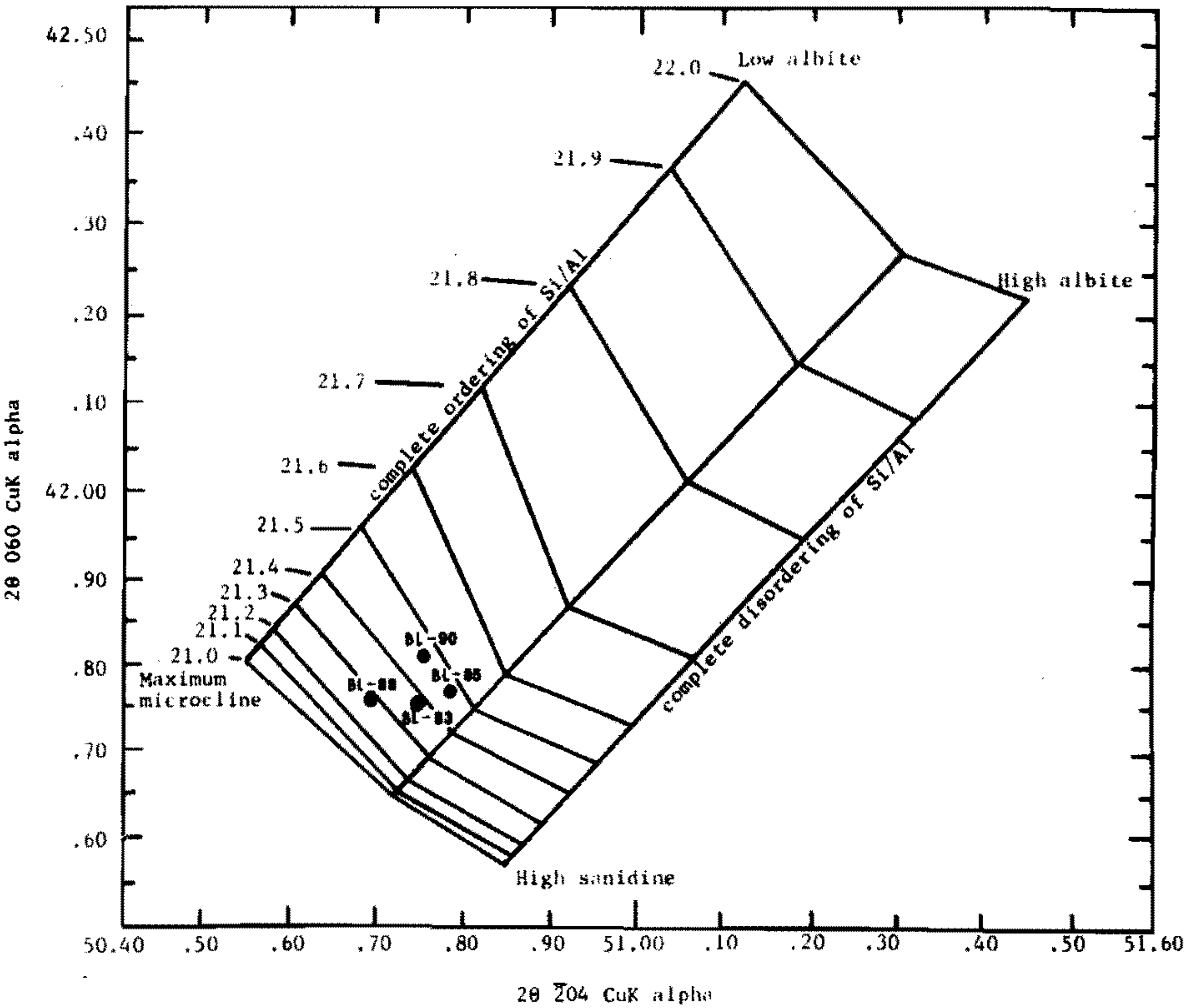
TABLE 7

MODAL ANALYSES OF THE HOUSTON CREEK TRACHYTE PORPHYRY IN VOLUME PERCENTAGES

Sample number	BL-83	BL-84	BL-85	BL-86	BL-86A	BL-94	BL-98
Groundmass	59.0	54.8	61.0	54.0	51.6	57.2	59.8
Orthoclase	22.0	23.0	26.4	27.4	29.2	22.6	21.0
Aegirine-augite	13.8	18.0	9.6	11.2	13.2	14.2	13.8
Aegirine	pr	pr	pr	pr	pr	pr	pr
Melanite	1.0	1.2	1.4	1.4	0.2	1.2	1.0
Analcime	1.8	0.6	pr	3.2	3.4	1.2	2.2
Natrolite	0.4	0.4	0.4	0.6	0.4	0.6	0.6
Sphene	0.4	1.0	0.6	1.0	1.2	1.4	1.0
Magnetite(?)	0.2	pr	0.6	pr	pr	0.2	0.4
Calcite	0.4	pr	pr	pr	pr	0.8	pr
Hematite	0.8	0.6	pr	1.0	0.2	0.6	0.2
Apatite	0.2	0.2	0.4	0.2	0.2	pr	0.4

pr = present; noted optically but not point counted

Figure 12. Ordering of Si/Al in alkali feldspars from the Houston Creek trachyte porphyry as determined by the three-peak method of Wright (1968). Orthoclase phenocrysts (samples BL-83 and BL-85) are intermediately ordered. Groundmass orthoclase (samples BL-88 and BL-90) show slightly higher ordering.


42.50
.40
.30
.20
.10
42.00
.90
.80
.70
.60
2θ 060 CuK alpha
50.40
.50
.60
.70
.80
.90
51.00
.10
.20
.30
.40
.50
51.60
2θ $\overline{2}$04 CuK alpha
22.0
Low albite
21.9
21.8
21.7
21.6
21.5
21.4
21.3
21.2
21.1
21.0
Maximum microcline
High albite
High sanidine
complete ordering of Si/Al
complete disordering of Si/Al
BL-90
BL-85
BL-88
BL-83

Wright's (1968, p. 93) plot of Or content versus $2\theta(\bar{2}01)$, the orthoclase phenocrysts were determined to be Or_{84} (± 3%). A composition of Or_{87} was obtained for orthoclase from the groundmass. Microprobe analyses of an orthoclase phenocryst and orthoclase from the groundmass, presented in Table 8 (columns A and B, respectively), are shown to be chemically very similar.

Aegirine-augite occurs as phenocrysts that comprise from 10 to 18 percent of the rock (Table 7). Grains are subhedral to euhedral and attain lengths of 4 mm. The phenocrysts are typically strongly pleochroic with X=green, Y=yellowish-green, and Z=greenish-brown. Most of the aegirine-augite phenocrysts show well developed color zoning, with colorless to pale green cores and deep green margins. A zoned aegirine-augite crystal from trachyte porphyry sample BL-83 is shown in Figure 13. The same zoned crystal was analyzed for iron and magnesium along a margin-to-margin traverse. The results, presented in Figure 14, clearly indicate magnesium enrichment in the core and iron enrichment at the crystal margins. Microprobe analyses of a similarly zoned aegirine-augite phenocryst from sample BL-85 are given in Table 8 (columns C and D). The analyses show increased MgO and CaO in the core area, with increased FeO and Na_2O at the margin.

Phenocrysts of melanite garnet comprise between 1 and 2 percent of the rock (Table 7). Crystals have hexagonal cross sections and are typically rimmed by a thin zone of aegirine-augite crystals. Inclusions of sphene, apatite, and pyroxene occur poikilitically. The larger phenocrysts of melanite generally display sharp, oscillatory, color zoning; smaller grains show normal color zoning with gradational zone boundaries.

TABLE 8

CHEMICAL ANALYSES OF HOUSTON CREEK TRACHYTE PORPHYRY MINERALS IN OXIDE WEIGHT PERCENTAGES

	A	B	C	D	E	F
SiO_2	66.58	65.44	56.10	50.86	30.07	32.44
Al_2O_3	19.68	20.20	1.77	1.55	2.83	2.14
FeO	0.00	0.00	8.72	25.85	9.65	20.64
Fe_2O_3	0.56	0.68	1.92	2.29	11.21	5.25
MgO	0.00	0.00	14.11	0.46	0.35	0.10
Ca9	0.19	0.17	23.23	8.19	32.25	31.54
Na_2O	4.50	5.09	1.74	8.24	0.34	0.00
K_2O	10.28	8.96	0.00	0.35	0.00	0.00
TiO_2	0.00	0.00	0.42	0.79	9.71	3.75
MnO	0.00	0.00	0.61	0.71	0.64	0.68
P_2O_5	0.00	0.00	0.00	0.00	0.91	0.19
BaO	0.50	0.79	0.00	0.00	0.00	0.00
SO_3	0.00	0.00	0.00	0.00	0.16	0.23
Total	102.29	101.33	108.62	99.29	101.88	97.95

Explanation of Column Headings

A = Orthoclase, sample BL-98, phenocryst

B = Orthoclase, sample BL-98, groundmass

C = Aegirine-augite, sample BL-85, zoned phenocryst, core

D = Aegirine-augite, sample BL-85, zoned phenocryst, margin

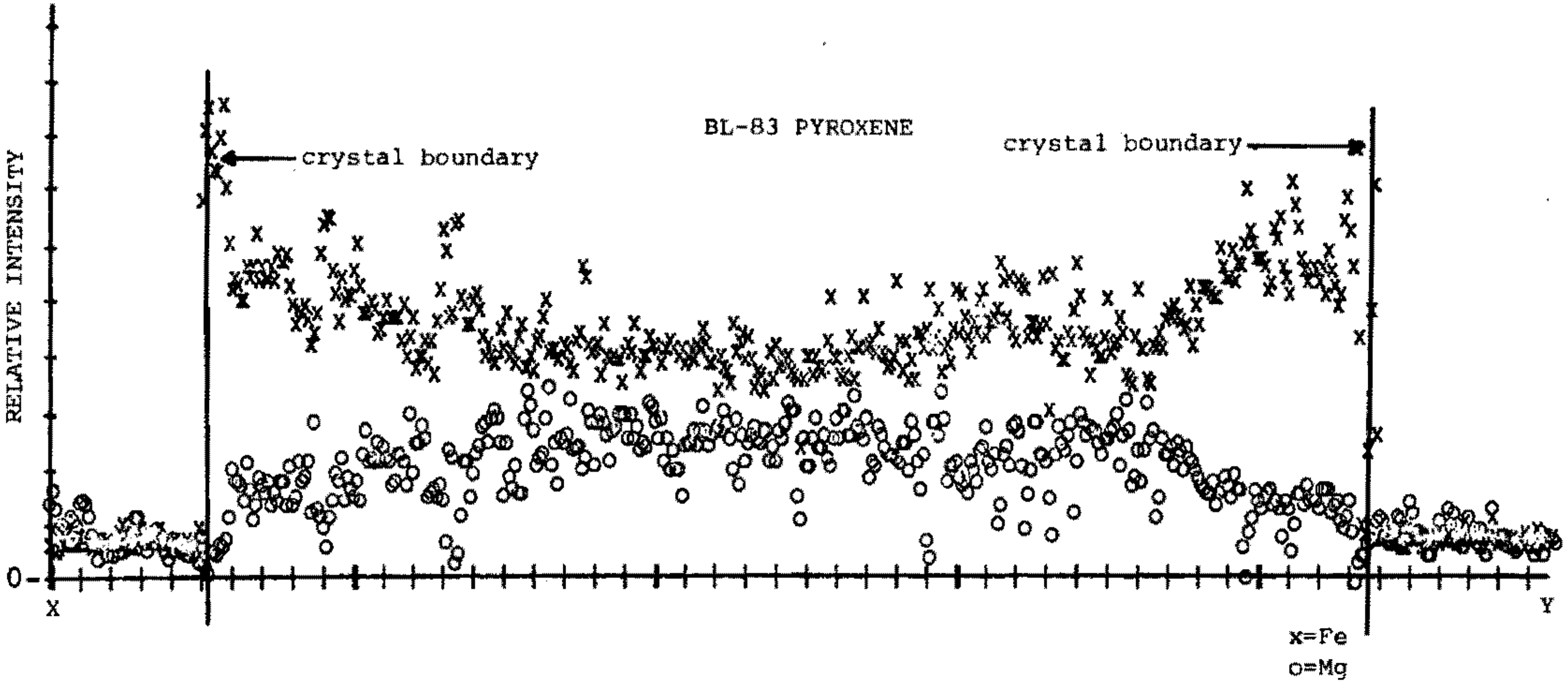
E = Melanite, sample BL-85, zoned phenocryst, core

F = Melanite, sample BL-85, zoned phenocryst, margin

Figure 13. Photomicrograph of zoned aegirine-augite phenocryst from trachyte porphyry sample BL-83. A microprobe profile along trace XY is presented in Figure 14. Plane polarized light, 57X.


Y
X

Figure 14. Microprobe profile across a zoned aegirine-augite phenocryst. Profile shows enrichment of Fe at the margins and enrichment of Mg in the core area. Trace of profile shown in Figure 13. Sample BL-83.


BL-83 PYROXENE
crystal boundary
crystal boundary
RELATIVE INTENSITY
0
X
Y
x=Fe
o=Mg

Zoning is distinguished by color variations from dark brown to light reddish-brown. An oscillatory zoned melanite crystal from trachyte porphyry sample BL-85 is shown in Figure 15. A margin-to-margin microprobe profile across the zoned crystal is given in Figure 16. The profile (trace XY) shows a relative enrichment of titanium in the dark colored zones, and a relative enrichment of iron in the light colored zones. Microprobe analyses of a zoned melanite crystal from trachyte porphyry sample BL-85 are given in Table 8. The dark brown core area (column E) shows a relatively high TiO_2 content; the light brown margin (column F) shows enrichment in total Fe-oxides. CaO and SiO_2 contents of the two zones are nearly identical.

Sphene crystals, typically euhedral with rhombic cross sections, occur as phenocrysts and as poikilitic inclusions. Several grains of sphene are partially replaced at their margins by anhedral grains of opaque material, possibly ilmenite. Apatite is common as poikilitic inclusions and as occasional grains up to 0.5 mm within the matrix. Magnetite(?), frequently altered to hematite at its rims, is commonly associated with pyroxene. Analcime and radial clusters of natrolite are widespread alteration products of orthoclase.

Rock Chemistry

The bulk rock chemistry and CIPW mineralogy of seven samples of Houston Creek trachyte porphyry are listed in Table 9. All of the samples are either slightly oversaturated or slightly undersaturated with SiO_2, as they range from 1.56 percent normative quartz to 2.94 percent normative nepheline. The rocks have SiO_2 percentages between 61 and 63. These values are very similar to the SiO_2 content given for the

Figure 15. Photomicrograph of phenocrysts of melanite and aegirine-augite from trachyte porphyry sample BL-85. Note the dark and light oscillatory color zones of the melanite crystal and the flow-oriented groundmass. Sphene is present as inclusions in melanite and aegirine-augite crystals. Microprobe profile along trace XY is presented in Figure 16. Plane polarized light, 77X.

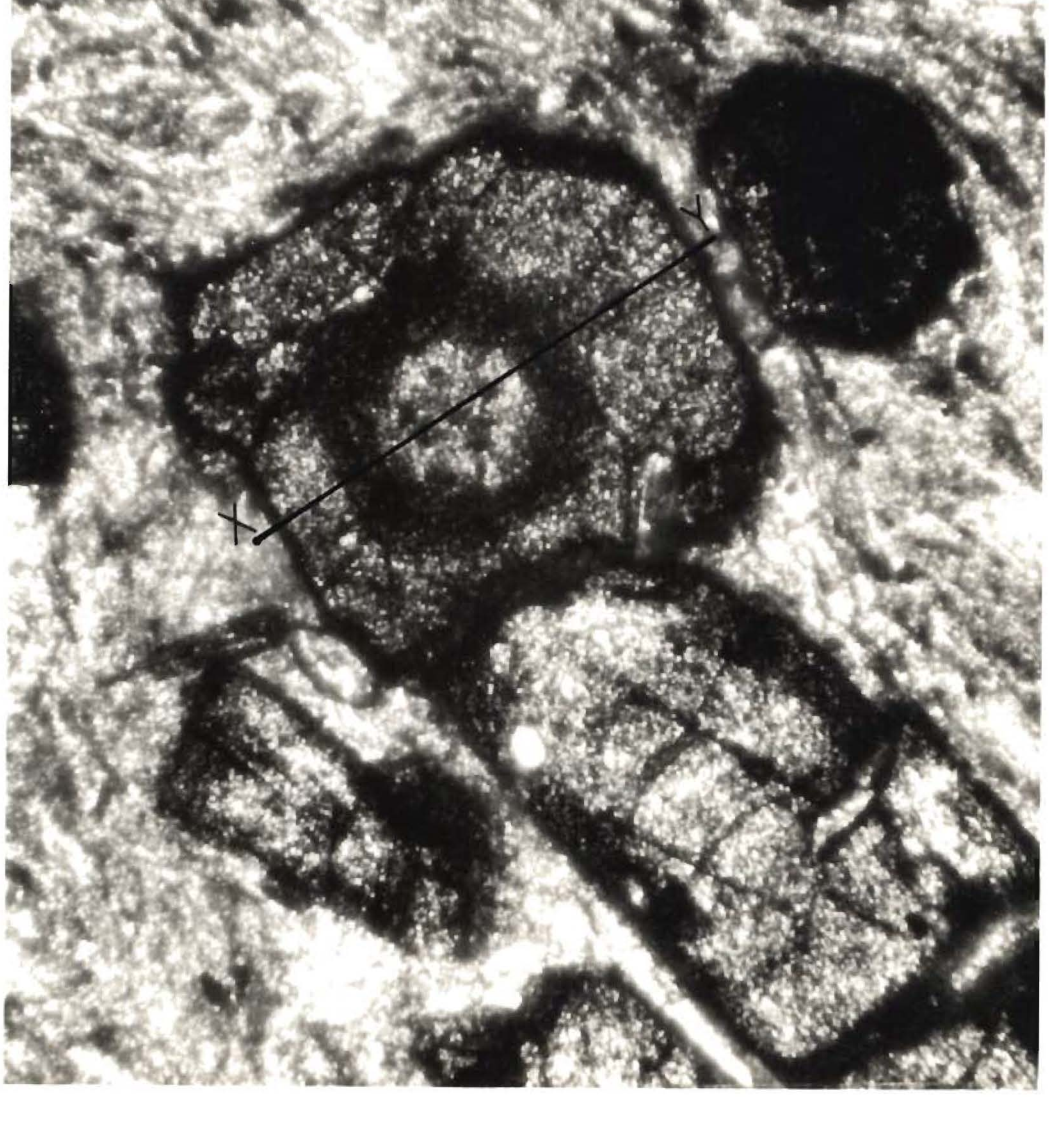

Y
X

Figure 16. Microprobe profile across a zoned melanite phenocryst. Profile shows zones of enrichment of Ti that correspond with relative depletions in Fe. Trace of profile shown in Figure 15. Sample BL-85.

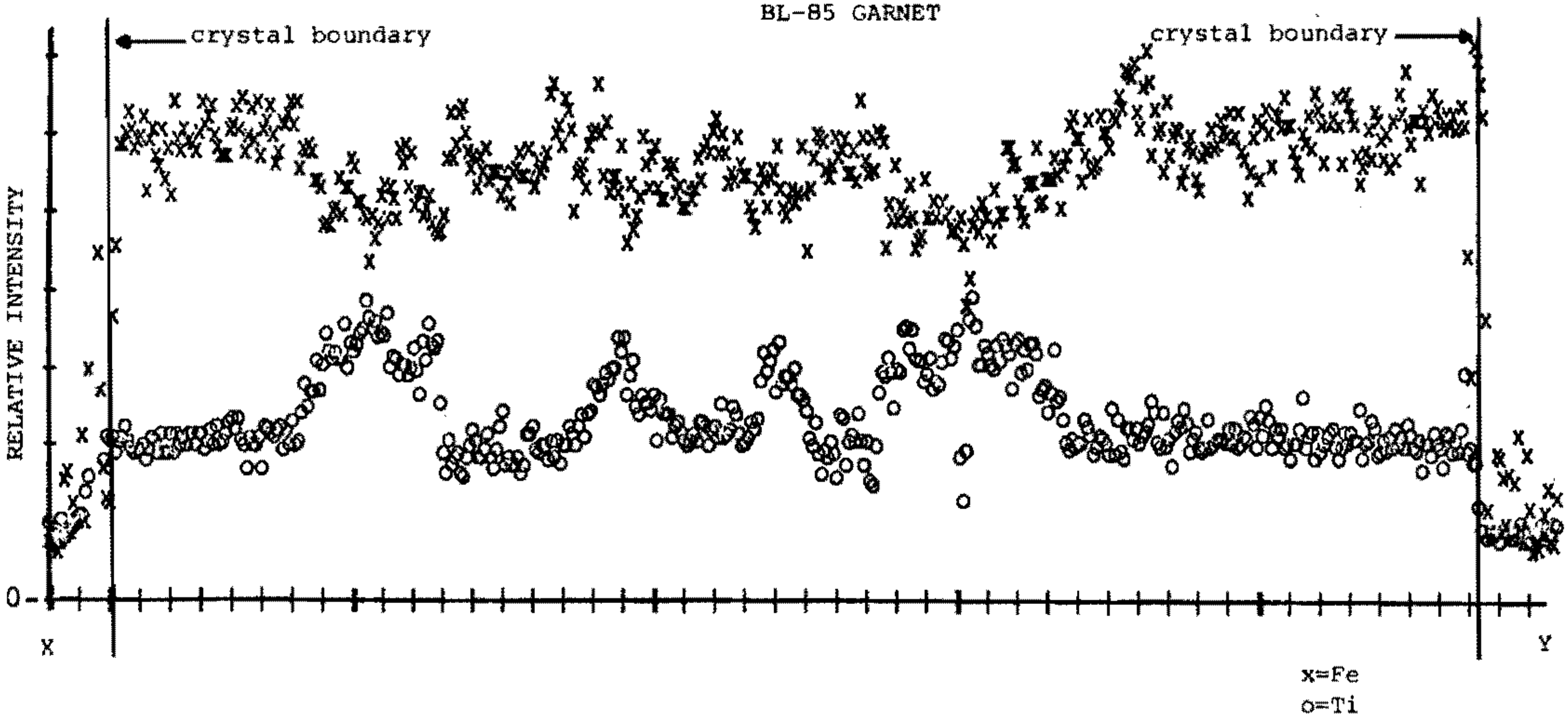

BL-85 GARNET
crystal boundary
crystal boundary
RELATIVE INTENSITY
0
X
Y
x=Fe
o=Ti

TABLE 9

NORMALIZED CHEMICAL ANALYSES, CIPW NORMATIVE MINERALOGY, AND Na_2O/K_2O RATIOS OF THE HOUSTON CREEK TRACHYTE PORPHYRY

Sample	BL-83	BL-84	BL-85	BL-86	BL-86A	BL-94	BL-98
SiO_2	61.36	62.48	62.12	61.92	61.56	61.90	62.44
Al_2O_3	18.20	18.87	18.43	18.31	18.84	18.35	18.21
Fe_2O_3	2.14	2.05	2.00	2.13	2.05	1.98	1.91
FeO	1.49	1.12	1.34	1.42	1.47	0.98	2.40
MgO	0.87	0.76	0.51	1.28	1.00	1.76	0.74
CaO	2.87	1.68	2.20	2.45	2.79	2.70	2.18
Na_2O	5.88	5.62	6.36	5.50	5.44	4.78	5.25
K_2O	6.05	6.32	6.31	6.41	6.33	7.07	6.44
TiO_2	0.64	0.55	0.50	0.63	0.55	0.48	0.41
P_2O_5	0.36	0.00	0.00	0.13	0.00	0.00	0.00
MnO	0.12	0.17	0.12	0.00	0.23	0.00	0.16
SO_3	0.00	0.14	0.11	0.00	0.00	0.00	0.00
quartz	0.00	1.56	0.00	0.00	0.00	0.00	1.16
corundum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
orthoclase	35.75	37.43	37.28	37.81	37.31	41.77	38.00
albite	47.39	46.75	47.66	46.45	44.71	40.44	44.36
anorthite	5.40	8.10	3.48	6.33	8.27	7.73	7.09
nepheline	1.28	0.00	2.94	0.00	0.65	0.00	0.00
diopside	4.92	0.19	3.12	3.85	4.39	4.40	3.09
hypersthene	0.00	1.80	0.00	0.32	0.00	1.85	2.73
olivine	0.00	0.00	0.00	0.75	0.66	0.34	0.00
magnetite	3.10	2.57	2.90	2.74	2.96	1.76	2.76
ilmenite	1.21	1.04	0.95	1.19	1.04	0.91	0.77
apatite	0.85	0.00	0.00	0.31	0.00	0.00	0.00
acmite	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O/K_2O ratio	0.97	0.89	1.01	0.86	0.86	0.68	0.82

average trachyte of Nockolds (1954). The samples are all peraluminous in terms of Shand's (1947) alumina saturation index, as Al_2O_3 exceeds $CaO + K_2O + Na_2O$. Total alkalis ($Na_2O + K_2O$) versus SiO_2 content plot in the trachyte field of Cox and others (1979, p. 14) for all seven samples. Na_2O/K_2O ratios for these rocks fall between 0.68 and 1.01 with a mean value of 0.87 (Table 9).

Sodalite-bearing Phonolite

General

Two small, north-south trending exposures of sodalite-bearing phonolite occur in the NE ¼ of section 32 (Plate 1). Brown (1952) mapped these bodies, and similar bodies throughout the region, as "tinguaite" dikes. He concluded that they invaded a fracture "mosaic" developed in the central igneous core of the Bear Lodge Mountains, and that they represent the final phase of igneous activity in the area. Field studies for this thesis support Brown's (1952) hypothesis, as the bodies occur as relatively unaltered phonolite that cross-cut country rocks of Precambrian granitic gneiss and highly altered Cenozoic felsite.

Petrography and Mineral Chemistry

The sodalite-bearing phonolite is a dark green, holocrystalline, aphanitic rock that is slightly porphyritic. Phenocrysts include orthoclase, sodalite, aegirine-augite, and melanite, interspersed in a dense, trachytic matrix of microcrystalline orthoclase and aegirine. The phenocrysts are characteristically blue to violet colored on fresh surfaces, but rapidly fade to shades of brown upon exposure to light. Accessory minerals consist of sphene, magnetite(?), apatite, and fluorite.

Analcime, natrolite, calcite, and iron oxides occur as alteration products.

Modal analyses of four samples of sodalite-bearing phonolite, presented in Table 10, show that the groundmass is 85 to 91 percent of the rock. The major constituents of the groundmass are lath-shaped orthoclase crystals and tiny needles of aegirine. The abundance of aegirine in the groundmass accounts for the distinct green color of the rock. Irregular patches of analcime, between 2 and 5 percent of the rock (Table 10), are found dispersed throughout the groundmass.

Phenocrysts of sodalite, almost entirely altered to natrolite, analcime, and calcite, comprise up to 2 percent of the rock (Table 10). The alteration is typically zonally arranged, with cores of calcite surrounded by zones of fibrous natrolite and weakly anisotropic analcime (Figure 17). Isotropic patches of remnant sodalite are generally centrally located within the altered phenocrysts. The phenocrysts are commonly arranged in glomerophyric clusters up to 7 mm in diameter (Figure 17). Isolated phenocrysts display hexagonal cross sections with well-defined crystal faces.

A microprobe analysis of an altered sodalite crystal is given in Table 11 (column C). The analysis shows an enrichment in SiO_2 and a depletion in Na_2O and ClO compared to analyses of unaltered sodalite listed in Deer and others (1963B). Also, the analysis shows a relatively low total oxide weight of 92.89 percent. This is probably due to the observed secondary alteration by volatile-rich phases.

Subhedral to anhedral phenocrysts of orthoclase comprise 1 to 3 percent of the rock (Table 10). These feldspars frequently appear highly resorbed and are quite extensively replaced by analcime. The grains

TABLE 10

MODAL ANALYSES OF THE HOUSTON CREEK SODALITE-BEARING PHONOLITE IN VOLUME PERCENTAGES

Sample number	BL-44	BL-44B	BL-44C	BL-44D
Groundmass	9.06	86.6	85.6	88.6
Orthoclase	1.2	1.8	3.0	1.4
Aegirine-augite	0.4	1.6	1.6	3.2
Aegirine	pr	pr	pr	pr
Sodalite	1.2	0.4	0.8	0.6
Melanite	0.2	pr	0.4	pr
Analcime	3.4	4.6	3.8	2.6
Natrolite	0.8	2.4	2.2	2.0
Fluorite	0.2	0.2	0.0	pr
Sphene	pr	pr	pr	pr
Magnetite(?)	pr	0.2	0.2	0.2
Calcite	1.6	2.0	2.2	1.0
Iron Oxide	0.2	pr	0.2	0.2
Apatite	0.2	0.2	pr	0.2

pr = present; noted optically but not point counted

Figure 17. Photomicrograph of a glomerophyric aggregate of sodalite crystals from sodalite-bearing phonolite sample BL-44C. Remnant sodalite occurs as dark material within zonally arranged alteration products. Groundmass shown to be flow-oriented around the phenocrysts and interspersed with clear patches of secondary analcime. Glomerophyric cluster is approximately 5 mm in maximum dimension. Plane polarized light, 22X.

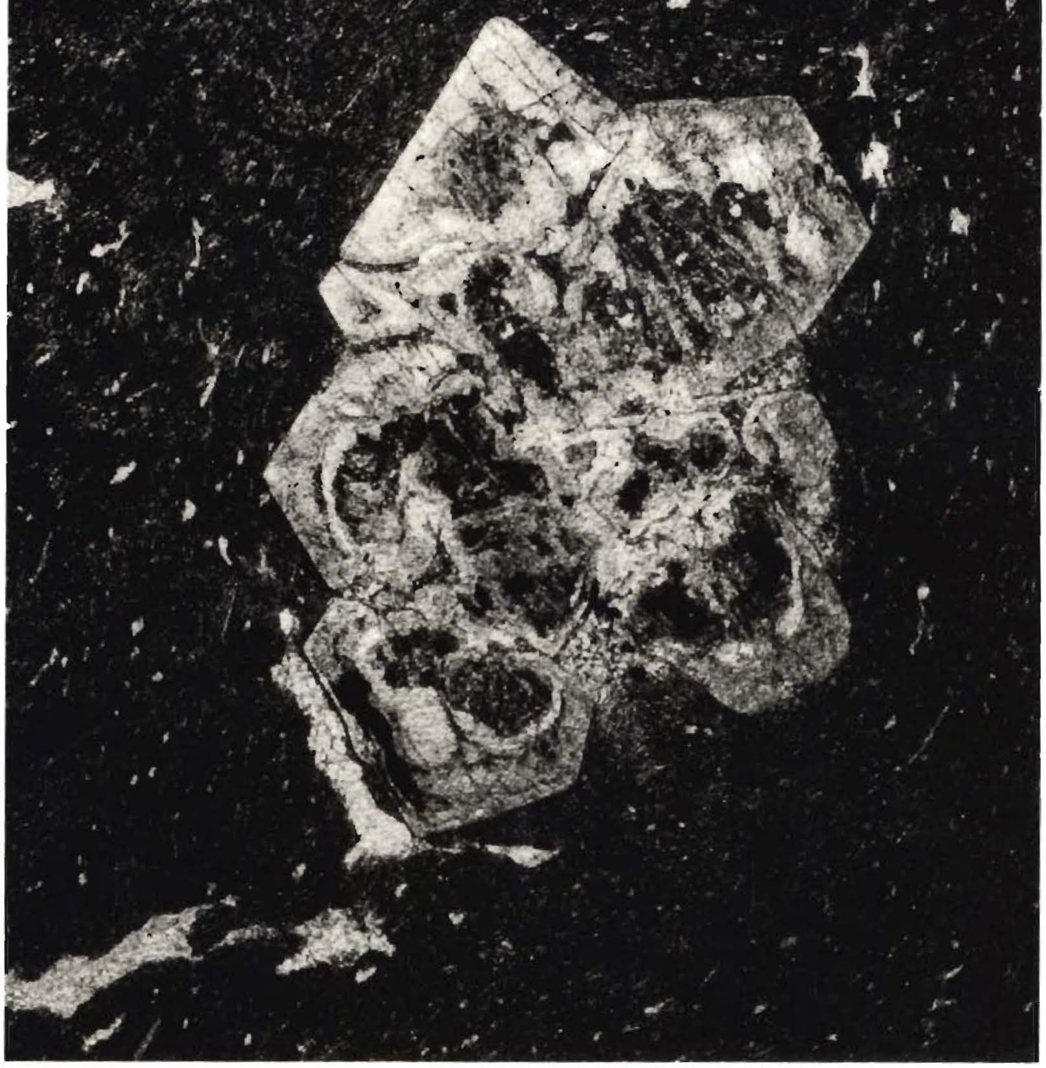


TABLE 11

CHEMICAL ANALYSES OF HOUSTON CREEK SODALITE-BEARING PHONOLITE MINERALS IN OXIDE WEIGHT PERCENTAGES

	A	B	C	D
SiO_2	56.65	46.93	47.94	33.60
Al_2O_3	20.57	1.85	26.34	2.43
FeO	0.00	21.20	0.00	20.03
Fe_2O_3	0.62	2.76	0.29	5.16
MgO	0.00	2.50	0.00	0.00
CaO	0.20	16.59	0.61	31.58
Na_2O	7.11	3.87	15.42	0.00
K_2O	8.46	0.12	0.30	0.11
TiO_2	0.00	1.26	0.00	3.66
MnO	0.00	1.13	0.00	0.98
P_2O_5	0.20	0.29	0.19	0.35
ClO	0.00	0.00	1.64	0.00
SO_3	0.10	0.08	0.17	0.00
Total	93.91	98.58	92.89	97.89

Explanation of Column Headings

A = Orthoclase, sample BL-44D, groundmass

B = Aegirine-augite, sample BL-44D, phenocryst

C = Altered sodalite, sample BL-44D, phenocryst

D = Melanite, sample BL-44D, phenocryst

range from less than 1 mm to 3 mm in length and often poikilitically enclose small crystals of aegirine, apatite, and sphene.

Aegirine-augite, comprising from 1 to 3 percent of the rock (Table 10), is the major mafic phenocryst. It occurs as stubby subhedral to anhedral prisms up to 1 mm in length. The grains lack zoning and are strongly pleochroic with X=green, Y=yellowish-green, and Z=brownish-green. Magnetite(?) is commonly present along fractures and crystal margins. A microprobe analysis of an aegirine-augite phenocryst is given in Table 11 (column B). The analysis shows a higher total Fe-oxide content than previously described pyroxenes from the Houston Creek area (Tables 2, 5, and 8), but is similar to a wide range of aegirine-augite analyses published in Deer and others (1963A).

Minor amounts of reddish-brown melanite garnet are present in the sodalite-bearing phonolite (Table 10). Melanite has subhedral outlines and is typically in contact with sodalite phenocrysts in glomerophyric clusters. Melanite grains, up to 1 mm in diameter, are separated from the groundmass by a thin zone of radially arranged aegirine needles. A microprobe analysis of a melanite crystal, presented in Table 11 (column D), is very similar to an analysis of melanite from the Houston Creek phonolite (Table 5).

Analcime occurs in the sodalite-bearing phonolite as a secondary mineral replacing feldspar and sodalite. The analcime is generally cloudy and is often associated with secondary natrolite and calcite. Granular magnetite(?), present in association with mafic phenocrysts, is commonly replaced by red and yellowish-brown iron oxides. Purple fluorite occurs in several samples as rare, isolated grains within the groundmass. Apatite and sphene are present as poikilitic inclusions within orthoclase and aegirine-augite.

Rock Chemistry

The bulk rock chemistry and CIPW mineralogy of four samples of Houston Creek sodalite-bearing phonolite are listed in Table 12. The rock is undersaturated with respect to SiO_2, as indicated by the presence of normative nepheline in all four samples. SiO_2 content ranges between 60 and 62 percent, while normative nepheline varies from 10 to 13 percent. In terms of Shand's (1947) alumina saturation index, the rocks are strongly peraluminous as Al_2O_3 exceeds $CaO + Na_2O + K_2O$. Total alkalis plotted against SiO_2 content fall within the phonolite field of Cox and others (1979, p. 14) for all four samples. The mean Na_2O/K_2O ratio of the sodalite-bearing phonolite is 1.34 with values ranging from 1.26 to 1.41 (Table 12).

Altered Felsite

General

The NE ½ of section 32 and the NE ¼ of section 30 (Plate 1) are dominated by subvolcanic rock types that are collectively referred to in this thesis as "altered felsite", because of their characteristic altered appearance. These rocks were mapped as monzonite and syenite porphyries by Darton (1905) and as trachyte porphyry by Brown (1952). Extensive alteration and replacement of major constituents has made classification of these rocks by contemporary modal or chemical schemes unfeasible.

Field relations indicate that the altered felsite is part of a complex of Cenozoic igneous rocks that comprises the core of the Bear Lodge Mountains uplift. This igneous core, located 4-6 km northeast of

TABLE 12

NORMALIZED CHEMICAL ANALYSES, CIPW NORMATIVE MINERALOGY, AND Na_2O/K_2O RATIOS OF THE HOUSTON CREEK SODALITE-BEARING PHONOLITE

Sample	BL-44	BL-44B	BL-44C	BL-44D
SiO_2	60.69	60.70	61.71	60.79
Al_2O_3	18.94	19.36	19.71	19.45
Fe_2O_3	1.69	1.76	1.72	1.81
FeO	2.65	1.86	1.87	2.06
MgO	0.22	0.00	0.14	0.36
CaO	1.65	1.67	1.56	1.69
Na_2O	7.97	8.14	7.57	7.64
K_2O	5.74	5.79	6.01	5.93
TiO_2	0.19	0.26	0.22	0.31
P_2O_5	0.12	0.34	0.00	0.00
SO_3	0.13	0.07	0.00	0.00
quartz	0.00	0.00	0.00	0.00
corundum	0.00	0.00	0.00	0.00
orthoclase	33.92	34.23	35.23	35.02
albite	42.68	43.06	44.57	43.30
anorthite	0.00	0.00	2.05	1.26
nepheline	12.35	13.18	10.56	11.54
diopside	7.15	4.58	3.85	5.27
hypersthene	0.00	0.00	0.00	0.00
olivine	0.37	0.00	0.00	0.00
magnetite	1.95	2.08	2.49	2.62
ilmenite	0.36	0.49	0.41	0.58
apatite	0.00	0.00	0.00	0.00
acmite	0.99	0.95	0.00	0.00
Na_2O/K_2O ratio	1.39	1.41	1.26	1.29

the Houston Creek area, appears to be related to an alkaline carbonatite-pyroxenite association of rocks (Karner, 1981; Wilkinson, in preparation). Brown (1952) proposed that the core rocks (altered felsite) are laccolithic in origin and predate the phonolitic rocks that occur as dikes and sills on the flanks of the uplift.

The mapping of altered felsite was conducted almost exclusively on the basis of identification of float material, as outcrops of this unit are quite rare. The altered felsite surrounds a large (approximately 400 m X 100 m) block of Precambrian gneiss, and forms an interdigitating contact with the Deadwood Formation in section 32 (Plate 1). The altered felsite appears to be in direct contact with the base of the Deadwood in section 30 (Plate 1). Evidence of contact metamorphism is limited to occasional exposures of baked and iron-stained Deadwood shales and limestone-pebble conglomerates.

Petrography

Samples of altered felsite are generally red to reddish-brown, with shades of light brown and yellow being less common. The rocks consistently have porphyritic textures with aphanitic groundmasses. Groundmass fabrics vary from strongly trachytic to pilotaxitic, and are often masked by an abundance of secondary alteration products. Major primary minerals, often identifiable only be relict crystal outlines, include alkali feldspar, plagioclase, feldspathoid, pyroxene, and sphene. Felsic constituents are characterized by persistent replacement by fine-grained muscovite, clays(?), orthoclase(?), calcite, zeolites, and quartz. Pseudomorphs of mafic phenocrysts consist of iron oxides, clays(?), and calcite. Several samples have tiny fracture fillings of microcrystalline calcite, zeolite, and quartz. Secondary oxides of iron are distributed throughout the groundmass and account for the color of the altered felsite.

Phenocrysts of alkali feldspar are typically the least altered of the major mineral phases. The grains are usually Carlsbad twinned and attain lengths of 25 mm. These large alkali feldspar phenocrysts are the dominant constituents of several samples, but are absent in others. Natrolite, analcime, and clays(?) are the major alteration products of alkali feldspar. Crystal forms range from euhedral to highly rounded and embayed. Poikilitic fabrics are common among the phenocrysts, with sphene and relatively unaltered apatite as the dominant inclusions.

Plagioclase is the predominant feldspar in some of the altered felsite samples. Grains are typically obliterated by fine-grained muscovite and orthoclase(?) replacement, but are distinguished by relict albite, combined albite-Carlsbad, and pericline twins. The albite twinning is most common and is characterized by numerous and narrow lamellae. Zoning is apparent in some phenocrysts by concentric arrangements of alteration products. Plagioclase grains are frequently surrounded by a thin mantle of less altered alkali feldspar. Plagioclase compositions range from An_{16} to An_{23} (oligoclase).

Pseudomorphs of completely replaced feldspathoid crystals typically occur in samples that contain alkali feldspar phenocrysts and lack plagioclase phenocrysts. The feldspathoid pseudomorphs have hexagonal cross sections that range up to 2 mm in diameter. They are commonly highly resorbed, sometimes to an extent that skeletal arrangements are developed. The dominant replacement minerals of feldspathoid are orthoclase(?) and fine-grained muscovite.

Ghosts of subhedral to euhedral crystals of pyroxene and sphene are common to most altered felsite samples. These phenocrysts are entirely altered to iron oxides, calcite, and clays(?). Occasional six-sided, iron oxide-rich pseudomorphs of garnet are present in some samples. Relatively fresh prismatic and hexagonal grains of apatite occur in all samples as groundmass crystals and poikilitic inclusions. Disseminated cubes of pyrite are occasionally present, but were observed only in hand specimen.

Rock Chemistry

The bulk rock chemistry and CIPW normative mineralogy of seven samples of altered felsite are presented in Table 13. All seven samples are oversaturated with SiO_2, as indicated by the persistence of normative quartz. SiO_2 content of these rocks ranges between 60 and 66 percent, with a mean of 62.8 percent.

A striking chemical distinction is evident between the first four samples (BL-14, BL-16A, BL-16B, and BL-40B) and the final three samples (BL-13A, BL-49, and BL-111A) of Table 13. The first four samples are characterized by exceptionally high K_2O contents, which range between 11 and 13 percent. The extremely potassic character of these rocks is manifested by an abundance of normative orthoclase, which varies from 66 to 75 percent, and by conspicuously low Na_2O/K_2O ratios of 0.03 to 0.07 (Table 13). Such high K_2O contents suggests that these rocks are probably not genetically related to the remainder of the Houston Creek igneous suite. They appear to be widespread throughout the Bear Lodge Mountains intrusive core area and are currently being studied by Wilkinson (in preparation). The origin of these ultrapotassic rocks may be related to fenitization (alkali metasomatism) of the country rocks in

TABLE 13

NORMALIZED CHEMICAL ANALYSES, CIPW NORMATIVE MINERALOGY, AND Na_2O/K_2O RATIOS OF THE HOUSTON CREEK ALTERED FELSITE

Sample	BL-14	BL-16A	BL-16B	BL-40B	BL-13A	BL-49	BL-111A
SiO_2	63.58	63.33	63.42	65.26	61.84	62.77	60.37
Al_2O_3	20.20	19.79	20.52	20.33	18.66	17.95	18.35
Fe_2O_3	3.44	2.14	1.83	1.91	2.06	1.98	2.31
FeO	1.56	1.29	1.27	0.47	1.26	5.96	3.15
MgO	0.00	0.00	0.00	0.00	0.41	0.16	1.65
CaO	0.10	0.00	0.00	0.00	3.83	0.51	2.74
Na_2O	0.55	0.66	0.93	0.34	6.03	5.03	4.75
K_2O	11.57	12.13	12.71	11.22	4.93	4.99	5.31
TiO_2	0.44	0.64	0.33	0.41	0.56	0.48	0.81
P_2O_5	0.00	0.00	0.00	0.00	0.11	0.11	0.26
MnO	0.00	0.00	0.00	0.00	0.14	0.00	0.16
SO_3	0.12	0.00	0.00	0.00	0.09	0.00	0.12
quartz	20.35	16.16	13.07	8.24	1.67	9.52	4.07
corundum	7.63	6.74	5.57	5.23	0.00	3.61	0.58
orthoclase	66.34	68.37	71.69	75.09	29.15	29.50	31.38
albite	2.87	3.87	5.58	8.86	50.47	42.58	39.41
anorthite	0.00	0.49	0.00	0.00	9.60	1.81	11.89
nepheline	0.00	0.00	0.00	0.00	0.00	0.00	0.00
diopside	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hypersthene	0.00	0.59	0.00	0.27	0.00	8.92	6.94
olivine	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnetite	0.32	2.73	2.30	2.65	2.89	2.87	3.35
ilmenite	0.78	0.84	1.21	0.62	1.06	0.91	1.53
apatite	0.00	0.00	0.00	0.00	0.26	0.26	0.61
acmite	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O/K_2O ratio	0.03	0.04	0.05	0.07	1.22	1.01	0.89

response to the intrustion of carbonatite magma, as carbonatite crops out approximately 10 km north of the altered felsite exposure. Sutherland (1965) has proposed that carbonatite-related fusion of fenitized country rock led to the mobilization and intrusion of a potassium-rich trachytic magma in the Toror Hills, Uganda. Chemical analyses of Houston Creek altered felsite and pseudoleucite trachyte porphyry reported by White (1980) from the central Bear Lodge Mountains closely resemble analyses of fenitic trachyte presented by Sutherland (1965, p. 371).

The remaining altered felsite samples (the last three analyses of Table 13) lack the ultrapotassic character of those samples just discussed, as demonstrated by their mean Na_2O/K_2O ratio of 1.04. Except for a slight enrichment of total Fe-oxides and a slight depletion of total alkalis, these altered felsite samples appear to be chemically similar to the unaltered Houston Creek rock types described in the previous sections. Their enrichment in iron and depletion in alkalis are typical of rocks that have undergone hydrothermal alteration and/or chemical weathering (Krauskopf, 1979).

INTERPRETATION

Emplacement

Consideration of the field relationships and the petrography of the Houston Creek rocks allows certain interpretations to be made concerning the character of the magma and the structural controls governing its emplacement. Altered felsite, which occurs in the study area as a small peripheral part of an intrusive center located to the northeast, will not be discussed further in this thesis; it appears that the magmatic origin of these rocks is not closely related to the phonolite and trachyte intrusions of the Houston Creek area, as pointed out in the previous section.

Structure

In his study of the shallow intrusives of the northern Black Hills, Noble (1952) noted that sills or thin laccoliths are common within the Paleozoic section. There are several stratigraphic horizons that provide easy access to invading magma, especially unconformable contacts and incompetent shale units. Noble (1952) stated that dikes are usually confined to vertically foliated Precambrian metasediments or to more massive units, such as preexisting thick bodies of igneous rock.

The above generalizations appear to be true for the igneous bodies of the Houston Creek area. Phonolite porphyry forms a sill at the disconformable contact between the Deadwood and Whitewood Formations, whereas phonolite and trachyte porphyry appear to have been emplaced as sills along a shale horizon within the Minnelusa Formation. The relative ages of the phonolite and trachyte porphyry are unclear and the contact between them can only be inferred (Plate 1). The two small bodies of sodalite-bearing phonolite that are exposed in the study area appear to have been intruded as steeply dipping dikes, possibly along fractures developed in Precambrian gneiss and altered felsite of the core of the Bear Lodge Mountains.

One can only speculate on the immediate source of the Houston Creek igneous bodies. Darton's (1905) geologic map of the Bear Lodge Mountains region shows a number of phonolite and trachyte sills that crop out to the south and southwest of the intrusive core, and phonolite dikes that occur within the intrusive core. Studies by Fashbaugh (1979) and Wilkinson (in preparation) and reconnaissance work for this thesis confirmed field occurrences mapped by Darton (1905). It is inferred that these bodies derived from some central source, possibly a feeder dike arising from just south of the central core of the uplift. The preexisting igneous core material (of which the Houston Creek altered felsite is a part) has been interpreted to be laccolithic in form near the surface (Brown, 1952), and would have presented a formidable barrier to upwelling magma. Thus the magma was forced to spread out laterally and migrated down dip within the inclined Paleozoic strata to solidify as sills. Some magma possibly continued towards the surface along uplift-induced fracture systems to form nearly vertical dikes. Denudation of the slopes of the uplift has since exposed the sills as prominent ridges that conform to the regional strike of the Paleozoic strata.

Character of the Magma

The consistent development of an aphanitic groundmass in the Houston Creek rock types suggests that crystallization progressed rapidly when magma was injected into the relatively cool country rocks. However, persistent porphyritic textures indicate that the magma was already partially crystallized at the time of emplacement. Further evidence of partial crystallization prior to intrusion is the parallel arrangement of feldspar phenocrysts and microlites near the contacts of igneous bodies. These crystals are interpreted to have been frozen along flow paths shortly after intrusion.

Field observations suggest that the partially crystalline magma was probably relatively cool at the time of emplacement, as thermal metamorphic effects caused by the intrusions appear to be minor. Sandstone contacts show little more than thin zones of secondary silicification and iron staining, and carbonate contacts usually show only very minor recrystallization. Detailed microscopic examination of country rocks was not performed, however, and may be necessary for confirmation of field indications. The observation that alkalis are generally easily transferred by volatile fluids, so that metamorphic and metasomatic effects are common around alkaline intrusives (Bailey, 1974A), implies that the magma probably had a relatively low volatile content. A low volatile content is further indicated by the general lack of hydrous primary silicate phases, such as micas and amphiboles, in the Houston Creek rock types. In a study of the system Na_2O-Al_2O_3-Fe_2O_3-SiO_2 at 1 atmospheric pressure and anhydrous conditions, Bailey and Schairer (1966) determined that crystallization temperatures for typical phonolites occur at approximately 715° C. As indicated previously, crystallization appears to have been in progress at the time the magma was emplaced, so a magmatic temperature of somewhat below 715° C. is inferred.

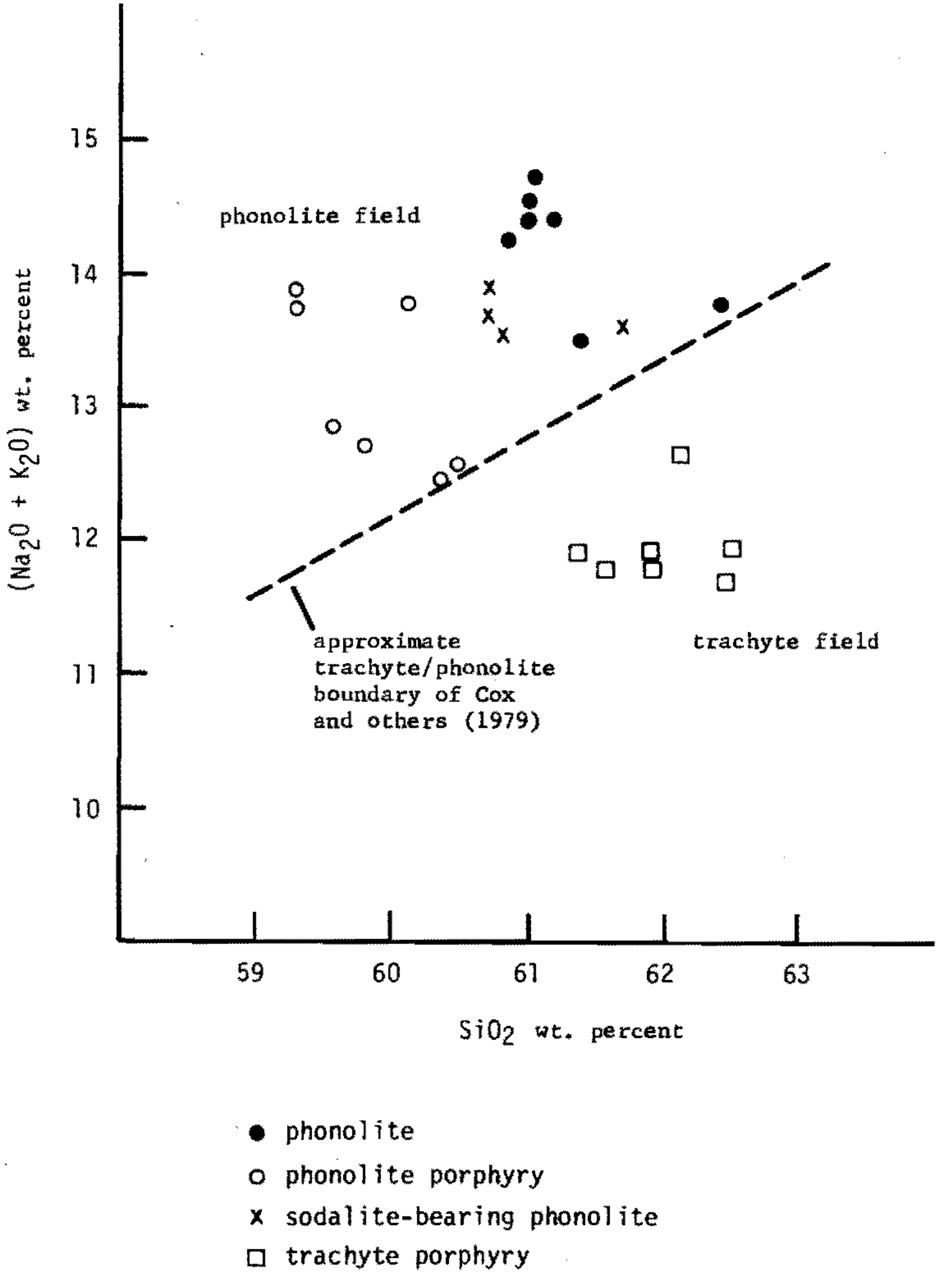
Crystallization was probably followed by the infiltration of hydrothermal fluids of either magmatic or meteoric origin. This phase was probably relatively volatile-rich and produced secondary analcime, natrolite, calcite, and clays(?) at the expense of feldspars and feldspathoids.

Chemical Trends

In Figure 18, total alkalis ($Na_2O + K_2O$) are plotted against SiO_2 for phonolite, phonolite porphyry, sodalite-bearing phonolite, and trachyte porphyry from the Houston Creek area. As defined by the phonolite/trachyte boundary of Cox and others (1979, p. 14), the phonolites are characterized by a higher alkali content and somewhat lower SiO_2 than the trachyte porphyry. Inspection of the chemistry of the Houston Creek rock types (Tables 3, 6, 9, and 11) shows that the phonolites are also comparatively more sodic than the trachyte porphyry. The three varieties of phonolite have a mean Na_2O/K_2O ratio of 1.19, whereas the trachyte porphyry has a mean value of 0.87. The lower Na_2O/K_2O ratios of the trachyte porphyry, as well as their oversaturation of SiO_2, has been shown to be a possible result of granitic crustal contamination of a phonolitic magma (Wilcox, 1979).

Analyses of phonolite presented by Halvorson (1980) from the Devils Tower-Missouri Buttes-Barlow Canyon igneous center, located approximately 35 km to the northwest, show a striking chemical similarity to phonolitic rocks of the Houston Creek area. Phonolites from both areas are characteristically sodic with very similar Na_2O/K_2O ratios. Conversely,

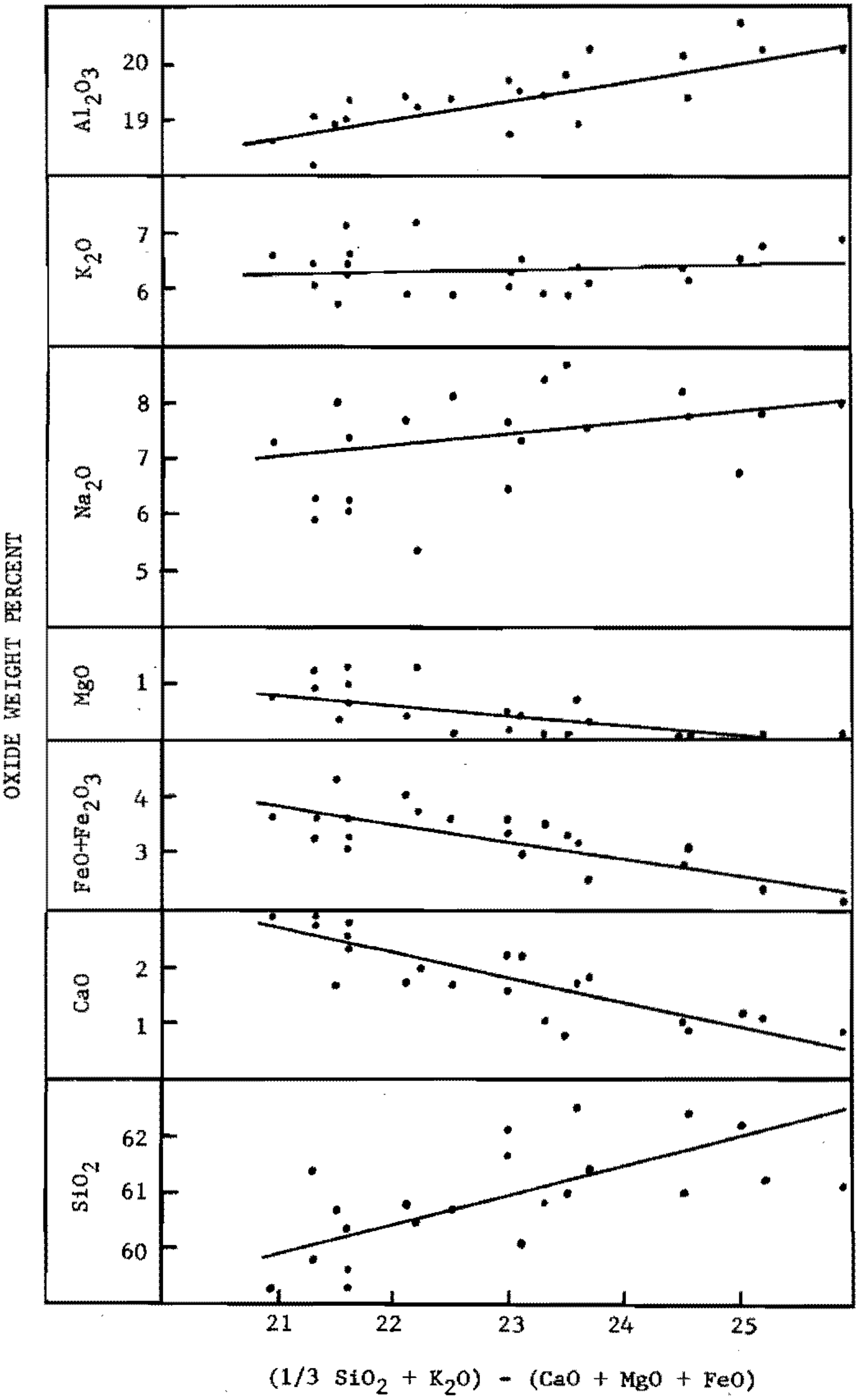
Figure 18. Plot of $Na_2O + K_2O$ versus SiO_2 illustrating the chemical variation among Houston Creek rock types. The approximate trachyte/phonolite field boundary of Cox and others (1979) is shown.


phonolite field
trachyte field
approximate trachyte/phonolite boundary of Cox and others (1979)
$(Na_2O + K_2O)$ wt. percent
15
14
13
12
11
10
59
60
61
62
63
SiO_2 wt. percent
● phonolite
○ phonolite porphyry
x sodalite-bearing phonolite
□ trachyte porphyry

chemical analyses of phonolites and trachytes from the central Bear Lodge Mountains presented by White (1980) show strong potassic trends. His analyses show Na_2O/K_2O ratios of less than one, and more closely resemble analyses of trachyte porphyry from the Houston Creek area. Karner (1981) has pointed out that rocks from the Bear Lodge Mountains and the Devils Tower-Missouri Buttes-Barlow Canyon center, as well as rocks from the Sundance-Sugarloaf Mountain center, illustrate relationships in a phonolite-trachyte-quartz latite association. In these centers, phonolite appears to be gradational in petrographic character and chemistry with feldspathoidal to quartz-bearing trachyte. White (1980) has indicated that partial melting of granitic crustal material may account for the formation of SiO_2-oversaturated trachyte by contamination of a phonolitic magma. Quartz latite and felsic breccias and tuffs(?) from Sundance and Sugarloaf Mountains, located 7-9 km southeast of the Houston Creek area, may have resulted from large scale granitic contamination (Karner, 1981).

A Larsen (1938) variation diagram (Figure 19) of chemical analyses of Houston Creek igneous rocks (excluding altered felsite) illustrates a trend of enrichment of SiO_2, Na_2O, K_2O, and Al_2O_3, with a corresponding depletion of CaO, MgO, and total Fe-oxides. These chemical trends may indicate variation within an igneous rock series by either fractional crystallization or partial melting processes (Cox and others, 1979). The departures from linearity shown in Figure 19 may represent subtraction of materials by crystal accumulation or addition of materials by assimilation (Wilcox, 1979). The presence of mafic and granitic xenoliths and widespread porphyritic textures suggests that crustal contamination and

Figure 19. Larsen (1938) diagram illustrating general trends of chemical variation in Houston Creek igneous rocks. Closed circles represent analyses of phonolite, phonolite porphyry, sodalite-bearing phonolite, and trachyte porphyry. Lines are best-fitted by least-squares linear regression method.



OXIDE WEIGHT PERCENT
Al_2O_3
20
19
K_2O
7
6
Na_2O
8
7
6
5
MgO
1
$FeO+Fe_2O_3$
4
3
CaO
2
1
SiO_2
62
61
60
21
22
23
24
25
(1/3 SiO_2 + K_2O) - (CaO + MgO + FeO)

crystal accumulation were causes of chemical variation in the Houston Creek igneous rocks.

On the basis of Peacock's (1931) alkali-lime index, the Houston Creek rocks are decidedly alkalic. This index is determined by evaluating the lineages of SiO_2, CaO, Na_2O, and K_2O, and calculating the weight percentage of SiO_2 at which CaO and $Na_2O + K_2O$ would be equal. Using a plot of $Na_2O + K_2O$ versus SiO_2 (Kuno, 1966, O. 320), the Houston Creek rocks correspond to an alkali olivine basalt lineage, which has a greater $(Na_2O + K_2O)/SiO_2$ ratio than a tholeiitic series.

In summary, the rock types of the Houston Creek area are predominantly sodic in character and show a strong affinity to a phonolite-trachyte-quartz latite association. Chemical data from this study and from recent studies of the Bear Lodge Mountains region (Fashbaugh, 1979; Halvorson, 1980; White, 1980; Karner, 1981) indicate that crustal contamination of a preexisting phonolitic magma may have been a principal cause of igneous variation. Finally, petrochemical indicators seem to favor an alkali olivine basaltic parentage for the alkalic rocks of the Houston Creek area.

Magma Genesis

The origin of alkaline magmas has long been discussed in geological literature, but no single origin clearly stands out as controlling their development. A popular mode of origin for phonolite and trachyte is by fractional crystallization of an alkali olivine basaltic magma (Hyndman, 1972). According to this model, alkali olivine basaltic magma may fractionate to a trachytic melt, which, if fractionated further, would produce a phonolitic magma. The requirement of a large volume of basaltic magma makes this model unfeasible, as the northern Black Hills region is noted by a lack of basaltic rocks (Kirchner, 1971). It could be argued that a large volume of such mafic rock exists at depth, buy Hyndman (1972) points out that mafic magmas are noted for their unrestricted passage to the surface.

A popular alternative to the fractional crystallization model is partial melting of crystalline material in the deep crust (Bailey, 1974B) or upper mantle (Carmichael and others, 1974) to generate magmas of alkaline composition. It is believed that partial melting processes, probably in the lower crust, were responsible for the alkaline magma emplaced within the Houston Creek area. Bailey (1974B) proposes that such alkali-rich felsic magmas are generated on a large scale by partial melting in the lower crust in response to uplift-induced pressure relief at depth. The relief of pressure leads to an influx of volatiles, probably from the underlying mantle, which reduces the melting range of the crustal rocks, focuses heat in the active zone, and gives the felsic magmas their alkaline character. It seems likely that the mantle system beneath the Bear Lodge Mountains was concentrated in the volatiles necessary to initiate deep crustal melting. as indicated by the presence of carbonatite outcrops immediately north of the study area. These volatile-enriched rocks are generally considered to have been generated in the upper mantle (Carmichael and others, 1974; Tuttle and Gittins, 1966).

Several workers in the northern Black Hills region have proposed that the parental alkaline magmas were trachytic in composition, and that they were differentiated to late-stage phonolites (Kirchner, 1971; Halvorson, 1980). Although evidence is less than conclusive, it is thought that the parental magma responsible for the Houston Creek rocks was phonolitic in composition. Bailey (1974B) states that partial melting in the deep continental crust would initially produce phonolitic magma, and as the melting regime moved to higher levels (generally to more silicic source rocks), the magma would become more trachytic. This upward progression of anatexis may be demonstrated by the common occurence of granitic xenoliths in the Houston Creek phonolite. This xenolith-bearing phonolite consistently has a higher SiO_2 content than the Houston Creek phonolite porphyry (Figure 19), which appears to be devoid of granitic xenoliths. Furthermore, the xenolith-bearing phonolite occupies the same stratigraphic horizon as a body of SiO_2-oversaturated (quartz normative) trachyte porphyry. As discussed previously, the trachyte porphyry may represent a compositional gradation from phonolite, resulting from increased crustal melting, and possibly granitic assimilation, at depth. White (1980) has demonstrated similar gradational trends in a phonolite-trachyte association of rocks from the central Bear Lodge Mountains, and has recognized what appears to be intergranular melt material in granite exposed in his study area.

Further petrographic evidence of a parental phonolitic melt is the widespread presence of melanite (rimmed by aegirine-augite) in the Houston Creek trachyte porphyry. Melanite, according to Shand (1947), can form only in undersaturated rocks such as phonolites. Its presence indicates that the oversaturated trachyte porphyry was derived from a melt originally undersaturated with SiO_2 (i.e. phonolite). Also, ferromagnesian minerals in the trachyte porphyry show very strong compositional zoning compared to the phonolitic rocks of the study area. This suggests that the trachyte porphyry had undergone substantial changes in chemical equilibrium during crystallization, whereas the phonolites had not been subjected to significant chemical variation.

The composition of the source material in the deep crust is uncertain, although chemical trends indicate an affinity for an alkali olivine basaltic parentage, which when partially melted, would yield magma of phonolitic composition (Bailey, 1974B). Pyroxene-rich xenoliths and highly replaced olivine xenocrysts(?) in the Houston Creek phonolite and phonolite porphyry could possibly represent a link to the ultimate mafic source.

SUMMARY

Geologic History

The magmatic processes and intrusive events in the Houston Creek area following emplacement of the central Bear Lodge Mountains core material are summarized below. The author has accepted the following order of succession as the best working hypothesis:

1. Continued or renewed Laramide-induced uplift of the Bear Lodge Mountains center caused relief of pressure at depth.

2. Pressure relief caused an influx of alkali-enriched volatiles to the lower crust from the underlying mantle; the volatiles served to focus heat and lower the melting temperature of the deep crustal rocks.

3. Partial melting of probable alkali olivine basaltic material occurred in the deep crust, which generated primary phonolitic magma of sodic character.

4. Upward progression of the melting regime and increased granitic crustal contamination resulted in compositional gradations of the magma from feldspathoidal phonolite to quartz-bearing trachyte.

5. Magma was invaded into the inclined Paleozoic strata and emplaced along stratigraphic planes of weakness.

6. Magma migrated down dip to form sills of phonolite porphyry (at the Deadwood-Whitewood Formation contact) and phonolite and trachyte porphyry (along a shale horizon within the Minnelusa Formation).

7. Late-stage phonolitic magma was injected into uplift-induced fractures developed in the core area and solidified as sodalite-bearing phonolite dikes.

8. Infiltration of volatile-rich hydrothermal fluids produced secondary alteration products.

Recommendations for Future Study

Further work is necessary to fully understand petrologic relationships in the Bear Lodge Mountains area. Isotope and trace element analyses would be useful in determining if chemically diverse rock types are indeed genetically related. Exploratory drilling programs, resulting from renewed interest in potentially economic rare earth oxide and base metal deposits in the Bear Lodge Mountains, may provide valuable subsurface information. And finally, accurate absolute dating of the major rock types may clarify time and space relationships and aid in the construction of a regional petrogenetic model.

APPENDICES

APPENDIX I

OPTICAL CHARACTERISTICS OF MINERALS

TABLE 14

OPTICAL CHARACTERISTICS OF MINERALS OCCURRING IN CENOZOIC IGNEOUS ROCKS OF THE HOUSTON CREEK AREA

Mineral	Alkali Feldspar	Plagioclase	Aegirine-Augite	Melanite	Analcime	Natrolite
Approximate Crystal Size	<0.001 mm to 25 mm	<0.001 mm to 20 mm	<0.001 mm to 4 mm	0.1 mm 2 mm	<0.001 mm to 1.5 mm	<0.001 mm to 0.1 mm
Crystal Form	Subhedral to euhedral	Subhedral	Euhedral to anhedral	Euhedral to subhedral	Anhedral	Anhedral
Color/ Pleochroism	Clear	Clear	x=green y=green z=pale greenish brown	Dark brown to light red-brown	Clear	Clear
Zoning	Normal	Normal	Normal, oscillatory	Normal, oscillatory	***	***
Refractive Index	alpha=1.520 beta =1.526 gamma=1.528	...	alpha=1.710 beta =1.722 gamma=1.743	n=1.880	...	...
Replaces	***	***	Melanite	***	Alkali Feldspar, Sodalite	Alkali Feldspar, Sodalite
Alters to	Natrolite, analcime, clays, calcite	Sericite, Calcite	Hematite, Opaques	Opaques, Aegirine-Augite, Analcime	***	***

TABLE 14--Continued

Mineral	Sphene	Biotite	Olivine	Magnetite(?)	Hematite	Limonite(?)
Approximate Crystal Size	.05 mm to 1.5 mm	1 mm to 4 mm	1 mm	0.001 mm to 0.5 mm	0.001 mm	<0.001 mm
Crystal Form	Euhedral to subhedral	Anhedral to	Anhedral	Anhedral to subhedral	Anhedral	Anhedral
Color/ Pleochroism	Pale gray-brown	x=light brown y=brown z=dark brown	Clear	Opaque	Deep red	Yellow-brown
Zoning	***	***	***	***	***	***
Refractive Index	...	...	...	...	...	...
Replaces	***	Aegirine-Augite	***	Olivine, biotite, Melanite, Aegirine-Augite	Opaque minerals	Opaque minerals, Sodalite
Alters to	Calcite, opaques	Limonite, Opaques	Opaques, Aegirine-Augite	Hematite	***	***

TABLE 14--Continued

Mineral	Calcite	Hauyne	Sodalite	Fluorite	Apatite	Aegirine
Approximate Crystal Size	0.001 mm to 1 mm	0.001 mm to 1.0 mm	0.1 mm to 1 mm	0.1 mm to 0.3 mm	0.01 mm to 0.5 mm	0.01 mm to 0.1 mm
Crystal Form	Anhedral	Subhedral to Euhedral	Anhedral to Subhedral	Anhedral	Euhedral to Subhedral	Anhedral to Euhedral
Color/ Pleochroism	Clear	Clear	Clear	Purple	Clear	x=green y=green z=dark green
Zoning	***	***	Normal	***	***	***
Refractive Index	...	...	...	...	...	...
Replaces	Alkali Feldspar, Hauyne, Sodalite	***	***	***	***	Aegirine-Augite
Alters to	***	Analcime, Natrolite, Calcite, Clays	Analcime, Natrolite, Calcite, Clays	***	***	***

... = Optical characteristic was not determined.

*** = Optical characteristic was not noted.

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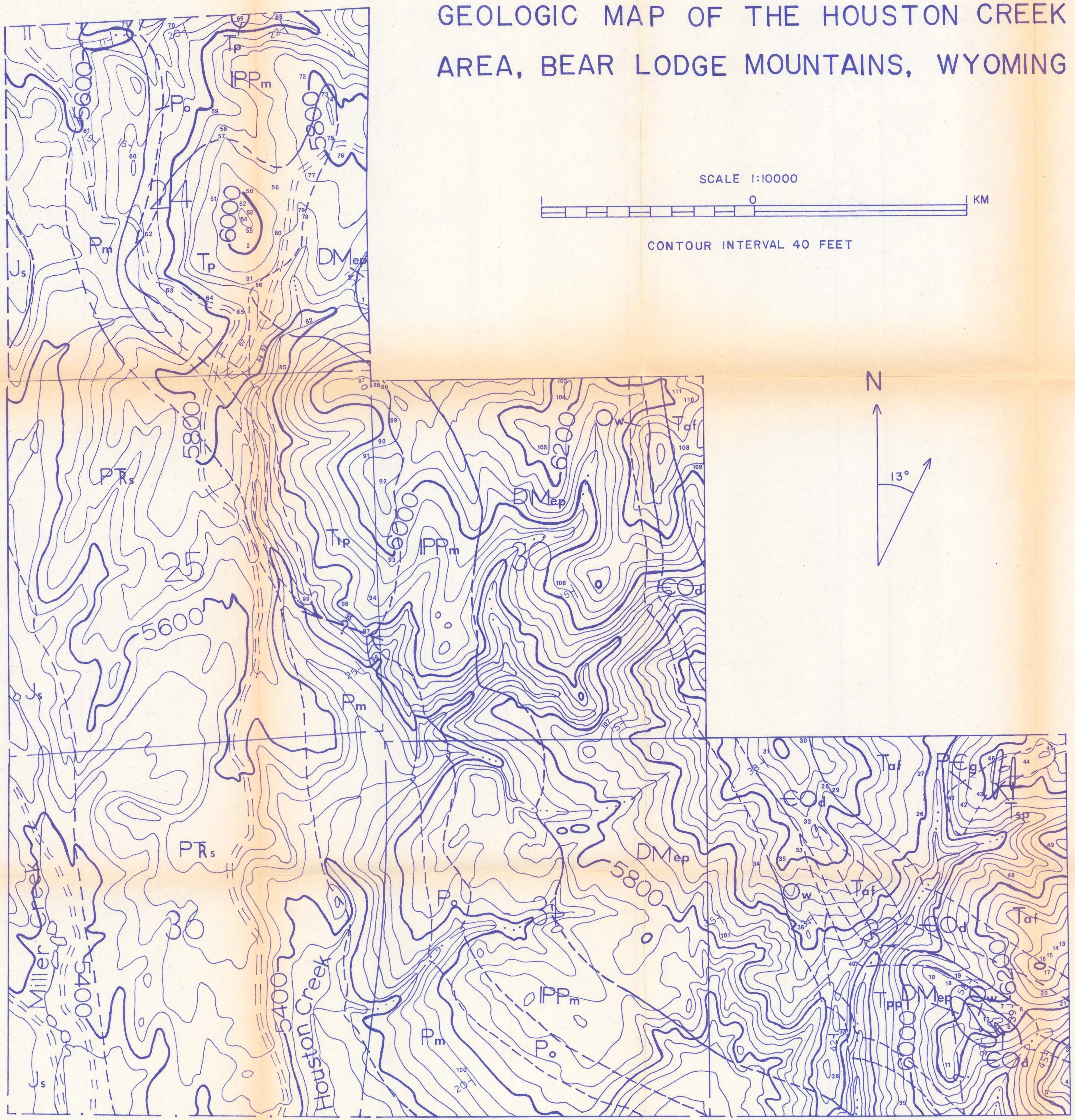
PLATE I
OToole Thesis

GEOLOGIC MAP OF THE HOUSTON CREEK AREA, BEAR LODGE MOUNTAINS, WYOMING



Base map from Sundance Quadrangle, USGS topographic map

EXPLANATION

TERTIARY

Tsp

Igneous rock

Sodalite-bearing phonolite: *dark green, holocrystalline, aphanitic, porphyritic to glomerophyric, trachytic; major minerals include orthoclase, aegirine-augite, aegirine, melanite, and sodalite; secondary minerals include analcime, natrolite, and calcite*

Tp Tpp Ttp

Igneous rock

Phonolite: *medium to dark gray, holocrystalline, aphanitic, trachytic to randomly oriented groundmass; major minerals include orthoclase, aegirine-augite, melanite, and hauyne; secondary minerals include analcime, natrolite, hematite, and calcite; mafic and granitic xenoliths occur locally*

Phonolite porphyry: *dark green to greenish-gray, holocrystalline, porphyritic; phenocrysts include sanidine, aegirine-augite, sphene, and hauyne in a trachytic to pilotaxitic groundmass of orthoclase laths and aegirine needles; secondary minerals include analcime, natrolite, hematite, and calcite*

Trachyte porphyry: *light to medium gray, holocrystalline, porphyritic; phenocrysts include sanidine, aegirine-augite with aegirine margins, melanite, and sphene in a trachytic groundmass of orthoclase laths and aegirine needles; secondary minerals include analcime, natrolite, hematite, and calcite*

Taf

Igneous rock

Altered felsite: *yellowish- to reddish-brown, porphyritic, trachytic groundmass; phenocrysts of alkali feldspar, plagioclase, and pseudomorphs of pyroxene, amphibole, and feldspathoid; calcite, kaolinite, natrolite, analcime, and iron oxide occur as alteration products; altered mafic xenoliths occur locally*

JURASSIC

Js

Sundance Formation

Sandstone; light yellowish-gray, fine-grained, friable

UNCONFORMITY

PERMIAN AND TRIASSIC

PTRs

Spearfish Formation

Sandstone, siltstone, and shale; red to reddish-brown, interbedded, poorly lithified; thick beds of gypsum locally near the base

PERMIAN

Pm

Minnekahta Limestone

Limestone; gray to lavender, flaggy; red shale at the base

Po

Opeche Formation

Siltstone and shale; reddish-brown to maroon, poorly lithified; thin beds of gypsum occur locally

PENNSYLVANIAN AND PERMIAN

IPPm

Minnelusa Formation

Sandstone; light brown to yellow, cross-bedded; dolomite in part; red shale at the base

UNCONFORMITY

DEVONIAN AND MISSISSIPPIAN

DMep

Pahasapa and Englewood Limestones, undifferentiated

Pahasapa Limestone. Limestone; light gray, massive, contains chert nodules; dolomite in part
Englewood Limestone. Limestone; light brown to pink, poorly indurated; shale locally at the base

ORDOVICIAN

Ow

Whitewood Formation

Dolomite; brownish-gray, massive, mottled; limestone in part

UNCONFORMITY

CAMBRIAN AND ORDOVICIAN

€Od

Deadwood Formation

Sandstone, shale, and limestone; sandstone, light brown, glauconitic; shale, greenish-gray, glauconitic; limestone, light gray, dolomitic, flaggy

UNCONFORMITY

PRECAMBRIAN

P€g

Metamorphic rock

Granitic gneiss: *light grayish-brown to pink, fine- to medium-grained, allotriomorphic granular to cataclastic; minerals include microcline perthite, quartz, oligoclase, and biotite; chlorite, muscovite, and epidote occur as alteration products*

Contact

Dashed where approximately located

—— ——?—— ——

Fault

Existence uncertain

8

Strike and dip of beds

43

Igneous outcrop and sample location

Darker shades indicate igneous outcrops; numbers indicate sample locations

by
Frederick S. O'Toole
1981