UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

[REPORTS - OPEN FILE SERIES]

THE GEOLOGY OF ALKALIC COMPLEXES IN NORTH-CENTRAL WASHINGTON

By

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Open-file report

1973

73-73

Released: 6-6-73

This report is preliminary
and has not been edited or
reviewed for conformity with
Geological Survey standards

ABSTRACT

The alkalic complexes of north-central Washington form two subparallel belts of alkalic rocks which, including the weakly alkalic Tulameen ultramafic complex and Copper Mountain intrusions of British Columbia, have an aggregate length of about 130 miles.

The Kruger complex, with an area of 17 sq. mi., is composed of intergrading pyroxenite, malignite, shonkinite, and foyaite. The complex forms a semicircular arc bordering the east side of the alkalic-calcic Similkameen batholith, which is a mesozonal, concentrically zoned intrusion grading outward from quartz monzonite to monzonite. The monzonite grades to the shonkinite of the Kruger, even though dikes of the Similkameen cut the Kruger complex. Thus although the alkalic complex was emplaced in advance of the Similkameen, the two are grossly coeval, and form a single composite pluton.

The Shankers Bend, Copper Mountain, Oroville, Bimetallic Mountain, and Cumberland Mountain alkalic complexes lie at distances of 2, 6, 8, 22, and 30 miles, respectively, east-southeast of the Similkameen batholith. They range in exposed area from about 0.15 to 1.2 sq. mi., and are composed of rocks compositionally and texturally similar to those of the Kruger complex. They differ, however, in that the alkalic rocks and locally the nearby country rocks are shattered or brecciated, and the wall rocks at several of the complexes are fenitized. The brecciation probably is a product of internal processes accompanying formation of the alkalic complexes, and indicates that some of the complexes are alkalic diatremes.

Harker diagrams and modified QLM diagrams show that although the alkalic magma series is distinct from the Similkameen alkalic-calcic series, compositional trends of the two series intersect at a composition near that of shonkinite. The chemical trends and modal composition of the alkalic rocks are compatible with their formation from a shonkinitic parent magma through fractional crystallization and sinking of clinopyroxene, accompanied by minor biotite and magnetite, and with concurrent flotation of leucite. The compositional range of the Similkameen series probably corresponds to inhomogeneities in the primary magma. The order of intrusion established from contact relations suggests that the alkalic magma was intruded first, and it therefore is assumed to be the initial product of the melting episode in which the Similkameen magma series was formed. The primary alkalic magma and the alkalic-calcic magma series were derived through partial melting along a chemical path beginning with small volumes of silica-undersaturated magma followed by increasing volumes of more siliceous magma.

The potassium-rubidium ratios of the Similkameen rocks average about 265, whereas those of the alkalic rocks are higher, averaging about 390. If the primary alkalic magma were an initial extract from the same source material as that from which the later saturated to oversaturated magmas were derived, then the ratio of about 0.68 between the potassium-rubidium ratios of the alkalic rocks and the potassium-rubidium ratios of the Similkameen rocks means that the potassium-bearing crystalline phase(s) present during melting must

have captured rubidium relative to potassium. Leucite is a possible candidate for this phase, but its presence restricts the maximum depth of partial melting to that of the upper mantle.

The location of the alkalic belts does not appear to be controlled by supracrustal structures. Possibly the belts reflect the position of compositional streamlines formed as the lithospheric plate slid across the asthenosphere, and from which the alkalic and alkalic-calcic magmas were derived through partial melting during the late Triassic and early Eocene magmatic events.

ACKNOWLEDGEMENTS

The author is deeply indebted to C. Dean Rinehart for advice and assistance in the mapping and petrographic studies, to T. P. Miller for many thought-provoking discussions concerning the petrology of alkalic rocks, and to R. B. Yates for advice on regional geology of northeastern Washington. The author also wishes to thank F. C. Dodge for discussions on the application of biotite and K-Rb data to problems of igneous petrology, R. H. Jahns for helpful suggestions and for constructive comments on the manuscript, James A. Fox, the author's brother, for translation of Mme. Lagache's article, and R. R. Compton, W. C. Luth, and K. B. Krauskopf, for advice and comments on the manuscript. The author is particularly grateful for the encouragement and support of his wife, Shirley A. Fox.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

(Plates I - V are in pocket)

INTRODUCTION

Alkalic rocks are found within a number of small intrusive complexes in north-central Washington and southern British Columbia (Fig. 1). The best known of these is the Kruger alkalic complex, which was discovered and mapped by R. A. Daly (1906, 1912). The complex, according to Daly, is composed of malignite and nepheline syenite, and is intruded on the west by the Similkameen batholith. Daly proposed that the undersaturated magma from which the alkalic rocks crystallized was produced by desilication of a subalkalic magma through assimilation of limestone (Daly, 1910). Although the Kruger alkalic complex faded into obscurity, Daly's limestone assimilation hypothesis continues to be a popular albeit controversial[1] explanation for the origin of alkalic rocks.

The petrology of the Kruger rocks was restudied by Campbell (1939), who concluded that the alkalic complex was locally intruded by and elsewhere graded into the Similkameen batholith. A similar opinion was offered by Bostock (1941) who mapped that part of the Kruger complex and Similkameen batholith lying north of the International Boundary.

More recently, that part of the Similkameen batholith and Kruger complex lying south of the International Boundary was mapped by C. D. Rinehart and myself (Fox and Rinehart, 1967). Particular

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[1] For recent opinion for and against the limestone assimilation hypothesis see Schuiling (1964), and Watkinson and Wyllie (1964).

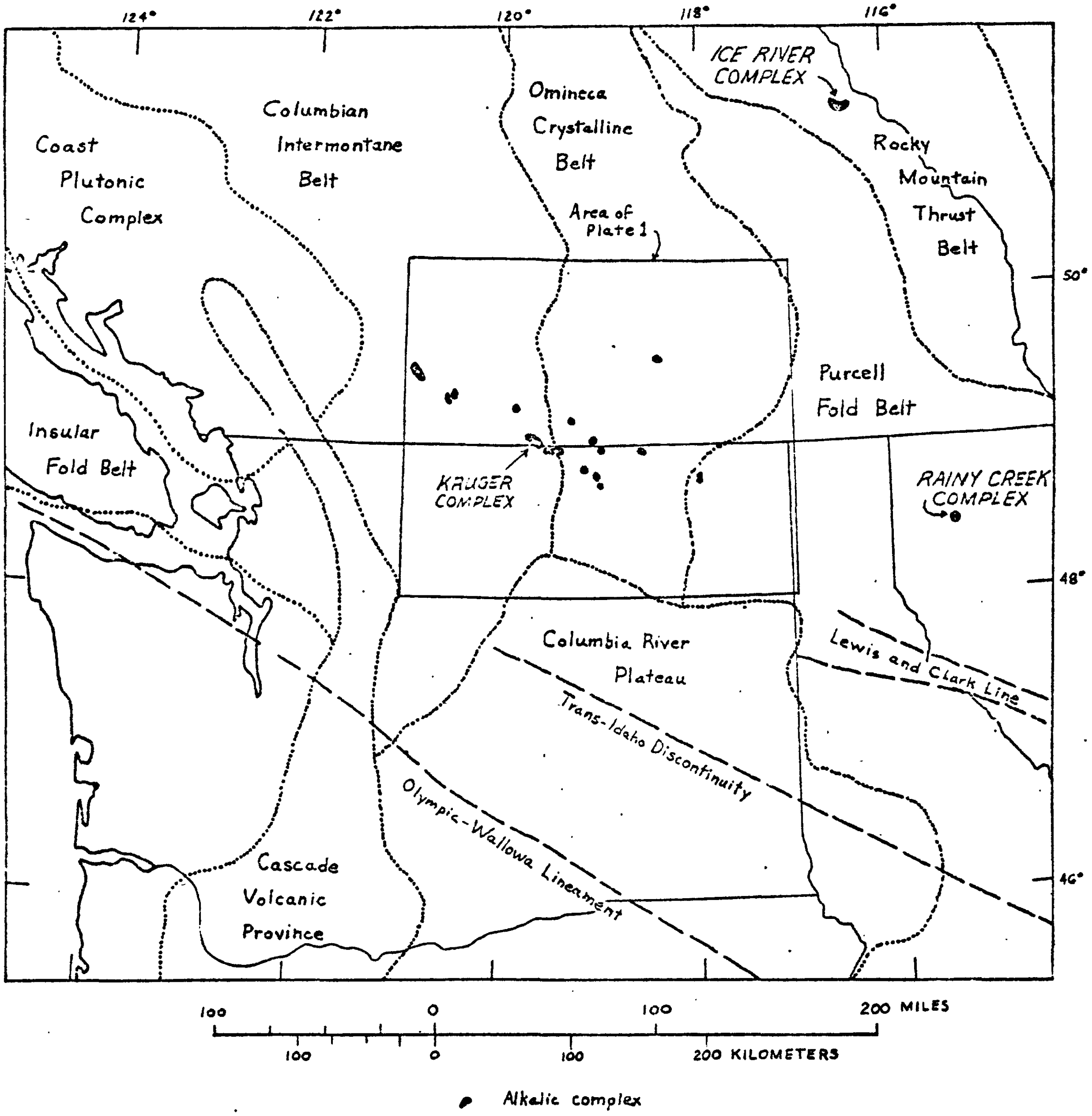

Fig. 1.--Alkalic complexes, geologic provinces, and regional lineaments of Washington, southern British Columbia, northern Idaho, and northwestern Montana.

attention was given by us to the contact relations of the granodiorite and monzonite of the Similkameen with the mafic undersaturated rocks of the "Kruger." We concluded that the contact was in part gradational, in part crosscutting, and that the oversaturated and undersaturated series were comagmatic (Rinehart and Fox, in press [a]).

During the course of our mapping of the Similkameen, C. D. Rinehart found and generously invited the author to participate in the exploration of a previously unreported complex of alkalic rocks, which we subsequently concluded was an alkalic diatreme. The complex, which is less than a square mile in exposed area and located 3 miles east-southeast of the Kruger rocks, near Shankers Bend, contains a potpourri of alkalic breccia, fenite, and malignite, the latter indistinguishable from the malignite of the nearby Kruger complex.

Additional alkalic complexes lying east-southeast of the Kruger-Similkameen area at Oroville and Bimetallic Mountain were later reconnoitered, and were found to possess features similar to those of the Shankers Bend complex, suggesting emplacement of alkalic breccias at shallow depth, with concomitant fenitization of the country rock. However, the breccia which constitutes much of the rock at the Oroville alkalic complex was attributed by Waters and Krauskopf (1941), and Krauskopf (1941), to in situ crushing of malignite plugs by forceful intrusion of the nearby "Colville Batholith."

The many lithologic similarities between the alkalic rocks of the Kruger area and the alkalic complexes to the east suggest that they owe their origins, at least in part, to common factors. If so, their elucidation depends on a better understanding of the geology of the complexes, which are the least well known of the alkalic rocks in the area. The chief objective of the current study accordingly has been to describe and interpret the geology and petrology of the Shankers Bend, Oroville, and Bimetallic Mountain complexes, and those allied alkalic rocks in the immediate vicinity. The secondary objectives were to review the salient features of the Kruger rocks, and their relation to the Similkameen, and to speculate on the implications of the petrologic and geographic situation of the alkalic rocks considered as a group.

CLASSIFICATION

Since the main thrust of this paper concerns the so-called "alkalic" igneous rocks, it is appropriate to define at the outset what this author regards as an alkalic rock. Rocks containing feldspathoids and/or sodic pyroboles, indicating the presence of an excess of alkali ($K_2O + Na_2O$) with respect to available silica or alumina,, are commonly considered alkalic rocks.[1] Shand (1923) has quantified this conception by defining an alkalic rock as one in which the molecular proportion of alkali to either alumina or silica exceeds the 1:6 ratio in which these elements are combined in feldspars, a definition favored by Barth (1962). However, in mafic rocks considerable silica may be combined with calcium, iron, and magnesium in the ferromagnesian minerals, and therefore feldspathoids may be present notwithstanding the fact that the alkali to silica ratio is less than 1:6. Clearly the term "alkalic" should embrace all feldspathoidal rocks. Furthermore, in mafic magmas a declining ratio of silica to alkali is to some extent buffered by crystallization of decreasingly silicic mafic minerals, so that modal feldspathoids may not appear in rocks which normatively are modestly undersaturated in silica. To accommodate rocks of these categories, an alkalic rock is herein defined as a rock which contains modal or CIPW normative feldspathoids

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[1] "Alkalic" and "alkaline" are used interchangeably in this sense, but alkalic is apparently preferred, and will be used throughout this paper.

and/or sodic pyroboles. This is tantamount to changing Shand's definition to read . . . "available" alkali, alumina, and silica . . ., and supplying a means whereby this availability may be determined.

Little accord has been reached by petrographers in classifying the great variety of rocks which make up the alkalic clan. It is therefore unfortunately necessary for each worker to arbitrarily erect or adopt from the jumble of names and systems in use a classification appropriate to the particular rocks under study. Ideally, by substituting a few archetypes for many individuals classification helps in recognition of regularities in nature and consequently aids in the perception of underlying principles. Explicit definition of archetypes has proven impractical in igneous petrology, however. Instead, current practice is to establish rigidly defined fields or "pigeonholes," which for phaneritic rocks are based on the modal composition. Opinion differs over which modal constituents to employ in the classification of alkalic rocks. Streckeisen (1967), with ample precedent, has recently put forward a ternary classification of alkalic rocks based on the proportion of feldspathoids, plagioclase, and alkali feldspar. But in many alkalic complexes the color index shows the greatest range of any parameter, is easiest to measure or estimate, has undoubted genetic importance, and is naturally used by many for delimiting map units. These attributes justify the use of the color index as a main fulcrum of the classification of alkalic rocks, as was recognized, for example, by Shand (1921), Parsons (1961), and most recently by Miller (1972). The classification used here (Fig. 2) is adapted from Miller (1972) and is based on the modal

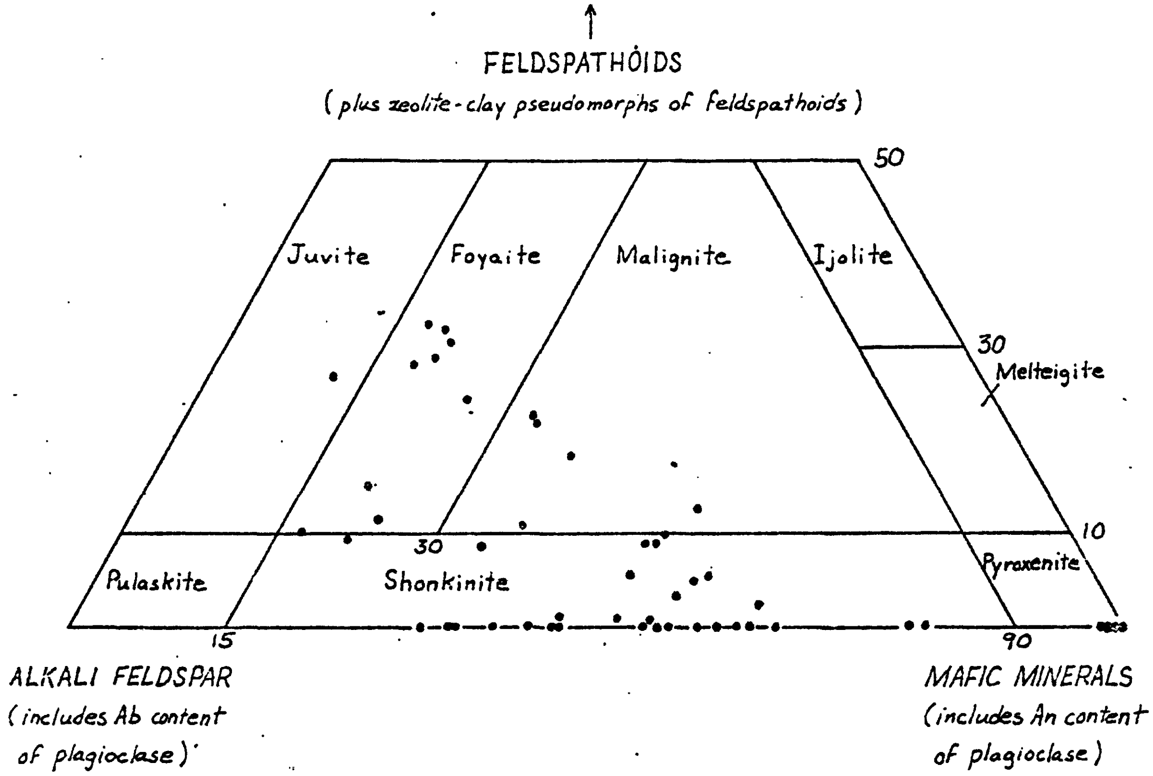

Fig. 2.--Diagram showing modal classification of alkalic rocks modified from Miller (1972), and the distribution of modal feldspathoids and/or their alteration products, feldspar, and mafic minerals of the alkalic rocks of north-central Washington.

proportion of feldspathoids, alkali feldspar, and mafic minerals.

Because plagioclase is a major constituent of the alkalic rocks of north-central Washington, some provisions for its inclusion in the modal basis of the classification is desirable. Therefore, plagioclase is calculated as albite and anorthite, which are added to alkali feldspar and the mafic minerals, respectively.

The classification of the granitic rocks (Fig. 3) is modified from the scheme given by Bateman, et al. (1963).

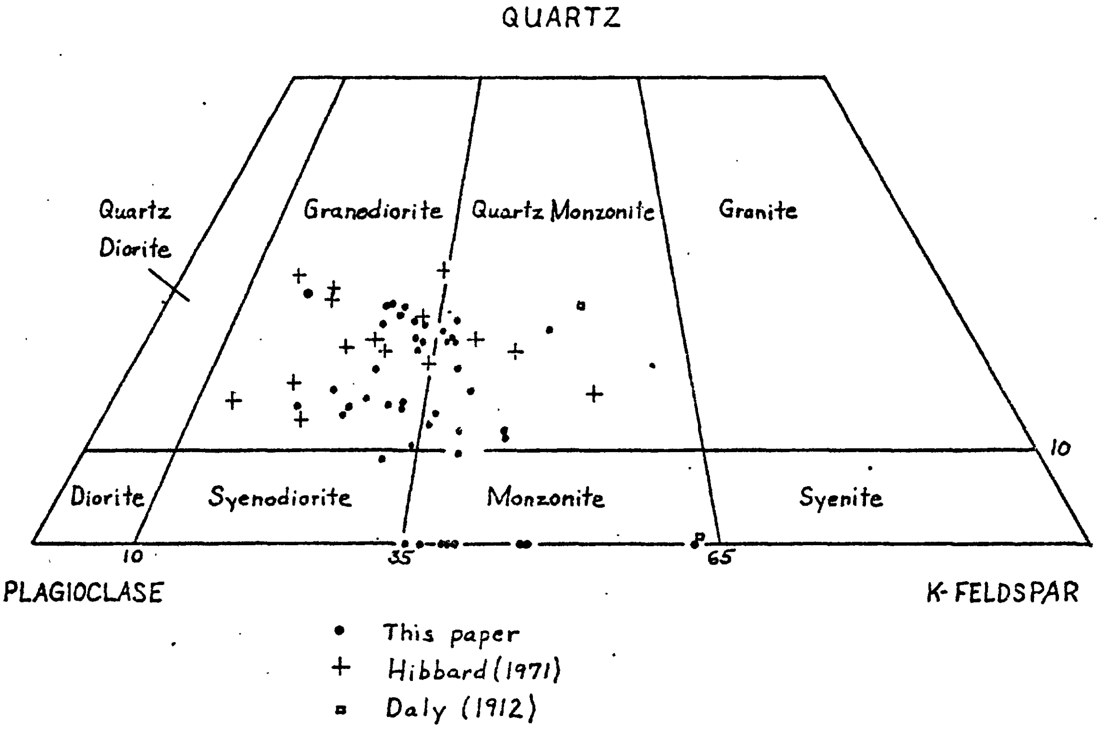

Fig. 3.--Diagram showing classification of granitic rocks, and the distribution of modal quartz, K-feldspar, and plagioclase of rocks of the Similkameen batholith.

REGIONAL SETTING

Introduction

South-central British Columbia and northeastern Washington overlap two quite dissimilar geologic provinces, an eastern province characterized by a thick accumulation of Precambrian and early Paleozoic miogeosynclinal rocks, and a western province characterized by an equally thick accumulation of late Paleozoic and Mesozoic eugeosynclinal rocks (Yates and others, 1966). The boundary between the miogeosynclinal rocks and the eugeosynclinal rocks is apparently abrupt.

An alternative division of the region, based on differing orogenic character, has been proposed for British Columbia and may be conveniently extended to northeastern Washington (Fig. 1). That part of the miogeosynclinal province within the map area (PLATE I) is approximately equivalent to the Purcell Fold Belt and the eugeosynclinal province comprises two distinctive terrains, the Omineca crystalline belt on the east, and the Columbian intermontane belt on the west.

The Omineca crystalline belt is distinguished from the intermontane belt mainly by the presence within the Omineca of the high- to medium-grade gneisses and schists of the Monashee Group of the Shuswap Series. These rocks are chiefly migmatitic paragneisses and orthogneisses possessing a distinctive penetrative fabric whose main elements are a strong, persistently west- to northwest-trending lineation and a regular, shallowly dipping foliation (Jones, 1959). The western limit of the Shuswap rocks of British Columbia and correlative rocks of northern Washington forms the boundary between the Omineca crystalline belt and the Columbia intermontane belt.

Alkalic rocks are found in all three belts, although calc-alkalic plutonic rocks, high- to medium-grade gnesses and schists, pre-Tertiary stratified and low-grade metamorphic rocks, and Tertiary volcanic rocks and epiclastic continental deposits constitute most of the bedrock.

Geologic History

Pre-Pennsylvanian

The record of sedimentation in the miogeosyncline begins in the Proterozoic, with the deposition of the Belt Super Group. The Belt is a thick, widespread deposit of monotonously similar siltite, argillite, and quartzite, possessing abundant mud cracks and ripple-marks, and believed therefore to represent the product of protracted deposition, in a stable shallow water sea, of sediments derived from the interior of the craton (Yates and others, 1966). On the west the Belt is flanked by the somewhat similar and probably in part correlative rocks of the Deer Trail Group (Miller, 1969), which are overlain by Precambrian conglomerates and greenstones of the Huckleberry Formation. The western lip of the Belt in Canada (Purcell Series) is overlain by the younger Precambrian rocks of the Windemere, which are chiefly feldspathic sandstone, phyllite, slate, siltstone, and conglomerate, with fine-grained carbonate rock in the upper part (Gabrielse, 1972). A regional unconformity between the Purcell and the Windemere is attributed to widespread epeirogenic uplift occurring along with local folding, plutonism, and metamorphism during the East Kootenay Orogeny (White, 1959). Both the Belt (Purcell), Deer Trail Group, and Windemere contain intercalated flows and/or sills of basic to intermediate volcanics.

Harrison and Peterman (1971) suggest that the Belt (Purcell) was deposited between 1450-850 m.y. ago, and Gabrielse suggests that the Windemere was deposited during the interval 800-600 m.y. ago. The Purcell and the overlying Windemere represent sediment derived from easterly sources and deposited along the continental margin (Gabrielse, 1972), thus the boundary between the miogeosynclinal province and the eugeosynclinal province roughly coincides with the edge of the craton as it existed from 1450 to 600 m.y. ago.

The Precambrian rocks were overlain by a thick accumulation of limestone and dolomite, orthoquartzite, slate, and shale during early Paleozoic time. The youngest fossils found in the miogeosynclinal rocks are Mississippian (Miller, 1969). No important angular unconformities of regional scope have been established within the post-Windemere miogeosynclinal section.

Pennsylvanian - Cretaceous

Eugeosynclinal province.--The upper Paleozoic Cache Creek Series and its correlatives, which include the Anarchist Group (Rinehart and Fox, in press [a]), the Mount Roberts Formation, and the Hozameen Group, are the oldest bedded rocks of the Eugeosynclinal province known within the map area. Although fossils are only rarely present, Devonian fossils have been identified at two localities, Mississippian fossils at several, and Pennsylvanian and Permian at many (Monger and Ross, 1971). The history of the eugeosyncline begins, therefore, in the late Paleozoic, with deposition of thick wedges of siltstone, slate, sharpstone conglomerate, limestone, and graywacke, accompanied, particularly in the upper part, by large volumes of lava, bedded chert, and pyroclastic rock. Laterally the bedded rocks thicken and thin abruptly, interfinger, and intergrade. Individual lithologic units can seldom be traced for more than a few miles. These features suggest that the rocks of the Cache Creek Series and its correlatives were probably deposited in a rapidly subsiding basin, on complexly coalescing shelf areas peripheral to or within a series of volcanic archipelagos. The immaturity of most of the non-volcanic clastic sediments indicates that they, along with the volcanic rocks, were locally derived, rather than being contributed from sources within the craton to the east.

The Nicola Group and its probable correlative, the Kobau Formation, overlie the Cache Creek rocks disconformably, or locally along a mild angular unconformity (Rinehart and Fox, in press [a]), indicating brief uplift and erosion of the Cache Creek in the late Permian or early Triassic. The Nicola is predominantly a thick sequence of basaltic flows, pyroclastics, and thick, massive, bedded chert, except for local accumulations of limestone, dolomite, and siltstone.

South of the International Boundary the contacts of Permo-Triassic eugeosynclinal deposits with the older strata of the miogeosyncline to the east are tectonic. Depositional overlap has not been proven, but Yates (1970) regards the argillites of the Grass Mountain sequence (Yates, 1964), which contain rare volcanic material, as transitional between the Devonian argillites of the miogeosyncline and Pennsylvanian volcaniclastic beds of the eugeosyncline.

Neither the eugeosynclinal nor miogeosynclinal provinces had been subjected to important regional deformation prior to the Triassic. In the late Triassic, however, strata of the Nicola and Cache Creek Series were folded along north-northwest axes, regionally metamorphosed, intruded by alpine type ultramafic rocks, and subsequently intruded by calc-alkalic magmas which formed large plutons, some of batholithic dimensions. The oldest of the plutons within the map area is the Loomis, believed to be about 190-200 m.y. old (Rinehart and Fox, in press [a]). The Guichon Batholith, which lies just north of the map area at 121° west longitude is also about 190-200 m.y. old (White and others, 1967). Both the Guichon and the Loomis are elongate, with long axis oriented parallel to the north-northwest "grain" of the eugeosynclinal province.

Deposition, which had ceased in the central and western parts of the eugeosynclinal province during the late Triassic, resumed on the west flank during the Jurassic. The record on the east flank is more difficult to interpret. If the age of the Slocan Group overlaps the upper Triassic and lower Jurassic, as indicated by Hyndman (1968), deposition in this area must have been roughly concurrent with deformation and plutonism in the central and western parts of the eugeosynclinal province. In middle and late Jurassic time, however, both flanks of the province were accumulating deposits, which on the east side were primarily lavas and related rocks, and on the west side were primarily marine deposits of volcaniclastic sediment derived from erosion of the Nicola-Cache Creek terrain in the central part of the map area (Coates, 1970).

Sedimentation in the western basin continued periodically through the lower Cretaceous, marked by the appearance of material eroded from sources west of the basin as well as to the east, and by the appearance of granitic detritus (Coates, 1970). Apparently deposition of volcanics and related sediments continued into the lower Cretaceous on the east side of the province also.

The central part of the eugeosynclinal province was positive and the site of continued plutonism through the Jurassic and early Cretaceous, and by mid-Cretaceous most of the province was positive and the area of plutonism had spread eastward and westward through the whole of the eugeosynclinal province within the map area.

The place of the Shuswap Series in the geologic history of the province is an unsettled question. Earlier workers believed the Shuswap to be Precambrian, but this hypothesis has been weakened by failure to find overlap of Paleozoic rocks or even Mesozoic rocks, on the Shuswap. Results of repeated attempts to date the series isotopically indicate that retention of radiogenic argon in various minerals began in the late Mesozoic.

Gneiss domes have been located within rocks of the Shuswap

Series, and within the map-area they include the Valhalla and Passmore domes in British Columbia (Reesor, 1965), and the Okanogan gneiss dome in Washington (Fox and Rinehart, 1971). The presence of others is suspected. Some of the domes represent diapiric emplacement of hot, mobile tongues of gneiss. If so, the question of age of the Shuswap may be divisible into (1) the age of emplacement of the gneiss, and (2) the age of the immediate parent of the gneiss. The source of much of the Shuswap was probably within the infrastructure and is thus likely to be Precambrian. In view of the K-Ar and fission track ages, and field relations with Mesozoic wall rocks, probably some and perhaps all of the Shuswap was emplaced during the late Mesozoic.

<u>Miogeosynclinal province</u>.--Plutonism in the miogeosyncline began as early as late Paleozoic (Gabrielse and Reesor, 1964) and continued intermittently through the Mesozoic. Rocks of the miogeosyncline were strongly folded on northeast trending axes before 100 m.y. ago, according to Yates and Engels (1968), because some folds of this system are cut by isotopically dated plutons of that age. The miogeosynclinal rocks are cut by numerous faults of diverse type, of which many cannot be older than Mesozoic, in view of the tectonic contact between the eugeosynclinal and miogeosynclinal rocks. The ages of fault and fold systems are in general poorly known, partly because of the absence of Mesozoic sedimentary rocks within the province.

Tertiary

The Tertiary record within the map-area indicates two periods of plutonism and volcanism, the earlier in the Eocene and the later in the Miocene, with an intervening period of relative quiescence (Matthews, 1964). The Eocene episode began with the roughly contemporaneous deposition in local basins of arkose, wacke, and conglomerate, consisting at the base of quartzo-feldspathic material eroded from nearby sources, and containing pyroclastic material in increasing proportions higher in the section. The sedimentary beds are typically overlain by pyroclastic rocks and lava flows, and intruded by the hypabyssal intrusive equivalents of the volcanic rocks. The Eocene rocks were deposited on a profound angular unconformity beveled on older rocks. In the Republic area deposition was accompanied by penecontemporaneous faulting and subsidence of a north-northeast trending graben (Muessig, pp. 95-96, 1967). There and elsewhere in the map-area the Eocene rocks were folded and faulted, partially eroded, and overlain in places by basalts during the Miocene. The Miocene rocks include the Columbia River Basalt, which overlaps the south edge of the map-area, and its erosional outliers, and other smaller patches of basalt distributed over the remainder of the map-area.

The record of plutonism during the Tertiary parallels that of the volcanism, with pronounced intervals of maximum activity during the Eocene and Miocene.

The Miocene and Eocene volcanic rocks and the Eocene plutonic rocks are patchily distributed over both the Eugeosynclinal and

Miogeosynclinal provinces. Except for the apparent absence of Miocene plutonic rocks in the Miogeosynclinal province, the two provinces have a common geologic history in the Tertiary, in contradistinction to the individual depositional, structural and plutonic histories which had been a feature of their development until the close of the Cretaceous.

Regional Igneous Petrology

The igneous rocks within the map-area whose character is relevant to the origin of alkalic rocks can be advantageously grouped into four broad divisions: Permian-Cretaceous volcanic rocks of the eugeosynclinal province, calc-alkalic plutonic rocks, ultramafic and alkalic plutonic rocks and Tertiary volcanic rocks. Although the distribution of the various rocks of the four classes is reasonably well known, quantitative data on their detailed chemical and modal composition and other attributes are very inadequate.

Permian-Cretaceous volcanic rocks of the eugeosynclinal province

The petrochemistry of the pre-Tertiary volcanic rocks of the eugeosynclinal province has not yet been studied in the detail that their large volume, widespread occurrence, and possible role in the genesis of the calc-alkalic plutonic rocks would warrant. No chemical data are available for either the Permian or Cretaceous volcanic rocks. However, several analyses have been reported for rocks of the Nicola Group, Palmer Mountain Greenstone, and Ellemeham Formation, of probably Triassic age, and the Rossland Group, of Jurassic Age. Lavas of the Nicola Group and its correlatives have been described as (meta) basalts and (meta) andesites. The silica content of a suite of differentiated, weakly metamorphosed volcanic rocks of the Palmer Mountain Greenstone and related hypabyssal intrusive rocks ranges from 49 to 66.4 (Rinehart and Fox, in press [a]).

Lavas of the Rossland Group were classified by Daly (1912, p. 324) as latite, olivine basalt, olivine-free basalt, augite andesite, and "possibly picrite." The silica content of the latites, based on four analyses, ranges from 52 to 59 percent.

The Triassic-Jurassic meta-volcanics and their hypabyssal intrusive correlatives can be collectively classified as alkalic-calcic (Fig. 4).

Calc-alkalic plutonic rocks

The calc-alkalic plutonic rocks are mostly granodiorite and quartz monzonite, with subordinate quartz diorite, granite, and syenite (Fig. 5). Although representatives that run the entire gamut of this compositional range are widely distributed within the map-area, quartz diorite and granodiorite are most abundant on the west, and granodiorite and quartz monzonite on the east. The easterly transition to increasingly alkali-rich plutonic rocks accords with that for the western cordillera as a whole (Moore, 1959).

Typical mafic minerals of the quartz diorites, granodiorites, and quartz monzonites are biotite, hornblende, and locally augite. Several plutons of this group located in the Miogeosynclinal province, however, are two-mica rocks, containing primary biotite and muscovite

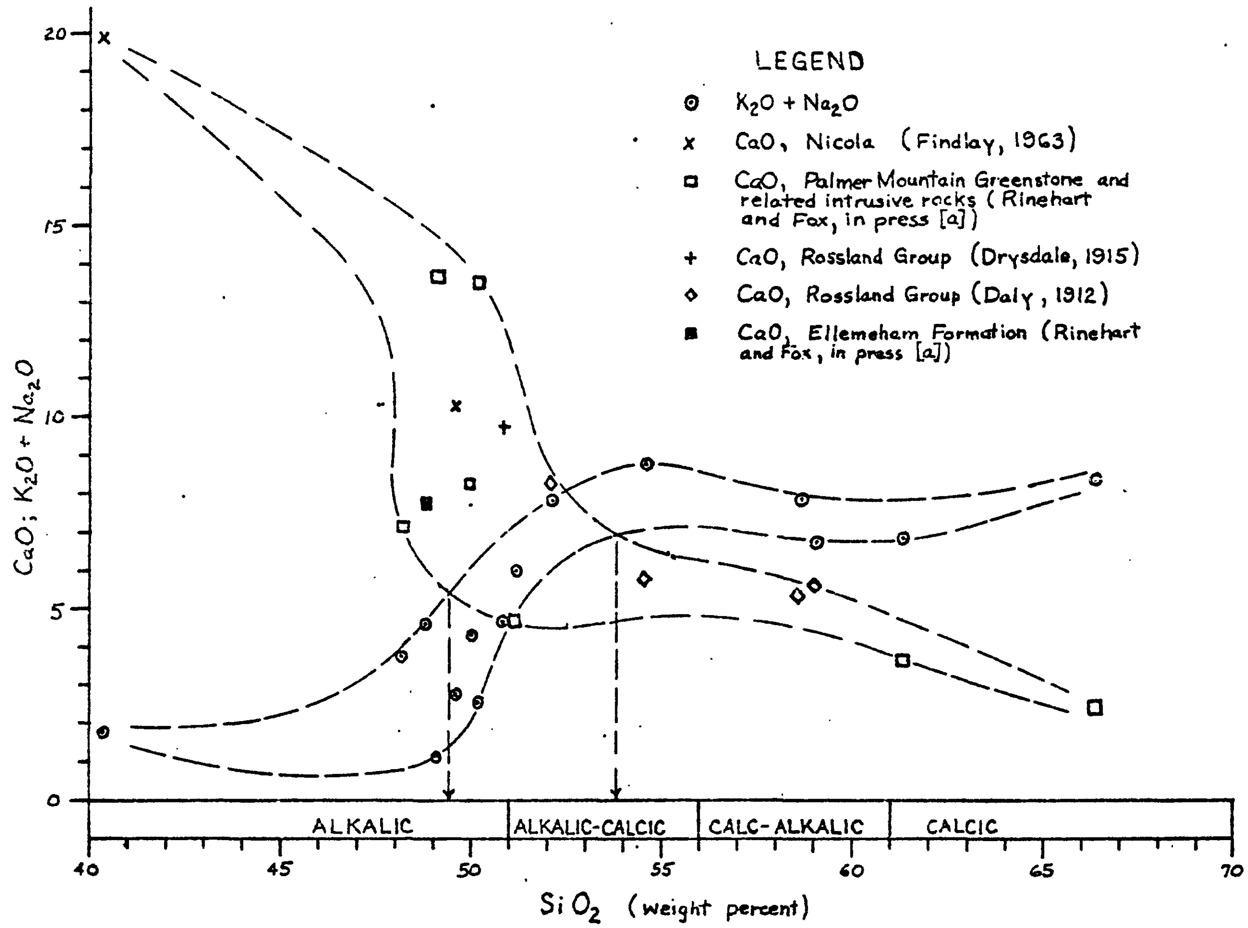

Fig. 4.--Silica variation diagram showing range of the "alkali-lime index" (Peacock, 1931) of Triassic and Jurassic metavolcanic rocks and related hypabyssal intrusive rocks, that is indicated by intersection of envelopes (drawn by inspection) enclosing points showing $K_2O + Na_2O$ versus SiO_2, and CaO versus SiO_2. Amphibolite-grade rocks of the Palmer Mountain Greenstone plotted at 13.5 and 13.6 percent CaO have probably been non-isochemically metamorphosed.

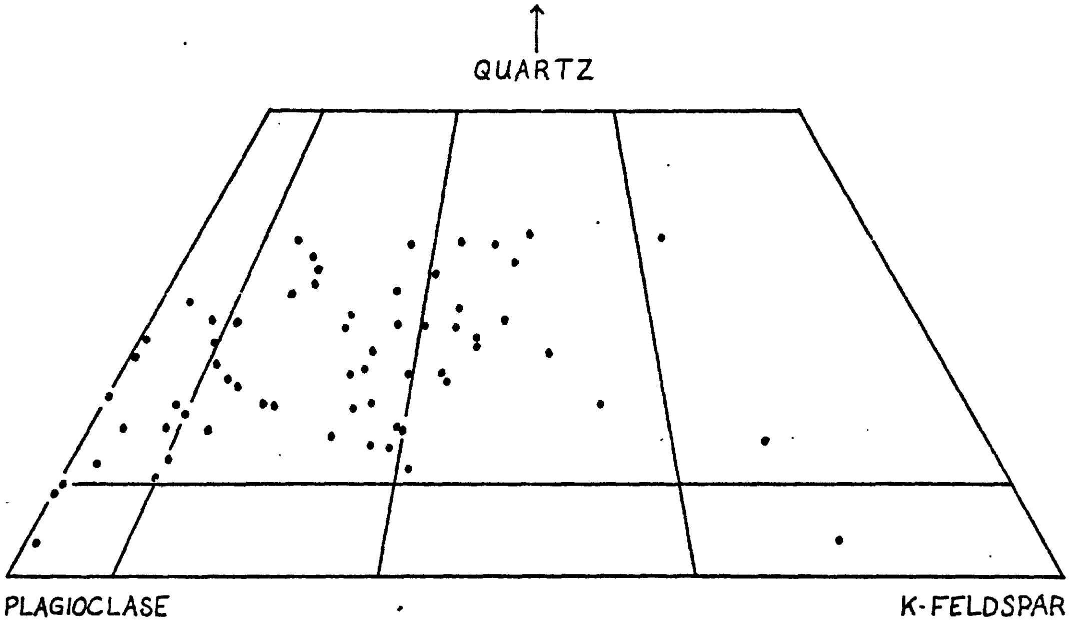

Fig. 5.--Diagram showing distribution of average modal composition of plutons of south-central British Columbia and northeastern Washington.

(Miller, 1969; Clark and Miller, 1968). Only a few plutons within the map-area are known in which the proportion of alkali-feldspar to plagioclase exceeds 2:1. They tend to be peralkaline, commonly containing aegirine and riebeckite, and contrary to expectations based on the regional easterly increase in alkali feldspar noted above, are as abundant in the western part of the map-area as the eastern.

The $Sr^{87/86}$ ratios of 22 granitic rocks located within the eugeosynclinal province of south-central British Columbia were found by Fairbairn, Hurley, and Pinson (1964) to range between 0.705 and 0.710. These values are nearer those of mantle-derived oceanic and continental basalt (means of 0.704-0.705) than to average continental crust (0.725), apparently ruling out derivation of their parent magmas by simple anatexis of sialic material. The southern British Columbia $Sr^{87/86}$ ratios are similar to those of Sierran granitic rocks, and may result from contamination of magma derived from the mantle by sialic material, as suggested by Fairbairn, Hurley, and Pinson, or from anatexis of the late Paleozoic-Mesozoic eugeosynclinal basement, as proposed by Peterman, Hedge, Coleman, and Snavely (1967).

Ultramafic and alkalic plutonic rocks

The rocks of this group are of three main types: (1) relatively small, elongate plutons, composed wholly of serpentinized dunite or peridotite, the "alpine" type ultramafic of Hess (1939): (2) small to large, roughly oval alkalic complexes (Table 1), each composed chiefly of two or more but never all of the following rocks:

TABLE 1

ALKALIC ROCKS OF SOUTH-CENTRAL BRITISH COLUMBIA AND NORTH-CENTRAL WASHINGTON

Name (and reference) Description	Area (sq. mi.)	Age (in m. y.) or age relations
Tulameen ultramafic complex (Findlay, 1969)	22	174, K-Ar isochron, hornblendes (Roddick and Farrar, 1971a)
Comprise mafic and ultramafic rocks. The mafic rocks include syenogabbro, syenodiorite, minor gabbro. The ultramafic rocks include dunite, peridotite (minor), clinopyroxenite, hornblende pyroxenite, hornblendite. Zoned, with ultramafic rock forming core in north-central part of complex, and also forming subparallel belts in southern part. No modal feldspathoids, but four of eight analyses of pyroxenite and one of three analyses of gabbro show normative nepheline or leucite.		
Copper Mountain intrusions (Montgomery, 1967)		
Copper Mountain stock	7.5	193 ± 7 (Sinclair and White, 1968)
Armstrong Bluffs complex	0.5	
Smelter Lakes stock	0.6	197 ± 8, 200 ± 8 (Preto, *et al.*, 1971)
Voigt stock	2	181 ± 7, 194 ± 7 (Preto, *et al.*, 1971)
Copper Mountain stock: syenodiorite, syenogabbro, monzonite, and pegmatitic syenite-perthosite. Zoned, with inner zone of syenite-perthosite flanked to north, east, and south by successive shells of monzonite, then syenodiorite. Satellitic plutons to north include Armstrong Bluffs complex, monzonite-syenite; Smelter Lake stock, and Voigt stock, both syenodiorite. No modal feldspathoids, but analyses of rocks of all phases except syenite-perthosite show significant normative nepheline.		

TABLE 1--Continued

Name (and reference) Description	Area (sq. mi.)	Age (in m. y.) or age relations
Olalla pyroxenite (Bostock, 1940, 1941b)	2.9	Cuts Nicola (Triassic) and overlain by Springbrook (Eocene)
Pyroxenite, biotite pyroxenite, biotite-hornblende-augite gabbro, biotite-hornblende-augite monzonite. Zoned, with monzonite core.		
Rock Creek Chonolith (Daly, 1912)	7.6	K-Ar age of associated extrusive rock is Eocene
Barium anorthoclase-augite rhomb-porphyry. Intrusive phase of alkalic lavas of the lower part (Division 4A) of the Marron Formation of the Greenwood map area (Monger, 1968). Several smaller plutons of similar rock in vicinity.		
Marron Formation of White Lake Basin (Church, 1971)		51.6 K-Ar, biotite
Thick sequence of lava flows and pyroclastic deposits. Basal member (Yellow Lake member) composed of biotite- and pyroxene-feldspathic phonolite and mafic phonolite with primary analcite and rhomb-shaped anorthoclase-sanidine phenocrysts. Overlain by trachyte and trachyandesite of Kitley Lake Member. Succeeding members of the sequence are in general progressively less alkalic, with upper member composed of andesite. Overlain by rhyolite and rhyodacite of Marama Formation.		
Marron Formation of Greenwood map area (Monger, 1968)		49 ± 2, 48 ± 2 (Mathews, 1964, see Monger [1968] for interpretation)
Thick sequence of lava flows and pyroclastic deposits. Basal division 4A consists of sodic trachyte, in part transitional to phonolite. These rocks are overlain by andesite to trachyandesite, which are in turn overlain by andesite tending towards dacite.		

TABLE 1--Continued

Name (and reference) Description	Area (sq. mi.)	Age (in m. y.) or age relations
Oroville alkalic complex (this paper)	1.2	Cuts Kobau (Triassic?) and probably Ellemeham (Triassic or lower Jurassic) Trachyte at complex cuts Eocene epiclastic deposits.
Complex of brecciated, highly varied mafic alkalic rocks, chiefly shonkinite, malignite, foyaite, and monzonite. Fenitized border rocks. Cut by trachyte-trachyandesite plug. Probably an alkalic diatreme.		
Bimetallic Mountain alkalic complex (this paper)	0.4	Cuts Anarchist (Permian), and also rock provisionally referred to Ellemeham (Triassic or lower Jurassic). Overlain by epiclastic deposits of probable Eocene age.
Complex of brecciated mafic alkalic rocks, chiefly shonkinite and monzonite. Flanked by brecciated and fenitized wall rock on two sides. Probably an alkalic diatreme.		
Cumberland Mountain area (Pearson, 1967; this paper)	0.2 (Cumberland Mountain complex) and other smaller plutons	Some plutons cut the O'Brien Creek (Eocene), but not the overlying Sanpoil Volcanics (Eocene).
Small alkalic plutons within a 10 sq. mi. area are of three types: (1) hypabyssal intrusives composed of augite-biotite shonkinite; (2) alkalic intrusive breccia; (3) a complex (Cumberland Mountain complex) of foyaite, malignite, and pyroxenite (minor).		

TABLE 1--Continued

Name (and reference) Description	Area (sq. mi.)	Age (in m. y.) or age relations
Similkameen Batholith and Kruger alkalic complex (Daly, 1912; Campbell, 1939; this paper)	138 (121 of saturated rocks, 17 of alkalic rocks)	Cuts Kobau (Triassic?). Detritus found in Eocene epiclastic deposits nearby. 152, K-Ar hornblende (Cannon, 1966).
Batholith is composed of oversaturated or saturated rocks, mainly quartz monzonite, granodiorite, and monzonite. The Kruger complex is composed of undersaturated rocks, mainly malignite, biotite pyroxenite, and foyaite. The batholith is zoned, with central core of quartz monzonite, grading gradually outward to granodiorite, next monzonite, which in turn is flanked by a discontinuous peripheral zone of mafic, variably undersaturated rocks of the Kruger complex. Peridotite found at two localities adjacent to outer contact of the batholith.		
Shankers Bend alkalic complex (this paper)	0.35	Cuts Kobau (Triassic?) and Ellemeham (Triassic or lower Jurassic)
Complex of malignite, shonkinite, alkalic gneiss, and varied alkalic breccias. Country rock at contact locally brecciated, hornfelsed, and fenitized. Later dikes of brecciated feldspathic rock and carbonatite. Probably an alkalic diatreme.		
Copper Mountain alkalic complex (this paper)	0.15	Cuts Ellemeham (Triassic or lower Jurassic) and overlain by Eocene epiclastic deposits.
Complex of brecciated, highly varied mafic alkalic rocks, chiefly shonkinite, malignite, foyaite, and monzonite. Probably an alkalic diatreme.		

TABLE 1--Continued

Name (and reference) Description	Area (sq. mi.)	Age (in m. y.) or age relations
Shasket Creek pluton (Parker and Calkins, 1964)	1.2	Cuts limestone of Late Triassic age, and in turn is cut by Scatter Creek Formation of Eocene age.
Complexly intergrading monzonite, hornblende syenite, nepheline(?) syenite, and shonkinite.		
Franklin complex (Drysdale, 1915)	2.4	Believed to be Eocene based on lithologic similarity of associated lavas to Eocene rocks of the Greenwood map area.
Monzonite stocks, with associated porphyritic syenite and shonkinite-pyroxenite, the latter grading abruptly to augite syenite. Nearby lavas ranging from alkalic basalts to phonolitic trachytes are probably the extrusive phase of alkalic plutonism.		

serpentinized dunite, serpentinized peridotite, biotite pyroxenite, syenodiorite, syenogabbro, malignite, shonkinite, nepheline syenite, and monzonite. The alkalic rocks of north-central Washington, which are the main subject of this paper, are members of this group; (3) large and in places contiguous plutons composed chiefly of leucocratic quartz syenite, which together constitute the Coryell batholith of southeastern British Columbia.

The alpine-type ultramafics are widely distributed within the map-area. The eastern limit of their occurrence is roughly coincident with the boundary between the eugeosynclinal and miogeosynclinal provinces, and their age of emplacement probably ranges from Mississippian to Cretaceous (McKechnie, 1965). They are not characteristically found in association with alkalic rocks.

Most of the alkalic complexes are confined to two narrow, slightly diverging belts which trend about N65-70°W (Fig. 1 and PLATE I). The westernmost complex, and seemingly the point of divergence of the two belts, is the Tulameen ultramafic complex (Findlay, 1963). The Tulameen contains a core of dunite and periodotite located in the north-central part of the complex, which is flanked to the east, south, and west by biotite pyroxenite and syenogabbro. The complex was considered by Noble and Taylor (1960) to be a member of their "eastern" belt of ultramafic complexes, which extends from Alaska to California. The rocks of the Tulameen have higher K_2O content than their average counterparts of the peridotite-pyroxenite-gabbro clan, however, and are weakly undersaturated in silica. These features confer an alkalic character on the Tulameen rocks

(Findlay, 1963) apparently not possessed by the zoned ultramafics complexes correlated with the Tulameen by Noble and Taylor.

The Copper Mountain stock and the Olalla pyroxenite resemble the Tulameen in that they are zoned plutons composed partly of slightly undersaturated and K_2O enriched mafic and ultramafic rocks. They differ in that they contain more leucocratic differentiates, e.g., monzonite and syenite-perthosite, than are present at Tulameen, and in that the rocks of the inner zones are less mafic than those of the outer, contrary to the situation at Tulameen. The other alkalic complexes of the map area are also composed primarily of rocks weakly undersaturated in silica and enriched in K_2O, with conspicuous felsic, mafic, and ultramafic variants, some of which are sufficiently undersaturated in silica for feldspathoids to appear.

The Similkameen composite pluton is an exception in that alkalic rocks similar to those mentioned above are present only within a discontinuous outer zone. Quartz-bearing rocks are present inside the outer zone of alkalic rocks, and they constitute the bulk of the composite pluton.

The Coryell plutonic rocks include numerous plutons, both large and small, composed ". . . dominantly of syenite, but with some granite, shonkinite, and apparently related monzonite" (Little, 1960, p. 90) and aggregating 655 sq. mi. in area. Little considers the Coryell syenite to comprise a red phase and a pale buff phase, the red being composed mainly of orthoclase, microperthite, andesine, quartz, chloritized hornblende, and biotite, and the buff phase of orthoclase, microperthite, microcline, oligoclase, biotite, augite, and hornblende. Nepheline has not been detected but appears in the norm calculated from an analysis of a basic phase developed at a contact (Daly, 1912, p. 361).

There are clearly certain compositional similarities between the Coryell plutonic rocks and the alkalic rocks previously described, suggesting a genetic similarity as well. However, the propensity to include alkalic rocks of diverse type with the Coryell plutonic rocks, has perhaps obscured real differences that may exist between the two groups. Tentatively, however, certain of the smaller stocks considered part of the Coryell by Little have been classified on the map (PLATE I) as members of the ultramafic-alkalic group. These include the stocks near Ymir (Drysdale, 1917b, pp. 36-40; McAllister, 1951, p. 32-33; Mulligan, 1952, pp. 16-18); Stewart Creek (Mulligan, 1952, p. 17), Sheep Creek (Daly, 1912, pp. 304-306; Walker 1934, pp. 16-17), Tillicum Creek (Daly, 1912, pp. 356-357; Walker, 1934, p. 16), and Creggan Creek (Walker, 1934, p. 16) which are composed of monzonite, commonly grading to basic syenite.

Tertiary volcanic rocks

The Tertiary volcanic rocks and their hypabyssal intrusive equivalents include Miocene olivine basalt, and Eocene andesite, dacite, rhyodacite, phonolite, trachyandesite, and trachybasalt. The Eocene volcanic rocks are of particular interest because of their widespread distribution within the map-area (PLATE I), their highly differentiated character, and the presence within the series of potassic and subsilicic rocks.

The potassic and subsilicic lavas were first described by Daly (1912, p. 98), who found an analcitic lava and extrusive rhomb porphyry within a series of lavas he named the Midway Volcanic Group, cropping out along the International Boundary between Rock Creek and Midway. The series also included olivine basalt, augite andesite, hornblende-augite andesite, biotite-augite andesite, hornblende-augite-biotite andesite, biotite andesite, and trachyte. The rhomb porphyry resembles and is very probably an extrusive phase of the anorthoclase-augite (biotite) porphyry composing the Rock Creek chonolith (Table 1). The analcitic lava carries phenocrysts of anorthoclase and augite, which are set in a pale-brownish glass crowded with dodecahedral analcite crystals, feldspar microlites, and accessories.

The rocks of the Midway Group in the Greenwood map area were later correlated with Bostock's Marron Formation of the Okanogan Valley (Monger, 1968). Monger found that the analcitic and rhomb porphyry lavas were part of a basal unit up to 4000 ft. thick, consisting of sodic trachytes and phonolites, within a volcanic succession which became progressively more silicic and less alkali-rich higher in the section. Uppermost members are of andesitic composition, with silica contents up to 60 percent. B. N. Church (1971) found a similar progression at the type area of the Marron Formation at White Lake Basin in the Okanogan Valley. The basal member there is composed of biotite- and pyroxene-feldspar phonolite and mafic phonolite lavas and pyroclastic rocks. Many feeder dikes and lava flows contain primary analcite and anorthoclase-sanidine phenocrysts. This member is overlain by other members composed of trachyte and trachyandesite, which are in turn overlain by rhyolite and rhyodacite of the Marama Formation.

Eocene volcanic rocks similar to the upper part of the Marron Formation or to the Marama Formation and situated to the south had been described as porphyritic quartz latite and rhyodacite, with silica contents ranging up to 62-63 percent in the Curlew area (Parker and Calkins, 1964), increasing to 67 percent farther south in the Republic area (Muessig, 1967), leading Monger to postulate a gradual southward increase in silica content.

The silica content of the volcanic rocks of the Greenwood map-area is, in general, lower than that of other areas (Fig. 6). The alkali-lime index of the Greenwood rocks is undefined by the available analyses, and surprisingly, the alkali and CaO trends appear to diverge even at the low-silica end of the suite. These lavas are clearly alkalic. The silica range of the White Lake Basin rocks exceeds that of the other suites, and shows an alkali-lime index near the boundary between the alkalic-calcic and alkalic magma series. The alkali-lime index of the other two suites probably falls within the alkalic-calcic range.

In both the Greenwood area and the White Lake area, the lowermost (oldest) rocks of the Eocene sequence are alkalic, and these are overlain by a succession of generally more silicic rocks. Two conclusions are worthy of emphasis. First, although the lavas of the Eocene magmatic event are distributed throughout the region, the hypabyssal alkalic plutons, and to a lesser degree their extrusive

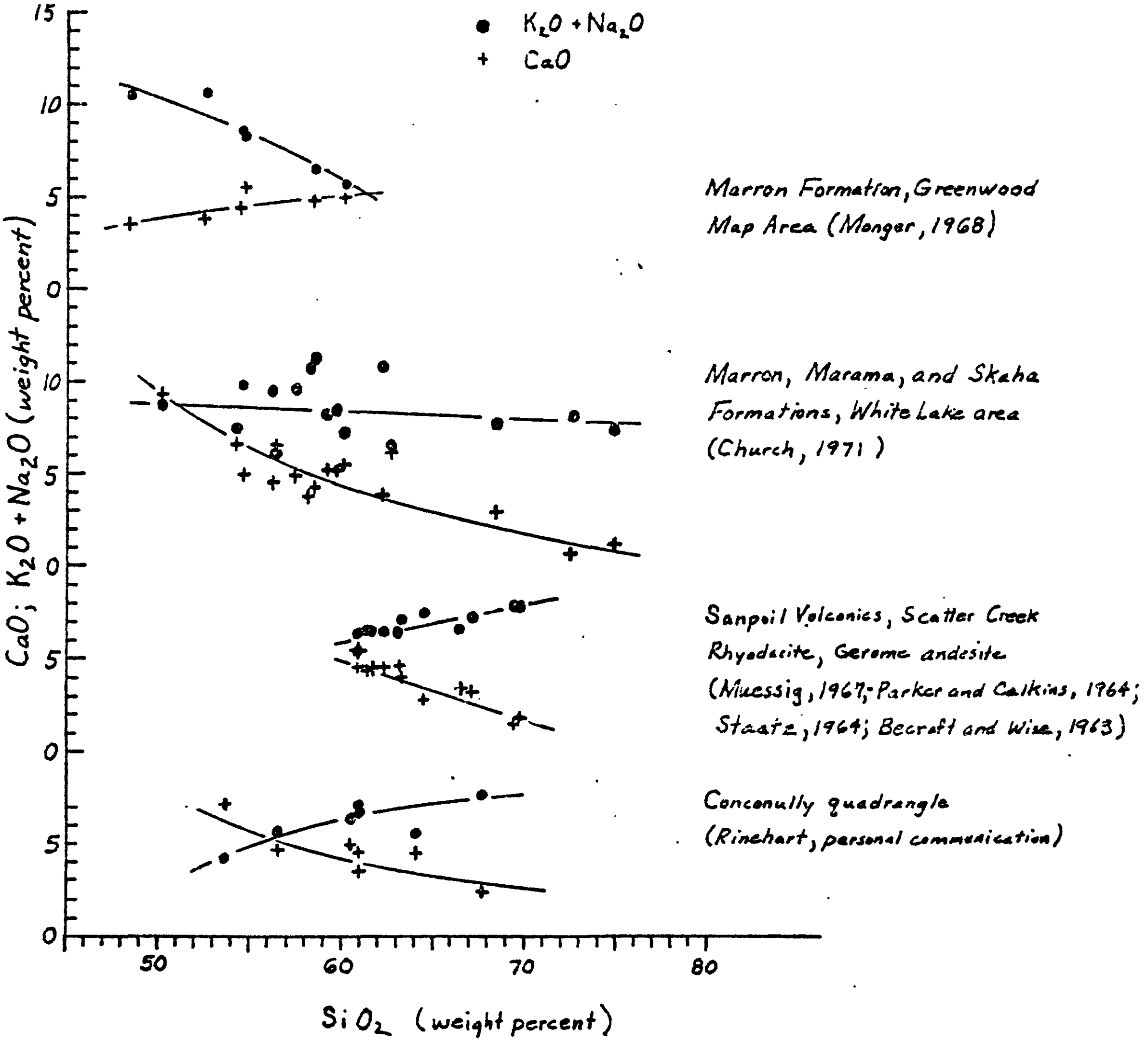

Fig. 6.--Variation diagrams showing the alkali-lime index of selected series of Eocene volcanic rocks of south-central British Columbia and northeastern Washington.

counterparts generated during this event, are chiefly restricted to areas on strike with, and east-southeast of the belts defined by the occurrence of Mesozoic alkalic rocks. Second, the alkalic magmas were extruded or emplaced at the onset of the Eocene magmatic event and were followed immediately by successive volumes of increasingly siliceous magma.

Age of plutonism

Plutonism in the eugeosynclinal province began in the Triassic and continued through the Miocene (Fig. 7). The Pb-Alpha and K-Ar hornblende dates show a 30 m.y. periodicity with maxima at about 175, 145, 115, 85, 50-55, and 25 m.y., a periodicity that was previously suggested by Gabrielse and Reesor (1964). Ages of Sierran plutonic rocks exhibit a periodicity approximately synchronous to that given above (Everndon and Kistler, 1970). Plutonism in the miogeosynclinal province probably was also episodic, with apparent maxima at about 135, 95-100, and 45-50 (Yates and Engels, 1968).

The ages of the alkalic rocks, although poorly known, appear to be roughly bimodal, with an older group with apparent ages of 175-195 m.y., and a younger group with apparent ages of about 50-60 m.y. The Tulameen-Cumberland Mountain belt of alkalic rocks apparently comprises 175-195 m.y.-old rocks along its western part, and 50-60 m.y.-old rocks along its eastern part. The Tulameen-Shasket Creek alkalic belt also includes members of both the 175 and 50 m.y. plutonic episodes with older on the west and younger on the east, although the absolute age of neither the Shasket Creek nor the Olalla is yet known.

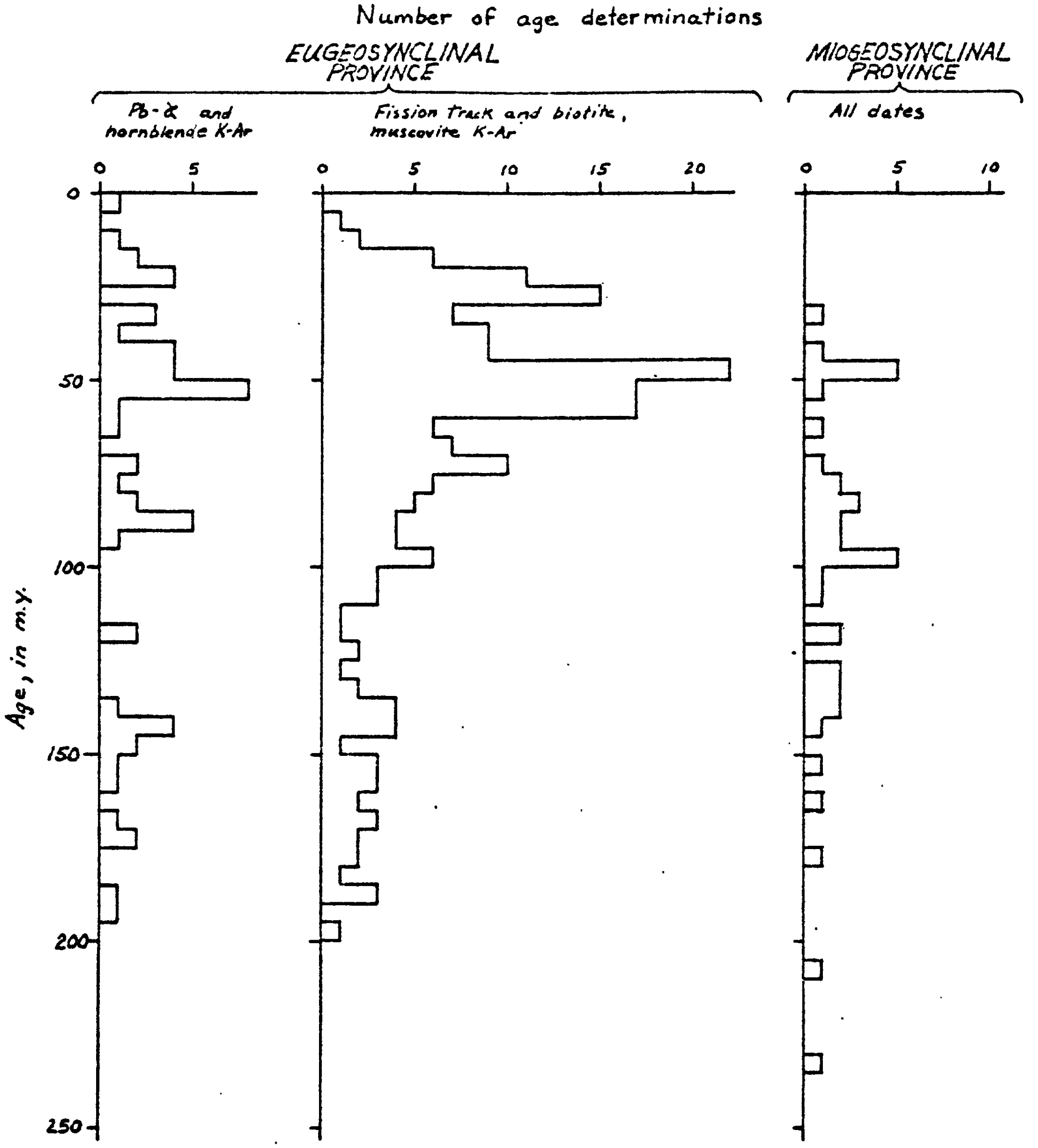

Fig. 7.--Histograms showing frequency distribution by age of 304 age determinations, from published and unpublished sources, of igneous rocks, both extrusive and intrusive, located between 48°-51° north latitude and 116°-127° west longitude (southern British Columbia and northern Washington and Idaho).

Discussion of Regional Geology

The alkalic rocks of the map-area (PLATE I) are predominantly rather femic, showing both potassium enrichment and modest undersaturation with respect to silica as compared to their more "normal" counterparts. Each of the major alkalic complexes or plutons, however, contains a varied assemblage of rocks which locally includes ultramafic and/or feldspathoidal varieties, and this diversity within an individual complex sets them apart from the calc-alkalic rocks quite as effectively as their alkalic character. Most of the alkalic rocks, exclusive of the Coryell plutonic rocks, are disposed along two slightly diverging belts cutting the Eugeosynclinal province with a trend of N 65-70° W.

The eugeosynclinal province differs from the miogeosynclinal province in many of its vital characters. Unlike the miogeosynclinal province, the eugeosynclinal province does not appear to be floored by sialic crust, judging by the apparent absence of exposed crystalline basement, the relatively youthful volcanogenic history, the widespread occurrence of alpine-type serpentinites, and the relatively primitive $Sr^{87/86}$ content of the plutonic rocks. The results of a recent study by Small (1971) of isotopic ratios of lead in ores lends additional weight to this hypothesis, for lead in deposits located within the eugeosynclinal province are of primitive character, whereas those from the miogeosyncline are not.

Two hypotheses have been offered to explain the juxtaposition of the eugeosynclinal province with its floor of oceanic crust against the miogeosynclinal province with its floor of sialic crust. These may be conveniently referred to as the accretionary hypothesis and the mobilist hypothesis. According to the accretionary hypothesis, the eugeosyncline represents the cumulative sum of material gradually accreted to the craton since Precambrian time, and the eugeosynclinal rocks depositionally onlap the miogeosyncline at their contact. Therefore the position of the eugeosynclinal province vis-a-vis the craton has been roughly fixed through the Mesozoic.

According to one version of the mobilist hypothesis, the eugeosyncline or a part of it represents one or more mini-continental slices of neocrust rafted eastward, finally colliding with and joining the craton along what was previously a west-dipping subduction zone at the eastern edge of the minicontinent, or alternatively, an east dipping subduction zone at the edge of the craton. Monger and Ross (1971) suggest that the distribution of Upper Paleozoic fusulinid assemblages could be explained by the joining of crustal segments as the intervening oceanic plate was consumed along subduction zones, or alternatively, by transposition of crustal segments along San Andreas-like right lateral faults. Their boundary between an "eastern" and "central" crustal segment is drawn approximately along what is herein referred to as the contact between the Columbian intermontane belt and the Omineca crystalline belt. The belts of alkalic rocks cross this lineament without deviation, however, as do numerous Mesozoic geologic contacts.

As has been mentioned, the alkalic rocks consist of an older group of rocks considered part of the 175 m.y. plutonic episode, and a younger group considered part of a 50 m.y. plutonic episode. Curiously, insofar as is currently known, the alkalic rocks of the 175 m.y. plutonic episode lie within the Columbian intermontane belt while the alkalic rocks of the 50 m.y. episode lie largely but not entirely within the Omineca crystalline belt.

DESCRIPTION OF THE ALKALIC ROCKS

The alkalic complexes that are the main topic of this paper are located partly or wholly in Washington, situated at intervals of 2 to 14 miles along the eastern 50-mile-long segment of the Tulameen-Cumberland Mountain belt. From west to east they are the Similkameen batholith and Kruger complex, the Shankers Bend complex, the Copper Mountain complex, the Oroville complex, the Bimetallic Mountain complex, and the Cumberland Mountain complex. The syenitic border of the Okanogan gneiss dome also lies within this segment of the belt, but it, unlike the aforementioned alkalic complexes, is probably a metasomatite rather than an intrusive rock.

Country rocks at all but the Cumberland Mountain complex are low-grade metavolcanics and metasediments of the Anarchist Group, the Kobau Formation, and the Ellemeham Formation, of probable Permian to Lower Jurassic age. Alkalic rocks in the vicinity of the Cumberland Mountain complex intrude rocks which are probably correlative with one or more of the listed units, and also cut rocks of the Eocene O'Brien Creek Formation (Pearson, 1967).

Similkameen Batholith and Kruger Alkalic Complex

The Simikameen batholith contains a core of quartz monzonite, which grades through granodiorite to a wide outer zone of monzonite. Malignite, shonkinite, nepheline syenite, and pyroxenite of the

Kruger alkalic complex discontinuously fringe the batholith.

The southeastern sector of the batholith and the Kruger rocks were mapped by Lounsbury (1951), and later by the author in collaboration with C. D. Rinehart (Fox and Rinehart, 1967; Rinehart and Fox, in press [a]). The northeastern, central, and western sectors were mapped by Daly (1912), the northeastern and southeastern sectors by Campbell (1939), and the southwestern by Hibbard (1971). That part of the map area (PLATE II) lying north of the International Boundary was mapped and very briefly described by Bostock (1940).

Topographic setting

The Similkameen River meanders southward through a broad, U-shaped alluviated valley carved across the batholith to which it has given its name. The river then hooks abruptly northeastward leaving its ancestral valley, which continues some distance to the south, and rushes through a steep, narrow canyon to its confluence with the Okanogan River some eight miles to the east. The western wall of the north-south part of the valley of the Similkameen River rises abruptly from elevations of about 1100 feet at the valley floor to a forested, mountainous, poorly accessible highland developed on the western two-thirds of the batholith, with summit elevations of 7000-7500 feet. The topographic surface over the eastern third of the batholith and the Kruger complex is a moderately rugged, lightly timbered grassland, with excellent access via a good primary and secondary road net. Rock exposure is reasonably good, notwithstanding a patchy cover of glacial drift.

Geologic setting

The batholith and the rocks of the Kruger complex intrude rocks of the Kobau Formation, a folded sequence of interlayered light- to bluish-gray metachert, greenish-gray metalava, and lustrous, green phyllite. Certain of the thicker and more extensive greenstone (metalava) bodies within the Kobau Formation, mapped as the Palmer Mountain Greenstone (Rinehart and Fox, in press [a]) or the Old Tom Formation (Bostock, 1940) are very probably ancient volcanic piles.

The Kobau Formation in the southeast corner of the map-area (PLATE II) is overlain along a profound angular unconformity by meta-conglomerates and metavolcanics of the Ellemeham Formation. The meta-conglomerates contain clasts of greenschist-grade metamorphic rock believed to have been derived from the Kobau Formation and from subjacent beds. The clasts are poorly bonded in a crumbly, brownish gray matrix which contains hornfelsic orange-brown biotite at localities nearest the Similkameen batholith, indicating that hornfelsing of the Ellemeham Formation may be attributable to thermal metamorphism by the Similkameen batholith.

Small bodies of serpentinized and metamorphosed peridotite are located at or near the periphery of the batholith. Although these ultramafic rocks are clearly older, a genetic relationship to the batholith and the rocks of the Kruger complex cannot be ruled out in view of the general association of ultramafic rocks with alkalic rocks at other localities in the region (see Table 1).

Massive Eocene conglomerate and thin-bedded wacke unconformably overlie the Ellemeham Formation in the southeast corner of the map-area.

The basal few tens of feet of the conglomerate is composed of bouldery detritus derived from the Kruger complex and the Similkameen batholith.

The above relationships establish the following chronology, from earliest to most recent: 1) Folding of Kobau Formation (probably during late Triassic orogeny; 2) erosion of Kobau Formation, deposition of Ellemeham Formation; 3) intrusion of Similkameen and Kruger rocks; 4) unroofing and erosion of Similkameen and Kruger rocks, deposition of Eocene clastics.

Kruger alkalic complex

Bostock (1940)described the batholith and the "Kruger Syenite" as a "concentrically zoned structure centered where the Similkameen River crosses the International Boundary." The "syenite" forms the outermost zone, and in areas east of the Similkameen River corresponds approximately to the "Kruger alkaline body" of Daly (1912) or the "Kruger alkaline syenite" of Campbell (1939). Bostock described the syenite as containing three zones, an exterior mafic zone about half a mile wide, bordered by an intermediate zone of dark, more feldspathic alkali syenite, which forms the main part of the Kruger Syenite, and which in turn is bordered by a coarser grained, more feldspathic inner zone about 1000 feet wide. The Kruger Syenite west of the Similkameen River is represented by rocks of the inner two zones. No more detailed account is available of that part of the alkalic rocks, or of the batholith, lying west of the Similkameen River and north of the International Boundary.

The Kruger rocks lying east of the Similkameen River and north of the International Boundary are reported by Daly (1912) as characterized by great lithological variability, with ten distinguishable varieties of malignite, nepheline syenite, and porphyritic syenite. Campbell (1939) later mapped the alkalic rocks as (1) malignite; (2) salic nepheline syenite; (3) femic nepheline syenite; and (4) porphyritic syenite. A fifth lithologic unit, pyroxenite, was mapped by Lounsbury (1951) and by Fox and Rinehart (1967) within the Kruger rocks south of the International Boundary.

The lithologic variations between and within map units are the result of variations in relative abundance rather than identity of the constituent minerals, which are roughly the same throughout the complex (Table 2). Essential minerals include microcline-perthite, albite, oligoclase-andesine, nepheline, augite, amphibole, biotite, and garnet. Accessories include apatite, sphene, zircon(?), magnetite, and illmenite. Secondary minerals include epidote, clinozoisite, chlorite, calcite, hydromica, muscovite, cancrinite, analcite, and other minerals of the zeolite group.

Chemical analyses and CIPW norms of the alkalic rocks are presented in Table 3. Chemical analyses of biotite from a sample of shonkinite and from a sample of biotite pyroxenite are presented in Table 4.

<u>Malignite-shonkinite</u>.--The malignite is a hard, dark-greenish-gray, fine-grained mafic rock commonly resembling a fine-grained gabbro. Judging from the modal analyses given by Daly (1912) and Campbell (1939) and listed in Table 2, the malignite north of the International

TABLE 2

MODES OF THE KRUGER ALKALIC COMPLEX
(in Volume Percent)

Sample	Number Points	Nepheline	Hydromica[1]	K-feldspar	Plagioclase	An of Plag.	Amphibole	Clino-pyroxene	Biotite	Garnet	Sphene	Apatite	Magnetite & Ilmenite	Calcite	Epidote Group	Sericite & Muscovite	Chlorite	Others	Specific Gravity
L-209A	1271			32.1	39.1	Alb.-Olig.			8.6	0.8	0.7	0.3	1.4	tr.	6.1	10.8		tr.	n.d.
L-223A	1421		0.8	26.5	26.3	Alb.-Olig.	4.5	0.6	18.5	10.1	tr.	1.5	1.6		2.3	7.2	tr.		2.81
L-223B	1352			25.9	35.4	Olig.	23.5	0.7	4.3	1.0	tr.	0.7	0.2		8.1			tr.	2.84
L-224A	1066			24.9	15.4	Olig.	31.5	6.7	0.7		0.4	1.7	1.9		16.9		tr.		3.04
L-224B	1356			31.0	41.5	Olig.			14.5	0.3	0.5	0.7	0.1		11.1	tr.		tr.	2.74
L-229A	1269			17.3	30.7	Olig.-And.	32.4	5.0	3.5	0.9	0.7	0.9	tr.	0.7	7.4	0.3	0.2		2.89
L-232A	1270			23.5	20.4	And.	42.2	11.0	0.3		0.4	1.3	tr.		0.7				n.d.
L-246C	1210			23.5	27.3	Alb.-Olig.	13.6	16.1	16.4			1.3	tr.	tr.	1.4	0.2	0.2		n.d.
L-249	1340						1.2	62.2	30.9		1.1	0.5	4.0						n.d.
L-256D	1464	1.9	4.2	42.4	32.0	15-20			8.0	2.5	1.0	0.4	tr.		4.2	1.8		1.5	n.d.
L-263B	1058			0.3	0.3	30	2.6	66.8	8.6		0.4	8.5	12.3		0.2				3.35
L-269A	1290			23.6	15.4	45	28.4	26.0	0.2		tr.	2.1	2.3		0.2			1.9	3.00
L-269B	1262			34.2	29.0	30-40	21.5	5.8	1.6		0.5	1.1	1.5		3.4	1.0	0.2	tr.	2.84
L-272A	1257			43.5	17.4	Olig.-And.	17.5	14.7	0.3		0.5	1.0	1.6		3.1	0.2	0.2	tr.	2.92
L-272C	1506			42.1	20.0	Olig.-And.	11.6	4.2	6.5	0.2	0.4	0.2	0.6		8.9	5.2	tr.	tr.	2.815
L-273BB	1296			48.8	21.9	15-20	15.8	10.1	0.3	0.4	0.3	0.7	0.8		0.7		0.1	tr.	2.82
L-275B	1279			38.3	24.6	Olig.	24.9	3.2	2.9	1.1	0.4	0.7	tr.	0.2	1.8	2.0	tr.	0.5	2.84
L-275C	1165			2.1	tr.		53.1	39.3	tr.		0.4	3.1	1.2	tr.	0.4				3.30
L-276A	1041				1.2	And.(?)		77.4	20.9			0.1						0.3	n.d.
L-276B	1051		0.1	18.4	0.4	Alb.	0.9	52.4	24.7	tr.		1.8	0.6		0.7				n.d.
L-277E	1369							71.8	13.0		0.1	3.6	11.6						3.41
L-277T	1201			3.4	21.0	Alb.-Olig.		35.7	35.2			2.2	tr.		2.4				n.d.
L-277Z	1021				1.6	Alb.	0.7	84.0	3.3		0.2	7.5	2.1	0.4	0.2				n.d.
L-301	1255	0.3	3.0	25.4	22.7	20-25	15.5	16.2	14.5		0.2	1.4	tr.	tr.				0.2	n.d.
L-504B	1257			25.6	26.7	Olig.	23.5	8.8	0.4		tr.	1.4	0.8		12.3	0.4		tr.	2.87
L-506A	1077			31.0	20.4	n.d.	26.5	7.7	1.2	0.1	0.7	0.7	1.7		9.8	tr.	0.2		2.88
L-507B	1199						19.1	61.2	10.3		0.5	3.1	5.6	tr.	0.2				3.42
L-508B	1042						30.6	57.0	1.8		0.7	2.8	6.4		0.7				3.34
L-569	1342	tr.?	tr.	26.9	18.1	35	30.2	18.2	0.8		tr.	1.9	1.6		0.6	0.7			n.d.
1100[2]		5.4		36.3				36.5	11.0	9.5		1.0	0.3[3]						2.849
1110[4]		15.1		63.9[5]					11.1	8.8	0.5	0.6							2.719
[6]		13		33	3	And.	16	34	1	2									n.d.
[7]		10		69	2	Alb.	8	5	2	2									n.d.
[8]		9		41			10	9	16	16									n.d.

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[1] Includes intergrowths of analcite plus clay minerals, analcite plus natrolite, and cancrinite (rare). Presumed to be secondary replacement of primary feldspathoids.

[2] Daly (p. 451, 1912).

[3] Includes titanite.

[4] Daly (p. 452, 1912).

[5] Includes albite.

[6] Campbell (p. 538, 1939), average of 8 Rosiwall counts.

[7] Campbell (p. 538, 1939), average of 6 Rosiwall counts.

[8] Campbell (p. 538, 1939), average of 5 Rosiwall counts.

TABLE 3

CHEMICAL ANALYSES AND CIPW NORMS OF ROCKS OF THE KRUGER ALKALIC COMPLEX[1]

	L-275C[2]	L-507B[2]	L-569[2]	L-301[2]	No.1100[3]	L-504B[2]	No.1110[3]	No.1109[3]	L-209A[2]
	Biotite pyroxenite		⟵	Malignite		→ Shonkinite	Femic nepheline syenite	Nepheline syenite	Syenite
				Chemical Analyses (weight percent)					
SiO_2 —	40.3	39.7	49.0	52.1	50.49	53.1	52.53	55.11	57.1
Al_2O_3 —	11.3	7.0	14.5	14.9	15.83	16.8	19.05	21.28	20.4
Fe_2O_3 —	7.3	10.2	4.7	2.5	6.11	4.7	4.77	2.64	3.5
FeO —	10.0	8.9	6.1	5.6	3.04	4.1	2.10	1.29	1.0
MgO —	7.7	9.5	4.7	5.5	3.38	3.0	1.99	.59	.9
CaO —	14.5	18.7	10.2	7.7	7.99	7.2	5.75	2.82	3.5
Na_2O —	2.0	.76	3.0	3.2	3.12	3.1	4.03	6.24	4.2
K_2O —	1.7	.80	4.1	5.7	6.86	5.3	7.30	8.36	7.5
H_2O- —	.13	.08	.15	.13	.29	.15	.13	.14	.10
H_2O+ —	.97	.72	.67	.87	1.20	.73	1.49	.58	.49
TiO_2 —	1.6	1.6	1.0	.65	.92	.80	.07	.48	.46
P_2O_5 —	1.5	1.6	.81	.67	.42	.63	.28	.27	.21
MnO —	.37	.34	.24	.18	.11	.20	.13	.08	.14
CO_2 —	.15	<.05	<.05	.08	.07	<.05	.27	.08	.21
Total	100.	100.	99.	100.	99.83	100.	100.17[4]	99.96	100.
				CIPW NORMS (weight percent)					
ne —	9.0	3.5	6.2	7.1	10.4	.1	11.7	21.0	3.6
or —	10.1		24.5	33.8	40.7	31.4	43.1	49.5	44.5
ab —	.4		14.1	14.2	7.3	26.2	12.4	14.1	29.0
an —	16.9	13.4	14.1	9.5	9.0	16.3	12.3	5.4	14.7
Lc —		3.7							
wo —	18.6	28.2	13.2	10.0	11.6	6.4	5.5	2.7	tr.
en —	11.4	20.5	8.2	6.1	8.5	4.4	4.7	1.5	tr.
fs —	6.2	5.1	4.3	3.3		1.6	tr.		
fo —	5.5	2.3	2.6	5.4		2.2	.2		1.6
fa —	3.3	.6	1.5	3.2		.9	tr.		
cs —		.5							
mt —	10.6	14.8	6.9	3.6	7.5	6.8	6.9	3.0	2.4
hm —					.9			.6	1.9
il —	3.1	3.0	1.9	1.2	1.8	1.5	.1	.9	.9
ap —	3.6	3.8	1.9	1.6	1.0	1.5	.7	.6	.5
cc —	.3			.2	.2		.6	.2	.5
Total	99.0	99.4	99.4	99.2	98.9	99.3	98.2	99.5	99.6

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[1] See PLATE II for locations of specimens, and Table 2 for modal analyses of specimens.

[2] From Rinehart and Fox (in press[a]). Rapid chemical analyses.

[3] From Daly (Pt. I, pp. 450-453, 1912).

[4] Analysis includes 0.09 percent BaO, and 0.19 percent SrO.

TABLE 4

CHEMICAL ANALYSES OF BIOTITES FROM ROCKS OF THE SIMILKAMEEN BATHOLITH AND KRUGER ALKALIC COMPLEX

	Kruger Alkalic Complex			Similkameen Batholith		
	L-277Z[1] Biotite Pyroxenite	L-301 Shonkinite		L-589B Quartz Monzonite		L-618[2] Granodiorite
		Chemical Analyses (weight percent)[3]				
SiO_2	37.1	36.4		37.3		40.8
Al_2O_3	15.2	15.6		14.2		13.1
Fe_2O_3	4.8	3.0		6.2		6.0
FeO	12.8	16.0		13.5		12.0
MgO	13.1	11.9		12.0		10.5
CaO	0.80	0.50		0.94		4.0
Na_2O	0.10	0.17		0.26		0.50
K_2O	8.5	9.1		8.4		5.7
H_2O-	--[4]	--[4]		0.52		--[4]
H_2O+	--[4]	3.6		3.7		2.8
TiO_2	2.2	1.8		1.8		1.6
P_2O_5	0.02	0.11		--[5]		0.28
MnO	0.15	0.23		0.62		0.81
F	--[5]	--[5]		0.49		--[5]
$(-)O{=}F_2$				(−)0.2		
Total	94.77	98.41		99.73		98.09
		Number of ions on the basis of 24(O,OH,F) per formula unit				
Si		5.59	8.00	5.64	8.00	
Al^{iv}		2.41		2.36		
Al^{vi}		0.41	5.77	0.16	5.55	
Ti		0.21		0.20		
Fe^{+3}		0.35		0.70		
Fe^{+2}		2.05		1.71		
Mn		0.03		0.08		
Mg		2.72		2.70		
Ca		0.08	1.91	0.15	1.85	
Na		0.05		0.08		
K		1.78		1.62		
F			3.69	0.23	3.96	
OH		3.69		3.73		
100(Fe/[Fe+Mg])	42.3	46.9		47.1		48.2
$Fe^{+3}/(Fe^{+2}+Fe^{+3})$	0.25	0.14		0.29		0.31

[1] Partial analysis.

[2] Impure biotite concentrate.

[3] Unpublished rapid chemical analysis of samples L-277Z, L-301, and L-618 by U.S. Geological Survey, Washington, D.C. analytical laboratories under the direction of Leonard Shapiro (personal communication, Tom G. Lovering, 1972). Chemical analysis of sample L-589B by U.S. Geological Survey, Menlo Park, Calif. analytical laboratories, Sarah Neil, analyst, W. W. Brannock, Project Leader.

[4] Insufficient sample.

[5] Not determined.

Boundary contains feldspathoids in excess of 10 percent and is properly classified as malignite, according to the classification used in this report, whereas rock south of the Boundary contains less than 10 percent and is therefore shonkinite rather than malignite. According to Campbell, the malignite comprises three main varieties: structureless; porphyritic-gneissic; and spotted.

The spotted malignite is the most distinctive, and also the most extensive of the three types found north of the International Boundary, although it is apparently not present to the south. In it sub-spherical or irregularly shaped light-gray "spots" commonly ranging from 0.2 to 1 cm in diameter are dispersed through a fine-grained matrix showing "salt and pepper" texture (Fig. 8). The proportion of spots to matrix varies; locally the spots are closely packed. They are composed of aggregates of microcline and either albite-muscovite or natrolite-hydromica pseudomorphs of nepheline. Campbell (1939) estimated the ratio of microcline to the pseudomorphs of nepheline at 5 to 1, and proposed that the spots were pseudoleucite. The outer borders of the aggregates are serrate, and the internal texture is either fine to medium grained and granoblastic, or shows the "finger print" intergrowths known to characterize pseudoleucite at other localities. The fingerprint texture is probably rare, since Campbell (1939) indicated that he had not observed it in the rocks he studied. The spotted malignite is locally gneissose, with the spots drawn out into ellipsoids lying in the plane of gneissosity.

The spotted malignite grades by decrease in the abundance of spots to unspotted or "structureless" malignite (Fig. 9), with which

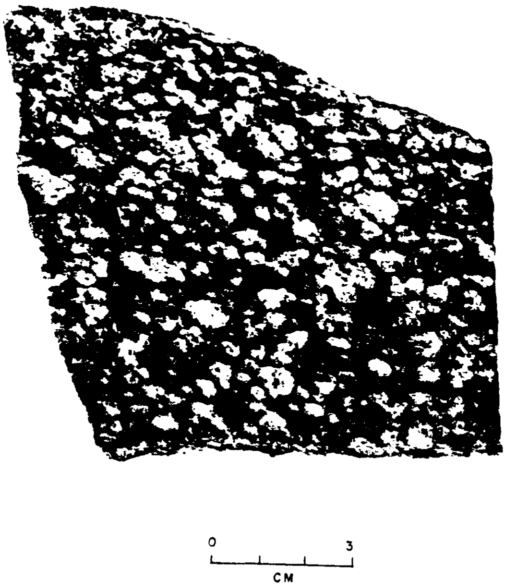

Fig. 8.--Photograph showing specimen of spotted malignite. White spots are probably pseudoleucite. They are composed of patchy intergrowths of anhedral K-feldspar and hydromica and are set in a dark-gray, fine-grained, xenomorphic gneissic matrix.

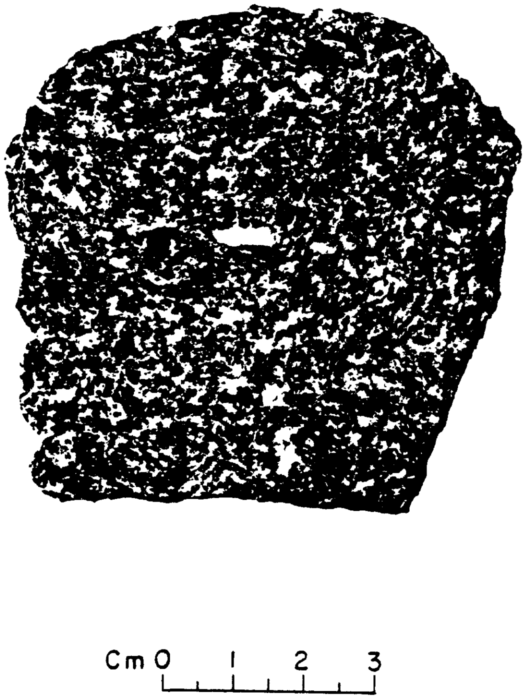

Fig. 9.--Photograph showing specimen L-301 (see Tables 2 and 3) of structureless shonkinite.

it is otherwise similar. The structureless malignite locally shows a weak primary gneissosity, and in places grades through appearance of subparallel tablet-shaped microcline phenocrysts to trachytoid malignite. Locally the microcline phenocrysts constitute a sufficiently large proportion of the rock, even being closely packed in places, to make the rock quite felsic relative to the nonporphyritic malignite. Campbell termed the trachytoid variants porphyritic-gneissic malignite, or porphyritic alkaline syenite depending on the relative proportion of phenocrysts and matrix.

Although the phenocrysts of the trachytoid malignite appear megascopically euhedral, they are microscopically ragged in outline. Their length is as great as 60 mm, although lengths of 15-20 mm are probably most typical. The trachytoid shonkinite south of the International Boundary is present within a transitional zone between structureless shonkinite and the monzonitic outer zone of the batholith, analogous to the situation described by Bostock (1940) north of the Boundary. Elsewhere dikes of trachytoid shonkinite cut both the structureless shonkinite and the pyroxenite (Fig. 10).

Microscopically the malignite and shonkinite are colorful and striking rocks, with lathy pale-green poikilitic augite mantled by intensely pleochroic, dark-bluish-green to light-yellowish-brown hastingsite, and riddled by similarly colored hastingsite and by green- or reddish-brown biotite. The strongly colored mafic minerals contrast vividly with the felsic minerals, which include blocky, anhedral, poikilitic microcline-perthite tablets, sparse, ragged laths of andesine showing relict zoning and rimmed with albite, and

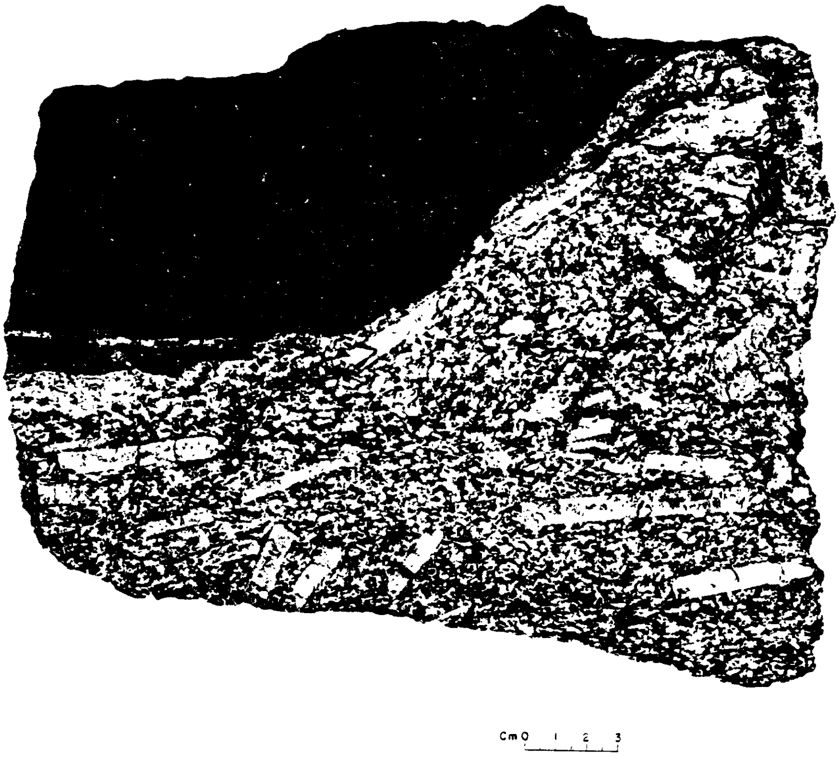

Fig. 10.--Photograph showing specimen of dike of trachytoid shonkinite cutting pyroxenite of the Kruger alkalic complex.

interstitial microcline, nepheline, hydromica, and zeolite minerals. In addition, patches of anhedral, amoeboid or skeletal grains of melanite garnet are commonly present, associated with clots of the other mafic minerals. Epidote and other secondary minerals are widespread.

The gneissic malignite and shonkinite are similar to the malignite and shonkinite described above, except that mafic minerals are segregated into ill-defined subparallel bands, to which prismatic or platy minerals such as biotite and microcline tend to be parallel.

The malignite and shonkinite are fine to medium grained, seemingly possessing a continuous range of grain size from very fine to 5 mm or larger. However, clinopyroxene grains typically average between 0.5 and 1 mm in diameter, about twice to four times the average diameter of the other constituents, excluding the pseudoleucite or microcline phenocrysts. Textures tend toward xenomorphic granular, with most intergrain contacts sutured or serriate.

The contact of the shonkinite with the Kobau quartzites and schists south of the Boundary is covered by drift, but judging by outcrop distribution, it is irregular and locally crosscuts bedding. Numerous inclusions of quartzite are present within the shonkinite near the contact.

Throughout much of its extent the shonkinite-pyroxenite contact is gradational. Along the southern border of the Kruger complex, the gradational zone is only 5-15 ft. in width. Within the gradational zone the pyroxenite acquires a gabbroic appearance through the addition of felsic minerals and becomes slightly gnessic, then somewhat porphyritic with the development of ragged lenticular microcline phenocrysts in the plane of gneissosity. The transitional zone between the pyroxenite and the shonkinite north of the Similkameen River is wider and more diffuse, and for this reason the location of the contact on a map is somewhat arbitrary. Small patches and zones of shonkinite can be found within the pyroxenite and vice versa.

Salic nepheline syenite.--The salic nepheline syenite is a light-gray to medium-gray, very fine- to fine-grained rock, which by the quantitative classification adopted here (Fig. 2), ranges in modal composition from a felsic shonkinite to juvite (Table 2). According to Campbell (1939) it is slightly foliated in most of its occurrences and decidedly so at some. It is quite foliated at localities south of the International Boundary, where it forms a thin, discontinuous zone between the wall rocks and the shonkinite. Foliation there is planar, with strike parallel to the contact with the Kobau, and dips of 65°-90° to the southeast.

Except for garnet, which can locally be distinguished with the aid of a hand lens, the salic nepheline syenite is too fine grained for megascopic identification of its constituent minerals. Microscopically the garnet is revealed as poikilitic, skeletal to amoeboid-shaped crystals of yellow-brown melanite, which average about 0.5 mm in diameter. Grain size of the other constituents is less, averaging about 0.15 to 0.30 mm. They include sodic oligoclase, microcline, and lesser amounts of biotite, epidote, calcite, and nepheline or its alteration products, cancrinite and analcite, along with accessory muscovite, apatite, sphene, and magnetite. Pleochroic light-olive brown to deep-bluish-green hastingsite and pale-green augite are locally present. Crystals of uralitic augite up to 0.8 mm across were observed in one specimen, and hastingsite of comparable size is present in places.

Texture is xenomorphic gneissic. The mafic minerals occur both as discrete grains and as lenticular aggregates. The aggregates, along with ill-defined bands of "mortar-texture" and subparallel prismatic minerals define the gneissosity. Spotted nepheline syenite analogous to the spotted malignite was observed by Campbell, but was not found south of the International Boundary in the present study.

South of the International Boundary the contact between the salic nepheline syenite and the rocks of the Kobau Formation lies within a covered interval several meters wide. Nearest the contact the Kobau Formation is a very fine-grained, very thinly laminated epidote-biotite-hornblende-labradorite schist, with foliation parallel to the contact. A few tens of meters away from the contact the metamorphic grade declines and the Kobau Formation is represented by interlayered sericitic quartzite (metachert) and dark-gray chloritic phyllite. No nepheline syenite dikes were observed cutting the Kobau Formation, although alaskitic and granitic dikes are abundant.

No inclusions of other rocks were observed in the salic nepheline syenite gneiss. The gneiss grades to the more mafic rock of the malignite-shonkinite unit by gradual coarsening, decreasing gneissosity, and increasing color index over an interval which locally is only a few meters wide. North of the Boundary, Campbell described a hybred zone 50 feet wide at the malignite-nepheline syenite contact, and he noted the presence of somewhat sharper contacts elsewhere.

Femic nepheline syenite.--According to Campbell (1939), the femic nepheline syenite is dark gray, fine-grained, and structureless, with a greenish cast on weathered surfaces due to the presence of epidote. This rock is present north of the Boundary as irregular masses and thin dikes sharply cutting both malignite and salic nepheline syenite. The modal composition of the femic nepheline syenite reported by Campbell (1939) is similar to but more felsic than his average malignite (Table 2), and could be classified as a (nephelinitic) shonkinite.

Pyroxenite.--The pyroxenite is heavy, massive, greenish black, and comprised chiefly of two variants, biotite-hastingsite pyroxenite, and hastingsite pyroxenite. Both are marked by extreme variation in grain size, which ranges over distances of a few meters from fine, almost aplitic, to very coarse, almost pegmatitic.

Two bodies of pyroxenite have been distinguished on the map (PLATE II) within the Kruger complex. The smaller lies near the southern periphery of the batholith, the larger in the east-central part of the Kruger complex. The pyroxenite at the latter area contains disseminated magnetite, and prospectors exploring for minable concentrations have opened numerous sidehill cuts and trenches, affording good exposure. The pyroxenite is disaggregated into a sandy grus at the surface over much of its extent, but at shallow depth the rock is hard and fresh.

The hastingsite pyroxenite is composed of closely packed, anhedral to subhedral smoky-gray or slightly pleochroic, pale-yellowish-brown to pale-bluish-green poikilitic augite, with interstitial hastingsite, euhedral apatite, magnetite, subhedral sphene, and rarely microcline and andesine. Hastingsite and apatite form inclusions in the augite. Traces of biotite, calcite, and epidote are sometimes present. The hastingsite is strongly pleochroic from light yellowish brown to dark green, and in some areas is present in scattered clots containing interstitial felsic minerals and secondary biotite. The biotite-hastingsite pyroxenite is similar to that described above, except that it contains sparsely scattered equant books of black biotite 2 to 3 mm in diameter, or more rarely, thin, randomly oriented biotite plates up to 15 mm across. In places the pyroxenite contains as much as 50 percent biotite.

Pyroxenite within an unmapped zone located within the malignite about 750 meters west of the mapped pyroxenite-malignite contact differs from the normal hastingsite pyroxenite in that the uralitic development of hastingsite after augite is much further advanced. In one specimen (L-275C) the hastingsite accounts for over half of the modal composition (Table 2). The accompanying pyroxene is strongly zoned and rudely interlayered with the hastingsite.

The microscopic texture of the pyroxenite is xenomorphic granular, tending to hypautomorphic granular.

The contact of the pyroxenite with the country rocks of the

Kobau south of the Boundary and north of the Similkameen River is sharp. There, thin, semi-concordant pyroxenite veins and tongues penetrate along foliation of the enclosing schist and the interlayered thin-laminated to laminated quartzite. The foliation is considerably crumpled along and near the contact. The pyroxenite contains inclusions of metamorphic rocks similar to the enclosing Kobau, and also inclusions of granitic rock.

The pyroxenite is in turn cut by numerous dikes of varied habit and composition, chiefly of shonkinite, trachytoid shonkinite, lamprophyre, alaskite, or pegmatitic muscovite syenite. The pegmatitic muscovite syenite dikes are abundant at locality L-277 (PLATE II). They are up to half a foot thick, and composed of intergrading fine-grained syenite and syenitic pegmatitic. In one dike the fine-grained syenite forms marginal layers one-half to one inch thick, which grades inward to a medial layer of pegmatitic syenite about four inches thick. In another dike, the pegmatitic syenitic predominates but grades to isolated patches of fine-grained syenite. Texture of the fine-grained phase is xenomorphic granular. Both the fine-grained and pegmatitic phases are composed chiefly of microcline, plagioclase, and muscovite. In one ten-pound sample the microcline ranged from Or_{78-93}, and the plagioclase from An_{7-12}, based on determination of their refractive indices (to ± 0.001).

At distances of a quarter of a mile or more from the contact with the pyroxenite and the nearby shonkinite the Kobau Formation consists of greenish-gray chloritic phyllite and interlayered very fine-grained quartzite (metachert). Towards the contact the greenish hue of the phyllite changes to leaden gray, foliation becomes pronounced, and foliation planes glisten with very fine-grained biotite. The metachert coarsens to sugary impure quartzite. Some of the more mafic interlaminae are marked by sparsely scattered brown, anhedral spots about 2 mm across. The spots are aggregates of equant, subhedral hypersthene, calcic andesine, fibrous anthophyllite, and biotite, and are set in a hornfelsic matrix of similar but finer grained minerals, along with green spinel.

Similkameen batholith

The batholith consists chiefly of light-gray, medium- to coarse-grained granitoid rocks, which possess an intermediate color index and are saturated or oversaturated in silica, thereby differing from the more mafic, undersaturated rocks of the Kruger complex. The granitoid rocks have been mapped as a single unit encompassing quartz monzonite, granodiorite, and monzonite, which intergrade so gradually that their demarcation in the field was not feasible, notwithstanding their wide compositional range. They are sharply cut by dikes and small plutons of alaskite, which are particularly abundant along the southeastern margin of the batholith. Pegmatite dikes are very rare; those observed are associated with the alaskite.

Modal analyses are presented in Table 5, partial modal analyses in Table 6, and chemical analyses in Table 7.

Quartz-monzonite, granodiorite, monzonite.--The quartz monzonite and granodiorite are typically fresh, massive, and porphyritic, with light-gray, poikilitic, tabular microcline perthite phenocrysts

TABLE 5

MODES OF THE SIMILKAMEEN BATHOLITH
(in Volume Percent)

Sample	Number Points[1]		Quartz	K-feldspar	Plagioclase	An of Plag.	Hornblende	Biotite	Clino-pyroxene	Magnetite & Ilmenite	Apatite	Sphene	Zircon	Epidote Group	Chlorite	Sericite	Tourmaline	Garnet	Calcite	Allanite	Pumpellyite	Other	Specific Gravity
	Slab	Section																					
L-218A	1229	1159	32.6	32.1	32.1	Alb.-Olig.				tr.		tr.		1.8	0.3	1.0						tr.	n.d.
L-218C	1078	1450	7.5	26.8	41.6	Olig.	18.0	0.7	tr.	1.2	0.5	0.6	0.2	2.5	0.2	0.1							2.78
L-221B	959	1460	21.8	35.7	37.5	Olig.		1.1		tr.	tr.	tr.	tr.	2.4	0.3	0.9							2.63
L-232B	1520	1507		28.0	51.8	And.	10.6	2.0	0.4	1.0	0.7	1.0		4.4	tr.								2.74
L-233	1743	~1500		34.5	53.7	20-25	7.1	0.2	1.0	1.1	0.4	0.6		1.3									2.69
L-235A	1506	1140	8.2	28.4	35.8	20	19.3	0.4		0.7	1.5	0.4		3.7	1.1	tr.	tr.	tr.				0.2	2.75
L-267	1284	~1500	11.8	18.2	49.4	30-35	12.3	1.9		1.2	0.4	0.7		3.2	0.9					tr.			2.76
L-269C		1278		31.8	55.6	35	0.4		8.5	1.3	0.5	0.8		1.1									n.d.
L-270	1721	1518	4.4	17.0	55.0	30-35	12.4	2.9	tr.	1.2	0.4	1.0	tr.	5.5						0.2			2.79
L-279	1368	1391	22.0	20.0	45.3	35-45	1.2	6.8		0.6	0.2	0.2		3.2	0.5	tr.							2.69
L-281	1377	1392	21.7	20.0	46.2	20-33	3.3	2.9		0.3	0.2	0.9		4.0	0.4				tr.	tr.			2.705
L-283	1599	~1450	12.3	21.9	48.1	20-35	9.5	3.0		1.3	0.4	0.5		3.1			tr.			tr.			2.74
L-286	1294	~1400	11.4	14.1	52.5	Olig.-And.	7.7	7.7		0.8	0.6	0.9		3.7	0.6	tr.	tr.		tr.				2.76
L-289C	1339	~1400	11.0	24.5	43.4	Olig.-And.	8.3	5.4		0.9	0.2	0.6		5.4	0.2	tr.	tr.						2.74
L-376B	1369	~1200	23.4	19.4	48.8	20-33	3.5	3.1		0.5	tr.	0.4		0.9	tr.	tr.	tr.?						2.69
L-377A	1387	~1460	12.3	21.9	48.8	35	10.8	2.0		1.0	0.2	0.7		1.5	0.6	tr.	tr.						2.74
L-442	2553	~1200	6.9	21.8	47.6	22-33	12.8	0.6	tr.	0.9	0.6	0.9		7.6	tr.		tr.	tr.					2.85
L-504A		1392		38.3	44.4	Olig.	10.3	0.4	tr.	1.4	0.6	0.6		4.1									2.72
L-589C	1390	~1200	20.3	23.8	40.8	25-35	3.6	5.8		0.6	0.2	0.4	tr.	4.3		tr.	tr.?				tr.(?)		2.71
L-618	1327	~1450	17.5	22.1	45.0	30-35	5.0	5.9		0.6	0.3	0.3		3.3			tr.				tr.		2.71
No.1355[2]			22.0	33.7	29.8	Olig.	4.2	5.5		1.8	0.8	1.1		1.1									2.693
No.1107[3]			0.4	40.1	23.4	Olig.	22.8		9.0	1.8	1.3	1.1	0.1										2.819

[1] Quartz, K-feldspar, and plagioclase determined by point-count of stained slab. Remaining minerals prorated according to ratio determined from point-count of thin section, except L-269C, L-504A.

[2] Daly (p. 456, 1912).

[3] Daly (p. 458, 1912).

TABLE 6

PARTIAL MODES[1] OF THE SIMILKAMEEN BATHOLITH
(in Volume Percent)

Sample	Number Points	Quartz	K-feld-spar	Plagio-clase	Color Index	Specific Gravity
L-217	1920	11.0	18.0	50.2	20.8	2.77
L-218B	1394	0	38.3	43.7	17.9	2.72
L-225	1804	9.0	25.8	48.9	16.2	2.73
L-234	1111	8.8	25.0	39.0	27.2	2.75
L-235B	1630	9.3	29.6	37.6	23.5	2.74
L-263K	1127	10.8	25.8	46.8	16.6	2.73
L-264	999	18.4	24.1	42.5	14.9	2.715
L-265	1619	12.1	22.8	47.2	18.0	2.71
L-266	1619	12.9	15.8	48.6	22.9	2.76
L-268	1361	13.4	27.0	40.8	18.7	2.725
L-271	1742	0	32.8	51.2	15.9	2.70
L-273A	1115	0	31.9	49.0	19.1	2.73
L-278A	1643	22.6	18.7	46.4	12.2	2.68
L-278B	1506	20.9	21.7	46.2	11.2	2.69
L-280	1138	23.1	11.1	51.4	14.4	2.71
L-284	1290	18.6	22.6	45.2	13.6	2.71
L-285A	1195	19.8	23.7	43.1	13.4	2.71
L-287	1494	18.7	24.8	41.9	14.6	2.70
L-302	1425	18.3	23.7	40.5	17.5	2.72
L-303	1623	20.1	21.9	43.7	14.3	2.69
L-376A	1361	21.9	22.3	47.0	8.8	2.69
L-376C	1302	20.1	23.1	47.5	9.2	2.69
L-390	999	16.2	26.4	43.0	14.4	2.73
L-392	1234	16.1	19.8	49.5	14.6	2.72
L-592C	1401	12.1	18.7	47.0	22.2	2.76

[1] Determined from point-count of stained slab.

TABLE 7

CHEMICAL ANALYSES AND CIPW NORMS OF ROCKS OF THE SIMILKAMEEN BATHOLITH[1]

	L-233[2]	L-235A[2]	L-281[2]	L-283[2]	L-376B[2]	L-442[2]	L-589C[2]	L-618[2]	No.1355[3]	No.1107[3]
					Chemical Analyses (weight percent)					
SiO_2	60.0	60.4	66.2	62.2	67.8	56.3	65.5	65.2	66.55	54.06
Al_2O_3	19.1	15.9	16.1	17.1	16.2	15.9	16.1	16.7	16.21	18.75
Fe_2O_3	2.0	2.7	1.9	2.5	1.5	4.3	2.1	2.4	1.98	4.64
FeO	2.0	3.3	1.7	2.6	1.6	4.4	1.8	1.7	1.80	3.10
MgO	1.5	2.5	1.1	1.9	.9	3.1	1.4	1.4	1.32	2.75
CaO	3.9	4.9	3.9	5.0	3.4	6.9	4.0	4.1	3.86	7.35
Na_2O	5.7	3.7	3.9	4.0	4.0	3.4	3.9	3.9	4.07	4.60
K_2O	4.5	4.5	3.6	3.4	3.5	3.0	3.5	3.1	2.84	3.00
H_2O-	.08	.19	.11	.10	.11	.16	.04	.05	.01	.10
H_2O+	.34	.60	.60	.32	.41	.71	.64	.52	.24	.41
TiO_2	.47	.63	.37	.51	.32	.90	.38	.42	.40	.80
P_2O_5	.19	.38	.18	.29	.15	.52	.19	.18	.15	.55
MnO	.12	.14	.13	.13	.10	.22	.12	.13	.12	tr.
CO_2	<.05	<.05	.06	<.05	<.05	<.05	.05	<.05		.11
Total	100.	100.	100.	100.	100.	100.	100.	100.	99.59[4]	100.22
					CIPW Norms (weight percent)					
Q		8.9	20.4	13.2	22.3	8.1	19.4	20.1	21.8	
C					tr.					
or	26.6	26.7	21.3	20.1	20.7	17.8	20.7	18.4	16.9	17.7
ab	48.3	31.4	33.1	33.9	33.9	28.9	33.1	33.1	34.6	38.9
an	13.3	13.5	15.8	18.7	15.9	19.3	16.1	19.0	17.6	21.6
wo	2.0	3.5	.8	1.8		4.8	.9	.1	.3	4.4
en	3.6	6.3	2.7	4.7	2.2	7.7	3.5	3.5	3.3	6.4
fs	1.4	3.1	1.2	2.1	1.4	3.5	1.2	.7	1.2	.5
fo	.1									.3
fa	tr.									tr.
mt	2.9	3.9	2.8	3.6	2.2	6.3	3.1	3.5	2.9	6.7
il	.9	1.2	.7	1.0	.6	1.7	.7	.8	.8	1.5
ap	.5	.9	.4	.7	.4	1.2	.5	.4	.4	1.3
cc			.1				.1			.3
Total	99.6	99.4	99.3	99.8	99.6	99.3	99.3	99.6	99.8	99.6

[1] See PLATE II for locations of specimens, and Table 5 for modal analyses of specimens.

[2] From Rinehart and Fox (in press [a]). Rapid chemical analyses.

[3] From Daly (Pt. I, pp. 456-457, 1912).

[4] Analysis includes 0.01 percent SrO, and 0.03 percent BaO.

sparsely scattered through a medium-grained matrix (Fig. 11). The matrix contains prominent crystals of hornblende and biotite, whose black color contrasts with the chalky white of the plagioclase and microcline, and the oily gray of the quartz. Small, but conspicuous, amber-colored euhedra of sphene are ubiquitous. A hint of foliation is locally present, but is seldom well enough developed to permit determination of attitude.

The microcline phenocrysts are up to 17 mm long, but typically are about 5-7 mm long. They contain abundant inclusions of plagioclase and sparse inclusions of hornblende, biotite, and quartz, which locally are rudely concentrated in zones parallel to the exterior of the phenocryst. Although the phenocrysts are roughly tabular, their edges are sutured or interlocked with other minerals. The phenocrysts are set in a hypautomorphic granular matrix of plagioclase, hornblende, biotite, and quartz. Quartz is anhedral and commonly undulatory. Plagioclase is lathy and subhedral, and commonly zoned from An_{20}-An_{35}. Hornblende and biotite are tabular and subhedral to anhedral, and commonly partially replaced by chlorite and epidote. Accessories include sphene, magnetite, ilmenite, apatite, and zircon. Secondary tourmaline was noted in many specimens.

The abundance of microcline phenocrysts is variable, and in certain areas, particularly near the central part of the batholith, the rock is essentially nonporphyritic. Except for the near absence of phenocrysts, the nonporphyritic phase is petrographically similar to the porphyritic.

Traces of myrmekite (oligoclase grains with vermicular

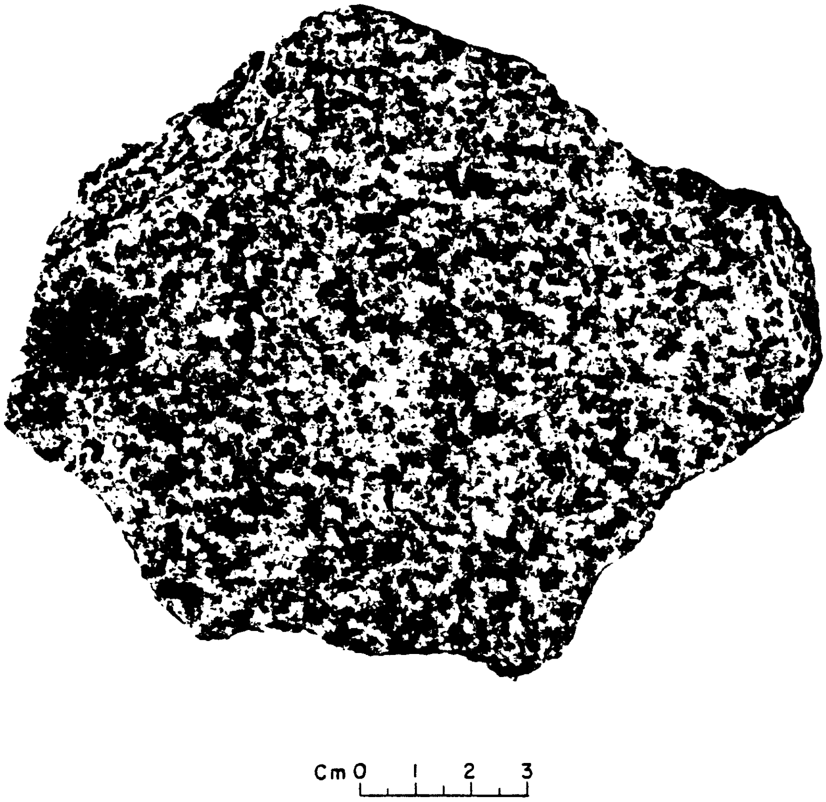

Fig. 11.--Photograph showing specimen L-589C (see Tables 4 and 6) of granodiorite of the Similkameen batholith.

intergrowth of optically continuous quartz) are apparently present throughout the quartz monzonite and granodiorite. The myrmekite forms small intergranular patches at quartz-plagioclase-microcline junctions or narrow selvages at plagioclase-microcline contacts.

The gradation of the quartz monzonite and granodiorite to monzonite is accompanied by an increasing development of the foliation, a transition from hypautomorphic granular to xenomorphic granular texture, an increasing color index, and a generally increasing abundance of microcline phenocrysts. However, the monzonite, like the more quartz-rich rocks, is not uniformly porphyritic, and instead grades unpredictably to local areas almost devoid of phenocrysts.

Plagioclase in the monzonite is partially saussuritized, with relict zoning from An_{20-33}, and has margins of clear albite. In shape it retains only a hint of the subhedral form prevalent in the quartz monzonite and granodiorite. The plagioclase and mafic minerals, which include hornblende, biotite, and clinopyroxene, are seemingly self-supporting or loosely floating in a matrix of perthitic microcline or perthitic microcline and subordinate quartz. The clinopyroxene is generally a minor constituent, present only as relict cores within hornblende grains, but in some areas accounts for as much as 10 percent of the mode. In addition to the microcline phenocrysts, which are similar to those of the granodiorite and quartz monzonite, microcline is present in the groundmass, and as narrow vienlets cutting all other grains. Accessory minerals include garnet in addition to those accessories also present in the granodiorite and quartz monzonite.

Intergrain contacts in the monzonite are commonly slightly mortared. The foliation, although irregular is grossly parallel to the exterior contact of the batholith, and is defined by subparallel phenocrysts and indistinct trains of mafic minerals. The foliation probably is a primary flowage feature rather than a result of cataclasis, although effects of post-consolidation cataclasis are somewhat more pronounced in the monzonite than in the granodiorite and quartz-monzonite.

Alteration is also more evident in the monzonite than in the quartz monzonite or granodiorite. Epidote, clinozoisite, and chlorite are commonly intergrown with the mafic minerals, and the central parts of plagioclase grains are flecked with sericite and saussurite. An actinolitic amphibole, weakly pleochroic, is secondarily developed from pyroxene or the more strongly pleochroic primary hornblende.

Both the monzonite, which is the outermost lithologic zone of the Similkameen batholith, and the enclosing malignite-shonkinite of the Kruger complex are highly variable over short distances. Near their contact the monzonite is typically trachytoid with tabular subparallel microcline phenocrysts and laminae rich in mafic minerals combining to produce a distinct gneissosity, which along with the long dimension of inclusions is oriented parallel to the contact. This rock grades over a few tens of feet by increase in color index to shonkinite. The trachytoid texture is common in local patches in the malignite-shonkinite as well as the monzonite. The contact with the malignite west of the Kaaba Texas Mine (PLATE II) is quite different. There the monzonite is an intrusion breccia (Wright and Bowes, 1963), containing angular to oval fragments of shonkinite and country rock, the latter presumably metamorphosed rock of the Kobau Formation, in various stages of assimilation, and closely packed in a monzonitic matrix.

The Kobau Formation along the southern contact of the batholith and west of the point where the alkalic rocks of the Kruger complex wedge out is composed of thick, massive to thin-bedded metachert and interlayered greenstone, locally containing thin lenses of metalimestone. Within a zone adjacent to the contact and up to half a mile wide, the rocks of the Kobau Formation are schistose and some are distinctly gneissic. The gneissic rocks are layered on a microscopic scale, exhibiting granoblastic textures within the layers. Typical mineral assemblages include the following:

Calcareous rocks: wollastonite, garnet, calcite

Mafic schist and gneiss: andesine-labradorite,
hornblende, diopside, clinozoisite-epidote,
garnet, (K-feldspar, biotite).

Alaskite.--Numerous dikes and small, irregularly shaped masses of fine- to medium-grained, light yellowish- to light pinkish-gray alaskite cut rocks of the batholith, the Kruger complex, and adjacent Kobau Formation. The alaskite is particularly abundant near the periphery of the batholith, where the shonkinite and contiguous monzonite are locally criss-crossed by anastomosing or bifurcating alaskite dikes and veinlets. Most dikes are not more than half a foot thick, but they are locally so closely spaced that in some zones several hundred feet across the volume of alaskite probably equals or exceeds the volume of country rock.

The alaskite is composed mainly of oligoclase, microcline, and quartz. Other minerals present in trace or accessory amounts include muscovite or biotite, and sphene, magnetite, zircon, and apatite, locally garnet, and in addition secondary epidote and chlorite. Texture of the alaskite is hypautomorphic granular tending to xenomorphic granular.

The southern boundary of the alaskite mass at the southeastern margin of the batholith (PLATE II) apparently conforms to the contact between the salic nepheline syenite and rocks of the Kobau Formation. The alaskite is separated from the salic nepheline syenite by an intervening 10 ft.-thick zone of fine-grained shonkinite at the one locality found with continuous exposure across the contacts. The northern contact of this alaskite is extremely irregular. There the alaskite grades to an intrusive breccia, which is charged with angular pebble- to cobble-size fragments of massive shonkinite, trachytoid shonkinite, and gneissic shonkinite, and fingers irregularly out into the wall rock.

Alteration zone.--The rocks of the batholith and the Kruger complex, although outwardly fresh, have almost everywhere been mildly but pervasively altered. The petrographic character of this alteration has been briefly noted in the description of the various rock units, and need not be repeated here. The rocks of both units are also criss-crossed with a multitude of joints, which are commonly coated with a film of epidote or chlorite. Pervasive alteration of the rock is no more severe near the joint surfaces than away, except for the rocks within an area of perhaps half a sq. mi., centered on American Butte (PLATE II). There micaceous rinds of altered rock have developed along closely spaced joints. The micaceous rinds attain thicknesses of several inches, and at their extreme development in the interior of the altered zone constitute over half of the volume of the rock.

The altered zone is riddled with small pods and veinlets of quartz, and joint surfaces locally are studded with crystals up to 2 inches across of pyrite and also of similarly sized aggregates of chlorite, the latter possibly pseudomorphing an earlier mineral. The altered rock is a medium-grained xenomorphic granular aggregate of muscovite, quartz, and albite, with subordinate chlorite and calcite, relic biotite and amphibole, and minor to accessory leucoxene, epidote, zoisite, magnetite, sphene, and apatite.

Modal composition.--The modal composition of the 48 specimens (Tables 4 and 5) representing the southeastern 20 percent of the area of the batholith shows a scattered distribution centered near the division between the granodiorite and quartz monzonite fields of the quartz- K-feldspar - plagioclase triangular diagram (Fig. 3) at about 20 percent quartz, and trailing away to the zero percent quartz side.

The distribution of modes on the (K-feldspar + plagioclase)-quartz-mafic section (Fig. 12) shows a somewhat tighter clustering of the bulk of the points along a linear trend. This arrangement, considered in conjunction with the shotgun distribution of projected

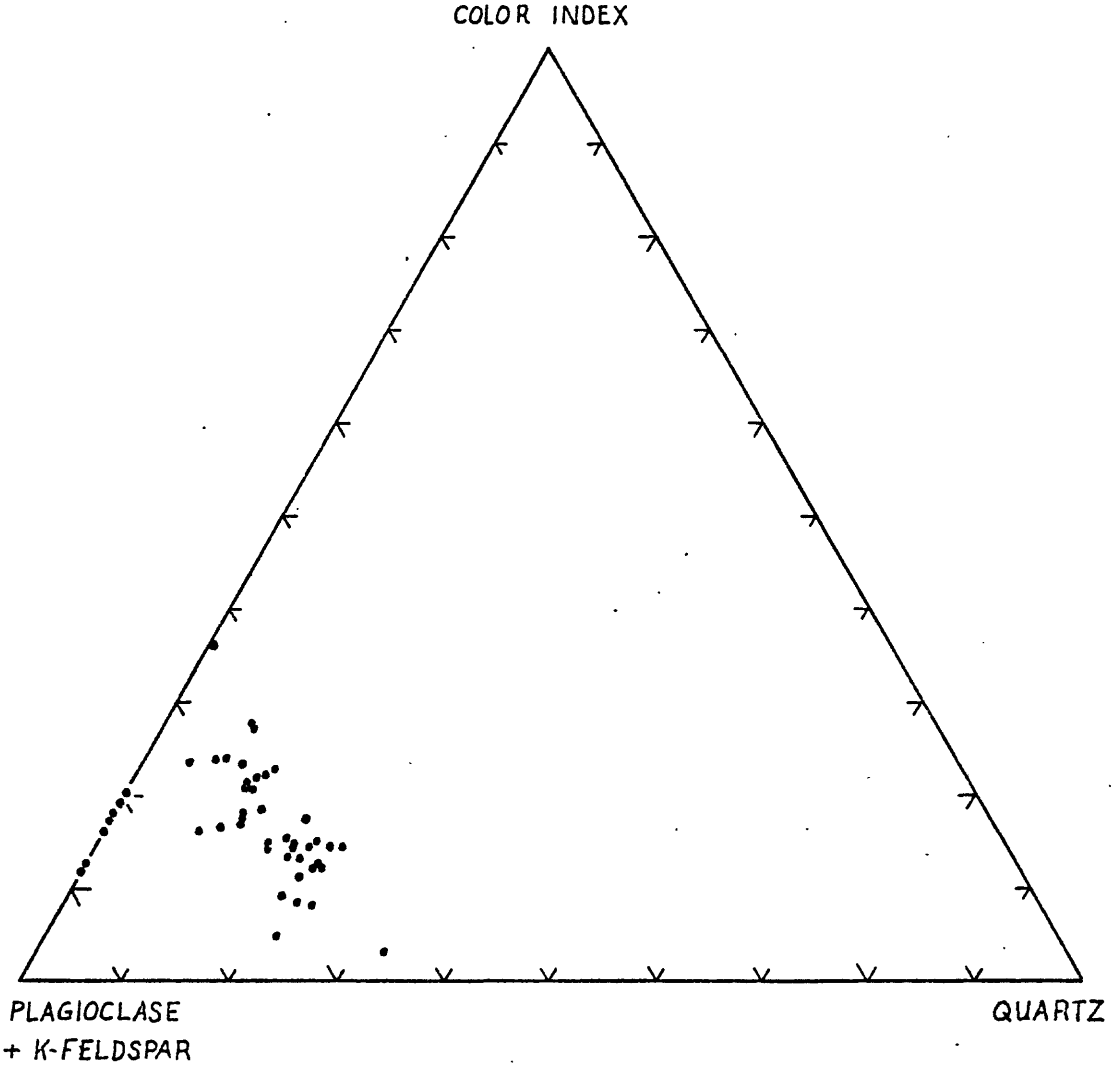

Fig. 12.--Diagram showing distribution of modal quartz, K-feldspar + plagioclase, and mafic minerals of the Similkameen batholith.

points on the K-feldspar-plagioclase-quartz face and the (quartz + plagioclase)-K-feldspar-mafic section (not illustrated) suggests that the modes are roughly located near a plane within the tetrahedral space lying approximately perpendicular to the (K-feldspar + Plagioclase)-quartz-mafic section and steeply inclined to both the K-feldspar-plagioclase-quartz and the K-feldspar-plagioclase-mafic faces. Points representing rocks with little or no quartz do not lie on the trend described, and instead form a clearly unique group.

The geographic variation in modal content of the rocks of the southeastern 20 percent of the batholith confirms the regular increase in quartz content from zero at the southeastern margin next to the Kruger complex, to 23 percent towards the interior of the pluton (PLATE II). Color-index shows a reciprocal relationship to quartz, ranging from 8-9 percent towards the interior to amounts in excess of 20 percent at the borders. Color-index in the part of the batholith nearest the Kruger alkalic rocks is quite irregular, however, showing local reversals in the trend.

Modal analyses of alkalic rocks from the Kruger complex (Table 2) cannot be represented in the K-feldspar-plagioclase-quartz-mafic minerals tetrahedron because of their undersaturation in silica; thus the possibility that they lie on a continuation of the planar trend established for the Similkameen rocks cannot be conveniently tested.

Summary and interpretation

The contacts between the major lithologic units within the Kruger complex are gradational, with local exceptions, as is the contact between the Kruger complex and the Similkameen batholith. The batholith and the Kruger complex are therefore judged to be components of a single composite pluton.

The exterior contact of the composite pluton is nearly vertical, considering the map expression of the contact afforded by topographic relief in excess of 3000 ft. at Richter Mountain on the north side of the pluton (Bostock, 1940) and at Chopaka Mountain and the valley of the Similkameen River on the south side (Rinehart and Fox, in press [a]).

The composite pluton sharply crosscuts the country rock, and intrusion breccias are locally present at the contact. Dikes in the country rock that can be definitely attributed to the pluton are relatively few, however. Foliation in the composite pluton parallels the exterior contact, but is poorly developed except near that contact. Foliation and fold axes in the country rock swing around the southeastern saliant of the pluton, but the pluton is clearly discordant on a more regional scale (PLATE II). These attributes suggest that the composite pluton is intrusive. Judging from the regional discordancy, much of the country rock that was displaced during intrusion of the batholith was not simply wedged aside.

The metamorphic aureole at the southeastern flank of the composite pluton is probably not over half to a quarter of a mile in width. To the southeast of that zone, rocks are regionally metamorphosed within the greenschist facies of the Abukuma facies series (Winkler, 1965), highest grade rocks typically containing andesine, epidote, hornblende, and chlorite (Rinehart and Fox, in press [a]).

Within the aureole and adjacent to the Kruger malignite about half a mile north of the Similkameen River the assemblage andesine-hypersthene-anthophyllite-cummingtonite-biotite-spinel which was observed in metamorphosed greenstone suggests metamorphism within the orthopyroxene-hornblende subfacies of the Abukuma amphibolite facies (Winkler, 1965, p. 106). Metamorphosed mafic rocks along the contact six miles to the west contain the assemblage andesine-labradorite, hornblende, diopside, clinozoisite-epidote, and garnet, suggesting metamorphism within the Barrovian almandine-amphibolite facies. These circumstances indicate that the wall rocks along the southeastern contact of the composite pluton were heated to temperatures in excess of those of the boundary between greenschist and amphibolite facies, say 530° to 550° C. (Winkler, 1965, p. 74) at pressures of the Abukuma facies series near the Kruger complex, and at the higher pressures of the Barrovian facies series farther west.

The temporal sequence of the major units within the composite pluton in the order of their emplacement is: (1) pyroxenite; (2) malignite; (3) nepheline syenite; (4) monzonite-granodiorite-quartz monzonite; (5) alaskite, judging by crosscutting relations and diking of older by younger rocks. Contacts of apophysal offshoots of nepheline syenite cutting malignite are commonly highly irregular and intimately welded, suggesting that the malignite was still hot when intruded by the nepheline syenite (Daly, 1912, p. 449). Indeed, the parallelism of flow structures across mixed areas of extremely varied alkalic rocks suggests continuation of viscous deformation or "stirring" after amalgamation of the diverse alkalic rock types, and possibly the adjoining monzonite as well.

The anular or concentric distribution of the major lithologies of the pluton, and the relations between these lithologies can be accounted for by the rise, emplacement, and partial differentiation of the parent magma of the alkalic rocks, followed by successively larger increments of the progressively more silicic magma of the monzonite-quartz monzonite series of the Similkameen batholith.

The femic nepheline syenite sharply cuts both malignite and salic nepheline syenite. The femic nepheline syenite is not foliated, but contacts of the larger masses are gradational. Campbell (1939) concluded that they had been injected into an almost wholly solidified host, and that they had not moved during their crystallization. The alaskite dikes and other alaskitic masses sharply crosscut other rocks of the composite pluton, and are not foliated. These rocks have therefore been intruded after emplacement and solidification of the main mass of the pluton at the level presently exposed.

The blocky habit and large size of the clinopyroxene in the malignite-shonkinite unit south of the International Border suggests that in that rock it was the earliest mineral of the discontinuous reaction series to crystallize. Crystallization of clinopyroxene was followed by formation of hastingsite, both as shells mantling the pyroxene and as independent grains. The microcline phenocrysts locally show relic euhedral growth lines marked by fine-grained inclusions, including plagioclase, indicating early growth of the K-feldspar phenocrysts followed by or concomitant with crystallization of plagioclase. The pyroxene and the hastingsite were later partially replaced by biotite, which also formed interstitially between the felsic constituents. This stage was probably followed by corrosion of the K-feldspar phenocrysts and the plagioclase laths, then by crystallization of late, intergranular K-feldspar. Clusters and strings of anhedral garnet appear to have replaced clinopyroxene, hastingsite, and biotite, possibly during subsolidus reactions.

These observations generally accord with Campbell's (1939) conclusions that the paragenesis of the Kruger alkalic rocks was ". . . augite; hastingsite, and the first microcline and nepheline; biotite and the rest of the microcline; melanite and the rest of the nepheline."

The paragenesis of the Similkameen rocks is similar to that of the Kruger rocks. Augite was the earliest, followed by hornblende, then biotite. Plagioclase was the earliest of the felsic constituents, possibly in part forming concurrently with augite and hornblende, and later along with K-feldspar and quartz.

The secondary minerals, namely epidote, chlorite, hydromica, analcite, natrolite, sericite, and calcite are probably products of deuteric alteration. We may infer from the prevalence of cataclastic textures in both the batholith and the Kruger complex that crystallization was followed by mild crushing. Daly (1912) hypothesized that the cataclasis apparent in the Kruger rocks resulted from forces accompanying forceful intrusion of the nearby Similkameen batholith. Similar textures are widely distributed through at least the southeastern fifth of the batholith, however. Therefore, the cataclasis is probably due to external forces applied to both the Kruger rocks and the batholith simultaneously at some unknown time following their consolidation.

Shankers Bend Alkalic Complex

Introduction

Three miles west of the Kruger complex, the Similkameen River is checked in its swift descent to its confluence with the Okanogan River, located five miles farther east near Oroville (PLATE I), by a barrier of resistant greenstone of the Ellemeham Formation. The river veers northward, then after cutting through the greenstone, doubles sharply back forming the hairpin turn in its canyon known as Shankers Bend. The southern slope of the canyon near Shankers Bend rises about 1500 feet to a rugged, sparsely timbered highland underlain chiefly by variously folded, low-grade metamorphic rocks of the Anarchist, Kobau, and Ellemeham Formations. Two inconspicuous and otherwise undistinguished rocky hills with a sparse cover of sage and grass, located at the northern edge of the highland and overlooking Shankers Bend below, are underlain by the rocks of the complex, a remarkably varied assortment of brecciated alkalic rocks--shonkinite, malignite, fenite, and monzonite breccia--which aggregate about half a square mile in area. Zones of brecciated or fenitized rocks of the Kobau and Ellemeham Formations girdle the complex and grade outward to their "normal" counterparts. Eocene conglomerates unconformably overlie the rocks of the Kobau and the Ellemeham and are presumed to have once covered the complex as well.

The rocks of the complex and the country rocks in the immediate vicinity are generally well exposed in ledgy slopes and low crumbling cliffs, but glacial drift mantles much of the adjacent bedrock.

The alkalic rocks of the diatreme and the dynamic, thermal and metasomatic products of their emplacement are highly varied. For this reason the accompanying map (PLATE III) is necessarily much generalized, with each map unit embracing an overlapping spectrum of rocks.

Modal analyses are presented in Table 8, and chemical analyses and CIPW norms in Table 9.

Kobau Formation

The Kobau Formation, of probable Triassic age, forms the country rock along the northern flank of the alkalic complex (PLATE III) and is the oldest rock in the immediate vicinity. The Kobau Formation is less well exposed than the younger rocks; even within the area shown as outcrop on the map it is partially covered with a thin veneer of glacial drift, soil, and colluvium. The Kobau Formation near the alkalic complex is apparently composed chiefly of greenish-brown, mafic, possibly tuffaceous metasiltstone, commonly containing thin siliceous laminae and locally containing limy layers up to two inches thick. The metasiltstone is interbedded with thin beds of quartzite (metachert) and phyllitic greenstone. The quartzite is commonly impure and is present as beds less than a foot thick, although several zones of massive, relatively pure, light-gray to bluish-gray quartzite attain thicknesses of as much as 50 feet. The thick zones of quartzite are separately distinguished near the complex, but are not differentiated elsewhere within the map area, although they are probably an important component of the bedrock there as well.

TABLE 8

MODES OF THE SHANKERS BEND, COPPER MOUNTAIN, AND OROVILLE ALKALIC COMPLEXES
(in Volume Percent)

Sample	Number Points	Nepheline	Hydromica[1]	K-feldspar	Plagioclase	An of Plag.	Hastingsite	Clino-pyroxene	Biotite	Garnet	Sphene	Apatite	Magnetite	Calcite	Prehnite	Chlorite	Zeolite Group	Sodalite?	Epidote Group	Others
Shankers Bend Alkalic Complex																				
L-444A	1384			33.3	27.3	10-25	31.7	5.8	tr.	0.7		0.7	0.1						0.2	0.2
L-620Q	1139		11.4	24.6	22.0	5	17.0	9.6	10.3	2.9	1.0	0.6	0.6							0.1
L-620H-1	1441		13.5	48.6	24.5	25-30	10.0	0.2	0.5	0.8	0.2	0.2	0.2	tr.			1.4			
L-620M-1	1252		8.8	34.5	31.5	26-35	20.2	0.4	0.8	tr.	tr.	0.9	0.6	tr.					1.4	0.5
L-620M-2	1262	1.0	6.8	43.1	31.0	20-28	12.8	0.5	0.2	tr.	0.2	0.5	tr.	tr.	0.4		2.8	0.4		tr.
L-620M-4	1223		8.7	25.4	20.6	23-28	39.5	1.1	0.9		tr.	1.9	tr.	tr.				0.2		1.3
L-620P	1259	tr.?	4.8	22.5	22.2	23-25	34.8	9.1	2.3	2.3		1.0	tr.	tr.						tr.
L-690R[2]	1166		16.5	43.1	tr.	Albite	8.8	20.4	5.1	2.3		0.8	1.2					0.9		tr.
L-693A[3]	3			43.7	23.6	3-5	tr.					tr.		11.1						
L-693C	2445[5]	tr.?	23.2	46.8	3.5	3	8.9	0.1	13.6	1.4	0.2	0.6	0.5				1.1			tr.
L-696	1305		1.0	38.2	21.2	25-40	18.2	16.2	tr.		tr.	1.4	2.3				tr.			
Copper Mountain Alkalic Complex																				
0-14A-1	1133			24.6	20.4	35-42	19.8	11.2		0.9	0.4	1.2	4.4	5.3		9.3	0.4			2.0
0-14G-1	1357		17.3	37.1	14.7	26-35	12.6	14.7			0.7	0.6	1.1				1.3			
0-449A	1128		10.4	29.5	23.9	5	17.4	3.7	4.3	5.8	0.3	1.1	0.4	tr.		2.5	0.3			
Oroville Alkalic Complex																				
0-72D	1442	16.9	1.2	52.3	9.1	15	6.2	0.6	0.8	2.5	0.3	tr.		tr.			8.2			tr.
0-77D	1151		11.8	61.3	14.8	35-45	5.0	5.0		tr.	0.1		1.3	0.2			0.3			0.2
0-77E	1317		8.1	66.7	18.8	22-37	4.3	1.1	0.2	0.2			0.6	0.1			0.1			
0-77N	1225			56.4	23.3	23-27	14.3	3.3				0.2	0.9	tr.		0.2	1.1			0.1
0-77P	1368			33.7	15.4	32-47	33.3	14.0	tr.	tr.	tr.	1.0	1.5	tr.			0.4			
0-457B	1299		25.6[4]	37.0	1.9	22-32	15.9	15.2	0.1		0.2	0.9	2.5	0.6						
0-462B	1351		8.7	30.9	7.7	15-28	20.8	26.7	tr.		tr.	1.1	2.7	tr.			1.2	tr.		tr.
0-464A	1267		10.7	38.5	14.8	35-45	18.1	14.9			0.5	0.7	1.9							
0-464B	1276			39.8	5.1	30	16.9	10.7	tr.			1.3	2.8	tr.	6.1	0.2	3.0	10.3		3.6
0-465B	1377		8.1	41.7	15.8	24-38	15.9	15.6		tr.	0.2	0.5	1.5				0.7			
0-465C	1318		9.0	27.0	5.2	42-46	21.0	29.8	0.7			1.8	4.4	tr.			0.8	tr.		tr.

[1] Includes intergrowths of analcite plus clay minerals, analcite plus natrolite, and cancrinite (rare). Presumed to be secondary replacement of primary feldspathoids.

[2] Plus 0.9 percent pseudoleucite (fingerprint intergrowth orthoclase plus hydromica).

[3] Plus 18 percent quartz, 3.7 percent unidentified opaque material. Mode determined from point-count of 1495 on section, and of 874 and 1049 on stained slabs.

[4] Secondary after plagioclase and primary feldspathoid. Mode not plotted on Fig. 2.

[5] Four thin sections.

TABLE 9

CHEMICAL ANALYSES AND CIPW NORMS OF ROCKS OF THE SHANKERS BEND, COPPER MOUNTAIN, OROVILLE, BIMETALLIC MOUNTAIN, AND CUMBERLAND MOUNTAIN ALKALIC COMPLEXES[1]

	Shankers Bend[2]				Copper Mountain[3]		Oroville[3]	Bimetallic Mtn.[4]		Cumberland Mtn.[5]
	L-444K[6]	L-620P[6]	L-693A[7]	L-696[7]	O-14A-1[7]	O-14G-1[7]	O-72D[7]	O-431F[7]	O-433A[7]	O-491F[7]
Rapid Chemical Analyses (weight percent)										
SiO_2	44.9	49.9	59.6	51.5	47.0	51.5	55.8	48.3	47.3	53.2
Al_2O_3	16.8	16.0	14.4	16.4	14.2	17.2	21.3	15.8	17.4	19.8
Fe_2O_3	2.7	4.8	1.0	4.4	6.0	4.4	.42	5.0	3.7	3.8
FeO	10.0	4.5	.18	4.7	4.8	4.0	2.8	6.3	6.9	1.7
MgO	4.4	4.2	.30	3.3	5.0	3.3	.52	4.1	3.8	1.1
CaO	8.4	9.1	7.6	7.7	9.5	7.6	2.6	8.6	10.6	3.8
Na_2O	4.0	3.9	4.3	3.5	2.6	3.1	5.5	3.1	3.3	5.4
K_2O	2.3	3.9	6.2	5.3	3.7	5.8	8.5	4.1	2.8	8.6
H_2O-	.25	.11	.08	.10	.59	.25	1.0	.08	.09	.92
H_2O+	2.4	1.2	.52	1.3	1.9	1.2	.08	1.1	1.1	.08
TiO_2	2.9	.76	.07	.76	1.0	.78	.40	1.0	1.0	.61
P_2O_5	.63	.62	.03	.72	1.0	.67	.13	.97	1.1	.29
MnO	.23	.25	.02	.05	.02	.05	.13	.00	.00	.22
CO_2	.08	.05	5.6	.15	2.3	.14	.18	.55	.18	<.05
Total	100.	99.	100.	100.	100.	100.	99.	99.	99.	100.
CIPW Norms (weight percent)										
Q			9.6		.1					
ne	8.8	7.7		5.3		4.7	17.3	2.7	4.8	20.7
or	13.6	23.2	36.7	31.4	22.1	34.4	50.6	24.5	16.7	51.1
ab	17.7	19.1	36.5	19.9	22.2	17.6	14.9	21.5	19.3	7.8
an	21.1	14.8	1.7	13.4	16.3	15.9	8.4	17.3	24.5	4.4
wo	6.7	11.0	.2	8.0	4.2	6.9	1.1	6.7	8.3	5.3
en	3.2	7.6	.7	5.1	12.6	4.9	.3	4.0	4.4	2.8
fs	3.4	2.5		2.4	2.3	1.5	.9	2.3	3.7	
fo	5.5	2.1		2.2		2.4	.7	4.4	3.6	
fa	6.5	.8		1.1		.8	2.7	2.8	3.3	
mt	3.9	7.0	.4	6.4	8.8	6.4	.6	7.3	5.4	4.5
hm			.7							.8
il	5.5	1.5	.1	1.4	1.9	1.5	.8	1.9	1.9	1.2
ap	1.5	1.5	.1	1.7	2.4	1.6	.3	2.3	2.6	.7
cc	.2	.1	12.8	.3	5.3	.3	.4	1.3	.4	
Total	97.6	98.1	99.5	98.6	98.2	98.9	99.0	99.0	98.9	99.3

[1] See Tables 8, 10, for modal analyses of specimens.

[2] See PLATE III for location of specimens.

[3] See PLATE IV for location of specimens.

[4] See PLATE V for location of specimens

[5] See Fig. 22 for location of specimen.

[6] From Rinehart and Fox (in press [a]).

[7] Analysts P. L. D. Elmore, S. D. Botts, L. Artis, G. Chloe, H. Smith, D. Taylor, and J. Glenn.

The metasiltstone and the thinner metachert beds are well bedded in places, but in other rocks bedding is absent or obscure. Foliation within the Kobau Formation is generally poor, and parallels bedding wherever these features were observed together. Attitudes are quite variable over short distances, and the rocks in some areas are plicated or crenulated, and the unit is strongly folded and perhaps refolded on a large scale.

Rocks of the Kobau Formation in areas adjoining the map-area (PLATE III) on the west and north are regionally metamorphosed to chlorite grade (Rinehart and Fox, in press [a]). However, very fine-grained biotite is megascopically visible in rocks within 500 feet of the complex, concentrated in thin films on foliation planes in the impure metachert layers and in hornfelsic laminae in the metasiltstone. Rocks within this zone are locally cut by closely spaced fractures and grade to weak, rubbly, poorly lithified subbrecia and breccia.

Ellemeham Formation

The Ellemeham Formation flanks the complex to the south and west. Regionally the Formation comprises two rather dissimilar members, a lower member composed of spilitic lavas and interlayered pyroclastic rock and mafic siltstone, and an upper member composed of volcanic conglomerate, fine-grained epiclastic rock, and metamorphic conglomerate, the latter distinguished by clasts of metamorphosed rock derived from the Kobau and Anarchist Formations. The rocks of both members of the Ellemeham Formation, although everywhere weakly metamorphosed, lack the penetrative planar metamorphic fabric--foliation, cleavage, or schistosity--characteristic of much of the subjacent Kobau or

Anarchist Formations.

Within the map-area the Ellemeham Formation is composed of metasiltstone and minor greenstone referable to the lower member. The metasiltstone is predominantly rubbly, brown weathering, dark purplish gray or greenish gray and phyllitic in thin bands, and in places contains laminae or thin beds up to a foot or more thick which are vitreous, medium light gray to yellowish gray, and siliceous. The metasiltstone and the greenstone are locally subbrecciated or brecciated, even at outcrops most distant from the complex. The subbrecciated rock is loosely coherent, with fine pebble-size subangular to angular fragments packed closely together and with little, if any, matrix. Primary compositional layering can be followed across the outcrop in places indicating that the original position of the clasts relative to each other has not been vastly changed. The subbreccias grade erratically to zones of breccia, in which fine-pebble size clasts are loosely dispersed through a matrix of more finely comminuted material.

The rocks of the Ellemeham are cut by shear surfaces at intervals ranging from 1-10 feet, which at Ellemeham Draw, dip moderately north-northwest toward the complex and on Hill 2644 (section 14) eastward toward the complex. These surfaces apparently mark the axial plane of low-amplitude kink fold on Hill 2644, and the axial plane of chevron folds in Ellemeham Draw. In places the shear surface is poorly expressed and only the fold axis could be reliably measured, elsewhere the shear surfaces are well expressed with little suggestion of a fold.

The intensity of the brecciation increases as the alkalic rocks are approached, ultimately grading to the alloclastic explosion breccia, the contact being arbitrarily placed at the point where continuity of primary layering through the breccia was lost.

Metavolcanic rocks of the lower member outside the map-area have primary fragmental textures suggesting derivation from pillow-lavas, flow breccias, and agglomerates. However, they are also cut by numerous chaotic shears, close-set joints, and grade locally to subbreccia at distances well beyond any possible influence of the complex. For this reason the evidence of deformation and brittle failure of the Ellemeham Formation within the map-area cannot be attributed solely to forceful emplacement of the alkalic complex.

The Ellemeham Formation overlies the Kobau Formation along a marked angular unconformity. The contact is exposed near the railroad tunnel at the north edge of the map-area. There, little deformed or disturbed massive, aphanitic greenstone and intercalated thin-laminated meta-pyroclastic rocks of the Ellemeham Formation sharply truncate crumpled and subbrecciated graphitic quartzite (metachert) and inter-layered greenish-gray phyllitic meta-wacke of the Kobau Formation.

Regionally the Kobau Formation is moderately to tightly folded (Okulitch, 1969, Rinehart and Fox, in press [a]) whereas the overlying Ellemeham Formation exhibits broad open folds and homoclines. Bedding attitudes in the Ellemeham Formation near the complex are commonly steep but erratic, a result of severe local deformation, but judging from its areal distribution, the unit in a gross sense dips moderately to the east.

The metamorphic grade of the Ellemeham Formation is variable but low except within the thermal aureole of intrusive rocks. Specimens of meta-lava from localities outside the map-area showing only "background" metamorphism have albite phenocrysts or microlites set in a microcrystalline to cryptocrystalline matrix of quartz and feldspar, sometimes showing plumose or spherulitic structure, and are cut by calcite filled cracks and overprinted with a smear of leucoxene, and fine-grained, patchy chlorite. Biotite is locally present along spider-web cracks and in clots at the intersection of cracks, but is not generally megascopically visible, except within several hundred feet of the alkalic rocks or the metasomatized zones shown on the map.

Thin sections of two specimens of typical medium-gray aphanitic metasiltstone with olive-gray laminae from the rubbly cliffs marking the western limit of the Ellemeham Formation within the map-area revealed decussate to schistose biotite, and granoblastic albite (by X-ray), quartz, K-feldspar, and magnetite or ilmenite. K-feldspar was present as late hair-like veins in one rock and disseminated through the matrix of the other. Grain size ranges from .003-.045 mm, averaging about .01 mm.

Adjacent to the gradational contact with alkalic gneiss in the southeastern corner of section 14 the metasiltstone is dark gray, weathering brown, with crumpled light-gray laminae, and contains either megascopically visible schistose biotite oriented subparallel to primary layering, or has visibly coarsened texture compared to its previously described counterpart. Thin sections of two specimens revealed a very fine-grained texture, gneissose in one, hornfelsic in the other. Reddish-brown biotite is the most abundant constituent of the gneiss, followed by albite, analcite, strongly pleochroic dark-green hornblende, pale-brown augitic pyroxene, K-feldspar, and accessory illmenite, zircon, sphene, and apatite. Veinlets of analcite, prehnite, and thomsonite cut the rock. A chemical analysis of the gneissose rock (sample L-444K) is given in Table 9. Reddish-brown biotite is also the most abundant constituent of the hornfels, followed by calcite, which is confined mostly to discrete laminae, albite, untwinned K-feldspar mostly in veinlets and lensoid masses, actinolitic amphibole, relict clinopyroxene, and accessory apatite, sphene, and illmenite.

Alloclastic explosion breccia

Monolithologic breccia composed of sharply angular, fine-pebble to granule size clasts packed in a finer grained matrix borders the alkalic rocks on the west in section 14. Three types have been distinguished on the map based on whether the parent material was (1) greenstone and thin-laminated metasiltstone, probably of the Kobau Formation; (2) quartzite (metachert) of the Kobau Formation; or (3) thin-laminated mafic metasiltstone of the Ellemeham Formation.

The breccias are weakly bonded and generally break around the clasts or along irregular fractures. On fresh surfaces the clasts in the metasiltstone breccia are medium gray and the matrix greenish gray. The clasts weather in relief with accentuated light-gray laminations in a medium-gray host, and the matrix weathers to a distinctive orange-brown color. The quartzite breccia is medium bluish gray, and the greenstone and metasiltstone breccia is greenish gray with phyllitic clasts. In places the latter rock resembles breccia derived from the Ellemeham Formation, for example at the northeasternmost exposures in section 14, and may in fact be derived from the Ellemeham Formation in part. The breccias grade erratically to isolated masses of massive, or more commonly, chevron-folded and subbrecciated rock of the parental formation, which have been included with the breccia units on the map.

The larger clasts in the breccia derived from the Ellemeham metasiltstone can locally be matched across the intervening matrix, which consists of more finely comminuted material. The clasts in some areas show a fair phyllitic cleavage without parallism between clasts. There is no throughgoing penetrative planar structure.

The metasiltstone breccia grades abruptly--over a distance of several tens of feet or less--to fine-grained mafic alkalic gneiss. Within the transition zone the brecciated character is obliterated by development of salt and pepper texture through recrystallization, locally with development of anhedral ellipsoidal K-feldspar porphyroblasts. In places, however, replacement breccias of striking appearance (Fig. 13) have developed, apparently through segregation of femic and felsic constituents during the metasomatic process. The replacement breccia contains dark-gray, very mafic, oval to lenticular "clasts" 10-30 mm long, dispersed through a medium-grained light-gray matrix which is studded with black, lathy hornblende crystals. Pockets and bands of fine-grained alkalic gneiss, some showing incipient development of tabular phenocrysts of K-feldspar, are present in the adjacent hornfelsed Ellemeham metasiltstone and greenstone.

Breccia near this transition zone contains K-feldspar in thin

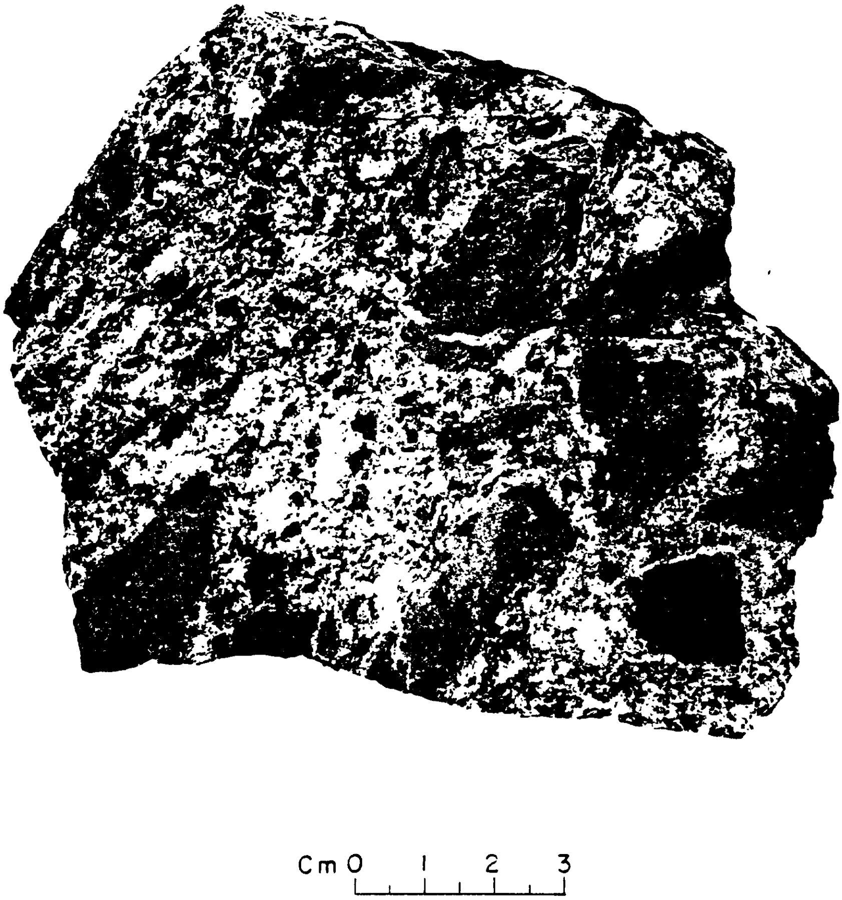

Fig. 13.--Photograph showing specimen of replacement breccia collected from transition zone between fine-grained alkalic gneiss and mafic metasiltstone ("greenstone") breccia.

films and as a selective replacement of certain laminae in the metasiltstone clasts. Outside of this transition zone clasts in the two specimens of the breccia that were thin-sectioned were composed of thin, irregularly contorted and microfaulted felsic and mafic laminae and augen-shaped pods 1.0 to 1.5 mm thick. Clasts of one rock were composed of varying proportions of very fine-grained fibrous amphibole, albite, chlorite, decussate biotite, calcite, clinozoisite, and were cut by prehnite veinlets. The other specimen was composed of anhedral laths of brownish-green hornblende, granoblastic andesine, and minor biotite, unidentified clay minerals in veins, chlorite, calcite, relict pyroxene, illmenite, and leucoxene.

Metasomatized metasiltstone of the Ellemeham Formation

Fine-grained but thoroughly recrystallized thin-laminated mafic metasiltstone of the Ellemeham Formation containing thin ill-defined bands and lenses of fine- to medium-grained feldspathic gneiss flanks the mafic alkalic rocks on the south in section 13 and part of section 14. The gneissic layers are commonly between 2 and 18 inches thick, and are conformable, even following the layering in the enclosing metasiltstone around the numerous folds and plications present. Contacts with the metasiltstone host are typically gradational but some appear megascopically sharp.

The felsic minerals in the gneissic layers are chiefly K-feldspar and plagioclase, and in this particular and their general megascopic appearance they closely resemble the rocks of the fine-grained alkalic gneiss with which they intergrade. The interlayered metasiltstone of the Ellemeham Formation is light gray to brownish gray, with thin light-gray to reddish-brown, much contorted laminae, and are variously hard and dense or weak, brittle, and soft. Biotite is easily visible and is widespread, and garnet is locally identifiable within tactitic laminae. Other minerals revealed by the microscope include oligoclase or andesine, K-feldspar (sparse, mostly confined to veinlets), hornblende, secondary clinozoisite and chlorite, and apatite. Diopside is present in some laminae.

The unit grades by diminishing abundance and poorer development of the gneissic layers into hornfelsed rocks of the Ellemeham Formation. This contact is drawn at the outermost limit of occurrence of the gneissic layers, but their distribution is erratic and the contact is therefore highly generalized. The contact with the fine-grained alkalic gneiss is more abrupt, but also is gradational, being placed at the innermost limit of the occurrence of interlayered metamorphic rocks whose primary thin-laminated meta-sedimentary appearance has not been obliterated by recrystallization and reconstitution.

Alkalic gneiss

The core of the alkalic complex is occupied by fine- to medium-grained alkalic gneiss, composed essentially of one-half to three-fourths K-feldspar, plagioclase, and hydromica or nepheline and one-fourth to one-half mafic minerals and accessories (Table 7). The alkalic gneiss shows considerable variation within the outcrop and even within the hand specimen in its texture, color index and degree of development and attitude of foliation. The two most widespread variants are weakly foliated, almost massive "gneiss," and indistinctly banded or mottled, hybrid-appearing gneiss.

The weakly foliated gneiss is fine grained, dark gray to medium gray, weathering to light bluish gray, and in places shows a distinctive "salt and pepper" texture. The banded gneiss contains thin, wavy light-gray schlieren of coarser grained and less mafic gneiss enclosed in a mafic, fine-grained, dark-gray gneissic host. Both types intergrade erratically. In addition, they are commonly laced by a trellis-like network of 1-4 mm thick feldspathic veinlets which show feathery contacts with their host. The gneissosity is typically a penetrative, curving and anastomosing gneissic foliation rather than a regular, planar fabric.

The petrography of the alkalic gneiss is roughly uniform. The major constituents are perthitic untwinned K-feldspar, in places showing undulose extinction, sericitized and locally saussuritized plagioclase (An 15-30), and in most areas, fibrous hydromica, probably pseudomorphous after nepheline. Other constituents include pale-green aegirine-augite or augite, highly pleochroic pale-greenish-tan to greenish-black hastingsite, and dark-green biotite. Accessories include orange-brown garnet, smoky to clear apatite, sphene, cancrinite, calcite, clinozoisite, magnetite, and various zeolites.

The alkalic gneiss is xenomorphic granular. Although the clinopyroxene is roughly prismatic in gross outline, its exterior is serrate, or mantled by a thin uralitic shell of hastingsite. The hastingsite is also present as anhedral intergrown aggregates. Biotite appears to be secondary after hastingsite. Hydromica is present as pale-green to pale-brown aggregates associated in one slide with accessory cancrinite. Nepheline is commonly completely replaced or represented only by a few much altered cores in pools of hydromica, but fresh nepheline, in places partially replaced by hydromica, was found in one specimen. Thomsonite and analcite are present as veinlets and alteration products of other minerals.

The contact of the alkalic gneiss along the northern side of the complex with rocks of the Kobau Formation is covered, but probably is abrupt. To the south the gneiss grades to the metasomatized metasiltstone of the Ellemeham Formation and to the west to the monolithologic breccia derived from the Ellemeham Formation. The alkalic gneiss is generally closely jointed to sub-brecciated, and is cut by numerous high-angle dip-slip faults with red, striated films of hematite coating the shear surfaces. The gneiss is also cut by numerous thin, stubby, feldspathic dikes, generally less than a foot thick and only 10-30 feet in length.

Malignite

Two small masses of medium-grained, locally gneissose, medium-gray malignite grading to shonkinite are present at the eastern extremity of the alkalic complex. The northerly of the two masses is thoroughly sub-brecciated; the southerly is jointed but not sub-brecciated.

The malignite-shonkinite is very similar in appearance to certain phases of the alkalic gneiss, except that the malignite is relatively uniform in composition and in texture within the outcrop, whereas the gneiss even within the hand specimen is quite inhomogeneous and streaky. The malignite is also distinctly coarser grained than the gneiss. The contact between the two rocks is apparently gradational, however.

The shonkinite consists essentially of untwinned perthitic K-feldspar, andesine, hastingsite, and augite, with accessory magnetite, biotite, apatite, and sphene. The texture is hypautomorphic granular, dominated by blocky subhedral augite with anhedral uralitic overgrowths of dark-, almost blackish-green hastingsite showing the customary strong optical absorption, and by aggregates of subhedral lathy plagioclase. The malignite is similar but contains essential nepheline or hydromica. Two additional varieties of malignite are present, spotted and pseudoleucite porphyry. The spotted resembles the spotted malignite found at the Kruger complex (Fig. 14). The porphyry contains scattered phenocrysts of pseudoleucite (fingerprint intergrowth of orthoclase and hydromica) in a medium-grained groundmass.

Alkalic gneiss breccia

Breccia composed of pebble-size clasts of mafic alkalic gneiss and monzonite, dispersed through a matrix of more finely comminuted rock fragments and mineral grains, is patchily distributed over the alkalic complex. A greenish-gray layer of breccia scabbing the southeast flank of the complex is conspicuous in distant views. It overlies alkalic gneiss and thin-laminated metasiltstone of the Ellemeham Formation, which in part is metasomatized (fenitized); and conformably underlies a sheet of monzonite breccia. The gross dip of the layer of alkalic gneiss breccia is 32° to the east-southeast.

The rock within the layer typically resembles a conglomerate,

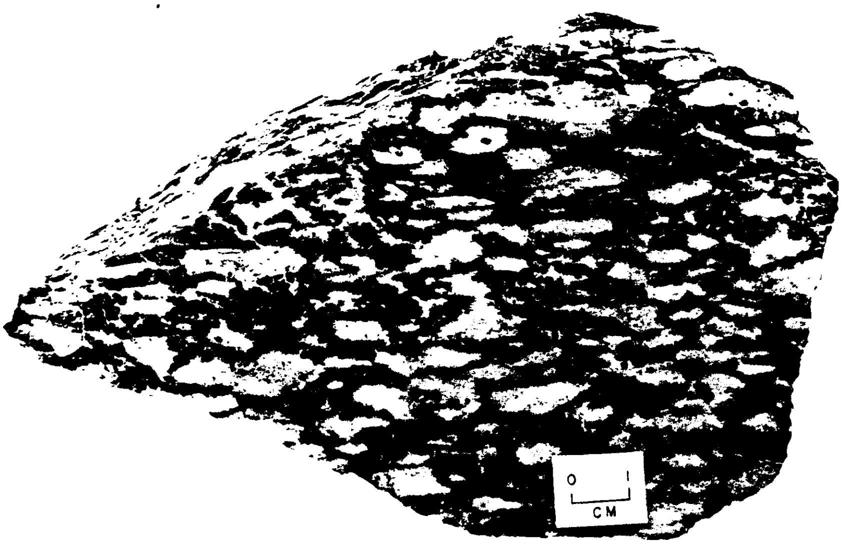

Fig. 14.--Photograph showing specimen of spotted malignite L-693C (see Table 8) representing small unmapped area within alkalic gneiss unit. White spots may be pseudoleucite. They are composed of patchy intergrowth of anhedral orthoclase and hydromica (pseudomorphing nepheline) and are set in a dark-gray, fine-grained, xenomorphic gneissic matrix.

(Fig. 15), with light-gray to medium-gray, angular to subspherical clasts mostly between 3 and 20 mm long, of medium-grained monzonite or fine-grained mafic alkalic gneiss, suspended in an aphanitic greenish-gray matrix. The matrix is marbled by poorly defined grayish-red ferruginous streaks. In places the clasts are closely packed, with the matrix filling only the interstices. The breccia is well indurated, breaking across the lithic fragments, but is weak due to the presence of abundant irregular fractures.

The mineralogy and texture of the gneissic clasts is similar to that of the previously described alkalic gneiss. The "matrix" is composed of more finely comminuted gneiss, and discrete crystals of its component minerals, particularly orthoclase, light-brown garnet, hastingsite, and aggregates of calcite, hornblende, opaque minerals, and biotite apparently pseudomorphing pyroxene, and with interstitial analcite and brown (reflected light) subopaque, irresolvable fine-grained material. Microscopic veinlets of analcite with minor prehnite and others of calcite cut the breccia. There is no conclusive indication of post-cataclastic recrystallization other than that ascribable to secondary alteration.

Both the upper and lower contacts appear to be gradational through transitional zones of brecciated to subbrecciated material of the adjacent unit several feet to several tens of feet wide.

The gneiss breccia is cut by lensoid clastic dikes (see succeeding paragraph on dikes) with a maximum width of 10-15 inches. Judging by their sharp, planar walls these dikes were emplaced after formation of the breccia. In addition, carbonate lenses and nodules,

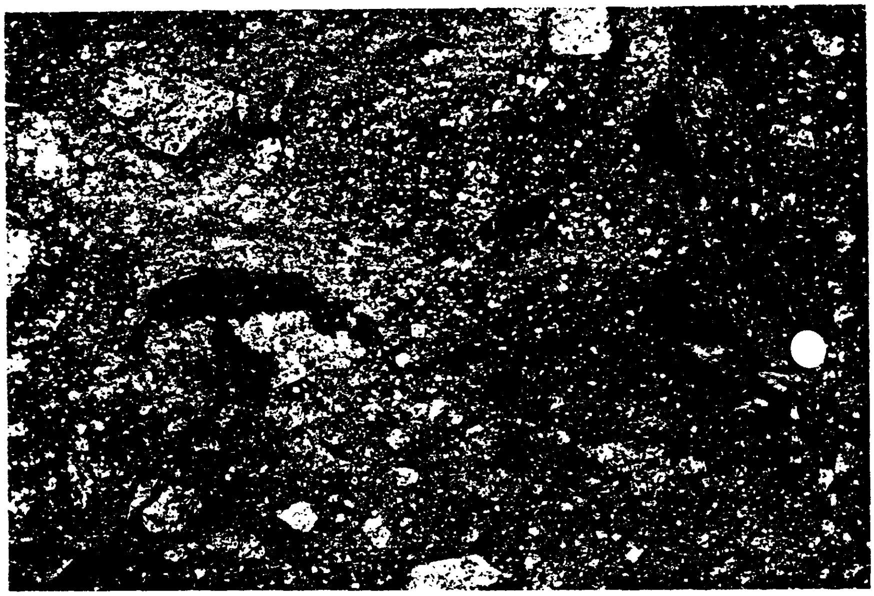

Fig. 15.--Photograph showing alkalic gneiss breccia. Coin for scale is 1.75 cm in diameter.

which individually are up to 2 by 4 feet in size, are strung out over two linear zones about 50 feet in length. These probably represent carbonatite dikes, which were broken up during final deformation of the host.

In places the breccia is streaked by thin marbly bands of light-yellowish-gray, quartz-bearing feldspathic breccia. The feldspathic breccia contains monzonite clasts composed of xenomorphic granular aggregates of fine- to medium-grained clear, perthitic orthoclase and untwinned plagioclase, mostly riddled with a smear of alteration products. In addition, dark-green hastingsite, biotite, garnet, and muscovite are present in minor amounts, as well as accessory apatite. The clasts are suspended in a finer grained matrix composed mostly of small grains of clear orthoclase plus many of the minerals listed above. However, certain rare lensoid zones probably not over 10 mm in length are composed of a fine-grained breccia of quartz, clear plagioclase with albite twinning, and brown kaolinized orthoclase.

Monzonite breccia

Breccia composed of dispersed to closely packed, pebble- to cobble-size clasts of monzonite with a matrix of similar but more finely comminuted material overlies the east-southeasterly dipping gneiss breccia at the southeast flank of the alkalic complex. The monzonite breccia comprises two intergrading compositional variants of about equal areal extent, in which (1) monzonitic clasts are fine- to medium-grained, quartz-bearing, leucocratic (visually estimated color index 5-10), and slightly gneissose; and (2) monzonite clasts are medium to coarse grained, apparently quartz-free, mesocratic (visually estimated color index 25-35), and in places are trachytoid, containing crowded, tabular K-feldspar phenocrysts up to 25 mm long. The matrix of the latter type is olive gray in color and typically predominates, imparting a somber brownish hue to the outcrop.

The proportion of clasts to matrix varies erratically; in some areas the breccia resembles a monolithologic conglomerate, with pebbles and cobbles dispersed through the matrix, but elsewhere the rock is more nearly a sub-breccia, with considerable suggestion of continuity of primary fabric over distances of a meter or more. There is no suggestion of metamorphic recrystallization within the matrix.

The monzonite breccia is cut by contorted, subparallel dikes 1-2 ft. thick and up to 30 ft. in length, of light-orangish-gray aplite, composed of quartz, K-feldspar, and plagioclase (Fig. 16). Within the dike the aplite is sub-brecciated to brecciated and individual masses, particularly of the thinner dikes, are disconnected, so that in places the dike grades to a zone resembling a twisted string of giant beads. Contacts of individual aplite masses with the enclosing breccia are sharp.

After intrusion and solidification, the aplite dikes were crushed, folded, and kneaded into the wall rock concomitantly with brecciation and deformation of the monzonitic host.

Dikes

The rocks within the alkalic complex and the bordering country rock are cut by widely scattered but ubiquitous thin, short dikes, including carbonate dikes and a variety of feldspathic dikes.

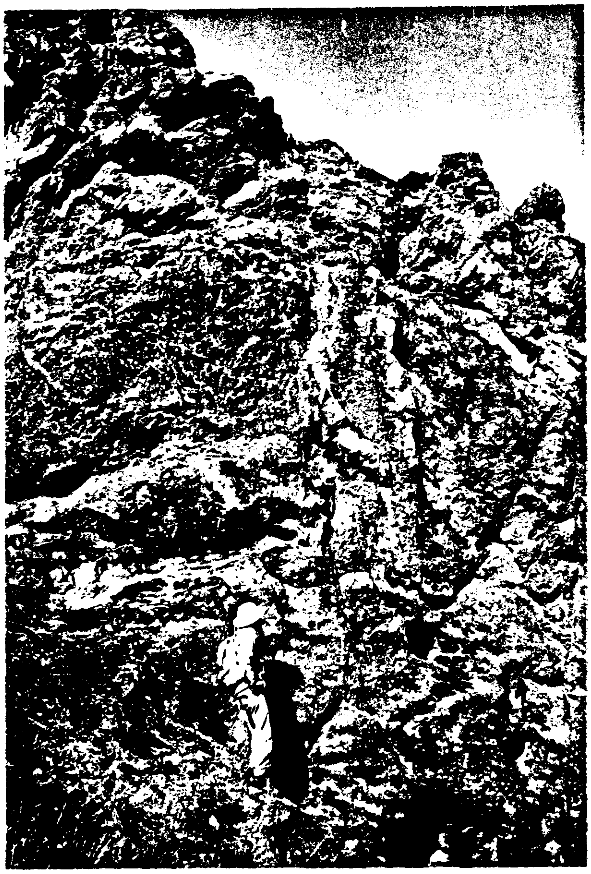

Fig. 16.--Photograph showing contorted and brecciated aplite dikes cutting monzonite breccia.

The carbonatite dikes weather light bluish gray, and are up to 5 feet thick and 50 feet long. They are brecciated to subbrecciated, and composed mainly of medium-grained, weakly bonded calcite. The carbonatite dike lying athwart the line between sections 13 and 14 (PLATE III) is marked by fine laminations, resembling bedding, parallel to its strike. It is somewhat fetid, and the chief accessory mineral is celsian. The contact zone of this dike with the enclosing alkalic gneiss is a fine-grained breccia composed of lithic fragments of alkalic gneiss, calcite, and angular to rounded crystals of K-feldspar dispersed through a calcite matrix, along with scattered grains of garnet, anhedral hastingsite, plagioclase, sphene, apatite, biotite, and opaque minerals.

The carbonatite dipping 25° to the northeast in section 13 is composed of medium- to coarse-grained calcite with accessory muscovite, apatite, diopside, feldspar, and graphite, and is markedly fetid. This dike ranges from 3 to 5 feet in thickness and is 50 feet long, with bulbous terminations.

Alternatively, the carbonatites could be bodies of limestone which were not assimilated during the metasomatic conversion of the parent of the adjacent rock, which is presumed to be the Ellemeham Formation, to alkalic gneiss. This is not likely, however, as the linear character of the dikes contrasts with the folded and sheared character of the nearest recognizable rocks of the Ellemeham Formation, and since limestone is almost unknown elsewhere within that formation.

The feldspathic dikes are of several compositional types, including coarse-grained, almost pegmatitic, perthitic microcline breccia, oligoclase breccia, and melanocratic to leucocratic monzonite breccia. The aplitic breccia dikes cutting the monzonite breccia and noted in the description of that unit constitute an additional category of dike, but no attempt was made to map them.

The microcline breccia dikes are pale orange, 2-12 inches thick, and not more than 20 feet in length. Based on examination of thin sections of specimens of two of these dikes, they are composed of angular to oval clasts 1 to 10 mm long of microcline perthite with subordinate crystal fragments of oligoclase and anomalously biaxial calcite, accessory hastingsite, apatite, tiny shreds of aegirine, and traces of biotite. The clasts are packed and firmly cemented in a reddish aphanitic matrix containing hematite and calcite and finely comminuted feldspar. Clasts of fenite and clusters of subhedral quartz grains are rarely present.

The oligoclase breccia dikes are very light gray and similar to the microcline breccia dikes, except that oligoclase is the major constituent, with only minor amounts of K-feldspar. A monzonite dike in the southeast corner of section 14 is apparently about 10 feet wide and 200 feet in length. It is gneissic, and shattered or brecciated, and composed chiefly of microcline, subordinate andesine and biotite, and accessory hematite and muscovite.

A few of the microcline breccia dikes differ in that the clasts are quantitatively much subordinate to the reddish aphanitic matrix through which the clasts are dispersed. These dikes typically have planar walls with knife-edge contacts. Well-rounded fragments of fenite are abundantly present among the clasts. The cataclastic fabric of these dikes cannot be attributed solely to the pervasive post-emplacement shattering which might explain the brecciation of the other dikes. Their appearance and contact relations suggest instead that they were emplaced as breccias, and therefore are probably "alloclastic intrusive breccias" (Wright and Bowes, 1963).

Conglomerate, wacke, volcanic conglomerate, and dacite-andesite

The rocks of the Kobau and Ellemeham Formations are unconformably overlain by an east-dipping succession of Eocene clastic rocks. The basal unit of the Eocene deposits near the complex is a well-lithified conglomerate composed of rounded pebble- to boulder-size clasts derived chiefly from granitoid rocks, packed in an arkosic matrix. The unit interfingers laterally with interbedded wacke, arkose, and siltstone, and is overlain by volcanic conglomerate and wacke--beds containing rare to abundant pebbles or cobbles of Tertiary hornblende andesite or dacite.

The basal few tens of feet of the granitic conglomerate locally are composed partly to almost exclusively of oval cobbles and boulders of trachytoid monzonite porphyry, mafic alkalic gneiss, malignite, and shonkinite. These clasts are probably detritus of the Kruger complex and the Similkameen batholith, which are located about three miles to the west, and perhaps in part are derived from the alkalic rocks of the Shankers Bend complex.

The Tertiary clastic rocks are cut at the east edge of the map-area by two plugs of hornblende andesite-dacite similar to that composing the distinctive clasts of the volcanic conglomerate and wacke. The K-Ar age of the plugs is about 50 m.y. (Rinehart and

Fox, in press [a]).

Summary and interpretation

The "core" of the Shankers Bend alkalic complex consists of an irregularly shaped body of mafic alkalic gneiss of foyaitic to shonkinitic composition, grading on the east to malignite. The complex is cut by scattered thin dikes of potassic, sodic, or of carbonatitic composition. The western lobe of the alkalic gneiss (PLATE III) is girdled by breccia whose clasts are of three compositional types, corresponding to the lithology of the adjacent country rock, namely greenstone, mildly metamorphosed mafic siltstone, and metachert. The breccias grade outward to their "normal" counterparts through an intermediate zone of rocks that are shattered but retain considerable continuity of primary structure, and inward by recrystallization and replacement of the breccia to the mafic alkalic gneiss. These circumstances suggest that the breccia is an "alloclastic explosion breccia" (Wright and Bowes, 1963) developed by explosive fragmentation of the country rocks, in situ. Locally the breccia was either subsequently or concomitantly converted to alkalic gneiss.

The western, eastern, and southern contacts of the alkalic gneiss with the mafic metasiltstone are gradational. The southern contact is marked by a wide, irregularly shaped zone in which thin layers and lenses of alkalic gneiss are interlayered and intergrade with thinly laminated metasiltstone. The alkalic gneiss within this zone has apparently originated through selective recrystallization and metasomatism of the metasiltstone. The overall gradation from mafic metasiltstone to alkalic gneiss shows the following mineralogical sequence: biotite; biotite and orthoclase; orthoclase and feldspathoids with clinopyroxene, hastingsite, and garnet.

The alkalic gneiss throughout much of its extent is a streaky, xenomorphic granular rock, seemingly an imperfectly blended mixture of felsic and mafic constituents. The inhomogeneity, gneissic fabric, and gradational border relations of the alkalic gneiss suggest that much of it originated through fenitization of the country rock. Conversion of the mafic metasiltstone to the alkalic gneiss could have been accomplished by addition of potassium and sodium coupled with removal of silica. These changes, and the mineralogical changes noted above, are consistent with those observed where basic igneous rocks have been fenitized (Verwoerd, 1966).

A penetrative gneissose fabric with streaky compositional banding is present over a considerable area of the alkalic gneiss. The attitude of this foliation is coherent over areas of several hundred square feet, trending grossly east-west, parallel to the northern contact of the alkalic gneiss with the country rock. The east-west structure probably reflects extension by flowage of the alkalic gneiss in this direction, indicating that the gneiss acquired at least limited mobility in the final stages of its development. The northern contact is not exposed, but is probably sharp, since no hint of a transitional zone was observed in outcrops bracketing the contact. The alkalic gneiss, therefore, may be intrusive.

The malignite-shonkinite, in contrast to the alkalic gneiss, is a homogeneous, hypautomorphic granular rock, except for locally gneissose areas. Its contact with the alkalic gneiss appears to be gradational over a narrow zone. Contacts with the country rock are not exposed, but are probably sharp. Therefore, the malignite unit is probably intrusive, and if so, it crystallized from a magma. On the basis of compositional similarity to the alkalic gneiss (compare analyses L-696 with L-620Q, etc.), as well as field and petrographic evidence, that magma could have been either rheomorphic or primary.

The monzonite breccia is in some respects the most enigmatic rock at the complex. Although generally possessing a conglomeratic appearance, in certain outcrops the trachytoid and gneissose structure can be traced through the fragmental fabric. Also remnants of crushed and crumpled syenite dikes were found with continuity of several feet to several tens of feet. These features are compatible with derivation of the breccia through crushing of a body of monzonite, which judging by the distribution of clasts of varying lithology within the breccia, was composed largely of discrete mafic and felsic phases. Both phases had been intruded by syenitic dikes prior to the crushing.

The monzonite breccia forms a tabular mass, dipping moderately southeast and capping the southeast flank of the complex. At the base it grades abruptly to alkalic gneiss breccia or overlies metasomatized country rock along a covered contact. Evidently the monzonite breccia was emplaced either as a breccia, the parent mass being broken up during or prior to emplacement, or it was intruded as a magma, solidified, and was deformed and brecciated essentially in place during explosive episodes preceding or accompanying development of the main part of the alkalic complex. The contrast in degree of mechanical fragmentation between the "conglomerate-like" breccia and nearby subbrecciated and hornfelsed country rock, and the failure to find evidence of metasomatism or hornfelsing in the matrix of the breccia accord best with intrusion of the monzonite breccia as a body of fragmented rock late in the development of the alkalic complex.

The alkalic gneiss, in common with all of the rocks at the complex, is variously closely jointed, subbrecciated, or brecciated. The brecciated masses, which have been mapped as alkalic breccia, are patchily distributed over the central part of the complex. They probably mark domains of greatest brittle failure during a period of deformation following the cessation of fenitization and recrystallization. That deformation records a final episode of explosive shattering at the complex, possibly concurrent with the brecciation and intrusion of the monzonite breccia.

The history of the complex is interpreted as follows:

1. Rupture and fragmentation of the country rock
2. Thermal metamorphism, fenitization, and rheomorphism of the country rock
3. Intrusion of malignite-shonkinite at the present level of erosion, and of monzonite at depth
4. Intrusion of feldspathic and also of carbonatitic dikes
5. Rupture and fragmentation of rocks of the alkalic complex
6. Emplacement of monzonite breccia

The order given above is considered a series of chronologically overlapping developments rather than a succession of entirely discrete events.

The complex is evidently a diatreme of the alkalic variety, belonging to a class including numerous representatives elsewhere, e.g., in Canada (Currie and Ferguson, 1969; Dimroth, 1970; Gold, 1969) and in Africa (Strauss and Truter, 1950).

The Oroville and Copper Mountain Alkalic Complexes

Introduction

The Oroville and Copper Mountain alkalic complexes were first described by Krauskopf (1941) and by Waters and Krauskopf (1941). The complexes are located on either side of the wide, north-trending valley of the Okanogan River (PLATE IV). The one and a half mile expanse of valley floor intervening between the two alkalic complexes is covered by glacial drift and by an alluvial fan deposited athwart the Okanogan Valley at the mouth of a tributary, Tonasket Creek. Waters of the Okanogan River have been impounded behind the fan to form Osoyoos Lake. The alkalic rocks are well exposed in low, but rugged and rocky, sage-clad hills overlooking the lake, with the Oroville complex on the east and the Copper Mountain complex on the west.

The alkalic rocks have been emplaced into phyllite and weakly metamorphosed limestone of the Spectacle Formation, and greenstones of the Kobau and Ellemeham Formations. Rocks of the Okanogan gneiss dome lie southeast of the alkalic rocks. The complexes are partially covered by Eocene conglomerate and arkose, and the alkalic rocks at the Oroville complex are cut by augite-biotite trachyandesite.

The rocks of the Oroville and Copper Mountain complexes consist chiefly of mafic alkalic rocks, including medium- to coarse-grained shonkinite and malignite, fine-grained foyaite and juvite, metasomatized greenstone, and monzonite, most of which are shattered or brecciated. These rocks are internally extremely variable, both in primary lithology and degree of fragmentation, so that here as at Shankers Bend, each map unit encompasses a wide spectrum of rocks.

Spectacle Formation

Weakly metamorphosed, white to dark-gray limestone and crumpled silvery-gray to black phyllite, which apparently underlie greenstone of the Kobau Formation north of the Oroville Complex and flank the complex to the south, are provisionally referred to the Spectacle Formation. The limestone is uniformly very fine grained, and typically is light gray, massive to thin bedded, and contains laminae or irregular lenses of bluish-gray chert. Minor areas of impure dark-bluish-gray limestone breccia and siliceous white limestone are present in places adjacent to the Oroville alkalic complex. The limestone breccia is composed of closely packed, angular, fine pebble size clasts of dark-bluish-gray limestone, and crops out as a flat lying layer, several feet thick, capping massive to sub-brecciated white to light-gray limestone north of Tonasket Creek. A large angular boulder excavated from the road cut through the outcrop shows a 3-10 inch thick, dike-like finger of the dark-bluish-gray limestone breccia enclosed within the white to light-gray limestone. Limestone at outcrops more distant from the alkalic complex is somewhat deformed and in places is closely jointed but is not brecciated.

The phyllite is a soft, incompetent material which disintegrates rapidly after exposure, judging from its appearance in recent road cuts.

It is composed chiefly of much contorted silvery-gray, graphitic phyllite, black gypsiferous and graphitic phyllite, and black graphitic and siliceous thin-laminated limestone. Whole-rock X-ray spectographic analyses of the phyllite indicate that its major components are quartz, gypsum, graphite, sericite, and chlorite. The graphitic limestone contains the same minerals in addition to calcite.

Kobau Formation and metamorphased mafic intrusive rock

Foliated greenish-gray greenschist of the Kobau Formation, and weakly metamorphosed mafic intrusive rock flank the Oroville alkalic complex to the north. The greenschist is irregularly sheared and the foliation is much crumpled at the western extremity of its outcrop. The greenschist grades to massive, poorly foliated greenstone to the east. Bedding was recognized at only one locality, where it was parallel to the foliation. A specimen of the massive rock collected from an outcrop adjacent to the malignite unit appears to be a weakly metamorphosed crystal tuff, composed chiefly of fine-grained, broken crystals of plagioclase, and minor quartz in a matrix of chlorite, calcite, and opaque material.

The mafic intrusive rock is a rubbly, irregularly sheared and foliated, locally brecciated metadiabase, generally brownish gray to greenish gray, limy, and fine to medium grained. At outcrops farthest from the alkalic complex it is composed of albite, intergranular chlorite, and opaque minerals, with an overprint of hornfelsic acicular actinolite and traces of orange-brown biotite. Nearer to the alkalic complex the plagioclase of the metadiabase is oligoclase and the orange-brown biotite is a major constituent.

The contact between the mafic intrusive rock and the Spectacle Formation is probably conformable. The nature of the contact with the greenschist was not established. Numerous bodies of similar metadiabase were found associated with Anarchist and Kobau rocks to the south and west of the alkalic complexes and are probably the hypabyssal intrusive equivalents of the volcanics of the Kobau Formation (Rinehart and Fox, in press [a]), and thus are probably Triassic.

Ellemeham Formation

Weakly metamorphosed light-olive-gray to greenish-gray mafic siltstone cropping out north of the Copper Mountain alkalic rocks and forming a narrow sliver along the south border of the Oroville alkalic rocks is tentatively assigned to the Ellemeham Formation.

At Copper Mountain the meta-siltstone is a soft, brittle aphanitic rock composed of very fine-grained quartz with interstitial decussate muscovite and chlorite. No primary structures or sedimentary textures were observed. The Ellemeham metasiltstone at the Oroville alkalic complex is similar, except that tiny grains of hornblende and patches of calcite are present in addition to the minerals listed above. The metasiltstone overlies the Spectacle Formation along a sharp, even, and apparently conformable contact, and grades up through talcose green phyllite to brecciated and altered, orangish-gray, calcareous metasiltstone, which is in turn overlain along a low-angle contact by brecciated malignite.

Metamorphosed dikes

Weakly metamorphosed dikes cut rocks of both the Kobau Formation and the Ellemeham Formation. The northernmost of the two dikes shown on the map (PLATE IV) which cut the metadiabase of the Kobau Formation is a coarse-grained light-olive-gray feldspathic rock with a gabbroic texture, composed of large, lathy albite crystals and intergranular graphic intergrowths of quartz and untwinned K-feldspar, chlorite and secondary biotite, amphibole, and clay minerals. The southern dike is a dense, coarse-grained, greenish-gray metapyroxenite, probably originally composed of clinopyroxene and hornblende, which are now largely altered to chlorite, and magnetite with interstitial plagioclase.

The dike cutting the Ellemeham Formation in the NW 1/4 section 21 is a light-brownish-gray porphyry contained tabular phenocrysts of K-feldspar and albite up to 10 mm long set in an aphanitic matrix.

Okanogan gneiss dome

Strongly lineated and foliated granodioritic augen gneiss cropping out in the southeastern corner of the map-area (PLATE IV) is part of the Okanogan gneiss dome (Fox and Rinehart, 1971), a vast body of gneissic granodiorite, augen gneiss, and layered gneiss lying to the southeast of the Oroville alkalic complex. The augen gneiss is medium to coarse grained, light gray and displays a penetrative cataclastic fabric. The gneiss is typically composed of about 30 percent quartz, 65 percent feldspar (orthoclase and calcic oligoclase), and 5 percent mafic minerals, mainly biotite, allanite, and locally muscovite. Accessory minerals include apatite, magnetite, ilmenite, sphene, zircon, garnet, and monazite. Near the northwestern extremity of the dome the gneiss is in covered contact with a fine-grained, chalky-white rock, which appears to be a shattered and locally brecciated and altered rock of granitic derivation.

The rocks of the gneiss dome apparently dip approximately 25° northward beneath cherty, light-gray, fine- to medium-grained marble of the Spectacle Formation. The tiny fraction of the gneiss dome exposed within the map-area (PLATE IV) is largely the exhumed surface of this contact, which is at least grossly conformable with the foliation in the gneiss. Thermal metamorphism of the nearby country rock did not exceed chlorite grade, therefore this part of the gneiss dome must have been relatively cool at the time of its ultimate implacement.

The small patch of malignite-shonkinite breccia plastered against the contact surface is probably the eroded remnant of a sheet which was formerly continuous with the malignite to the north. Despite the juxtaposition of the gneiss and malignite, no concrete evidence bearing on their relative age was observed.

Mafic alkalic rock

Malignite-shonkinite and malignite-shonkinite breccia.--Fine- to coarse-grained, dark-grayish-green to dark-bluish-gray malignite and malignite breccia are the most conspicuous and widespread rocks at both the Copper Mountain complex and the Oroville complex. Rocks within this unit span a compositional range overlapping parts of both the malignite and shonkinite fields (Table 8 and Fig. 2) but for simplicity will be referred to as malignite. At Copper Mountain the malignite breccia forms a discontinuous outer girdle around the complex, grading inward to closely jointed, massive malignite. At the Oroville complex, the malignite breccia has been mapped at several widely scattered localities, and is present at numerous unmapped localities of limited extent within the malignite unit, which occupies most of the western half of the complex.

The malignite is typically a weak, brittle rock, crumbling away along myriad intersecting fractures. It is composed of one-third to one-half dark-greenish-gray mafic minerals and two-thirds to one-half light-gray felsic minerals. The primary mafic minerals include hastingsite, aegirine-augite or augite, garnet, biotite, and magnetite; the primary felsic minerals include orthoclase, nepheline, sodalite(?) and oligoclase or andesine. In addition, certain secondary minerals including albite, chlorite, hydromica, sericite, calcite, and various minerals of the zeolite group are widespread. Accessories commonly include sphene, apatite, and magnetite.

Nepheline as an essential constituent was observed in several specimens, including samples from both the Copper Mountain and the Oroville complexes. It is more commonly pseudomorphically replaced by hydromica, and probably by analcite, although both of the latter minerals in places appear to have partially replaced plagioclase as well. The plagioclase is present as ragged, normally zoned laths with albitic rims. Orthoclase is perthitic, forming large poikilitic grains and filling intergranular areas.

Clots of blocky to lathy, pale-green uralitic aegirine-augite or augite and highly pleochroic dark-blackish-green to pale-yellowish-green hastingsite are commonly major constituents. In some rocks the clinopyroxene is much subordinate, being present only as scattered relict cores in grains of hastingsite. In others the hastingsite is present only as thin borders on the clinopyroxene. Biotite is sparsely present as decussate laths, associated with the other mafic minerals. Garnet is common in some rocks as anhedral, yellow-brown skeletal crystals or as anhedral granular aggregates replacing other mafic minerals.

The malignite is xenomorphic granular, with sutured and interdigitating grain boundaries. Most of this rock shows at least mild brecciation (Fig. 17), and microscopically displays a web-like network of chlorite- and calcite-filled cracks.

The breccia in its extreme development resembles a conglomerate (Fig. 18), with blocky to oval or lenticular clasts of malignite and rarely monzonite up to 1-1/2 inches long, and smaller broken crystal fragments, suspended in an aphanitic reddish-brown matrix, the whole cut by anastomosing veinlets of carbonate up to one-eighth inch thick.

The clasts of malignite resemble their less brecciated analogs described above. The intergranular material includes angular fragments of most of the mineral constituents of the malignite, which are entrained in a hematitic dust, along with untwinned calcite as discrete grains; as a constituent of rock fragments associated with orthoclase, apatite and sphene; and as intergrowths with clinopyroxene or hastingsite. Thin veins of twinned calcite cut the breccia.

All gradations from closely jointed and fractured malignite to fragmental rock with interlocking clasts, and to breccia of conglomeratic

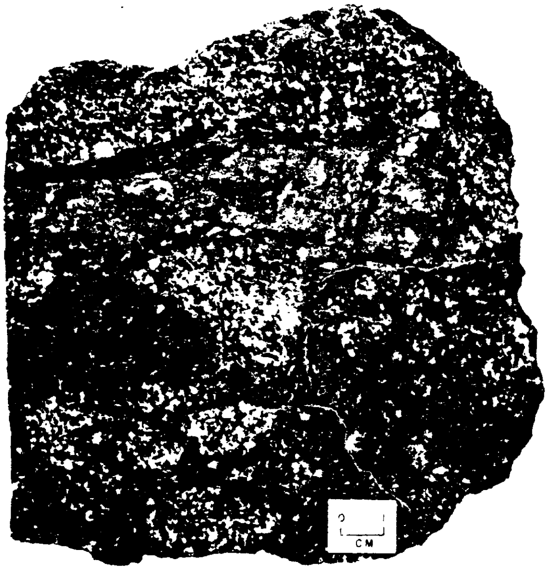

Fig. 17.--Photograph showing specimen of mildly brecciated malignite.

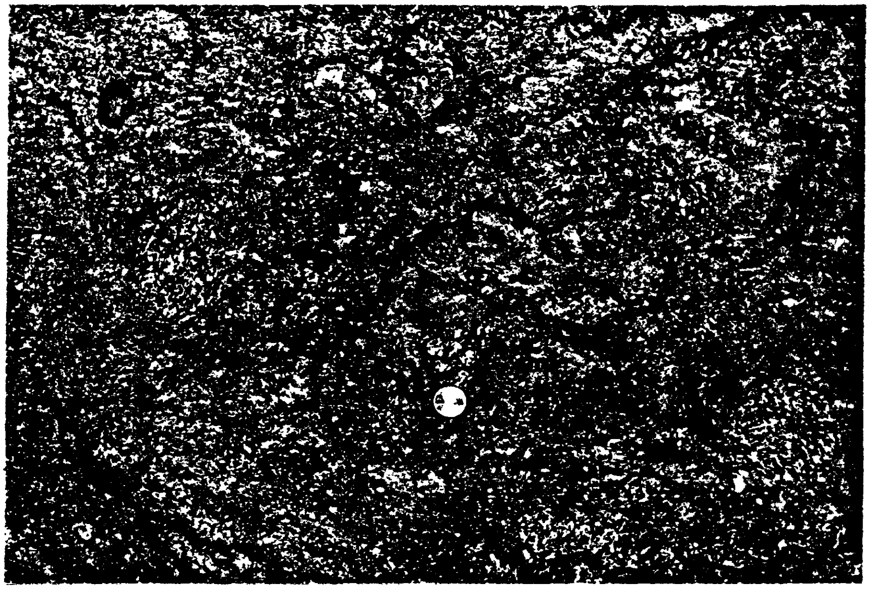

Fig. 18.--Photograph showing intensely brecciated malignite.

aspect are present. The mapped outline of the breccia represents at best a highly subjective attempt to show areas of relatively continuous breccia.

Both the malignite and the malignite breccia are criss-crossed by several sets of curving joints and shear planes with a slickensided surface coating of calcite and brick-red hematite. The joints and shears show little continuity on strike or regularity in attitude.

The malignite and malignite breccia are faulted against rocks of the Kobau Formation along the northwest side of the Oroville complex. The fault there is apparently steep. At the south margin of the Oroville complex, the malignite overlies rocks of the Spectacle and Ellemeham Formations along a sharp, shallowly north-dipping tectonic contact. The temperature of the fine-grained, micaceous meta-siltstone of the Ellemeham Formation below the contact was probably briefly elevated to that of the hornblende hornfels facies, as indicated by the presence within this rock of very-fine-grained hornblende.

Foyaite.--Light-bluish-gray, fine-grained foyaite composed chiefly of K-feldspar, plagioclase, nepheline or its alteration products, aegirine-augite, and hastingsite forms an irregular zone located at the northeast side of the Oroville complex, transitional between the coarser grained, darker colored malignite and the finer grained feldspathic biotite hornfels. Similar rock also occupies an irregular belt trending through the center of the Copper Mountain complex. The foyaite is inhomogeneous, with irregular streaks and splotches of slightly differing color index or grain size, and at Copper Mountain is weakly gneissose. In common with other rocks of the alkalic complex, the foyaite is everywhere fractured or subbrecciated, and locally is brecciated.

The composition and mineralogy of most of the foyaite differs little from that of the malignite (Table 8), except that the color index of the foyaite is less. Within the map unit the foyaite grades to juvite and to felsic shonkinite. K-feldspar is the main constituent, and in places at the Oroville complex shows poor development of the grid twinning of microcline, differing in this respect from other rocks at the complex, with the exception of the feldspathic biotite hornfels to the west. Albite or oligoclase is present as intergranular films and small anhedral grains between the K-feldspar grains. Plagioclase in a specimen from near the contact with malignite showed relict oscillatory zoning in lathy grains and ranged from An_{15} to An_{65}; another specimen from near the contact with the hornfels contained a few relict phenocrysts of andesine.

Hastingsite, aegirine-augite, and melanite singly or in combination with each other form conspicuous skeletal grains enclosing feldspar, or more commonly are present as clots of subhedral poikilitic pyroxene with uralitic overgrowths of hastingsite, which enclose patches and strings of anhedral garnet.

Nepheline or its pseudomorphs are subhedral; other constituents are typically anhedral. Some parallism of elongate K-feldspar grains is apparent even in the massive foyaite. The gneissic foyaite microscopically shows poor to fair segregation of mafic constituents into curving bands and displays fair orientation of elongate grains of K-feldspar, plagioclase, pyroxene, and hastingsite.

The contact of the foyaite with malignite is gradational; in the south half of section 14 at the Oroville complex, the location of the contact was placed at a narrow zone not wider than several tens of feet, across which the texture and color index of the rock graded abruptly from that of fine-grained foyaite to that of a medium-grained malignite of gabbroic appearance. At other localities the contact is rather arbitrarily placed in a wide zone across which a similar transition was observed.

Feldspathic biotite hornfels.--Dark-gray to greenish-gray, very fine-grained mafic rock megascopically resembling greenstone and composed essentially of a granoblastic aggregate of K-feldspar, plagioclase, and biotite fringes the Oroville alkalic complex on the northeast, and the Copper Mountain complex on the east. Other constituents present include apatite, muscovite, calcite, magnetite, and secondary chlorite. The K-feldspar is anhedral, locally poikiloblastic, and in one specimen from the Oroville complex showed grid twinning, and in two others did not. Plagioclase is present as anhedral laths of oligoclase smeared with alteration products and rimmed by albite. The feldspars are bordered by patches of finer grained magnetite, and flecked with much finer grained decussate biotite. No directional structure or relict fabric was observed.

The feldspathic hornfels is intensely sub-brecciated and locally is brecciated. At the Oroville complex the rock lightens in tone and becomes perceptibly coarser grained toward the southeast, where it ultimately grades to foyaite.

Felsic alkalic rocks

Monzonite and monzonite breccia. Monzonite and monzonite breccia occupy the northwest sector of the Copper Mountain complex, and a small part of the southwest sector of the Oroville complex. At Copper Mountain, the monzonite is grayish orange pink, massive, very coarse grained and trachitoid. It grades to feldspathic breccia composed of rounded to sharply angular, pebble-sized clasts of monzonite similar to the massive monzonite, fragments of very coarse-grained K-feldspar, and broken crystals of other minerals, which are firmly bonded within an aphanitic to very fine-grained matrix. The contact of the monzonite and monzonite breccia with the enclosing foyaite and malignite is sharp, crosscutting gneissosity in the foyaite at a shallow angle. On the north side of Copper Mountain, sills of monzonite breccia 2-3 feet thick, trending about N45E, and dipping 60° NW, which cut unbrecciated gneissic malignite are apparently offshoots of the mass of breccia to the south.

The monzonite and breccia at Copper Mountain are almost bereft of the small feldspathic dikes so abundantly present in the malignite. Several were observed, however, the largest about 1 ft. thick and 12 ft. in length.

The monzonite located in section 23, at the Oroville complex is coarse grained, leucocratic, and is pervasively crushed, except for a few areas not larger than about 50 sq. ft. The monzonite there is composed of plagioclase and large rounded perthitic orthoclase, embedded in a fine-grained interstitial mortar of plagioclase, along with abundant pale-green augite, minor chlorite, and accessory sphene, apatite, and magnetite. Accessory quartz is also present.

Alkalic dikes. The malignite, malignite breccia, and foyaite are cut by numerous thin dikes of leucocratic monzonite, monzonite breccia, and of mafic alkalic breccia. The monzonite dikes typically range between 1-12 inches in thickness, and are composed of coarse-grained perthitic orthoclase, minor oligoclase or andesine, accessory chlorite (pseudomorphing an unknown primary mafic mineral), apatite, magnetite, and calcite. The monzonite breccia, which in places grades to massive monzonite within the same dike, is composed of angular to rounded clasts of monzonite similar to the foregoing, firmly bonded in a matrix of more finely comminuted material. The mafic alkalic breccia dikes are of similar size, and composed of rounded clasts of malignite, monzonite gneiss, and angular crystal fragments. The clasts in these dikes are widely dispersed to closely packed in an aphanitic hematite- or magnetite-rich matrix (Figs. 19 and 20).

The dikes are exceptionally as thick as 10 feet, but most are short and lens-like, with strike lengths of only a few feet, although several could be followed for distances of as much as 40 feet. The longer dikes are contorted, rather than planar, and they pinch, swell, and bifurcate. Along strike their fabric varies from massive to conglomeratic. Some of the dikes terminate as strings of bead-like feldspar-rich lithic fragments which have apparently been kneaded into their brecciated host.

The monzonite at the Oroville complex is cut by thin white felsite dikes composed mainly of oligoclase (An_{12-18}). Except for a

Fig. 19.--Photograph showing specimen of dike of mafic alkalic breccia, with lithic and crystal fragments closely packed in an aphanitic hematitic matrix.

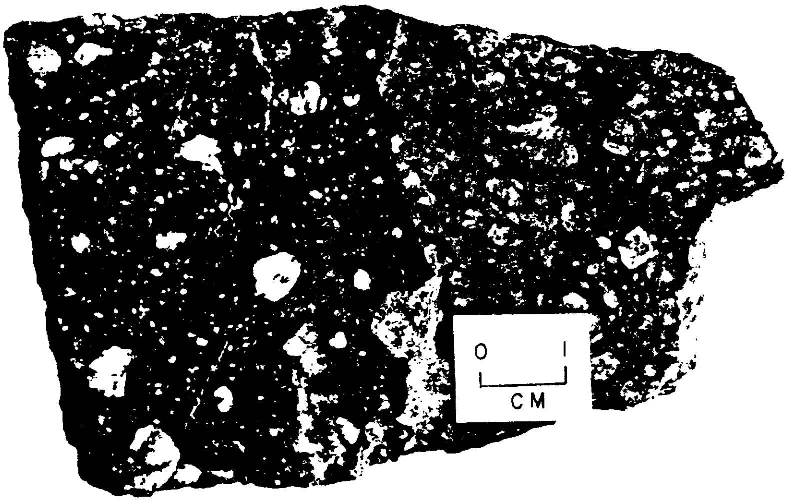

Fig. 20.--Photograph showing specimen of dike of mafic alkalic breccia with clasts loosely scattered through an aphanitic matrix.

few dikes within the relatively uncrushed area of the monzonite, the dikes have been converted to zigzag zones of white breccia.

The brecciation of the dikes could be partly or wholly a secondary feature, due to brecciation along with the host following their emplacement, and partly a primary feature originating, for example, through emplacement of the dikes as a gas-charged slurry of fragmental material derived from greater depths.

The contacts of the monzonite and the monzonite breccia dikes with their host is sharp, but typically the nearby wall rock is as brecciated as the dike, or nearly so. However, at the north side of Copper Mountain several two-inch thick brecciated monzonite dikes of conglomeratic appearance cut unbrecciated gneissose malignite. The massive malignite grades to subbreccia or breccia within a zone several inches wide bordering several of the mafic alkalic breccia dikes. The contrast in degree of comminution between dikes and wall rock is elsewhere less marked, but easily recognizable, even where the wall rock is itself a breccia of close-packed malignite cobbles with interstices filled with a hard, red-brown hematitic matrix similar to the matrix of the dikes.

The mafic alkalic breccia dikes were probably intruded as breccias, cutting the massive and brecciated phases of the malignite and the foyaite. The monzonite breccia dikes are at least in part intrusive breccia. All the alkalic dikes were extensively disrupted, deformed, and crushed after their emplacement along with their host.

Conglomerate and wacke

Epiclastic sedimentary rock composed of coarse conglomerate, wacke, and siltstone occupy a structural basin centered southwest of Oroville. Erosional remnants of a previously more extensive blanket of these sediments flank the Copper Mountain complex on the west and south and cover much of the central part of the Oroville complex (PLATE IV). The basal member of the sedimentary sequence is a massive conglomerate comprising two facies, a "malignite" conglomerate (Fig. 21) composed chiefly of unsorted clasts of malignite and shonkinite, with subordinate foyaite and monzonite, and a "monzonite" conglomerate composed mainly of clasts of monzonite. The alkalic constituents of the two facies are lithologically similar to ther counterparts within the crystalline rocks of the alkalic complexes.

The malignite conglomerate at the Copper Mountain complex is overlain by thick, massive beds of "granite" conglomerate, which is composed chiefly of unsorted clasts of quartz monzonite, monzonite, and granodiorite, and rarely of shonkinite and malignite. The malignite conglomerate at the Oroville complex interfingers with massive arkose containing interlayers of laminated to thin-bedded siltstone.

The malignite conglomerate is a somber brownish gray, and the monzonite conglomerate is gray to light gray. Both facies are composed of angular to rounded, rarely faceted, pebbles and cobbles up to 2-1/2 ft. long, packed in a matrix of wacke. The contact between the two facies is gradational. Outcrops are rubbly and the rock normally tends to break around the clasts. Thin arkosic interbeds are present, but rare. Except for the arkosic interbeds, little

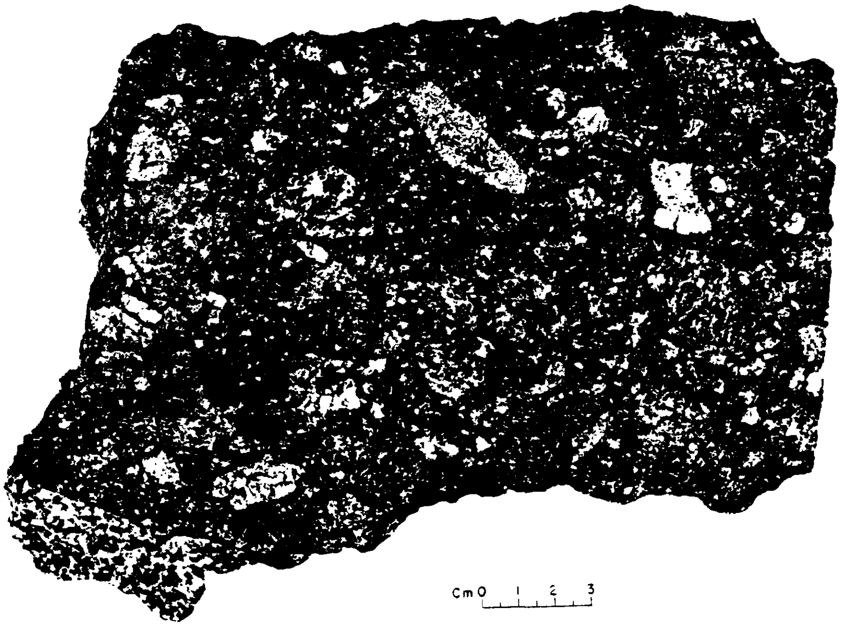

Fig. 21.--Photograph showing specimen of malignite conglomerate.

vestige of bedding is apparent. The basal contact of the conglomerate is somewhat arbitrarily drawn in places because of the close similarity of the unit with certain brecciated phases of the underlying alkalic rocks. At Copper Mountain the malignite conglomerate grades upward to the granitic conglomerate.

The arkose is friable to flaggy, thick bedded, and white to light olive gray and yellowish gray. It contains interbeds of very light greenish-gray arkose or wacke, and interbeds of thin-bedded very light-gray or light-brownish-gray siltstone. The arkose is thicker and more extensive several miles southwest and west of Oroville, where it intertongues with both the granitic and malignitic conglomerates. A fossil flora collected from the arkose in the NW 1/4, section 13, T. 40 N., R. 26 E. was considered "probably early Eocene" in age by J. A. Wolfe (Rinehart and Fox, in press [a]).

The granite conglomerate is massive and resistant, forming cuestas bounded by prominent, medium-light-gray cliffs. The cobbles are mostly between 4 and 10 inches in diameter but a few are as large as 4 feet in diameter. The matrix is greenish-gray, very fine to coarse sand-size arkose containing scattered small pebbles of metamorphic rock.

The monzonite clasts of the granite conglomerate are commonly trachytoid, containing large tabular phenocrysts of K-feldspar, and closely resemble the trachytoid monzonite of the Similkameen batholith. This feature, in conjunction with the presence of a few clasts of shonkinite and malignite, suggests that the source of the material of which the conglomerate is composed is the Similkameen batholith and the Kruger complex, which lie seven miles to the west-northwest.

The structural configuration of the malignite and monzonite conglomerates at the Oroville complex and the nature of their basal contact is somewhat puzzling. Bedding attitudes are surprisingly steep, and in places disagree with the attitude of the basal contact inferred from its topographic expression. For example at hill 2088, which straddles the line between sections 14 and 23, the crystalline rocks exposed on the summit area are scabbed by conglomerate on the flanks of the hill, indicating a shallow centripetal dip of the base of the conglomerate. Bedding along the west side of the hill dips steeply into the contact, however. Since the bedding attitudes were measured on thin interbeds of arkose or wacke, it is probably safe to assume that their initial dip was low. These relations indicate that the conglomerate has been deformed and at least locally dislocated along its contact with the underlying alkalic rocks.

Augite-biotite trachyandesite

Small plugs of massive, olive-gray to brownish-black trachyandesite cut the malignite conglomerate, arkose, and feldspathic hornfels along the northeast side of the Oroville complex. The trachyandesite is composed of augite and andesine phenocrysts 1-3 mm long which are scattered sparsely through a very fine-grained diabasic matrix, or more rarely form glomeroporphyritic aggregates. Other minerals present include sanidine, biotite, apatite, and magnetite. Accompanying these are scattered small amygdules of nontronite and natroalunite(?), and in places tiny xenoliths composed of fine-grained calcite.

The contact with the arkose and with the conglomerate, which is exposed at several localities, is vertical or nearly so, and sharply crosscutting.

Hornblende dacite

The hornblende dacite is massive to flow banded, light gray to olive gray, with black glomeroporphyritic hornblende "rosettes" up to 5 mm across, and smaller hornblende needles set in a very fine-grained, light-gray matrix. The matrix is composed of oligoclase or andesine with sparse grains of augite, apatite, and magnetite. The hornblende dacite in the northwest part of the map-area is part of a small plug which cuts the granite conglomerate. That north of the Oroville alkalic complex is part of a poorly exposed mass lying to the north and east, which may be in part extrusive.

Summary and interpretation

The alkalic rocks of the Copper Mountain complex comprise chiefly medium- to coarse-grained malignite (and shonkinite), fine-grained foyaite grading locally to juvite, medium- to coarse-grained monzonite, and minor very fine-grained feldspathic metamorphic rock. The malignite grades to an irregular inner zone of the foyaite, and to a discontinuous outer zone of malignite breccia. The monzonite occupies the northeast sector of the complex, and is massive to sub-brecciated near the center of the complex, grading northward to monzonite breccia. The monzonite clearly intrudes the malignite and the foyaite. The malignite and the foyaite grade to feldspathic hornfels at two localities along the eastern periphery of the complex.

The Oroville complex is composed chiefly of medium- to coarse-grained malignite (and shonkinite). The malignite grades locally to malignite breccia, and at the northeastern flank grades to fine-grained foyaite, which in turn grades to feldspathic hornfels. The malignite is cut by a small plug of monzonite, lithologically similar to that at Copper Mountain.

The alkalic rocks of the Copper Mountain complex are similar to those at the Oroville complex, and indeed, it is possible that the two complexes connect beneath the 1-1/2 mile wide alluvial-filled valley intervening between them. However, at Copper Mountain, the presence of feldspathic hornfels along the eastern side and the annular pattern revealed by the distribution of malignite breccia suggest that the complex is not much larger than its exposed area. If not, the two areas of alkalic rocks are probably discrete complexes. Aside from this argument there is little reason not to believe that the two complexes are in reality the eastern and western extremities of a single complex, whose major part is concealed by valley fill.

The malignite unit at both the Oroville and Copper Mountain complexes shows radical local variation in degree of fragmentation, grading from closely jointed to sub-brecciated and to brecciated zones. The degree of alteration also shows considerable variation, but over a somewhat broader scale, with the dark-gray, fresher rocks exhibiting glistening black mafic minerals, in contrast to the brownish-green altered rocks with their splotchy aggregates of chlorite and relict primary mafic minerals. However, the primary character of the malignite is probably much more homogenous than the superficial diversity in external appearance would suggest. The malignite is typically fine grained, although grading to coarse-grained variants in places, and possesses a texture which could be described as hypautomorphic granular were it not for ragged uralitic overgrowths of anhedral hastingsite mantling and corroding the pyroxene.

The foyaite is similar to the malignite, except that it possesses a patchy variability in grain size, color index, and fabric, and in general is finer grained and more felsic than the malignite. The corroded relics of zoned plagioclase, and glomeroporphyritic clumps of lathy augite or aegirine-augite present in both units suggest that they crystallized from a magma.

Augite or aegirine-augite with or without plagioclase crystallized early during the solidification of the malignite and of the more mafic parts of the foyaite, and later were partially resorbed during the crystallization of nepheline, orthoclase, and amphibole. Garnet partially replaced the pyroxene during the final stages of primary crystallization, or perhaps was an early product of deuteric alteration. Biotite appears ubiquitously as small anhedral decussate shreds, and rarely as larger corroded relics, indicating two generations of this mineral. Crystallization of the earlier may have been partly contemporaneous with crystallization of the pyroxene.

The paragenesis of one part, perhaps the most felsic part, of the foyaite differs from that given above. In it the skeletal form of the pyroboles and their interstitial relation to the felsic minerals suggests that their crystallization followed that of the bulk of the felsic minerals.

Judging from the diffuse character of their mutual contact, and their compositional and mineralogical similarities, the malignite and the foyaite were probably intruded at each of the alkalic complexes as a single composite mass.

The feldspathic biotite hornfels is probably a fenitized derivative of the country rock located adjacent to the alkalic complexes. The high color index, fine grain size, and lack of layering, bedding, or other primary depositional structures indicate that the parent rock may be massive greenstone of either the Ellemeham Formation or the Kobau Formation. Conversion of a greenstone to a rock with the composition of the feldspathic hornfels would require addition of substantial quantities of potassium. In view of the gradational contact with the silica-undersaturated foyaite at the Oroville complex, the introduction of potassium was probably accompanied by a reduction in silica.

Except for those rocks included within the feldspathic biotite hornfels, the thermal metamorphism attributable to emplacement of the alkalic complexes was slight. Dynamic metamorphism related to their emplacement is reflected by brecciation of limestone at the south border of the Oroville complex, and brecciation of metadiabase along the northeast flank.

One of the more perplexing features associated with the alkalic complexes is the monolithologic alkalic conglomerate found at the base of the Tertiary epiclastic deposits. Remnants preserved at the Oroville complex of what was surely a much more extensive layer of the alkalic conglomerate are composed dominantly of detritus of either monzonite or malignite and foyaite, the clasts of which are indistinguishable from the corresponding bedrock lithologies of the Oroville complex. Clasts which could have been derived from the nearby metamorphic bedrock are rare. The overlying "granite" conglomerate to the west was probably derived largely from the Similkameen pluton and Kruger complex, but the absence of sorting and sizing in the alkalic conglomerate, its monolithologic character and identity with the bedrock compel the conclusion that the alkalic conglomerate was eroded from and deposited on the alkalic complexes with but short transport and little mixing. The small outcrop area of the monzonite at the Oroville complex is out of proportion with the large extent of the monzonitic phase of the nearby alkalic conglomerate. Possibly the alkalic conglomerate is a partly reworked relic of a former shallow vent or crater filling.

The steep dips among the measured attitudes indicate considerable post depositional deformation. Also, as has been mentioned, the attitude of the basal contact of the alkalic conglomerate at the Oroville complex as inferred from topographic relations does not agree with attitudes measured on nearby interbeds of wacke. These relations can best be accounted for by local subsidence and concomitant inflation elsewhere within the complex, coupled with erosion, deposition, and perhaps land-sliding, of early Eocene age. If so, deformational activity restricted to the Oroville complex and therefore related to it continued into early Eocene time.

The Eocene deformation of the complex is at least partly attributable to intrusion of the augite-biotite trachyandesite plugs which cut the complex on its eastern flank. Crosscutting contact relations and near vertical attitudes of the nearby Tertiary epiclastics suggest sapping and foundering of the wall rock or roof rock into the magma chamber. The association of the trachyandesite with the alkalic complexes may be significant in itself, since coeval hypabyssal intrusives and volcanic rocks more distant from the complexes are both more silicic and less potassic relative to their silica content than is the trachyandesite.

The proximity of the Okanogan gneiss dome to the Oroville alkalic complex introduces some uncertainty in the interpretation of the cataclastic or deformational history of the alkalic rocks. Other plutons within the aureole of dynamic metamorphism bordering the dome were severely crushed, acquiring thereby a penetrative cataclastic fabric in which each domain of even microscopic dimensions is crisscrossed by anastomosing bands of mortared felsic minerals and smeared out mafic minerals. These bands are typically entwined around augen or augen-shaped aggregates of variously abraded and mortared minerals.

Krauskopf (1941) attributed the brecciation of the alkalic complexes to dynamic metamorphism accompanying the intrusion of the Okanogan gneiss dome, nee "Colville batholith," while recognizing that the alkalic breccia differed from the usual cataclastic product of the intrusion of the dome. The alkalic rocks, even where reduced to breccias of conglomeratic appearance, are essentially intact within any particular clast, showing no internal granulation or mortaring, nor bending of biotite laths, nor typically even undulose extinction. The monzonite breccias and the breccia dikes are exceptions to this generalization, in that they do show in numerous sections internal cataclasis within clasts, resembling that attributed to intrusion of the dome in other localities.

Probably the breccias at the Copper Mountain and Oroville complexes are primarily the products of internal processes related to the development of the alkalic complexes, and are not the products of crushing by the Okanogan gneiss dome. In this connection, the alkalic rocks, both massive and brecciated, resemble those at Shankers Bend, which lie five miles from the nearest exposed part of the gneiss dome, and which are probably at or just outside the outermost fringe of the zone in which dynamic metamorphism attributable to the intrusion of the dome can be discerned.

The absence of cataclastic effects within the alkalic complexes clearly attributable to crushing by the gneiss dome is poor evidence that the dome is the older, since the complexes could have yielded passively through further dislocation along the myriad fractures previously formed by internal processes. Also there is no assurance that the crushing action of the dome in the direction of the complexes was as severe as elsewhere. Unfortunately, the age of the alkalic complexes relative to the dome remains an unsolved problem, although at least the final stages of alkalic plutonism, as represented by the intrusion of biotite-pyroxene trachyandesite and the related Eocene deformation, postdate the emplacement of the dome.

The three chief attributes of the Oroville and Copper Mountain complexes which are not shared by more conventional intrusive bodies are: (1) the alkalic character of much of the rock within the complex; (2) the several episodes of brecciation and deformation related to formation of the complexes; and (3) the alkalic metasomatism of certain nearby parts of the country rocks. To account for these features, and those detailed in the preceding descriptions, the following sequence of events is postulated:

(1) Fracturing of country rock in advance of an ascending column of magma and vapor.

(2) Fenitization in the path of the magma through reaction of the vapor phase with portions of the country rock.

(3) Emplacement of an inhomogenous magma, and solidification of the magma to malignite-shonkinite and foyaite.

(4) Emplacement of gas-charged slurries of malignite breccia, forming thin dikes.

(5) Emplacement of monzonite as large masses and as thin dikes, partly as intrusive breccia.

(6) Shattering and remobilization of the previously crystallized alkalic rocks as an intrusive breccia, resulting in disruption of earlier dikes, followed by upward advance of the breccia column, then final lithification of malignite breccias.

(7) General shattering and jointing of the alkalic rocks, and erosion and deposition of alkalic conglomerate.

(8) Passive intrusion of trachyandesite accompanied by local inflation and in places, foundering of the wall and roof rocks.

The Copper Mountain and Oroville complexes are probably alkalic diatremes.

Bimetallic Mountain Alkalic Complex

Introduction

Brecciated shonkinite and trachytoid monzonite occupy the crestal area of Bimetallic Mountain, a low, convex, partially forested hill located 16 miles east of Oroville (PLATE V). The alkalic rocks are well exposed on the crest and on the southwest and southeast slopes of the hill, but elsewhere are concealed by glacial drift and heavy timber.

Deposits of molybdenum and copper which are present within the northeastern sector of the complex were described by Storch (1946), and by Purdy (1954). A sharply defined magnetic high at the site of the alkalic complex was revealed by an airborne magnetometer survey (Hunting Geophysical Services, Inc., 1960).

Geologic setting

The plutonic rocks of the complex intrude metasiltstone, phyllite, and meta-limestone of the Anarchist Group, and massive, mafic metasiltstone and greenstone tentatively correlated with the Ellemeham Formation (PLATE V). Rocks referable to the Ellemeham Formation have not been found in this area except in the immediate vicinity of the alkalic complex. The nearest exposures of the Ellemeham Formation outside the Bimetallic Mountain area are located 16 miles west along the Okanogan River valley. The complex is partially covered by massive to laminated siltstone, wacke, and arkose.

The siltstone, arkose and wacke are probably an erosional outlier of a thick and extensive sequence of Tertiary epiclastic and volcanic rocks, the nearest exposures of which lie six miles to the east of Bimetallic Mountain (PLATE I).

Isolated exposures of porphyritic hornblende-quartz monzonite containing poikilitic phenocrysts of orthoclase, are present in the south-central and southwestern parts of the map area. The quartz monzonite is brecciated, except for the outcrop of massive rock in the NW 1/4 section 35. The brecciation is probably the result of crushing during emplacement of the Okanogan gneiss dome, which flanks the quartz monzonite and low-grade metamorphic rocks on the south and east along a contact concealed by a wide expanse of glacial drift.

Rocks of the Anarchist and Ellemeham Formations have been only weakly metamorphosed except within the metamorphic aureole of the complex. The Anarchist Formation possesses a penetrative foliation, generally parallel to bedding and primary layering. Mineral assemblages are compatible with regional metamorphism within the quartz-albite-muscovite-chlorite subfacies of the Barrovian greenschist facies. The Ellemeham Formation has been metamorphosed to at least chlorite grade, but is not foliated. The low metamorphic grade of these rocks is surprising in view of the effects of contact metamorphism expected this near to the north border of the gneiss dome. Rocks of the Anarchist bordering the eastern side of the dome, six miles to the northeast have been metamorphosed to staurolite grade within a half to a quarter mile of the gneiss dome. Similarly, country rocks at the contact three miles to the northwest of the alkalic complex show a conspicuous increase in grade within a half to a quarter mile of the gneiss dome.

The physical appearance of the alkalic rocks is much varied, both because of their primary compositional diversity, and because of radical areal variation in the degree of brecciation and the degree of hydrothermal alteration. Dark-gray, fine- to medium-grained shonkinite of gabbroic appearance is the most widespread rock. It apparently grades erratically in the central and eastern sectors of the complex to coarsely trachytoid monzonite, but contact relations are obscured by brecciation. Possibly the monzonite intrudes the mafic alkalic rock. Both the shonkinite and the monzonite are cut by thin dikes and irregularly shaped masses of alaskite.

Brecciation is most intense in the central and eastern sectors. The rocks there are locally reduced to monolithologic breccia. Hydrothermal alteration, manifested chiefly by chloritization and locally by silicification is most pronounced in the eastern sector near the copper-molybdenum deposits.

Shonkinite

The complex is composed chiefly of medium-grained, dark-gray shonkinite, which grades locally through decrease in plagioclase and a reciprocal increase in hydromica to malignite. The hydromica is assumed to be a pseudomorphic replacement of primary nepheline. The distinction between malignite and shonkinite could not be made in the field.

The shonkinite is hypautomorphic granular, tending to xenomorphic granular. The chief constituents are orthoclase, aegirine-augite (or augite), hastingsite, and plagioclase (Table 10). The pyroxene is lathy, subhedral pale-brown augite or pleochroic

TABLE 10

MODES OF THE BIMETALLIC MOUNTAIN AND CUMBERLAND MOUNTAIN ALKALIC COMPLEXES
(in Volume Percent)

Sample	Number Points	Nepheline	Pseudo-leucite[1]	Hydromica[2]	K-feldspar	Plagioclase	An of Plag.	Hastingsite	Clino-pyroxene	Biotite	Garnet	Sphene	Apatite	Magnetite	Calcite	Prehnite	Zeolite Group	Sodalite?	Epidote Group	Others
							Bimetallic Mountain Alkalic Complex													
0-401A	1315				31.8	27.8	Olig.-And.	21.3	11.2		tr.	0.8	0.5	2.1	tr.					3.6
0-428B	1218			9.8	49.2	13.3	Olig.-And.	14.5	10.7			0.4	0.7	1.4	0.1		tr.			
0-428C	1512				20.4	21.3	And.-Lab.	36.7	19.0		0.7	0.1	0.8	0.6						0.1
0-428D	1210				39.3	2.9	Alb.	38.4	10.6[3]	0.2		0.1	1.9	0.6					3.3	3.2
0-431F	1458				22.4	20.1	Olig.-And.	34.8	13.9				1.9	1.9	0.3				4.4	0.3
0-433A	1452			2.3	9.3	38.8	29-47	36.4	10.5	0.3	0.2	tr.	1.1	0.5					0.4	
							Cumberland Mountain Alkalic Complex													
0-490A	1552			20.4	44.7			0.9	25.4	1.4	0.5	0.6	0.5	3.9	0.3		1.4			
0-491C	1365	tr.		24.4	53.2			0.4	11.0	1.5	2.1	0.8	0.1	2.3	0.4	0.4	2.8			0.4
0-491D	1509	tr.	3.6	27.3	49.6			0.7	11.8	0.9	0.8	0.7	0.1	2.7	tr.	0.3	1.2			
0-491F	1404	29.8			48.4			0.4	13.2	1.4	1.3	0.7	1.1	1.4				2.1		
0-492B	1492			27.7	49.8	1.1	Alb.	5.8	9.0	2.1	0.7	0.7	0.6	1.3		0.3	0.9			
0-493D	1503		1.3	28.7	48.6				16.2	0.2	0.3	0.7	0.4	3.0		0.6				
0-495D	1585			3.8	34.3	19.2	50	10.5	24.8	0.2		0.3	0.4	2.7	2.2		1.1			0.6

[1] Fingerprint intergrowth of orthoclase plus hydromica.

[2] Includes intergrowths of analcite plus clay minerals, analcite plus natrolite, and cancrinite (rare). Presumed to be secondary replacement of primary feldspathoids.

[3] Includes 3.2 percent leucoxene-like alteration of clinopyroxene.

light-green to very light-green aegirine-augite. Accessory biotite, where present, is intergranular and sometimes embays both the pyroxene and the accompanying plagioclase. Tabular poikilitic phenocrysts of perthitic orthoclase and anhedral glomeroporphyritic plagioclase are the major felsic minerals. The orthoclase phenocrysts are locally well developed and oriented, imparting a trachytoid texture to the rock. Plagioclase in some rocks is as abundant as orthoclase, but commonly is less abundant, and in some rocks is scarcely more than an accessory. Magnetite occurs interstitially with pyroxene and biotite, and is typically rimmed by sphene. The abundance of hastingsite varies from rocks in which it is the dominant mafic mineral to those in which it is entirely absent. The hastingsite appears in three fashions: as ragged uralitic overgrowths on pyroxene; as discrete subhedral grains showing fair development of 110 exterior faces; and as skeletal grains intergranular to the felsic constituents. The three are commonly present within a single thin section.

The malignite is similar to the shonkinite, except that hydromica is present occupying subhedral to anhedral areas rimmed by albite and usually surrounded by orthoclase. Except for the albite, plagioclase and hydromica tend to be antipathetic, and although commonly present within a single thin section, they usually occupy discrete zones. Melanite is a common accessory in the malignite, in contrast to the shonkinite where it is rarely present.

The probable paragenesis of the major constituents of the shonkinite and malignite based on their textural relations is as follows: Clinopyroxene and plagioclase were the earliest to crystallize, followed by biotite. Hastingsite and orthoclase crystallized later, probably with concomitant corrosion of the plagioclase and partial conversion of biotite and the marginal areas of the clinopyroxene to hastingsite. In the malignites a feldspathoid, probably nepheline, crystallized along with orthoclase during the final stages of solidification of the rock, and was later replaced by hydromica.

Monzonite

The trachytoid monzonite differs from the shonkinite in being more leucocratic and possessing strikingly well developed tabular phenocrysts of poikilitic orthoclase, some of which are as long as 2-1/2 inches. Length to width ratios of the orthoclase phenocrysts are approximately 4:1. Borders of the phenocrysts are ragged on a microscopic scale. The intergranular material is a medium-grained xenomorphic aggregate of andesine and partially chloritized and poikilitic to skeletal hornblende. Accessories include magnetite, apatite, large wedge-shaped grains of sphene, and shreds of biotite.

Border rocks

Greenstone of the Ellemeham Formation lying east of the complex is a subbrecciated, brittle, light-green chlorite-sericite meta-basalt, showing blastointersertal texture with scattered albitized phenocrysts of plagioclase. As the contact with the plutonic rocks of the complex is approached the greenstone grades to a coarser grained, recrystallized and feldspathic rock composed chiefly of granoblastic K-feldspar, locally showing incipient grid twinning, along with anhedral lathy albite and an intergranular to skeletal mafic mineral, which has been pseudomorphically replaced by a serpentine-like mineral. The transition from greenstone is accompanied by a progressive increase in abundance of thin albitic dikes and stringers, which are locally kneaded into breccia along with the wall rock. The contact with the brecciated shonkinite is covered, but is probably fairly abrupt.

The Ellemeham Formation at the southeast border of the complex comprises greenstone, greenstone breccia, and thin-laminated metasiltstone. The greenstone breccia is dark greenish gray, and composed of angular clasts 1-10 mm long packed in an aphanitic matrix. The clasts are mainly very fine-grained greenstone and micro-laminated greenschist along with scattered clasts of fine-grained marble, coarsely crystalline calcite and also fine-grained feldspathic dike(?) rock.

The metasiltstone shows contorted grayish-black laminae alternating with olive-gray and light-gray laminae, which are composed of varying proportions of K-feldspar, quartz, muscovite, biotite, chlorite, and very fine-grained opaque material.

The greenstone, greenstone breccia, and metasiltstone grade to mafic, medium-gray, fine-grained hornfels near the contact with the alkalic rocks. The hornfels is streaked by wispy, light-gray veinlets of coarse-grained calcite with intergranular chlorite, and by zones of coarser grain size. The hornfels consists of patches of fine-grained mosaic-textured orthoclase with intergranular decussate biotite and poikilitic porphyroblasts of a mafic mineral now completely replaced by chlorite. These patches grade to areas of coarser grained orthoclase which have intergranular albite films, and interstitial aggregates of chlorite and calcite. Carbonate-rich zones composed of anhedral calcite, quartz, partially chloritized biotite, and garnet are present in the hornfels near the contact with the alkalic rocks.

Rocks of the Anarchist Group nearest the complex on the west are fine-grained quartz-biotite-muscovite schist with interlayered fine-grained sericite-quartz metalimestone. Poikiloblastic garnet appears in schists 500 feet west of the north-northwest trending metalimestone in section 34 (PLATE V). Northeast of the complex, in section 26, fine-grained calcite-sericite-quartz phyllite and graphitic quartz-sericite limestone are exposed at the portal and on the dump of the lower tunnel of the molybdenum prospect.

Dikes

The brecciated and metasomatized bordering rocks of the Ellemeham Formation and the alkalic rocks are cut by numerous thin dikes and irregular masses of fine-grained alaskite, probably by thin dikes of hematitic breccia, and by two thicker dikes of felsite. The felsite dikes and one of the larger masses of alaskite, which is exposed in the mine workings and prospect pits at the northeast sector of the complex, are shown on the map (PLATE V).

The alaskite is the most abundant, being distributed throughout the complex, mostly as thin dikes a few inches thick but ranging up to irregular masses several tens of feet across. It is typically xenomorphic granular, composed of orthoclase, quartz, and oligoclase-andesine, with minor hornblende, magnetite and accessory apatite. The alaskite is brecciated to the same degree as its host and is locally hydrothermally altered and mineralized.

Grayish-red hematitic breccia exposed at the southern extremity of the brecciated shonkinite in section 34 may be intrusive in part. The breccia contains equant, but angular clasts up to 30 mm across, sparsely scattered through a grayish-red matrix of hematite and finely disseminated magnetite. The clasts are predominantly coarse-grained monzonite and trachytoid malignite, along with discrete grains of their constituent minerals. Many clasts show patches or bands of mortar texture in their interior and at their periphery, indicating granulation. The relation of the hematitic breccia to the country rock, which in this vicinity is a poorly exposed hodgepodge of brecciated shonkinite and recrystallized metamorphic rock, could not be established.

The felsite dikes are yellowish gray, porphyritic, with feldspar and mafic phenocrysts scattered through a very fine-grained matrix. Only the easterly of the two dikes was sampled and thin-sectioned. It proved to be highly altered, with feldspar largely replaced by muscovite and calcite, and primary mafic minerals replaced by chlorite. Neither dike is brecciated, in contrast to other rocks within the complex, thus their emplacement probably postdates the alkalic activity in the area.

The border rocks are cut by small, irregular, brecciated veins and stringers of albitite, hydromica ("nepheline") syenite, and orthoclasite. Too few samples were collected to establish the areal distribution or relative abundance of the three lithologies.

Arkose and siltstone

The alkalic rocks are overlain by massive arkose, containing rare conglomeratic zones and interbeds of laminated siltstone. The arkose is hard, massive, light olive gray and very fine to medium grained. Locally it contains scattered disc-shaped pebbles of siltstone. It also contains scattered angular pebbles of monzonite, shonkinite or malignite, and alaskite near its contact with the alkalic rocks.

A monolithologic granitic breccia, grading to conglomerate, crops out at the southeastern edge of the arkose in section 26. The clasts are angular to rounded pebbles and cobbles of hornblende quartz monzonite, packed in a matrix of olive-gray wacke. The granitic clasts closely resemble the rocks of the pluton exposed only 500 feet to the south, and are therefore probably detritus derived from that body.

The arkose is apparently faulted against the alkalic rocks at its northwestern contact. Olive-gray arkose fills cracks and angular cavities in the alkalic rocks where exposed on the face of a 5-8 ft. high faultline scarp which marks this contact, suggesting that faulting occurred before lithification of the arkose.

In addition to detrital mica, the arkose contains fine shreds of secondary muscovite, and the very fine-grained matrix between the sand grains exhibits a granoblastic texture suggesting recrystallization. These features suggest that the arkose has been weakly metamorphosed, as previously noted by Purdy (1954). However, Purdy's correlation of the arkose with the Anarchist Group is unacceptable, since the arkose contains detritus from both the subjacent alkalic complex and the nearby quartz monzonite pluton, both of which intrude the Anarchist Group. The arkose is probably early Tertiary in age, judging from its similarity to other continental epiclastic deposits of that age in the region.

Summary and interpretation

The alkalic complex at Bimetallic Mountain consists of a core of massive to brecciated shonkinite, trachytoid monzonite, and alaskite, which is partially girdled by recrystallized and locally metasomatized, brecciated greenstone and metasiltstone, and is patchily overlain by massive arkose, siltstone, and conglomerate. The shonkinite grades unsystematically to malignite. The shonkinite and malignite also grade erratically to trachytoid monzonite. Rocks of both shonkinite and the monzonite map units are cut by alaskite, and the alaskite is brecciated to the same degree as is its host.

The greenstone and metasiltstone of the Ellemeham Formation bordering the complex are cut by numerous leucocratic dikes and veins, including albitite, orthoclasite, and hydromica "nepheline" syenite, and has been locally converted to hornfels composed essentially of K-feldspar, albite, and the alteration products of primary intergranular mafic mineral(s). This conversion would require metasomatic addition of potassium, and possibly sodium, changes consistent with those expected during fenitization. The border rocks, like the alkalic rocks, are erratically brecciated.

The arkosic beds overlying parts of the complex are provisionally correlated with early Tertiary epiclastic deposits to the east.

The alkalic rocks cut rocks of the Ellemeham Formation, which is probably Triassic or younger. If these correlations are correct, the complex is not younger than early Tertiary nor older than Triassic. The age of the complex relative to the gneiss dome or to the quartz monzonite pluton was not established.

The history of the complex inferred from the foregoing is as follows:

1. Piercement of the Anarchist Group and Ellemeham Formation by a gas-charged inhomogeneous alkalic magma.
2. Crystallization of magma to a complex of mafic alkalic rocks and trachytoid monzonite, with concomitant fenitization of bordering greenstone and mafic metasiltstone.
3. Intrusion of dikes and irregularly shaped masses of alaskite.
4. Pervasive brecciation of rocks of the complex and the fenitized wall rock. Hydrothermal alteration and mineralization.
5. Erosion, then burial of alkalic complex in the early Tertiary by arkose, siltstone, and conglomerate probably eroded from nearby sources.
6. Faulting of alkalic complex and unconsolidated overlying beds.
7. Lithification and weak thermal metamorphism of arkose.

Alkalic Rocks of the Cumberland Mountain Area

Introduction

A group of small alkalic plutons was located and mapped by Pearson (1967) within an area of 10 square miles near Cumberland Mountain in the southwestern part of the Bodie Mountain quadrangle (Fig. 22). The area embraces a rugged, heavily forested, upland surface which includes the gently sloping northwest flank of Cumberland Mountain and the adjoining highlands. The upland is deeply dissected by a system of canyons occupied by the North Fork and South Fork of Beaver Creek and their tributaries. The Cumberland Mountain area lies about eight miles east-southeast of the Bimetallic Mountain alkalic complex, and includes the easternmost known occurrence of alkalic plutons alined directly east-southeast of the Similkameen batholith.

The alkalic rocks resemble those at the alkalic complexes previously described, both in their overall diversity and in the similarity of specific rock types, of which malignite, foyaite, shonkinite, monzonite, and intrusive alkalic breccia are most abundant. Significantly, however, some of the alkalic plutons of the Cumberland Mountain area cut the Eocene O'Brien Creek Formation, yet are older than the Eocene Sanpoil Volcanics, and therefore are Eocene in age (Pearson, 1967).

A detailed investigation of these alkalic rocks was not attempted. But since the age of the Oroville, Copper Mountain, Shankers Bend, and Bimetallic Mountain alkalic complexes could not be established from field relations, except within very wide limits, several of the plutons

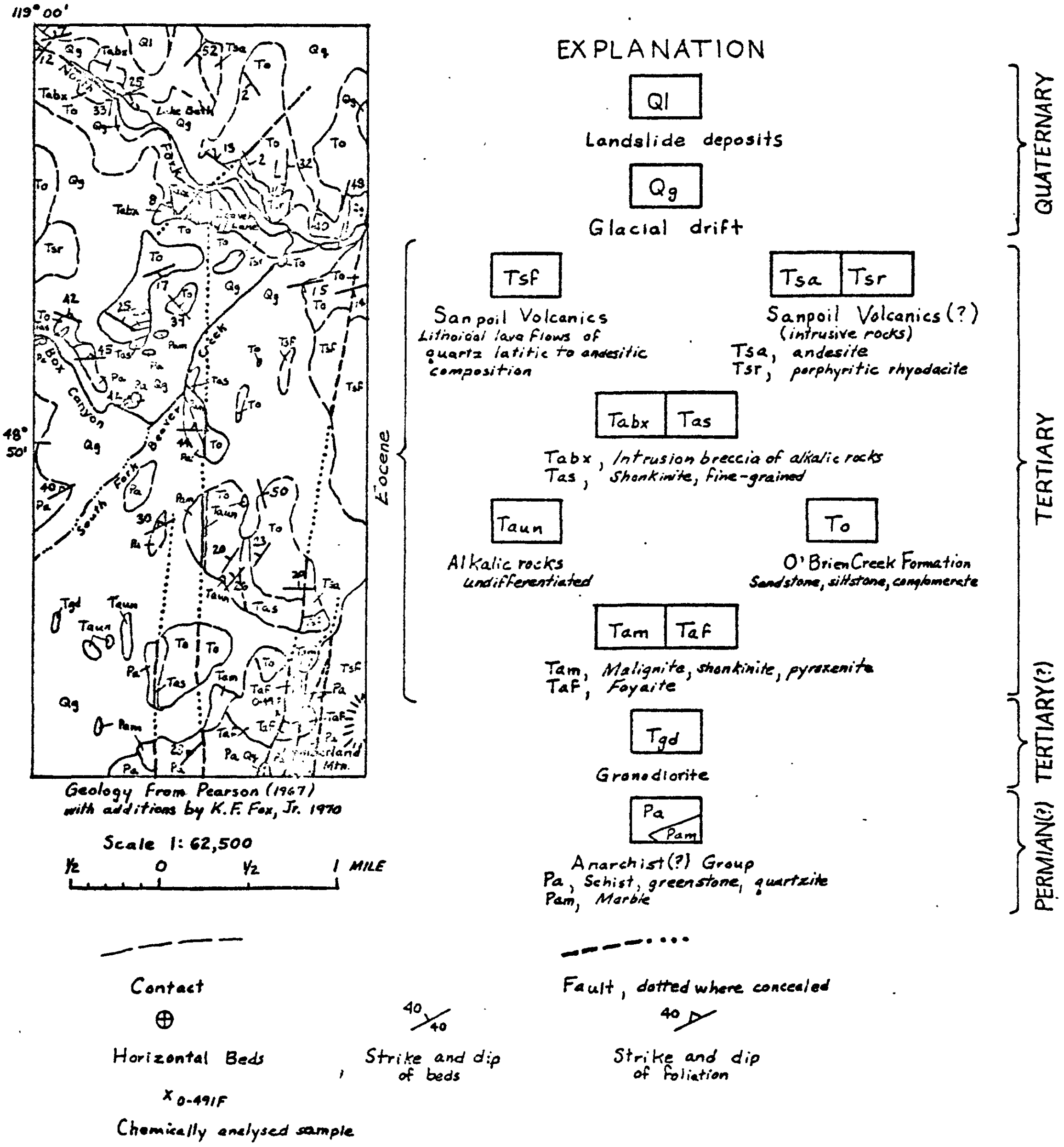

Fig. 22.--Geologic map of alkalic rocks of the Cumberland Mountain area, Bodie Mountain 15' quadrangle, Washington.

in the Cumberland Mountain area whose ages were more closely bracketed were reconnoitered by the author with the limited purpose of comparing them with the alkalic complexes to the west.

Geologic setting

Dark-gray schist, locally studded with crystals of staurolite, and containing scattered interlayers of both medium- to coarse-grained white marble, and fine-grained dark-bluish-gray impure meta-limestone is exposed in scattered windows through the glacial drift in the southwest sector of the map-area (Fig. 22). The schist flanks the Okanogan gneiss dome, whose eastern border lies only one mile west of the map-area. About three miles northwest of Box Canyon, outside the map-area, the staurolite schist is interlayered with garnet schist and the sequence grades abruptly northward to black slate, and weakly metamorphosed siltstone and sharpstone conglomerate. These rocks are believed to belong to the Anarchist Group, because of close lithologic similarity, and their stratigraphic position in the Chesaw area below the distinctive basal magnesitic zone and overlying greenstone-metachert beds of the Kobau Formation (Fox and Rinehart, 1967). The staurolite-grade metamorphism of the Anarchist rocks in the Box Canyon area is attributed to thermal metamorphism by the nearby granodioritic phase of the Okanogan gneiss dome (PLATE I).

Metamorphic rock along the eastern contact of the gneiss dome is cut by numerous dikes, plugs, and sills of granodioritic to quartz monzonitic alaskite exhibiting a remarkable variation from fine to pegmatitic grain size within the outcrop and even within the hand specimen. One outcrop of this rock is located in the extreme southwest corner of the map-area (Fig. 22).

The map-area (Fig. 22) overlaps the western fringes of the O'Brien Creek Formation and the Sanpoil Volcanics, parts of a thick sequence of Tertiary epiclastic deposits, volcanic flows and hypabyssal intrusive rock occupying extensive areas to the east. The O'Brien Creek Formation is the basal unit of this sequence, and is widely distributed within the Cumberland Mountain area; where it consists of interbedded massive to thin-bedded arkose, laminated siltstone, and conglomerate. Pearson (1967) describes the unit as consisting of tuff, lapilli tuff, tuffaceous sandstone, siltstone, and shale, gray carbonaceous siltstone and shale, and conglomerate. The O'Brien Creek Formation is overlain along the east border of the map-area by lava flows of the Sanpoil Volcanics, which are of andesitic to quartz latitic composition, and is cut by small, irregular plutons of andesitic and of rhyodacitic composition (Pearson, 1967).

Alkalic rocks

Those alkalic plutons for which sufficient information is available for classification are of three types: (1) hypabyssal intrusive dikes or sills of augite-biotite shonkinite, intruded into the basal part of the O'Brien Creek Formation, (2) alkalic breccia intruded into the basal part of the O'Brien Creek Formation, and (3) the Cumberland Mountain complex, composed chiefly of malignite and foyaite. The complex is located in the southern part of the map-area, and cuts schists and greenstone of the Anarchist Group.

The shonkinite is a massive, fine-grained, light-olive-gray to medium-greenish-gray mesocratic rock, composed of euhedral lathy oligoclase and ragged but equant and poikilitic augite floating in a matrix of perthitic orthoclase. Thin, ragged, randomly oriented plates of red-brown biotite are scattered through the rock. Magnetite and apatite are accessories. Calcite with tiny euhedral crystals of clinozoisite occupies interstitial areas bounded by the euhedral terminal planes of the enclosing orthoclase, indicating that the calcite is a late cavity filling. The rock is extensively altered, with abundant development of secondary clay, chlorite, serpentine, epidote-group minerals, calcite, and zeolite-group minerals. The relatively fine grain size, blurring of grain contacts by alteration, and distinctive needle-like appearance of the biotite plates as commonly viewed end-on, combine to give the rock a volcanic rather than granitoid appearance, contrasting with the granitoid appearance of the malignite and shonkinite from nearby localities. The plutons composed of the shonkinite, unlike the other alkalic plutons within the map-area, appear comparatively uniform in composition and primary fabric throughout their extent.

The pipe-like body of alkalic breccia at Lake Beth is composed essentially of a monolithologic light-green breccia in the southern part, probably grading to massive but much altered shonkinite occupying the northern part. The breccia is an aggregate of angular granules resembling either shonkinite or the volcanic rock of the nearby Sanpoil Volcanics, and which are packed and firmly bonded with finer grained interstitial material of similar character. Waxy light-green aphanitic greenstone was observed on the dump of a now inaccessible tunnel driven into the mass. Judging from Pearson's map and cross-section (Pearson, 1967), the breccia pipe is intruded into the lower part of the O'Brien Creek Formation.

The elongate mass of alkalic breccia at the west end of Beaver Lake was not visited by the author. However, the other two masses of alkalic breccia located between Box Canyon and the North Fork of Beaver Creek are composed of various mixtures of medium- to coarse-grained leucocratic monzonite, which is locally porphyritic or trachytoid, and fine- to medium-grained malignite or shonkinite.

The western contact with the enclosing beds of the O'Brien Creek Formation of the southerly of these two masses is exposed in a recent road cut. The breccia there is composed of angular, cobble-size clasts of monzonite firmly bonded together by thin seams of dark-gray aphanitic cement which is probably siltstone. In places the clasts can be visually refitted together like pieces of a jig-saw puzzle. Nearby, however, the clasts are angular to well rounded with an arkosic matrix and the rock resembles a conglomerate. The contact with the O'Brien Creek Formation is sharp and conformable over the 10 feet exposed, although the O'Brien Creek beds have been rotated to a near vertical attitude. They are composed of hard, thin-laminated, dark-gray siltstone, but interestingly enough, a 3-6 inch thick layer of the siltstone about 8-10 inches from the contact has embedded in it angular clasts of alkalic rock similar to that composing the breccia. This circumstance suggests that during deposition of the siltstone on or near the breccia, the quiet accumulation of silt was interrupted by sudden deposition of a thin mudflow carrying alkalic detritus derived from a nearby source, perhaps another part of the same breccia mass. Still later, the silt beds and their plane of contact with the breccia were rotated almost 90 degrees, probably during a final resurgence of the emplacement process of the alkalic breccia.

The Cumberland Mountain complex is comprised of a central area of foyaite, flanked on the east and west by marginal areas of mafic alkalic rocks, mainly malignite and shonkinite. The foyaite is typically massive and medium light gray, with well aligned, greenish-black laths of aegirine-augite 1-4 mm long scattered through a chalky, light-gray, very fine-grained matrix of orthoclase and hydromica (the latter pseudomorphing nepheline). The orthoclase is tabular and like the aegirine-augite shows good flow alignment. The hydromica shows considerable variation in properties between samples--from sub-opaque material with negative relief, presumably mostly analcite with subordinate intergrown clay--to a translucent, moderately birefringint, pale-brown material with positive relief, which is probably an intergrowth of clay minerals with but little admixed analcite or natrolite. Unaltered nepheline was found in only one of the seven samples of the foyaite that were thin-sectioned.

Light-gray, ragged, oval or hexagonal spots devoid of mafic minerals and up to 20 mm across are scattered through the foyaite. The oval areas are glomeroporphyritic aggregates of tabular orthoclase and intergranular hydromica, and the polygonal areas are occupied by a fingerprint intergrowth of orthoclase and hydromica. Accessories include garnet, hastingsite, sphene, apatite, magnetite, and biotite.

The garnet is present as anhedral grains apparently developed at the expense of aegirine-augite, and as skeletal crystals formed intergranularly to the felsic constituents. Hastingsite and sphene also show skeletal habits.

The mafic alkalic rocks are composed chiefly of blocky, subhedral aegirine-augite or augite and tabular orthoclase. Hydromica, with variable properties comparable to those of the hydromica found in the foyaite, is present in major amounts in some rocks and absent in others. The other primary constituents include andesine, melanite, biotite, sphene, apatite, magnetite, and hastingsite. The garnet is present as granular aggregates associated with and evidently formed at the expense of pyroxene. The plagioclase is present as corroded laths, and with aegirine-augite as glomeroporphyritic aggregates, and seemingly shows a reciprocal relationship with hydromica, in that rocks with abundant hydromica are devoid of plagioclase and vice versa.

Presuming that the hydromica is pseudomorphing a primary feldspathoid, probably nepheline, the observed variation in its abundance suggests that the degree of undersaturation in silica ranges from significant to slight. The mafic alkalic rocks are classified accordingly as malignite and shonkinite (Table 10).

The malignite and shonkinite can be grouped according to their primary texture into three intergrading classes: (1) massive, dark-greenish-gray, fine-grained hypautomorphic granular, (2) like (1), but containing sparse to abundant ragged, oval, light-gray patches 5-8 mm long, which are composed of tabular orthoclase with intergranular hydromica, and (3) trachytoid porphyry, with subparallel tabular phenocrysts of orthoclase set in a fine-grained, dark-greenish-gray matrix similar to (1).

Greenish-black pyroxenite is present along the western edge of the complex. The pyroxenite is very coarse grained, and composed of aegirine(?)-augite, with accessory orthoclase, garnet, skeletal to poikilitic hornblende, magnetite, and apatite.

The rocks of the complex are locally shattered and in places where cataclasis has been most extreme are better described as a breccia. Most also show signs of hydrothermal alteration, which has been most pervasive in the more fractured rocks. In these rocks the primary mafic constituents have been replaced by serpentine and chlorite, the feldspar has been argillized or saussuritized, and the rock is cut by microveins of calcite and zeolites.

The contact between the alkalic rocks of the complex and the clastics of the O'Brien Creek Formation was not actually observed. However, the closest outcrop of the O'Brien Creek at one locality along the north side of the complex exposes sedimentary breccia composed of angular, unsorted granules and pebbles of alkalic rock, and tabular orthoclase crystals firmly cemented in an arkosic matrix. If this material is detritus derived from the complex, as seems likely, the O'Brien Creek beds must depositionally overlie the complex.

Summary and conclusions

The numerous small plutons of alkalic rock in the Cumberland Mountain area are composed of one or more of the following six lithologic types: (1) fine-grained, "hypabyssal" shonkinite, (2) foyaite, (3) complexly intergrading malignite and shonkinite, (4) pyroxenite,

(5) coarse-grained, leucocratic monzonite, and (6) intrusive breccia whose clasts are chiefly one or more of the preceding lithologies. The plutons themselves can be classified as (1) breccia pipes, (2) hypabyssal monolithologic dikes and sills of shonkinite, and (3) the Cumberland Mountain complex, composed of foyaite, malignite-shonkinite, and pyroxenite.

The age relations of the alkalic rocks with the O'Brien Creek Formation are complex. The fine-grained shonkinite apparently cuts parts of the O'Brien Creek unit and thus is younger, whereas the alkalic breccia pipes appear to be overlain by O'Brien Creek beds locally, but elsewhere penetrate the basal few hundred feet of the formation. The Cumberland Mountain complex cuts the metamorphic rocks of the Anarchist Group, and apparently is overlain by epiclastic rocks of the O'Brien Creek Formation. Clearly the alkalic rocks were intruded not as a single synchronous event, but by stages through an appreciable length of geologic time, which began prior to and terminated during or after deposition of the O'Brien Creek Formation.

The areal extent of the Cumberland Mountain complex may be considerably greater than the exposed area. The relation to the O'Brien Creek Formation of the other bodies of alkalic rocks adjacent to the complex is not known, but except for the fine-grained shonkinite, which probably cuts the O'Brien Creek Formation, they may be parts of the complex and thus coextensive with the main exposure of alkalic rocks beneath a relatively thin cover.

The alkalic rocks were considered by Pearson (1967) to be older than the Sanpoil Volcanics, which overlies the O'Brien Creek

Formation. Since the greatest exposed thickness of the O'Brien Creek Formation in the Bodie Mountain quadrangle is somewhat greater than 2000 ft. (Pearson, 1967), the depth of intrusion at the present level of exposure of those alkalic rocks which cut the O'Brien Creek Formation, namely the breccia pipes and the fine-grained shonkinite, probably did not exceed this figure. Indeed, the evidence of slumping of O'Brien Creek beds at the contact of one of the breccia masses, and the presence within the breccia of a matrix of siltstone and arkose near this contact, indicates that the breccia breached the surface of a thin layer of then unconsolidated sediments of the O'Brien Creek.

In summary, the geologic history of the alkalic plutons is as follows:

(1) Mafic alkalic rock of the Cumberland Mountain complex intruded Anarchist metamorphic rock during or prior to the Eocene. Time of this event conjectural, but probably Eocene, assuming that these rocks are part of the same general magmatic episode to which the later alkalic intrusives in this area belong.

(2) Alkalic breccia intruded Anarchist bedrock in Box Canyon-Beaver Lake area. May be coeval with (1).

(3) Erosion exposed rocks intruded in (1) and (2).

(4) O'Brien Creek basin subsided, and basal conglomerate, arkose, and siltstone were deposited over the alkalic plutons.

(5) Renewed or continued intrusion of Box Canyon-Beaver Lakes alkalic breccia into basal O'Brien Creek beds. Intrusion

of Beth Lake pipe, and of "fine-grained" shonkinite into O'Brien Creek Formation.

Alkalic Rocks Bordering the Okanogan Gneiss Dome

Introduction

A discontinuous belt of mafic syenitic and monzonitic gneiss half a mile or less in width borders most of the northern contact of the gneiss dome. The belt trends west-northwest, and comprises three segments, which from west to east are one, ten, and seven miles in length, respectively (PLATE I). The alkalic rocks are chiefly quartz-bearing monzonitic gneiss, grading to mesocratic monzonitic gneiss, quite unlike the alkalic rocks of the previously described complexes in mineralogy and lacking the markedly undersaturated variants found within those complexes. Alkalic rocks of the mile-long western segment, where pyroxenite and shonkinite which are megascopically indistinguishable from analogous rocks of the complexes predominate, are the exception. Despite the dissimilarities, the general coincidence of the monzonitic border with the belt of alkalic complexes suggests at least the possibility of a genetic link.

The essential features of the central segment of the border zone (termed the "Osoyoos-Colville-greenstone hybrid syenite") were accurately described by Waters and Krauskopf (p. 1398-1405, 1941). Much of this segment of the border was remapped by the author (Fox, 1970) and mapping of the eastern segment is in progress.

Geologic setting

The central segment of the belt forms a thin septum flanked to the north by rocks of the Osoyoos quartz diorite at the west end, and greenschist-grade meta-clastic rock and greenstone of the Anarchist Group at the east end. The Osoyoos quartz diorite is an elongate pluton straddling the International Boundary. The pluton shows a cataclastic foliation which becomes progressively stronger towards the contact with the alkalic border zone, indicating that the cataclasis was a result of the forceful enplacement of the gneiss dome to the south. The eastern segment of the alkalic border zone is flanked by staurolite-grade schists of the Anarchist Group at the northwestern end, and crushed granodiorite porphyry at the southeastern end.

The rocks of the gneiss dome adjacent to the alkalic border along most of its length are directionless, fine- to medium-grained porphyritic granodiorite or quartz monzonite of the "homophanous" phase of Waters and Krauskopf (1941).

The border zone is intricately crisscrossed by dikes of pegmatite and fine-grained alaskite of several generations, but all are believed to be diaschistic offshoots of magmatic phases of the gneiss dome.

Chemical analyses and CIPW norms of rocks of the border zone are presented in Table 11.

Syenitic and monzonitic gneiss

The gneiss is light to medium gray, medium grained, with a conspicuous curving foliation imparted by the subparallel orientation of shiny, black hornblende crystals, which are set in a chalky-white

TABLE 11

CHEMICAL ANALYSES AND CIPW NORMS OF ROCKS OF THE SYENITIC BORDER OF THE OKANOGAN GNEISS DOME[1]

Rapid Chemical Analyses (weight percent)[2]				CIPW Norms (weight percent)			
	0-118A	0-131B	0-131M		0-118A	0-131B	0-131M
SiO_2	61.2	58.7	58.7	Q	12.9	1.3	
Al_2O_3	17.2	18.8	19.0	ne			tr.
Fe_2O_3	2.2	1.6	2.1	or	17.1	26.7	34.4
FeO	3.3	3.2	2.4	ab	33.0	40.7	40.7
MgO	2.1	1.6	1.3	an	20.9	16.5	13.2
CaO	5.4	4.8	4.0	wo	1.4	2.1	2.0
Na_2O	3.9	4.8	4.8	en	5.2	4.0	1.2
K_2O	2.9	4.5	5.8	fs	3.5	3.6	.7
H_2O-	.08	.09	.12	fo			1.5
H_2O+	.80	.76	.70	fa			.9
TiO_2	.52	.60	.56	mt	3.2	2.3	3.1
P_2O_5	.39	.34	.26	il	1.0	1.1	1.1
MnO	.07	.02	.05	ap	.9	.8	.6
CO_2	<.05	<.05	.05	cc			.1
Total	100.	100.	100.	Total	99.1	99.1	99.5

[1] Location of specimens:

0-118A Mt. Bonaparte 15' quadrangle: 400 ft. west of east line and 1500 ft. south of north line of S.12, T.39 N., R.28 E.

0-131B Oroville 15' quadrangle, at abandoned railroad cut, 2750 ft. west of east line and 700' south of north line of S.28, T.40 N., R.28 E.

0-131M Oroville 15' quadrangle, 2400 ft. west of east line, and 200 ft. south of north line of S.28, T.40N., R.28 E.

[2] Analysts P. L. D. Elmore, S. D. Botts, L. Artis, H. Smith, J. Glenn, and J. Kelsey.

aggregate of perthitic orthoclase and plagioclase. Certain parts of the gneiss along the western segment of the zone show a particularly striking gneissose fabric in which numerous, wavy, fine-grained zones or surfaces intersect or coalesce, dividing the gneiss into lenticular or wedge-shaped domains. The primary penetrative gneissosity of each domain is randomly oriented, and curves toward and feathers into the bounding fine-grained zones or surfaces. This "festoon structure" is probably a consequence of numerous cycles in which initial failure through plastic deformation culminated in failure by shear, possibly resulting from a varying rate of application of force attending emplacement of the adjacent gneiss dome.

The plagioclase is oligoclase-andesine, locally showing weak relict zoning. The amphibole is a highly pleochroic dark-green variety of common hornblende with excellent development, in places, of (110) terminal faces. Locally the hornblende is concentrated in thin layers or sheets which are interlaminated with the felsic minerals, further accentuating the foliation. These mafic laminae are richly studded with large tabular crystals of amber-colored sphene which reach up to 1 cm long. Other minerals present in varietal or accessory proportions include epidote, apatite, sphene, zircon, garnet, magnetite, calcite, and chlorite.

The border zone is distinctly more mafic and less quartz-rich than either the homophanous phase of the gneiss dome, or the Osoyoos quartz diorite. It is also more potassic, and less quartz-rich than the gabbroic rocks of the dome (Fig. 23).

The following compositional trends have been discerned within

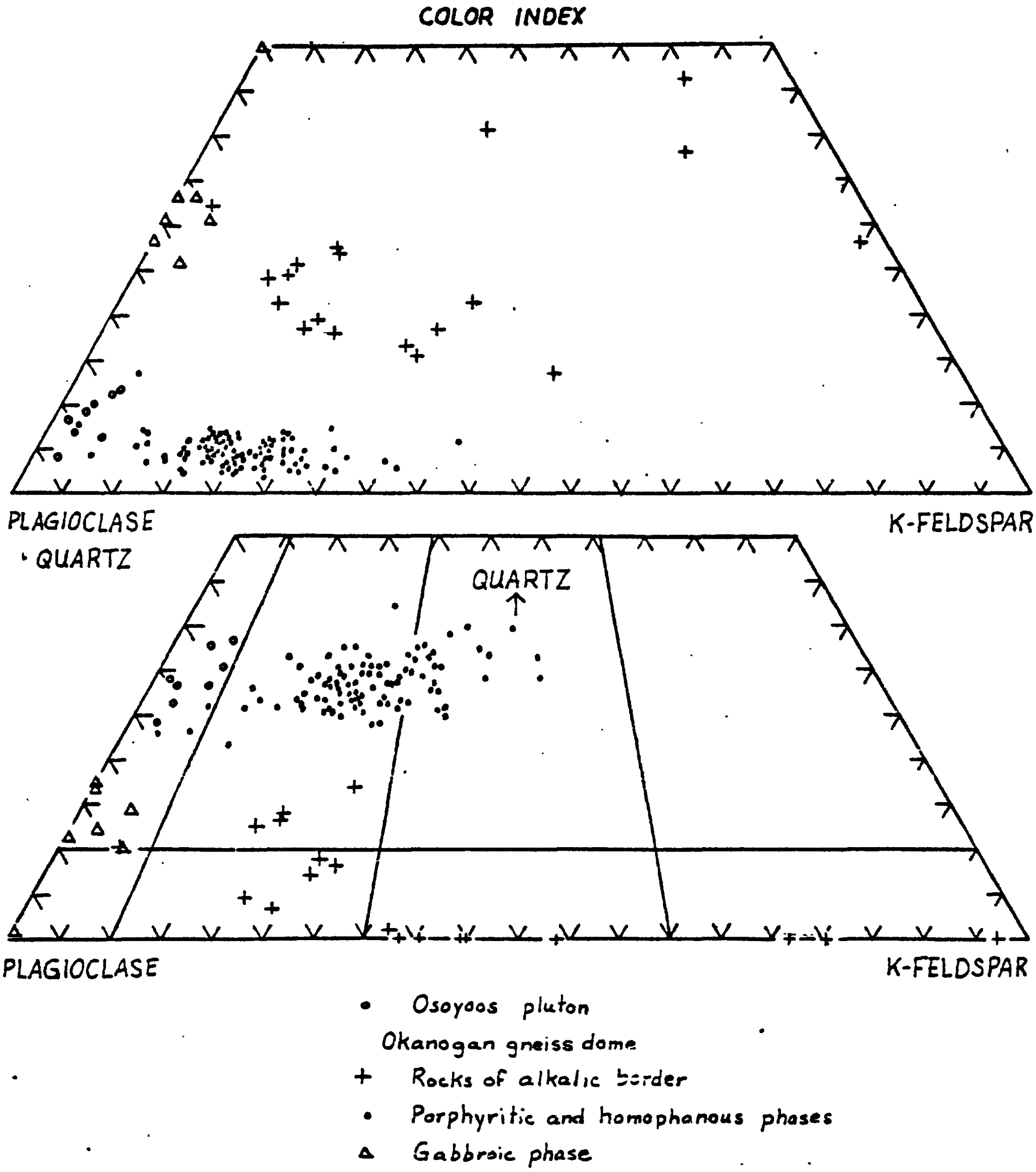

Fig. 23.--Diagram comparing modal composition of the bordering alkalic rocks with that of other phases of the Okanogan gneiss dome and with that of the Osoyoos pluton. Modal analysis by point-count of stained slabs, M. B. Norman, analyst.

the rocks of the alkalic border: (1) In the central and eastern segments, the border rocks become progressively more felsic southward across the strike of the belt, grading to oversaturated rocks at the contact with the gneiss dome, and (2) the ratio of K-feldspar to plagioclase increases progressively from east to west. Rocks at the east end are syenodiorite with variable but low ratios of K-feldspar to plagioclase, those at the west end are syenite and shonkinite, with high ratios.

The texture of the monzonitic rock is medium grained, xenomorphic gneissic, showing a ragged smear of very fine-grained mortar at intergrain contacts. In places even the apatite crystals are crushed to lenticular aggregates. Both plagioclase and orthoclase show undulatory extinction, and biotite laths are commonly bent. In places the gneiss is porphyritic, with ellipsoidal to blocky, tabular phenocrysts up to two inches long and three-eighths inch wide.

Quartzo-feldspathic and feldspathic pegmatite-alaskite dikes which ribbon the western segment of the monzonitic gneiss range in thickness from one-quarter of an inch or so up to several tens of feet. The maximum size of those cutting the eastern segment is much greater, some bodies measuring several hundred feet across, and containing abundant lens-like inclusions several feet thick of the monzonitic gneiss. The dikes pinch and swell, bifurcate, wedge out abruptly, and crosscut one another. Some are gneissose parallel to their length, others parallel to the enclosing gneiss. Contacts with the gneiss are rarely sharp; more typically the pegmatite on close inspection can be seen to feather into the foliation of the host.

Contact relations

The western segment forms a septum which is about 700 feet in width at the wider, southeast end, and gradually narrows on strike to the northwest. The septum divides biotite-quartz dioritic gneiss of the Osoyoos pluton on the northeast from thinly layered gneiss on the southwest. The layered gneiss is composed of interlayered, strongly foliated, almost schistose augen gneiss, gneissic porphyry, and very fine-grained leucocratic gneiss, all of which possess a penetrative lineation striking west-northwest. This rock is tentatively correlated with the layered gneiss of the gneiss dome. The contact with the layered gneiss is confused by extensive brecciation and by numerous apparently minor faults with diverse orientation, resulting in an undulating, or irregular, stairstepping tectonic contact. The alkalic rocks which here are chiefly shonkinitic or femic syenitic gneiss, interfinger with the Osoyoos gneiss on the northeast.

The central segment is composed chiefly of shonkinitic, femic monzonitic, and quartz-bearing monzonitic gneiss. The contact with the rocks of the gneiss dome, which here are fine-grained, directionless quartz monzonite, is knife-edge sharp at the one locality where it is exposed, in contrast to the gradual transition to the schist, phyllite, and greenstone of the Anarchist Group at the other side of the belt. Within this transitional zone, which is up to several hundred feet wide, the monzonitic or shonkinitic gneiss is thinly streaked by laminae of differing grain size or color index, some crowded with trachytoid ellipsoidal K-feldspar phenocrysts. Others are composed of garnet gneiss or diopside-calcite-quartz gneiss or of fine-grained biotite gneiss. The central segment, like the western, is much jointed and crisscrossed by numerous minor faults.

The central segment of the alkalic zone is extensively mantled by glacial drift, and may in fact be continuous with the western segment beneath the intervening four miles of covered area.

The eastern segment lies eight miles east of the central segment, and although the contact zone of the granodiorite phase of the gneiss dome in this intervening area is poorly exposed, it is probable that no border zone of alkalic rocks is present over most of this distance. The eastern segment is predominantly mesocratic monzonitic and syenodioritic gneiss. Its contact with the granodiorite is sharp at the single known exposure. A fine-grained phase of the granodiorite, although itself slightly gneissic, cuts the gneissosity and contains xenoliths of the syenodioritic and monzonitic gneiss, thus is clearly intrusive. The contact of the monzonitic and syenodioritic rock with adjacent schists of the Anarchist Group is gradational over a distance of 10-20 feet.

Interpretation

A thorough discussion of the alkalic border is beyond the scope of the present study, involving controversial and as yet undocumented ideas on the nature and origin of the gneiss dome. Nevertheless, certain features of the alkalic border require further elaboration. The features of the border zone of chief interest are its alkalic character, its geographic localization along the contact of the gneiss dome, and its coincidence with the belt of alkalic complexes. The gradational nature of the northern contact, coupled with the absence of magmatic features such as satellitic dikes and xenoliths, suggests that the border gneiss originated through the metasomatic conversion of the metamorphic rocks of the Anarchist Group, as hypothesized by Waters and Krauskopf (1941), and at the west segment, by replacement of the adjoining Osoyoos gneiss. The sharp, locally crosscutting contact with the granodioritic phase of the gneiss dome, coupled with the presence within the latter rock of xenoliths of the alkalic gneiss at one locality, indicates that the alkalic border is cut by rocks of the gneiss dome. The cataclastic fabric of the border gneiss could thus be attributable to stress associated with emplacement of the dome. Yet, in plan view the border gneiss of the eastern segment follows the dome around its northeastern salient, and in cross-section view follows it around the outwardly convex curve where wall rock joins with roof rock. The configuration of the border gneiss is therefore controlled by the northern contact of the dome, and both units must be roughly consanguineous, with movement of the dome continuing after formation of the alkalic border.

What, then, controlled the location of the north boundary of the gneiss dome? A major fault can be ruled out, because of the non-linear nature of the contact and the apparent continuity of the country rock around the corners of the dome. Probably the contact was controlled by a combination of local structural features in conjunction with the barrier effect of pre-existing plutons like the Osoyoos quartz diorite.

The compositional gradation along the long axis of the alkalic border from shonkinite at the west end to syenodiorite at the east end could be related to variation in physical conditions of the metasomatism due to differing depth below the roof of the dome. The shonkinitic gneiss of the western segment occupies a zone between wall rock and the dome and lies at an unknown distance, which is probably measurable in thousands of feet, below the former roof level. The eastward slope of the roof brings the juncture of roof and wall rock to the present level of erosion at the eastern side, where monzonitic and syenodioritic gneiss is exposed. These relations indicate that the eastern side has been eroded to a lesser depth, consequently exposing a lower pressure facies of metasomatism. This compositional gradient could also be related to geographical differences in the composition of the vapor phase responsible for the metasomatism.

The compositional gradation from felsic, quartz-bearing gneiss at the "inner" contact with the dome to mafic, mildly undersaturated gneiss at the outer contact could reflect the interplay of two factors: (1) reaction of the alkalic "vapor" responsible for the alkalic metasomatism with relatively cool wall rock and the hot, viscous, water-undersaturated mass of the granodioritic phase of the gneiss dome; and (2) the change in metasomatic environment as the water content of the residual liquid portion of the crystallizing granodiorite magma increased, an increase culminating in the exsolution of a vapor phase. The development of such a phase during crystallization is implied by the mixed alaskitic and pegmatitic textures of certain parts of the main mass of the granodioritic part of the gneiss dome, and also by the similar textures characteristic of the leucocratic dikes riddling the alkalic border zone (Jahns and Burnham, 1969). Evidence of potassium metasomatism was observed along the west border of the dome at Earl Mountain (Waters and Krauskopf, 1941), and near Tonasket (Woodward, 1936). Neither locality shows the desilication and wholesale conversion to alkalic gneiss found along the north border.

The localization of alkalic metasomatism along the belt of alkalic complexes suggests a common source of the alkalic magmas of the complexes and the vapor phase responsible for the metasomatism.

The geologic history of the alkalic border is proposed as follows:

(1) Intrusion of earliest phase of the gneiss dome.

(2) Alkalic metasomatism of contact rock at north border of dome, by a vapor phase channeled along the contact plane, but originating at depth below the source area of the material of the dome.

(3) Alkalic border diked by a water-saturated magma solidifying to pegmatite-alaskite, derived from a residual magma phase of the dome.

(4) Continued shift of dome--a spasmodic upward lurching--coincident with temperature decline through plastic range of the alkalic border, resulting in festoon structure, and the development of intrusive features of contact of dome with alkalic border.

(5) Faulting localized along the west and central segments of the alkalic border during final tectonic adjustment of gneiss dome.

CHEMICAL TRENDS

Major Elements

Available information on chemical composition of the alkalic complexes and the Similkameen batholith includes 27 whole rock analyses, of which 5 were previously reported by Daly (1912) and 14 are reported by Rinehart and Fox (in press [a]). These analyses are compared, utilizing conventional variation diagrams and QLM diagrams modified from Niggli (1954), in the hope of illuminating the nature of the relation of the undersaturated rocks of the Kruger complex and other alkalic complexes to the saturated and oversaturated rocks of the Similkameen batholith, and the relation of the various alkalic rocks to each other, and in order to deduce those restrictions on the genesis of the rocks that are imposed by their chemical composition.

Comparison of the variation diagrams reveals sharp divergences in trends of silica-oxide ratios between rocks of the alkalic complexes and those of the Similkameen batholith (Fig. 24). Oxide ratios of rocks from the oversaturated interior of the Similkameen batholith show only small deviations from the trends. However, those samples representing the saturated marginal phases show increasing scatter with decreasing silica content, probably reflecting the compositional continuum indicated by the appearance of gradation in the field with the various phases of the bordering alkalic rocks of the Kruger complex.

Although the trends of the two rock series overlap at about

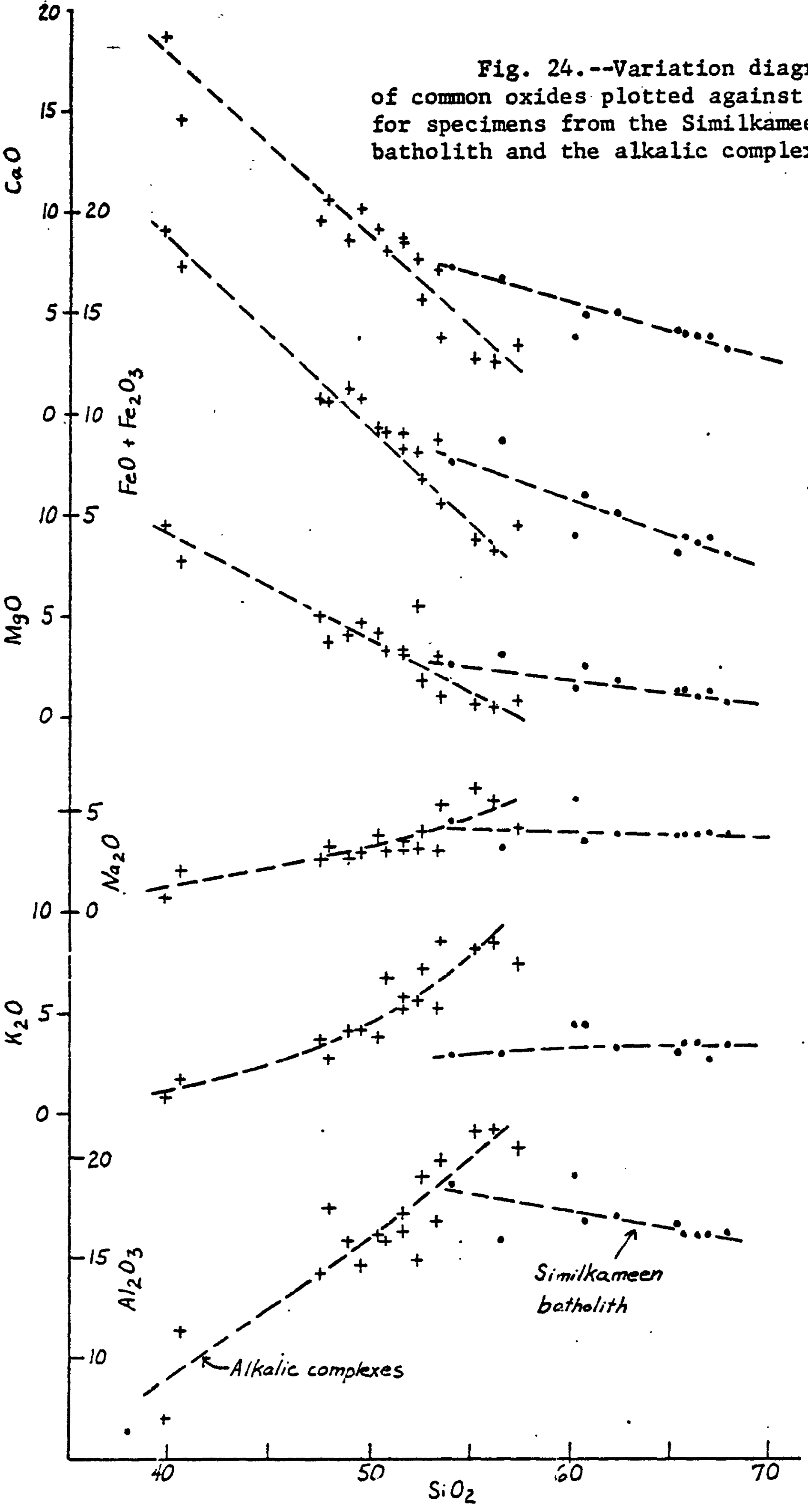

Fig. 24.--Variation diagrams of common oxides plotted against SiO_2 for specimens from the Similkameen batholith and the alkalic complexes.

53-54 percent silica, at slightly higher silica content the alkalic rocks have lower CaO, FeO + Fe_2O_3, and MgO, and higher Na_2O, K_2O, and Al_2O_3 than do the Similkameen rocks.

The alkali-lime index of the alkalic magma is about 50-51 (Fig. 25), thus falls slightly to the alkalic side of the boundary between the Alkalic and Alkalic-Calcic magma series of Peacock (1931). In contrast, the alkali-lime index of the Similkameen magma falls at 54, within the Alkalic-Calcic field.

Modal compositions of the Similkameen rocks roughly group along a planar trend within the K-feldspar-quartz-plagioclase-mafic minerals tetrahedron. The possibility that this trend extends into some otherwise undefined but silica undersaturated region below the base of the tetrahedron, as suggested by the appearance of gradation with the Kruger alkalic rocks, could not be tested by plotting modal constituents because of the mutually exclusive relationship of quartz and feldspathoids, and because of the complex modal composition of the alkalic rocks. This difficulty can be obviated by plotting normative constituents chosen so that both the undersaturated and oversaturated rocks are represented by the same components. This procedure is designed to represent the largest possible part of the chemical analysis of any common igneous rock by the fewest possible constituents. No importance is attached to the likelihood of the presence or absence of these normative constituents in the mode, and indeed, the constituents may amount to no more than hypothetical compounds. This approach departs from the conventional practice of calculating norms and comparing the results with the observed modes, e.g., CIPW norm,

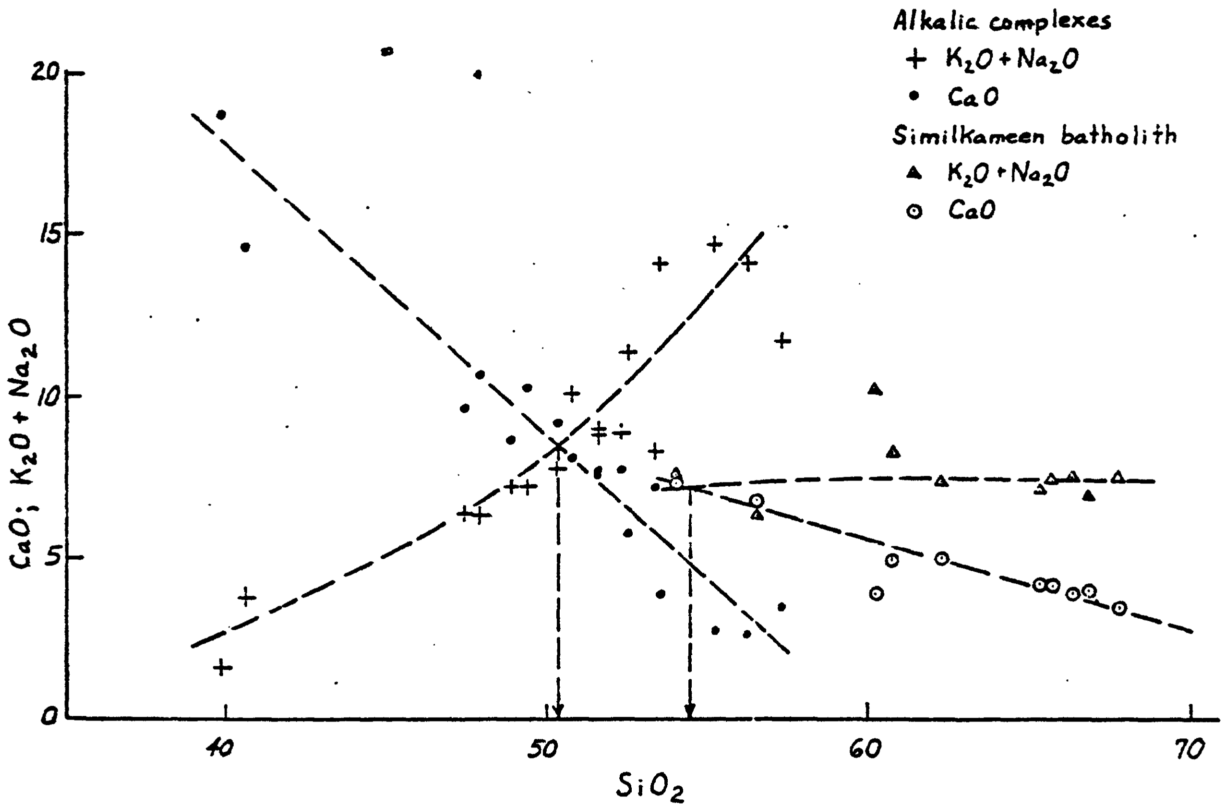

Fig. 25.--Variation diagrams showing the alkali-lime index of suites of specimens of the Similkameen batholith and the alkalic complexes.

catanorm, mesonorm, epinorm.

Niggli's "base groups" (Niggli, 1954, p. 122) are well suited to this purpose. The analysis is first converted to molecular percent, then to the base groups according to the procedure given by Niggli, except that spinel and hercynite are omitted, and "calcium-alumino-silicate" (Calc) is substituted for calcium-aluminate (Cal), with a corresponding compensation for the difference in silica content.

For purposes of graphic comparison, the following base groups are summed to 100, then grouped and plotted in the ternary QL'M' diagram given in Fig. 26.

Formula of Base Group	Symbol	Name of Base Group
SiO_2	Q	Quartz
$1/3(KAlSiO_4)$	Kp	Kaliophilite
$1/3(NaAlSiO_4)$	Ne	Nepheline
$1/15(4CaO \cdot 4Al_2O_3 \cdot 3SiO_2)$	Calc	Ca alumino-silicate
$1/3(K_2O \cdot SiO_2)$	Ks	K silicate
$1/3(2CaO \cdot SiO_2)$	Cs	Ca silicate
$1/3(2MgO \cdot SiO_2)$	Fo	Forsterite
$1/3(2FeO \cdot SiO_2)$	Fa	Fayalite
$1/3(Na_2O \cdot SiO_2)$	Ns	Na silicate
$1/3(Fe_2O_3 \cdot SiO_2)$	Fs	Fe silicate

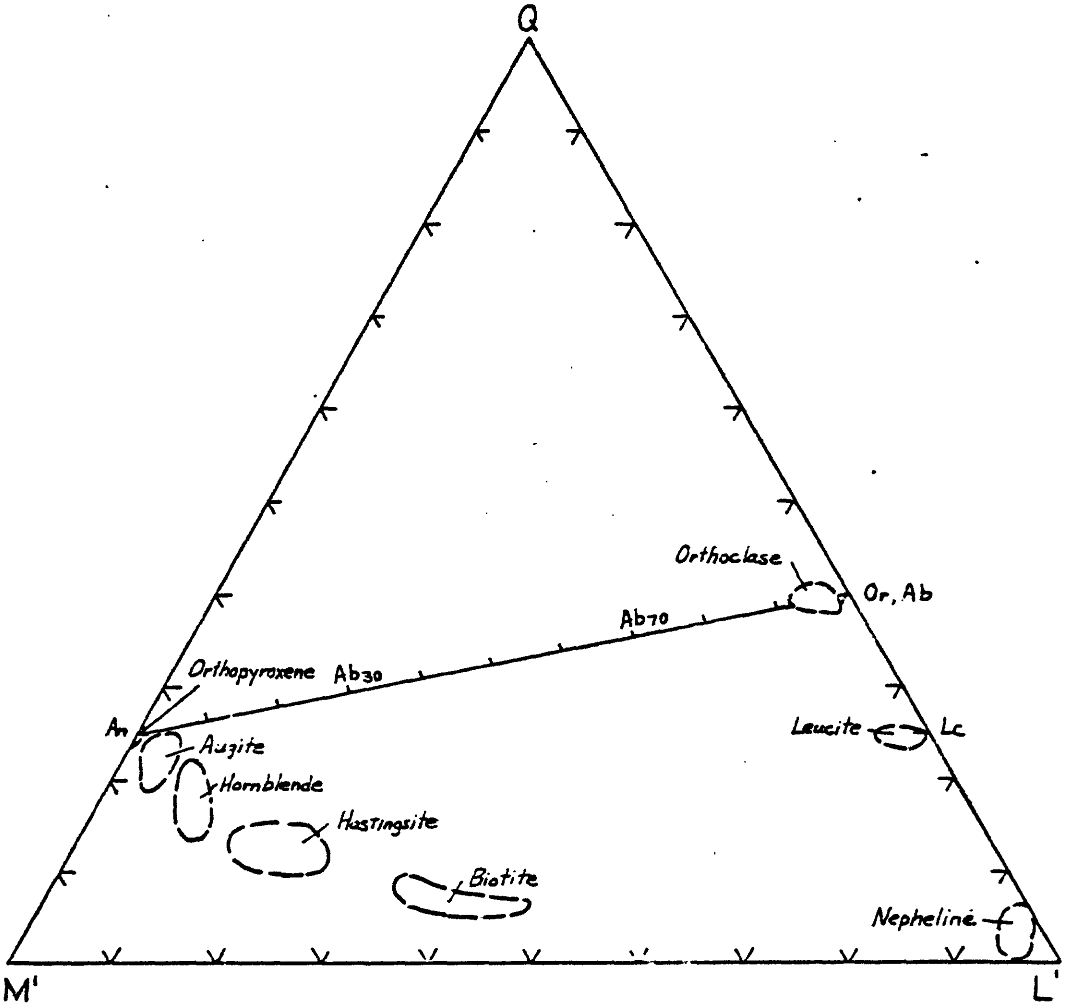

Fig. 26.--Ternary QL'M' diagram showing distribution of common minerals.

The QL'M' diagram is similar to the QLM diagram of Niggli (p. 124, 1954), except that the position of Cs and Ns are interchanged, and Calc is plotted at M', in lieu of Cal at L. For this reason anorthite plots at P' rather than F', and plagioclase plots on the line P'F'. The position of certain mineral fields within the triangle (Fig. 26) has been outlined by plotting representative analyses copied from compilations of Deer, Howie, and Zussman (1963).

The effect of fractional crystallization of these or other minerals from a hypothetical melt may be gauged, since cumulates will plot along a path extending from the starting composition toward the composition of the fractionally crystallizing material (one or more minerals), while the composition of the complementary magmas depleted in this material will plot along the extension of this path on the opposite side of the starting composition. That path may be curved if the composition of the fractionating mineral(s) varies with changing composition of the magma.

The position of common rock families on the QL'M' diagram has been estimated by plotting their counterparts from Nockold's averages (1954) in Fig. 27. The apparent separation of some fields such as granodiorite and diorite is a poor representation of the natural situation, where continuous variation is more likely. Despite these crudities the general distribution is probably accurate.

The rocks of the alkalic complexes show a well-defined trend extending from the vicinity of Nockold's average alkali pyroxenite to the field of Nockold's nepheline syenites (Fig. 28). The rocks of the Similkameen batholith show a less well defined trend extending

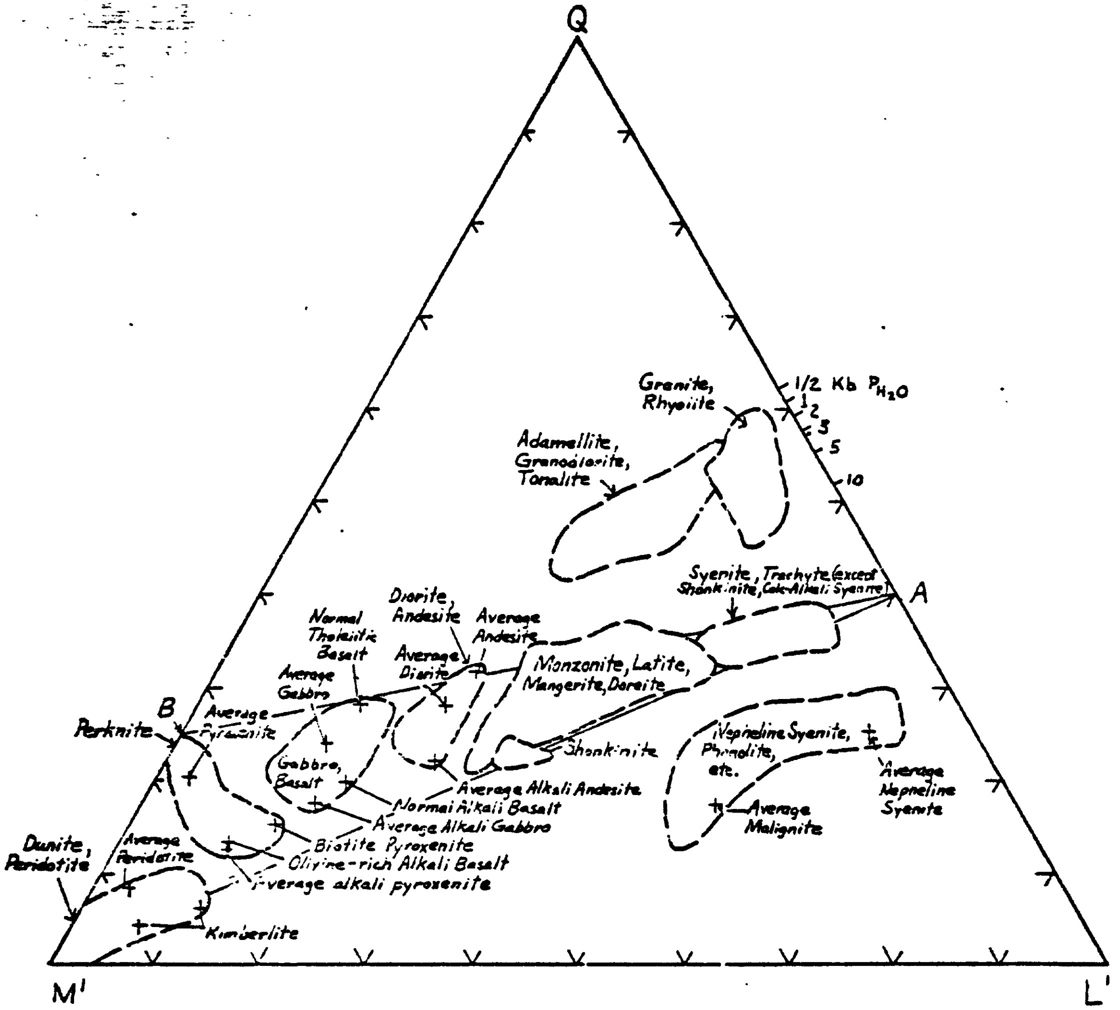

Fig. 27.--Ternary QL'M' diagram showing distribution of common rock families of Nockolds (1954). Position of ternary isobaric minimums at ½, 1, 2, and 3 kb P_{H_2O} from Tuttle and Bowen (1958), and of ternary isobaric eutectics at 5 and 10 kb P_{H_2O} from Luth, Jahns, and Tuttle (1964).

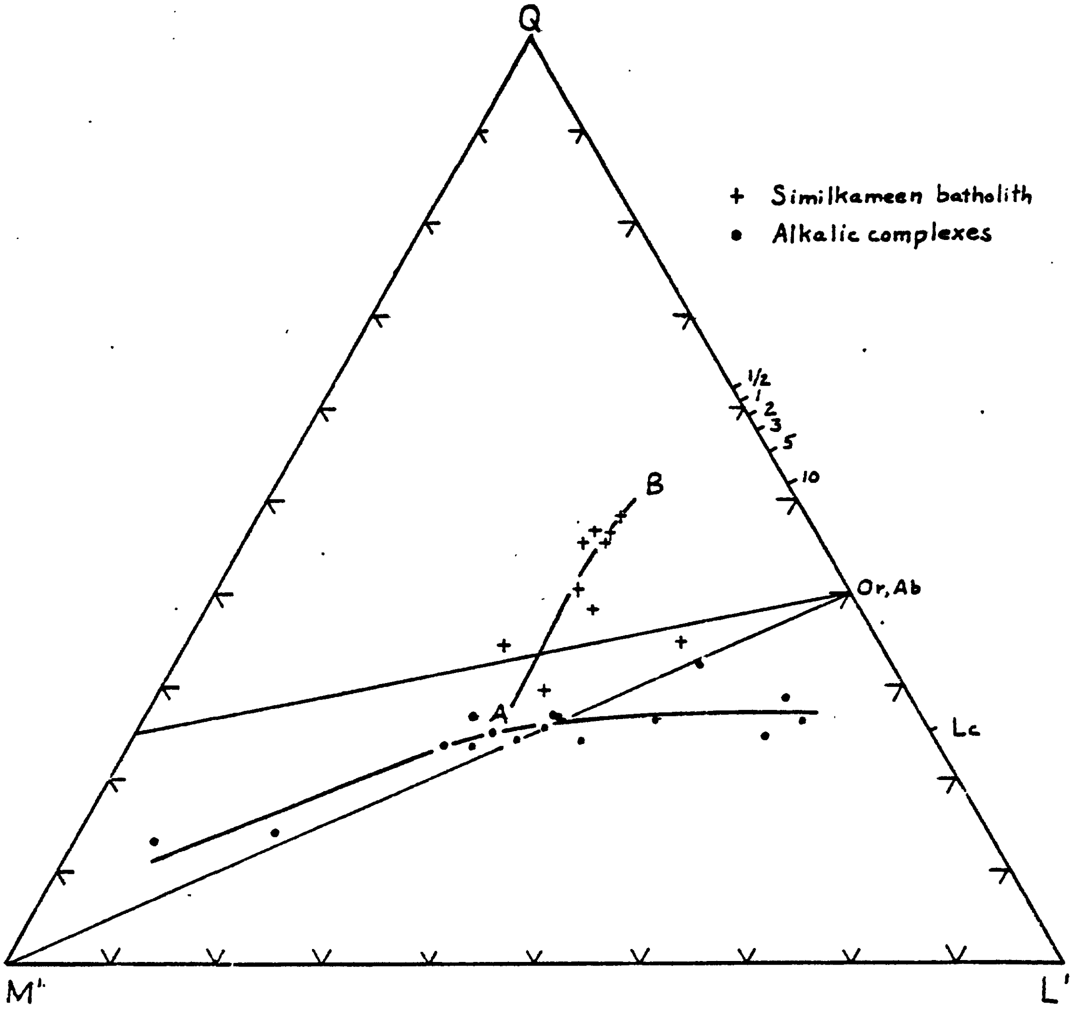

Fig. 28.--Ternary QL'M' diagram showing distribution of specimens of the Similkameen batholith and the alkalic complexes.

from Nockold's granodiorite and intersecting the alkalic trend at a sharp angle.

The QL'M' triangle may be considered a bisecting plane of the quaternary "system" Qtz-(Fo+Fa+Cs+Fs+Calc)-(Ne+Ns)-(Kp+Ks). Both trends are linear in projection to the base (Fig. 29) of the tetrahedron representing this system, and in the projections of the analogous system represented in Fig. 30.

Crystalline rocks whose analyses plot within the triangle QAB (Fig. 27) will necessarily contain modal quartz, those within the triangle AM'B will probably contain neither modal quartz nor feldspathoids, and those within the triangle AL'M' will have either modal feldspathoids or undersaturated mafic constituents, or both. These generalizations must be qualified, however, because of the varying silica content of mafic phases, and because some constituents such as Fe shown here in combination with silica as Fa or Fs will normally be present in part as oxides, causing some rocks with modal quartz to plot below the AB silica saturation line.

Variations in rock compositions within the AM'B triangle can be attributed both to variations in original magma composition and to fractionation or hybridization processes. Although fractional crystallization of olivine, biotite, or hornblende could drive the composition of a residual magma from the AM'B triangle across the AB silica saturation line and into the QAB field, the near absence of rock compositions except those clustered along the trend from diorite, through granodiorite, quartz monzonite, granite, and terminating in the vicinity of the experimentally determined

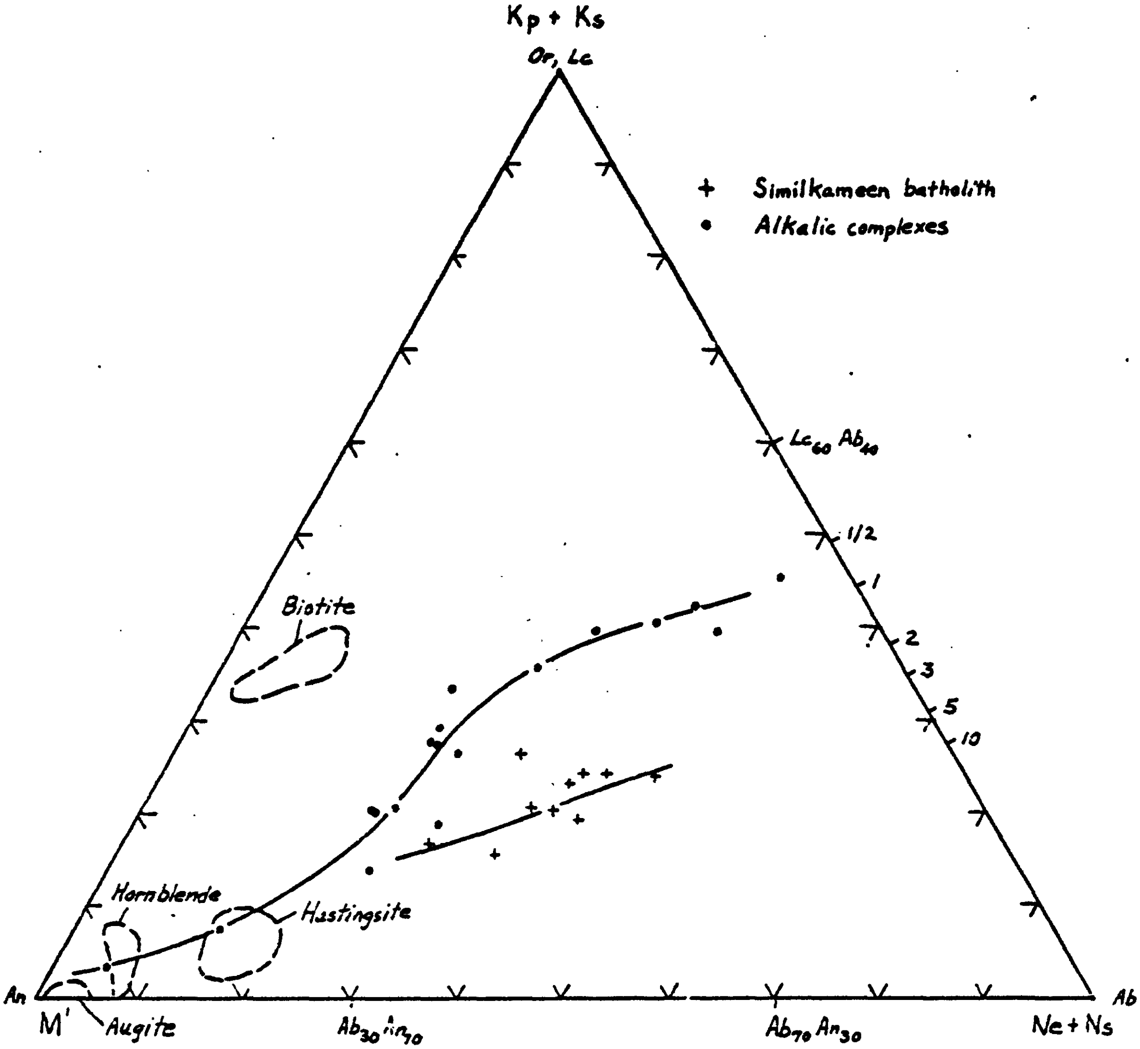

Fig. 29.--Ternary (Kp+Ks)-(Ne+Ns)-M' diagram showing distribution of specimens of the Similkameen batholith and the alkalic complexes, and also common mineral groups.

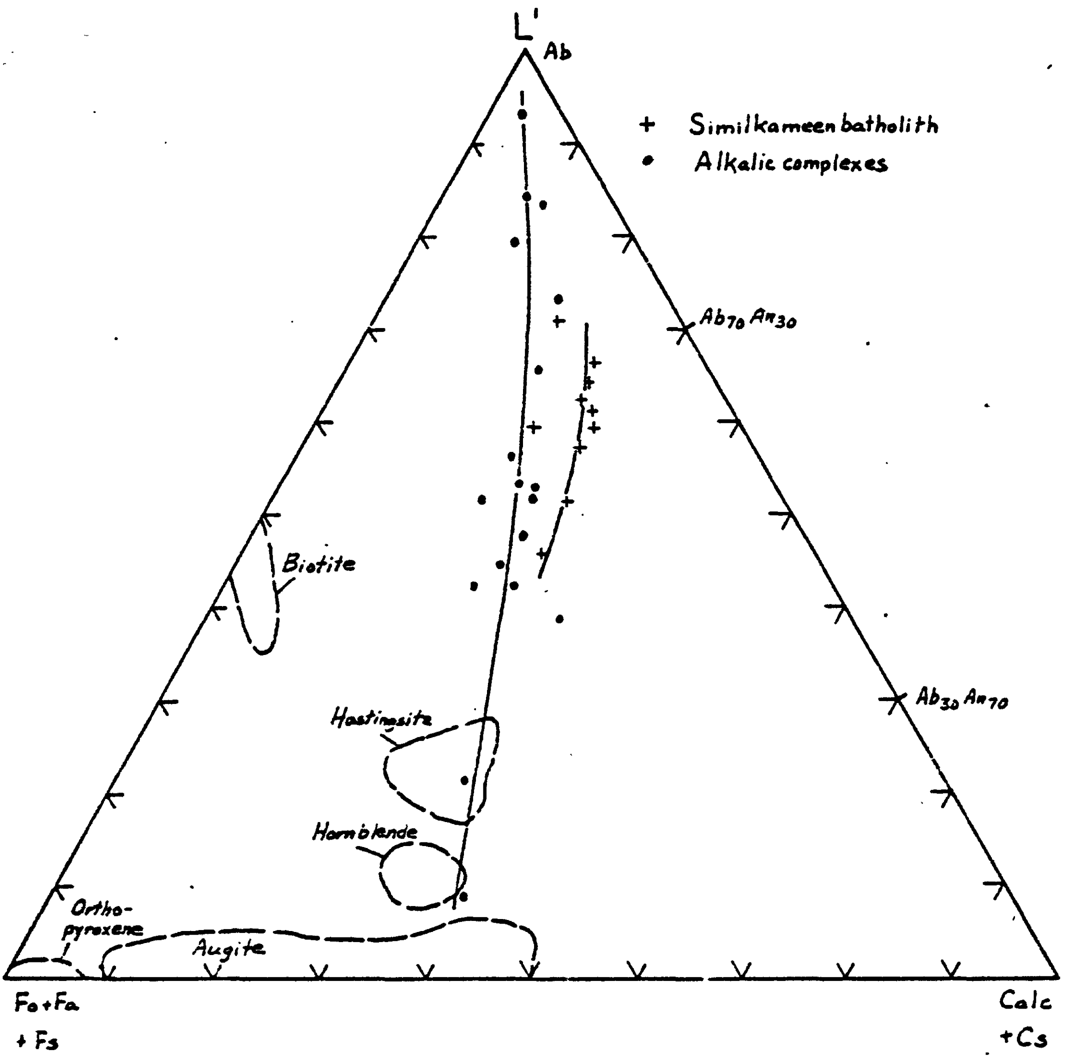

Fig. 30.--Ternary L'-(Calc+Cs)-(Fo+Fa+Fs) diagram showing distribution of specimens from the Similkameen batholith and the alkalic complexes, and also common mineral groups.

low-melting area of the granite system suggests that magma compositions in the QAB field are more strongly influenced by the phase relationships controlling fractional melting than by processes of fractional crystallization.

Fractional crystallization of pyroxene and/or plagioclase could drive the composition of residual magmas from the AM'B field toward the AL'M' field. And indeed, the wide dispersion of alkalic and ultra-alkalic rocks within the AL'M' field suggests that fractional crystallization plays an important role in the genesis of these rocks.

Except that they lack markedly undersaturated variants, the rocks of the Tulameen, Copper Mountain, Franklin, and Rock Creek plutons resemble those of the Kruger alkalic group (Fig. 31). The mafic rocks of the Tulameen, etc. are less silicic than rocks along the trend through Nockold's alkali basalt-alkali pyroxenite, and are in general less silicic and more highly differentiated than the other plutonic rocks of the region. These comparisons support the hypothesis that the Tulameen, etc. group and the Kruger alkalic group constitute a clan of rocks which are in general slightly to moderately undersaturated in silica, and compared to other rocks in the region are moderately to strongly enriched in potassium, and more highly differentiated with respect to color index.

K-Rb

Quantitative determinations of K-Rb ratios in six specimens of the chemically analyzed alkalic rocks range from 340 to 628, and average 426 (Table 12). The rubidium content of 18 other chemically

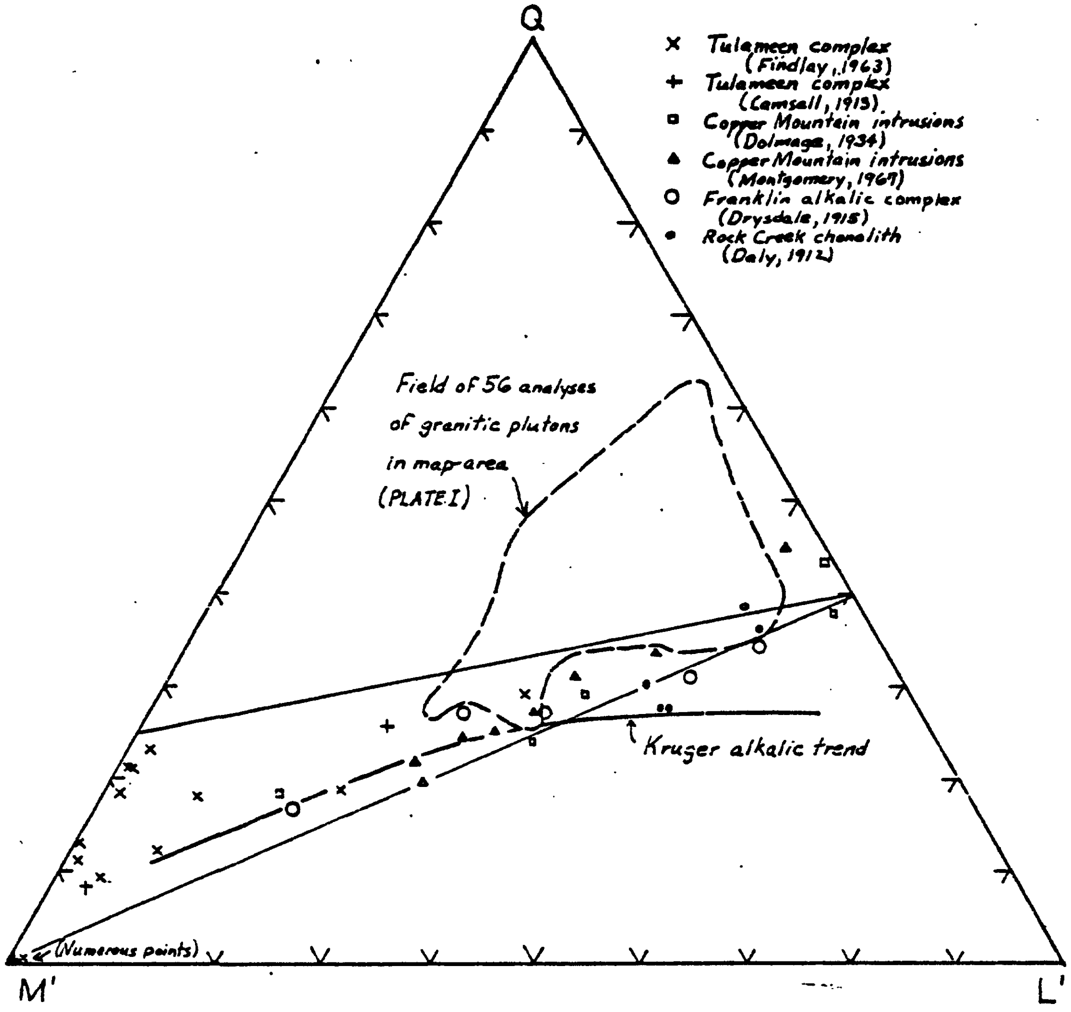

Fig. 31.--Ternary QL'M' diagram comparing the Kruger alkalic trend with the distribution of specimens of the other alkalic complexes and granitic plutons within the region.

TABLE 12

POTASSIUM AND RUBIDIUM CONTENTS OF ALKALIC ROCKS OF NORTHERN OKANOGAN COUNTY, WASHINGTON

Sample Number	K (wt. percent)	Rb (ppm)	K/Rb
L-209A	6.03	175	345
L-275c	1.45	23	628
L-693A	5.30	156	340
L-696	4.37	95	453
0-72D	7.04	186	378
0-491F	7.26	176	412

Analyses by X-ray fluorescence. L. F. Espos, Analyst; B. P. Fabbi, Project Leader.

analyzed specimens, including samples of the Similkameen batholith as well as alkalic rocks, was estimated by a semi-quantitative X-ray fluorescence procedure similar to that described by Jack and Carmichael (1969) utilizing quantitatively analyzed specimens as standards. Samples of the Similkameen batholith average about 265. The overall average of the alkalic rocks is about 390. Two trends can be discerned from the plot of K versus Rb (Fig. 32). Samples of the Similkameen are clustered along the line marking a K-Rb ratio of 230, the "Main Trend" of Shaw (1968), and the trend to which most igneous rocks conform (Dodge, Fabbi, and Ross, 1970; Ahrens, Pinson, and Kearns, 1952). K and Rb content of the alkalic rocks define a subparallel trend of

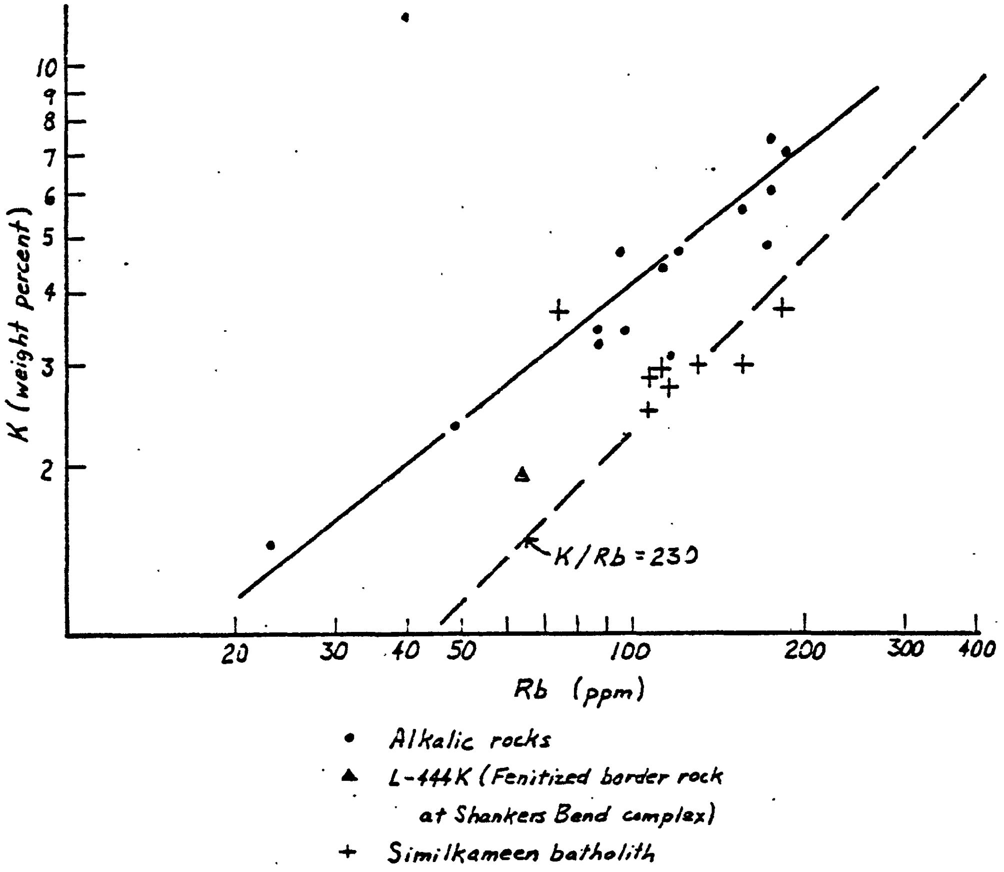

Fig. 32.--Diagram showing plot of K versus Rb of specimens of the Similkameen batholith and the alkalic complexes.

K-Rb ratios almost twice those of the Similkameen batholith. However, several samples of both the alkalic and Similkameen groups plot at positions intermediate between the two trends, or on the trend of the alternate group. A sample of the metasomatized border rock from the Shankers Bend complex (L-444K) falls on the Similkameen trend.

The tendency for alkalic rocks to have higher K-Rb ratios than those of the Main Trend is well established. For example, the K-Rb ratios of a continental alkalic igneous rock suite in the Nandewar Mountsins, N.S.W., Australia, average 426 (Abbott, 1967), alkalic lavas in Hawaii average 505 (Lessing et al., 1963), the Shonkin Sag laccolith, Montana, range from 250-420 (Nash and Wilkinson, 1971), continental alkalic rocks of the East African Rift Valley System range from 169-552 (Bell and Doyle, 1971), averages of the several zones of the Blue Mountain nepheline syenite range from 430 to 805 (Payne and Shaw, 1971), and the nepheline syenite at Stjernoy, North Norway, ranges from 484 to 802, and averages 579 (Heier, 1966).

Three features of the alkalic-Similkameen K-Rb pattern require explanation. These are as follows: (1) the decline in K-Rb ratios at increasing K content found along the alkalic trend, (2) the appearance of gradation between the alkalic and Similkameen trends through a succession of intermediate K-Rb ratios at about 3 percent K, and (3) the high K-Rb ratio of the alkalic trend relative to both the Similkameen trend and the Main Trend.

The geochemical behavior of Rb in silicate melts depends on the fact that Rb forms no minerals of its own, instead substitutes diadochically for K in K-minerals such as biotite, muscovite, and K-feldspar, or for Ca in minerals in which bonding relationships and lattice structure permit substitution of K for Ca, such as amphibole and plagioclase. For most minerals, Rb is admitted, rather than captured, because of the greater size of the Rb+ ion (1.47Å) with respect to the similarly charged K^+ (1.33Å) ion, and therefore is concentrated in the later liquid fraction of the crystallizing melt, and the rocks and minerals formed from it. Based on these generalizations, one would predict a decrease in the K-Rb ratio with relative age within fractionated suites of comagmatic rocks.

This prediction has been confirmed for granitic rocks (Normand, 1969) and is supported by the K-Rb ratios of pegmatites, which probably are derived from residual water-saturated magmas (Jahns and Burnham, 1969), and whose K-Rb ratios are low compared to the bulk of granitic rocks (Shaw, 1968). However, the K-Rb ratios of at least some suites of alkalic rocks increase with relative age. Nash and Wilkinson (1971) attributed the increase of K-Rb ratios observed in the more evolved rocks of the Shonkin Sag laccolith to preferential entry of Rb into biotite compared to coexisting sanidine. Payne and Shaw (1968) attributed the increasing K-Rb ratios observed between early and late zones of the Blue Mountain nepheline syenite to fractionation of biotite or hornblende from a more basic magma.

The K-Rb ratios of amphiboles are generally much higher than those of biotite (Hart and Aldrich, 1967; Griffin et al., 1967; Jakes and White, 1970).

The contrast in K-Rb ratios between biotite and hornblende suggests, according to Shaw (1968), that the most obvious control of the K-Rb ratio in ordinary igneous rocks is the modal proportion of biotite and amphibole. Little correlation is apparent, however, between modal content of biotite, amphibole, or K-feldspar and the whole rock K-Rb ratios of either the alkalic rocks or the Similkameen batholith (Fig. 33), therefore the variation in K-Rb ratios between the Similkameen and the alkalic groups or within the alkalic group cannot be attributed to fractionation of these minerals. In view of the high K contents of these rocks, fractional crystallization of low K-minerals such as clinopyroxene, olivine, or garnet, could have little effect on the observed K-Rb distribution.

Heier (1964) suggested that the high K-Rb ratio of nepheline syenite at Stjernoy could result from element partition between a crystallizing melt and a gas or gas in a fluid phase which later escaped. Payne and Shaw (1968) suggested that this mechanism might account for the difference in K-Rb ratios between the pegmatites and earlier muscovite syenite at the Blue Mountain nepheline syenite, and Bell and Doyle (1971) suggested that the K-Rb ratios observed in continental alkalic rocks of the East African rift system could be produced by redistribution of K and Rb through transport in a fluid phase.

Local redistribution of K and Rb both within and exterior to the alkalic complexes through the action of a vapor phase cannot be denied, in view of the zones of fenitized rocks forming parts of the alkalic complexes at Shankers Bend, Oroville, and Bimetallic Mountain. However, the K-Rb ratio of a sample of biotite ienite (L-444K) from

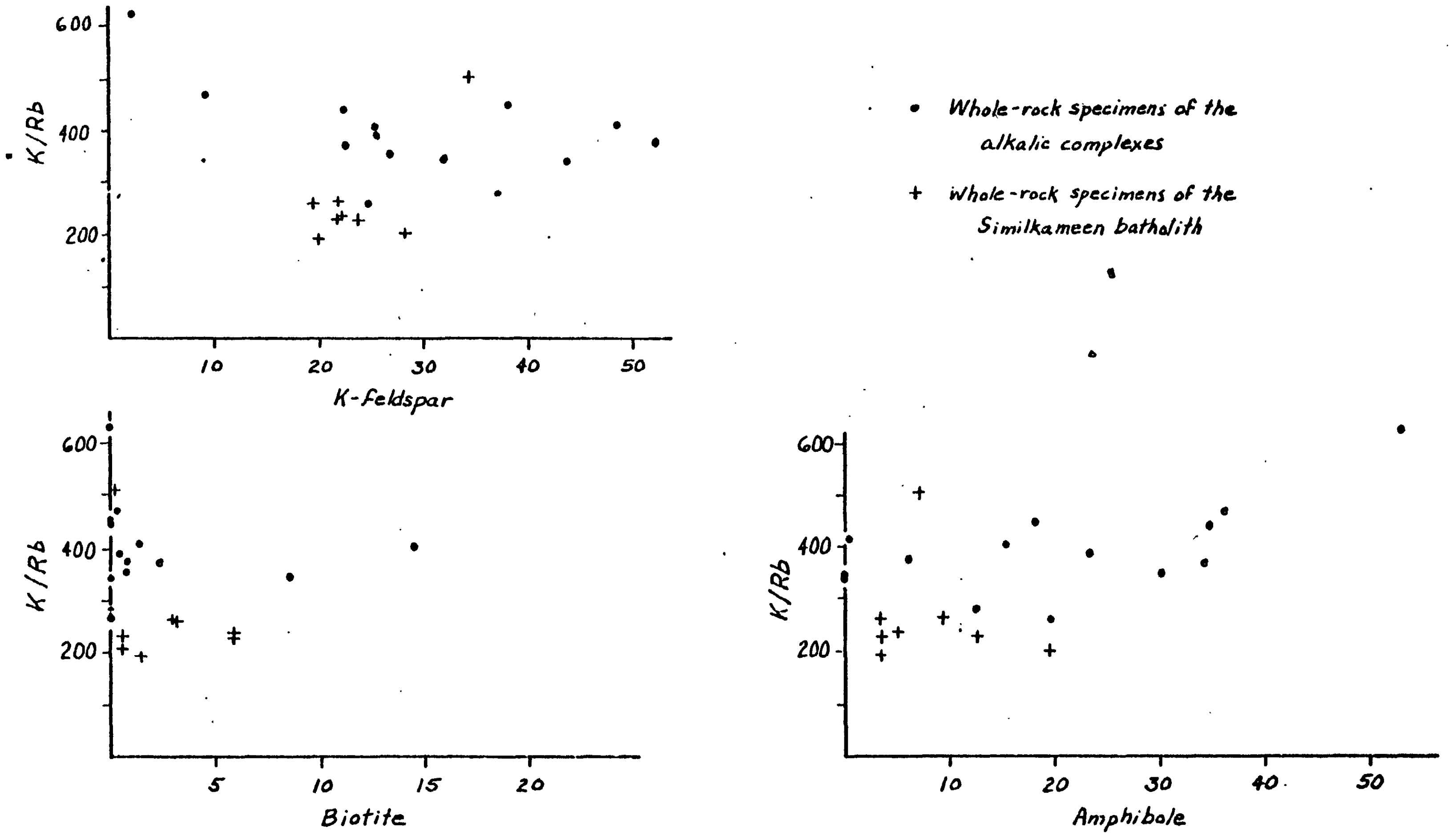

Fig. 33.--Diagram showing correlation of K-Rb ratios with modal K-feldspar, amphibole, and biotite of specimens of the Similkameen batholith and of the alkalic complexes.

the Shankers Bend complex falls closer to the Similkameen trend than to the Kruger trend (Fig. 32), and is greater than the K-Rb ratios of samples of other rocks at the complex, including malignite, alkalic gneiss, and a pegmatitic microcline breccia dike. Based on this admittedly skimpy evidence, the fenitization does not appear by itself to be responsible for the high K-Rb ratios of the alkalic rocks at the Shankers Bend complex.

The Similkameen and Kruger magmas were probably initially undersaturated in water, and remained so until a vapor phase was exsolved during crystallization of the last traces of magma. Diking of malignite by nepheline syenite and of the Kruger complex by rocks of the Similkameen indicates that the major compositional features of the composite batholith had been established prior to the appearance of this vapor phase. It is therefore unlikely that the observed variation of K-Rb ratios is largely a result of redistribution of potassium or rubidium through the agency of a vapor phase.

In view of the inadequacy of these mechanisms to effect substantial redistribution of K and Rb, the K and Rb contents of the Similkameen batholith and the alkalic rocks is tentatively regarded as a primary feature of the respective magmas from which these rocks were derived. Several authors have proposed or intimated that the K-Rb ratios of certain rocks, such as abyssal basaltic magmas (Gast, 1968), and alkalic magmas (Abbott, 1967), simply reflects the prevailing K-Rb ratio of the source material. This may be so for magma generation through batch melting, but for fractional melting processes, the K-Rb content of the magma depends on the partition of K and of Rb between the melt and the various crystalline phases being melted (Philpotts and Schnetzler, 1970) as well as the overall K-Rb ratio of the source material. Partition coefficients of K-Rb and other elements have been estimated between minerals and melt through measurement of the ratios of K-Rb ratios between phenocrysts and matrix (Phillpotts and Schnetzler, 1970), and have been experimentally determined between minerals and hydrothermal solutions (Lagache, 1968). If the "average" K-Rb ratios of the Similkameen batholith and the alkalic rocks are a primary magmatic compositional feature as hypothesized, then the partition coefficients and the observed K-Rb ratios place restrictions on models in which the respective magmas are derived through fractional melting.

PETROGENESIS

Discussions and hypotheses relating to the petrogenesis of the alkalic complexes and Similkameen batholith form a five-tiered hierarchy, which when arranged in terms of progressive degree of abstraction, may be categorized as follows: (1) Physical and compositional interrelationships, (2) depth and temperature of emplacement, (3) derivation of chief lithologic types from the source magmas, (4) origin of the primary magmas, and (5) causes of geographic alinement of the alkalic complexes.

Physical and Compositional Interrelationships

The main conclusions that emerge from the foregoing descriptions and discussions are that the Similkameen batholith and the Kruger complex are related, forming a composite batholith zoned from quartz monzonite at the center to shonkinite, malignite, and pyroxenite at the periphery, and that the alkalic complexes at Shankers Bend, Copper Mountain, Oroville, Bimetallic Mountain, and Cumberland Mountain constitute a family of intrusives related to the Kruger complex in composition but distinctive because of their mode of emplacement as alkalic diatremes. The alkalic rocks of the diatremes are both chemically similar and physically similar, except for being brecciated to varying degrees, to rocks of the Kruger complex. Because of these similarities and their geographic association, the diatremes are assumed to be genetically related to the alkalic rocks of the Kruger complex.

Depth and Temperature of Emplacement

The early development of clinopyroxene, then amphibole, and then biotite in the paragenesis of the alkalic rocks and the rocks of the Similkameen batholith suggests a trend toward increasing water content of the residual magmas as they crystallized. The textures of the pegmatitic syenite dikes at the Kruger complex and of the rare pegmatite dikes at the Similkameen batholith probably indicate that an exsolved aqueous phase was present during their crystallization (Jahns and Burnham, 1969). If the dikes are late derivatives of the Kruger and Similkameen magmas, as seems likely, their presence suggests that the increase in water content of the residual magma culminated in the appearance of a "vapor" phase.

In this connection, the widespread presence of myrmekite in the quartz-bearing rocks may be significant. The origin of myrmekite has been recently discussed by Barker (1970), Hubbard (1969), Shelley (1969), Ranson and Phillips (1969), Shelley (1967), and Hubbard (1966). Although no consensus is apparent, theories of origin involving unmixing or replacement processes currently are the most popular. However, the formation of myrmekite would probably require rapid diffusion relative to the rate of nucleation--properties commonly ascribed to magma systems with a coexisting vapor phase. This fact, in conjunction with the constant association of myrmekite with K-feldspar, suggests that myrmekite may form through crystallization of a terminal water-saturated interstitial liquid. The presence of myrmekite may therefore indicate that a vapor phase had exsolved from the late intercrystalline rest-magma.

Thus there is reason to believe that the interstitial rest-magmas of both the alkalic and the alkali-calcic magma series were water-saturated. Jahns and Burnham (1969) have noted that the formation of a water-saturated rest-magma is a necessary consequence of the crystallization of a water-bearing primary magma, provided that the tendency for the proportion of water to increase in the diminishing volume of rest-magma is not entirely offset by the crystallization of hydrous minerals, such as amphibole and mica, or by escape of an aqueous phase from the magma chamber through the equivalent of a semi-permeable membrane.

Crystallization of the final fraction of both the alkalic magma and the alkali-calcic magma could therefore have been at a pressure and temperature approaching that of the solidus for water-saturated magmas of these compositions. The "average" solidus of the granodioritic and quartz monzonitic facies of the Similkameen batholith is assumed to be roughly similar to the experimentally determined solidus of granodiorite 766 (Piwinskii and Wyllie, 1968) (curve B, Fig. 34). The solidus of the muscovite-bearing pegmatitic syenite dikes cutting the alkalic rocks at the Kruger complex is assumed to correspond approximately to the average pressure and temperature of the beginning of melting of Kungnat syenite (McDowell and Wyllie, 1971) and of syenites of the Deboullie stock (Robertson and Wyllie, 1971) (curve B, Fig. 34). The solidus in the system albite-orthoclase-water (curve D, Fig. 34) was accepted as the syenite solidus by Merrill,

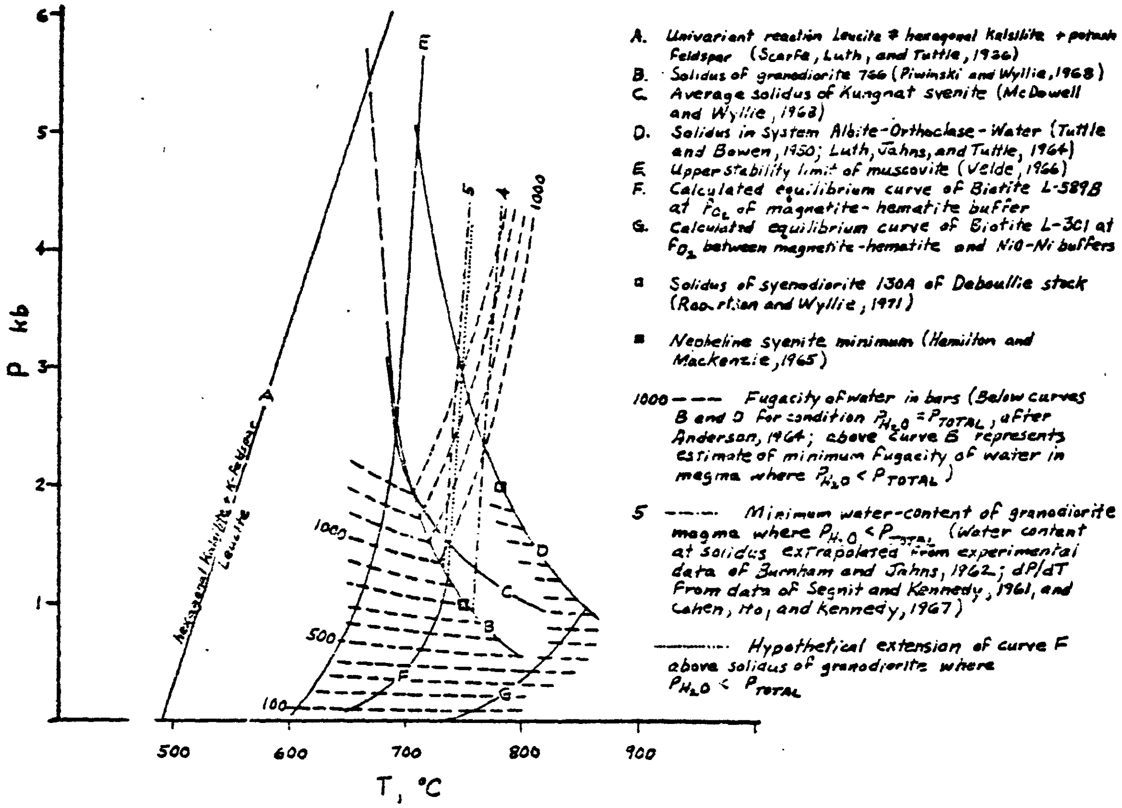

Fig. 34.--Relation of calculated equilibrium fugacity of water in biotites L-5898 and L-301 to pertinent reactions and minimum melting curves. Biotite equilibrium curves calculated using equation 6' of Wones (p. 1249, 1965), assuming that biotite compositions reflect equilibrium with coexisting magnetite and K-feldspar.

Robertson, and Wyllie (1970), but appears to be displaced to much higher temperatures than the minimum melting points of naturally occurring syenites.

The intersection of curve E (Fig. 34) showing the upper stability limits of muscovite for the case where P_{H_2O} equals P_{TOTAL} (after Velde, 1966) with curve B suggests emplacement of the pegmatitic syenite dikes at a minimum confining pressure of roughly 2-1/2 kb. This is assumed to be the lower limit of load pressure at time of intrusion of the Similkameen batholith and the Kruger alkalic complex.

The upper limit on load pressure is much more tenuous. As previously noted, two textural types of pseudoleucite are present in the Kruger alkalic rocks: fine- to medium-grained granoblastic intergrowths and fingerprint intergrowths. The latter probably represents the sub-solidus breakdown of leucite as postulated by Fudali (1963). If the leucite in the spotted, salic nepheline syenite was in equilibrium with a vapor phase at the solidus, then the load pressure was probably less than that given by the intersection of the extrapolated average solidus of the Kungnat syenite (curve C, Fig. 34) with the univariant curve representing the reaction with increasing pressure or declining temperature of leucite to kalsilite plus potash feldspar (after Scarfe, Luth, and Tuttle, 1966) (curve A, Fig. 34) at about 5-1/2 kb.

The composition of the vapor dissolved in the source magma and the composition of the aqueous phase which was hypothetically exsolved during the final stages of crystallization is unknown. However, the presence of probable carbonatite dikes and of calcite-microcline dikes at the Shankers Bend complex suggests that CO_2 was an important constituent of a residual fluid phase and therefore of the source magma. Probably it is safe to assume that CO_2 as well as H_2O was a constituent of the primary magmas at the other alkalic complexes as well. Kerrick (1972) has shown that addition of CO_2 to the aqueous phase shifts the reaction

muscovite + quartz = andalusite + K-feldspar + H_2O

to lower temperatures, but raises the minimum melting temperature of granite. Similarly, Millhollen (1971) has shown that dilution of the aqueous phase with CO_2 raises the minimum melting temperature of nepheline syenite. Therefore the intersection of curves B and E and the intersection of curves A and C (Fig. 34) would probably be shifted to higher pressures if the hypothetical aqueous phase at the Kruger complex consisted of both H_2O and CO_2, as is likely.

The ratio Fe/(Fe+Mg) in the four analysed biotites (Table 4) shows a narrow spread, ranging from 0.42 to 0.48. Wones (1965) suggested that this ratio in suites of comagmatic biotites would indicate a reducing trend by showing a progressive increase with declining temperature of formation, or indicate an oxidizing trend by remaining constant. The small variation in the ratio Fe/(Fe+Mg) of the Similkameen-Kruger biotites therefore suggests an oxidizing trend.

Two explanations of the oxidizing trend have been offered. Wones (1965) suggested that such a trend would result from crystallization of biotite in a water-saturated magma, due to reaction of the magma with the water and the resulting loss of hydrogen to the environment. In this situation, the f_{O_2} with which the biotites are in equilibrium remains constant or increases slightly. However, Dodge and Moore (1968) suggested that the constant ratio of Fe to Fe+Mg in biotites of the Cartridge Pass pluton indicated equilibration under subsolidus conditions with late hydrothermal fluids.

If f_{O_2} is known, the f_{H_2O} in equilibrium with the assemblage biotite, magnetite, and sanidine can be calculated using equation 6' of Wones (p. 1249, 1965). Wones suggested that f_{O_2} may be estimated from the ratio $Fe^{+2}/(Fe^{+2}+Fe^{+3})$. For biotite L-589B, this ratio is similar to that in biotites crystallized in the presence of the Fe_2O_3-Fe_3O_4 buffer, and for biotite L-301, this ratio is somewhat more than that of biotite crystallized in the presence of the NiO-Ni buffer, as estimated by Wones (p. 1232, 1965). The composition of biotites L-301 and L-589B is assumed to reflect equilibrium with co-existing magnetite and K-feldspar. The f_{H_2O} in equilibrium with biotite L-589B has accordingly been calculated using the f_{O_2} of the Fe_2O_3-Fe_3O_4 buffer, and that of biotite L-301 using the f_{O_2} found by interpolating between the f_{O_2} of the Fe_2O_3-Fe_3O_4 buffer and that of the NiO-Ni buffer. In view of the crudity of these estimates of f_{O_2}, great refinement in the other parameters is probably unwarrented. Therefore the activity of $KAlSi_3O_8$ in the microcline and that of Fe_3O_4 in the magnetite coexisting with biotites L-589B and L-301 is assumed to be unity.

Given the assumptions stated above, the results (curves F and G, Fig. 34) indicate that biotite L-589B has equilibrated with a lower f_{H_2O} than that expected at or below the solidus of water-saturated granodiorite at a P_{H_2O} of 2-1/2 kb or greater. A similar claim for biotite L-301 cannot be confidently made, since the position of the solidus of shonkinite is not known. Perhaps the solidus of shonkinite is similar to that of syenodiorite 130A of the Deboullie stock, which at 2-1/2 kb is coincident with the orthoclase-albite solidus (Fig. 34). If so, the f_{H_2O} in equilibrium with biotite L-301 is also significantly less than that expected at the solidus at or above P_{H_2O} of 2-1/2 kb.

Equilibration of the biotites to f_{H_2O} significantly less than that expected had they crystallized under condition in which P_{H_2O} equals P_{TOTAL} militates against the applicability of both Wones' (1965) and Dodge and Moore's (1968) explanation of the constancy of the ratio Fe/(Fe+Mg). The late position of biotite in the paragenesis of the Similkameen and Kruger rocks, the evidence of increasing water content of the residual magma, and the low equilibrium f_{H_2O} of the biotites, suggest an alternative explanation. The percentage of water dissolved in the initial magma was probably very low, and consequently f_{H_2O} was less than that necessary for the formation of biotite. As the percentage of water increased through crystallization of anhydrous phases, the f_{H_2O} increased, ultimately reaching a level high enough for formation of biotite, but still well below that which would exist were the magma saturated in water. Probably the ratio of Fe to Fe+Mg of biotites of the Similkameen and Kruger rocks was fixed after the biotite crystallized from a water-undersaturated magma, in which P_{H_2O} was much less than P_{TOTAL}.

The constancy of the ratio Fe/(Fe+Mg) therefore may imply that the biotites equilibrated at about the same f_{H_2O} and f_{O_2} throughout the magma series, and that the magma series was undersaturated in water at the onset of biotite crystallization. This suggests a correlation between f_{H_2O} and f_{O_2}; possibly as suggested by Mueller (1971), f_{O_2} was more dependent on the increasing water content of the residual magma than on the buffering action of the coexisting silicate minerals.

The water content of the intercrystalline residual magma with which biotite L-589B equilibrated was probably about 5 percent, assuming the validity of the model set forth above. This estimate is based on extrapolation of the solubility data of Burnham and Jahns (1962) to the solidus of granodiorite 766. The water content of magma at the solidus may be regarded as the minimum water content necessary to prevent the magma from solidifying at that pressure and temperature. Contours showing the minimum water content for granodiorite 766 are drawn (Fig. 34) with a slope of 6.5° C per kb, based on the experimentally determined slope of the melting curve for a muscovite and quartz mixture approximating granite in composition (Segnit and Kennedy, 1961), and the slope of the melting curve of dry basalt between 1 and 10,000 bars (Cohen, Ito, and Kennedy, 1967). The position of curves showing the minimum fugacity of water in the water-undersaturated magma probably are slightly concave toward the pressure axis of Fig. 34, and approach parallelism with the contours showing minimum water content at high P_{TOTAL}. An estimate of a possible configuration of the minimum fugacity contours, and the resultant extension of the minimum temperature equilibrium f_{H_2O} curve of biotite L-589B into the water-undersaturated region is given in Fig. 34. This estimate was made by extrapolating the fugacity of water at the intersections of the minimum water-content contours with the liquidus to higher pressure at constant T, using the relation:

$$RT(\ln f_2 - \ln f_1) = \int_{P_1}^{P_2} \bar{v}_w dP \ .$$

The partial molar volume ($\bar{v}_w$) of H_2O in magma was assumed to be similar to that of the H_2O in $NaAlSi_3O_8 - H_2O$ melts and glasses as experimentally determined by Burnham and Davis (1971). If these speculations approximate the true situation, the water content and temperature at the intersection of the equilibrium f_{H_2O} curve of the biotite with the granodiorite solidus may not be greatly different from those prevailing at the higher P_{TOTAL} within the water-undersaturated magma at the time of equilibration of the biotite.

In summary, the Similkameen composite pluton was probably emplaced at depths greater than roughly 10 km, corresponding to a load pressure of 2-1/2 kb or more. Net water content of the magma at the site of emplacement at least slightly exceeded that given by averaging the chemical analyses of the rocks, and therefore was perhaps in the one-half to one percent range. If so, about 80 to 90 percent of the pluton had crystallized before cooling to the temperature of equilibration of the biotite in the granodiorite, possibly at about 735° C.

The field evidence indicates that some of the alkalic rocks of the Cumberland Mountain area were emplaced under a cover of less than 2000 feet. The Shankers Bend, Copper Mountain, Oroville, and Bimetallic Mountain complexes also show features suggesting emplacement at relatively shallow depth, but that depth has not been closely bracketed. Also a distinction must be made between the depth of crystallization and depth of emplacement, since certain rocks at these complexes have been emplaced as breccias.

The water content of the primary magmas at the alkalic diatremes was probably low initially, and increased as crystallization progressed, judging from the increasing hydration reflected by the paragenesis augite-hastingsite-biotite. The presence of fenite at all but the Cumberland Mountain complex indicates that a vapor phase was present. The vapor phase was associated with the alkalic magma, but did not necessarily coexist with it under conditions of $P_{AQUEOUS\ FLUID}$ equal to P_{TOTAL}, since the magmatic systems at the diatremes were probably vented to areas of lower pressure, possibly even to the surface.

Derivation of Lithologic Types from the Source Magmas

Alkalic rocks

The termination of the alkalic trend in or near the clinopyroxene field on each of the projections (Figs. 28, 29, 30) was expected since the most mafic of the analyzed specimens are composed mainly of clinopyroxene (L-507B, L-275C, Table 3). The nearly colinear trend of the alkalic rocks away from this point and the small deviations of the alkalic rocks from the trend are noteworthy, since five complexes of differing ages, geographically dispersed along a 35-mile-long belt are represented. Apparently most of the variation in composition of the alkalic rocks could be accounted for by fractional crystallization of clinopyroxene from a parent magma whose composition can be represented by a point located somewhere on the alkalic trend. Varying but minor quantities of magnetite and biotite must have accompanied the fractionating clinopyroxene, in order to account for the deflection of the alkalic trend at the M' corner of the QL'M' plot to lower silica content than is typical of clinopyroxene, and to account for the presence of these minerals in the modes of the pyroxenites. Fractional crystallization of complex associations of other minerals, which might be invoked to explain all or part of the trend, lack corroboration in the modal composition of the alkalic rocks.

The derivation of potassic, undersaturated residual magmas from shonkinitic primary magmas through fractional crystallization requires that clinopyroxene predominate over olivine as the solid phase at the liquidus over most of the rather wide compositional range of the alkalic rocks, and that the viscosity of the magma and density contrast between the early formed crystals and the magma be favorable for efficient crystal settling.

Clinopyroxene is generally the earliest crystalline phase in the paragenesis of the discontinuous reaction series throughout the alkalic series. Plagioclase in rocks in which it is a constituent is also an early phase. Crystallization of pyroxene probably preceded that of much of the K-feldspar, nepheline, and leucite ("pseudoleucite") except in the foyaite and juvite. There pyroxene is found along with garnet and hastingsite as skeletal crystals interstitial to the felsic minerals, suggesting concurrent crystallization in the final liquid fraction.

Clinopyroxene has been shown to be the crystalline phase at the liquidus for certain compositions and conditions, e.g., through melting experiments on gabbros and syenogabbros at 10 kb (Upton, 1971), olivine tholeiite at 31.4 kb (Tilley and Yoder, 1964), and felsic alkalic rocks from alkalic complexes in Canada, Africa, and South Greenland at one atm in air and at 2020 bars in argon (Piotrowski and Edgar, 1970), and 1030 and 2070 bars P_{H_2O} (Sood and Edgar, 1970).

That gravitative settling of clinopyroxene from shonkinitic primary melts is an efficient fractionation process has been documented through field studies on layered alkalic laccoliths such as Shonkin Sag (Hurlbut, 1939). Fractional crystallization of clinopyroxene thus can be regarded as a well verified differentiation mechanism operating in alkalic magmas.

The pyroxenite found at the Kruger complex in large masses, and at the Cumberland Mountain complex in minor amounts, is therefore probably a clinopyroxene cumulate, and the foyaite and juvite are its complement.

Fractionation of leucite was suspected, since pseudoleucite is present as fingerprint intergrowths of nepheline (or hydromica) and orthoclase, and as the more problematical coarse-grained intergrowths of these minerals which form the prominent spots found packed together within the spotted malignite and salic nepheline syenite. Fractionation of leucite would help explain the deflection at the felsic end of the alkalic trend in the QL'M' projection (Fig. 28) toward leucite (Lc), and in the M'-(Kp+Ks)-(Ne+Ns) projection (Fig. 29) toward the orthoclase-leucite (Or, Lc) corner.

Plagioclase apparently crystallized early in the paragenetic sequence, since it is present in glomeroporphyritic aggregates in parts of the malignite and shonkinite. Plagioclase is not, however, an important constituent of the pyroxenite, and it is nearly absent from the juvite and more undersaturated foyaite. Thus concentration of plagioclase in the shonkinitic rocks represented by analyses near the middle of the Kruger trend seems like a real possibility. Fractional addition of plagioclase would cause an increase in quartz (Q parameter, Fig. 28) of any rock within the Kruger group to which it was added, and a complementary decrease in rocks from which it was subtracted; thus accumulation of plagioclase in the shonkinite would contribute to the convexity observed in the Kruger trend in the QL'M' projection (Fig. 28).

Differentiation of the primary alkalic magma thus is visualized as the result of two and possibly three competing processes: (1) fractionation through crystallizing and sinking of clinopyroxene with minor biotite and magnetite, forming the pyroxenite as the accumulate and driving the composition of residual magmas toward more felsic and more silica-undersaturated compositions that might then have intersected the primary field of leucite; (2) fractionation through flotation of leucite, forming an accumulate of spotted malignite, foyaite, and juvite, and driving residual magmas toward more mafic and more silica-saturated compositions; and possibly (3) imperfect fractionation (by filter pressing?) of plagioclase, forming the less undersaturated shonkinite and driving residual magmas to more undersaturated compositions.

The primary magma hypothetically could have had any composition between pyroxenite and foyaite along the alkalic differentiation trend. The necessity of hypothesizing the existence of large volumes of unseen differentiates to provide quantitative balance is minimized by assuming an initial composition near the midpoint of the sequence, e.g., corresponding to a shonkinite with about 53 percent silica.

Similkameen batholith

The association of oversaturated rocks with alkalic rocks under circumstances suggesting a comagmatic relation is well known. Tilley (1957) divided such rocks into two classes, depending on whether the undersaturated rocks are older or younger than the associated oversaturated rocks. The Similkameen-Kruger association clearly belongs to the former class, which also includes alkalic complexes within the Permian Oslo province, at Red Hill in New Hampshire, Borolan in the Assynt district of Scotland, and Ilimaussaq, South Greenland. Other complexes showing a gradation from oversaturated to undersaturated parts include the Kangerlugssuaq intrusion of East Greenland, the Granite Mountain pluton of Western Alaska, and the Dezhnev Massif of east Siberia.

The Kangerlugssuaq intrusion of East Greenland is 33 km in diameter, zoned with quartz nordmarkite in the outer part, grading inward through nordmarkite and pulaskite to foyaite (Kemp, Deer, and Wager, 1970). Average composition is that of a quartz-poor nordmarkite with 5.3 percent normative quartz. According to Kemp et al., "Crystallization of the nordmarkitic liquid led to a change in magmatic composition towards the feldspar join, i.e. up the thermal gradient, and the last 10 percent of the liquid has given rise to the pulaskites and foyaite . . . thus poses once again the principal problem associated with the petrogenesis of the alkaline rocks, i.e. the apparent derivation of an undersaturated from an oversaturated liquid."

The Ilimaussaq intrusion in South Greenland is oval, 8 by 17 km in exposed dimensions, and constitutes a composite batholith which Ferguson (1964) interprets as being composed of derivatives of two primary magmas, alkali acid and augite syenite. Differentiation products of the augite syenite include sodalite foyaite, naujaite, lujavrite, and kakortokite. Those of the alkali acid magma include alkali granite and quartz syenite. The earliest magma corresponded to augite syenite, and it followed an undersaturated differentiation trend that was interrupted by injection of alkali granite magma.

Miller (1972) attributed zonation from quartz monzonite through monzonite to garnet syenite and nepheline syenite at Granite Mountain, Alaska, to a process of fractional and equilibrium crystallization of a primary magma of pseudoleucite porphyry (nepheline syenite) composition. The chemical composition of the alkalic rocks of western Alaska, including three samples of the silica-undersaturated rocks of Granite Mountain pluton, closely resembles that of the alkalic rocks of northern Washington (Figs. 35, 36, and 37), although the Alaskan rocks show generally higher ratios of (Kp+Ks) to (Ne+Ns) (Fig. 37). Except for this difference, the chemical composition of the alkalic rocks apparently provides little basis for distinguishing the primary magmas of the two series or the mechanisms of their differentiation.

At the Dezhnev Massif similar zonation has been ascribed to interaction between a granitic magma and the limestone country rock (Perchuk, 1965). The oversaturated rocks of the Dezhnev Massif are

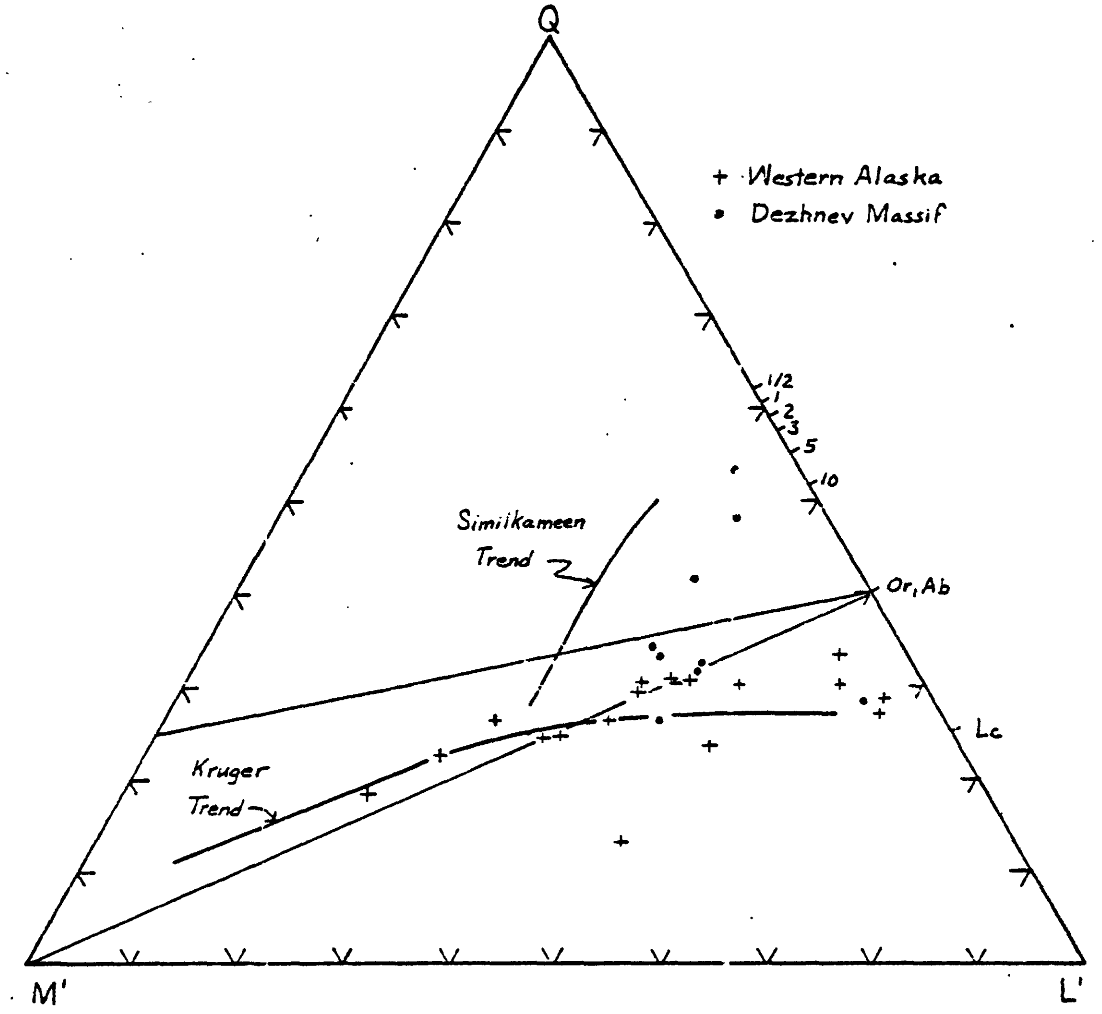

Fig. 35.--Ternary QL'M' diagram comparing the Similkameen trend and the Kruger alkalic trend with the alkalic rocks of western Alaska and of the Dezhnev Massif.

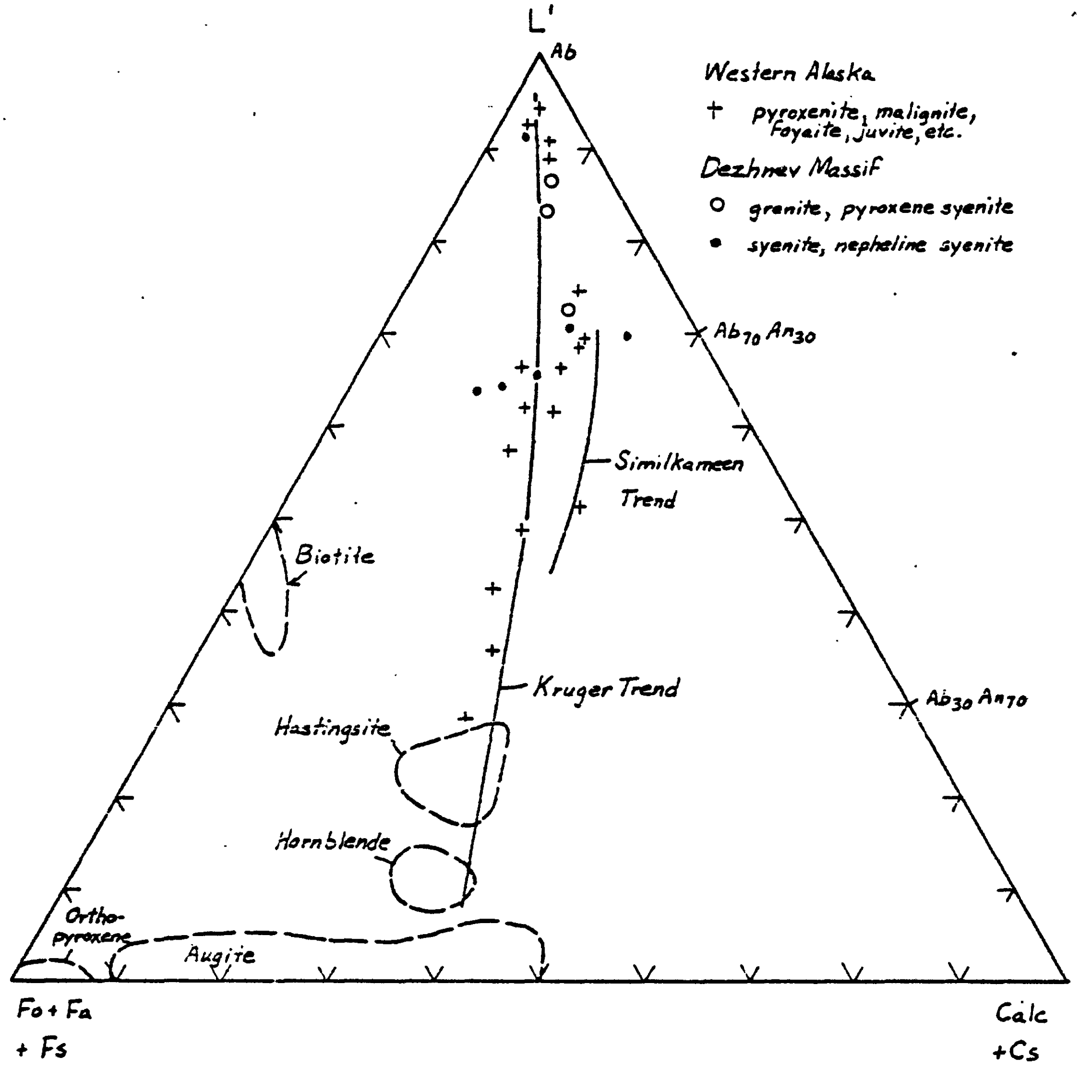

Fig. 36.--Ternary L'-(Calc+Cs)-(Fo+Fa+Fs) diagram comparing the Similkameen trend and the Kruger alkalic trend with the alkalic rocks of western Alaska and of the Dezhnev Massif.

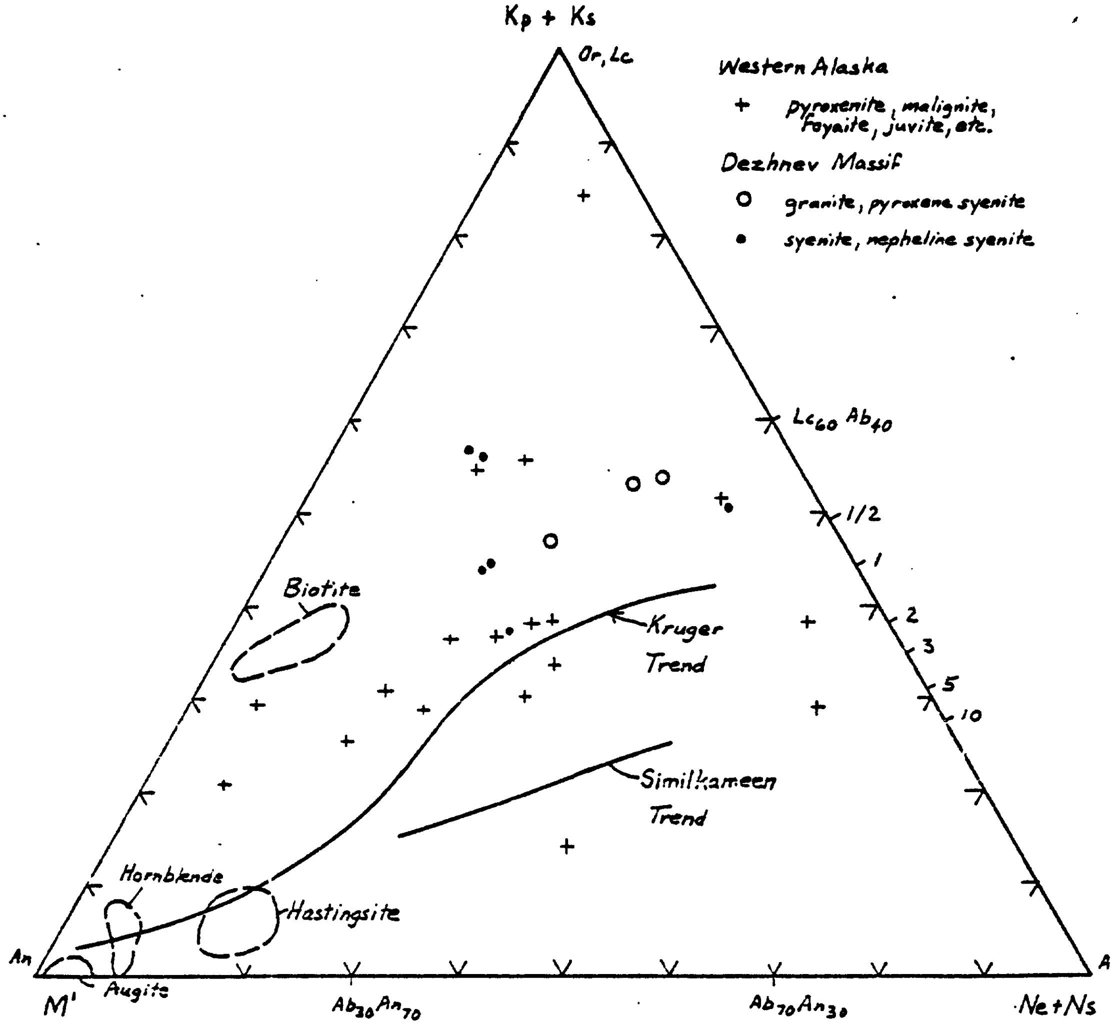

Fig. 37.--Ternary M'-(Kp+Ks)-(Ne+Ns) diagram comparing the Similkameen trend and the Kruger alkalic trend with the alkalic rocks of western Alaska and of the Dezhnev Massif.

more felsic and much higher in (Kp+Ks) than are the Similkameen rocks (Figs. 35, 37), but the apparent trend from undersaturated to oversaturated rocks parallels that of the Similkameen.

At Red Hill, syenite and feldspathoidal syenite surround a younger core of granite (Quinn, 1937). According to Wellman (1971), the quartzose and feldspathoidal rocks at Red Hill, although likely to be genetically related with respect to their ultimate source, apparently represent independent evolutions at higher levels in the earth's crust.

Dikes, sills, and chonoliths of nepheline-bearing alkalic rocks in the Quartz Spring area, California, were correlated with small masses of leucosyenite found as a border facies and offshoots of a nearby quartz-monzonite batholith, and their subsilicic character was attributed to limestone anatexis by late differentiates of the batholith (McAllister, 1952).

Limestone is present in thin lenticular beds in the Anarchist Group adjacent to the Similkameen batholith, but was not found in actual contact with the batholith. The differing K-Rb ratios of the Similkameen batholith and the alkalic series cannot easily be accounted for by limestone assimilation. Furthermore, the efficacy of the limestone anatexis process has been challenged on experimental grounds by Watkinson and Wyllie (1969).

The experimental results of Watkinson and Wyllie (1969) indicate that the addition of up to 25 percent of calcite to melts of water-saturated albite causes the crystallization of plagioclase and the formation of a residual silica-undersaturated melt. The solidus of the residual melt is apparently as much as 30° lower than that of the water-saturated albite melt. Nevertheless, Watkinson and Wyllie (1969) questioned the viability of the limestone assimilation hypothesis on several grounds, two of which are: (1) addition of calcite in amounts greater than 25 percent abruptly raises the solidus from below 900° C to above 1040° C, which would result in complete crystallization of a magma with little or no superheat; (2) addition of CO_2 to the system causes formation of a coexisting CO_2-rich vapor phase and the partition of water between the magma and the vapor phase, which results in a reduction in the water-content of the magma, inducing isothermal crystallization.

Judging from the QL'M' and allied plots, fractionation of clinopyroxene or any other individual mineral cannot account for a major part of both the variation in normative ratios of the femic minerals and the ratio of quartz to other felsic constituents defined by the compositional trend of the Similkameen batholith. Derivation of the Similkameen rocks through fractional crystallization of a primary mafic or undersaturated felsic magma is also considered unlikely because of the immense volume of the oversaturated and saturated rocks compared to the apparent volume of the comagmatic undersaturated rocks of the Kruger complex.

The Deboullie stock of northern Maine shows certain similarities to the Similkameen composite pluton, although it lacks markedly undersaturated variants and is much smaller in exposed area. The stock, according to Boone (1962) is composed, in the order of their intrusion, of syenodiorite and monzonite, calc-alkali syenite, and granodiorite. An elongate mass of shonkinite may have been emplaced last. The pluton is about 2 sq. mi. in area.

The series is believed to be comagmatic, based on locally gradational contacts and mineralogical similarities between units, but the intrusive sequence contradicts the expected differentiation trend toward the granite or nepheline syenite residua systems, and therefore the origin of the series cannot be reconciled with simple fractional crystallization. Therefore Boone (1962) attributes the observed lithological variation to sinking of calc-mafic crystals from a hypothetical primary dioritic magma, accompanied by diffusion of alkalis in coordination with H_2O or OH^- through the melt along the pressure gradient, resulting in potassium enrichment in the upper parts of the magma chamber. Boone does not appeal to a separate fluid or gas phase because of the lack of direct evidence of its existence, i.e. miarolitic structures or pegmatitic textures in main units of the stock.

Perhaps Boone's hypothesis is applicable to the origin of zoning in the Similkameen composite pluton, but both it and the limestone assimilation hypothesis fail to account for the localization of the alkalic plutons in belts.

The difficulties in accommodating the field relations and compositional trends with fractionation of an initially homogenous primary magma can be sidestepped if the observed compositional range is largely a primary feature. Thus, the annular or concentric distribution of the major lithologic zones of the Similkameen pluton and the Kruger complex could result from the rise and emplacement of successive volumes of primary magma of differing composition. The primary magmas would be, in the order of their generation and emplacement, the shonkinitic parent of the alkalic rocks of the Kruger complex, e.g., a magma with a composition near that represented by "A" in Fig. 28, followed by increased volumes of monzonitic, then granodioritic to quartz monzonitic magma. According to this model, the fractional crystallization and differentiation of the shonkinitic magma within the alkalic embryo of the pluton was interrupted by intrusion of the monzonitic magma, and the partially crystallized Kruger alkalic rocks were forced to the periphery of the mushrooming pluton. This hypothesis does not require derivation of both the alkalic rocks and the oversaturated rocks by differentiation of a body of magma of a volume and composition equivalent to that of the entire pluton, which would necessarily be much oversaturated in silica. Instead, small volumes of magma with a composition varying successively along the trend from "A" toward "B" (Fig. 28) could rise continuously or periodically from the source areas as the magma was generated.

Derivation of both the Similkameen and the Kruger rocks from the same primary material by either fractional melting or by crystallization differentiation along a path through the continuum with the silica-undersaturated alkalic rocks poses a problem, as that path would necessarily cross the thermal divide between undersaturated and oversaturated melts (Morse, 1968).

Origin of Primary Magmas

The major restrictions on a model for the origin of the hypothesized primary magmas imposed by the field relations, composition, and petrography of the alkalic and associated alkalic-calcic rocks are as follows: (1) The potassic, silica-undersaturated rocks of the Kruger complex grade to the less potassic, oversaturated rocks of the Similkameen batholith; but (2) local crosscutting relations, plus the geometry of the Similkameen composite pluton indicate that the undersaturated rocks are the older, that is, were first in the order of emplacement; similarly, the alkalic lavas of the Marron Formation are older than their more silicic counterparts; and (3) the volume of undersaturated rocks is small compared to the volume of the consanguineous saturated and oversaturated rocks in the composite Similkameen-Kruger pluton, although silica-undersaturated rocks predominate at the other alkalic complexes.

Therefore a viable melting model must have the following attributes: (1) The normal product of melting is a calc-alkalic magma, since that is the composition of the majority of igneous rocks in the region; (2) under certain circumstances, melting produces small volumes of potassic, undersaturated magma; and (3) locally, continuation of a melting episode which began with small volumes of an alkalic melt produces successively larger volumes of magma of increasing silica content. We might ascribe the variation in primary magmas to melting across a lateral or vertical boundary between local mineralogical and/or compositional inhomogeneities, which could include gross differences, e.g., P_{H_2O} or P_{O_2}. Alternatively, the alkalic magmas could be due to some variation in the physical circumstances of melting, such as a lesser degree of melting, or to higher P_{TOTAL} than that required to produce calc-alkalic rocks. Indeed, several authors have linked the formation of more alkalic magmas to increasing depths of magma generation (e.g., Kushiro, 1968).

Increasing alkalinity of basaltic magma was correlated with decreasing fraction of partial melting by Aumento (1967). Gast (1968) has hypothesized that alkalic basalts are produced through 3 - 7 percent partial melting and tholeiitic or abyssal basalts through 20 - 30 percent partial melting of the upper mantle. On the other hand, Ito and Kennedy (1968) concluded from melting experiments that tholeiitic basalt could be the product of fractional melting of a peridotitic mantle provided that the ascending magma fractionally crystallizes olivine and melts orthopyroxene from the wall rock, and that alkalic magmas were the product of fractional crystallization of the parent magma, probably at high pressure, and protected from hybridization with the wall rock.

Green and Ringwood (1968) hypothesized from results of melting experiments that magmas of the calc-alkalic series were derived through partial melting of quartz eclogite under dry conditions at depths of 100-150 km, or by partial melting of basalt under wet conditions at 30-40 km depth. They found that under dry conditions andesite, rather than the more silicic dacite or rhyodacite, has the lowest liquidus temperature at high total pressure. Also, under dry melting conditions and for lesser degrees of partial melting than that required to produce andesite, the liquids would be enriched in alkalis but not silica, thus showing affinity to certain oversaturated syenites found associated with calc-alkalic rocks.

An analogous relation, in which the alkalic primary magma of the Kruger complex was the product of a smaller degree of partial melting than that producing the alkalic-calcic magma of the Similkameen batholith, could account for the miniscule volumes of the alkalic rocks compared to that of the alkalic-calcic rocks, the appearance of gradation between the Kruger complex and the Similkameen batholith, the zonation within the Similkameen batholith, and the progressive increase in silica content with decreasing relative age of the Kruger and Similkameen rocks.

The chemical trend from "A" to "B" (Fig. 28) would therefore represent the melting path of the primary material. This path admittedly is almost diametrically opposed to that expected from comparison of parent material and its anatectic derivatives, e.g., gneisses and migmatites, or from comparison of rocks derived from residual magmas, e.g., alaskites and aplites, with the typically more mafic rocks representing the parent magma. Furthermore, it is contrary to the melting paths of quartz eclogite and of basalt at high pressure (Green and Ringwood, 1968), and to that expected by extrapolation from experimental studies in the granite system. However, the general rarity of alkalic rocks implies the operation of special circumstances, and it may be worthwhile to consider means whereby a melting path which might normally begin near and lead away from petrogeny's residue system could be reversed.

Such a change in the minimum melting composition could be the result of abnormally low P_{O_2}, so low perhaps that elemental iron appears as an additional phase. The plausibility of this mechanism hinges on (1) the efficacy of partial melting of the lower crust or upper mantle in the presence of "abnormally" low P_{O_2} in producing less silicic and more alkalic melts than would be the case in the presence of "normal" P_{O_2}; and (2) whether areas of abnormally lowered P_{O_2} can reasonably be expected in the area of melting.

Maun and Osborn (1956) have investigated melting relations in the SiO_2-MgO-iron oxide "system" at P_{O_2} varying from 0.21 atm (i.e. in air) to the much lower P_{O_2} obtaining in the presence of metallic iron. The effect of lessened P_{O_2} in this system is to markedly decrease the silica content and increase the iron content of the melt at the temperature minimum on the liquidus. For certain compositional fields within this system, the fractional melting path would be radically changed, even reversed, at the lower P_{O_2}. The effect of lowered P_{O_2} when CaO is added to the system is similar (Osborn, 1962), but the influence of varying P_{O_2} on melting relations of rock compositions comparable to those of the alkalic or calc-alkalic series have not been experimentally determined.

Speculation on the oxidation state within the lower crust and upper mantle is based on (1) deductions from models of the composition and origin of the earth; (2) evidence from deep-source xenoliths in igneous rocks; and (3) oxidation state of lavas. Accepting the facts that the core of the earth is composed of metal or metal plus silicate, and is probably highly reduced, that the mantle is at least partly the product of outgassing of the earth during its evolution, and that the earth's crust is relatively oxidized, one must conclude that the mantle, like the crust, is inhomogenous and composed of derivatives variously removed from some primordial composition. For these reasons we may conclude that the mantle probably exhibits varying degrees of oxidation.

The occurrence of native iron in basalts has been cited as evidence for the presence of native iron at high levels in the mantle, which would imply low P_{O_2} (Urey, 1951; Lindgren, 1933). Native iron is also a common accessory in serpentinites and serpentinized peridotite, but there it is a product of the serpentinization of iron-bearing olivine (Chamberlain et al., 1965; Randohr, 1967). The most renowned occurrence of native iron is in plateau basalt at Disco Island and the nearby Nugsuaks Peninsula, Greenland. The iron ranges in size from fine particles to large masses, the largest of which weighs 25 tons (Bøggild, 1953), and it is found at numerous localities along a 150 km span of the coast. The iron is nickeliferous and carbon-bearing, and it occurs with cohenite and graphite (Lovering, 1964). Lovering (1964) suggests that the metal has the composition of a hyper-eutectoid steel containing about 3 percent C, 1.7 percent Ni, 0.6 percent Co, and 0.2 percent Cu. The iron-bearing rocks are charged with angular xenoliths composed of plagioclase (An_{70}), spinel, and rarely corundum (Melson and Switzer, 1966). The basalts overlie or intrude bituminous shales and coal-bearing strata of Cretaceous and Tertiary age, and the prevailing opinion of most who have first-hand knowledge of the Disco occurrence is that the iron originated through reduction of the iron content of the basaltic magma by carbon from inclusions of either the underlying coal, as postululated by Steenstrup (1884), or the bituminous shales (Pauly, 1958). However, this theory fails to explain certain features of the deposits, of which the most important are: (1) the high platinum content of the iron (Goldschmidt, V. M., and Peters, Cl., cited by Urey, p. 253, 1951); (2) oxygen isotopic composition of the basalt is similar to that of stony meteorites (S. Silverman, Dissertation, Chicago, 1950, cited by Urey, p. 253, 1951); and (3) the high nickel content of the iron; native iron in basalt adjacent to tree molds at Mt. Fugi, Japan contains less than 0.5 percent nickel (Kanehira and Shimazaki, 1971); (4) the iron-bearing zones at Disco are not ubiquitously distributed throughout the entire thickness of the basalt, given as several thousand meters by Pauly (1958), but judging from Steenstrup's description (1884), are apparently restricted to a specific flow or flows; (5) some of the basalt is graphitic, but does not contain native iron; and (6) decrease in iron content of the basalt toward the larger iron masses, as expected if the large masses represented an accumulation of finer particles from the surrounding basalt, was not detected by Lorenzen (1884). These features are explicable, however, if the native iron as well as the graphite and anorthite-spinel aggregates are xenolithic.

Adopting Gast's (1968) partial melting model for the origin of basaltic magmas, Philpotts and Schnetzler (1970) suggest that alkalic basaltic magmas could be the product of smaller fractions of partial melting than that producing the tholeiitic basaltic magmas. Philpotts and Schnetzler assume that the minor element content, including K and Rb, of the entire mass of the parent material is removed through partial melting and contained in the early alkalic basaltic extract and the later tholeiitic extract, which together comprise 3-7 percent of the mass of the original material. If so, the K/Rb ratio of the alkalic basalt bears the same relation to the K/Rb ratio of the tholeiitic basalt as the K/Rb ratios of matrix to phenocrysts in lavas. Assuming that the partition coefficients of K and Rb, etc., between the early alkalic extract and the larger fraction of the source rock whose melting produces the tholeiitic extract, are similar to those measured between matrix and phenocrysts, limits on the identity and the proportions of the various minerals present in the source material which contain these elements may be deduced.

The ratio of average K-Rb ratios of Similkameen versus alkalic rocks is about 0.68; while that defined by their respective trends (Fig. 32) measured at corresponding K content ranges from 0.6-0.8. Assuming that the partial melting model outlined above applies to the origin of the alkalic-Similkameen primary magmas, the K and Rb in the source area must necessarily be present in a phase or phases in a ratio corresponding approximately to that of the Similkameen trend, i.e. about 265. Additionally, Rb must be captured rather than admitted by the K-bearing phase(s), contrary to the usual geochemical behavior of Rb. Clearly this poses a severe restriction on the identity of the K-bearing phase(s). Phenocryst-matrix partition coefficients measured by Philpotts and Schnetzler militate against pyroxene, plagioclase, orthoclase and probably biotite being the K-bearing phase in the source material, although the three determinations of this ratio in biotite of 0.866, 1.08, and 1.73 may be regarded as equivocal. Lagache (1968) measured an Rb/K partition coefficient between leucite and hydrothermal solution of 3.3 at a temperature of 600°C, and pressure of 800 bars, showing that under these conditions leucite captures Rb. If these results qualitatively apply to magmas at high pressure, then leucite is a possible candidate for the phase containing the bulk of the K and Rb in the source material during the partial melting event. Although information on K/Rb partition coefficients between possible K-bearing mineral phases and magma at high pressure is too sketchy to place much confidence in this conclusion, it may be profitable to consider some of its ramifications.

The high-pressure stability limit of leucite has not been closely bracketed except in the systems kalsilite-silica and kalsilite-silica-water. For melting of $KAlSi_3O_8$, leucite is present at the solidus up to 2.6 kb P_{H_2O}, and up to about 19 kb $P_{TOTAL(DRY)}$, and for $KAlSi_2O_6$ up to about 30 kb $P_{TOTAL(DRY)}$ (Lindsley, 1967). In the system kalsilite-silica-water, leucite is stable at temperatures above those of the univariant reaction leucite=kalsilite+orthoclase up to a pressure of 8.4 kb, and to higher pressures if P_{TOTAL} exceeds P_{H_2O} (Scarfe, Luth, and Tuttle, 1966). Thus, although speculation on the identity of the K-bearing phase(s) in the lower crust and upper mantle usually focuses on phlogopite or amphibole (Kushiro, 1969; Griffin and Murthy, 1969), leucite is a potential K-bearing phase at these depths provided that P_{H_2O} is low.

The possibility that leucite is the K-bearing phase in the source region of the felsic alkalic magmas suggest an alternative explanation for their origin. Lindsley (1967) noted that the melting temperature of leucite should be depressed by increasing pressure, since it melts to a liquid denser than itself. The melting points of other solid phases in the quartz-nepheline-kalsilite system are expected to increase with increasing P_{TOTAL}. As a consequence, the thermal valley between the granite and nepheline syenite minimums may deepen and shift toward leucite as, in the absence of appreciable water, the primary field of leucite at the solidus contracts with increasing P_{TOTAL}, possibly even eliminating the supposed thermal barrier between the undersaturated and oversaturated residua systems at sufficiently high pressure.

Lowered P_{O_2} might then play a secondary role in the genesis of the alkalic rocks, by decreasing the maximum temperature for a given P_{TOTAL} at which K-bearing ferromagnesian phases such as biotite are stable (see Wones, 1963), and thus widening the area in PT space below the minimum melting curve within which leucite would be stable.

Geographic Alinement of the Alkalic Complexes

The linear arrangement of alkalic complexes observed in the Okanogan alkalic province of northern Washington and southern British Columbia is a common feature of the distribution of alkalic rocks elsewhere. In other regions this has been attributed to structural control of the generation and/or emplacement of the alkalic rocks, for example by deep-seated, regional faults (Egorov, 1970; Zartman and others, 1967; Doig, 1970) and by crustal warping (Bailey, D. K., 1964).

The following features of the Okanogan distribution seem especially pertinent: (1) no major structure is known at the surface following the traces of the geographic trends; (2) the trends cut known major structures (north-northeast faults of the Republic graben, and the boundary between the Columbian intermontane belt and Omineca crystalline belt); and (3) alkalic plutons along the trend are of varying age--from about 195 m.y. near the west end to about 50 m.y. at the east end. However, the eastward change to diminished ages is apparently abrupt rather than progressive.

What is the significance of the west-northwest orientation of the trends? This direction is transverse to the orientation of the Republic graben of early Tertiary age; thus it may be parallel to a direction of tensional stress at some time in the late Mesozoic and early Tertiary. The alkalic belts are subparallel to fold axes and lineations in the gneiss domes and rocks of the Shuswap Series, and also to several hypothesized regional lineaments, including the Trans-Idaho Discontinuity (Yates, 1968); the Lewis and Clark Line (Billingsley and Locke, 1933), and the Olympic-Wallowa lineament (Raisz, 1945; McKee, 1967) (Fig. 1).

These three lineaments have been interpreted as zones of strike-slip faults. This interpretation of the Olympic-Wallowa lineament has been questioned by Taubeneck (1966), who found no evidence of lateral offset along it in northeastern Oregon. The lineament transects but does not offset the early Mesozoic Oxbow-Cuprum shear zone near the Idaho-Oregon boundary. Taubeneck concludes that the lineament has been tectonically inactive since early Mesozoic time, and is only a topographic feature.

Nevertheless, the west-northwest orientation of diverse structural features is clearly a feature of the tectonic fabric of the region, and the location of the alkalic belts is an additional expression of this element of the regional grain. The seeming geographic permanence of the alkalic belts through the Mesozoic may indicate that the source region of the magma lay within the lithospheric plate and not below a hypothetical zone of detachment with the underlying asthenosphere, whose existence is a postulate of the "plate tectonic theory" (recently summarized by Dickinson, 1971). The alkalic belts could mark a streamline formed at the base of the lithospheric plate as it slid over a point feature in the asthenosphere. Because of the bimodal age distribution of the alkalic rocks, that feature cannot have been the direct source of the alkalic magmas, but must instead have generated a linear zone at the base of the overriding plate which when melted during episodes of magma generation produced alkalic magmas. The nature of this point source is of course conjectural, but if the alkalic magmas were partial melts of strongly reduced parental material as hypothesized, then it follows that the linear source zone must have been strongly reduced. The point feature could have been the logical cause of that reduction. Therefore the feature could have represented an area of high P_{H_2}, possibly developed from outgassing of the lower mantle, or it could have been associated with a zone of incompletely homogenized, highly reduced primitive material of chondritic composition.

Alternatively, the zone of alkalic rocks could reflect control by a deep-seated structural feature not otherwise manifested at the surface. If the eugeosynclinal province is floored by material which was part of an active oceanic plate as recently as early Paleozoic time, that structural feature could be a fossil transform fault. This explanation is less satisfactory because it leaves unanswered the question of why the alkalic magmas were initially generated within the transform, why the alkalic magmas were followed by increasingly silicic magmas, and why the transform is parallel to Mesozoic and Cenozoic structural elements.

SUMMARY AND CONCLUSIONS

The alkalic complexes of north-central Washington are composed of varied but predominantly mafic, weakly subsilicic and moderately potassic rocks. Their alkalic character is sufficiently marked, however, to readily discriminate them from the calc-alkalic and alkalic-calcic plutons of the region, thereby permitting definition of an east-southeast trending belt of alkalic rocks, which terminates on the east at Cumberland Mountain. Mafic and ultramafic plutons on strike to the west-northwest in Canada, including the Tulameen ultramafic complex and the Copper Mountain intrusions, are weakly alkalic and are therefore presumed to represent a western extension of the belt. Alkalic rocks between Olalla and Kettle Falls, British Columbia, constitute a second, clearly defined belt, which is subparallel to the Tulameen-Cumberland Mountain belt.

The alkalic rocks lie chiefly within the eugeosynclinal province of central and western Washington and British Columbia. The volcanogenic nature of the late Paleozoic-early Mesozoic rocks of this province and the apparent rarity of older rocks, coupled with the primitive character of lead ores (Small, 1971), low Sr^{87}/Sr^{86} of the Mesozoic plutonic rocks (Fairbairn, Hurley, and Pinson, 1964), and the widely distributed ultramafic rocks suggest that much of the eugeosynclinal province is floored by oceanic crust, which probably is early Paleozoic in age. The eugeosynclinal province was the scene of widespread, possibly episodic, calc-alkalic and alkalic-calcic plutonism beginning in Late Triassic and continuing into the Tertiary. The ages of the alkalic rocks apparently span the range from about 195 to 50 m.y. ago.

While the episodicity of plutonism (and vulcanism) during the Mesozoic may be suspect, that during the Tertiary is not. Dating by Mathews (1964) and by Hills and Baadsgaard (1967) shows conclusively that the pre-Miocene Tertiary volcanic rocks which are spread widely throughout the region were extruded during a geologically brief interval about 50 m.y. ago. The Tertiary alkalic rocks are clearly an expression of this magmatic event. Within the alkalic belts, the 50 m.y. old volcanic rocks and associated hypabyssal plutonic rocks show a progressive increase in silica saturation with decreasing relative age.

The alkalic belts cross the boundary between orogenic subprovinces, the Columbian intermontane belt and the Omineca crystalline belt, without measurable deviation, as do numerous other Mesozoic geologic contacts--thus this boundary cannot have been a zone of major dislocation after the Triassic. The alkalic belts apparently terminate at or near the boundary between the eugeosynclinal-miogeosynclinal provinces.

The Kruger complex is one of the larger intrusive bodies of alkalic rocks in the region, with an area of about 17 sq. mi. It forms a semicircular arc, bordering the eastern perimeter of the Similkameen batholith, which underlies an area of about 121 sq. mi. The Kruger body intrudes the rocks of the adjacent Kobau Formation, judging from the sharply crosscutting contacts, and the presence of xenoliths of Kobau-like rock within the complex near its outer contact.

The complex is composed of alkalic rock modestly to strongly undersaturated in silica--chiefly mafic, including shonkinite, malignite, and pyroxenite--with subordinate more felsic rocks, chiefly foyaite and juvite. Internal contacts within the complex are in part sharp, and in part gradational, and establish that although grossly contemporaneous, the (1) pyroxenite, (2) malignite-shonkinite, and (3) foyaite-juvite were intruded in that order. Subsequently, the complex was intruded by femic nepheline syenite, whose modal and chemical composition resembles the main mass of the malignite-shonkinite.

The Similkameen batholith is concentrically zoned with quartz monzonite at the center grading outward to granodiorite, which in turn grades to monzonite near the border with the Kruger complex. Although dikes of trachytoid monzonite of the Similkameen cut the rocks of the Kruger complex, the contact of the outer zone of monzonite with the malignite-shonkinite of the alkalic complex is gradational. Thus, although the emplacement of the Kruger complex preceded that of the Similkameen batholith, the two are grossly coeval, and therefore probably components of a single composite pluton. The composite pluton was emplaced during a period of widespread plutonism in the late Triassic, judging from the K-Ar data.

Metamorphic mineral assemblages at the contact suggest emplacement at pressures near the pressure boundary between the Abukuma and Barrovian Facies Series. Thus the depth of intrusion at the present level of exposure exceeded that of the hornfels facies. The evidence that various rock units within the composite pluton were emplaced sequentially indicates that they had been differentiated from their parent magmas prior to their final emplacement.

The Shankers Bend, Copper Mountain, Oroville, Bimetallic Mountain, and Cumberland Mountain alkalic complexes lie at distances of 2, 6, 8, 22, and 30 miles, respectively, east-southeast of the Similkameen batholith. The alkalic complexes range in area from about 0.15-1.2 sq. mi., and are composed of rocks compositionally and texturally similar to those of the Kruger complex. They differ, however, in that the alkalic rock and locally the nearby country rock is shattered or brecciated, and the wall rock at several of the complexes has been fenitized.

At Shankers Bend, the core of the complex is composed chiefly of streaky alkalic gneiss showing a compositional range from shonkinite through malignite to foyaite. The alkalic gneiss grades to replacement breccia on the west, to fenitized country rock on the south, and is probably itself a rheomorphic fenite. The alkalic gneiss grades internally to breccia and is partially girdled by breccia. Monolithologic breccia on the west is composed of fragments resembling adjacent bedrock units of the country rock, and was probably formed explosively during development of the complex. Breccias capping the alkalic gneiss are composed of fragments of alkalic rock, and may be intrusive.

These features suggest that the complex was formed through a sequence of rupture, fragmentation, and fenitization of the country rock, with intrusion of malignite-shonkinite plugs, alkalic dikes, and monzonite breccia. The complex is probably an alkalic diatreme.

The Oroville and Copper Mountain alkalic complexes are composed chiefly of variably brecciated malignite, shonkinite, foyaite, and monzonite, and are bordered by fenite in places. Both complexes are patchily overlain by monolithologic conglomerate composed of alkalic rocks, with discrete areas of either predominantly malignite-shonkinite detritus, or of monzonite detritus. The alkalic conglomerate may be a partially reworked relic of a shallow vent or crater filling. The Oroville complex and capping alkalic conglomerates are cut by trachyandesite plugs of probable Eocene age.

The origin of the brecciation at the Oroville and Copper Mountain alkalic complexes is complicated by the presence nearby of the northwestern shoulder of the Okanogan gneiss dome. Other plutonic bodies at the contact of the dome have been pervasively crushed. However, it is likely that the alkalic complexes formed as alkalic diatremes, similar to the Shankers Bend complex, and that much if not all of their internal brecciation is a consequence of internal processes rather than of postemplacement cataclasis accompanying emplacement of the dome.

The Bimetallic Mountain alkalic complex is composed of erratically brecciated shonkinite, trachytoid monzonite, and alaskite, which are intrusive into phyllite, metalimestone, greenstone, and metasiltstone. The bordering greenstone and metasiltstone are locally fenitized and brecciated. The complex is capped by weakly metamorphosed arkose and wacke of probable Eocene age. The Bimetallic Mountain complex probably originated as an alkalic diatreme, in view of its similarity to the Shankers Bend, Oroville, and Copper Mountain complexes.

The alkalic plutons of the Cumberland Mountain area comprise (1) breccia pipes; (2) hypabyssal dikes and sills of shonkinite; and

(3) the Cumberland Mountain complex, a differentiated mass composed of foyaite, malignite, shonkinite, and pyroxenite. The breccia pipes are locally intrusive into, and elsewhere overlain by the O'Brien Creek Formation of Eocene age. The shonkinite cuts the basal beds of the O'Brien Creek Formation, yet the O'Brien Creek rocks probably overlie the Cumberland Mountain Complex. Thus the intrusion of the alkalic rocks was not perfectly synchronous; instead they were emplaced over an interval of geologic time possibly spanning much of the time of deposition of the O'Brien Creek Formation..

The alkalic border of the Okanogan gneiss dome comprises three narrow segments, which from west to east are of one, ten, and seven miles in length, disposed along the north border of the dome. The western segment is composed of syenitic, shonkinitic, and pyroxenitic gneiss. The central and eastern segments grade from syenodioritic gneiss at the eastern end through monzonitic gneiss to syenitic and shonkinitic gneiss at the western end. They also show a gradation across the strike of the belt from felsic, quartz-bearing rocks at the contact with the gneiss dome to mafic, quartz-absent, slightly nepheline normative rocks at the other contact. The contact with the gneiss dome is linear and sharp, while the contact with the country rocks to the north is highly irregular in plan and is gradational.

The alkalic border zone is probably the product of alkalic metasomatism of the country rock bordering the gneiss dome, by a vapor phase channeled along the contact plane early in the emplacement history of the dome. Coincidence of the alkalic border with the Tulameen-Cumberland Mountain belt of alkalic rocks suggests that the metasomatising vapor and the alkalic magma of the previously described complexes share a common source at depth.

The alkali-lime index of the magma series represented by the rocks of the Kruger, Shankers Bend, Copper Mountain, Oroville, Bimetallic Mountain, and Cumberland Mountain complexes is about 50-51, thus falls within the alkalic range (Peacock, 1931), while the alkali-lime index of the rocks of the Similkameen is 54, falling within the alkalic-calcic range. Harker diagrams show that the two magma series possess unique trends of oxides versus silica. The individuality of the two magma series is confirmed by the appearance of two well defined linear trends when the analyses are expressed as various combination of Niggli's (1954) base groups.

The chemical and lithologic variation of the alkalic series can be explained by fractional crystallization and sinking of clinopyroxene, along with minor biotite and magnetite, coupled with concurrent flotation of leucite, from a primary magma of shonkinitic composition. Fractional accumulation of plagioclase in the shonkinite, which is suggested by its glomeroporphyritic habit and its rarity in the other alkalic rocks, cannot be ruled out but is not necessary to account for the chemical trends. The chemical variation of the Similkameen rocks cannot be easily explained by fractional crystallization and is instead considered a reflection of the initial variation in composition of the primary magma.

The chemical trend of the Similkameen batholith intersects that of the alkalic series at a composition near that of the presumed shonkinitic parent magma of the alkalic rocks. The field data and chemical trends are consistent with the hypothesis that the primary magmas from which the two series evolved possessed a continuous range in composition from shonkinite to quartz monzonite.

K-Rb ratios of Similkameen rocks average about 265 and conform to the main trend of Shaw (1968), but those of the alkalic magma series are higher, averaging about 390 and ranging up to 628. The K-Rb ratios do not correlate with modal content of biotite, K-feldspar, or hornblende; thus the variation between the alkalic series and the Similkameen series is not due to fractional crystallization and variable concentration of these minerals from a common parent.

The circumstances outlined above lead to the following restrictions on a model of the genesis of the primary magmas: (1) the alkalic rocks are chiefly confined to well defined geographic belts, on which supracrustal structures show no obvious control; (2) the alkalic rocks were generated within the belts through melting during province-wide episodes of alkalic-calcic to calc-alkalic plutonism in the late Triassic and mid-Eocene; and (3) within the belts, alkalic magmas are generated in small quantities either as the exclusive product of melting, or as the forerunner of progressively more voluminous and increasingly silicic magma.

These features are explicable if the primary magma formed through partial melting of lower crust or upper mantle material under circumstances in which the initial melt was mafic and alkalic, and later increments were successively more felsic and more siliceous. The alkalic melt was apparently more susceptible to fractionation through fractional crystallization than were the succeeding increments of more siliceous magma. No definitive evidence on the physico-chemical basis for the apparent reversal in the usual melting path or its crossing of the supposed thermal barrier between oversaturated and undersaturated melts can be offered, but judging from experimental work in simpler systems reported in the literature, such a melting path could be a consequence of abnormally low P_{O_2}.

The great length (about 130 miles, or 225 km) of the alkalic belts, their disregard of mapped structures and provincial boundaries, and the lack of observable geologic control of their location, points to source areas at great depth. Assuming the validity of the partial melting model outlined above, the ratio of K-Rb ratios of 0.68 between the Similkameen rocks and their alkalic precursor indicates that the K-bearing phase(s) present during meling must capture Rb relative to K, and at the same time possess a K-Rb ratio similar to that of the Similkameen rocks, i.e. about 265. The ratio of K-Rb ratios measured between leucite and hydrothermal solutions (Lagache, 1968) indicates that leucite captures Rb relative to K, and is a better candidate for the K-bearing phase than biotite, hornblende, or orthoclase. However, the instability of leucite at high pressures limits the maximum depth at which it could participate in the melting process to depths not greater than those of the upper mantle.

The evidence adduced in the preceding chapters favors the following hypothesis: the subsurface feature controlling the location of the western segment of the Tulameen-Cumberland Mountain belt of alkalic rocks was established prior to Late Triassic, perhaps as a compositional streamline formed by reduction of a streak of material composing the basal part of the lithospheric plate, as it drifted over a local source of abnormally high P_{H_2} in the mantle. Mafic and weakly alkalic magmas then formed through partial melting as the general area of melting during the Late Triassic magmatic event intersected the streamline and were fractionated, probably through fractional crystallization, and were intruded, forming the Kruger complex and probably the Tulameen and Copper Mountain plutons. The monzonitic to quartz monzonitic magma of the Similkameen batholith was probably generated through continuation of melting with increasing degree of melting of the parent material within or near the source area of the Kruger primary magma.

The eastern segment of the alkalic belt was formed during or prior to early Eocene, when alkalic magmas were generated within the zone during a widespread magmatic event, and following differentiation at depth, again through fractional crystallization, were explosively intruded with local concomitant fenitization by the associated vapor phase.

The apparent age range of the alkalic rocks suggests incremental growth of the streamline to the east. This requires that the lithospheric plate have drifted to the west-northwest relative to the lower mantle at least 50 km between the late Triassic and early Eocene, or at an average rate of not less than about 0.035 cm per year.

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