PETROLOGY

OF

SOME LAVAS OF THE KETTLE RIVER REGION, B.C.

PETROLOGY
OF
SOME EARLY TERTIARY LAVAS OF THE KETTLE RIVER REGION
BRITISH COLUMBIA

By

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SCOPE AND CONTENTS: A petrological study has been carried out on some early Tertiary lavas of the Kettle River map area of south-central British Columbia. This includes petrographic descriptions, mineralogical studies, and chemical investigations of these rocks together with a discussion concerning the subdivision of the lavas into separate series and the more general problem of petrogenesis. The various analytical methods are explained and a discussion of the results is included.

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Abstract

Information provided by previous workers shows a considerable diversification of lava types in the early Tertiary deposits of the Kettle River region of British Columbia. The aim of the present study is to establish, on the basis of mineralogical and chemical evidence, whether or not these lavas form a single magma series.

A suitable spectrochemical technique was adapted for the determination of Sr, Ba, CaO, MgO, and FeO in rock samples and mineral extracts. A method based on the work of Shaw and Filby, using lanthanum as an internal standard for determination of Sr, Ba, and Ca, is extended to include the determination of MgO and FeO.

Extension of the available chemical data was possible using a fused glass bead technique for refractive index determination of the lavas. In view of good correlation between refractive index and the most refractory constituents of the lavas CaO, MgO, and FeO, the refractive index serves as a good magmatic differentiation index.

Examination of the refractive indices of three suites of samples, taken from widely separated points within the Kettle River region, shows that the lavas range from semi-basic to acid composition with intermediate types, andesites and trachyandesites, predominating. There is a marked paucity of basaltic rocks. The stratigraphic distribution of the lavas reveals no consistant trends toward either acid or basic compositions; neither is there any relation between stratigraphic position and lava types within the region concerned.

In spite of close age and spatial association of the lavas, petrological evidence points to a three-fold division of these rocks (termed 'A', 'B', and 'C' series). 'A' series is similar to the silica-enrichment 'calc-alkali' trend showing regular mineral and chemical progression from andesites to latite and rhyolite. 'B' series is characterized by a somewhat less well defined group of two-feldspar lavas, trachyandesites, and trachytes. An unusual undersaturated lava, termed 'analcite rhomb-porphyry' or 'shackanite' is thought to be genetically related to 'B' series but probably belongs to a poorly developed semi-basic alkali trend, 'C' series.

A mechanism involving crystal fractionation of hornblende, or alternately, augite and plagioclase, is envisaged as the probable mode of origin for many of the rocks of 'A' series. On the other hand, Daly's view that the shackanite lavas were formed as a result of limestone assimilation is supported by field evidence as well as mineral and chemical data. The rocks of 'B' series, the trachyandesites and trachytes, are intermediate in composition to 'A' and 'C' series and have probably formed by process of crystal fractionation in consequence of normal cooling conditions and limestone assimilation.

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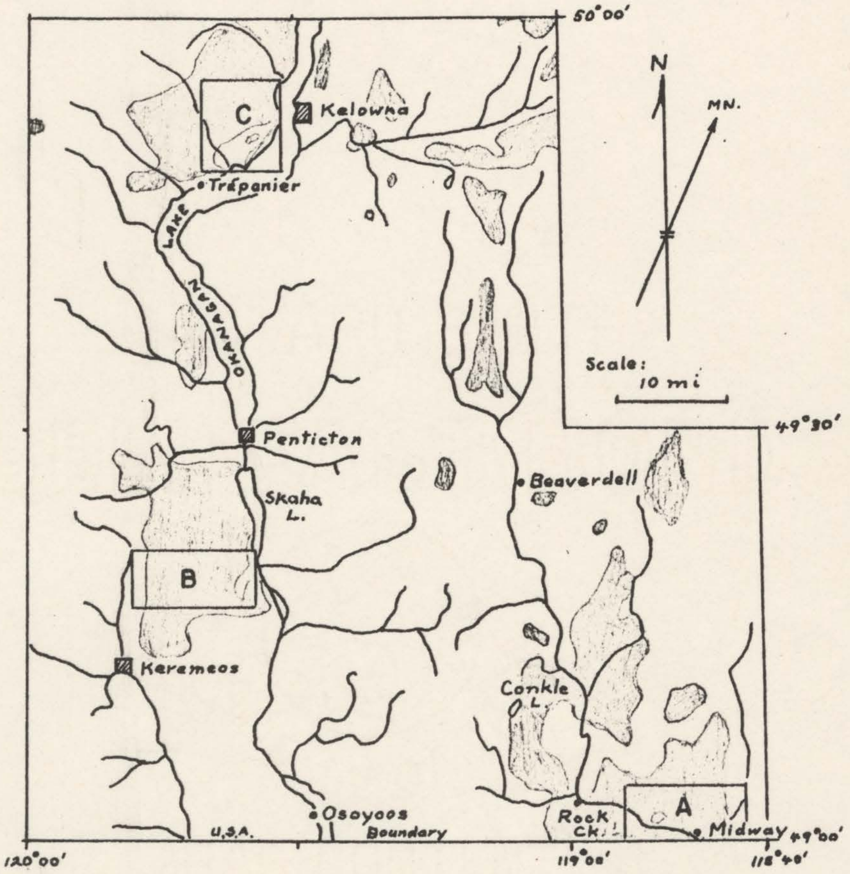
I. Introduction

The south-central plateau area of British Columbia is blanketed by a deeply dissected assemblage of Tertiary lavas, associated pyroclastics, and intercalated lacustrine sediments. These lie in a northwesterly trending belt about 100 miles wide extending about 500 miles from the Republic Mining District in Washington State to the Babine Lake area of central British Columbia. Stratigraphic thicknesses measuring more than 4000 feet are common. The basal horizon of the Tertiary succession is composed, at least in part, of granite pebble conglomerate; the upper surface, particularly on undeformed or moderately folded sequences, is generally coincident with a gently rolling 'upland surface'. In some areas, however, the upper surface is unconformably covered by a thin veneer of columnar basalt, the 'Plateau basalt' - an erosional remnant of a Miocene formation once widely distributed throughout central and south-central British Columbia.

Although the occurrence of these volcanic rocks has been noted by many geologists, little information is available concerning their petrological character. It is the purpose of the present study to investigate the mineralogy and chemistry of the lavas in the Kettle River region of British Columbia with the hope that some light might be shed on the nature of their compositional variations.

The general region concerned in the present study is shown in Figure 1.1. The lavas of the Midway, Marron, and Kelowna areas have been chosen for detailed examination largely because of the completeness of the geological sections in these areas, ease of access, relatively good bed rock exposure, and the regular spacing of these areas within the Kettle River region.

Figure 1.1 Kettle River Region
British Columbia



<u>Legend</u>

A Midway Area
B Marron Area
C Kelowna Area
Local maps are given in Appendix 'B'

(Early Tertiary volcanics are shaded)

1. Previous Work

Bauerman (1884) first briefly reported these volcanic rocks in Southern British Columbia, however, geological interest was not stimulated until the turn of the century when copper deposits were discovered and developed in the Boundary District. Brock (1901-2) mapped a belt about 13 miles wide along the International Boundary extending from Grand Forks west to Midway. This work was projected westward as a five mile wide strip by Daly (1912). Daly's report contains a brief petrographic and stratigraphic description of the Tertiary section at Midway. LeRoy (1912), mapping in the Pheonix mining camp, correlated a minor sequence of Tertiary effusives with Daly's Midway suite. Similarly, Reinecke (1915) suggested correlation of a thick succession of volcanics in the Beaverdell area with the Tertiary Midway volcanics.

McEvoy (1914) measured and described a Tertiary sedimentary section in the White Lake basin, located approximately 40 miles northwest of Midway. Between 1926 and 1930 Bostock mapped and studied the rocks in the quadrangle lat. 49° 00' to 49° 30' and long. 119° 30' to 120° 00'. As a result of this work Bostock defined the Tertiary 'Marron' volcanic sequence in this area.

Mapping by Cairnes (1936) has clearly delineated the extensive Tertiary deposits near Kelowna, situated about 40 miles north of White Lake.

Recently Little (1957) has mapped and described the geology of the Kettle River area (east half) i.e., lat. 59° 00' to 50° 00' and long. 118° 00' to 119° 00'. As well as outlining the distribution of Tertiary rock in this area, Little has reinterpreted some of Daly's mapping at Midway.

2. Evaluation of Previous Work and Outline of Present Study

Previous geological investigations have been mainly concerned with mapping the Tertiary rocks. In a few instances the sedimentary units have been described in some detail because of the associated coal deposits, however, the volcanic rocks have been largely neglected.

Daly's work (1912, pp. 398-420) contains the only significant petrographic and chemical information available to date on the volcanic rocks. However, his interest was almost entirely centered around one peculiar lava type, the rhomb-porphyry's or "shackanites" of the Midway area. According to Daly (p. 412), "The real character of this lava, unique in the whole transmountain section, was revealed after its optical and chemical analysis had been performed." The rock frequently contains abundant analcite, rhombic shaped anorthoclase feldspar, and unusually high concentration of strontium and barium. The other lavas of the Midway area were described as having 'normal character'. Unfortunately, no chemical analyses were offered for these 'normal' lavas nor was there any attempt to relate them petrographically to the above-mentioned shackanites.

The main aim of the present study is to determine whether or not the early Tertiary lavas of the Kettle River region are commonly associated in a single magma series. The petrographic and geochemical investigation begun by Daly on a few Midway lavas, is extended to cover as many lava types as possible. The lavas to the west and northwest of Midway in the Kettle River region, in the Marron valley and at Kelowna, are investigated in a similar manner.

To establish the petrological relationships between the various lavas, an attempt was made to discover compositional associations and trends for both rocks and minerals. On the basis of preliminary thin section examination of the rock samples from the Midway, Marron, and Kelowna areas, a suite of distinctive lava types was analysed using wet chemical and spectrochemical methods. An equivalent suite of porphyrytic rocks was used for detailed petrographic description. A fused glass bead technique was worked out in conjunction with the chemical methods in order to extend the chemical interpretation to non-chemically treated samples. Major silicate minerals were separated and analyzed by oil immersion, universal stage, spectrochemical and X-ray techniques. The results were then viewed in the light of established theory and conclusions were drawn. Also, speculation on the possible petrogenesis of the lavas is included in final analyses of the data.

3. Geological Setting

The Tertiary rocks of the Kettle River region lie unconformably on Mesozoic plutonic rocks and pre-Jurassic metamorphosed sediments and volcanics. Locally they are overlain unconformably by the Miocene Plateau basalt formation, scattered Pleistocene deposits, and recent alluvium.

The Tertiary lithological sequence in the Midway, Marron, and Kelowna areas are similar. In each case a conglomeratic basal sediment is followed by two volcanic units separated by a thick series of (upper) sediments. In all three areas the uppermost volcanic unit is thinner than the lower. The most recent fossil and radio-isotope evidence indicates a Paleocene or Eocene age for these rocks.

The lithological sequence of the Kettle River region bears considerable similarity to other regions containing Tertiary rocks in south-central British Columbia. This evidence together with good radio-isotope age correlation suggests contemporaneous volcanic activity over large areas of British Columbia during early Tertiary times.

A discussion of regional correlation and the detailed stratigraphy of the Midway, Marron, and Kelowna areas is given in Appendix 'A'. Generalized columnar sections are reproduced in Figure 1.2.

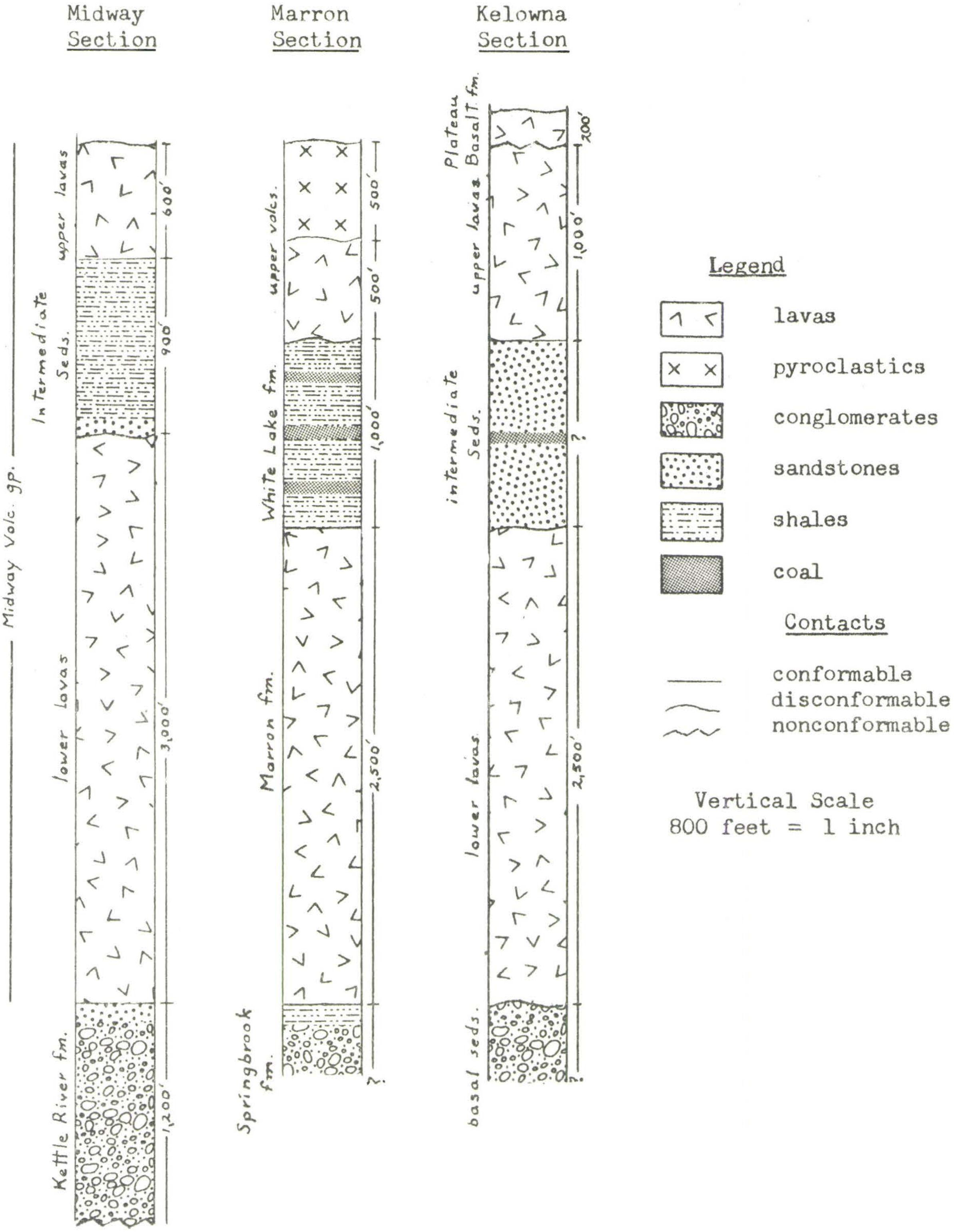
4. Sampling Procedure

During the summer of 1959 the writer was attached to a field party of the Geological Survey of Canada which was engaged in reconnaissance work in the central and southern parts of the Okanagan valley and areas to the east. At this time a suite of samples was collected comprising more than 280 pounds of rock and 234 individual samples.

Sampling of the volcanic rocks was carried out on the basis of a two-fold scheme. First, in order to estimate the relative frequencies of the various acid to basic lavas in each area, samples were taken at regular intervals across the volcanic units of the Midway, Marron, and Kelowna sections. Second, to obtain complete information about the range of mineralogical and chemical compositions, an attempt was made to sample all the various lava types cropping out. Since the samples collected for the first purpose were not always suitable for the second, it was necessary to extend the sampling programme beyond the immediate area of the main sections.

The order and general position of the samples in the sections is shown in Figure 3.2. Sample distribution maps together with a more detailed account of the sampling procedure is given in Appendix 'B'.

Figure 1.2 Generalized Columnar Sections of the Early Tertiary Strata in the Kettle River Region



II. Analytical Methods

Sample analysis includes spectrochemical, wet chemical, and fused-bead methods. Twenty samples were analysed spectrochemically for Fe, Mg, Ca, Sr, and Ba. The SiO_2, TiO_2, Al_2O_3, and MnO composition of ten of these samples was determined by Mr. W. Chesworth and Dr. A. Ruschil using wet chemical methods. A fused bead method was adapted as a means of extrapolating some of the chemical data to unanalysed rocks.

1. Spectrochemical Analysis

The various parameters used for the spectrochemical method are given in Appendix 'C'. Approximately 10 mgs. of homogenized rock powder were required for each determination. The fact that the rocks of this study are find grained and often glassy was helpful during the crushing and homogenization procedure. Triplicate analyses were carried out for each rock sample and the mean concentrations for each element were accepted as the final values.

A. Spectrochemical Method

According to Ahrens (1955, p. 7) Mg and Fe are classified among the involatile elements with La, Ba, Sr, and Ca. On account of this association it would be expected that these elements would behave similarly under similar arcing conditions. Shaw (1957) has described a method for the determination of Ba using La as an internal standard, and Filby (1957) has extended this method for determination of Sr and Ca.

In the present study the La method was also used for the determination of Mg and Fe. To illustrate the behaviour of Ca, Sr, Ba, Mg, Fe, and La under similar arcing conditions a plot of the 'log. I' or 'y' values of these elements against replicate rock analysis is given in Figure 2.1. It is seen that La is a satisfactory internal standard since the 'y' values rise and fall with the other elements. However, Ca shows the least sympathetic behaviour with La. If this tendency is characteristic of Ca then inferior results are to be expected for this element.

Determinations of Fe, Mg, and Ca were made only on rock samples. In the case of Fe and Mg a few wet chemical analyses were used to fix the position of the working curve and the well-known standards 'G-1' and 'W-1' were used as checks on the slopes of the curves[1]. For Ca, 'G-1' and 'W-1' were accepted as working curve end-points. A 1:9 sample to graphite mixture was found to be suitable, permitting lines Fe 4326, Mg5184, and Ca 4302 to be read. In all cases the La_2O_3 concentration level was maintained at 0.5% in the graphite plus sample mixtures.

To establish the working curves for Sr and Ba a synthetic matrix of the following composition was prepared: SiO_2 60%, Al_2O_3 20%, KCl 10%, Fe_2O_3 5%, and $CaCO_3$ 5%. The sensitivity range for Sr and Ba for rock and mineral analysis was increased by using two sample-to-graphite mixing ratios 1:9 and 1:2. The analysis lines Sr 4607 and Ba 4934 were usable with both ratios. The working curves were fixed

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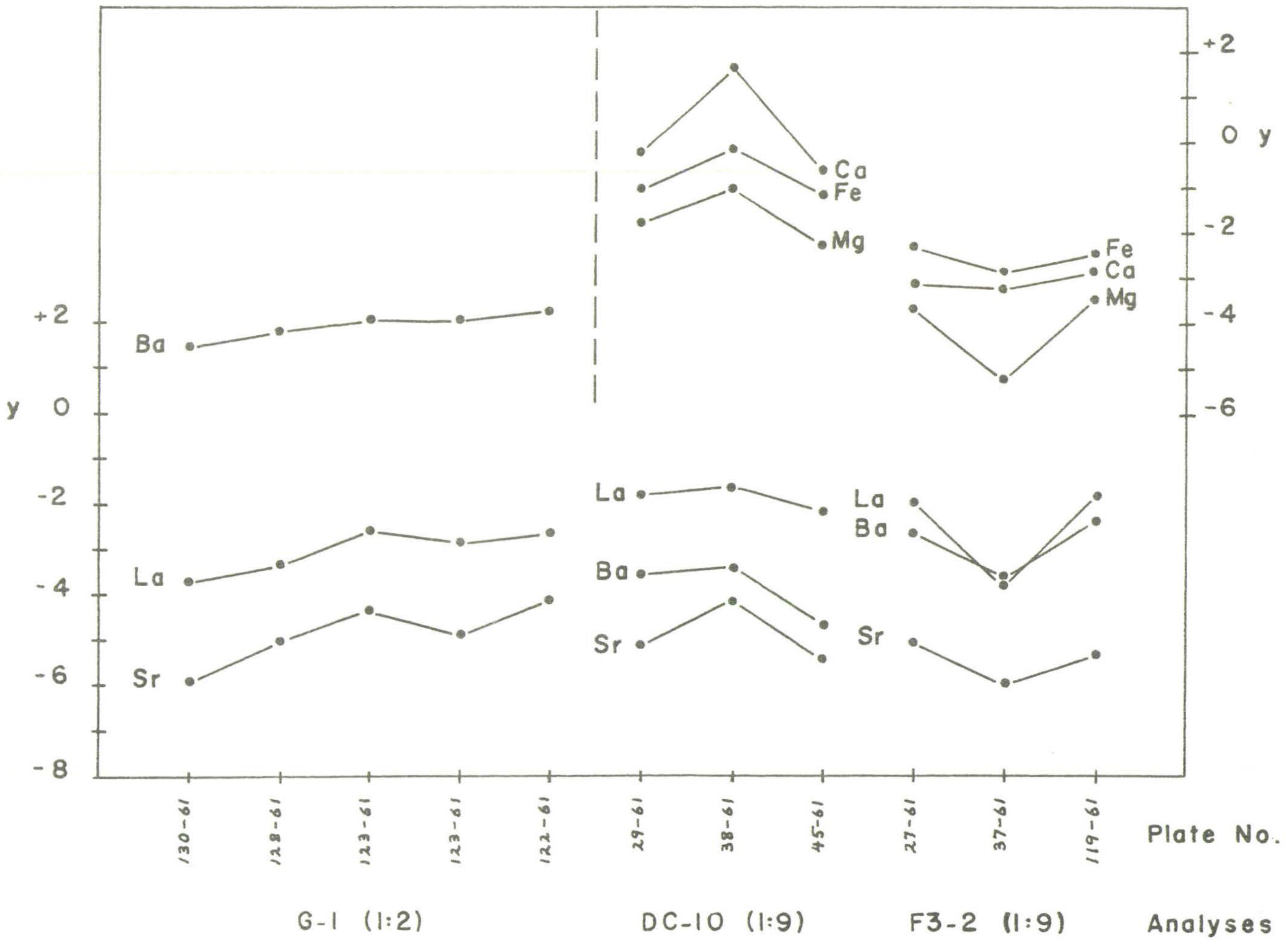
[1] G-1 refers to the Westerly granite Rhode Island and W-1 refers to the Centerville diabase form Virginia, Fairbairn et al. (1951).

Figure 2.1 Coherence Plot



with the following Sr and Ba concentrations: 125, 250, and 500 ppm. for the 1:2 mixtures and 625, 1250, 2500, and 5000 ppm. for 1:9 mixtures. Synthetic salite, plagioclase ($Ab_{50}An_{50}$), and anorthoclase ($Or_{50}Ab_{50}$) were run against these curves together with G-1 to establish their accuracy and test possible matrix effects.

B. Calibration

Plate calibration was achieved without the use of an iron arc, employing a modified two-step technique using light line transmission values for the internal standard and the various analysis lines. The dispersion of points about the preliminary two-step curve was found to be small for the 4920-5187 Å region, somewhat greater in the vicinity of 4607 Å and large for the 4300-4325 Å region. The preliminary curve for the 4200-4325 Å region was, therefore, redrawn several times in order to obtain the best agreement with emulsion sensitivity changes in different batches of photographic plates which were used in the analysis.

C. Precision

Precision estimates in terms of coefficients of variation are given in Table 2.1.

$C = 100s/\bar{x}$

C = coefficient of variation

s = standard deviation

$\bar{x}$ = arithmetic mean

Standard deviations have been calculated in terms of logarithms of the data using a one-way analysis of variance computer program.[1]

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[1] Bendix precision program No. 17, intercom 1000 d.p.

Table 2.1. Precision for Spectral Lines

Line	C
Fe 4325	4.81%
Mg 5184	9.95%
Ca 4302	10.04%
Sr 4607	7.60%
Ba 4934	5.62%

2. Composition of the Lavas

Spectrochemical and wet chemical results are given in Tables D-1 and D-2, respectively, of Appendix 'D'. The partial oxide composition of 10 lavas determined for this study and two analyses of Daly (1912) are listed in Table D-3.

3. Fused Bead Analysis

A method developed by Mathews (1951) for the rapid estimation of chemical composition of fine grained igneous rocks is readily adaptable to this study. The procedure involves the complete fusion to glass of a rock powder and refractive index measurement of the glass using sodium yellow light. The significant changes brought about in the composition of the rock as a result of artificial melting are essentially the loss of water and the homogenization of the oxidation state of iron. The refractive index values thus obtained from the glass are a function of the concentrations and physical properties of the chemical constituents.

A. Sample Preparation and Analysis

Part of the quartered rock powder set aside from chemical analysis was used for the bead analysis. For each rock sample several 5 mg. portions of this powder were ground to less than 200 mesh in an agate mortar and thoroughly mixed. This powder was then introduced into a broad crater about 2 mm. deep in the upper end of the lower electrode of a carbon arcing device. Uncored carbon electrodes 7 mm. in diameter were used after their ends had been tapered to about half the original diameter with a pencil sharpener. This reduced the arc wandering tendencies and heat loss from the vicinity of the crater. Using 120 volts (on open circuit) and 10 amperes, it was possible to completely fuse a rock sample in about 1.5 seconds.

To establish the optimum arcing period for complete fusion, experiments were carried out on samples F6-2 (pyroxene trachyte) and DC-12 (biotite andesite). Table 2.2 gives refractive index data for six beads of each rock arced for different length of time. From this analysis there does not appear to be any significant difference in the refractive index of the glass arising from differential fusion effects or selective volatilization for arcing periods ranging from two to five seconds.

For each rock sample collected at least five glass beads were synthesized using arcing periods of three to four seconds. The beads were then crushed and the refractive indices of the fragments were measured. The results of the analysis of 43 rock samples are given in Appendix 'E'.

Table 2.2 Arcing Time vs. Refractive Index

Sample DC-12			Sample F6-2		
Arcing Time	R.I.	Range	Arcing Time	R.I.	Range
1.5 sec.	1.541	± .001	1.5 sec.	1.515	± .002
2.0 sec.	1.535	± .002	2.0 sec.	1.516	± .002
3.0 sec.	1.538	± .003	3.0 sec.	1.516	± .002
4.0 sec.	1.537	± .001	4.0 sec.	1.515	± .002
5.0 sec.	1.539	± .002	5.0 sec.	1.515	± .002
6.0 sec.	1.537	± .001	6.0 sec.	1.516	± .003
Average R.I.	1.538		Average R.I.	1.516	

(Average weight of analyzed beads is 1.7 mg.)

B. Correlation of Refractive Index with Composition

The relationship between the refractive index of the bead glasses and the composition of the corresponding rocks has been stated by Mathews (1951, p. 92):

> "The early work on the refractive indices and composition, of which Stark and George were well aware, makes it clear that the proportion of any one constituent, even if the major constituent, does not alone determine the refractive index of the glass, but instead each constituent contributes according to its abundance and its specific properties."

For chemically analysed samples, plots of R.I. versus FeO (total iron calculated as FeO), MgO, and CaO are given in Appendix 'F'.

A quantitative measure of the degree of linear correlation between the refractive index of the fused rocks and the corresponding iron oxide, magnesia, and lime contents has been calculated using the product-moment correlation coefficient as described by Ostle (1954, p. 174 et seq.). The following symbols and formula are used:

Y = refractive index of fused rock

$\bar{Y}$ = average refractive index for all the analysed rocks

X = oxide composition of fused rock

$\bar{X}$ = average oxide composition for all analysed rocks

r = product-moment correlation coefficient

$$r = \frac{\Sigma (X-\bar{X})\ (Y-\bar{Y})}{\sqrt{\Sigma (X-\bar{X})^2\ \Sigma (Y-\bar{Y})^2}}$$

Using the refractive index values for 20 chemically analysed rocks the results of correlation calculation are given as follows:

'r'	coefficient	for	FeO	versus	R.I.	0.95
"	"	"	MgO	"	"	0.95
"	"	"	CaO	"	"	0.88

According to Ostle (1960, p. 459) correlation coefficient values greater than 0.561 are considered a significant indication of correlation between variables at the 1% level for 20 observations. Since this value is considerably smaller than the 'r' values given above for FeO, MgO, and CaO versus refractive index, the general correlation of refractive index with composition appears to be highly significant for the rocks of the present study.

III. Distribution and Petrography of the Lavas

The aims of this chapter are, first, to assign a system of nomenclature to the lavas of this study and, second, to investigate the distribution and petrographic relations of the lavas for possible trends, associations, or differences.

1. Classification

Since complete chemical data are few for the lavas examined in this study, a generalized mineralogical classification was adapted. Modal analyses of 20 lavas, given in Appendix 'G', show these rocks to contain an average of approximately 80% groundmass composed essentially of fine grained felted microlites and glass. It is apparent that these rocks are not amenable to modal classification. Nevertheless, the presence or absence, and relative abundance of the various phenocrysts is usually some reflection of the chemical composition of the rock.

The method of subdividing the rocks of this study is outlined in Table 3.1. The scheme used is in keeping with standard usage (see Hatch, Wells, and Wells, 1956). The chemical composition of lava types defined on this basis shows good agreement with analyses from the literature (see Appendix 'H').

The refractive index averages and ranges for the various lava types are plotted in Figure 3.1. In general it may be seen that high indices are typical of andesite and basalt whereas the low values are characteristic of trachyte and rhyolite. Considerable overlap exists

Table 3.1 Nomenclature

Rock Name	R.I. Average	
Rhyolite	1.497 (1)	Leucocratic; quartz in excess of 10% total mineral content; the name is used in the broad sense for acid lava containing essential quartz; alkali-feldspar, sodic plagioclase, and minor biotite. (Ref. Hatch, Wells, and Wells, p.219)
Trachyte	1.509 (3)	Leucocratic; neither quartz nor feldspathoids observed; alkali-feldspar greater in abundance than plagioclase - sometimes plagioclase is absent; biotite and augite are the only ferromagnesian minerals (corresponds to orthotrachyte of Hatch, Wells, and Wells, p.246).
Latite	1.522 (3)	Leucocratic (color index arbitrarily set at $<20\%$); quartz phenocrysts not observed; alkali-feldspar restricted to groundmass and thin fringes on plagioclase phenocrysts; minor biotite or pyroxene; (equivalent to trachyandesite of Hatch, Wells, and Wells, p.274)
Trachyandesite	1.524 (10)	Usually leucocratic; quartz and feldspathoids not observed; arbitrarily distinguished from latite above by presence of alkali-feldspar phenocrysts; biotite and augite are the only ferromagnesian minerals.
Shackanite	1.532 (1)	Leucocratic; this is an unusual lava rich in analcite and rhomb-shaped alkali-feldspar (also termed analcite rhomb-porphyry)(this rock type was first described and named by Daly, 1912, p.411)
Andesite	1.538 (23)	Color index arbitrarily set $>20\%$; no quartz phenocrysts or alkali-feldspar; olivine absent; plagioclase of intermediate composition, sometimes zoned; any one of hornblende, pyroxene, or biotite may form the dominant ferromagnesian mineral. (Ref. Hatch, Wells, and Wells, p.265)
Basalt	1.602 (1)	Melanocratic, containing essential olivine and some pyroxene and calcic plagioclase, the latter two minerals being in the groundmass. (Ref. Hatch, Wells, and Wells, p.298)

Bracketed numbers refer to number of samples used for the average R.I. values.

between the refractive indices of the trachyandesites and the latite even though these rocks have indices characteristically lower than the pyroxene and hornblende andesite and higher than the trachyte. Similarly, it would be impossible to distinguish between the various andesitic lavas on the basis of refractive index values alone. However, in spite of these overlaps, there is a tendency for the rocks containing abundant biotite, and/or potassic feldspar, to have lower refractive index ranges than corresponding hornblende, or pyroxene and plagioclase rich rocks. This is in keeping with the association of high indices for the basic rocks, low indices for the acid rocks.

2. Distribution of Lavas

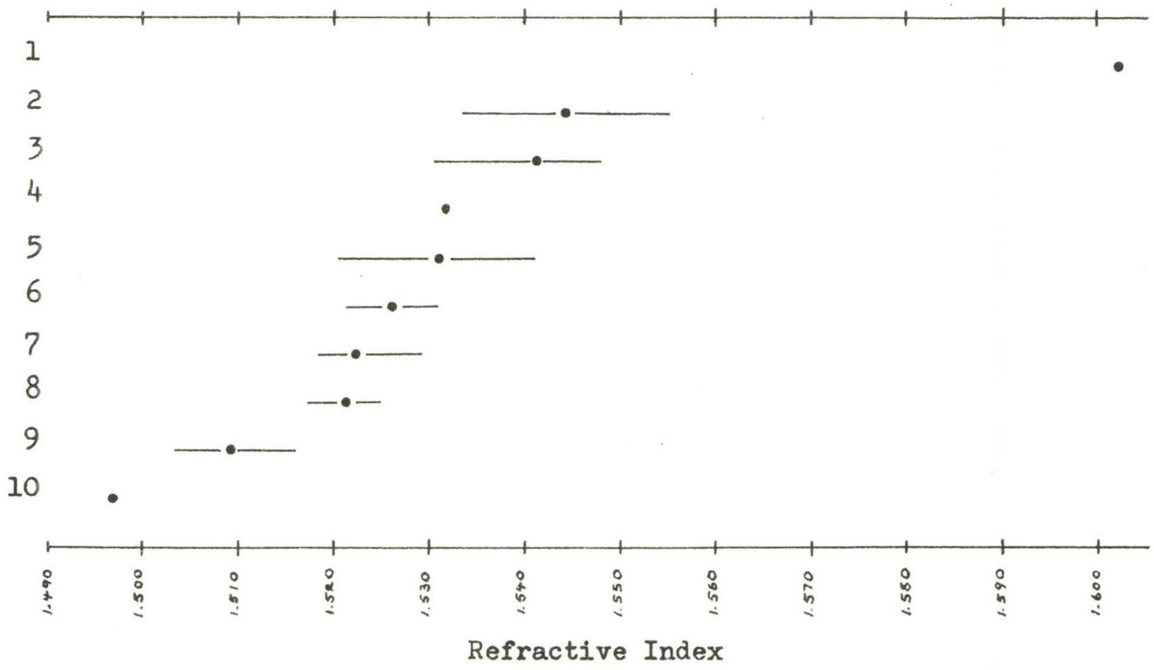
The relative frequency of acid to basic lava in the Midway, Marron, and Kelowna areas have been estimated using the refractive indices of samples collected at regular intervals across the strata in these areas. On the assumption that the method of sampling provides an adequate representation of rock, it was possible to construct histograms showing lava distributions.

To facilitate comparison, the histograms, illustrated in Figure 3.2, have been constructed by dividing the abscissas into a number of equal lengths and scaling the ordinate as percentage axes such that the total area is the same under each histogram.

From Figure 3.2 it is evident that the lavas of the Midway area are more basic than those of Kelowna; lavas of the Marron area are intermediate.

In Figure 3.3 the above data have been replotted in a single

Figure 3.1 Refractive Index Range for Lava Types



Legend

1 Basalt
2 Hornblende Andesite
3 Pyroxene Andesite
4 Shackanite (analcite rhomb-porphyry)
5 Biotite Andesite
6 Pyroxene Trachyandesite
7 Latite
8 Biotite Trachyandesite
9 Trachyte
10 Rhyolite

histogram with a refractive index base ranging from rhyolite to basalt. Two features stand out: the lavas of the Kettle River region are, predominantly, acid-intermediate composition, covering only about half the possible range; there is a marked paucity of basic and basaltic rock. In view of this rather restricted range for the lavas of the Kettle River region, the differences within the region, although probably positive, appear small.

The stratigraphic distributions of the lavas in the Midway, Marron, and Kelowna areas are illustrated as variation curves below the histograms in Figure 3.2. Refractive indices have been plotted against the approximate position of samples in corresponding sections. Additional data are summarized in Table 3.2. The main features are noted as follows:

1. Except for a steady increase in refractive index from sample No. 5 to 9 in the Marron section, no regular evolution of lava toward a basic or acid composition is detected.

2. A few interesting correlations in refractive index variation between the sections appear to be spurious when more detailed data is examined; i.e., the samples numbered No. 5 in the Midway, Marron, and Kelowna sections, which show a coincidence of low refractive indices, correspond to dissimilar lava types (biotite andesite, biotite trachyandesite, and pyroxene biotite trachyte, respectively). Nevertheless, similar patterns in the refractive index distribution might reflect a type of composition - eruption periodicity relation characteristic of the region.

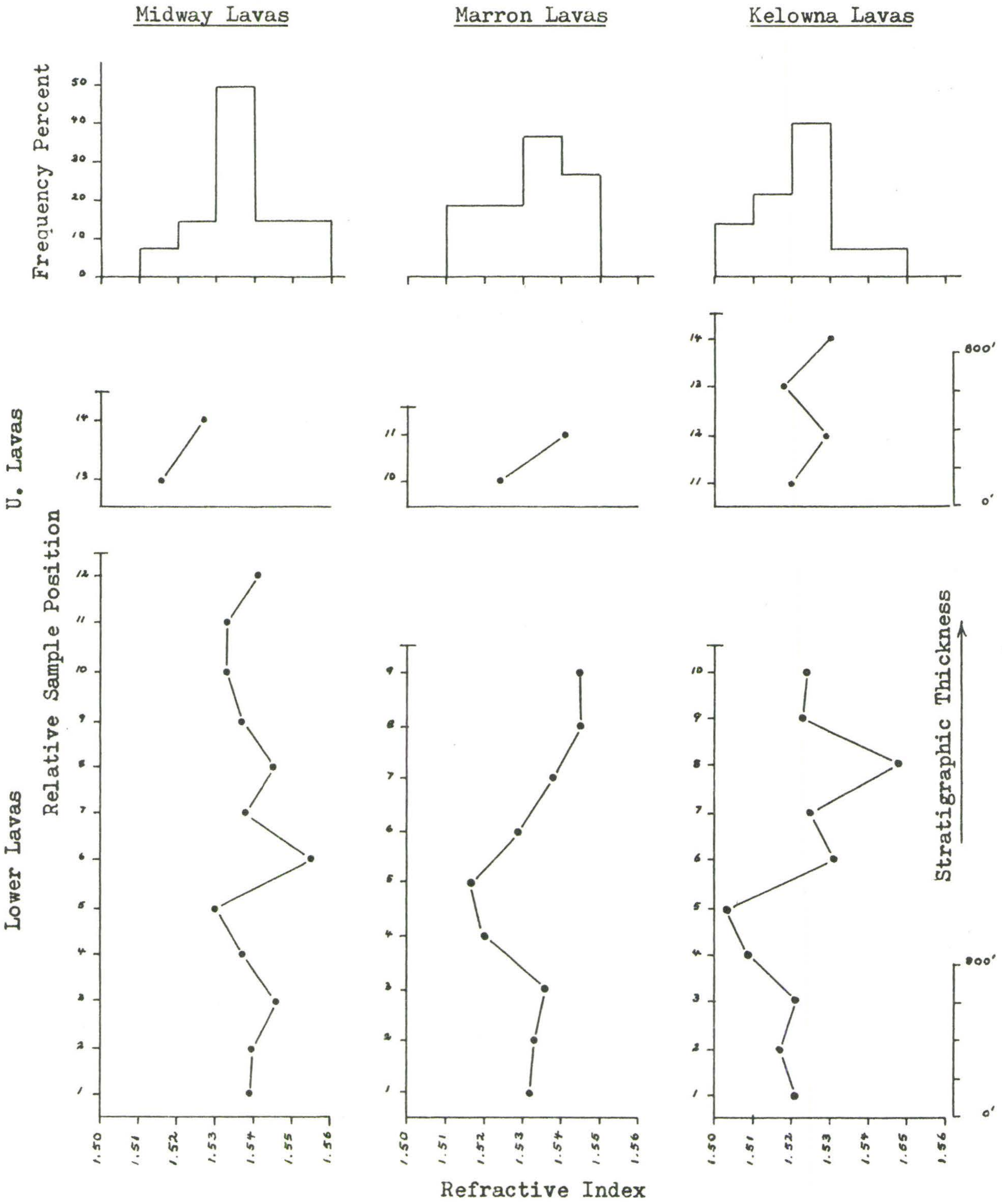
3. Stratigraphic correlation of lava types is particularly

unhopeful (see Table 3.2). Although several important lavas are common to all three areas there is little or no similarity in stratigraphic distribution patterns. The futility of attempts at this type of correlation is best demonstrated by the occurrence of shackanite lava. The first North American occurrence of this unusual lava was discovered by Daly (1912) uppermost in the Midway volcanic succession. Sample CC-1, described in this study, is petrographically very similar to Daly's Midway shackanite. Oddly enough, however, sample CC-1 was taken from a flow near the base of the lower Marron sequence. Stratigraphic correlation of the Midway and Marron shackanite lavas would create many more problems than it would solve. Moreover, it is unlikely that any single lava flow would extend as a continuous sheet from the Midway to the Marron area. A more plausible explanation is that the shackanite lavas were extruded at different times from a similar magma source influenced by similar environmental conditions. Such an explanation might also account for the apparent irregular distribution of many of the more common lava types of the region.

3. Petrography of the Lavas

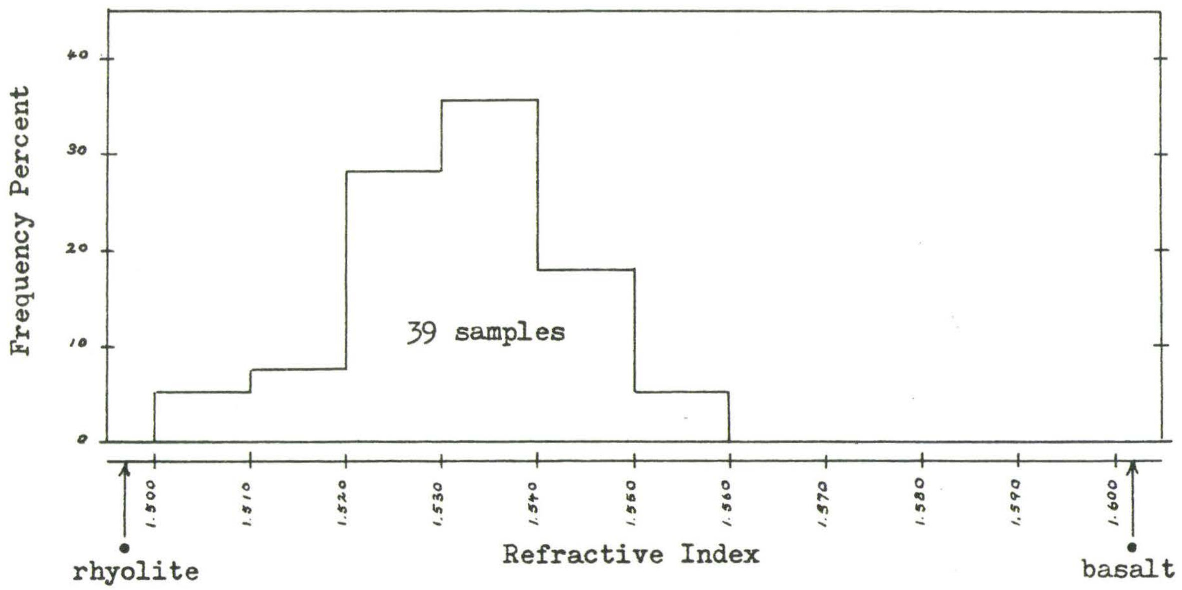
An abundance of pyroxene and biotite rich andesite and trachyandesite is characteristic of the Kettle River region. As pointed out above, relative frequencies differ a little between the Midway, Marron, and Kelowna areas and basaltic rocks are rare or absent. Hornblende andesite, latite, and trachyte are of limited occurrence; the first occurring only in the Midway area, the latter two types being best developed in the Kelowna area. Hornblende andesite often

Figure 3.2 Areal and Stratigraphic Distribution of the Lavas



(Histogram class interval is R.I. 0.010)

Figure 3.3 Frequency Distribution of the Lavas for the Kettle River Region



(Class interval for histogram is R.I. 0.010)

Table 3.2 Stratigraphic Distribution of the Lava Types

		Position[1]	Sample No.	Description
Midway Section	Upper Lavas	14	F4-3	pyroxene trachyandesite
		13	F6-2	pyroxene trachyte
	Lower Lavas	12	DC-21	hornblende andesite
		11	DC-19	hornblende andesite
		10	DC-17	pyroxene biotite andesite
		9	DC-15	pyroxene hornblende andesite
		8	DC-14	pyroxene andesite
		7	DC-12	pyroxene biotite andesite
		6	DC-10	pyroxene hornblende andesite
		5	DC-9	biotite andesite
		4	DC-8	biotite pyroxene andesite
		3	DC-6	biotite pyroxene andesite
		2	DC-4	pyroxene andesite
		1	DC-2	biotite pyroxene andesite
Marron Section	Upper Lavas	11	CC-18	biotite andesite
		10	CC-25	biotite andesite
	Lower Lavas	9	CC-9	biotite pyroxene andesite
		8	CC-8	pyroxene andesite
		7	CC-7	biotite pyroxene andesite
		6	CC-6	pyroxene trachyandesite
		5	CC-5	biotite trachyandesite
		4	CC-4	pyroxene biotite andesite
		3	CC-3	pyroxene biotite andesite
		2	CC-2	biotite andesite
		1	CC-1	shackanite (analcite rhomb-porph.)
Kelowna Section	Upper Lavas	14	AC-2	pyroxene andesite
		13	AC-9	latite
		12	AC-14	latite
		11	AC-18	latite
	Lower Lavas	10	20-C4	pyroxene biotite trachyandesite
		9	20-C5	pyroxene biotite trachyandesite
		8	20-C6	pyroxene andesite
		7	20-C7	biotite trachyandesite
		6	20-C9	pyroxene trachyandesite
		5	20-C12	pyroxene biotite trachyte
		4	20-C13	pyroxene biotite trachyte
		3	20-C14	biotite andesite
		2	20-C15	pyroxene biotite trachyandesite
		1	20-C16	biotite pyroxene trachyandesite

---

[1] Position in stratigraphic sequence relative to the base

contains pyroxene and feldspar and appears to grade into pyroxene andesite by increase of these minerals and decrease of hornblende. Similarly, trachyandesite passes into trachyte by increase of potash feldspar relative to plagioclase. Latite is closely allied to andesite but contains relatively few ferromagnesian minerals.

Although the mineral evidence suggests compositional gradation between the andesites and latites as well as the trachyandesites and trachytes, the relation between these two groups is less certain. Transition from the first to second group is not smooth; addition of potash feldspar to the mineral assemblage is not always accompanied by decrease in refractive index and, even less, a decrease in the frequency of ferromagnesian minerals.

However, the presence of both one and two feldspar lavas is no reason in itself to suspect more than one magma series in the Kettle River region. According to Tuttle and Bowen (1958, p. 130-131):

"The appearance of two feldspars during the crystallization in rhyolitic, trachytic, and phonolitic magmas depends to a large extent upon the amount of solid solution between the feldspars and on the temperature of crystallization."

These authors show that the formation of a single feldspar, plagioclase, is favoured at high temperatures whereas two coexisting feldspars, plagioclase and alkali-feldspar, may form at somewhat lower temperatures. They go on to point out (p. 137):

"The presence of phenocrysts of two feldspars in sialic extrusive rocks cannot be considered proof that two feldspars will continue to crystallize throughout magmatic crystallization. The equilibrium relations deduced from a study of the feldspars of extrusive rocks indicates that plagioclase phenocrysts may react with the liquid and leave a single alkali feldspar. If fractionation takes place during crystallization, the possibility of completing crystallization with only a single feldspar is greatly enhanced."

Mantling of plagioclase phenocrysts by alkali-feldspar is a common textural feature in the trachyandesites and trachytes and is indicative of fractional crystallization (see petrographic description of lava F4-3 in Appendix 'I'). The isolation of plagioclase from the melt by mantling may be responsible for the eventual formation of one-feldspar, alkali-feldspar, trachyte such as 20-C12 (see description of this rock in Appendix 'I'). Although this lava type is not common in the Kettle River region it may represent the final stage in Tuttle and Bowen's fractional crystallization sequence described above.

Perhaps the most marked feature of the mineralogy of these lavas is the widespread occurrence of augite and absence of orthopyroxene. Augite is associated with plagioclase in andesite, plagioclase and potassic feldspar in trachyandesite, and potassic feldspar in trachyte. It often coexists with hornblende in the most basic lava or biotite in the more acid lavas; occasionally it is even replaced as the dominant ferromagnesian mineral by hornblende or biotite in a few exceptionally 'wet' rocks. Invariably, augite exhibits a pale green color in thin section and lacks pleochroism. Also, exsolution lamellae and schiller effects are absent. In general, this pyroxene retains the same appearance throughout the whole suite of lavas from the most basic to the most acid types.

The failure of orthopyroxene or pigeonite to form may reflect either very high temperatures or a high lime reserve of the lavas. In view of the absence of exsolution structures the latter explanation seems most likely correct.

Biotite is present in most of the lavas usually as an accessory constituent but sometimes it occurs in abundance independent of other ferromagnesian minerals. However, no primary biotite has been observed with hornblende. The prevailance of biotite and rather limited occurrence of hornblende is no doubt a simple reflection of the acid or acid-intermediate composition of the bulk of the lavas, as pointed out in the previous section.

Of all the minerals examined biotite is the most prone to magmatic corrosion. The extent of corrosion differs greatly among the samples, however, the most acid rocks show a tendency to preserve at least subhedral forms.

It is difficult to assess the full significance of modal biotite in the evolution of these rocks because of this tendency to react with the magma and be resorbed. The presence of biotite probably indicates abundance of both water and potassium in the parent magma, but it seems doubtful that crystal precipitation of biotite was much effective in reducing these and other chemical constituents.

Although details of the mineralogy and chemistry have yet to be described in following sections, there seems little doubt that the bulk of the early Tertiary lavas in the Kettle River region are intimately related in space and to some extent in composition.

1. In no case can a particular lava type or group be attributed

to a specific stratigraphic horizon throughout the region.

2. These lavas, although showing considerable diversification in types, have a restricted range from semi-basic to acid composition.

3. The feldspars in these rocks appear to form a natural evolutionary sequence.

4. Only one pyroxene occurs in these rocks, a clinopyroxene, and is markedly similar in appearance throughout the sample suite.

However, the presence of both strongly undersaturated and oversaturated lavas in the region, shackanite (analcite rhomb-porphyry) and rhyolite, is anomalous (see descriptions of these rocks, CC-1 and 22-J1, in Appendix 'I'). Neither primary analcite nor quartz have been observed in the other lavas. Admittedly, the occurrence of shackanite and rhyolite is rare in the Kettle River region, nevertheless, their presence suggests a more complex relation between the lavas than indicated by the evidence presented so far.

IV. Mineral and Chemical Variations

A detailed investigation of the mineralogy and chemistry of the lavas is necessary to amplify the information already given and to resolve the petrographic anomalies. In this chapter special effort will be made to clarify the relations between the one-feldspar plagioclase rocks and the two-feldspar rocks. Also, the shackanite and rhyolite lavas will be examined to determine their relation to the more common rocks of the region.

1. Mineral Analysis

Twenty-four mineral samples were separated from the various lavas for special study including sixteen feldspars, six pyroxenes, one biotite, and one hornblende. Optical, X-ray, and spectrochemical methods were used for determinative purposes.

A. Mineral Separation

To separate the minerals from their parent rocks it was first necessary to crush the rock by hand in a steel mortar. The 100-200 mesh fraction was then screened out and passed through a Frantz isodynamic separator. It was found that the feldspar could be separated to a high purity upon several passes of the fraction through the magnetic separator. However, pyroxene and hornblende could not be completely isolated from the magnetite-charged groundmass by this method, and for complete separation it was necessary to use heavy liquids. A pure biotite concentrate was obtained by first using the magnetic separator and then sliding the biotite flakes on paper and seiving the residue.

The presence of impurities in the mineral separates could often be detected by examining X-ray diffraction patterns or using oil immersion methods.

On the basis of binocular microscope examination, the mineral separations are considered to be better than 99% pure. However, inclusions such as apatite and magnetite may reduce the absolute volume purity by a few percent.

All mineral separates were washed in distilled water and acetone before being analysed spectrochemically.

B. Feldspars

As previously indicated the lavas of the Kettle River region can be subdivided, for the most part, on the basis of feldspar phenocrysts into the following groups: one-feldspar (plagioclase) lavas, two-feldspar lavas, and one-feldspar (alkali-feldspar) lavas. The purpose of this section is to determine whether or not the composition of the feldspars is consistent with the theory that these lavas represent a single magma series.

a. Determination of Plagioclase

According to Smith (1958, p. 1191),

"The change in Nx accompanying the structural change from low- to high-temperature plagioclase is slight in the composition range An_0 to An_{20} and negligible from An_{20} to An_{100}."

Using Tsuboi's immersion technique (Tsuboi, 1923) the refractive index Nx of powdered plagioclase can be closely estimated by measuring the minimum refractive index of the grains resting on (010) or (001) cleavages. By comparing this index with established curves the composition of the feldspar can be readily determined.

In the present study eleven plagioclases were separated and determined using this method. Compositions together with optical and X-ray data are given in Table 4.1.

With the view to supplementing the compositional information given in Table 4.1, the possibility of using rapid 'extinction' methods for determining plagioclase in thin section was examined. Since the 'extinction' methods are dependent on the structural state of the plagioclase for their accuracy, a knowledge of the latter is desirable.

Two methods are available for determining the structural state of plagioclase; the 2V optical method and the $2\theta(131-1\bar{3}1)$ X-ray method.

Using the first method, the optic axial angles for eleven plagioclase separates (listed in Table 4.1) were plotted on a diagram proposed by Smith (1958). As illustrated in Figure 4.1 the high and low temperature boundary curves for 2V values are strongly divergent for anorthite contents less than 30% but for compositions greater than 40% these curves cross and run in close proximity to each other. Since 8 of the 11 plagioclases have anorthite compositions ranging between 40% and 60%, it is difficult to assess structural states using this method. The remaining 4 plagioclases, which have less than 40% anorthite content, show transitional or high temperature states.

Structual determinations on the plagioclases using the X-ray method are more satisfactory than the optical method. However, only 9 of 11 plagioclases yielded powder diffraction patterns suitable for measurement. Smith and Yoder (1956) have delineated the high temperature and low temperature boundary curves for the various feldspars by plotting $2\theta(131-1\bar{3}1)$ values against anorthite composition. A plot of the plagioclases analysed in the present study (see Figure 4.2) shows a complete gradation from high temperature to low temperature forms.

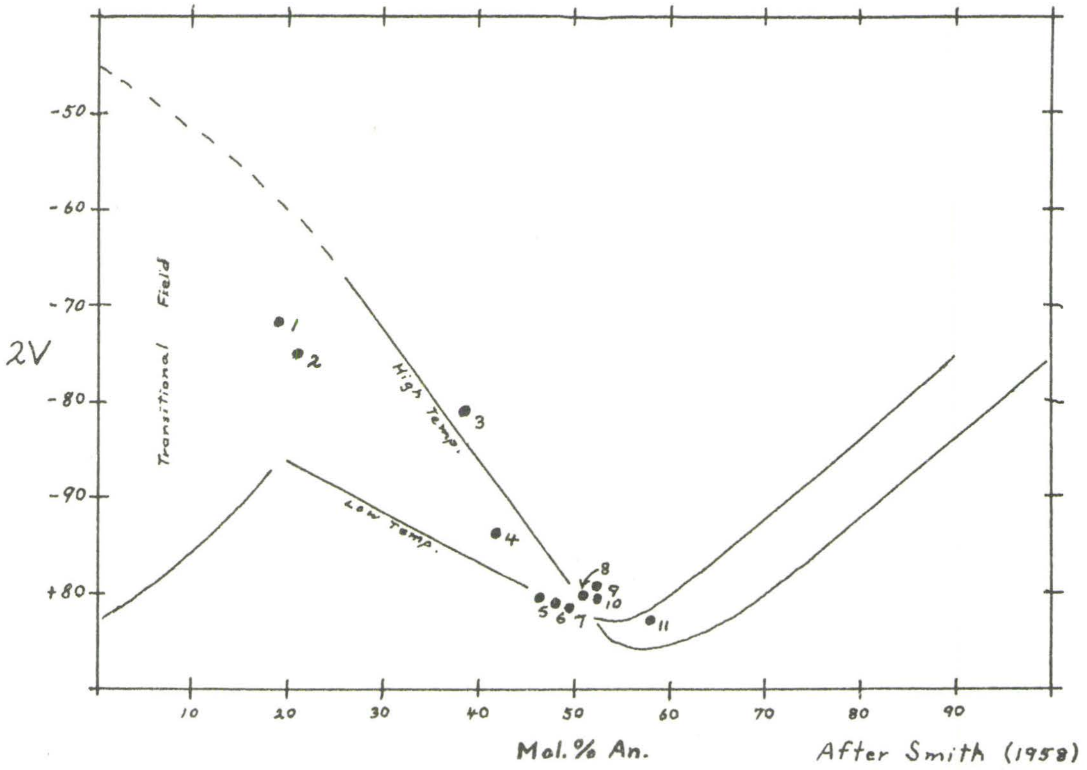
In conclusion, the mixture of high and low temperature plagioclase with transitional types precludes the use of 'extinction' methods for accurate determinative work.

b. Determination of Alkali-Feldspar

The X-ray method described by Tuttle and Bowen (1950) for the determination of alkali-feldspar has been used on five feldspar separates in this study. The 2θ position of the $(\bar{2}01)$ reflection plane was measured from powder diffraction patterns using quartz and olivine as optional internal standards. The composition of the five alkali-feldspars together with optical and X-ray data are given in Table 4.2.

The utility of the refractive index of alkali-feldspar for determinative purposes is limited because of the small difference in refractive index between the various members of the sanidine - anorthoclase series. This seems to hold true in the present study in that the Nx' values given in Table 4.2, show no simple relationship to composition.

Figure 4.1 Thermal States of the Plagioclase : 2V Measurements

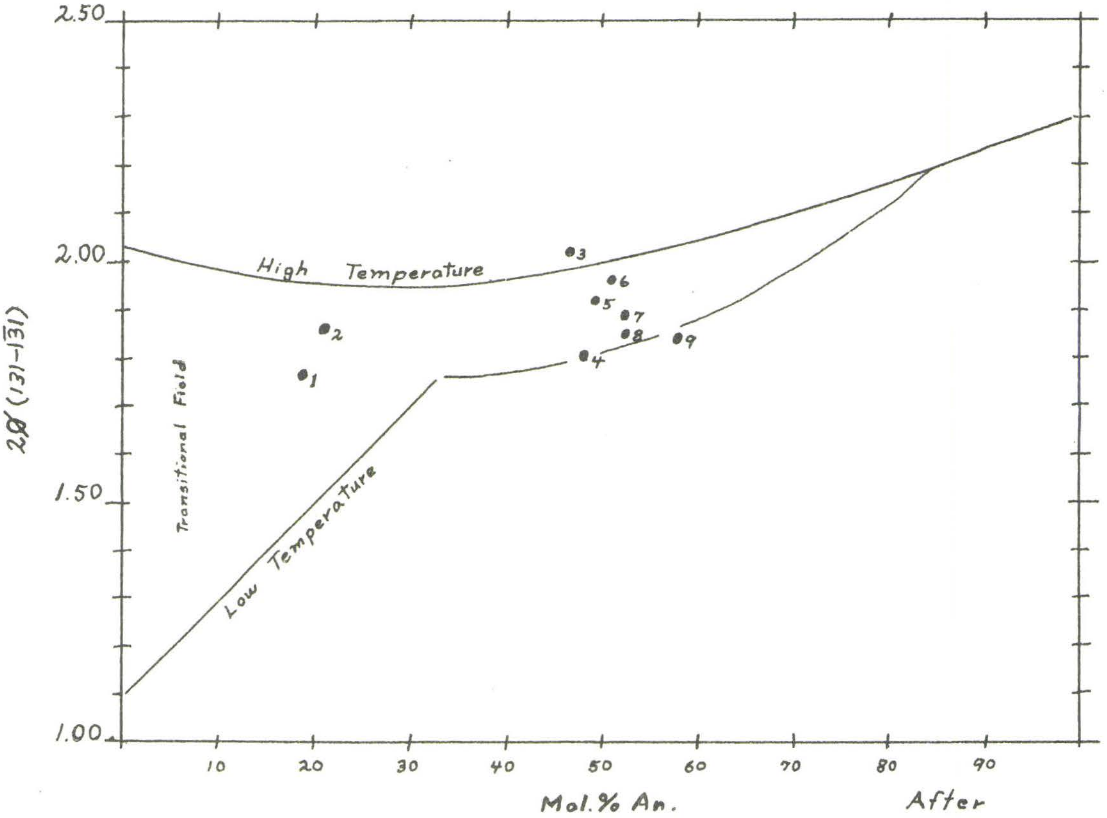


After Smith (1958)

Legend

1	22-J1	Biotite Rhyolite
2	DC-12	Biotite Andesite
3	20-C13	Biotite Trachyte
4	F6-2	Pyroxene Trachyte
5	AC-9	Latite
6	F4-3	Pyroxene Trachyandesite
7	CC-5	Biotite Trachyandesite
8	AC-18	Latite
9	CC-7	Pyroxene Andesite
10	DC-2	Pyroxene Andesite
11	20-C5	Biotite Trachyandesite

Figure 4.2 Thermal States of Plagioclase : X-Ray Measurements



After
Smith and Yoder (1956)

Legend

1.	22-J1	Biotite Rhyolite
2	DC-12	Biotite Andesite
3	AC-9	Latite
4	F4-3	Pyroxene Trachyandesite
5	CC-5	Biotite Trachyandesite
6	AC-18	Latite
7	DC-2	Pyroxene Andesite
8	CC-7	Pyroxene Andesite
9	20-C5	Biotite Trachyandesite

The system of nomenclature is based on both the composition and structural state. According to Tuttle (1952), "The optic axial angle (2V) is one of the most useful properties for classifying the alkali-feldspars."

In the present study the 2V angles of the five alkali-feldspar separates were determined using the universal stage. The resulting angles were plotted against the orthoclase content (Figure 4.3). From this plot it is clear that these feldspars fall together as a group close to the sanidine - anorthoclase cryptoperthite curve of the diagram.

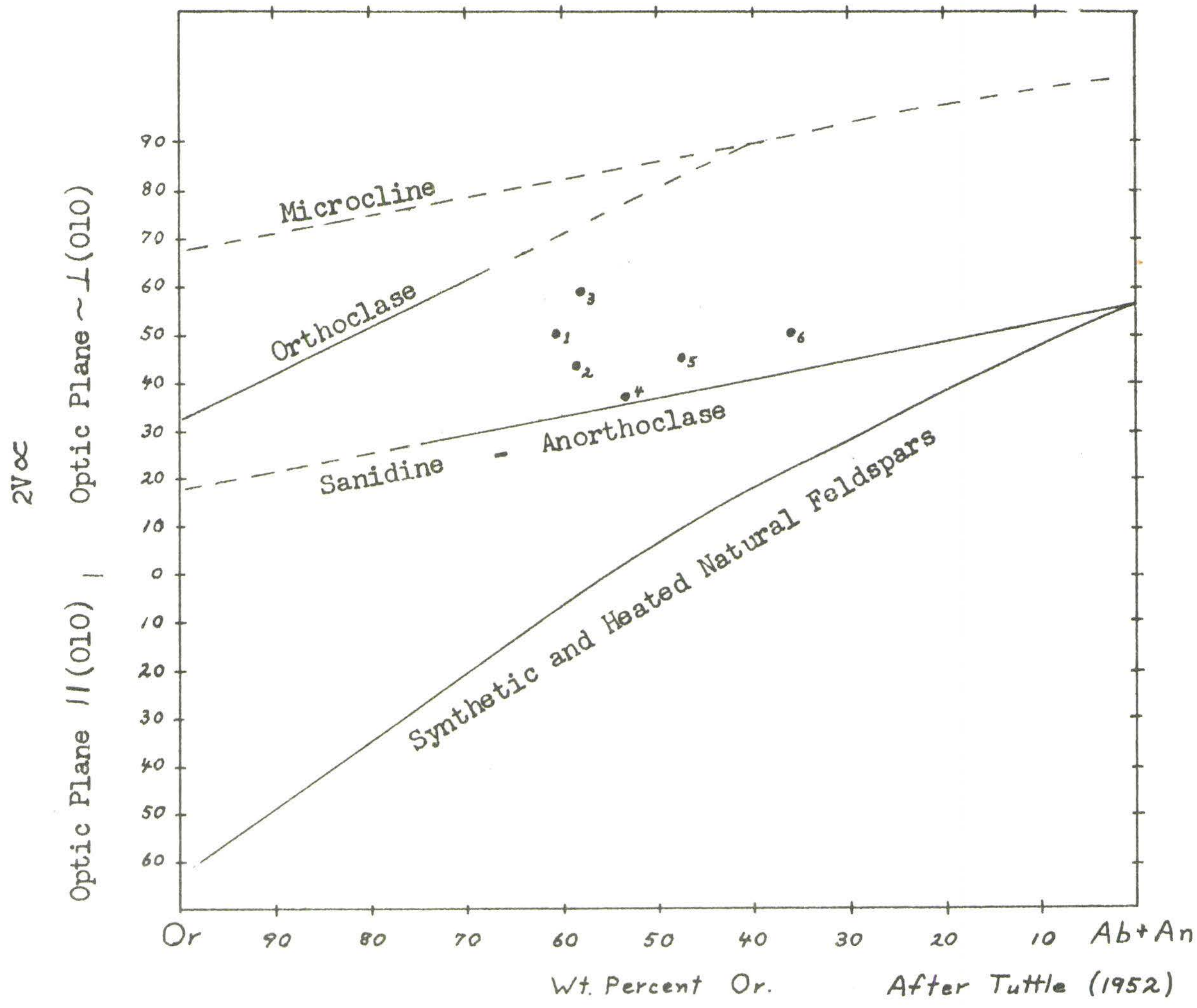
Daly (1912, p. 403-404) analysed an alkali-feldspar (rhomb-porphyry) from one of the effusive rocks of the Midway area. A plot of the composition against the 2V angle places this feldspar close to the other determinations in the sanidine - anorthoclase field.

As in the case of the plagioclase it was only possible to perform determinative analysis on a few feldspar samples because of the considerable time involved in the mineral separation and the optical and X-ray procedures.

c. Composition of the Feldspars and Host Rocks

The anorthite content of the analysed plagioclases appears to bear some relation to the host rocks. Arranging the rocks in order from acid to basic types, the anorthite content of the corresponding plagioclases shows a general decrease, with a few

Figure 4.3 Classification of Alkali-Feldspars



After Tuttle (1952)

Legend

1.	F6-2	Pyroxene Trachyte
2	22-J1	Biotite Rhyolite
3	F4-3	Pyroxene Trachyandesite
4	20-C13	Biotite Trachyte
5	20-C12	Biotite Trachyte
6	Daly's Rhomb Porphyry Feldspar	

Table 4.1 Composition, Optical, and X-Ray Data for Plagioclase

Sample	Mol. Comp.		Nx'	2V	$2\theta(131-1\bar{3}1)$
	Ab	An	r	r	s
DC-2	47.5	52.5	1.556 ± .001	79.3 ± 0.3	1.89 ± .02
CC-7	47.5	52.5	1.556 ± .002	80.7 ± 2.3	1.85 ± .00
DC-12	79.0	21.0	1.539 ± .002	75.0 ± 0.3	1.86 ± .01
F4-3	52.0	48.0	1.553 ± .002	79.0 ± 4.2	1.80 ± .02
20-C5	42.0	58.0	1.559 ± .001	77.1 ± 1.4	1.84 ± .01
CC-5	50.5	49.5	1.554 ± .002	78.4 ± 0.9	1.92 ± .01
AC-18	49.0	51.0	1.555 ± .003	79.8 ± 1.7	1.96 ± .01
AC-9	53.5	46.5	1.552 ± .002	79.3 ± 0.3	2.02 ± .02
F6-2	58.0	42.0	1.549 ± .002	86.1 ± 0.3	
20-C13	61.5	38.5	1.547 ± .002	80.8 ± 1.5	
22-J1	81.0	19.0	1.538 ± .001	71.7 ± 2.3	1.78 .01

r = range, s = standard deviation

Table 4.2 Composition, Optical, and X-Ray Data for Alkali-Feldspar

Sample	Wt.% Comp.		Nx	2V	$2\theta(\bar{2}01)-(10\bar{1}0)$
	Ab	Or	r	r	s
F4-3	42.9	57.1	1.529 ± .001	58.7 ± 0.7	0.49 ± .01
F6-2	40.9	59.1	1.527 ± .001	49.8 ± 0.4	0.47 ± .01
20-C13	49.0	51.0	1.524 ± .001	37.3 ± 2.5	0.56 ± .01
20-C12	54.0	46.0	1.525 ± .002	44.6 ± 1.6	0.61 ± .00
22-J1	42.9	57.1	1.521 ± .001	42.6 ± 1.0	0.49 ± .03

r = range, s = standard deviation

exceptions[1], from the most basic to the most acid rocks (see Figure 4.4). This trend is in keeping with the classical theories of thermal descent of plagioclase as first described by Bowen (1913).

According to theory, latite (a one-feldspar plagioclase rock) should occur somewhat earlier in the magmatic evolutionary cycle and contain a more calcic variety of plagioclase than trachyandesite (a two-feldspar rock)[2]. However, it is found that the latites and trachyandesites have very similar refractive indices and plagioclase compositions. Evidently, latite represents about the same evolutionary stage as trachyandesite. However, the absence of potassic feldspar phenocrysts in the latite suggests that this rock may have formed under environmental or, to some extent, chemical conditions somewhat different than those responsible for the formation of trachyandesite. It seems unlikely that both rocks belong to the same magma series.

Figure 4.5 illustrates the composition distribution of alkali-feldspars in the various lava types. Results for one and two feldspar rocks are plotted as separate groups. As would be expected from the

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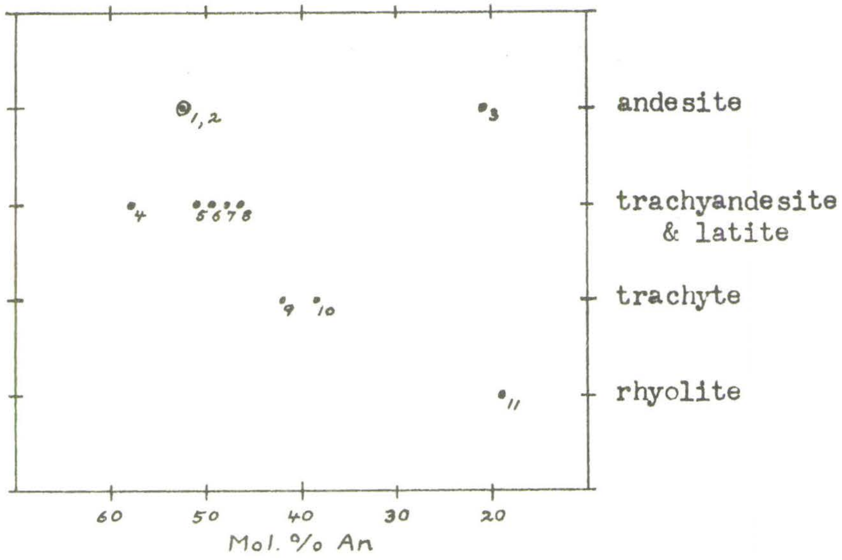
[1] Disregarding sample DC-12, the greatest dispersion of anorthite percentages in Figure 4.4 is coincident, as would be expected, with the lavas most analysed. Examination of plagioclase DC-12 in thin section reveals that this feldspar has normal type zoning. Central calcic cores grade regularly into sodic margins. It seems possible that the determination for plagioclase DC-12, given in Table 4.1, is not representative of the average composition but only the outer sodic zone. For some unknown reason many of the andesitic lavas of this study contain strongly zoned plagioclase (see petrographic description of rock DC-19, Appendix 'I'). Consequently, good estimates of the average composition of the plagioclase are sometimes difficult to obtain.

[2] Tuttle and Bowen 1958, p. 130-137.

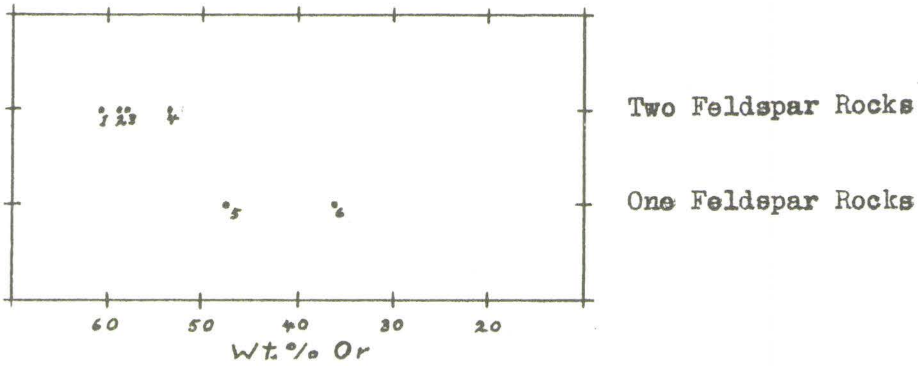
Figure 4.4 Compositional Evolution of the Plagioclase



Legend

1	DC-2	Pyroxene Andesite
2	CC-7	Pyroxene Andesite
3	DC-12	Biotite Andesite
4	20-C5	Biotite Trachyandesite
5	AC-18	Latite
6	CC-5	Biotite Trachyandesite
7	F4-3	Pyroxene Trachyandesite
8	AC-9	Latite
9	F6-2	Pyroxene Trachyte
10	20-C13	Biotite Trachyte
11	22-J1	Biotite Rhyolite

Figure 4.5 Alkali-Feldspar, Composition Variation



Legend

1	F6-2	Pyroxene Trachyte
2	22-J1	Biotite Rhyolite
3	F4-3	Pyroxene Trachyandesite
4	20-C13	Biotite Trachyte
5	20-C12	Biotite Trachyte
6	Daly's Rhomb Porphyry Feldspar	

thermal relations of the feldspars described by Tuttle and Bowen (1958) the orthoclase content of the alkali-feldspar is less in the one-feldspar than in the two-feldspar rocks. However, the refractive indices of rhyolite and shackanite[1] are anomalous. The index for rhyolite (1.497) is very low compared to the average of the other two-feldspar rocks (1.517); the index for the rhomb-porphyry (1.532) is quite high compared to (1.503) for the other one-feldspar rock (20-C12) (refractive indices for the rocks, corresponding to the plot in Figure 4.5, are given in Appendix 'E').

d. Ternary Relations of the Feldspars

Yoder, Stewart, and Smith, (1956-57) note that the orientation of the tie lines joining coexisting feldspars in the Or-Ab-An ternary system is a function of the temperatures and pressures existing in the melt during formation of the feldspars. According to these authors, steeply inclined tie lines are indicative of low pressures and high temperatures, characteristic of surface flows, whereas tie lines with gentle slopes are suggestive of high pressures and lower temperatures, more characteristic of magmatic conditions.

A plot of eight of the analysed feldspars used in this study is given in Figure 4.6 showing tie lines joining coexisting feldspar pairs. (Complete data on the solid solution state of these feldspars is not available. However, hypothetical solid solution boundaries are reproduced from Turner and Verhoogen (1960, p. 112-114) for volcanic and plutonic conditions.) For lavas F4-3, F6-2, and 20-C13

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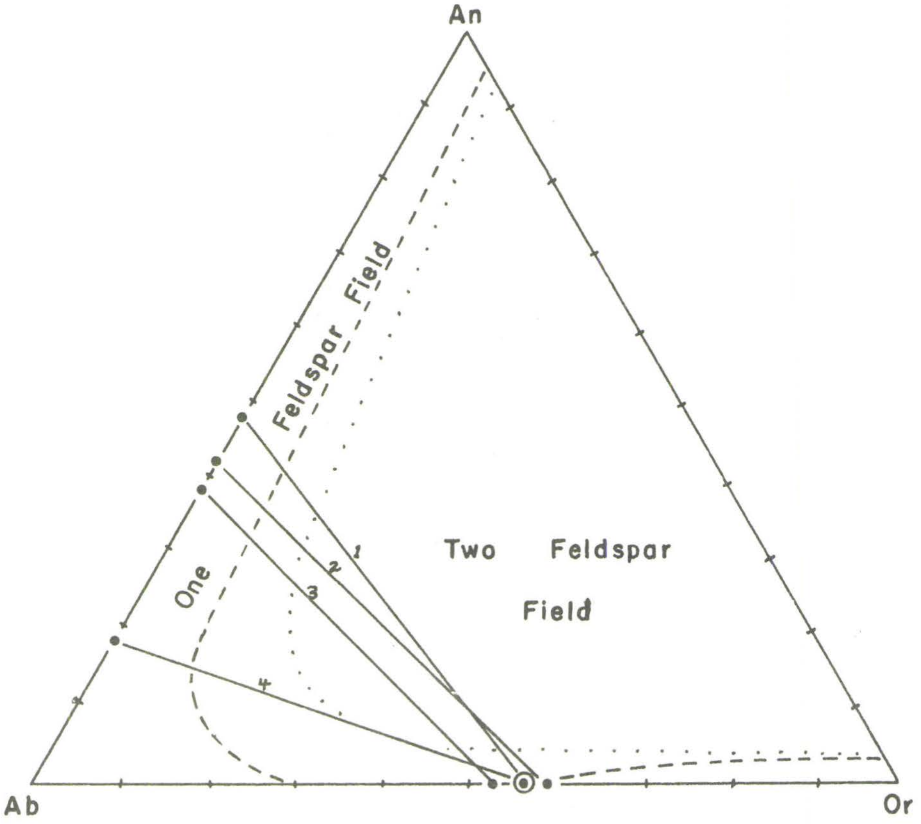
[1] Shackanite lava contains rhomb-porphyry feldspar (see petrographic description of CC-1, Appendix 'I').

Figure 4.6 Ternary Relations of the Feldspars



Legend

1	F4-3	Pyroxene Trachyandesite
2	F6-2	Pyroxene Trachyte
3	20-C13	Biotite Trachyte
4	22-J1	Biotite Rhyolite

····· volcanic } hypothetical solid solution boundaries
– – – plutonic }

(trachyandesites and trachytes) the coexisting feldspars are joined by steeply inclined tie lines characteristic of surface flows. In contrast the coexisting feldspars of rhyolite 22-J1 are joined by a gently sloping tie line characteristic of 'plutonic' conditions.

There is little doubt that rhyolite (22-J1) is of effusive origin (see petrographic description Appendix 'I'). However, it may have been extruded from a region of greater depth and higher pressures than the trachyandesites and trachytes.

It now seems certain that rhyolite 22-J1 is not directly related to the trachyandesite - trachyte series of lavas and there is little likelihood that it is related to the undersaturated shackanite lava. However, the possibility of a latite - rhyolite association has yet to be examined.

C. Pyroxenes

It was previously noted (Chapter III) that the pyroxenes in the lavas of this study are all monoclinic and bear marked similarity in general appearance. The purpose of this section is to determine whether or not this similarity is reflected in the major and minor element composition of these pyroxenes. Six pyroxenes have been analysed from a variety of pyroxene-rich andesites and trachyandesites.

a. Determination of Pyroxene

Determination of monoclinic pyroxene using optical methods has been outlined by Hess (1949). In the present study Ny was estimated from (100) parting tablets using oil immersion techniques, and 2V was measured on the universal stage. The resulting data, given in

Table 4.3, was plotted against Hess's curves for Ny and 2V for the diopside-hedenbergite-enstatite-ferrosilite system. As illustrated in Figure 4.7 there is only minor variation in these optical properties. Plots for the analysed pyroxenes fall in the salitic augite region of Hess's diagram. The average andesite pyroxene has a composition of $Wo_{44}En_{38}Fs_{18}$; the average trachyandesite pyroxene is $Wo_{44}En_{39}Fs_{19}$.

Some of the optical data was confirmed by X-ray analysis. According to Zwaan (1954) the members of the diopside-hedenbergite-enstatite-ferrosilite group can be partially determined by measurement of d(131-22$\bar{1}$) lattice spacings. This spacing is influenced by the structural state of the pyroxene similar to the behaviour of 2V. Thus, a change in the FeO:MgO ratio has only minor effect on 2V angles, whereas the entry of CaO into the crystal structure brings about significant increases. Similarly, d(131-22$\bar{1}$) spacings are only slightly effected by FeO:MgO changes but show substantial decreases when Ca enters the structure. Figure 4.8 shows the relationship between 2V and d(131-22$\bar{1}$) for all six analysed pyroxenes (pertinent data are given in Table 4.3). The small spread of 2V and d(131-22$\bar{1}$) values over total possible range emphasizes again the similarity of the pyroxenes.

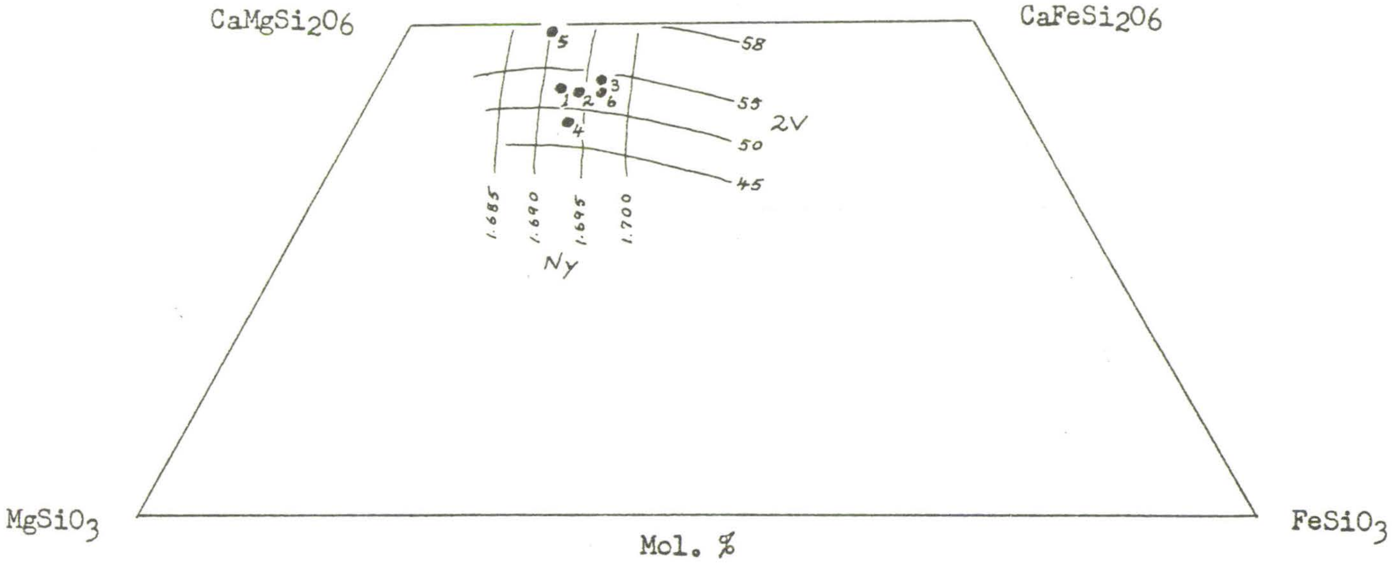
b. Pyroxene Compositions

Pyroxene compositions determined using optical and spectrochemical methods is given in Table 4.4.

1. Major oxide compositions and (FeO x 100/FeO + MgO) values are similar for andesite and trachyandesite pyroxenes.

2. Among the minor elements Ni, Sr, Ti, and V have notably

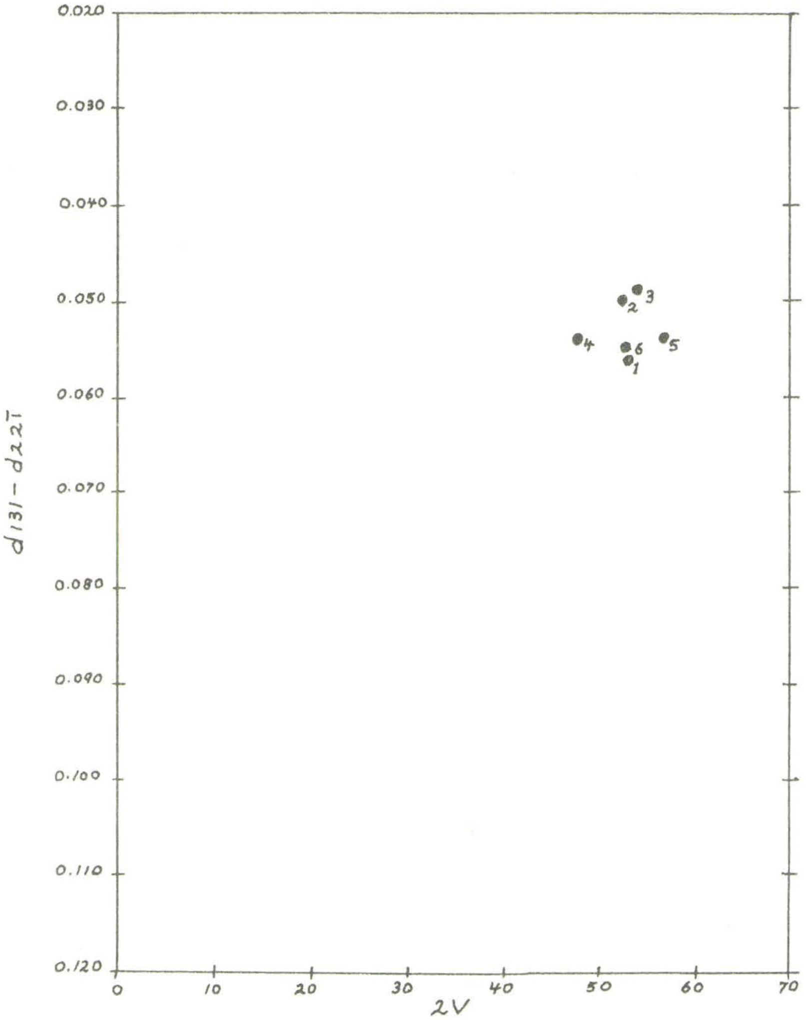
Figure 4.7 Optical Determinative Diagram for Pyroxenes



Legend

1	DC-10	Hornblende Andesite
2	DC-2	Pyroxene Andesite
3	CC-7	Pyroxene Andesite
4	CC-6	Pyroxene Trachyandesite
5	F3-2	Pyroxene Trachyandesite
6	20-C5	Biotite Trachyandesite

Figure 4.8 d(131-22$\bar{1}$) versus 2V for the Pyroxenes



Legend

1	DC-10	Hornblende Andesite
2	DC-2	Pyroxene Andesite
3	CC-7	Pyroxene Andesite
4	CC-6	Pyroxene Trachyandesite
5	F3-2	Pyroxene Trachyandesite
6	20-C5	Biotite Trachyandesite

Table 4.3 Composition, Optical, and X-Ray Data for Pyroxene

	Sample No.	Mol. Composition			Ny	2V	$2\theta(131-22\bar{1})$	ΔdÅ
		Wo	En	Fs	r	r	s	
A	DC-10	44	40	16	1.692 ± .002	52.6 ± 0.3	0.796 ± .009	.056
	DC-2	43	39	18	1.694 ± .002	52.3 ± 0.3	0.726 ± .020	.050
	CC-7	45	35	20	1.696 ± .002	54.0 ± 0.3	0.694 ± .022	.049
B	CC-6	40	41	19	1.693 ± .002	48.0 ± 0.3	0.770 ± .019	.054
	F3-2	49	38	13	1.690 ± .002	57.0 ± 0.3	0.755 ± .026	.054
	20-C5	43	37	20	1.696 ± .002	53.0 ± 0.3	0.788 ± .021	.055

r = range, s = standard deviation

A - Andesites, B - Trachyandesites

Table 4.4 Pyroxenes, Partial Composition

	Sample No.	CaO (%)	MgO (%)	FeO (%)	$\frac{FeO \times 100}{FeO + MgO}$	Sr (ppm)	Ba (ppm)	Co* (ppm)	Al* (%)	Ti* (ppm)	V* (ppm)	Ni* (ppm)	Cr* (ppm)	Mn* (ppm)	Zr* (ppm)	Cu* (ppm)
A	DC-10	22.0	14.4	10.2	41.5	133	74									
	DC-2	21.4	13.9	11.5	45.3	125	85	40	1.9	4750	295	93	930	2530	107	11.3
	CC-7	22.2	12.4	12.6	50.4	150	155	53	2.9	3030	188	98	500	3760	88	16.7
B	CC-6	19.9	14.7	12.1	45.2	215	62	41	3.3	8210	520	170	1940	2120	99	18.3
	F3-2	24.5	13.7	8.3	37.7	203	46									
	20-C5	21.2	13.2	12.7	49.1	215	125	32	3.7	6780	350	160	500	3200	102	12.6

(Total iron is calculated as FeO)

*Analysis by D. Watkinson

A - Andesites, B - Trachyandesites

CaO, MgO and FeO were calculated from optical data,
all other constituents were determined spectrochemically

higher concentration levels in trachyandesite than andesite pyroxenes; Al is slightly lower in the latter. Ba, Co, Cr, Cu, Mn, and Zr show no consistent preferential distribution.

Moxham (1957) observed that one of the most obvious differences between metamorphic and igneous pyroxenes is the relatively high concentration of minor elements in the latter. In Table 4.5 the average and minimum minor element concentrations obtained for six pyroxenes of this study are compared with the average of 38 metamorphic pyroxenes. In all cases the minimum values for the six pyroxenes exceed Moxham's metamorphic pyroxenes. On the other hand, minor element concentrations for two augites from the Keweenawan lavas (Cornwall and Rose, 1957) are similar to the pyroxenes of this study.

c. Pyroxene and Host Rock Composition Variations

Perhaps one of the most significant factors indicating the state of petrogenetic evolution of the pyroxenes and corresponding host rock is their relative concentration of iron oxide and magnesia. In his study of the crystallization of basalts, Fenner (1929, p. 238) concluded:

> "From the physico-chemical principles of general applicability it was deduced as probable that in the crystallization of ferromagnesian silicates of igneous magmas, such as pyroxenes and olivines, an excess of magnesia should be concentrated in the crystals and an excess of iron in the residual liquid."

In Figure 4.9 the various lavas have been grouped according to their general types and arranged in acid to basic order, from

Table 4.5 Minor Elements in Other Pyroxenes

	Pyroxenes of This Study		Keweenawan Lavas (Cornwall and Rose)		Metamorphic Pyroxenes (Moxham)
Elements	Av.	Min.	Augite 4-149	Augite 3-89	Av. of 38 Pyroxenes
Cr	967	500	300	570	31.3
Ti	5690	3030	5400	4200	331
Ni	130	93	93	160	13.5
Co	42	32	88	75	12
Cu	14.7	11.3	320	51	2.9
V	338	188	570	520	31.2
Zr	99	88	80	30	37.7
Mn	2903	2120	2800	2900	1348
Sr	208	125	200	60	80.4
Ba	109	46	40	--	11.2

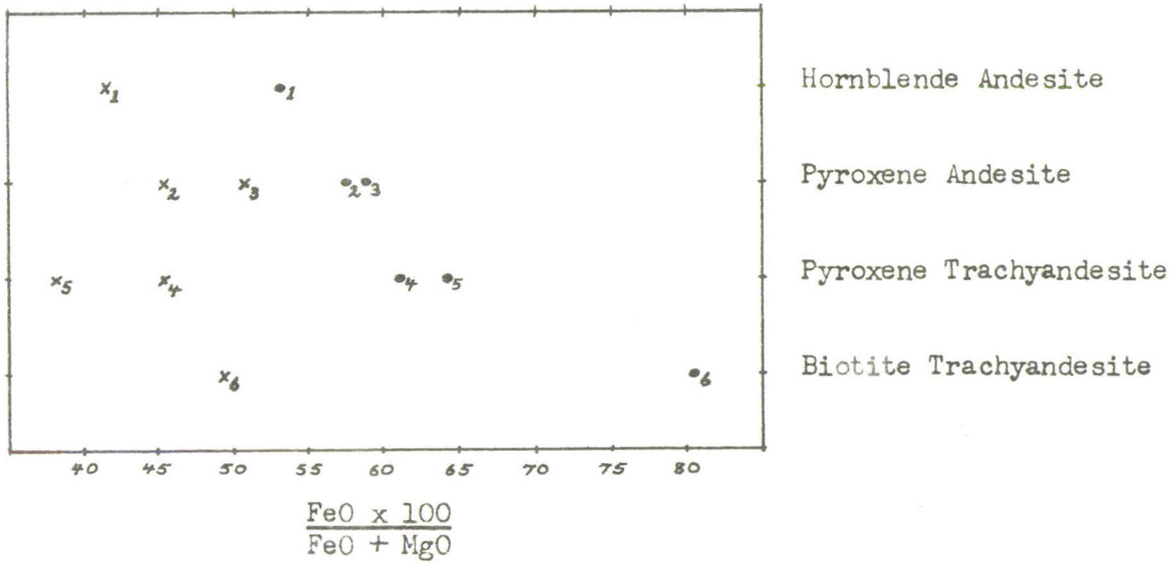
hornblende and pyroxene andesites to pyroxene and biotite trachyandesites (composition data is given in Table 4.4). As would be expected, in the light of Fenner's conclusions, the (FeO x 100/FeO + MgO) values for the host rocks show an increase from most basic to most acid types. The values for the pyroxenes are consistently smaller than the corresponding host rocks.

From evidence given so far there is no objection to the theory of possible genetic relation between andesites and trachyandesites other than the fact that the latites, which are mineralogically unlike the trachyandesites, are also related to the andesites. It seems possible that, under varying environmental conditions, a parent magma could give rise to two more or less independent lava series. For example, water pressure may greatly influence the evolutionary path of a magma. Osborn (1959) has demonstrated that 'Fenner type trends' may be the result of 'dry' magmas undergoing cooling and crystal fractionation (Skaergaard Intrusion). On the other hand, Tilley and Harwood (1931) have shown that marked iron relative to magnesium enrichment can be produced by lime assimilation (Scawt Hill). Although these theories will be discussed in more detail in the last chapter, it is interesting to note here that Ti enrichment in the trachyandesite pyroxenes of this study (and to a much lesser extent the Al enrichment) is in keeping with Tilley and Harwood's Scawt Hill observations.

D. Hornblende and Biotite

Since only general information on composition could be obtained from optical and X-ray analysis of hornblende and biotite the following

Figure 4.9 Composition Variation of Pyroxenes and Host Rocks



Legend

1 DC-10
2 DC-2
3 CC-7
4 CC-6
5 F3-2
6 20-C5
× Pyroxene Analysis
• Rock Analysis

discussions are brief. In view of the widespread distribution of biotite speculation is made on its possible significance in the rocks of this study.

a. Hornblende

Optical data for amphibole sample DC-10 is given in Table 4.6. This data agrees with the information given by Deer, Howie, and Zussman (1963, Vol. 2, p. 263) for the hornblende group. Although precise identification cannot be made using optical methods a common hornblende composition is suggested. A plot of refractive index and 2V values against curves for common hornblende gives the following molecular percentage:

(100 x Mg)/(Mg " Fe + Fe + Mn) = 50 to 60%.

Turner and Verhoogen (1960, p.140) point out that formation and stability of hornblende is favoured by high pressures (P_{H_2O}) typical of plutonic conditions. According to the interpretation of these authors, the occurrence of partially resorbed hornblende, such as found in the rocks of this study (see petrographic descriptions, Appendix I), is probably due to decrease of pressure in the magma at the time of extrusion.

b. Biotite

Optical data given by Deer, Howie, and Zussman, (1962, Vol. 3, p. 55) for biotite are similar to those obtained for mica 20-C5 of this study (see Table 4.7). An X-ray method described by Gower (1957) was used to estimate (Fe + 100/Fe + Mg + Al) octahedral content. Relative reflection intensities from planes (004) and (005) indicates approximately

Table 4.6 Hornblende (DC-10), Optical Data

Pleochroism
X smoked yellowish green
Y brownish green
Z greenish brown

Absorption Z Y X

Optic Axial Angle $2V = -79^{\circ}$

Extinction in (010) plane $Z \quad C = 13^{\circ}$

Refractive Indices
$n_x = 1.654$ (calculated)
$n_y = 1.671$
$n_z = 1.683$

Table 4.7 Biotite (20-C5), Optical Data

Pleochroism
X pale yellowish brown
Y medium brown
Z medium brown

Optic Axial Angle $2V = -20$

Refractive Indices
$n_x = 1.573$ (calculated)
$n_y = 1.663$
$n_z = 1.666$

60% Fe (read from Gower's curves). Most biotites examined in this study are similar in appearance to 20-C5 with high iron content being suggested by a prevalence of deep brown colors and sometimes dense charges of fine magnetite in partially altered grains.

The widespread occurrence of resorbed biotite was remarked upon in Chapter III. As in the case of hornblende, Turner and Verhoogen (1963, p. 138-139) attribute biotite resorption in volcanic rocks to release of pressure (P_{H_2O}) at the time of extrusion. According to theory the failure of biotite to precipitate would allow significant amounts of the potash feldspar molecule to accumulate in residual magmas. It is understandable then that continual escape of water from shallow-seated magma bodies could cause enrichment of normative potash feldspar and eventual crystallization of this mineral. On the other hand, escape of water from deep-seated magmas may be more difficult. In these deeper magmas biotite precipitation would tend to decrease normative potash feldspar in the melt delaying crystallization of this mineral until a very late stage.

The possible derivation of both the trachyandesites and latites of this study from a common magma (andesite) has already been suggested (pyroxene section). In the light of the above discussion, it appears that the potassic feldspar-rich trachyandesites could have been derived from andesite magma which was intruded and 'dried out' at shallow depths; the latites may have formed from the same andesite magma deep in the crust. This speculation is supported in part by the ternary feldspar relations which indicate shallow (low P_{H_2O} pressure) origin for the trachyandesites and trachytes. Also, from similar evidence, it is interesting that rhyolite 22-J1 has formed under higher pressure conditions than the trachyandesites and trachytes. This suggests that rhyolite may belong to the same deep magma series as latite.

Thus, the lavas of the Kettle River region can be tentatively assigned to two magma series:

A. a 'wet' series composed of andesite - latite - rhyolite, and characterized by late-forming potassic feldspar and a quartz-rich residuum- rhyolite 22-J1.

B. a 'dry' series composed of andesite - trachyandesite - trachyte, and characterized by early-forming potassic feldspar and a quartz-free residuum - trachyte 20-C12. (The relation of shackanite (analcite rhomb-porphyry) to the other lava types is not known; however, the high potassic feldspar content and obvious low silica composition of this rock are features more in keeping with the rocks of 'B' series than 'A'.)

It is important to note, however, that explanations other than simple biotite resorption or precipitation might adequately account for the formation of 'A' and 'B' series. For example, Osborn (1959) explains the origin of silica-enrichment series similar to 'A' as the product of fractional crystallization of 'wet' magmas by a process of precipitation of spinel minerals (mostly magnetite) and anhydrous silicates. Also, Daly (1910) and Shand (1945) are strong advocates of lime assimilation processes to explain the origin of alkali-rich silica-poor series such as 'B'.

Amplification of this discussion will be given in the last chapter.

E. Strontium and Barium Content of the Minerals

Strontium and barium are of special interest because of the high concentration of these elements in some of the minerals analysed by Daly (1912). For example he found an alkali-feldspar (rhomb-porphyry) to contain 0.92% SrO (7,780 ppm. Sr) and 1.28% BaO (11,460 ppm.)

According to Mason (1958) Sr^{++} (ionic radius 1.27Å) can replace Ca^{++} (1.06Å) or K^{+} (1.33Å) in minerals. It is admitted to calcium minerals and captured by potassium minerals. Ba^{++} (1.43Å), on the other hand, is somewhat too large to readily replace Ca^{++} but is easily captured by potassium minerals.

Cornwall and Rose (1957) point out that strontium and barium occur most abundantly in the feldspars of the Keweenawan lavas (a maximum of 2,000 ppm. Sr, and 800 ppm. Ba is reported for plagioclase). These authors conclude that Ba^{++} probably replaces both Ca^{++} and K^{+}.

Nockolds and Mitchell (1948), in their study of the Caledonian plutonic rocks, have observed that the main habitate of strontium is in plagioclase and alkali-feldspar. Barium is most abundant in alkali-feldspar but also occurs in large amounts in biotite.

The data for important minerals in this study (Table 4.8 and Appendix 'D') are largely in agreement with the findings of the above authors. Comparison of the strontium and barium concentrations in the minerals and host rocks shows that these elements enter the feldspars preferentially. Concentrations are somewhat higher than values given by Cornwall and Rose for plagioclase but Sr/Ba ratios are about the same. Except for the large amount of barium in biotite the ferro-magnesian minerals have notably small amounts of these elements.

Since mechanical separation of plagioclase from alkali-feldspar was not possible in the two-feldspar rocks, feldspar mixtures were analysed. As would be expected the Sr/Ba ratio for mixtures is intermediate (av. 1.18) to plagioclase (av. 2.62) and alkali-feldspar (av. 0.78).

An important aspect to be considered in the light of these data is the possible effect of crystal precipitation upon the distribution of strontium and barium in residual magmas. It is apparent that concentrations of strontium and barium and Sr/Ba ratios would be effected by the kind and amount of crystals precipitated. For example, in view of the high content of strontium and barium in the feldspars and low content in the ferromagnesian minerals (excluding biotite), it seems clear that fractional crystallization of the feldspars would most effectively reduce strontium and barium in residual magmas. Preferential precipitation of biotite might result in depletion of barium which would cause a marked increase in Sr/Ba ratios - a feature not observed in the available data (the average Sr/Ba ratio for 19 lavas of this study, ranging from acid to basic composition, was found to be a small value, 0.62).

In summary, two points are drawn from the above discussion:

1. Relative decreases or increases of the strontium and barium content of residual magmas may be due to preferential precipitation of feldspar or ferromagnesian minerals.

2. Low Sr/Ba ratios in the rocks of this study suggests that biotite has not been removed from the parent magmas (presumably by crystal fractionation) in any significant abundance. (Textural evidence

Table 4.8 Average Sr and Ba Composition of Minerals and Host Rock

Mineral	No. of Analyses	Sr	Ba	Sr/Ba
Plagioclase	4	3300 (1020)	1260 (1425)	2.62 (0.72)
Two Feldspar Mixtures	3	4650 (1062)	3930 (1740)	1.18 (0.61)
Alkali-Feldspar				
Normal Type	1	305 (25)	345 (100)	0.88 (0.25)
Rhomb-Feldspar	1	*7780 (3100)	*11460 (5500)	*0.68 (0.56)
Hornblende	1	355 (1300)	350 (1450)	1.01 (0.90)
Pyroxene	6	174 (1303)	90 (1858)	1.93 (0.70)
Biotite	1	125 (1560)	2000 (2200)	0.06 (0.71)

The average Sr/Ba ratio for 19 rocks analysed in this study is 0.62 with standard deviation of 0.20.

Bracketed values represent the Sr and Ba concentrations in the corresponding responding host rocks. Values with asterisk marking are from Daly's (1912) work.

See Appendix 'D' for complete spectrochemical data.

is compatible with this conclusion; see description of biotite in Appendix 'I').

2. Chemical Composition

> "Only an approximate idea of the chemical composition of a volcanic rock can be gained from its mineralogical composition, even in the case of holocrystalline rocks, since most of the constituent minerals will be members of a solid solution-series whose precise composition cannot be determined by optical means. Chemical analysis is therefore a most desirable corollary to optical examination, especially in the case of glassy volcanic rocks."
>
> Rittmann (1962, p. 104)

Wet chemical and spectrochemical analyses for rocks of this study are given in Appendix 'D'.

Since iron was determined spectrochemically, this method being insensitive to the oxidation states of iron, all values were arbitrarily calculated as ferrous oxide. According to Cornwall (1951, p.168) this is justified for volcanic rocks because iron tends to be more oxidized in extrusive than intrusive bodies so that recalculation of total iron as FeO gives values close to the actual FeO content of the parent magma.

A. Lava Trends

Silica-based variation diagrams are widely used in the literature to illustrate trends in igneous rock series. However, some authors find plots based on FeO and MgO or ratios of these oxides more satisfactory for this purpose (Walker and Poldervaart, 1949,

p. 652). In the present study a simple point plot of FeO vs. MgO showing SiO_2 percentages of plotted rocks seems adequate.

In Figure 4.10 rocks of the andesite - latite - rhyolite series show marked decrease in FeO and MgO, and increase in SiO_2 content passing from hornblende andesite (No. 1) to rhyolite (No. 7). Plots of these rocks lie close to a curve of almost constant FeO/MgO ratio. Trachyte - trachyandesite and shackanite (analcite rhomb-porphyry) rocks (No's. 8 and 9 respectively) plot below the andesite - latite - rhyolite curve and show relatively high FeO and low SiO_2 contents.

According to Bowen (1928, p. 110; 1947, p. 237) trends of the andesite - latite - rhyolite type are characteristic of normal magmatic evolution. However, Fenner (1929), Walker and Poldervaart (1949), and Osborn (1959) have shown that residual melts of many magma series are enriched in iron relative to magnesium often with little change in silica content (extreme cases of absolute iron enrichment are few).

In view of the nature of the plot in Figure 4.10 and the availability of magma types in the Kettle River region, it seems probable that the trachyte - trachyandesite and shackanite rocks were derived from parent magmas of andesitic composition. A process of moderate iron enrichment (relative to magnesium) without marked silica enrichment is envisaged. The trachyte - trachyandesite and shackanite rocks could not easily be derived from magmas of rhyolite or latite composition because of the high silica and low iron content of the latter. Also, it is unlikely that magmas of trachyte - trachyandesite or shackanite composition were capable of producing rocks of the andesite - latite - rhyolite series since this would involve relative magnesium enrichment - according to Fenner (1931, p. 547), a highly improbable trend. For the same reason it is unlikely that a shackanite magma could be parent to trachyte - trachyandesite rocks; the alternative, derivation of shackanite from trachyandesite, is also unlikely since this would require considerable increase in iron and decrease in silica content. However, the combination of high iron and magnesium and relatively low silica content of the andesites seems favourable for the formation of both the trachyandesite and shackanite rocks. In Figure 4.10 projection of the trachyte - trachyandesite field to the andesite - latite - rhyolite curve suggests a parent magma of hornblende of pyroxene andesite of a specific composition somewhere between No. 1 and No. 4. Shackanite may have been derived directly from the most basic andesite No. 1.

In summary, three compositional trends (series) are recognized in the lavas of the Kettle River region:

A. andesite - latite - rhyolite

B. andesite - trachyandesite - trachyte

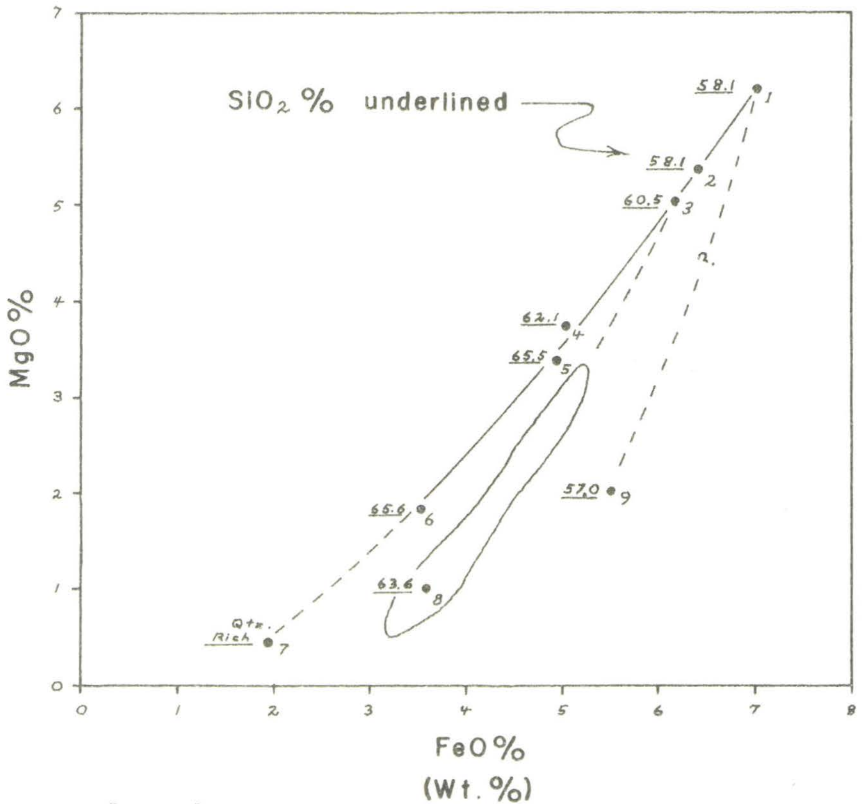
C. andesite - shackanite (analcite rhomb-porphyry)

A more detailed account of the chemistry of these rocks will be given in the following part.

B. Chemical Variations

The complete chemical data for 'A', 'B', and 'C' lava series are represented by plotting weight percentages and parts per million of the chemical constituents against refractive index of the corresponding rocks (Figures 4.11, 4.12, 4.13). The chemical characteristics

Figure 4.10 SiO_2 and FeO vs. MgO Variation



Legend:

No.	Sample	Description
1	DC-10	Hornblende Andesite
2	DC-21	Hornblende Andesite
3	DC-4	Pyroxene Andesite
4	DC-2	Pyroxene Andesite
5	CC-7	Pyroxene Andesite
6	AC-18	Latite
7	22-J1	Rhyolite
8	average of four trachyandesites-trachytes: 1010, CC-5, 20-C15, 20-C16.	
9	1064	Shackanite (analcite rhomb-porphyry)

All plots are based on anhydrous rock composition except sample 22-J1 which lacks sufficient data for recalculation purposes. The maximum composition range for non-recalculated (hydrous) trachyte and trachyandesite rocks is outlined. (See Appendix 'D' for chemical data) of the series are given as follows:

1. The behaviour of SiO_2 is markedly different in the different series.

'A' series is characterized by a sharp rise in SiO_2 content passing from andesite to latite (this increase probably continues through to rhyolite which was not analyzed for SiO_2 but contains abundant quartz).

'B' series shows a gentle overall increase in SiO_2 from andesite but values tend to be erratic.

'C' series shows a sharp rise from andesite to shackanite.

2. Al_2O_3 variations are distinctive for the different series.

'A' series shows little change in Al_2O_3 and values are uniformly low.

'B' series shows a gentle increase in Al_2O_3 from andesite.

'C' series shows a sharp rise in Al_2O_3 passing from andesite to shackanite.

3. CaO, MgO, and FeO, are the most refractory major constituents and it is therefore not surprising that these oxides decrease regularly with increasing 'acidity'[1] of the rocks in the three series. The main difference between the series is the high FeO content of 'B' and 'C'.

4. Values for total alkalies ($K_2O + Na_2O$) are somewhat scattered but show a general increase with increasing 'acidity'. 'C' series is distinguished by a sharper increase in total alkalies than 'A' or 'B'.

---

[1] The term 'acid' or 'acidic' is used here in a loose sense and refers to the relative color index of the rock rather than specific SiO_2 content. The color index generally coincides with refractive index of the rock.

5. TiO_2 decreases with increasing 'acidity'.

6. For many rocks, particularly 'B' and 'C' series, the behaviour of Sr and Ba is similar, although Sr content is always less than Ba.

Except for erratic values in the andesite rocks Ba shows little change in 'A' series. Sr differs from Ba by dropping to low values in the latites.

'B' Series is characterized by an early rise in Sr and Ba content followed by a marked decrease in the most acid rocks.

'C' series shows a very strong rise of Sr and Ba from andesite to shackanite.

Figure 4.11 Chemical Variation, 'A' Series

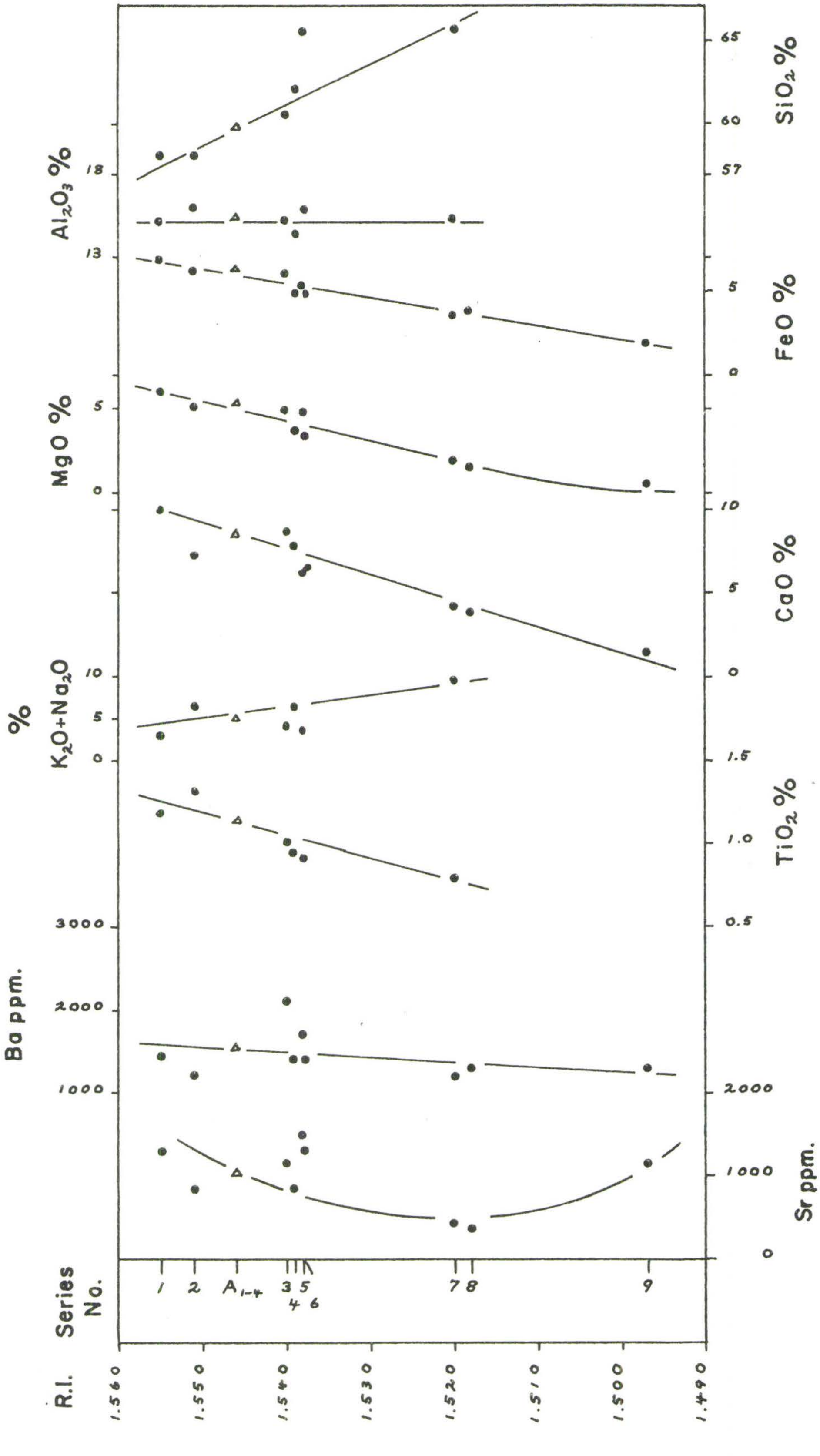


Figure 4.12 Chemical Variation, 'B' Series

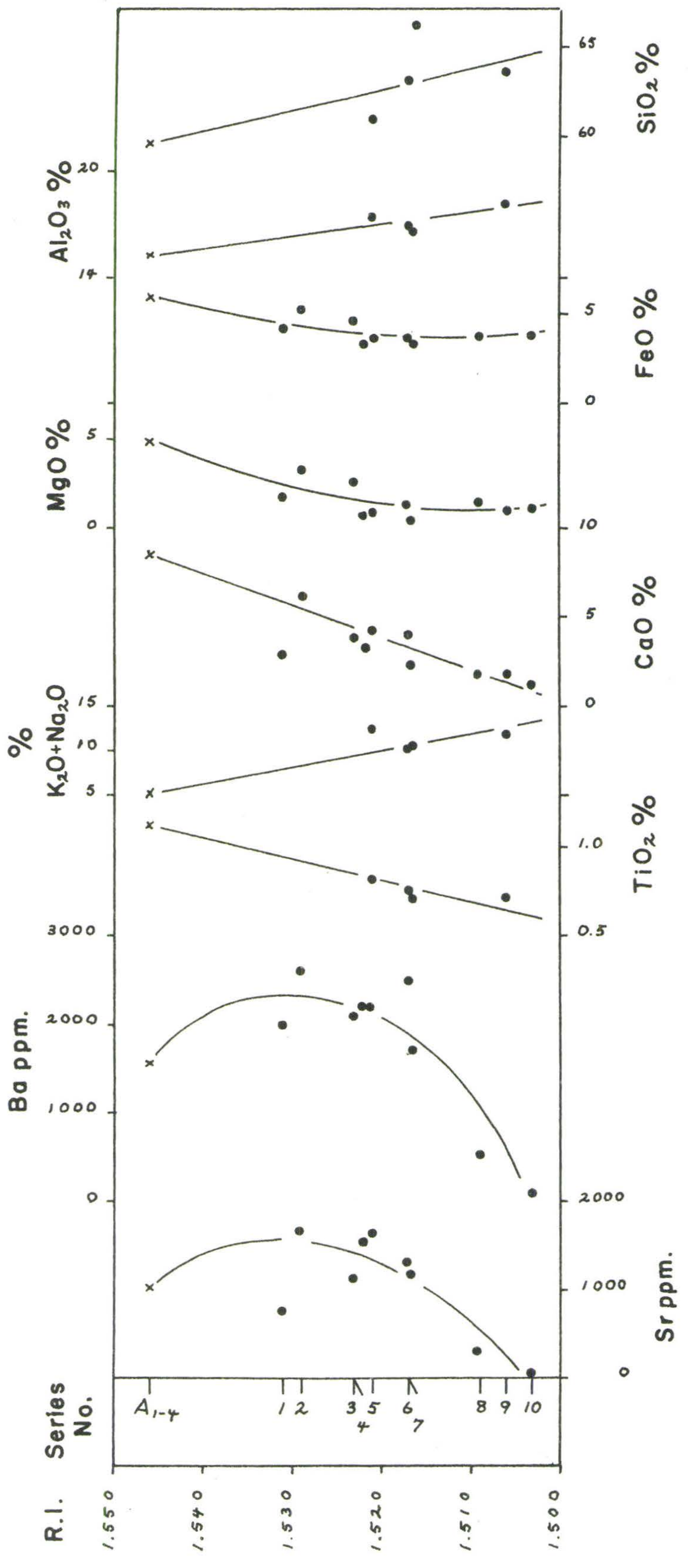


Figure 4.13 Chemical Variation, 'C' Series

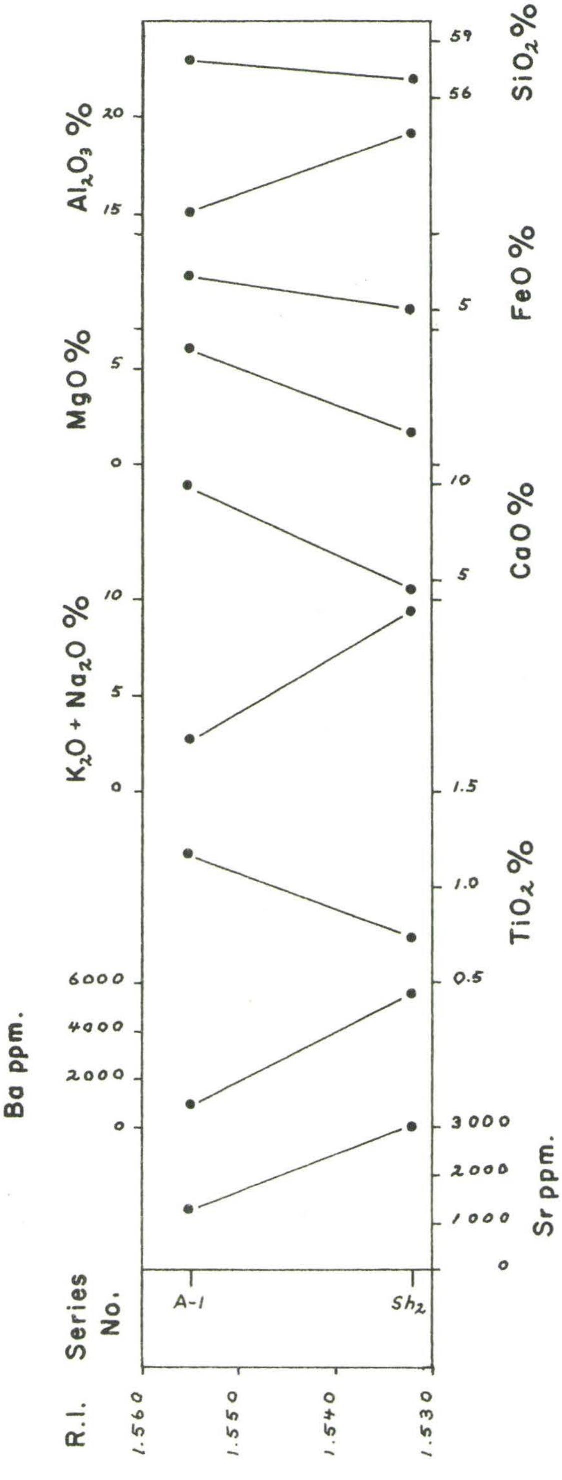


Table 4.9 Key to Variation Diagrams (Figs. 4.11 to 4.13)

	Series Number	Sample Number	Refractive Index	
'A' Series	1	DC-10	1.555	andesite
	2	DC-21	1.551	andesite
	3	DC-4	1.540	andesite
	4	DC-2	1.539	andesite
	A_{1-4}	average	1.546	andesites nos. 1 to 4
	5	DC-12	1.538	andesite
	6	CC-7	1.538	andesite
	7	AC-18	1.520	latite
	8	AC-9	1.518	latite
	9	22-J1	1.497	rhyolite
'B' Series	1	20-C9	1.531	trachyandesite
	2	CC-6	1.529	trachyandesite
	3	F3-2	1.523	trachyandesite
	4	20-C5	1.523	trachyandesite
	5	20-C16	1.521	trachyandesite
	6	CC-5	1.517	trachyandesite
	7	20-C15	1.517	trachyandesite
	8	20-C13	1.509	trachyte
	9	1010	1.506	pulaskite (feeder dike to trachyte flows), analysis by Daly, 1912; R.I. taken to be the average of nos. 8 and 10
	10	20-C12	1.503	trachyte
'C' Series	Sh_2	1064	1.532	shackanite, analysis by Daly, 1912; refractive index and Sr and Ba values taken to be the same as sample CC-1

(All chemical data is tabulated in Appendix 'D')

V. Speculation on Origin of the Lavas

Origin of the lavas of the Kettle River region is a complex problem and no simple hypothesis can be offered to explain all the features observed in this study. However, certain lines of thought emerge upon examination of the data.

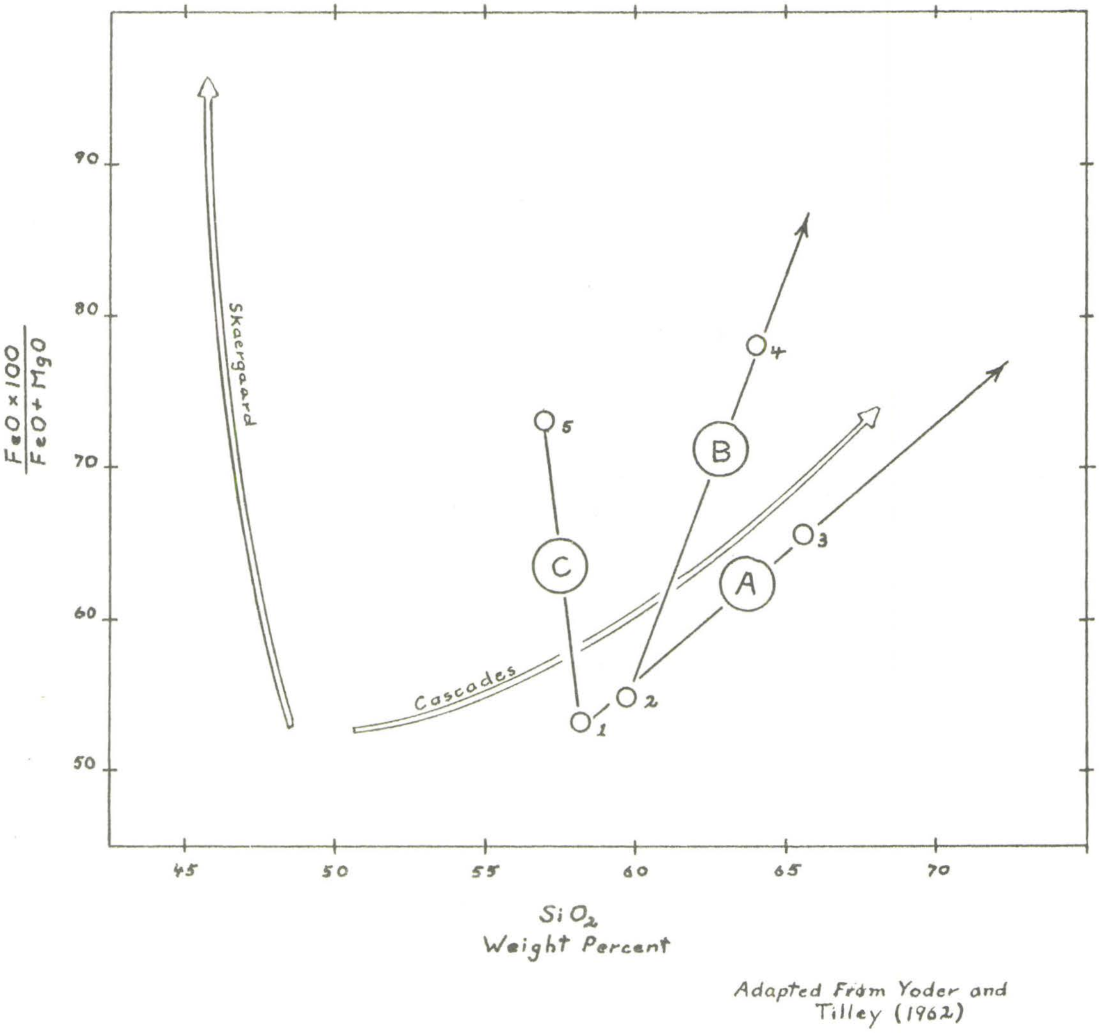
A plot of (FeO x 100/FeO + MgO) vs. SiO_2 (Figure 5.1) shows the nature of the main magma trends and the trends of the rocks of this study. The 'A' series closely parallels the Cascades curve (calc-alkali trend), 'C' series parallels the Skaergaard curve (tholeiitic trend), and 'B' series is intermediate to 'A' and 'C'. Essentially, the Cascades trend shows strong silica enrichment but little change in iron to magnesium ratios, whereas, the Skaergaard is an iron enrichment trend with little change in silica content.

According to Bowen (1947, p. 273):

". . . Skaergaard so closely resembles the results obtained in dry melts in the laboratory that it may be supposed that they were concerned with a substantially dry differentiation consequent upon the thin and porous character of the roof of the mass. Bodies with more competent roofs are able to retain their volatile constituents and give hydrous phases such as hornblende and biotite. It is these bodies that show the normal, natural differentiation series basalt to rhyolite, as distinct from the laboratory (dry) series approached by the Greenland example."

It is the opinion of recent authors that major differences

Figure 5.1 Comparison of Magma Trends



Adapted From Yoder and Tilley (1962)

Legend:

A	andesite - latite - rhyolite
B	andesite - trachyandesite - trachyte
C	andesite - shackanite (analcite rhomb-porphyry)

1. hornblende andesite DC-10
2. average of four andesites DC-10, DC-21, DC-4, DC-2
3. latite AC-18
4. average of four trachyandesites-trachytes CC-5, 20-C5, 20-C16, 1010 (Daly, 1912)
5. shackanite 1064 (Daly, 1912)

in magma trends are due to the effects of water but no special importance is attached to the formation and separation of hydrous minerals. For example Yoder (1954) shows that high water pressure in magma may enhance or suppress the formation of anhydrous silicates (plagioclase and pyroxene) thereby influencing the composition of residual melts. Kennedy (1955) and Osborne (1959) attribute the differences in the main magma trends to variations in oxygen partial pressure which, in turn, is largely a function of water content of magma.

1. 'A' Series - Andesite - Latite - Rhyolite

The chemical variations shown by Osborn (1959, p. 640, Fig. 14) for fractional crystallization of magma under constant oxygen pressure conditions ('wet' conditions) are similar to the variations in Figure 4.11 of this study for 'A' series. The sharp increase in silica, constant alumina, and sharp decrease in total iron oxide is particularly noteworthy.

Osborn considers precipitation of magnetite favourable for formation of iron-poor trends of this type. However, in the case of 'A' series it seems probable that iron was removed from the magma largely by precipitation of silicate minerals since magnetite occurs only in minor abundance in these rocks.

To test the theory that 'A' series has evolved by process of crystal fractionation, a subtraction diagram has been constructed using two rocks on 'A' line of descent, andesite 'r' and latite 's' (Figure 5.2). It is shown that subtraction of crystal aggregate 'x' from liquid 'r' moves the composition from 'r' towards 's'. Since 'x' is a mixture of plagioclase and pyroxene similar in composition to phenocrysts in the corresponding rocks (see Table 5.1) crystal fractionation is accepted as the probable mode of origin for these rocks.

Other rocks in 'A' series may be explained in the same way. The andesite average 'A_{1-4}' (see Table 4.9) falls between 'x' and 's' and fits the variation curves shown in Figure 5.2. Subtraction of plagioclase - pyroxene aggregate 'x' from 'A_{1-4}' moves the composition toward 's'. However, the composition of 'A_{1-4}' is based in part on hornblende andesite (see Appendix D). Calculations show that 'x' is also equivalent to hornblende, the composition of which is similar to that occurring in hornblende andesite (see Table 5.2).

Thus it appears that removal of hornblende or an aggregate of plagioclase and pyroxene from the magma by crystal fractionation could generate many of the rocks of 'A' series. Complete chemical data are not available for the acid rocks of 'A' series such as rhyolite, however, in view of the continuity of the chemical variations shown in Figure 4.11, it is probable that crystal fractionation is responsible for the formation of these rocks also.

2. 'B' and 'C' Series

Crystal fractionation is not a completely adequate explanation

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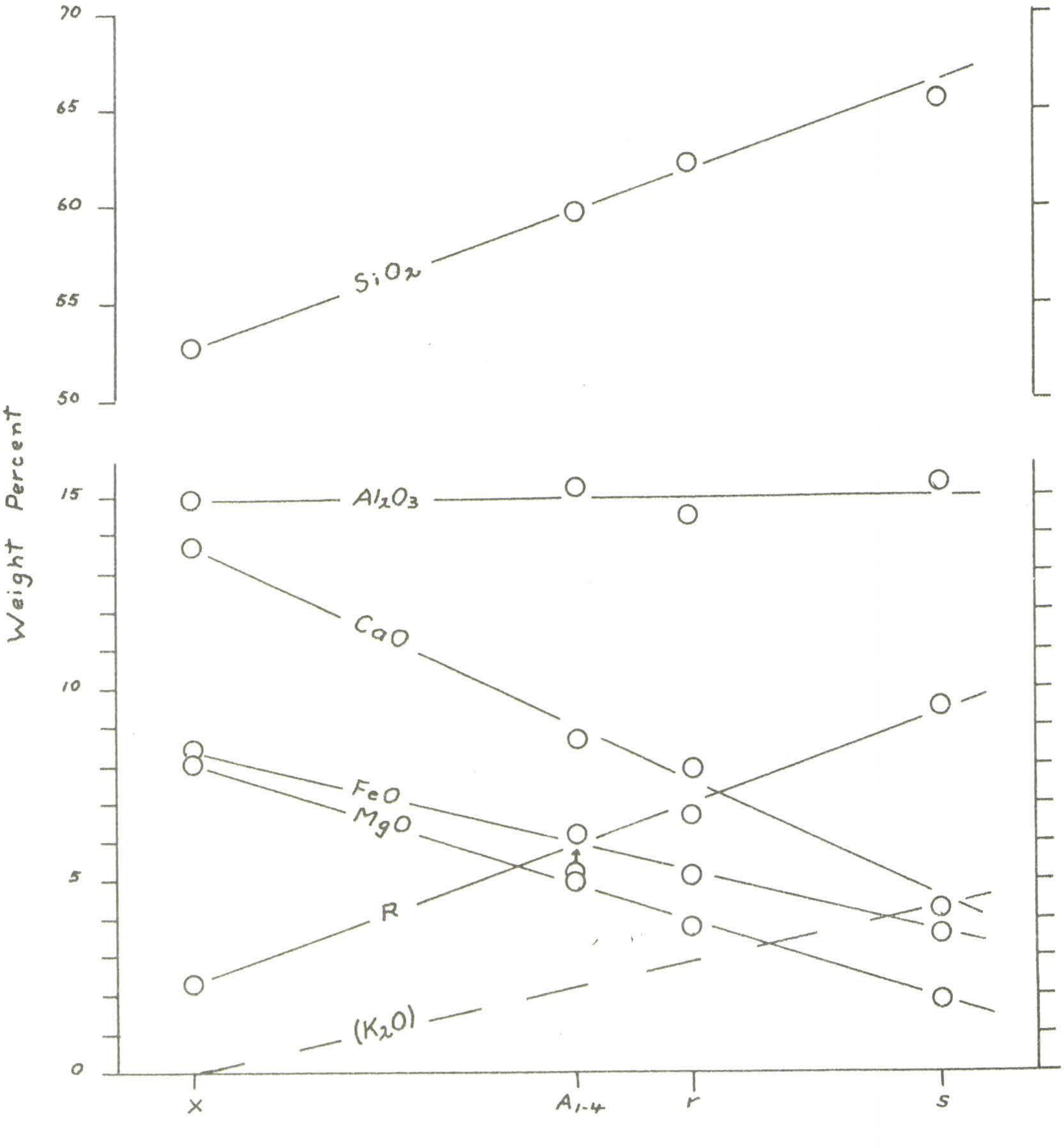
The theory and use of subraction diagrams is described by Bowen, 1928, p. 76.

The symbols 'r' and 's' refer to andesite DC-2 and latite AC-18, respectively (see Appendix 'D' for compositions).

Figure 5.2 Subtraction Diagram for 'A' Series



Legend:

R = total alkalies ($Na_2O + K_2O$)
r = andesite DC-2 (see Appendix D)
s = latite AC-18 (see Appendix D)
x = subtractive composition (see Table 5.1 and 5.2)
A_{1-4} = average of four andesites (see Appendix D)

The K_2O curve is hypothetical; at 'x' K_2O is assumed to be zero percent, and at 's' K_2O percent is based on known total alkalies for 's' and Na_2O/K_2O ratio for averages of quartz latite (Daly, 1933) and rhyodacite (Nockolds, 1954) ... (see Appendix H).

Table 5.1 'x' as Plagioclase and Pyroxene

	'x'	Crystalline Aggregate equiv. to 'x'			
	(Wt.%)	Plag.	Residual	Residual	Pyroxene
	- 1	- 2	- 3	(Pyrox)	DC-2
SiO_2	52.6	24.0	28.6	50.7	51.3
$A\ell_2O_3$	14.9	12.5	2.4	4.3	3.6
FeO	8.5	-	8.5	14.9	11.1
MgO	8.0	-	8.0	14.3	13.4
CaO	13.6	4.7	8.9	15.8	20.6
Na_2O	2.4	2.4	-		
		43.6	56.4		

Calculation Steps:

(1) Plagioclase is calculated as $Ab_{48}An_{52}$, the average composition of plagioclase DC-2 and AC-18 (see Table 4.1).

(2) Residual assumed to be clinopyroxene but high iron content suggests some magnetite included.

(3) Recalculation of residual to 100 and compared with pyroxene DC-2 (see Table 4.4).

Composition of 'x' and pyroxene DC-2 are totaled to 100 on a water and minor element-free basis.

Total alkali composition of 'x' is assumed to be Na_2O for calculation purposes.

Table 5.2 'x' as Hornblende

	'x' (Wt.%)	Mol. Cation Proportion		
SiO_2	52.6	7.55	8.00	Tetrahedral Positions
$A\ell_2O_3$	14.9	.45		
		2.06	4.78	Octahedral Positions
FeO	8.5	1.71		
MgO	8.0	1.01		
CaO	13.6	2.08	2.74	
Na_2O	2.4	0.66		

Hornblende Formula:

$$(OH)_2\ (Ca, Na)_{2.7}\ (Fe, Mg, A\ell)_{4.8}\ (A\ell, Si)_8\ O_{22}$$

Composition Comparison	Hornblende from 'x'	Hornblende DC-10
Mg x 100/Mg + Fe	63%	50 - 60%

(1) Total alkalies assumed to be Na_2O for calculation purposes.

(2) Since 'x' is calculated to 100, minor element and water-free basis, hydrogen is added to formula for $(OH)_2$.

(3) Composition inferred from optical data (see Table 4.6 and Deer, Howie, and Zussman., 1963, Vol. 2, p. 263).

for the origin of the rocks of 'B' and 'C' series. Daly (1912) examined the shackanite lavas in the Midway area and concluded from compositional evidence and field relations that these rocks were probably formed by lime assimilation. Evidence gathered in connection with the present study supports Daly's conclusions and also suggests a synthetic-differentiation origin for the trachyandesite-trachyte rocks.

A. Shackanite (analcite rhomb-porphyry)

Daly's (1912) general statement on the nature of the assimilation process is as follows (p. 789):

> "The new lime or magnesia (resulting from the assimilation of limestone or dolomite) must fix the silica to the extent of several times the weight of either base. The molecule thus formed is normally a pyroxene, which . . . will tend to settle out of the magma . . . The residual magma is necessarily higher in alkalies than the primary basalt. The fixing of silica by the new lime and magnesia means a desilication of the rest of the magma, and nephelite or leucite forms instead of feldspar. Since little alumina enters the sunken components, this oxide may be in excess . . ."

Significantly, shackanite contains considerable analcite (see description of CC-1 Appendix 'I') and is characteristically low in silica, high in alkalies, and high in alumina. This fits with Daly's theory but the high iron content of shackanite is not explained. It is known that under 'dry' magma conditions (see above) silica-poor iron enrichment fractionation trends are possible i.e., the Skaergaard intrusion (Figure 5.1). However, Walker and Poldervaart (1949, p. 662) remark that fractionation trends of the Skaergaard type show, in the main, no special tendency toward alkali enrichment. In the case of assimilation of chalk by olivine dolerite Scawt Hill, Ireland, Tilley and Harwood (1931, p. 464) observe:

> "Assimilation of the lime by olivine dolerite magma leads first to the formation of pyroxene-rich dolerite and ultimately pyroxenite, by conversion of the hypersthene molecule of the augite and conversion of the olivine to monoclinic pyroxene. This process is accompanied by enrichment of the pyroxenite in Mg relative to Fe. The liquid is correspondingly enriched in Fe and this is one of the most striking chemical features of the rock series . . ."

The ultimate product of assimilation at Scawt Hill is iron-enriched basic alkali rocks.

The field relations of shackanite to country rock are noted by Daly (p. 790) in the Midway area:

> "The rhomb-porphyries and shackanite of the Midway district are differentiated from one or more magmatic chambers not exposed. Their country-rocks are very seldom visible but in part at least have the same lithological character as those of the Rossland district. Heavy masses of limestone crop out at the few places where the Midway volcanics have been eroded off the Paleozoic formations."

There is a close spatial relation between the shackanite and limestone in the Marron area. Limestone marked (A) on G.S.C. map 628A (by Bostock, 1927) immediately underlies basal Tertiary sediments and shackanite lava CC-1 (the latter was discovered during the course of field work preliminary to this study).

In the light of the available evidence, shackanite appears to be the product of limestone (or dolomite) assimilation as Daly suggests. Although no compositionally intermediate rocks have been found, it is assumed that the uncontaminated parent of shackanite was a magma similar to andesite DC-10. This rock is the most basic in the early Tertiary lava suite and is considered highest in thermal line of descent (other magma types having cooled, no doubt, during the process of chemical evolution to acid compositions). Since reaction of magma with limestone is usually thought to be endothermic[1], a hot magma, probably similar in composition to DC-10, would be most capable of the assimilation process.

B. Trachyandesite-trachyte

In contrast to shackanite, the mineralogy and chemistry of the trachyandesite-trachyte rocks is not markedly unusual. There is a mineralogical-chemical trend from basic to acid rocks that may have been generated by simple crystal fractionation under 'dry' conditions (see Figure 4.12 and discussion above concerning iron enrichment). However, subtraction diagram Figure 5.3 and Table 5.3 shows that derivation of average trachyandesite-trachyte 'b' from average andesite 'A_{1-4}', as shown in Figure 5.1, requires subtraction of a crystalline aggregate close to 'y' in composition, an aggregate rich in quartz. Since quartz is not observed in these rocks, other factors than simple crystal fractionation are assumed to be operative.

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[1] Tilley and Harwood, 1931, p. 466.

Figures 4.11 to 4.13 show that the chemistry of 'B' series is intermediate in many respects to that of 'A' and 'C'. This suggests that formation of the trachyandesite-trachyte rocks may have been influenced to some degree by lime assimilation. Also Tilley and Harwood (1931, p. 465) note that lime assimilation leads to marked increase in titanium and aluminum content of lime-rich pyroxene. It has already been pointed out (Section C, Chapter IV) that the pyroxenes of the trachyandesites-trachytes of this study are enriched in titanium and aluminium.

Subtraction diagram Figure 5.4 shows the derivation of 'b', average trachyandesite-trachyte, from hypothetical lime-contaminated average andesite 'A_{1-4}''. Unlike crystalline aggregate 'y' of Figure 5.3, aggregate 'y''contains no quartz and is a mixture of potassic feldspar, plagioclase, and augite, minerals which are observed in the rocks. Thus a process of lime assimilation combined with crystal fractionation appears responsible for formation of the trachyandesite-trachyte rocks.

It should be pointed out that there is no evidence that lime assimilation actually leads to lime enriched compositions such as 'A_{1-4}''. This is not surprising in view of the refractory nature of lime in silicate melts[1]. Addition of new lime by assimilation would increase crystallization and precipitation of lime silicates and would tend to drive 'A_{1-4}' toward 'b' composition. However, it is believed that this transition is achieved not solely by lime assimilation but also normal cooling of the magma.

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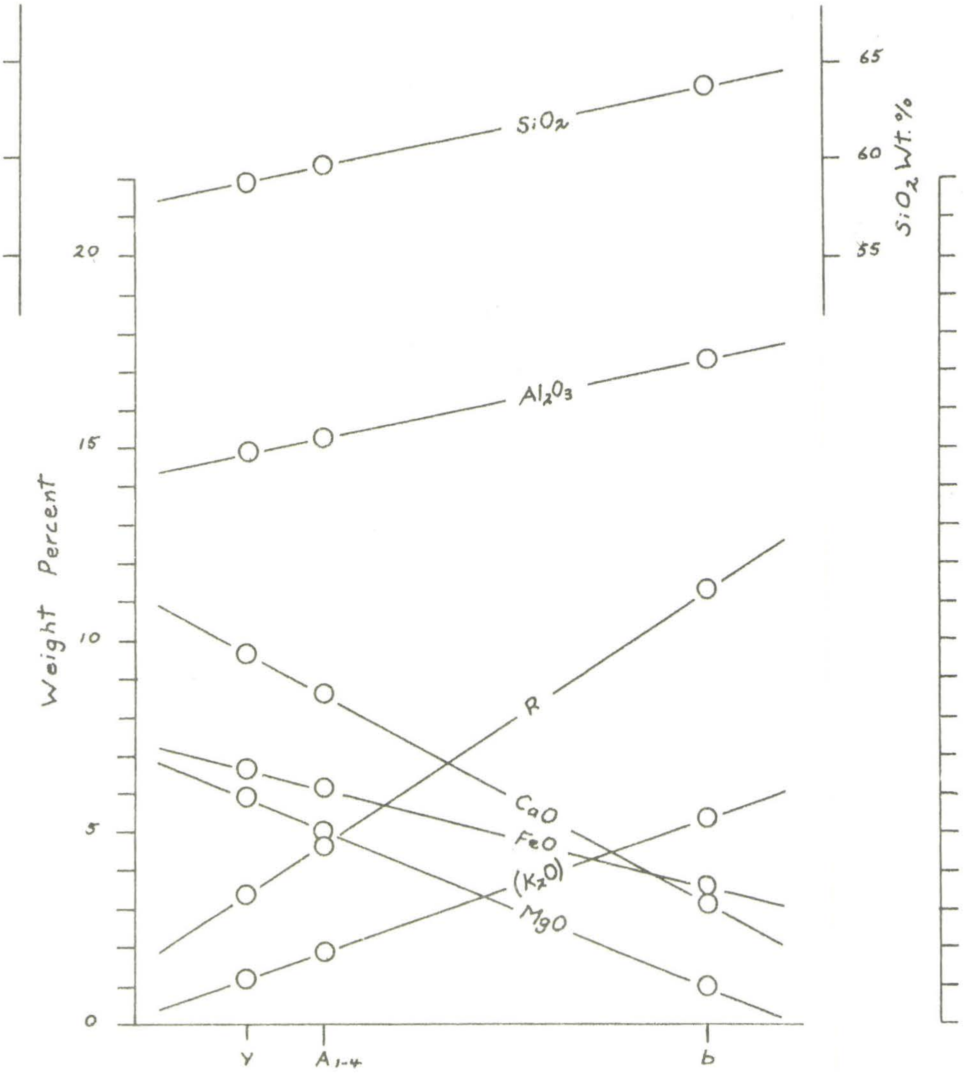
[1] Thornton and Tuttle, 1960.

Figure 5.3 Subtraction Diagram for 'B' Series Assuming Crystal Fractionation



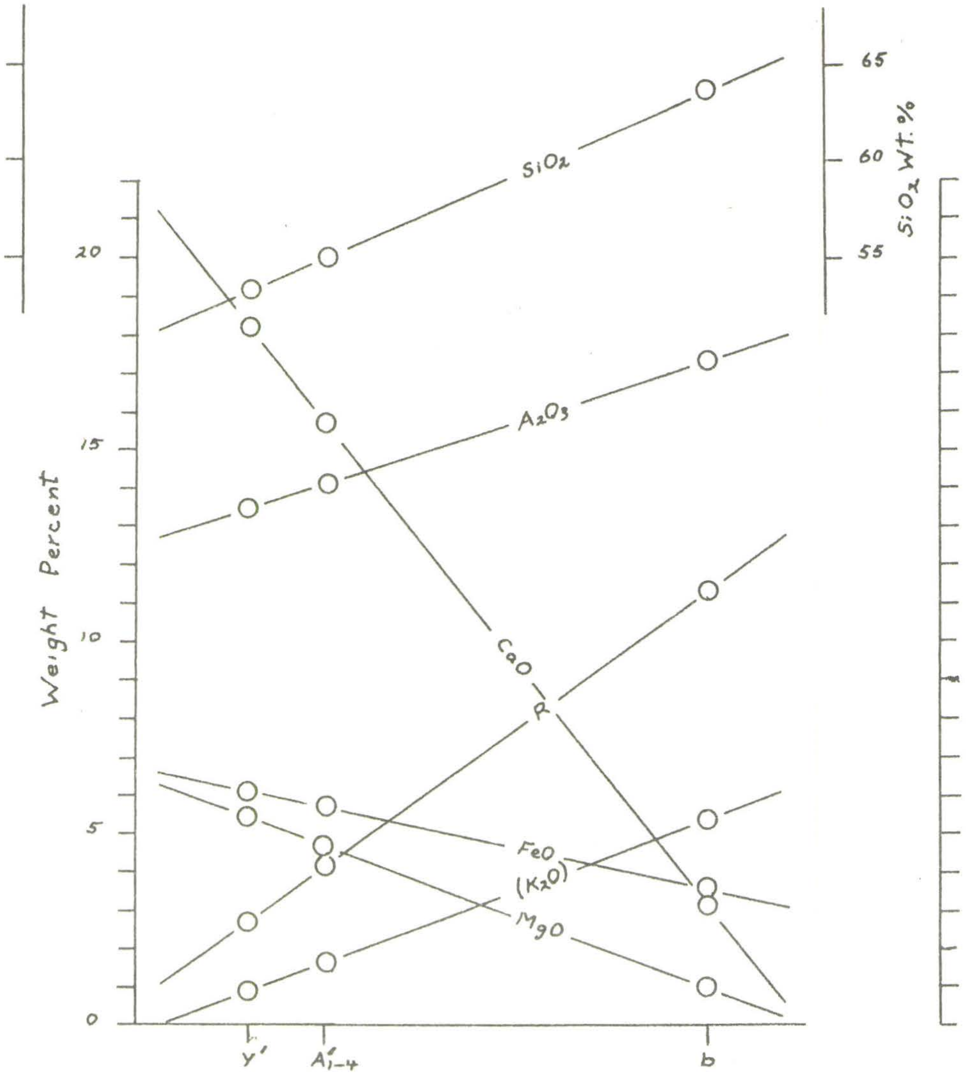
Legend:

R = total alkalies ($Na_2O + K_2O$)
A_{1-4} = average of four andesites (see Appendix 'D')
b = average of four trachyandesites-trachytes (see Appendix 'H')
y = subtractive composition (see Table 5.3)

The K_2O curve is hypothetical; value for 'A_{1-4}' is the same as in Figure 5.3; for 'b', K_2O is based on Na_2O/K_2O ratio given for pulaskite 1010, Daly (1912).

See Appendix 'D' for rock compositions and averages.

Figure 5.4 Subtraction Diagram for 'B' Series
Assuming Lime Assimilation



Legend:

R = total alkalies ($Na_2O + K_2O$)
A'_{1-4} = average of four andesites with added lime (see Appendix D)
b = average of four trachyandesites-trachytes (see Appendix H)
y = subtractive composition (see Table 5.3)

Curves are modified from those of Figure 5.3 on the basis added lime to 'A_{1-4}' and 'y' (see Table 5.3).

Table 5.3 Crystalline Aggregates 'y' and 'y''

(Wt.%)

	'y'		'y''	
SiO_2	58.9		53.3	
Al_2O_3	14.9		13.5	
FeO	6.7		6.1	
MgO	6.0		5.4	
CaO	9.7		18.3	
Na_2O	2.8	3.8	2.5	3.4
K_2O	1.0		0.9	

Equiv. Crystalline Aggregates

	'y'	'y''
Or	5.9	5.3
Ab	23.7	21.4
An	21.2	11.0
Cpx(a)	26.3	(b) 62.3
En	6.4	-
Fs	7.2	-
Qtz	9.3	-

Pyroxene Compositions

	a	b
SiO_2	50.2	48.8
Al_2O_3	5.6	7.0
FeO	10.6	9.7
MgO	12.9	8.7
CaO	20.6	25.8

Calculations:

Normative quartz in 'y' is converted to wollastonite by addition of lime (8.6% increase). Total wollastonite, enstatite (En), and ferrosilite (Fs) are calculated as clinopyroxene (Cpx) b in 'y''.

Cpx (a) is the average of six pyroxenes analysed in this study $Wo_{44}En_{38}Fs_{18}$. (See Table 4.4)

3. Strontium and Barium Evidence

Unusual high strontium and barium content of shackanite suggests a possible relation between lime assimilation and magmatic enrichment in these elements. Daly (1912) shows that shackanite from the Midway area contains 0.42% SrO (3600 ppm. Sr) and 0.36% BaO (3200 ppm. Ba). Spectrochemical analysis (this study) of shackanite sample CC-1 from the Marron area shows 3100 ppm. Sr and 5500 ppm. Ba. It is also interesting that a few trachyandesite rocks contain moderately high strontium and barium (see Figures 4.11 to 4.13).

In his study of the alkali volcanics of Southwestern Uganda, Higazy (1954), reviews the adequacy of the limestone assimilation hypothesis in explaining, among other peculiarities, the high strontium and barium content of these rocks. Analyses of local limestones shows low strontium and barium (average limestone, 150 ppm. Sr and < 5 ppm. Ba)[1] and, generally, marked empoverishment in minor elements. It seemed obvious that significant amounts of strontium and barium could not be gained by simple addition of limestone to the magma. However, Higazy did not consider the possibility of enrichment that could result if assimilation caused preferential precipitation of silicate minerals.

As described in the previous section, Daly, as well as Tilley and Harwood, regarded crystallization and precipitation of lime-rich pyroxene an important step in the lime-assimilation hybridization process. It has been shown (Chapter IV, Section C) that the pyroxenes of this study contain small amounts of strontium and barium. Thus it

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[1] Turekian and Wedepohl, 1961, give 610 ppm. Sr and 10 ppm. Ba for average sedimentary carbonate rocks.

might be expected that excessive precipitation of pyroxene would cause strontium and barium enrichment. Comparison of crystalline aggregates 'x' (for 'A' series) and 'y'' (for 'B' series) in Tables 5.1 and 5.3, respectively, shows a slightly higher pyroxene content in 'y'' (62.3%) than 'x' (56.4%). This may account for the generally higher strontium and barium content of 'B' series compared to 'A' series (see Tables 4.11 to 4.13).

It is interesting that 'B' series shows a marked decrease in strontium and barium in the acid rocks (see Figure 4.12). For example trachyte 20-C12 contains only 25 ppm. Sr and 100 ppm. Ba. Oftedal (1958) has noted a similar relation in the igneous complex of the Oslo region, Norway. The rocks of the Oslo complex carry abundant strontium and barium except the rock type termed ekerite (a type of alkaline granite). Oftedal has concluded that magmatic differentiation leads to depletion of strontium and barium from the parent magma and that strontium - barium poor ekerite represents a late stage residual magma. In view of the relatively high strontium and barium content of alkali-feldspar (see Chapter IV, Section E) and the abundance of this mineral in the acid rocks of 'B' series, it seems likely that crystal fractionation of this mineral may be responsible for the strontium and barium depletion in 'B' series.

Summary and Conclusions

The early Tertiary lavas of the Kettle River region are mainly intermediate in composition but range from semi-basic to acid types.

Petrological evidence points to a three-fold division of the lavas (termed 'A', 'B', and 'C' series):

'A' is a silica enrichment series showing a regular mineral and chemical progression from andesites to latite and rhyolite. The most basic rocks contain hornblende or augite and calcic plagioclase while the more acid rocks are rich in quartz, sodic plagioclase, alkali-feldspar, and biotite. Chemical variations are similar to rocks of the so-called calc-alkali magma trend.

Unlike 'A' series, 'B' is characterized by an abundance of two-feldspar lavas, trachyandesites and trachyte[1]. These pass into one-feldspar rocks, alkali-feldspar rich trachyte. Augite is the dominant ferromagnesian mineral in this series and biotite is usually accessory. Quartz or feldspathoids are not observed. 'B' shows relatively lower silica and higher iron oxide content than 'A' series and is similar in this respect to the so-called tholeiitic magma trend. However, unlike normal tholeiitic rocks, 'B' series is rich in alkalies.

Shackanite, of the 'C' series, is an unusual undersaturated lava occurring only in a few places in the Kettle River region. Like trachyte, it contains abundant alkali-feldspar; however, it is also

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[1] Only rhyolite in 'A' series contains two coexisting feldspars.

rich in analcite. Chemically, shackanite is distinguished by low silica, high iron, and high alkali content, and marked enrichment in strontium and barium. Although shackanite bears some resemblance to rocks in 'B' series, it is a mineralogical and chemical extreme case probably belonging to a semi-basic alkali trend ('C' series).

Two processes are envisaged as probably responsible for the origin and diversity of the lavas: crystal fractionation and lime assimilation.

The rocks of 'A' series have probably been formed by crystal fractionation. This is best illustrated by use of the subtraction diagram method. It is shown that removal (probably by crystal precipitation) or hornblende or an aggregate of augite and plagioclase, similar to the actual mineralogy of the rocks, could produce some of the andesites and latite of 'A' series. Generally, the chemical variations in this series are regular and the process of crystal fractionation seems an adequate explanation for most of the rocks.

The origin of the rocks of 'B' and 'C' series is explained, in part, by the lime-assimilation theory. It is thought that assimilation of lime may result in precipitation of calcic pyroxene, a mineral common to these rocks. This would explain some of the chemical features of 'B' and 'C' series, such as the relatively low silica content, high alumina, alkalies, and iron to magnesium ratios as well as the high strontium and barium content. An adequate supply of lime seems assured by the local abundance of limestone in the Kettle River region.

In accordance with the views held by Daly, lime assimilation is not incompatible with the process of magmatic differentiation, but instead, acts in conjunction with this mechanism perhaps to enhance the evolutionary processes.

APPENDIX 'A' Early Tertiary Stratigraphy of the Midway, Marron, and Kelowna Areas and Regional Correlation

1. Midway Sequence

In the Midway area the lowermost Tertiary beds were named the Kettle River formation by Daly (1912). A columnar section worked out by Daly piecing together several incomplete small sections is reproduced as follows:

Columnar section of the Kettle River formation

Top, conformable contact with overlying Midway lavas.

1000 feet	- fossiliferous, gray, feldspathic sandstones with interbeds of shale.
900 "	coarse conglomerate.
200 "	coarse arkose-breccia (a local deposit).
2100 "	

Base, unconformable contact with underlying Anarchist series (Paleozoic) and with pre-Tertiary plutonic intrusives.

Recently, however, Little (1957) has remapped the area and redefined part of Daly's upper 'sandstone' unit, which crops out along the Kettle River, as intervolcanic rather than basal sediment. With this modification, Daly's Kettle River formation is split into two parts - a basal part composed of 1200 feet of breccia, conglomerate, and sandstone, exposed along Rock Creek canyon, and an upper part of 900 feet of shale and sandstone lying between a series of 'lower' and 'upper' Midway lavas and exposed along the Kettle River. The lavas together with this intermediate sedimentary unit are known as the Midway Volcanic group.

Plant fossil dating and potassium-argon determinations by Rouse and Mathews (1961) indicates an Eocene age for the intermediate sediments. An exact date of 49 x 10^{-6} years has been arrived at using the latter method.

The lavas of the Midway Volcanic group represent two volcanic epochs in this area. According to Daly, the oldest lavas are augite andesites and olivine basalts.[1.] These are followed by a group of hornblende, augite, and biotite andesites. The youngest lavas (overlying the intermediate sediments) consist of shackanite flows (analcite rhomb-porphyry) and alkaline trachyte. Shackanite 1064, described and analysed by Daly, is uppermost of the youngest lavas and pulaskite 1010, also examined by Daly, is a feeder dike to the trachyte flows.

Comparing the Tertiary volcanics in the Beaverdell area with those near Midway, Reinecke (1915, p. 60) points out:

"Geographically they may be said to be practically coextensive for the Midway series is found for 15 miles north of Midway, that is, not over 15 miles south of the Beaverdell area."

Further similarity is suggested (p. 60):

"The time of their extrusion was in both cases shortly after the formation of a series of breccias, conglomerates, sandstones, and tuffs."

The total thickness of the volcanic series exposed on Nipple mountain is approximately 4500 feet.

[1.] Olivine basalt was not observed among the early Tertiary flows during the course of this study.

The Tertiary strata in the Midway area has been folded into a broad, open, northerly trending and shallow plunging synclinal structure. The strata on the west limb of the syncline have been considerably dissected by steeply inclined north-south faults; the east limb, however, remains intact.

A summary of the stratigraphic data is given in Table A.1.

2. Marron Sequence

In the Marron area the lowermost Tertiary beds are collectively known as the Springbrook formation. According to Bostock (1928) the Springbrook is composed of an assortment of soils, alluvium, talus, stream and lake deposits and some tuffaceous material. These beds grade upward from a coarse angular conglomerate into a conglomerate composed of smaller, more rounded, and better sorted fragments. The uppermost strata are composed mostly of sandstones and white tuffaceous silts. On the basis of plant fossils the Springbrook is dated as possible Paleocene age.

The Springbrook sediments are overlain by, and to some extent, interlayered with the Marron formation which consists of a thick sequence of mostly andesitic and trachytic lavas. The unusual shackanite lava, described by Daly as occurring at the top of the succession at Midway, is found near the base of the Marron formation. Flows range from 10 to 100 feet in thickness and are separated by occasional thin interlayers of shaly sediments.

The White Lake formation was deposited conformably on the Marron lavas. According to Camsell (1913, p. 249) the sediments are divisible into three lithological parts:

Table A.1 Formations of the Midway Sequence

Stratig. Unit	Section Location	Thickness	Composition	Structure
upper lavas of the Midway Volc. grp.	-north of the Kettle R. between Rock Ck. and Midway	600'	-largely shackanite, trachyte and trachyandesite flows	-tilted to S.E.
intermediate seds. of the Midway Volc. grp.	-4 mi. west and 2 mi. north of Midway	900'	-fossiliferous feldspathic s.s., shl., and tuffs cut by pulaskite dikes	-tilted to S.E. as above
lower lavas of the Midway Volc. grp.	-Kettle R. valley west from Midway to Myers Ck.	3000'	-andesite flows	-folded into a broad northerly trending syncline
Kettle River fm.	-Rock Ck. canyon	1200'	-upper 100' mostly s.s.; lower part mostly granite pebble conglomerate and other pre-Tertiary fragments	-faulted and tilted in west limb of syncline

"The lowest third of the section contains a preponderance of black and gray shales with a minor amount of sandstone. The shales are associated in places with thin seams of coal. The middle third of the section contains chiefly sandstone with some bands of gray shale. The uppermost third consists wholly of tuffaceous sandstones."

Camsell continues (p. 250):

"The sandstones are all grey in colour and vary in the coarseness and angularity from the east to the west side of the area. On the west they are very angular, showing a proximity to their original source."

McEvoy (1914) has elaborated on Camsell's description and gives the thickness of the sediments as 1000 feet.

Plant remains collected from these sediments by Bostock (1928) indicate a probable Eocene age.

The White Lake formation is overlain disconformably by an upper volcanic deposit consisting of lavas and some breccias. This in turn is followed by flat lying beds of agglomerate composed, in large part, of accidental fragments of the pre-Tertiary substratum. Bostock identified this latter unit as conglomerate failing to recognize the volcanic attributes of this rock.

The Tertiary strata of the Marron valley are folded into an open syncline. To the north and south of White Lake folding has been most severe and dips up to 60 degrees have been recorded. In this same area the synclinal axis plunges approximately 25 degrees to the east. The whole Tertiary basin is part of a down-faulted block. Both normal and strike slip faulting occurs to some extent within the basin.

Table A.2 summarizes the stratigraphic data for the Marron sequence.

3. Kelowna Sequence

Unlike the Marron and Midway areas, which were mapped in detail by Bostock and Daly respectively, a precise account of the Tertiary rocks in the Kelowna area is not available in the literature. However, using the reconnaissance map provided by Cairnes (1936) in conjunction with data gathered for the present study, it is possible to determine the local stratigraphic succession.

As in the Marron valley and at Midway, the volcanics of the Kelowna area are divisible into upper and lower sequences. The lower volcanics crop out on the high ridges and hills immediately opposite the Town of Kelowna on the west side of Okanagan Lake; whereas, the upper volcanics constitute the bulk of Mt. Boucherie, five miles south-west of Kelowna.

The lower volcanics are composed of approximately 2500 feet of gently dipping, light colored trachyte and trachyandesite flows. Some shale and pyroclastic beds are intercalated with the flows but are of minor importance. This formation rests with some angular unconformity on south-easterly dipping basal Tertiary sediments. These lowermost beds are similar to the Springbrook and Kettle River formations, in that, they contain granite pebble conglomerates and clastic rocks rich in other pre-Tertiary fragments. Well preserved leaves have been found in this sediment and are dated as Paleocene or Eocene by Little (1961).

The upper volcanics consist of close to 1000 feet of vesicular latite flows and a few breccias. These lavas are approximately flat lying and rest conformably on a series of conglomerates,

Table A.2 Formations of the Marron Sequence

Stratig. Unit	Section Location	Thickness	Composition	Structure
upper volcanic rocks (unnamed)	-eastern extremity of Marron valley, S.W. of Okanagan Falls	500'	-coarse volcanic ejecta, mostly accidental fragments of pre-Tertiary rocks	-flat lying strata
upper volcanic rocks (unnamed)	-main exposure is immediately west of above rocks	500'	-trachyandesite lavas and cognate volcanic ejecta	-tilted easterly
White Lake fm.	-strata immediately north, west, and south of White Lake	1000'	-predominantly silts and sandstones containing fragments of underlying Marron lavas; also coal seams	-folded into a gently plunging (to the east) syncline
Marron fm.	-central and western part of Marron valley	2500'	-mainly andesite and trachyandesite flows; minor intercalated carbonaceous shales near the top of the formation; shackanite lava near the base	-conformable with above
Springbrook fm.	-exposed at western extremity of Marron valley	?	-conglomerate and sandstone containing fragments of the underlying pre-Tertiary complex	-unconformably overlying the pre-Tertiary complex

sandstones, and shales. Abundant fragments of trachyte in this sediment indicate that they were derived, at least in part, from erosion of the lower volcanic rocks.

Non-porphyritic basalt and olivine basalt are among the youngest rocks in the area. Basalt flows form thin horizontal cappings 100 to 200 feet thick on some of the local hills and dikes of similar composition cut both upper and lower volcanic phases and related sediments. According to Little (1957),

"These basic lavas are correlated with those of the Columbia Plateau and are probably of Miocene age."

The basalts are not considered as part of the early Tertiary lithologic assemblage and are used in this study only for comparative purposes.

Structurally, the Tertiary rocks have not been greatly disturbed by folding but a certain amount of important faulting is present. According to Cairnes (1936),

"The Tertiary strata are intersected by many vertical faults striking in various directions but in most cases northerly and with the downthrow in most instances on the east."

Down-faulting of the type described by Cairnes appears to have been active along the northeast trending valley that separates Mt. Boucherie from the ridges to the west. This faulting has lowered the strata of Mt. Boucherie such that the upper volcanic rocks and sediments are juxtaposed with the lower volcanic rocks and basal sediments across the valley. Unfortunately, a thick deposit of glacial drift on the valley floor has obscured any direct evidence of faulting. Nevertheless, the composition of the volcanic rocks and sediments are distinctive enough to assume dislocation.

A summarized description of the Tertiary rocks is given in Table A.3.

4. Regional Correlation

The scattered remnants of Tertiary strata in the regions lying immediately west[1.], northwest[2.], and north[3.] of the Kettle River map-area have been tentatively correlated, by the most recent work, with the Tertiary section near Kamloops described by Dawson (1895).

Dawson divided the Tertiary volcanic rocks of the Kamloops area into two groups, a Lower Volcanic group and an Upper Volcanic group. These groups comprised a considerable thickness of rhyolites, trachytes, andesites, and basalts together with feldspar porphyrys, but the rocks are very largely composed of basalt and basalt breccias. This material plus a thick intermediate horizon of sediments, the Tranquille beds, have been termed the Kamloops Volcanic group by Drysdale (1914).

The lowermost Tertiary strata in this area are known as the Coldwater beds. This formation lies conformably below the volcanic rocks and consists of sandstone and shale together with large amounts of conglomerate containing pebbles of pre-Tertiary rocks.

Information provided by Dawson indicates a thickness of 5300 feet for the Kamloops Volcanic group at Kamloops Lake. This includes the Tranquille beds but does not take into account about 1000 feet of section represented by the Coldwater group.

In addition to this, the younger Plateau basalt formation is

[1.] H.M.A. Rice (1947) Geol. Survey of Canada, Mem. 243.

[2.] W.E. Cockfield (1948) Geol. Survey of Canada, Mem. 249.

[3.] A.G. Jones (1959) Geol. Survey of Canada, Mem. 296.

Table A.3 Formations of the Kelowna Sequence

Stratig. Unit	Section Location	Thickness	Composition	Structure
Plateau basalt fm.	-on crest of ridge 7 mi. due west of Kelowna	200'	-columnar basalt often containing abundant olivine	-flat lying
upper lavas (unnamed)	-forming Mt. Boucherie	1000'	-vesicular latite flows with a little intercalated breccia and pyroclastics; cut by basalt dikes	-flat lying almost
intermediate seds. (unnamed)	-underlying Mt. Boucherie	?	-similar to White Lake sediments; mostly s.s. and congl. with fragments of lower flows and a few seams of coal	-conformable with above rocks
lower lavas (unnamed)	-forming ridge immediately N.W. of Mt. Boucherie	2500'	-predominantly trachyte and trachyandesite flows with a few thin intercalated beds of shale and pyroclastics	-tilted gently to S.E., probably less than 5°
basal seds. (unnamed)	-west of Mt. Boucherie at the base of the hills	?	-abundant granitic and pre-Tertiary pebbles	-tilted to S.E. about 15°; unconformable on pre-Tertiary complex

present throughout the area. This lava is everywhere flat lying and rests unconformably on the early Tertiary rocks.

The most recent and specific age determination for the Kamloops succession has been carried out by Rouse and Mathews (1961) on a trachyte flow from the Upper Volcanics on Savona mountain situated immediately south of Kamloops Lake. Using potassium-argon methods a date of 45×10^{-6} years has been obtained.

In conclusion, the divisions of the Tertiary strata at Kamloops and in the Kettle River region are very similar; a basal conglomerate followed by two volcanic sequences and intervening sediments, and an uppermost horizontal basalt capping. The remarkable similarity of K-Ar dates at Kamloops and Midway, 45×10^{-6} and 49×10^{-6} years respectively, is taken as good evidence of contemporaneous volcanic eruption in these areas and perhaps throughout south-central British Columbia. This evidence is supported by a third K-Ar date of 48×10^{-6} years, by the same authors, for a volcanic ash bed in the Princeton area, approximately 80 miles west by northwest of Midway.

APPENDIX 'B' Sampling Procedure

The sampling procedure in the field has been influenced to some extent by access, exposure conditions, and the amount of time available for collecting. The Tertiary lavas in the Midway, Marron, and Kelowna areas are readily accessable and well exposed.

In the Midway area the sampling program was guided to a large extent by geological maps and descriptions provided by Daly (1912), Reinecke (1915), Little (1957), and Little (1959, personal communication). A total of 14 lava samples was selected from a more comprehensive collection of 43 samples, to represent the volcanic succession in this area. Twelve of these samples were taken at approximatley equal spacing across the east limb of the Midway syncline representing an estimated 3000 feet of 'lower' lavas. The remaining two samples were taken from a mountain due north of the Kettle River bridge situated six miles north-west of the town of Midway. These latter samples represent the 'upper' lavas in the sequence, approximately 600 feet thick, which overlie the intermediate sediments, about 900 feet thick, and the 'lower' lavas. The sampling interval across the strata is calculated as roughly 250 feet (only the lava was sampled).

From information gathered by Bostock (1928), Cairnes (1936), and McEvoy (1914), it was deduced that close to 4500 feet of volcanics and early Tertiary sediments were deposited in the Marron area. Approximately 1000 feet of this thickness represents the White Lake formation. The uppermost volcanic beds were not sampled because of the absence of lava flows and the predominance of accidental volcanic ejecta. A total of 11 samples of lava were collected at regular intervals across the section, each sample representing roughly 250 feet of lava.

In the Kelowna area a total of 14 samples have been selected from a general suite of 78 samples as representative of the lavas. As in the Midway and Marron areas, the early Tertiary volcanic succession is divided into a lower and an upper phase which are separated by a thick intermediate sedimentary unit. Of the total measured thickness of volcanic rocks (approximately 3500 feet) the lower volcanic phase constitutes slightly more than 2500 feet. A total of 10 samples were collected from this lower phase on a ridge situated about six miles due west of the town of Kelowna. The remaining four samples belong to the upper phase which is slightly less than 1000 feet thick. These were taken from a section on Mt. Boucherie four miles southwest of Kelowna. The approximate sampling interval across the strata is 250 feet, roughly the same as for the Midway and Marron areas.

Sample distribution maps for the three areas are given in Figures B.1, B.2, and B.3 .

Individual samples were selected in a manner recommended by Grout (1932). Since the lava is fine grained and often glassy, a single lump of fresh rock is considered sufficient for thin section and chemical analysis. The average weight of a lump sample taken for this study is in excess of one pound.

Figure B.1 Sample Distribution Map for the Midway Area

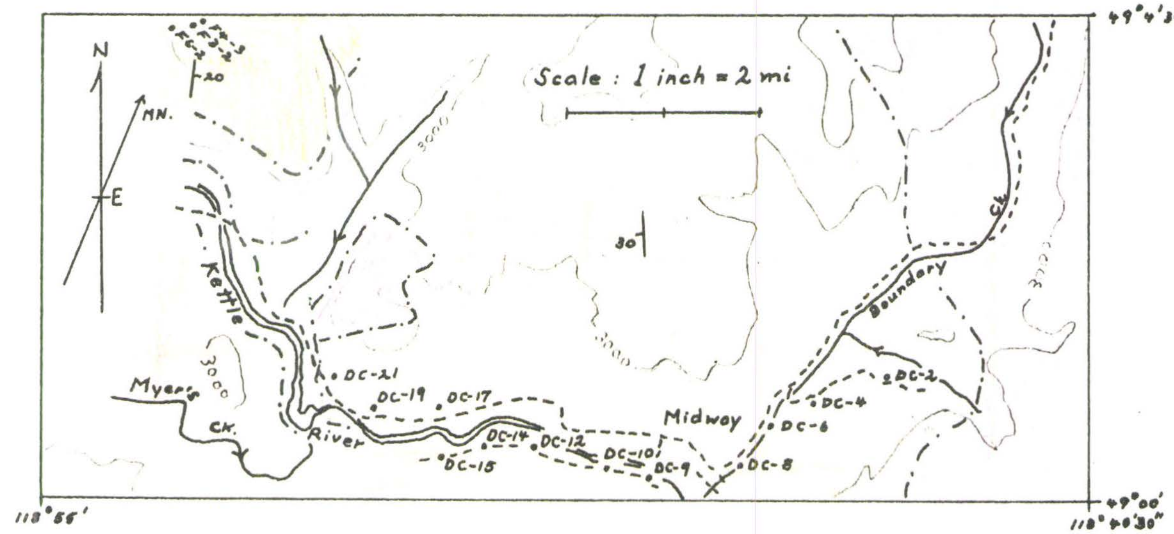
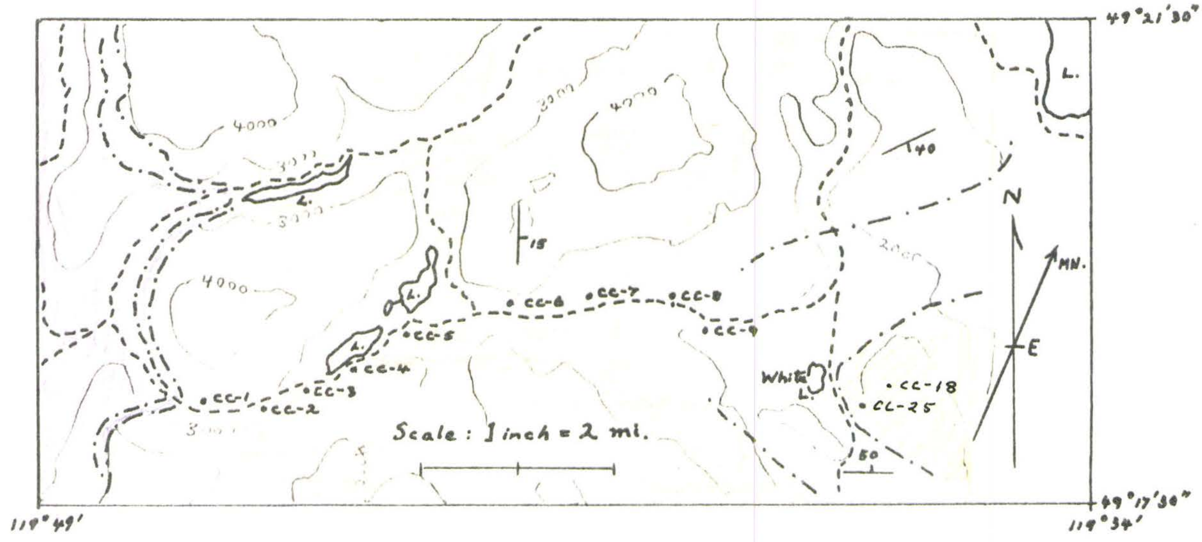
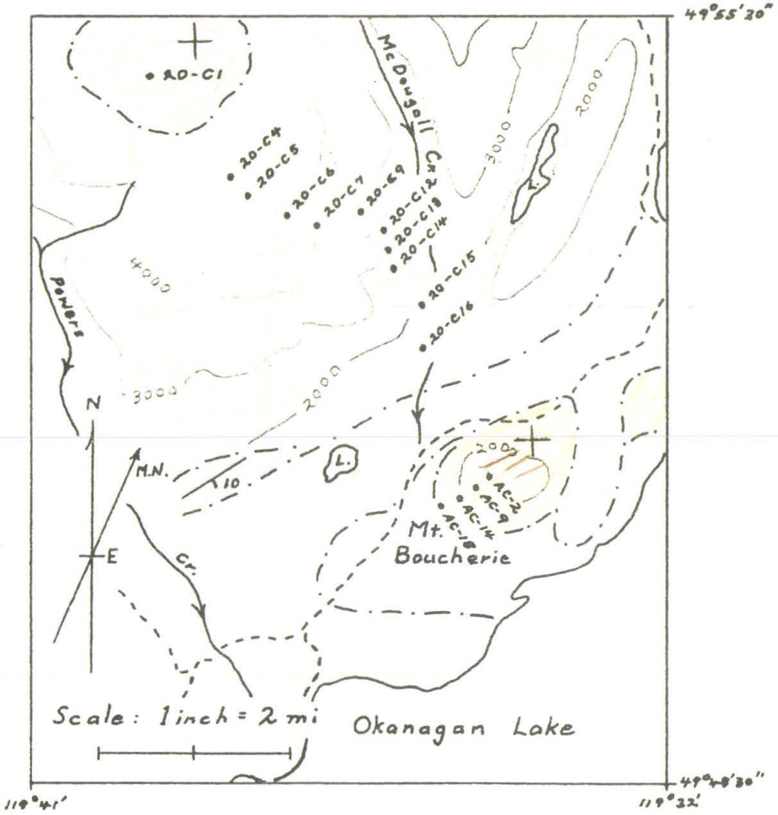


Figure B.2 Sample Distribution Map for the Marron Area



(see Figure B.3 for legend)

Figure B.3 Sample Distribution Map for the Kelowna Area



Legend

- ▭ Recent Alluvium
- ▭ Plateau Basalts
- Early Tertiary
  - ▭ Upper Volcanics
  - ▭ Intermediate Seds.
  - ▭ Lower Volcanics
  - ▭ Basal Sediments
- ▭ Pre-Tertiary Complex
- 10 Strike and Dip of Bedding
- \+ Horizontal Bedding
- Formational Contact
- L. Lake
- Stream
- Road
- 3000 Surface Contour (1,000' interval)

APPENDIX 'C' Spectrochemical Parameters for the 'La' Method

Spectrograph	JACO 21-foot grating, ARL arc-spark stand, first order dispersion 5Å/mm.
Condensing optics	25cm. focal length cylindrical lens (horizontal axis) at the slit. 6.7cm. focal length cylindrical lens (verticle axis) 16.1cm. from the slit. Diaphragm with 5mm. aperature 27.5cm. from the slit.
Slit width	30 microns
Intensity control	7-step sector at the slit, log intensity ratio 0.2; 1 screen.
Slit length	25mm.; sector height adjusted for steps 3, 4, and 5.
Electrodes	National Carbon Co. graphite (Special): sample (anode), 1/8'' rod, plain crater 1/16" x 3/8"; counter electrode, 1/8" rod.
Emulsion and range	Eastman Kodak Type III-F plates; 3900-5200 Å.
Processing	3 minutes development in D19 developer at 20 C. 15 seconds in stop-bath; 20 minutes acid fix; 20 minutes wash.
Voltage	225 V.D.C. on open-circuit.
Exposure	Completion, 70 to 80 seconds.
Current	Start at 3 and raised to 6 amperes.
Air-jet	8 units of flow
Water cooling system	5 units of flow
Sample	1 part rock powder to 9 parts graphite powder; 1 part mineral powder to 2 parts graphite powder; La_2O_3 0.5% and KCl 5.0% in graphite.
Artificial standards	Prepared from Johnson-Matthey "Specpure" compounds; matrix consisted of SiO_2, 60%: Al_2O_3, 20%: KCl, 10%: Fe_2O_3, 5%: $CaCO_3$, 5%: $BaCO_3$ and $SrCO_3$ were added and standards

	prepared by dilution to the following concentrations: 125, 250, 500, 625, 1250, 2500, and 5000ppm. Sr and Ba.
Natural standards	Granite G-1, total Fe as FeO, 1.83%; MgO, 0.39%; CaO, 1.4%; diabase W-1, total Fe as FeO, 10.05%; MgO, 6.6%; and CaO, 11.0%; gabbro I-60-114, CaO, 10.35%; pyroxene Q-3, total Fe as FeO, 17.79%; MgO, 6.77%; hornblende I-60-115, total Fe as FeO, 10.77%; MgO, 16.36%.
Photometry	Galvanometer readings between 1.0 and 95 were used (ARL photodensitometer); background adjusted to 100 for each reading except for weak lines where a background correction was made.
Spectral lines	Ca 4302.53 A, excitation potential 4.78 volts Fe 4325.77 " " 4.47 " Sr 4607.33 " " 2.69 " La 4920.97 " " 2.64 " Ba 4934.09 " " 2.51 " Mg 5167.34 " " 5.11 "
Plate calibration	Calibration curves were drawn using a modified two-step method.

APPENDIX 'D'

Analytical Results

Table D.1 Spectrochemical Results for Twenty Lava Samples

Sample Number	R.I.	FeO	MgO	CaO	Sr	Ba	Sr/Ba
20-C1	1.602	10.6%	12.0%	9.80%	760ppm.	490ppm.	1.55
DC-10	1.555	6.80	6.00	10.0	1300	1450	0.90
DC-21	1.551	6.20	5.20	7.20	840	1200	0.70
DC-4	1.540	6.00	4.90	8.60	1150	2100	0.55
DC-2	1.539	4.90	3.65	7.70	860	1400	0.61
DC-12	1.538	5.20	4.90	6.20	1500	1700	0.88
CC-7	1.538	4.81	3.30	6.40	1300	1400	0.93
CC-1	1.532	4.30	2.40	4.20	3100	5500	0.56
20-C9	1.531	4.30	1.80	2.80	760	2000	0.38
CC-6	1.529	5.20	3.30	6.20	1650	2600	0.64
F3-2	1.523	4.60	2.50	3.80	1150	2100	0.55
20-C5	1.523	3.30	0.79	3.30	1560	2200	0.71
20-C16	1.521	3.70	0.84	4.20	1650	2200	0.75
AC-18	1.520	3.45	1.80	4.10	420	1200	0.35
AC-9	1.518	3.70	1.45	3.80	350	1300	0.27
CC-5	1.517	3.70	1.50	3.90	1300	2500	0.52
20-C15	1.517	3.20	0.55	2.40	1200	1650	0.73
20-C13	1.509	3.75	1.50	1.80	325	520	0.63
20-C12	1.503	3.85	1.30	1.30	25	100	0.25
22-J1	1.497	1.96	0.45	1.40	1150	1300	0.89

(Total iron is determined as FeO)

Table D-2 Partial Rock Analyses

Sample No.	20-C1	DC-10	DC-21	DC-4	DC-2	CC-7	AC-18	20-C16	CC-5	20-C15
SiO_2	45.27	56.24	56.24	58.61	60.30	63.68	64.08	59.51	61.79	64.85
TiO_2	2.62	1.18	1.32	1.01	0.95	0.91	0.79	0.81	0.74	0.71
Al_2O_3	14.79	15.02	15.52	14.90	14.06	15.47	15.03	16.94	16.52	16.40
MnO	0.07	0.07	trace	0.02	0.04	0.07	0.03	0.04	0.05	0.03
FeO	10.60	6.80	6.20	6.00	4.90	4.81	3.45	3.70	3.78	3.20
MgO	12.00	6.00	5.20	4.90	3.65	3.30	1.80	0.84	1.50	0.55
CaO	9.80	10.00	7.20	8.60	7.70	6.40	4.10	4.20	3.90	2.40
SrO	0.10	0.15	0.10	0.14	0.11	0.15	0.05	0.20	0.15	0.14
BaO	0.06	0.17	0.13	0.23	0.16	0.16	0.13	0.25	0.28	0.19
P_2O_5	0.62	0.49	0.52	0.49	0.43	0.30	0.03	0.02	trace	0.02
H_2O	1.19	1.19	1.19	1.19	1.19	1.19	1.24	1.24	1.19	1.10
Total	97.12	97.31	93.62	96.09	93.49	96.44	90.73	87.75	89.82	89.59
Residual	2.88	2.69	6.38	3.91	6.51	3.56	9.27	12.25	10.18	10.41

Determinations of SiO_2, TiO_2, Al_2O_3, MnO, P_2O_5, and H_2O are by Dr. Ruschil and Mr. Chesworth using 'wet' chemical methods. FeO, MgO, CaO, SrO, and BaO were determined by the author using spectrochemical methods. The average H_2O values found for AC-18, 20-C16, CC-5, 20-C15, (1.19%) is applied to analyses 20-C1, DC-10, DC-21, DC-4, DC-2, and CC-7. The residual values represent the sum of $K_2O + Na_2O$, plus minor constituents not specifically determined, and the balance of the analytical error (However, it is assumed the residual represent largely total alkalies $K_2O + Na_2O$).

Table D-3 Major Element Composition of the Rocks

Series No.	A-1	A-2	A-3	A-4	A_{1-4}	A-6	A-7	'A' Series
Sample No.	DC-10	DC-21	DC-4	DC-2	average	CC-7	AC-18	average
SiO_2	58.13	58.14	60.47	62.09	59.71	65.50	65.57	61.65
Al_2O_3	15.52	16.04	15.37	14.48	15.35	15.91	15.38	15.45
FeO	7.03	6.41	6.19	5.05	6.17	4.95	3.53	5.53
MgO	6.20	5.38	5.06	3.76	5.10	3.39	1.84	4.27
CaO	10.34	7.44	8.87	7.93	8.64	6.58	4.20	7.56
Na_2O K_2O	2.78	6.59	4.04	6.69	5.03	3.67	9.48	5.54

Series No.	B-5	B-6	B-7	B-9	'B' Series	Sh_2
Sample No.	20-C16	CC-5	20-C15	1010	average	1064
SiO_2	61.07	63.32	66.30	63.81	63.62	57.04
Al_2O_3	17.39	16.93	16.77	18.13	17.30	21.05
FeO	3.80	3.79	3.27	3.45	3.58	5.50
MgO	0.86	1.54	0.56	1.02	1.00	2.02
CaO	4.31	4.00	2.45	1.80	3.14	4.84
Na_2O K_2O	12.57	10.42	10.65	4.86 6.93 } 11.79	11.36	6.95 2.62 } 9.55

Major element compositions are recalculated to 100 from data given in Table D.2 . Values for samples 1010 (pulaskite) and 1064 (shackanite) are Daly's (1912) results.

Table D.4 Sr and Ba Content of the Minerals

	Sr	Ba
Plagioclase		
DC-2	3500ppm.	1430ppm.
CC-7	4100	1950
DC-12	3450	700
AC-18	2150	970
Two Feldspar Mixtures		
20-C5	6900	5900
CC-5	5400	4100
20-C13	1650	1800
Alkali-Feldspar		
20-C12	305	345
Biotite		
20-C5	125	2000
Hornblende		
DC-10	355	350
Pyroxene		
DC-10	133	74
DC-2	125	75
CC-7	150	155
CC-6	215	62
F3-2	203	46
20-C5	215	125

APPENDIX 'E' List of Rock Samples

The rock samples used in this study are listed below with brief descriptions. They have been grouped according to rock types and arranged in order of refractive index of corresponding synthetically fused glass.

Field No.	Rock Type	R.I.	Location
20-C1	Olvine basalt	1.602	Kelowna area, Figure B.3
DC-10	(pyroxene) hornblende andesite	1.555	Midway area, Figure B.1
DC-21	hornblende andesite	1.551	Midway area, Figure B.1
DC-15	(pyroxene) hornblende andesite	1.537	Midway area, Figure B.1
DC-19	hornblende andesite	1.533	Midway area, Figure B.1
20-C6	pyroxene andesite	1.548	Kelowna area, Fig. B.3
DC-6	(biotite) pyroxene andesite	1.546	Midway area, Figure B.1
CC-8	pyroxene andesite	1.545	Marron area, Figure B.2
DC-14	pyroxene andesite	1.545	Midway area, Figure B.1
CC-9	(biotite) pyroxene andesite	1.545	Marron area, Figure B.2
DC-4	pyroxene andesite	1.540	Midway area, Figure B.1
DC-2	(biotite) pyroxene andesite	1.539	Midway area, Figure B.1
CC-7	(biotite) pyroxene andesite	1.538	Marron area, Figure B.2
DC-8	(biotite) pyroxene andesite	1.537	Midway area, Figure B.1
AC-2	pyroxene andesite	1.530	Kelowna area, Fig. B.3
CC-1	Shackanite (rhomb-porphyry)	1.532	Marron area, Figure B.2
CC-18	biotite andesite	1.541	Marron area, Figure B.2
DC-12	(pyroxene) biotite andesite	1.538	Midway area, Figure B.1
CC-3	(pyroxene) biotite andesite	1.536	Marron area, Figure B.2
DC-17	(pyroxene) biotite andesite	1.533	Midway area, Figure B.1
CC-2	biotite andesite	1.533	Marron area, Figure B.2
DC-9	biotite andesite	1.530	Midway area, Figure B.1
CC-25	biotite andesite	1.524	Marron area, Figure B.2
20-C14	biotite andesite	1.521	Kelowna area, Fig. B.3
CC-4	(pyroxene) biotite andesite	1.520	Marron area, Figure B.2
20-C9	pyroxene trachyandesite	1.531	Kelowna area, Fig. B.3
CC-6	pyroxene trachyandesite	1.529	Marron area, Figure B.2
F4-3	pyroxene trachyandesite	1.527	Midway area, Figure B.1
F3-2	pyroxene trachyandesite	1.523	Midway area, Figure B.1
20-C16	(biotite) pyroxene trachyandesite	1.521	Kelowna area, Fig. B.3
20-C7	biotite trachyandesite	1.525	Kelowna area, Figure B.3
20-C4	(pyroxene) biotite trachyandesite	1.524	Kelowna area, Fig. B.3
20-C5	(pyroxene) biotite trachyandesite	1.523	Kelowna area, Fig. B.3
CC-5	biotite trachyandesite	1.517	Marron area, Figure B.2
20-C15	(pyroxene) biotite trachyandesite	1.517	Kelowna area, Fig. B.3

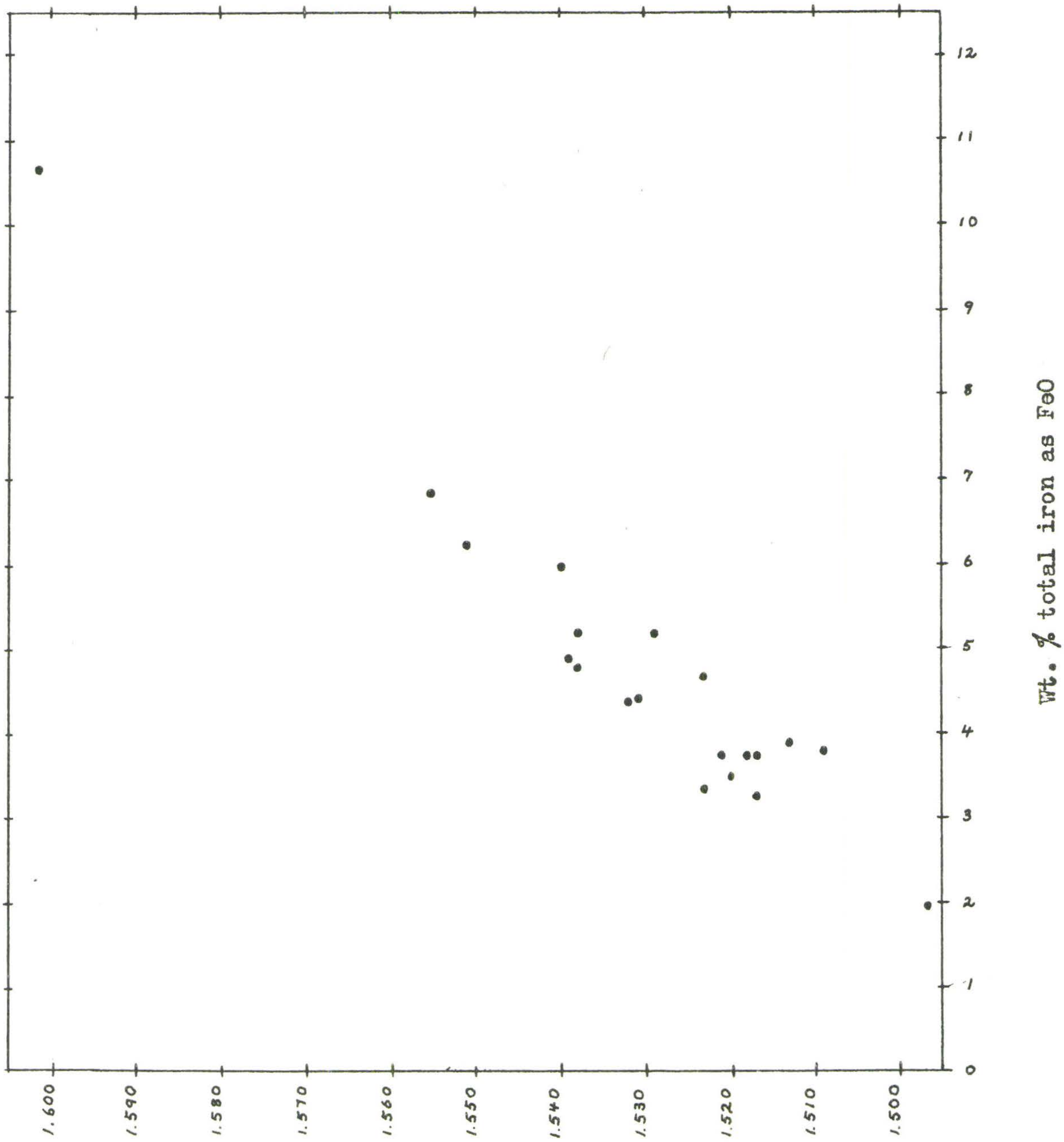
APPENDIX 'E' (cont'd)

Field No.	Rock Type	R.I.	Location
AC-14	latite	1.529	Kelowna area, Fig. B.3
AC-18	latite	1.520	Kelowna area, Fig. B.3
AC-9	latite	1.518	Kelowna area, Fig. B.3
F6-2	pyroxene trachyte	1.516	Midway area, Figure B.1
20-C13	(pyroxene) biotite trachyte	1.509	Kelowna area, Fig. B.3
20-C12	(pyroxene) biotite trachyte	1.503	Kelowna area, Fig. B.3
22-J1	biotite rhyolite	1.497	Kelowna area, see petrographic description

APPENDIX 'F'

Refractive Index vs. Composition Plots

Figure F.1 Refractive Index of Fused Rock versus FeO content



Refractive Index

Figure F.2 Refractive Index of Fused Rock versus MgO content

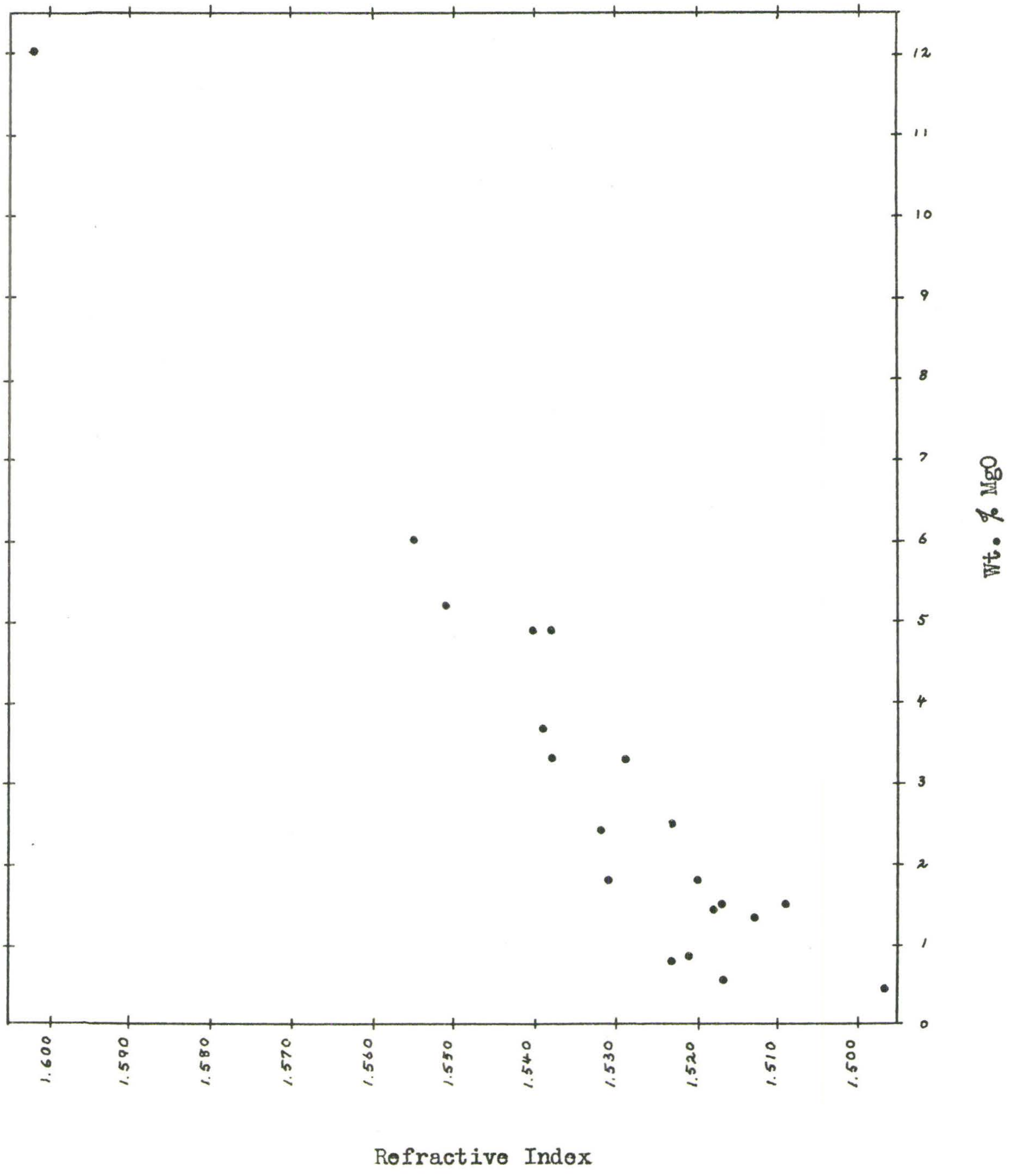
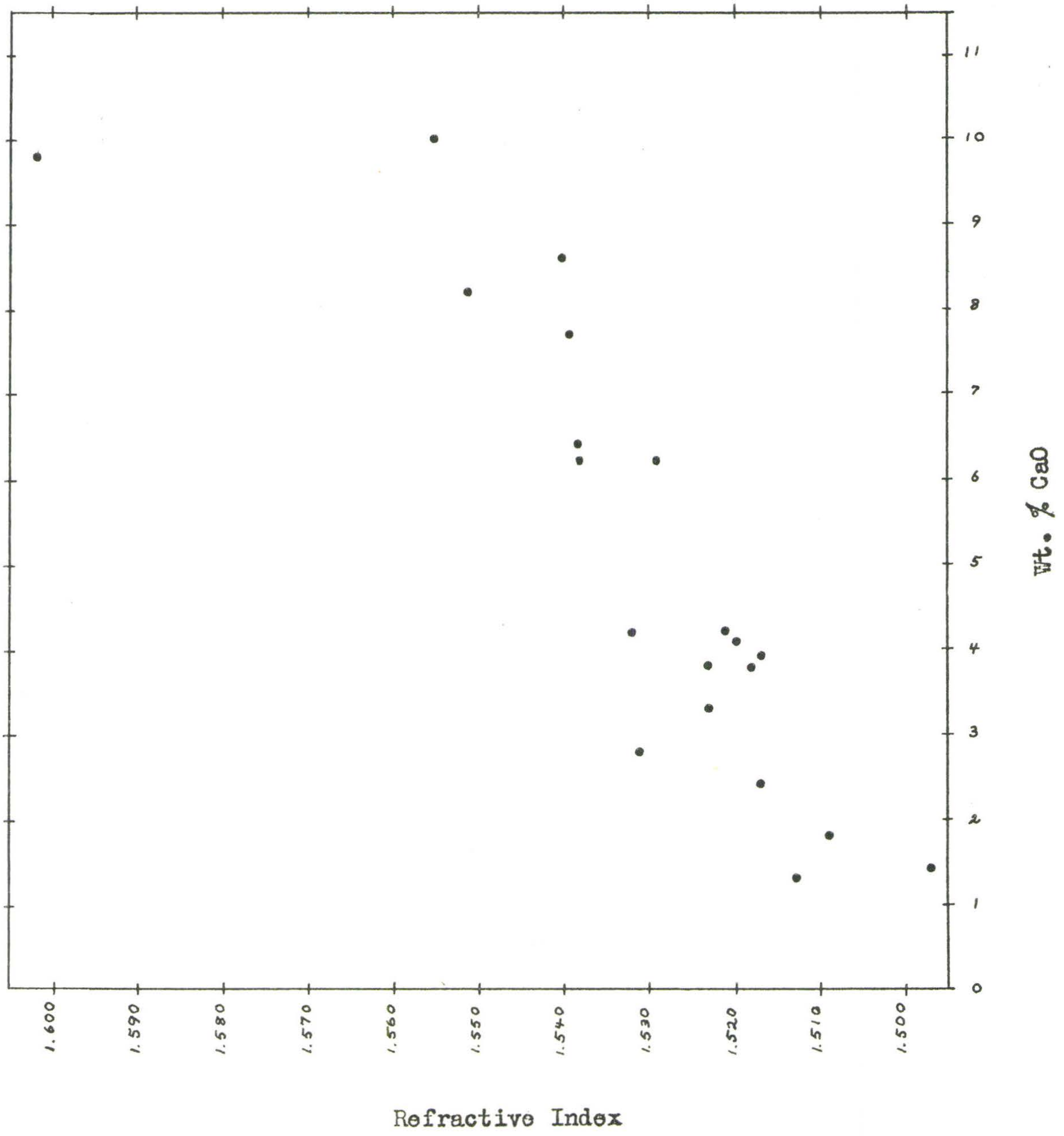


Figure F.3 Refractive Index of Fused Rock versus CaO content



APPENDIX 'G' Modal Analyses

Sample	**Percent Phenocrysts**							**Grndms.**	**Other**
	Qtz.	Kspar.	Plag.	Bio.	Hb.	Pyrox.	Olv.		
20-C1							1.0	99.0	
DC-10					12.4	3.6		84.0	
DC-21					6.1			93.9	
DC-4			21.7			8.8		63.3	6.2
DC-2			26.5	0.6		8.2		63.3	1.4
CC-7			27.3	1.0		12.3		57.8	1.6
DC-12			24.3	3.7		3.3		63.0	5.7
20-C9						2.5		97.5	
CC-6		0.6	6.3			3.9		88.7	0.5
F3-2		0.3	6.3			2.6		90.4	0.4
20-C16		2.7	14.1	0.5		0.7		81.5	0.5
20-C5		1.8	16.4	0.8		2.0		79.0	
CC-5		1.4	8.0	1.1				87.7	1.8
20-C15		0.1	10.8	2.0		1.1		68.3	17.7
AC-18			11.8					84.7	3.5
AC-9			7.0					78.7	14.3
CC-1		18.5				1.1		78.2	2.2
20-C13		7.1	1.9	1.2		0.9		88.3	0.6
20-C12		13.3		0.8		0.5		85.1	0.3
22-J1	5.2	9.9	10.8	1.2				72.9	

(The term 'other' refers to alteration, filling, and replacement material; Qtz. = quartz; Kspar. = alkali-feldspar; Plag. = plagioclase; Bio. = biotite; Hb. = hornblende; Pyrox. = pyroxene; Olv. = olivine; Grndms. = groundmass).

Percentages are based on a count of 1500 points for each rock using an integrating stage.

APPENDIX 'H' Rock Composition Comparison

Analyses of rocks used in this study are compared with analyses from the literature. Comparisons are made on the basis of major element values recalculated to 100. Total iron is given as FeO.

Table H.1 Average Composition of 'A' Series

	1	2	
SiO_2	61.65	60.23	
Al_2O_3	15.45	17.31	
FeO	5.53	7.15	
MgO	4.27	3.31	
CaO	7.56	6.79	
Na_2O	5.54	3.92	5.21
K_2O		1.29	

1. Average composition of 'A' series (average of DC-10, DC-21, DC-4, DC-2, CC-7, and AC-18).

2. Average of 50 dacites and 49 andesites (Nockolds, 1954).

Table H.2 Average Composition of 'B' Series

	1	2	
SiO_2	63.62	64.1	
Al_2O_3	17.30	16.3	
FeO	3.58	5.6	
MgO	1.00	1.0	
CaO	3.14	3.3	
Na_2O	11.36	4.6	9.7
K_2O		5.1	

1. Average composition of 'B' series (average of CC-5, 20-C16, 20-C15, and 1010 - 1010 is Daly's, 1912, pulaskite).

2. Average composition of quartz syenite from the Diana Complex of the Adirondacks (analysis reproduced by Turner and Verhoogen, 1960 p.344).

Table H.3 Average Composition of Hornblende Andesite

	1	2	
SiO_2	58.14	55.85	
Al_2O_3	15.78	17.69	
FeO	6.72	8.88	
MgO	5.78	4.50	
CaO	8.89	8.16	
Na_2O	4.69	3.78	4.92
K_2O		1.14	

1. Average composition of hornblende andesites DC-10 and DC-21.

2. Average andesite (Nockolds, 1954).

Table H.4 Average Composition of Pyroxene Andesite

	1	2		3	
SiO_2	62.69	60.23		61.31	
Al_2O_3	15.25	17.31		17.81	
FeO	5.40	7.15		6.30	
MgO	4.07	3.31		2.83	
CaO	7.79	6.79		5.97	
Na_2O	4.80	3.92	5.21	3.68	5.78
K_2O		1.29		2.10	

1. Average composition of pyroxene andesites DC-4, DC-2, CC-7.

2. Average composition of 50 dacites and 49 andesites (Nockolds, 1954).

3. Average andesite (Daly, 1933).

Table H.5 Composition of Olivine Basalt

	1	2	
SiO_2	47.48	47.84	
Al_2O_3	15.51	15.30	
FeO	11.12	12.09	
MgO	12.59	9.81	
CaO	10.58	11.22	
Na_2O	3.02	2.75	3.74
K_2O		0.99	

1. Plateau basalt sample 20-Cl.

2. Nockold's (1954) average alkali basalt.

Table H.6 Composition of Latite

	1	2	3
SiO_2	65.57	64.70	67.54
Al_2O_3	15.38	16.74	15.58
FeO	3.53	5.02	4.15
MgO	1.84	1.80	1.60
CaO	4.20	4.39	3.75
Na_2O	9.48	3.46 } 7.35	4.21 } 7.28
K_2O		3.89	3.07

1. Composition of latite AC-18.

2. Average composition of quartz latite (Daly, 1933).

3. Average composition of rhyodacite (Nockolds, 1954).

Table H.7 Composition of Trachyandesite

	1	2
SiO_2	61.07	59.89
Al_2O_3	17.39	17.85
FeO	3.80	6.99
MgO	0.86	1.30
CaO	4.31	4.35
Na_2O	12.57	5.87 } 9.62
K_2O		3.75

1. Composition of trachyandesite 20-C16.

2. Composition of average trachyandesite (Daly, 1933).

APPENDIX 'I' Petrographic Descriptions of Distinctive Lavas

Nine distinctive lava types are petrographically described. All but one, the Miocene Plateau basalt sample 20-Cla, belong to the early Tertiary suite of the Kettle River region.

Descriptions are arranged in order of increasing acidity from basalt to rhyolite. The system of nomenclature outlined in Chapter III is adhered to. The names and symbols of the various rock colors have been adopted from the 'Rock-Color Chart' distributed by the National Research Council, Washington, D.C. The textural terms used are those suggested by Williams, Turner, and Gilbert (1955).

1. Olivine Basalt (20-Cla)

This sample was taken from a feeder dike on the east flank of Mt. Boucherie (elev. 1,700 feet above m.s.l.) and, except for its more highly developed porphyritic character, it appears to be the equivalent of the chemically analysed Plateau basalt 20-Cl which occurs at the top of the volcanic sequence in the Kelowna area.

The rock is heavy and exhibits a dense, felted texture in hand specimen. It ranges from dark to light shades of gray but a medium dark gray (N4) color predominates. In the wet powdered state it is olive gray (5Y3/2). Small yellowish grains of olivine are scattered randomly throughout. The rock is brittle and has a tendency to fracture into irregular pieces with sharp corners and uneven surfaces, the broken surfaces having a rough or abrasive 'feel'. Glass beads formed from the artificial fusion of basalt 20-Cl have refractive indices averaging 1.602±0.003.

Microscopic examination reveals that the rock is holocrystalline and porphyritic. The main mineral constituents are olivine, pyroxene, plagioclase, and magnetite. Texturally, olivine is the dominant mineral, in that, it occurs both as phenocrysts and in the groundmass. However, pyroxene and plagioclase are present in about equal proportions to constitute the bulk of the groundmass and hence a large portion of the rock.

The high refractive index of the plagioclase suggests a calcic composition. It forms slender laths up to ½mm. in length which are disposed in both a crisscross and subparallel orientation.

In sub-ophitic fashion, the angular interstices between the feldspar crystals are almost completely filled with anhedral pyroxene. A great deal of difficulty was encountered in an attempt to identify this mineral largely because of the small size of the grains. However, the overall grayish-green pleochroic color is suggestive of hypersthene.

The olivine crystals are clear and exhibit extremely pale green colors in thin section. A continuous size range exists from fine groundmass material up to phenocrysts measuring 3mm. across. Stout euhedral prisms and diamond shaped individuals are commonly seen, but there is also a large admixture of crystals showing rounded or irregular outlines. The composition has been arrived at by two separate methods. Using the classical optical technique a composition of $Fo_{80}Fa_{20}$ was determined.[1.] The pertinent optical parameters are

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[1.] The optical curves given by Winchell and Winchell, 1951, were used.

as follows:

$$2V = -87 \pm 0.3$$

refractive index $n_y = 1.697$ calculated
" " $n_z = 1.713 \pm 0.002$
" " $n_x = 1.675 \pm 0.002$

Good agreement with this composition was obtained by measuring the (130) lattice spacing from an X-ray diffraction pattern after a method described by Yoder and Sahama (1957). X-ray data is given as follows:

hkl	$2\theta\,CuK\alpha$	dÅ	hkl	$2\theta\,CuK\alpha$	dÅ
020	17.13	5.176	112	36.39	2.468
021	22.70	3.917	041	38.05	2.365
101	23.70	3.754	122	39.50	2.281
111	25.36	3.512	140	39.78	2.266
002	29.70	3.008	211	41.59	2.171
130	32.13	2.786	132	44.33	2.043
131	35.54	2.526	150	48.21	1.888

(dÅ values closely coincide with hkl indices given by Yoder and Sahama)

Magnetite is invariably present as fine grained interstitial material. It is often included in the pyroxene but rarely in the plagioclase. Olivine contains only small amounts of magnetite.

Secondary alteration is almost negligible in this rock, hematite staining associated with a little serpentine being present around the margins of some of the mafic minerals.

2. <u>(Pyroxene) Hornblende Andesite (DC-10)</u>

This sample was taken from a railroad cut near the south bank of the Kettle River, approximately one quarter mile west of the road crossing near the village of Midway.

Preliminary examination of the rock shows that it is compact, heavy, and dark gray (N3) in color. Weathered surfaces are rusted to dark brown and powdered fragments exhibit a dark yellowish-brown color

(10YR4/2) when dampened with water. Elongate prisms of amphibole are visible embedded in a dense aphanitic groundmass. In general the rock shows a tendency to develop subparallel cracks when struck by a hammer, giving rise to lenticular or roughly tabular fragments. The fused glass has a refractive indix of 1.555±0.004.

Detailed microscopic examination reveals the presence of both amphibole and pyroxene phenocrysts; plagioclase phenocrysts are notably absent. The inherent flow structure of the rock is brought out by the amphibole crystals which tend to show homogeneity of orientation.

The groundmass minerals are very fine grained and consist of abundant feldspar laths, up to 1/10mm. in length, and finer interstitial pyroxene and magnetite, all of which are suspended in a glassy mesostasis. The feldspar laths are usually disposed in a crisscross manner except that in the vicinity of phenocrysts they show parallel arrangements.

The amphibole is a greenish brown variety forming phenocrysts 1½ to 6mm. in length. A common hornblende composition is suggested by the optical data given as follows:

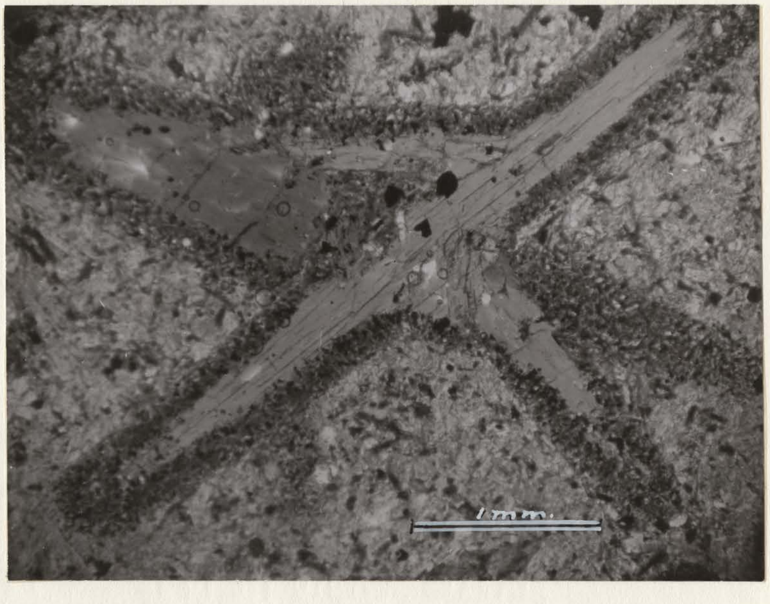
pleochroism	X yellowish smokey green	
	Y brownish green	
	Z greenish brown	

2V = -79.3 Z to c is 13

refractive index n_y = 1.671±0.002
" " n_z = 1.683±0.002
" " n_x = 1.654 calculated

Most of the hornblende phenocrysts are well separated from each other. Invariably they are encased in dense coronas of fine grained iron oxide granules and other undetermined reaction minerals indicating partial resorption. A typical example of resorbed hornblende is shown in Figure I.1. The morphology of these crystals ranges from good

Figure I.1 Partly Resorbed Hornblende



prismatic (110) forms with pinacoidal (010) modifications to irregular forms of almost completely resorbed hornblende. Zoning is prevalent and is usually seen as a series of concentric magnetite-rich layers within the mineral paralleling the various crystallographic faces. Simple paired twinning on (100) is occasionally present.

The composition of the pyroxene phenocrysts has been determined optically and is found to be $Wo_{44}En_{40}Fs_{16}$. The pyroxenes occur as small pale green crystals measuring from $\frac{1}{4}$ to 1mm. across. Inclusions consist mostly of small apatite grains but are rather scarce. In contrast to the hornblende the pyroxene has been little effected by magmatic corrosion. There appears to be a strong tendency for pyroxene in this rock to gather into large granular aggragates. The fact that patches of fine iron oxide and remnants of hornblende crystals are often associated with these pyroxene clusters is suggestive of probable replacement of the hornblende by pyroxene and iron oxides due to changing environmental conditions in the parent rock melt.

The rock is very fresh; the groundmass remains essentially unaltered but some of the phenocrysts have been replaced by secondary carbonates.

3. <u>Hornblende Andesite (DC-19)</u>

This sample was taken from a road cut on No. 3 Highway three and one half miles west of the village of Midway.

The hand specimen of this rock is dense, massive, and medium gray in color. The corresponding wet powder is light olive gray (5Y5/2). Phenocrysts of amphibole and feldspar are set in an aphanitic matrix. Broken fragments of the rock tend to have sharp edges and uneven surfaces. The refractive index of the corresponding fused glass is 1.533±0.002.

Examination of the microscopic characteristics not only brings out the porphyritic texture more clearly but also reveals the holocrystalline nature of the rock. The interspaces between the amphibole and plagioclase phenocrysts are filled with finely granular feldspar (less than 1/5mm.) and small amounts of evenly distributed magnetite. The amphibole prisms vary from $\frac{1}{4}$ up to 5mm. in length whereas the feldspar phenocrysts range from $\frac{1}{2}$ to 3mm.

Considerable compositionvariation is present within the individual plagioclase phenocrysts. This is largely due to the strongly developed zonal structure which is a characteristic feature of this rock. More than 15 oscillatory zones have been counted in some of the larger plagioclase crystals (see Figure I.2). Using the Rittmann method, determinations on one plagioclase phenocryst gave a composition range of An_{28} to An_{34}. Compositions as calcic as An_{40} have been detected on other grains. In general, two generations of phenocrysts appear to be present, a stubby, highly modified, prismatic type and a squarish or rectangular, lath shaped variety. The former tends to be larger and more highly zoned than the latter. Magmatic corrosion of the feldspars has been observed but is of very limited development.

The amphibole is a greenish brown strongly pleochroic variety. Extinction angles $Z \wedge c$ range from 15 to 17 degrees suggesting a common hornblende composition. Like the plagioclase of this rock the amphibole shows strong oscillitory zoning in the larger phenocrysts.

Figure I.2 Oscillatory Zoning in Plagioclase

This zoning is seen not only as a differential extinction phenomenon under crossed nicols but also as color variations within the mineral visible in plain light. A well developed prismatic habit is displayed by the larger phenocrysts but magmatic corrosion has badly rounded the smaller grains. Small amounts of magnetite, apatite, and feldspar form inclusions in the hornblende.

About one percent accessory pyroxene is present in this rock. It is a pale green variety showing irregular habit. It occurs as small grains usually intermixed with magnetite or remnants of corroded hornblende.

Alteration is restricted to slight kaolinization of the feldspar and partial decomposition of the fine hornblende. Most of the secondary products are concentrated along cracks in the phenocrysts or intergranular boundaries.

4. (Biotite) Pyroxene Andesite (CC-7)

This sample was taken from an outcrop about 200 feet north of the Marron valley road $2\frac{1}{4}$ miles west by north-west of White Lake.

Like most of the andesites this rock is porphyritic. The aphanitic dusky yellowish brown (10YR2/2) groundmass is charged with small grayish feldspar phenocrysts which average $1\frac{1}{2}$mm. in length. Upon weathering the rock takes on a rusty color and the feldspar phenocrysts show up in flat white tones. Wet powdered fragments are matched in color by the dark yellowish brown chip (10YR4/2) on the N.R.C. chart. In general the rock is massive and dense. It exhibits an elastic quality when struck by a hammer and tends to break into small irregular lumps. The corresponding fused glass beads of this rock have refractive indices averaging 1.538±0.004.

Microscopic examination of this rock reveals the following minerals in order of decreasing abundance: feldspar, pyroxene, magnetite, biotite, and apatite. All show a large size range but few have cross-sections greater than 4mm. except possibly some of the feldspar. A brown isotropic glass encloses and cements these minerals. Close examination of the glass, using a high power lens, indicates the presence of numerous rod shaped aggragates of iron ore granules (probably pseudomorphous after incipient pyroxene). The subparallel arrangement of this fine material is indicative of the inherent flow structure of the glass.

A composition of $Ab_{48}An_{52}$ has been determined for the plagioclase using Tsuboi's refractive index method. Oscillatory zoning, particularly in the larger phenocrysts, indicates some deviation from this composition within individual crystals. The smaller plagioclase crystals tend to be elongated or lath-shaped whereas the larger grains display a tabular and equant habit; both are well formed, however, and have not been appreciably corroded by magmatic fluids. Small amounts of pyroxene, magnetite, and glass are often included in these crystals. Twinning is universally developed in the plagioclases; albite twinning predominates but Carlsbad and pericline types are also present.

Biotite is very scarce in this rock but observed specimens seem to show good form. It occurs as small books of reddish brown mica measuring less than ½mm. across.

Next to plagioclase, pyroxene is the most abundant mineral. Optical determinations suggest an augite composition $Wo_{45}En_{35}Fs_{20}$. The pyroxene is typically pale green in color and non-pleochroic. Crystals are often well developed as short, stout prisms giving small broad tablets and hexagonal basal sections. The average grain size is slightly less than ½mm. in diameter. Inclusions are not particularly abundant but some glass, magnetite, and apatite is found. Twinning on (100) is fairly common both as simple paired individuals or polysynthetic types. Zoning is slight and usually difficult to detect.

A few clusters of intermixed pyroxene and plagioclase have been observed but these are relatively rare. Clusters of pyroxene and magnetite are much more prevalent. In spite of relatively high concentration of feldspar in this rock there seems to be remarkably little tendency for it to occur in aggregate form.

Traces of a brown, strongly pleochroic mineral have been detected. It bears a close resemblance to amphibole in general appearance, however, there is insufficient evidence for conclusive identification.

Secondary alteration appears to be largely restricted to partial zeolitization of the glassy matrix. This process is most advanced near the margins of the phenocrysts where the glass takes on a gray color and an anisotropic optical character.

5. Pyroxene Trachyandesite (F4-3)

This rock was taken from the lava flow at the crest of the ridge situated 1½ miles due north of the Kettle River bridge at an elevation of 4,350 feet above m.s.l.

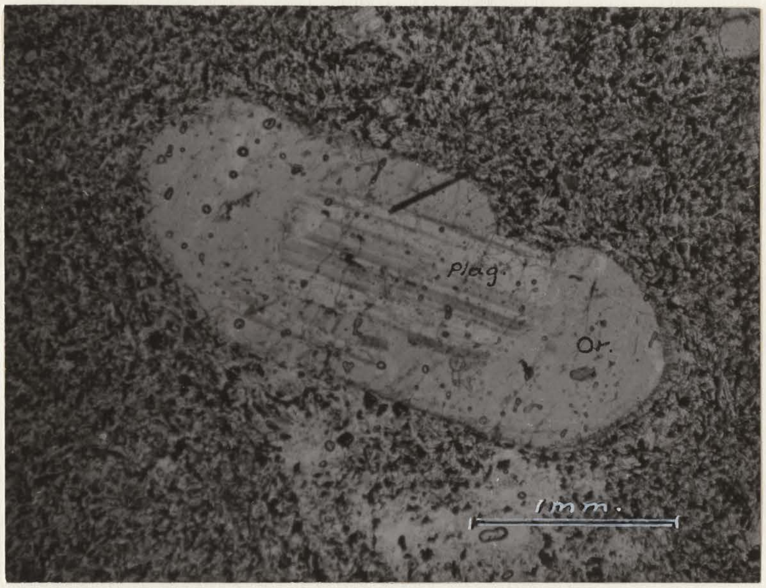
This is an olive gray (5Y4/1) colored rock on a freshly broken surface; it weathers to a pale gray with slight rust mottling and is a yellowish brown (10YR4/2) in the wet powdered state. Whitish rosettes of plagioclase, 2 to 5mm. across, and laths of alkali-feldspar are embedded in a dense, felted groundmass. Small dark grains of magnetite and clusters of pyroxene are sprinkled liberally throughout the matrix. The 'feel' of the rock on a broken surface is rough, possibly owing to the fractured ends of the microlites. Fused glass beads synthesized from this rock have an average refractive index of 1.527±0.004.

The microscope shows the texture to be porphyritic and holocrystalline. Microlites of anorthoclase are usually felted but may show subparallel flowage alignment in the vicinity of phenocrysts. The groundmass is charged with iron oxides and some pyroxene.

Anorthoclase occurs as doubly terminated free floating phenocrysts. It also forms thick mantles or jackets about plagioclase phenocrysts (see Figure I.3). In the latter case both the alkali-feldspar and plagioclase show good crystallographic habit, the contacts between the two feldspars being quite sharp. The anorthoclase phenocrysts are invariably fringed by a thin layer of alkali-feldspar, of slightly different composition, which tends to merge the margins of these large crystals into the microlitic groundmass. Extinction angles up to 8 degrees on (010) are visible in the anorthoclase and 2V values averaging 59 degrees have been measured in the (001) plane. The composition has been determined as $Ab_{43}Or_{57}$.

Plagioclase in this rock is easily distinguished from anorthoclase by its much higher relief and its polysynthetic twinning. Like anorthoclase some of the plagioclase grains are slightly corroded and all are fringed by alkali-feldspar. Compositional zoning is only slightly developed, but when present, is of the normal type. A few

Figure I.3 Alkali-Feldspar Mantling Plagioclase



magnetite and apatite inclusions are visible. The composition of plagioclase has been determined as $Ab_{52}An_{48}$.

Pyroxene occurs as short stout prisms of rounded or irregular form. The phenocrysts are usually a pale green color and are found as free floating individuals, or less frequently as small inclusions in plagioclase rosettes. Twinning is occasionally observed and when present is of the simple paired type with (100) composition plains. Apatite often occurs as small rod shaped inclusions in the otherwise clear pyroxene grains (see Figure I.4).

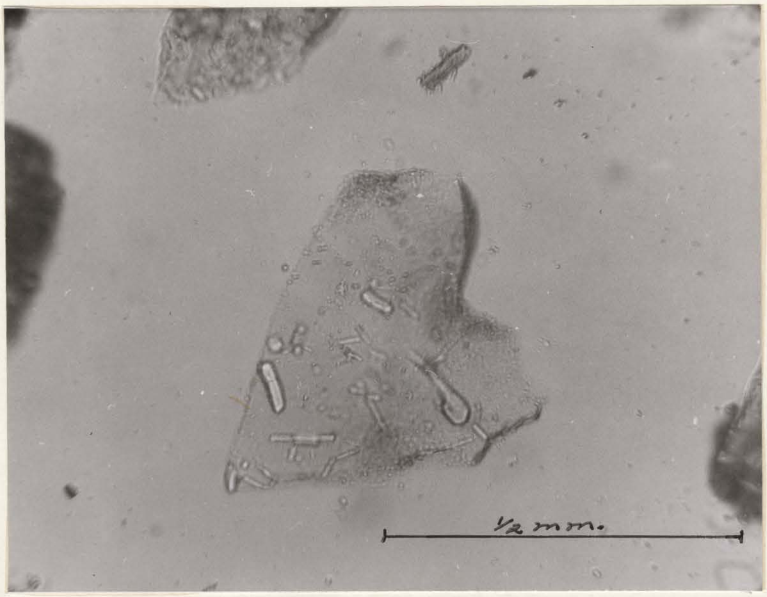
Carbonate occurs as a filling or replacement mineral in this rock in small amounts. Except possibly for slight hematitization of some of the iron ore in the groundmass secondary alteration is practically absent.

6. Latite (AC-18)

This sample was taken from a lava flow on the west flank of Mt. Boucherie at the elevation of 1,600 feet above m.s.l.

A fairly large sample of latite was available for examination. On the weathered surface and along joint cracks the rock is coated with a shallow skin of brown rust. On the fresh surface it displays a medium dark gray color (N4) and in the wet powdered state it is a dark greenish gray (5GY4/1). Small bleached crystals of feldspar, ranging up to 3mm. in length, are disseminated throughout the rock. A few grains of pyrite are also visible. In general, the rock is very hard and brittle. When struck with a hammer it tends to chip and flake leaving conchoidal depressions and sharp corners in the surface. The corresponding fused glass of this rock has a refractive index of 1.520±0.003.

Figure I.4 Apatite in Pyroxene



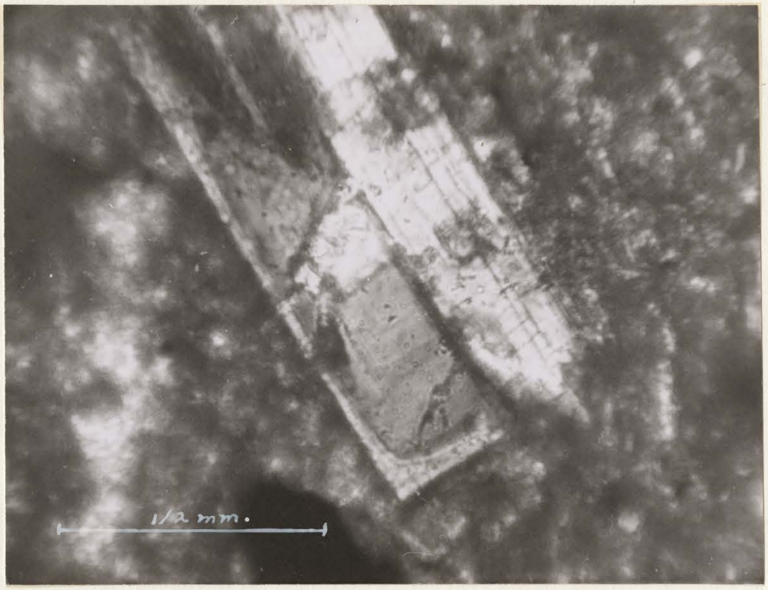
Microscopic examination of the rock reveals a vitrophyric texture. Slender laths of plagioclase, ranging from less than $\frac{1}{2}$mm. in length, are embedded in a glassy matrix. The inherent flow structure of the rock is brought out by the subparallel alignment of both the feldspar phenocrysts and microlites.

The approximate composition of the bulk of the plagioclase has been determined as $Ab_{49}An_{51}$. However, some deviation from this composition may be expected since many of the larger crystals show well developed zoning. Using the Rittmann method a difference of An_{05} has been detected between the normally zoned core and the margin of this feldspar. Distinct from this normal zoning a thin fringe of low relief feldspar is usually displayed on the plagioclase (see Figure I.5). This fringe invariably marks an abrupt change in the composition of the plagioclase and seems to weld the margins of the crystal into the groundmass. The fact that the lavas with a felted or holocrystalline groundmass display a stronger development of this texture than lavas with a glassy mesostasis seems to suggest that this is a late stage phenomenon due to the low rate of solidification of the melt after extrusion. (Probably slow cooling would permit large amounts of alkali-feldspar to nucleate and grow on pre-existing feldspar phenocrysts).

Primary ferromagnesian silicates were not detected during the thin section study. However, small patches of chlorite and carbonate in the matrix possibly mark the original positions of these minerals before alteration took place.

Magnetite is only moderately abundant. It forms amorphous, opaque granules and is scattered uniformly throughout the groundmass.

Figure I.5 Fringe Zoning in Plagioclase



Alteration has not affected much of the rock even though the ferromagnesians are apparently replaced. About 3½ percent of the total volume consists of secondary calcite and chlorite. Devitrification of portions of the glass is indicated by the local anisotropic behaviour of this material.

Although sample AC-18 is non-vesicular many of the latites in the immediate vicinity of this particular lava contain abundant vesicules and amygdales. In these rocks chalcedony is present in abundance as amygdaloidal filling material. In thin section chalcedony reveals a fibrous radiating habit, the fibers being disposed perpendicular to the walls of the amygdales. The refractive index of chalcedony ranges from 1.548 to 1.540 with 'n_z' normal to the length of the fibers. (see Figure I.6)

7. <u>Shackanite (analcite rhomb-porphyry) (CC-1)</u>

This sample was taken from an outcrop approximately 100 yards north of the Marron valley road and 6½ miles west of White Lake.

The rock is a yellowish brown color (10YR4/2) in fresh hand specimen. It weathers to a variety of dark brown shades and in the wet powdered state displays a moderate yellowish brown color (10YR5/4). The rock is characterized by large phenocrysts of alkali-feldspar up to 6mm. long and showing rhombic outlines. This feldspar is usually a pinkish color and is associated with glassy green pyroxene (1½ to 5mm. across); both minerals are embedded in a dense aphanitic groundmass. Bifurcating vesicles up to 1cm. or more in length are sometimes seen. Generally these are lined or partially filled with calcite. The rock has a tough consistency and tends to break into irregular fragments with rough surfaces. (Upon striking the rock with a hammer no unusual sonorous

Figure I.6 Chalcedony Pipe Filling

'phonolitic ring' could be detected). The artificially fused glass representing this rock has a refractive index of 1.532±0.001.

As seen under the microscope, the groundmass consists of a homogeneous mixture of analcite, alkali-feldspar, biotite, pyroxene and apatite. All these minerals are cemented together by a pale brownish glass. Analcite is the most abundant and forms sharply defined polygonal or rounded pinkish crystals averaging 1/3mm. in diameter. Except for tiny rods of apatite the majority of the analcite crystals are free from inclusions. Determination of isotropic analcite on the basis of optical methods proved difficult, however, conclusive identification was possible using X-ray powder diffraction techniques.

Plagioclase is absent from this rock but two forms of alkali-feldspar have been detected. The distinction between these feldspars is made on the basis of crystal size and habit. A small, clear, and rectangular or lath-shaped variety, less than ½mm. in length, is present together with a rhombic shaped type which always forms phenocrysts. (Apparently the rhombic outlines displayed by sections of this phenocrystic feldspar are due to crystallographic forms (110), $(1\bar{1}0)$, and $(20\bar{1})$; see Figure I.7). In the main, the rhombic feldspar has a feathery appearance with rather indefinite margins. Patches and fringes of light gray alteration products are observed in most crystals. Thin jackets of a younger generation of alkali feldspar are present encasing the fresh unzoned cores of the rhombic phenocrysts. Large, unjacketed, and apparently broken phenocrysts of the same feldspar have very wormy and corroded appearance. Good twinning has not been observed in the rhombic feldspar.

Figure I.1 Rhomb-Porphyry Feldspar

Pyroxene phenocrysts are rather scarce in this rock but when present are usually large and a clear, bright green variety. Extinction angle measurements ($Z \wedge c = 40$) and 2V determinations suggest an augite composition. The crystals are euhedral in outline and magmatic corrosion textures are absent. Glass, hexagonal apatite rods, and magnetite granules form distinctive inclusions in the pyroxene. Zoning is very regular and so slight that even in the largest phenocrysts it can scarcely be detected. Twinning, when present, is of the simple paired type.

Slight kaolinization of the feldspar appears to have taken place, particularly about the margins of the crystals, and small portions of some of the phenocrysts have been replaced by calcite. Chloritization of some groundmass constituents has been detected and the anisotropic behaviour of parts of the glass suggest possible zeolitization. In general, however, this rock has undergone only minor alteration effects.

8. (Pyroxene) Biotite Trachyte (20-C12)

This sample was taken from a rock outcrop at an elevation of 3,000 feet above m.s.l. on the ridge immediately west of McDougall Creek, north-west of Mt. Boucherie in the Kelowna area.

In hand specimen the rock is yellowish brown (10YR4/2) and exhibits a slightly darker tone (10YR5/4) as a wet powder. The rock is also hard and brittle and has a tendency to chip rather than break when struck by a hammer. Both individual feldspar phenocrysts and clusters of the same mineral are visible measuring up to 5mm. in diameter. Biotite phenocrysts measuring $\frac{1}{2}$ to 1mm. across give the rock a peppery appearance. The glass corresponding to the artificially fused rock has a refractive index of 1.503 ± 0.001.

Under the microscope the groundmass is seen to be holocrystalline. It is composed of aggregates of small laths of alkali-feldspar, small flakes of biotite, finely disseminated opaque iron oxide dust, and a few tiny interstitial grains that bear a resemblance to quartz. Unlike many trachytes the feldspar microlites have a felted texture and show no fluidal arrangement. Phenocrysts of potash feldspar, pyroxene, and biotite are present together with a few coarse grains of magnetite. Plagioclase is notably absent.

The composition of the potash feldspar has been determined as $Ab_{54}Or_{46}$. Phenocrysts of this mineral are unzoned and show both rounded and rectangular forms. Aggregates of two or more grains are more common than single crystals. Frequently these aggregates contain 'trapped' crystals of pyroxene or biotite. Twinning on the Carlsbad law is common in this feldspar.

Pyroxene phenocrysts in this rock are represented by only a few small grains of pale green augite. Euhedral crystals of both equant and lath shaped or rectangular habit occur as free floating individuals; subhedral and anhedral forms are characteristic of pyroxene grains incorporated in the feldspar clusters. Large opaque magnetite grains are frequently associated with the pyroxene.

Biotite forms about 6% of the total phenocrysts visible in the rock and is slightly more abundant than pyroxene. When observed in plain light biotite is pleochroic in dark brown and pale yellowish brown colors. It occurs in euhedral and subhedral books showing little evidence of resorption.

Secondary alteration in this rock has been slight. The feldspar microlites of the groundmass shows some alteration to kaolin and traces of hematite staining is present in the vicinity of magnetite grains.

9. Biotite Rhyolite (22-J1)

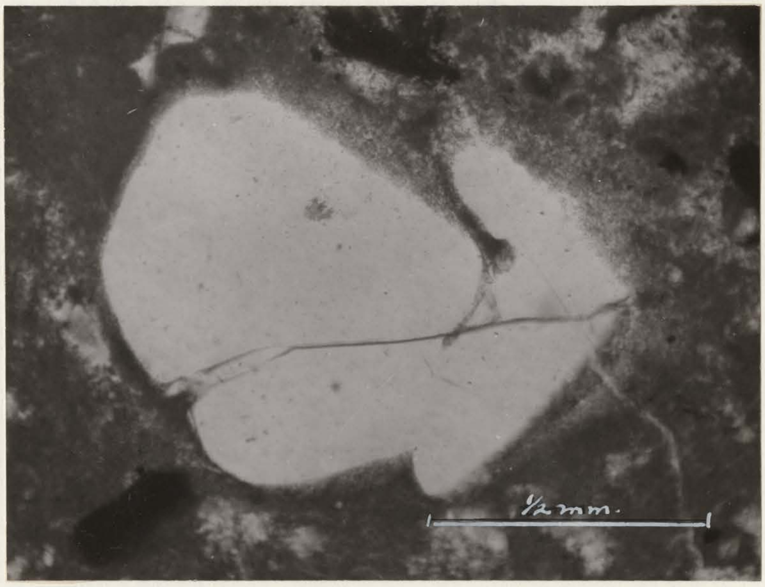
This sample was taken from a bed-rock exposure three miles due west of the village of Trépanier on a mountain slope at the elevation of 2,500 feet above m.s.l.

In hand-specimen this rock is light colored. On the freshly cut surface pale red (10R6/2) and yellowish gray (5Y8/1) bands are visible (these bands probably mark the original flowage planes of the lava). In the wet powdered state a pale yellowish brown (10YR6/2) is exhibited, and the weathered faces of the rock are a mottled gray color. Buff colored phenocrysts of feldspar, about 2mm. across, are abundant and glassy grains of quartz are scattered throughout the dense groundmass. Fine peppery biotite is also visible. The rock shows a tendency to break along flowage planes when struck with a hammer producing rough but regular surfaces. Glass beads formed from powdered fragments of this rock have an average refractive index of 1.497±0.002.

Microscopically, the rock is porphyritic with phenocrysts of quartz, anorthoclase, plagioclase, and biotite set in a glassy matrix. Microlitic biotite and fine iron oxide dust is dispersed throughout the glass in such a manner as to bring out the well developed flowage structure.

Primary quartz is usually present only in phenocrystic form. Crystals measuring $\frac{1}{2}$ to 1mm. across are most common. Owing to magmatic resorption small embayments have been developed in these crystals and most of the edges and angles have been greatly rounded (see Figure I.8). Cracked and broken crystals are present but undulose extinction and other signs of crystal straining have not been observed. At first glance some

Figure I.8 Quartz in Rhyolite



quartz appears to be aggregates of many grains; however, close examination reveals that such aggregates are actually optically deranged fragments of fractured single crystals. Quartz examined in this rock is clear and free of inclusions.

The composition of the alkali-feldspar has been determined as $Ab_{43}Or_{57}$. Like quartz this mineral shows poor crystallographic form, being rounded and corroded by magmatic resorption. Two modes of occurrence have been observed; solitary free floating phenocrysts 1 to 3mm. long and aggregates, measuring up to 5mm. across, composed of several grains. When occurring in aggregate form the boundaries between the alkali feldspar grains are often irregular, showing no detectable relationship to crystallographic directions. Small inclusions of tabular plagioclase crystals are commonly present in the larger phenocrysts. Twinning in the alkali-feldspar is either poorly developed or absent.

The plagioclase in this rock has the composition of $Ab_{81}An_{19}$. The size of the plagioclase crystals ranges between ½ and 2mm.; the smaller crystals occur as inclusions in the alkali-feldspar whereas the larger crystals tend to form independent phenocrysts. In spite of the corrosive action of the magma upon this mineral, rectangular outlines are often distinguishable. Polysynthetic twinning is a distinctive trait of this feldspar.

Both the plagioclase and the alkali-feldspar contain small amounts of a gray alteration material concentrated mostly along fractures and cleavage planes. Zoning and fringing effects have not been detected in these feldspars.

Biotite is relatively abundant in this rock and is the only mineral to show a complete size gradation from phenocrysts, up to 3mm. across, to microlites, less than ½mm. in maximum dimension. Although many biotite books are bent or broken, there is little indication of magmatic attack. Color ranges from pale yellow to dark brown and reddish brown; frequently the darker biotite flakes are charged with finely disseminated opaque iron oxide.

Primary accessory minerals consist of apatite, magnetite, and an undetermined yellowish colored mineral. (There is some suggestion from the relief, optic axis figure, and general habit of this yellowish mineral that it may be fayalite).

In spite of the alteration of some of the biotite and replacement of some of the groundmass glass by chalcedony the rock is fresh.

10. Supplimentary Information

A. Shackanite

Shackanite (CC-1) is perhaps the most unusual and among the rarest of the above described lavas. A similar rock, but lacking analcite, (sample 31-C10) was found in the Midway succession near the crest of the ridge (4,000 feet above m.s.l.) 12½ miles north of the International Boundary and 18½ miles north-west of the village of Midway. Previously, the only North American occurrence of Shackanite-like lavas was recorded by Daly (1912, p. 410-415) who described flows similar to CC-1 and 31-C10 cropping out along the crest of the ridge at an elevation of about 4,500 feet and located 5 miles north of the International Boundary and 15½ miles west by north-west of Midway.

B. Rhyolite

Rhyolite sample 22-J1 was taken from a bedrock exposure near the village of Trépanier in the Kelowna area. Little (1961) has mapped the rocks at this locality as part of the 'Eocene or Oligocene' volcanic succession; however, no reference has been made to the presence of rhyolite here. An older volcanic unit defined as 'Paleocene or Eocene', contemporaneous with the basal Tertiary sediments, contains rhyolite and, no doubt, it is to this unit that rhyolite 22-J1 should be assigned. The rhyolite is only of local distribution and has not been observed in the Marron or Midway areas.

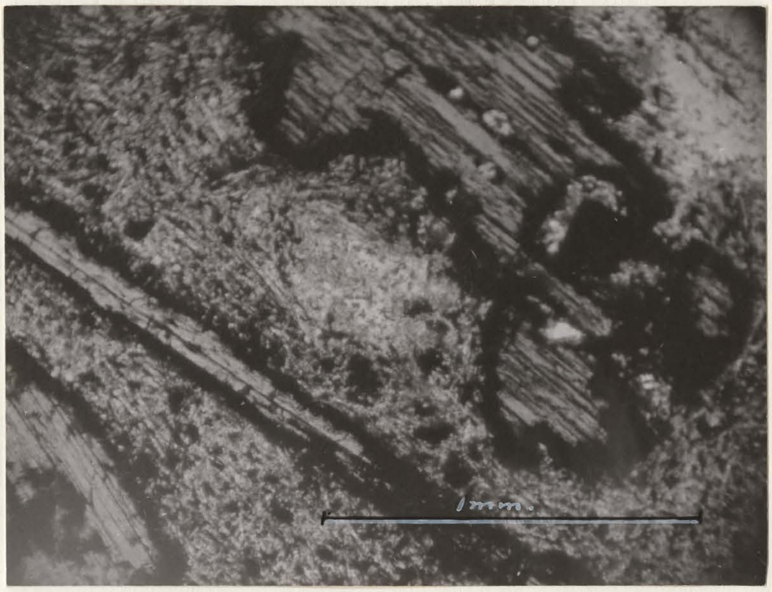
C. Basalt

The olivine basalt, represented by samples 20-C1 and 20-C1a, was taken from the Plateau basalt formation. Since this rock is probably of Miocene age (Little, 1957) it is not considered part of the early Tertiary sequence and is referred to in this study only for comparative purposes. However, Daly (1912, p. 398-399) has indicated the presence of certain olivine basalt flows which, supposably, form part of the lower lava sequence in the Midway area. These lavas were not found during the course of the present study nor have any Tertiary basalt flows of pre-Miocene age been detected in the Marron or Kelowna areas.

D. Resorption of Biotite

Of all the minerals examined biotite is the most prone to magmatic corrosion. The resorption process acts most readily on prismatic faces of biotite 'books'; basal faces show fewer embayments except in extreme cases. Often a rim of opaque iron oxide marks the resorbed margin of biotite and disseminated patches of opaque iron oxide remain from completely resorbed bitotite. (Since none of the rocks described in this section suitably examplify resorbed biotite a photomicrograph of sample CC-3 (Figure I.9) is used for illustration).

Figure I.9 Partly Resorbed Biotite



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