

GEOCHEMISTRY OF THE
TRIASSIC WATCHUNG BASALTS

By WILLIAM W. BLACK

A thesis submitted to
The Graduate School
of
Rutgers University
in partial fulfillment of the requirements
for the degree of
Master of Science

Written under the direction of
Professor Michael Piburn
of the Department of Geology
and approved by

Michael A. Piburn
At. Lawrence McKague
Dick E. Vogel

New Brunswick, New Jersey

April 1972

Table of Contents

	Page
Abstract	iv
Introduction	1
Geologic Setting	2
Analytical Methods	7
Major Element Chemistry	10
Major Element Chemical Variation	15
Trace Element Variations	25
Magmatic History	33
Relationships Between Flows and Intrusive	35
Conclusion and Summary	39

List of Tables and Illustrations

	Page
Figure 1: Geographical locations of Triassic basins	3
Table 1: Analytical Measuring conditions	8
Table 2: Mean values for Oxides	12
Figure 2: Plot of Na_2O plus K_2O versus SiO_2	13
Figure 3: Plot of Fe_2O_3 plus FeO versus SiO_2	16
Figure 4: Plot of Mafic Index versus SiO_2	17
Figure 5: Plot of Mafic Index versus SiO_2 for several well known suites	19
Figure 6: Plot of Mafic Index versus TiO_2	21
Figure 7: K/Rb versus K for Oceanic Basalts	26
Figure 8: Plot of K/Rb versus K	27
Table 3: K/Rb Ratios for several Feldspar separates	29
Table 4: Mean trace to Major Ratios for Watchung flow units	30
Figure 9: Plot of K/Rb versus K showing contamination of Oceanic Rocks to obtain Watchung Trend	32
Figure 10: Plot of Ti/Zr versus Ti	36

Abstract

The Watchung lava flows in the Newark Triassic basin are quartz normative tholeiite basalts which have fractionated along a tholeiitic Fenner trend to produce an iron enrichment/SiO₂ depletion with time. TiO₂ content varies with time. The first flows contain about 1.2% TiO₂, the second about .6%, while the third contains about 1.3%. Several dikes and sills analyzed plot within the TiO₂--Mafic Index fields of Weigand and Ragland (1971), while the flows seem to overlap and span the gaps between them. This behavior is unexplained. A well developed K/Rb trend is the result of a large variation in K with an invariant Rb content. The flows seem to be co-magmatic with the dikes, but this cannot be firmly established with chemical affinities.

Introduction

Recently, much attention has been focused on the Triassic graben-like structures of eastern North America because of the close relationship in time and space to the onset of sea floor spreading in the Atlantic Ocean. The associated basic igneous rocks offer an opportunity to sample mantle-derived materials from the earliest part of this period of sea floor spreading. Since the work of Yoder and Tilley almost a decade ago, a considerable theoretical and experimental body of knowledge on the origin and differentiation of basalts has been developed, and is now available as a framework into which one may fit work on a particular basalt series. Previous studies of eastern North American Triassic igneous rocks have largely dealt with the diabase dikes found in the basins and in the Appalachian Mountains. While such dikes provide useful chemical data, it is difficult to establish time relationships. However, the basalt flows of the Newark basins occur conformably within a well known sequence of sedimentary rocks. There is a definite time sequence established; moreover, there is some indication of the time interval between flows, based on sedimentation rates. The last detailed study of the Newark Group basalts was published in 1907 by J. V. Lewis for the New Jersey State Survey.

Geologic Setting

The subject of this study is a series of basalt flows which lie within the New Jersey portion of the Triassic Newark-Gettsburg Basin. This basin is a graben, bounded by border faults, which have been active since the Precambrian (Ratcliffe, 1971 and McKee, et al, 1959), and which were rejuvenated during the late Triassic. Similar features along the eastern coast of North America include the Acadia Basin, bordering the Bay of Fundy, the Connecticut Valley basin, several small basins in the area of Barboursville and Richmond, Virginia, and the Dan River and Deep River Basins of North Carolina (figure 1). These grabens occur on the eastern flanks of the Appalachian mountains, and all have accumulations of lithologically similar sediments. Intrusive diabase is found associated with all of these basins, but basalt flows are found only within the northern basins (Newark-Gettysburg, Connecticut Valley, and Acadia).

The stratigraphy of the Newark Basin was described by Van Houten (1969). The basin has an accumulation of sixteen to twenty thousand feet of northwest dipping terrigenous sediments. These sediments include three major lithologies; fanglomerate (Stockton Formation), argillite (Lockatong Formation), and shales and sandstones (Brunswick Formation). The Brunswick Formation comprises the major portion of the section. The basin is bordered on the northwest by Precambrian metamorphic rocks of the Reading Prong, and on

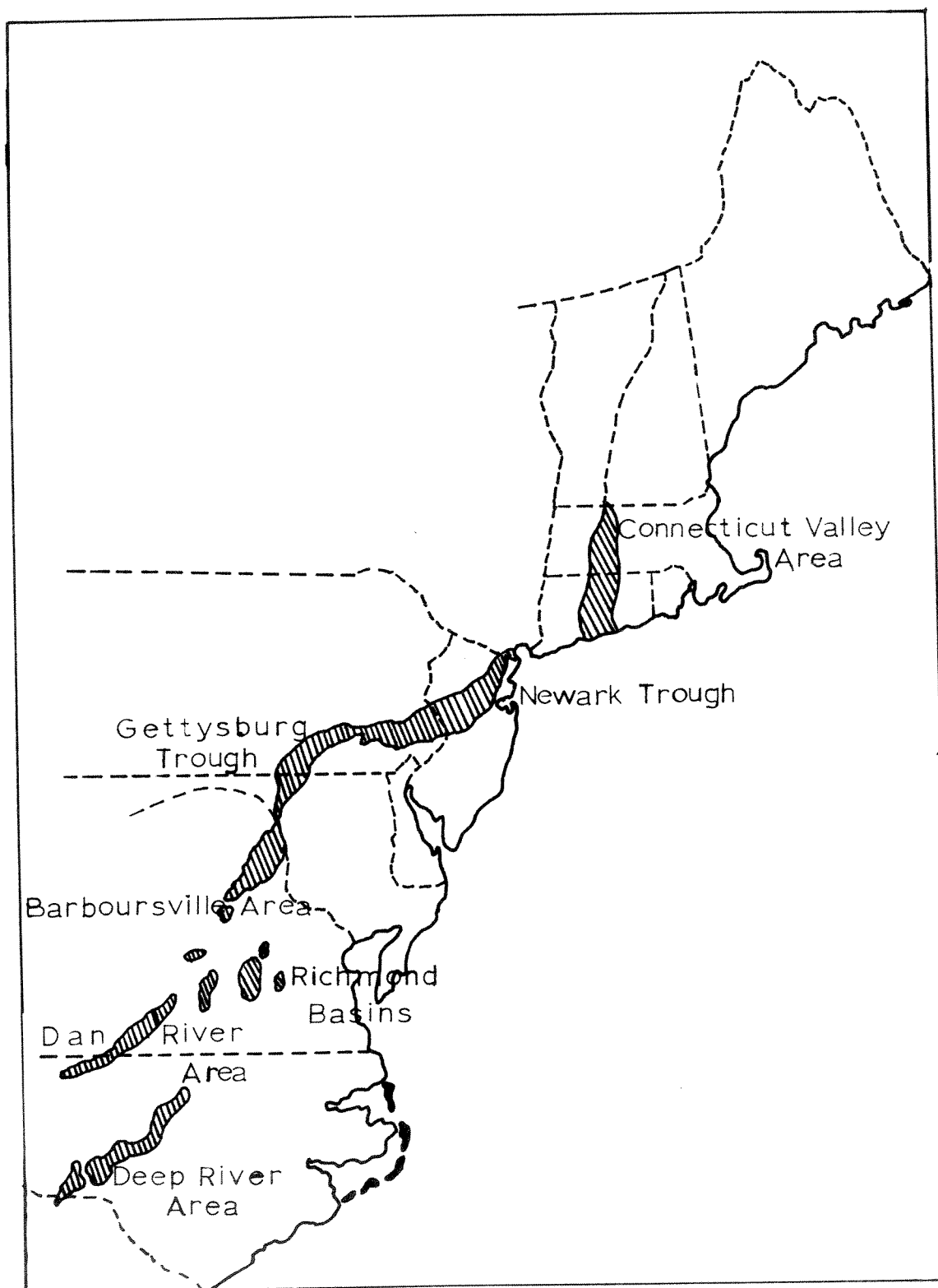


Figure 1: Geographical location of the Triassic basins after Darton (1890)

the southeast is overlain by Cretaceous and Tertiary sediments of the Coastal Plain.

The basalt flows in the basin are topographically expressed as a series of low ridges, referred to from east to west as the first, second, and third Watchungs. They form three distinct units in a sequence of shales and sandstones of the upper Triassic Brunswick Formation. Since regional dips are to the west, the flows of the first Watchung are the oldest, and those of the third Watchung the youngest, in the sequence. A fourth ridge is found east of the Ramapo fault between Bernardsville and Morristown. This ridge has been interpreted as a separate flow of limited extent (Sanders, 1963) and as an upwarp in the third Watchung (Lewis, 1907). At a sedimentation rate estimated by Van Houten (1969), of approximately six inches per thousand years, there is an interval of 500,000 to 600,000 years between the eruption of the first and second Watchung flows, and a 1,200,000 year interval between the eruption of the second and third Watchung flows.

Each of the Watchung ridges is composed of one or more separate flows. At Pluckemin a flow contact could be seen between a gray amygdaloidal pillow basalt with an undulating upper surface and overlying dark, fine grained columnar basalt. This contact can be traced for more than a mile along road cuts on Interstate 78. Such occurrences have been used as evidence of compound lava flows in the third Watchung (Darton, 1890). Other such subflow unit tops have

been noted at Bernardsville, Little Falls and Pompton Lakes, all in the second Watchung (Lewis, 1907).

The Watchung basalts are characterized by a lower chill margin and a contact aureole which varies in width from six inches to six feet, but lack exposed basalt-sediment contacts. At some locations in the Watchungs, such as the road cut for Interstate 280 at West Orange described by Manspeizer (1969), flow contacts are quite ambiguous. Manspeizer notes three mineralogical and structural changes in the exposed lower portion of the first Watchung, but is unable to show the definite presence of compound flows.

Diabase dikes and sills, which cut the entire stratigraphic column, are associated in time and space with the basalt flows. The Palisades diabase extends for a distance of more than one hundred miles from lower New York State where it forms the Palisades cliffs opposite New York City, then cutting upward through the section to form the Rocky Hill sill, and the Sourland Mountain and the Lambertville sill. Other diabase rock occurs at Round Mountain and Cusketunk Mountain. Numerous small dikes occur in the basin and to the northwest in the Reading Prong.

K/Ar radiometric dates clustering about 196 million years have been obtained on the Palisades sill and other intrusive bodies in the Newark and Connecticut basins. A date of 180 million years on basalt collected in the first Watchung is in close agreement. The analytical uncertainty of these dates is about ten percent. However, Armstrong

and Besancon (1970), have utilized all available and new dates on Triassic intrusions and extrusions in the Triassic grabens of the East Coast of North America and compared them to the dates of the plutonic intrusions in the Rocky Mountains. The spread of dates on dikes and sills of the Eastern North American basic rocks is 190 to 240 million years, while dates on the flows spread 160 to 200 million years. The dates of the plutons in the Rocky Mountains suggest a true date of 196 million years. Armstrong and Besancon suggest that a low temperature metamorphic event such as burial metamorphism resulted in an argon loss and a measured date that is too young.

De Boer (1968) has worked out a sequence of igneous events based on paleomagnetic dip inclinations. He correlates the three Watchungs and the Newark intrusives with the middle Holyoke sequence of flows in the Connecticut basin. Van Houten (1969) has criticized this correlation. The flows in the Connecticut basin are in similar types of sediment, and although more numerous and voluminous, they are in a similarly thick accumulation as the Watchungs, implying a similar time span.

Analytical Methods

Major and trace element concentrations in 60 samples were determined by x-ray fluorescence. Pressed powder pellets were used in a Norelco eight position vacuum spectrograph. Table 1 lists the measuring conditions for each of the elements determined. Major element concentrations, except for MgO and Na₂O, were determined by the heavy absorber method of Rose, et al (1963). Na₂O and MgO were determined in a non-heavy absorber pellet. The USGS standards W-1, BCR-1, and AGV-1 (Flanagan, 1969) were used as standards for the major elements determined.

The trace element concentrations were calculated using the calculated mass absorption coefficient method of Fairbairn and Hurley (1971). A value of three times the square root of the background was considered as the detection limit for the respective trace elements. The background radiation in the region of the trace elements Rb, Sr, Y and Zr was found to be a natural log function; the background in the region of the trace element Ni was found to be linear. A regression was run on background points between analytical peaks and an interpolated background under the peak was subtracted from the observed peak. The USGS standards W-1, AGV-1, and BCR-1 were included in each group of eight samples and the content of the trace element for each unknown was calculated using each standard in turn. The average of these three values was taken as the trace element content.

TABLE 1: ANALYTICAL MEASURING CONDITIONS

ELEMENT	ANGLE	COUNTS ¹	SLOPE ²	BACKGROUND	UNCERTAINTY	CRYSTAL
Si	79.2	64	590	258	±3%	PET
Al	115.2	16	12	23	±5	PET
Total Fe	57.5	128	650	390	±2	LiF
Mn	95.4	16	570	52	±5	LiF(110)
Mg	43.6	4	30	20	±10	KAP
Ca	15.2	128	140	730	±2	PET
K	20.7	64	3700	900	±2	PET
Na	53.0	4	75	13	±10	PET
Ti	6.67	128	2750	1000	±1	PET
Ni	110.9	5	nd	120	±10	LiF
Sr	23.8	140	nd	1500	±10	LiF
Rb	22.6	8	nd	1350	±10	LiF
Zr	25.1	80	nd	1200	±10	LiF

¹Accumulated counts X1000: ²Counts/second per %: nd=not determined
Analytical line K α 1,2 in all cases

FeO was determined using a wet chemical method (Schafer, 1966). Several geologic standards were used as controls on accuracy. Duplicate analyses of samples were used to indicate precision, and agreement was within 0.5 percent of the accepted value.

Major Element Chemistry

Basaltic rocks have been defined by Manson (1967) on the basis of a chemical screen which was derived empirically from 4300 published basalt analyses. Manson judged it to be quite effective in discriminating good from poor analyses. All the analyses from this study passed Manson's chemical screen.

Yoder and Tilley (1962), Green and Ringwood (1967), and Bailey, et al (1924) agree that a tholeiite is a rock of basaltic composition which contains normative hypersthene, and which may contain normative quartz. A tholeiite which contains normative quartz is said to be oversaturated with respect to silica. An undersaturated tholeiite lacks normative quartz, but carries normative olivine. Yoder and Tilley demonstrated that there is a thermal divide present between the tholeiites and the critically undersaturated alkali-olivine basalts which contain normative nepheline. This divide cannot be crossed by fractional crystallization or partial fusion and thus forms the basis for a genetic classification of primary magma types. Tholeiitic basalts occur in all environments in which basalts are found. A large area of the North Atlantic ocean floor is covered with tholeiites. They are found in other oceans of the world, and on continents as well. Oceanic basalts, including oceanic tholeiites, are thought to be uncontaminated because there is no sialic crust to contaminate them during or prior to extrusion.

The great majority of individual samples from this study (see Appendix I) as well as those given by Lewis (1907) and Walker (1940) are quartz-normative tholeiites. The average composition of each of the four Watchung flow units (table 2) is that of a quartz tholeiite. Two samples appear well into the field of alkali-olivine basalts on MacDonald's (1968) plot of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 (figure 2). A small number of this study's samples plot across this line, which is probably due to the analytical error for Na_2O .

Powers (1932), Tilley (1950) and Kuno (1960) have recognized a group of basalts with large amounts of Al_2O_3 which are usually called high-alumina basalts. Kuno believed these basalts to be a primary magma type. Yoder and Tilley (1962, p. 354) show that such rocks are commonly associated with quartz and olivine tholeiites, and alkali-olivine basalts, suggesting that they are not a primary magma, but rather a result of the presence of large amounts of plagioclase feldspar. Kuno (1960) has used a plot of $\text{K}_2\text{O} + \text{Na}_2\text{O}$ versus SiO_2 to differentiate high-alumina basalts from tholeiites (figure 2). A little more than half of the samples of this study plot in the high alumina field, a little less than half in the tholeiite field. On Kuno's plot of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus Al_2O_3 (not shown), one of three samples of the Cushetunk intrusion plots within the high-alumina basalt field. This could be due to analytical error. However, the $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 plot shows sufficient scatter within each flow to

TABLE 2:

MEAN VALUES FOR OXIDES

Major Elements (percent)	First Watchung		Second Watchung		Third and Fourth Watchungs	
	Mean	S.D.*	Mean	S.D.	Mean	S.D.
SiO ₂	50.2	1.0	50.1	2.8	48.9	2.2
Al ₂ O ₃	12.8	2.0	13.9	1.5	13.1	0.84
Fe ₂ O ₃	3.2	0.85	3.0	1.1	4.4	1.6
FeO	6.47	0.88	7.2	1.4	9.9	1.8
MnO	0.12	-	0.16	0.06	0.18	0.06
MgO	7.36	1.1	7.26	0.93	4.97	0.98
CaO	10.9	1.7	10.1	1.2	8.65	1.4
Na ₂ O	3.04	1.1	2.8	0.65	2.73	0.70
K ₂ O	0.19	0.1	0.41	0.29	0.60	0.34
TiO ₂	0.98	-	1.04	0.10	1.35	0.14
Trace Elements (ppm)						
Ni	80.0	6.5	73.0	13.0	77.0	10.0
Zr	136.0	24.0	124.0	14.0	111.0	25.0
Sr	248.0	94.0	115.0	47.0	95.0	30.0
Rb	27.0	13.0	28.0	11.0	28.0	8.0

*Standard Deviation

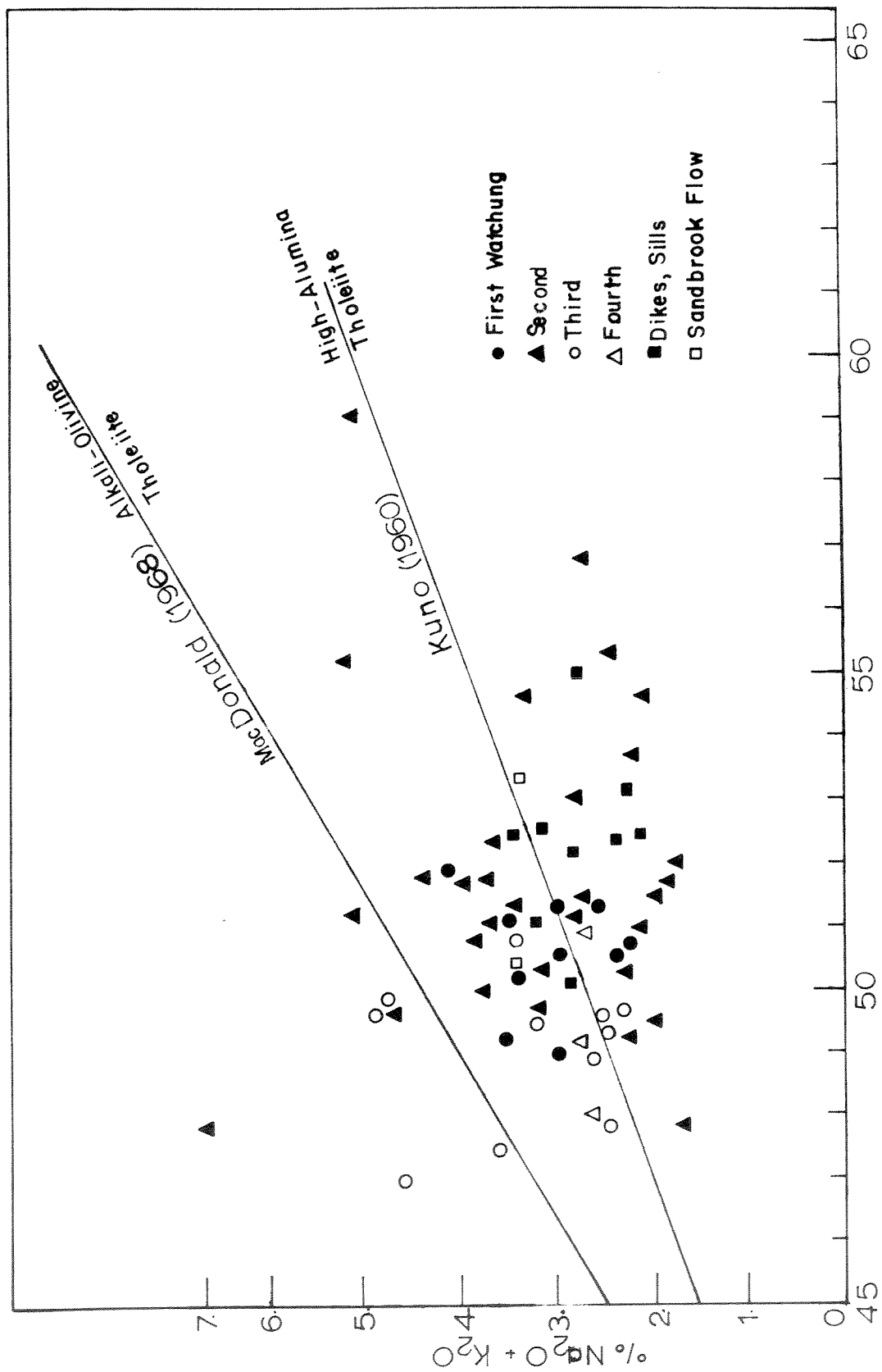


Figure 2: Plot of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2

suggest that they do not represent a separate magma type. The samples of Eastern North American Diabase from Weigand (1970, p. 24) show similar scatter.

In detail, the major element chemistry of the samples from this study, and those from Lewis (1907), and Walker (1940) are similar to that of other eastern North American basic rocks found in, and along, the numerous Triassic graben structures (Walker, 1940, Ragland, et al, 1968, Weigand and Ragland, 1971). The closest relationship is with the quartz-normative dikes of Weigand and Ragland. The average composition of 283 quartz tholeiites compiled by Manson (1967) is a close relation.

Major Element Chemical Variation

A plot of $\text{Fe}_2\text{O}_3 + \text{FeO}$ versus SiO_2 and MgO versus SiO_2 for samples taken from the Watchungs (figure 3) shows an enrichment in $\text{Fe}_2\text{O}_3 + \text{FeO}$ content and depletion in SiO_2 content with time. The first Watchung contains an average of 9.7, the second 12.0, and the third and fourth 14.5 percent $\text{FeO} + \text{Fe}_2\text{O}_3$. These figures show a strong clustering of points from each of the Watchung flow units and indicate change in iron and SiO_2 content with time. This is taken as evidence that a single magma was fractionating in a systematic manner and was occasionally vented to the surface. This trend is identical to a portion of Nocholds (1954) averages for tholeiites (shown on figure 5 as "Tholeiitic Series"), and is similar to compositional variation during the history of the Skaergaard layered intrusion. Another plot of the mafic index ($\text{MI} = \text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}$) versus SiO_2 for these same samples (figure 4) shows a similar relationship to the Skaergaard and tholeiites, as well as those of Hawaii's Kilauea (Tilley, 1960).

The plot of MgO versus SiO_2 (also figure 3) for Watchung basalt flows shows a general depletion in MgO which is clustered for each flow. However, the trend is more variable and exhibits less tight clustering. This is probably due to the greater analytical error for MgO .

Osborn (1959) has shown that variation in the partial pressure of oxygen during fractional crystallization may

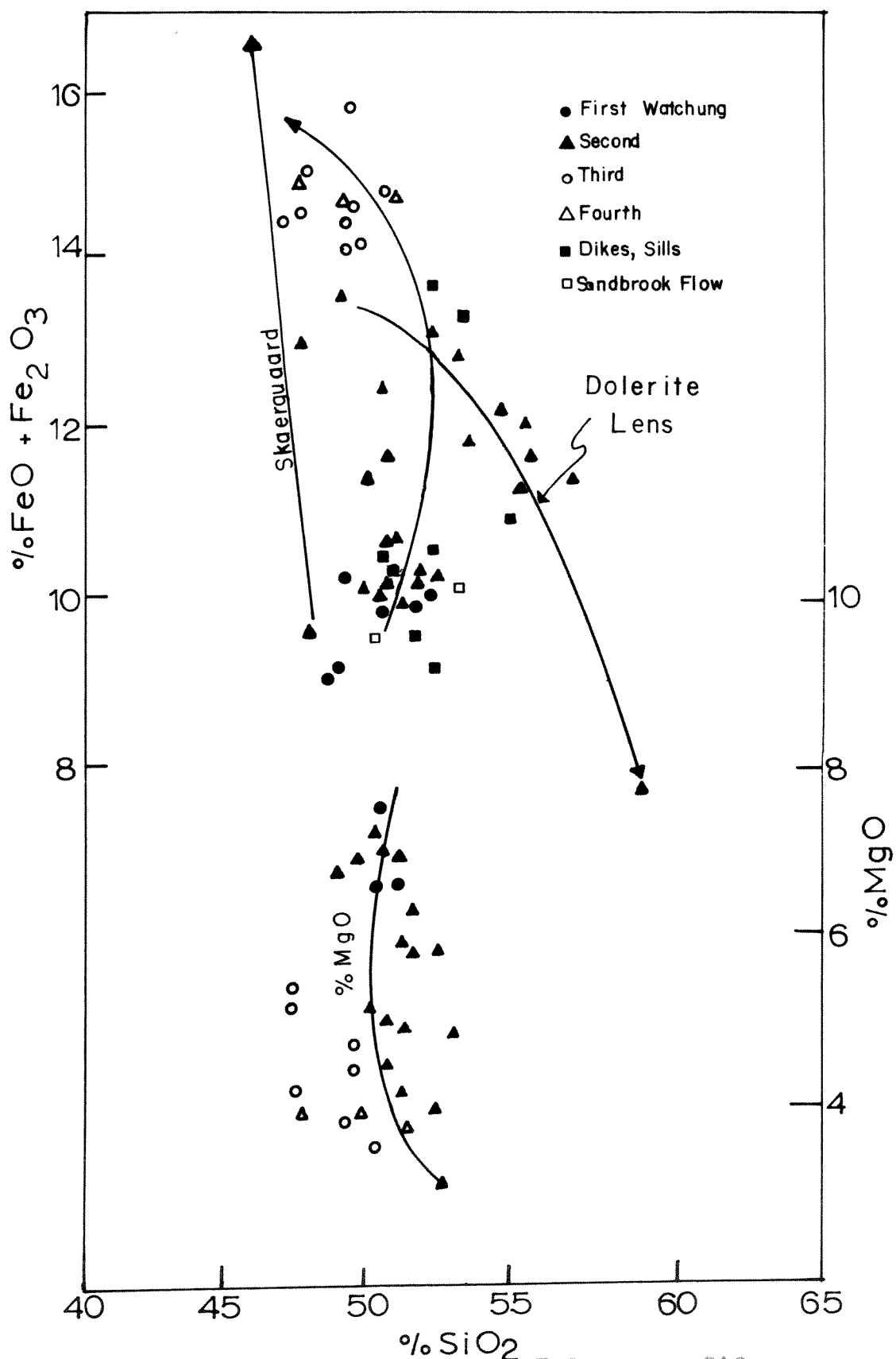


Figure 3: Plot of $\text{Fe}_2\text{O}_3 + \text{FeO}$ versus SiO_2
 Plot of MgO versus SiO_2
 Arrows indicate trend with time

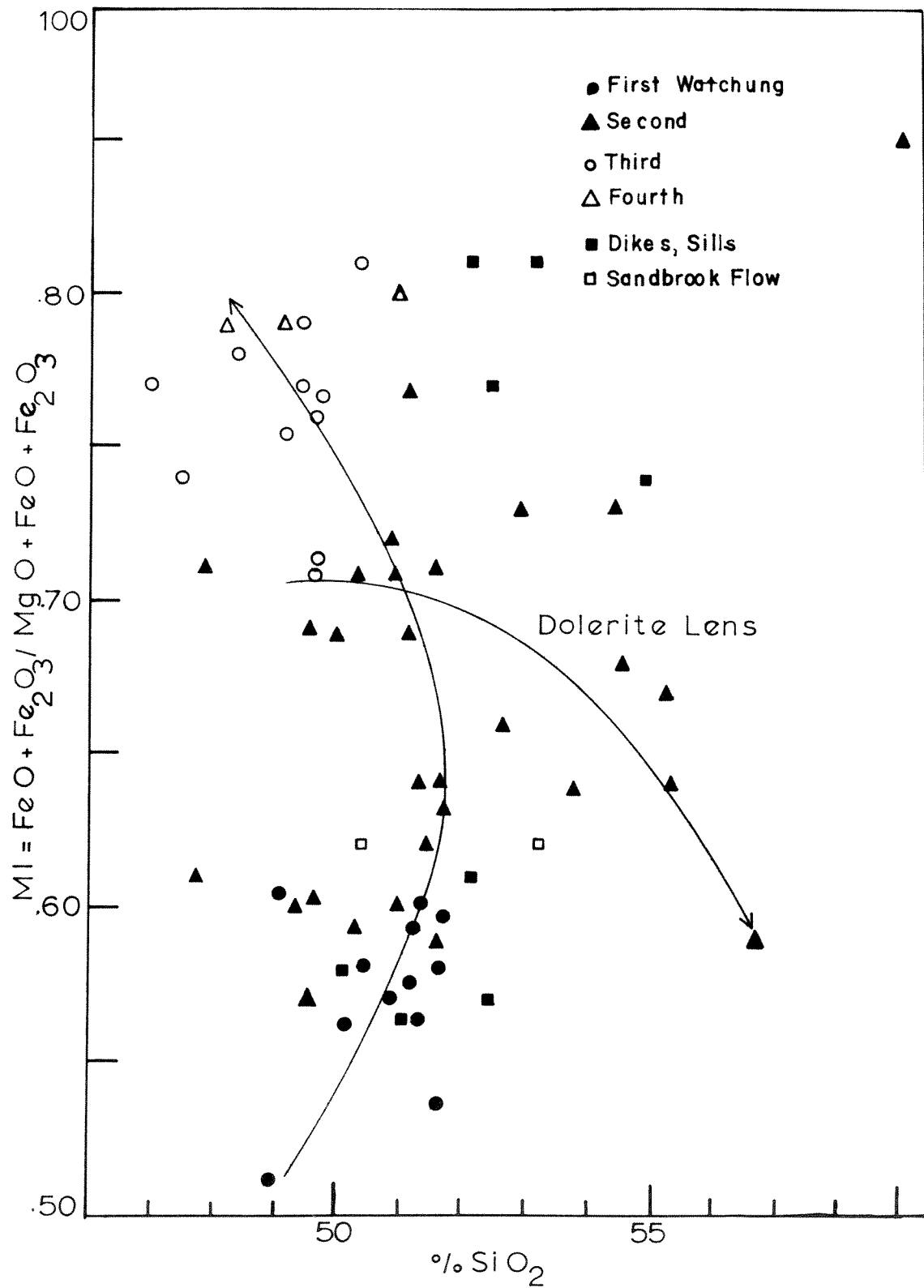


Figure 4: Plot of Mafic Index versus SiO₂
Arrows indicate trend with time

produce a SiO_2 depleted/iron enriched trend or a SiO_2 enriched/iron depleted trend in the residual magma. The former is observed between the Watchung flow units as well as in other tholeiitic suites. The iron enrichment trend between the Watchung flow units is essentially similar to that deduced by Osborn (1959, p. 629) for the path of a magma of "constant bulk composition" (figure 5) fractionating through the olivine and magnesioferrite field resulting in an initial increase in SiO_2 and then, upon encountering the cotectic surface, a SiO_2 and MgO decrease, all the while increasing the remaining liquid in iron.

Iron and SiO_2 content of samples taken from a coarse-grained diabase lens of limited extent in the second Watchung along Interstate 78 at Pluckemin, New Jersey, are also shown in figures 3 and 4. Some are higher in SiO_2 and lower in total iron than other samples from the second Watchung. The basalt exposed in this road cut grades from a fine-grained, columnar basalt, into the diabase. Samples with the highest SiO_2 values and the lowest mafic index were taken from the west end of the road cut, although coarse-grained rock with average compositions occur throughout. Just below this diabase is a pillow-like "flow-top" of the lower subunit flow noted earlier, so the diabase is near the base of the upper subflow unit.

This diabase lens shows a trend which is unlike any other shown in figure 5. Within this lens, the partial pressure was maintained and probably increased. For the

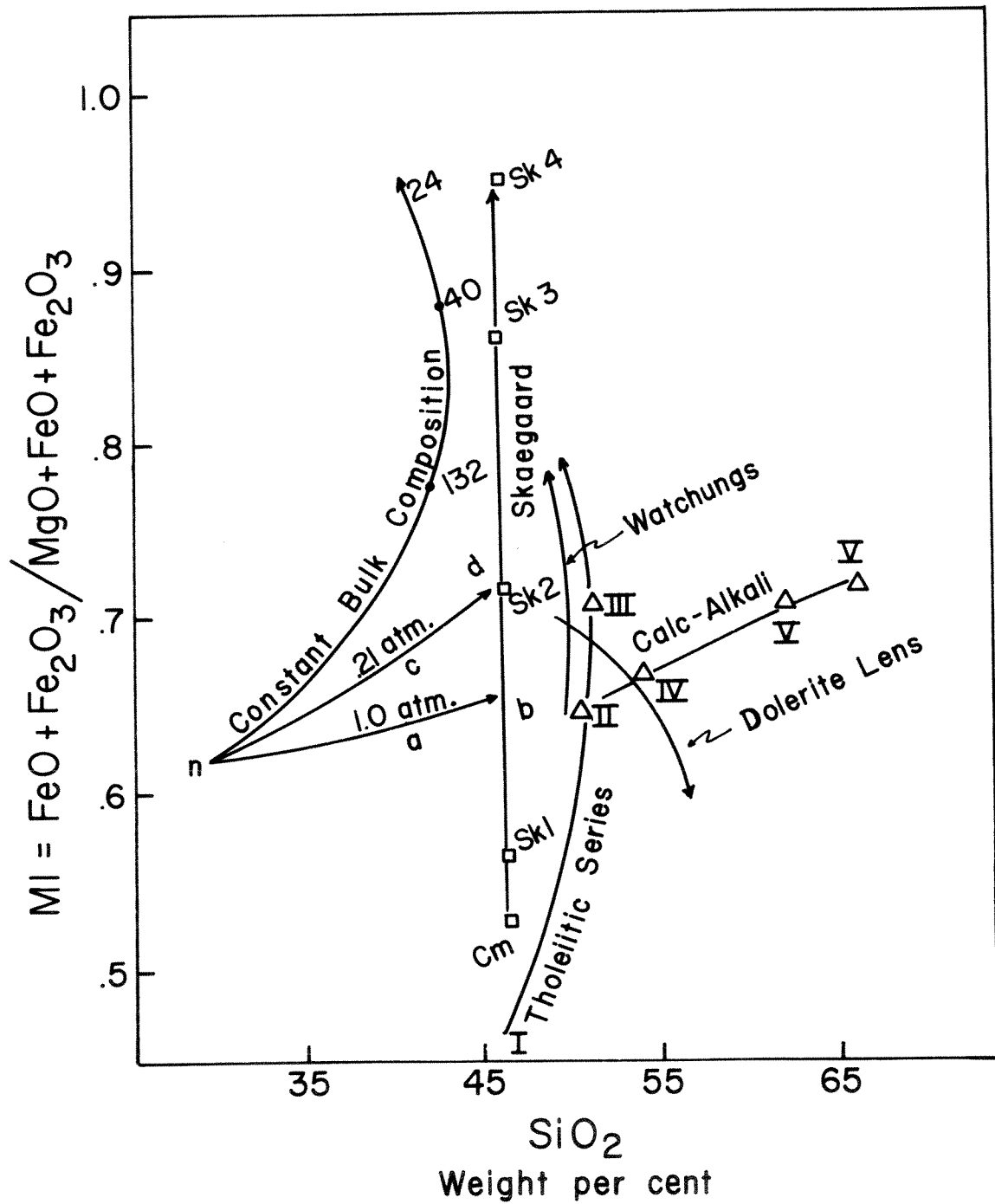
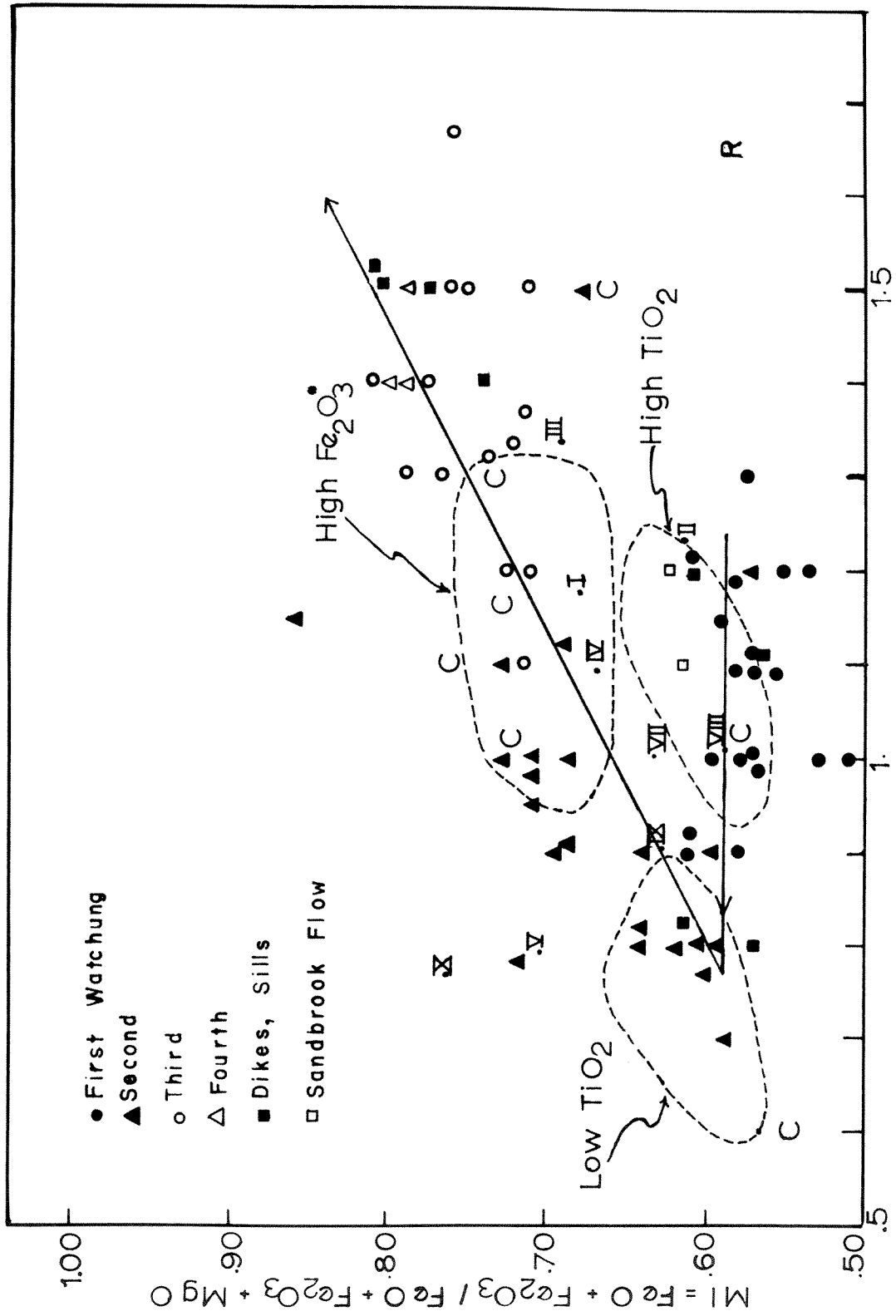


Figure 5: Plot of Mafic Index versus SiO₂ for several known suites. after Yoder & Tilley (1962)

curve n-c-d (figure 5) the partial pressure of oxygen is maintained at atmospheric normal, while for the curve n-a-b, the partial pressure is maintained at one atmosphere. The curve for the diabase lens would cut similar curves for a composition of the second Watchung, and continue below. Osborn (p. 630) states that if partial pressure of water is increasing at a sufficient rate, disassociation of water would increase the partial pressure of oxygen rapidly, and intersecting a successive family of curves for various constant levels of oxygen pressure. Thus, the diabase lens could represent a segregation of magma at the base of the subflow unit in which volatiles accumulated, resulting in a depleted and oxidized iron content and an increased SiO_2 and alkali content.

With the exception of this diabase lens in the second Watchung flow unit, the tight clustering and the uniform distribution along the tholeiite Fenner trend is taken as strong evidence for a single magma fractionating, probably in the manner proposed by Osborn, to produce the observed chemical variation.

Another systematic change in chemistry is suggested by the as yet unexplained behavior of TiO_2 in the Watchung flow basalts. Weigand and Ragland (1970) have used a plot of TiO_2 versus the mafic index $(\text{Fe}_2\text{O}_3 + \text{FeO} + \text{MgO})/(\text{Fe}_2\text{O}_3 + \text{FeO})$ to differentiate several magma types of Mesozoic dikes in eastern North America. Their plot, with the Newark basin igneous rocks of this study included (figure 6) show a

Figure 6: Plot of Mafic Index versus TiO_2

number of samples which plot within the areas of the magma types proposed by Weigand and Ragland. There is also a transitional group between the "Low TiO_2 " and "High TiO_2 " groups of Weigand and Ragland. In addition, there is a well defined group of higher MI and TiO_2 values. The latter are a combination of values obtained on third and fourth Watchungs, a single dike from Jugtown Mountain in the New Jersey Reading Prong and three samples from the Cushetunk intrusion. The "Low TiO_2 " field is composed of samples from the second Watchung flow unit. The samples which plot within the "High TiO_2 " field of Weigand and Ragland are from a small dike into Brunswick shale, and many of the samples from the first Watchung flow unit. The data from Lewis (1907) for each of the Watchungs plot with those in this study. All but two points from intrusions plot in one of the fields of Weigand and Ragland.

Weigand and Ragland believe that there is no single source for the "Low TiO_2 " and "High TiO_2 ", but that the "High Fe_2O_3^* " group could have fractionated along a tholeiitic Fenner trend from the "High TiO_2 " group without much change in TiO_2 content. These conclusions are not supported by the evidence from the Newark basin. A single source for the flows is probable and a Fenner tholeiitic trend has been demonstrated. The mafic index versus TiO_2 plot suggests that fractionation may occur from a source liquid in the "High TiO_2 " field, fractionating through the "Low TiO_2 " field, thence to the "High Fe_2O_3^* " field and

beyond. An alternate explanation would be that the source liquid for each of the flows originated in one of Weigand and Ragland's fields and then in-flow differentiation produced this trend toward the other pod. The difference between interpretations relates only to the location of differentiation--in a magma chamber or after extrusion within the flow. The implication is that transitions between Weigand and Ragland's fields seems to have occurred. Some additional data are available from the Connecticut basin. This data are shown in figure 6 as points labeled "C". This data, which includes samples from both flows and at least one dike, have a very similar trend.

The points from the diabase lens (labeled as Roman numerals I through X in figure 6) follow the same trend as those from the rest of the flows, indicating that the SiO_2 enrichment/iron depletion within-flow differentiation trend is superimposed on the tholeiitic Fenner trend.

The mafic index change through time is attributable to the tholeiitic Fenner trend, while the changes in the TiO_2 content are as yet unexplained. Yagi (1967) states that little is known of the participation of TiO_2 in the basalt system. There is no explanation for the trend's subsequent reversal within the area occupied by the second Watchung samples. The removal of a phase containing significant amounts of TiO_2 would result in an initial decrease; and cessation of precipitation while other phases continue to crystallize and are removed would result in an increase in

TiO₂ content. However, the change of the initial TiO₂ content as observed are substantial: a decrease of fifty percent, and then a subsequent increase of 130 percent. A second possibility is the precipitation of a TiO₂ rich phase re sorbed after cessation of precipitation.

L. Maxey (personal communication) has begun a study of the diabase dikes in the New Jersey Reading Prong, an area not yet studied in detail. His initial work shows the presence of another clustering of quartz-normative diabase from several dikes in the area of high TiO₂ and a low MI, near point "R" (figure 6).

Should further work confirm this tight clustering of data from the eastern North American diabase intrusions, then a considerable problem exists because of this conflicting history of an otherwise similar magma. Neither the Connecticut flows nor the Watchung flow units exhibit a tight clustering on this plot, but grade from one field to another. Apparently, the intrusive diabase were emplaced only during certain periods of the fractionation history represented more completely by the Watchung sequence.

Trace Element Variations

Gast (1968) has shown that the major to trace element ratio, K/Rb , varies linearly with the log percent K for oceanic basalts over a wide variety of types and locales (figure 7). The K/Rb trend for the samples from the Watchung flow basalts have a distinct and tightly controlled trend showing a decrease in the relative amount of Rb with increasing K content (shown schematically in figure 7, and in detail in figure 8). This trend is across that of other known basalt suites, and shows no clustering of samples from individual Watchung flow units. The K/Rb ratio of some samples is very low, possibly as low as has yet been observed in basalts.

Stueber and Murthy (1966) believe Gast's oceanic basalt trend is a result of an early but selective differentiation of the proto-mantle material. Green and Ringwood (1967) believed the ratio to be a result of simple fractionation within the mantle. Gast (1965) believes that the largely homogeneous mantle is partially melted to various extents to provide the particular ratio observed, and has shown (Gast, 1968) that the trend of ratios observed may be adequately accounted for by fractionally melting between three and six percent of any probably mantle composition, and that such a product will fall on the observed K/Rb versus K trend. Rocks with K/Rb ratios that do not fall on this trend probably did not originate by partial melting of the mantle. Gast also

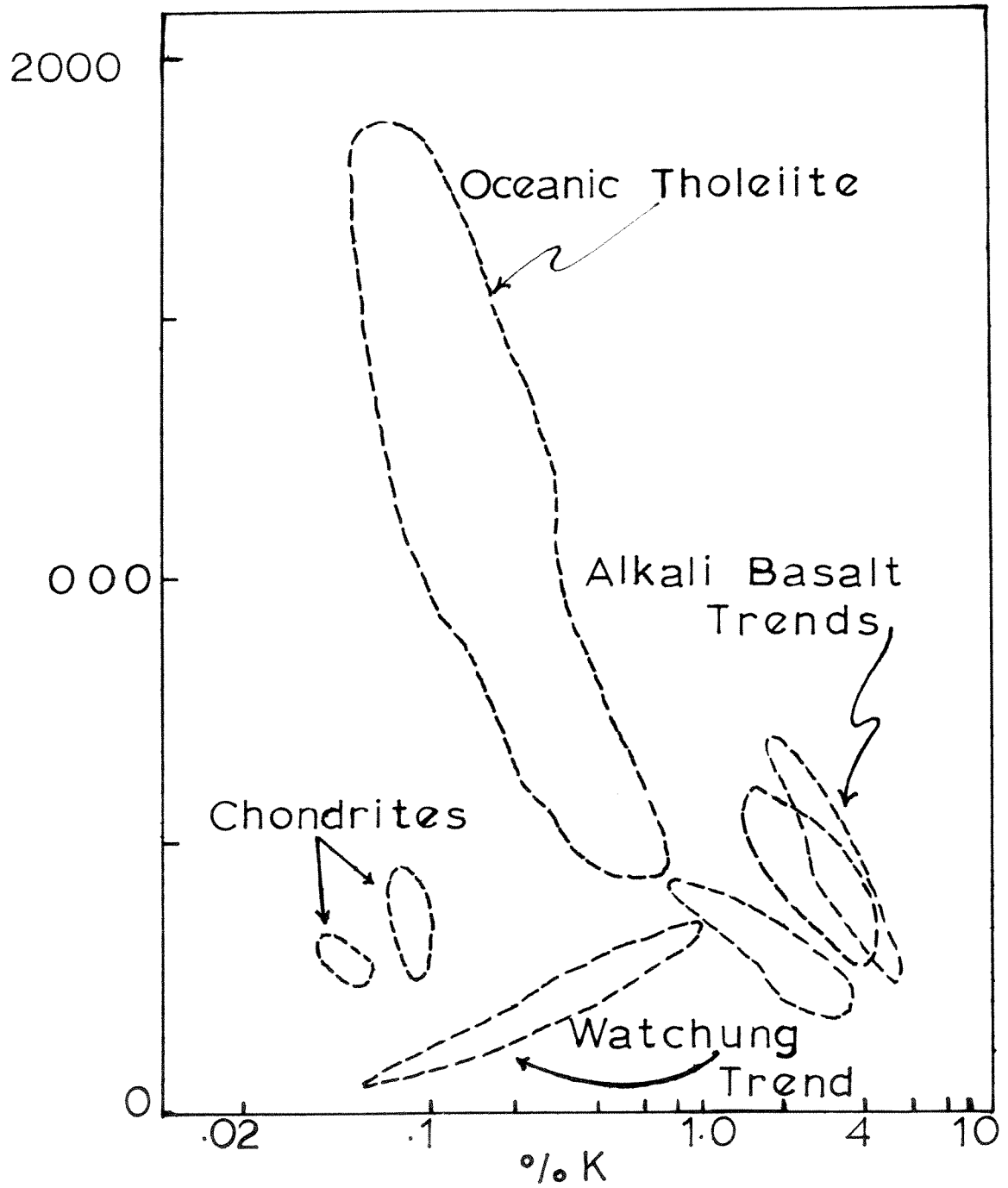


Figure 7: K/Rb versus K for Oceanic basalts after Gast (1965)

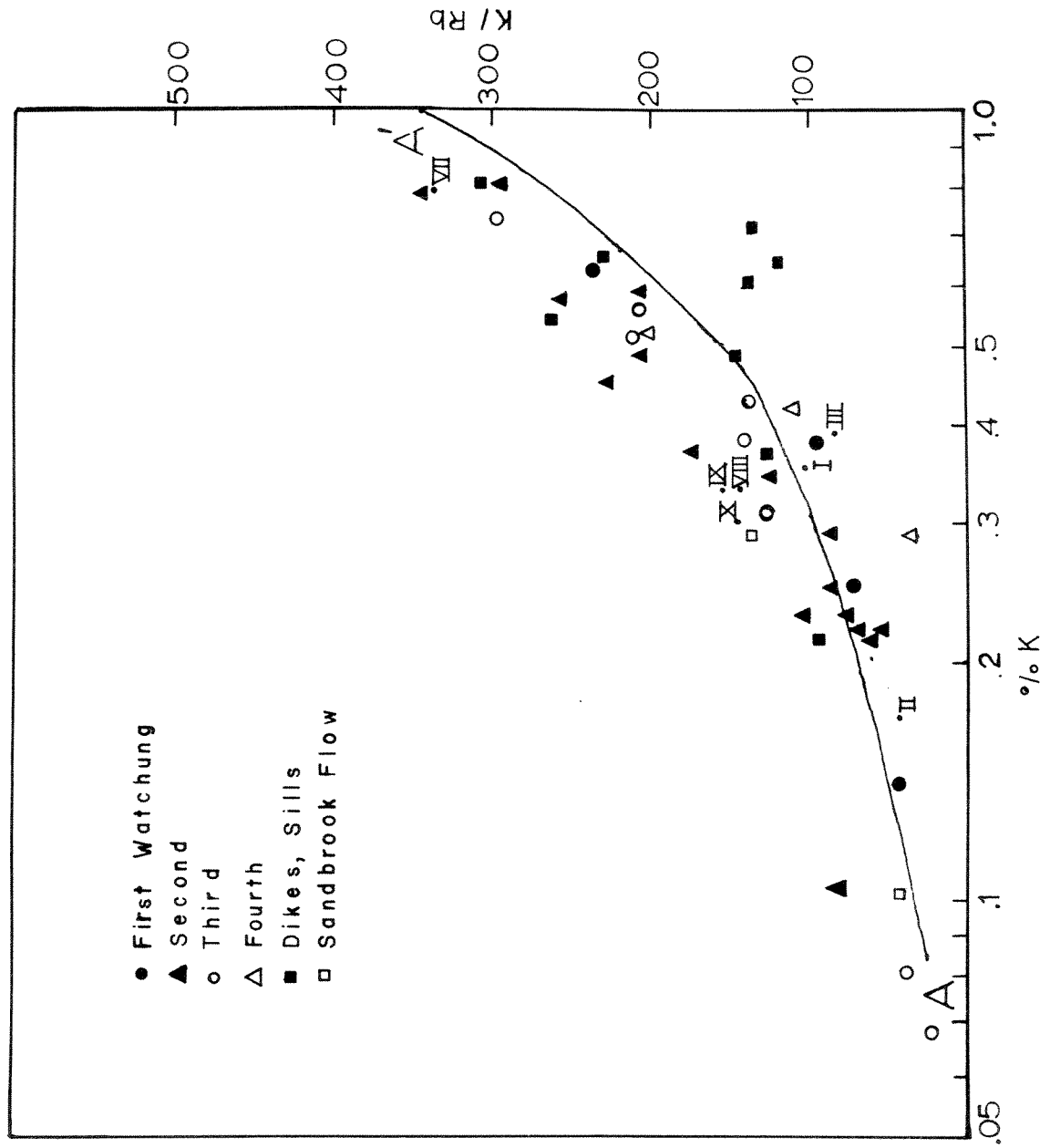


Figure 8: Plot of K/Rb versus K

contends that the K/Rb trend of oceanic basalts could not originate from fractional crystallization at depth without producing a differentiated liquid. At least 90 per cent of a liquid must crystallize as hornblende to produce the observed trend.

The Watchung K/Rb trend is a result of a large variation in K, but a relatively small change in the Rb content. An examination of the K and Rb content of the samples analyzed shows Rb varies between 20 and 40 ppm, while K varies between 800 and 10,000 ppm. A calculated plot of a changing K content with invariant Rb is shown in figure 8 as the curve A-A'. It produces a scatter of points similar to the trend for the Watchung flow units.

Plagioclase feldspar samples from the first, second, and fourth Watchung flow units were magnetically separated and analyzed. Visual microscopic inspection of the separated feldspar indicated it was almost entirely free of dark minerals, and only a very small quantity of pyroxene was still present. Sample 34B was treated with dilute HCl to dissolve calcite which was present in significant amounts. The K and Rb content of the feldspars was obtained by X-ray fluorescence. The range of the K/Rb ratio of the feldspar separates is identical for the samples from the first and fourth Watchung flow units and overlap that of the second flow unit substantially.

Table 3:

K/Rb Ratios for Several Feldspar Separates

<u>Sample</u>	<u>Watchung</u>	<u>K%</u>	<u>Rb (ppm)</u>	<u>K/Rb Range</u>
46	First	.56± .06	27± 3	167 to 260
34B	Second	.42± .04	22± 2	158 to 230
66b	Fourth	.40± .04	19± 2	171 to 260

Jakes and White (1970) have used this approach to show that there was no interferring phase, such as biotite, which controlled the distribution of K and Rb between the feldspar phase and itself in the history of the island arc basalts they studied.

The absence of any controlling phase which might selectively partition K or Rb suggests that the K/Rb ratios were not imposed during fractional crystallization of the parent basalt magma. The fact that the K/Rb values from each Watchung flow unit fail to cluster, and instead span the range of observed values, tends to confirm this conclusion and to suggest another process, operating subsequently to primary fractionation of the magma, is responsible for the observed trend.

Green and Ringwood (1967) have suggested that basalt magma in contact with the wall rock might undergo an enrichment in poorly fitting, incompatible elements through the precipitation of a purer phase and the resorption of an impure phase which melts at a lower temperature. The precipitation of the pure phase releases heat energy which

is used to dissolve the impure phase.

Table 4 is a listing of several incompatible element to major element ratios, indicates an increase in every case. However, the increases are small in the case of Ti/Zr, and K/Rb, while the Fe/Ni increases of one hundred percent are probably controlled by the iron enrichment trend. The Ca/Sr ratio is increased seventy percent largely due to a depletion of CaO during fractionation between the flows. A ratio which changes erratically over at least an order of magnitude within the sequence might indicate assimilation of crustal materials with their widely varying incompatible element to major ratios. A ratio which is reasonably stable through the sequence is an indication of a partial fusion product which has equilibrated with its wall rock within the mantle, and has been uncontaminated passing through the crust.

Oceanic basalts show the latter distribution of ratios. The Watchung flow units show no clustering along the K/Rb trend and do not display an unaccountably large variation of incompatible to major element ratio. Either the Watchung basalts did not undergo a wall rock reaction during the several million year history of fractional crystallization, or there was not sufficient wall rock in contact with the magma to produce a notable change in the ratio.

Table 4: Mean Major-to-Trace Ratios for Watchung Flow Units

<u>Watchung</u>	<u>Fe/Ni</u>	<u>K/Rb</u>	<u>Ti/Zr</u>	<u>Ca/Sr</u>	<u>Sample Size</u>
First	828	70	136	347	6
Second	1201	178	124	536	21
Third	1460	209	110	738	8
Fourth	1450	126	115	706	3

The low K/Rb ratio of the Watchung basalt sampled could have been induced by contamination of the magma by low ratio continental material. To test this hypothesis, the K and Rb values for the USGS standards were used as possible contaminants in varying amounts. To several points on the oceanic basalt trend, various amounts of each of the standards were added, and the resulting set of points plotted (figure 9). The new K content has been recalculated. The low K/Rb values of the Watchung basalt flows can be explained as the result of assimilation of one of several continental rocks: the USGS standards G-2, GSP-1, and AGV-1 would do notably well. For each of the standards, a contamination of seven to ten percent is sufficient.

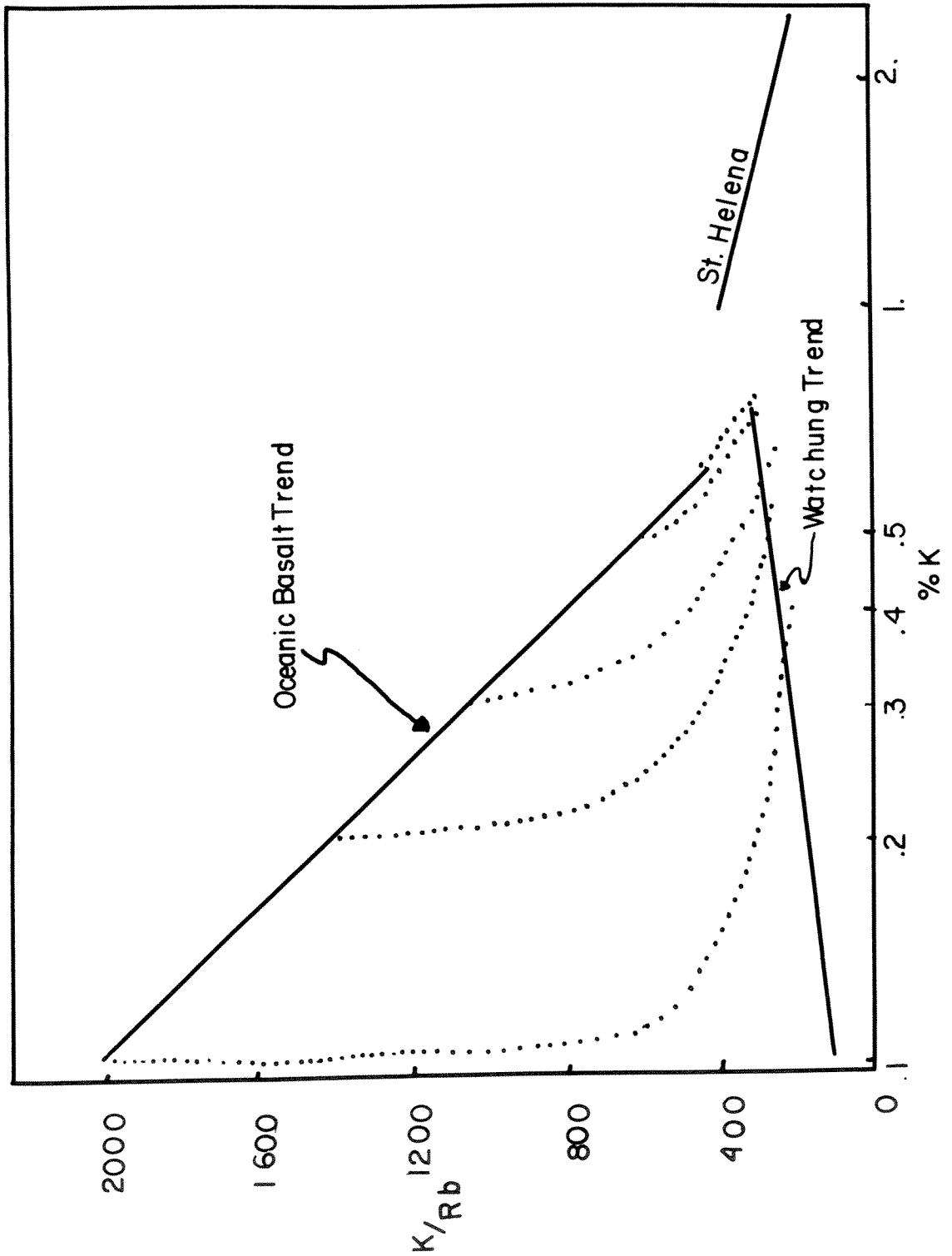


Figure 9: Plot of K/Rb versus K showing contamination of oceanic rocks to obtain Watchung trend. GSP-1 is contaminate.

Magmatic History

There are three possible times in the history of the magma during which it could have acquired its low K/Rb values. These are at the time of partial fusion in the mantle, during differentiation, and during the time of eruption of the individual flows.

The evidence of major element chemistry suggests that the Watchung basalts are the product of the differentiation of a single, homogeneous parent magma. It is not known whether the K/Rb ratio of this magma was similar to some point on the oceanic tholeiite trend, or as low as those observed now in the Watchung basalts. No point on the observed K/Rb trend intersects the oceanic tholeiitic trend, so that it is unlikely that any fusion process which produces tholeiites, unless totally unlike those operating beneath the oceanic crust, could have produced the extremely low ratios found.

The failure of individual Watchung flow units to cluster along the K/Rb trend suggests that the observed variation was not imposed during the differentiation of the parent magma, which produced such a systematic and uniform variation in the major element composition between each of the Watchung flow units. Instead, the observed variation must be the result of some process acting upon material of each flow unit after its isolation from the parent magma.

If the low range of values of K/Rb was produced during the eruptive phase, it was probably through a process of contamination in the crust. There is no obvious phase which was crystallizing during the later history of the Watchung basalt magma which could lead to such drastic changes in K/Rb ratios. The variation along the trend, and the failure of individual Watchung flow units to cluster along the trend may be simply a function of the amount of K which has accumulated within a particular sample. Individual feldspars from each of the flow units have essentially the same K/Rb ratio.

The case for contamination is by no means clear. Weigand and Ragland (1971) report that they were unable to mix continental rocks with oceanic tholeiites in any proportion to achieve the suite observed in the eastern North American dolerites they studied. They also report that P. D. Fullagar has obtained $\text{Sr}^{86}/\text{Sr}^{87}$ ratios on a number of these dolerites and has found the ratios indicate an uncontaminated basalt which could be directly derived from the mantle.

Relationship Between Flows and Intrusives

There is a close genetic relationship between the intrusive and extrusive Newark Group igneous rocks. On every chemical plot in which a systematic trend may be demonstrated, the dikes and sills plot in the same trend. Other eastern North America diabase do not plot on the same trend (see data of Ragland, et al (1968) or Weigand and Ragland (1970)). A plot of percent Ti versus Ti/Zr ratio for the flows and intrusives is shown in figure 10. There is no apparent clustering of points from a given flow or dike. The trend is well developed and shows a tight control of Zr by Ti content. Note that all dikes and flows plot on the same trend. The same situation prevails on the plot of percent K versus the K/Rb ratio (figure 8). Unlike the K/Rb trend, this trend is real and represents an order of magnitude change in both Ti and Zr contents. All values, whether from the flows or intrusives plot on the same trend (figures 3, 4, 6, 8, 10). This is taken to be indicative of a close genetic relationship between the Triassic intrusive and extrusive igneous rocks in the Newark basin.

Walker (1969) has suggested that the three Watchung flow units represent an external expression of multiple intrusions he postulates for the Palisades sill. However, the average compositions of the Watchung basalts are not similar to those he suggested for the Palisades, and

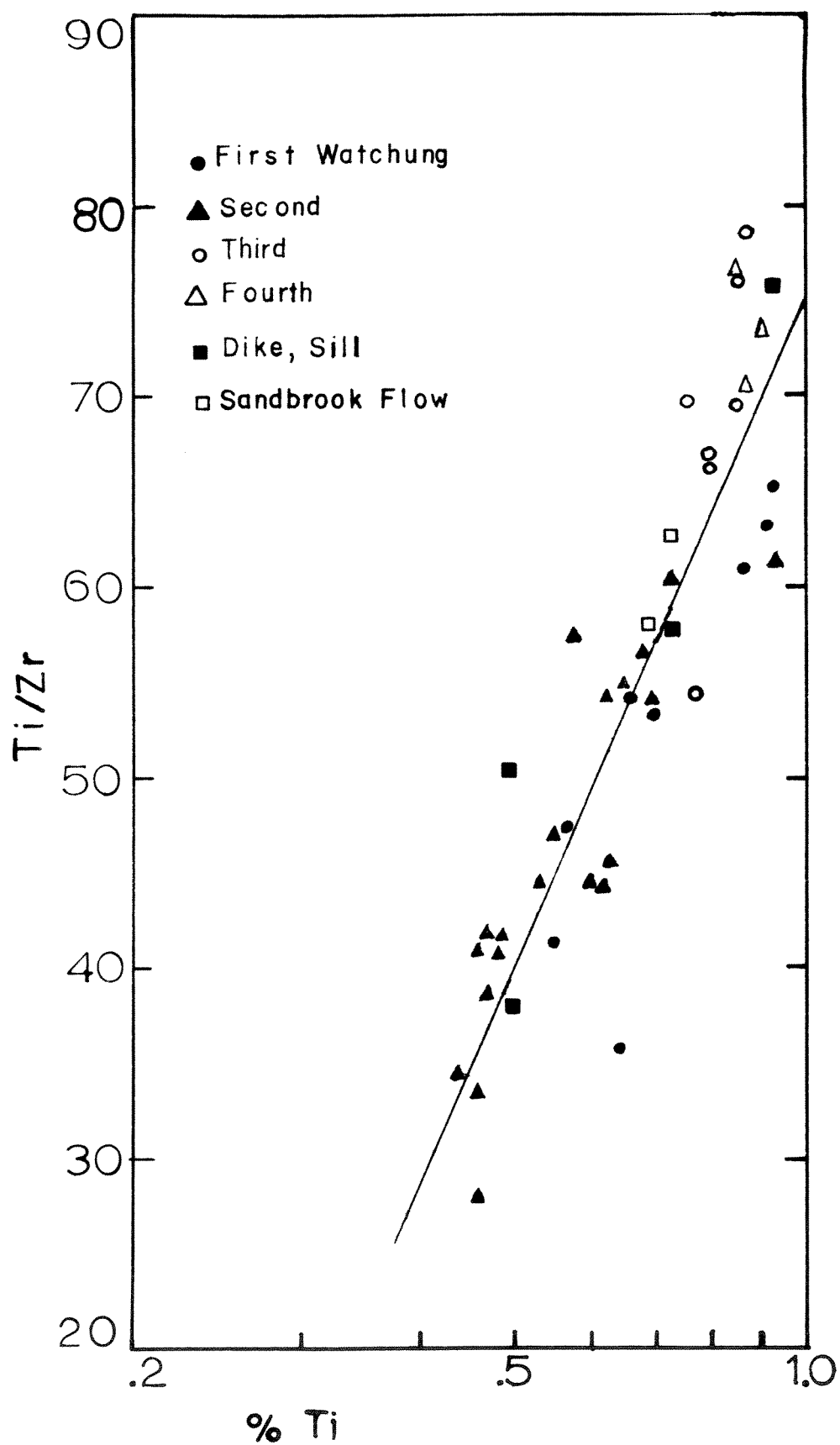


Figure 10: Plot of Ti/Zr versus Ti

the flows show a tight, well defined differentiation history which is quite different from that of the Palisades.

Discriminate Analysis for Several Groups (BMDO5M, Dixon, 1968) was applied to the available data for the three Watchungs as well as data for the Palisades sill and its extension at Rocky Hill and the Sourland Mountain. An approximation of the Chi-square test for independence of means with 69 degrees of freedom yields a statistic of 450 which is indicative of a highly significant independence of means at a 0.01 significance level. A value above 85 is significant. The Three Watchung flow units can be considered statistically different. However, the relationship of the third to the fourth Watchung is also in question.

Kummel (1897), Lewis (1907), as well as virtually all workers in the Newark basin, have suggested that the ridge composed of basalt which outcrops along the border fault between Morristown and Bernardsville is the result of a poorly developed syncline in the third Watchung. Three fresh samples were obtained from a location near Green Village. The analyses of these samples shows the closest chemical similarity between these samples and those from the third Watchung. They are characteristically low in SiO_2 and high in iron. A statistical test of the difference between the data from samples of the third and fourth Watchung flow units was made using Discriminate Analysis for Two Groups (BMDO4M, Dixon, 1968). Because of limitations imposed by the small sample size, the test was made using three variables

which were thought to discriminate well between the first three Watchung flow units: 1) $\text{SiO}_2/\text{FeO} + \text{Fe}_2\text{O}_3$; 2) Ca/Sr , both in ppm; and 3) mafic index/ TiO_2 . An F statistic and the associated Mahalanobis D-square statistic were derived using these variables from the two groups of data. The value of The F statistic ($F(3,7) = 0.045353$), where F greater than 18.77 at the 0.1 significance level, and the value of the D-square statistic (D-square with three degrees of freedom) where D-square greater than 17.73 at a 0.00005 significance level, are such that it is highly probable that these two populations are the same. The values from the fourth Watchung cluster with those from the third in figures 4 and 7. This, and the statistical evidence of this study, are strong support of the structural evidence of Lewis (1907) that the fourth and third Watchungs are both part of the same flow.

Conclusion and Summary

The Watchung flow units have been shown to be chemically a closely related series of basaltic lava flows. The average composition of each flow is that of a quartz normative tholeiitic basalt. These basalts are closely related to the other eastern North American diabase of other studies but do have certain unique features. The flows follow a differentiation sequence similar to the tholeiites of Hawaii. No oxygen buffer such as water and/or carbon-dioxide was present in sufficient quantities to produce a Bowen trend. However, upon extrusion, in at least one location in the second Watchung, a constantly increasing partial pressure of oxygen produced a silica enriched, iron depleted, coarse grained diabase. The iron was highly oxidized.

Another trend of major element variation is the mafic index- TiO_2 content. The relative amount of TiO_2 decreases between the first and second flow units, then increases between the second and third. This behavior is as yet unexplained.

The trace element to major element ratio of K/Rb shows extremely low values, and a trend which is contrary to that of oceanic tholeiites. The low values were probably the result of contamination of the primitive basaltic fluid. The trend may reflect the potassium content with an invariant rubidium content in any particular sample.

The three Watchung flow units are shown statistically to be chemically distinct, and the fourth is shown to be a portion of the third.

The flows and several intrusives are thought to have a close genetic relationship, but it has not been possible to relate the flows to a series of tectonic events by means of chemical affinities.

References Cited

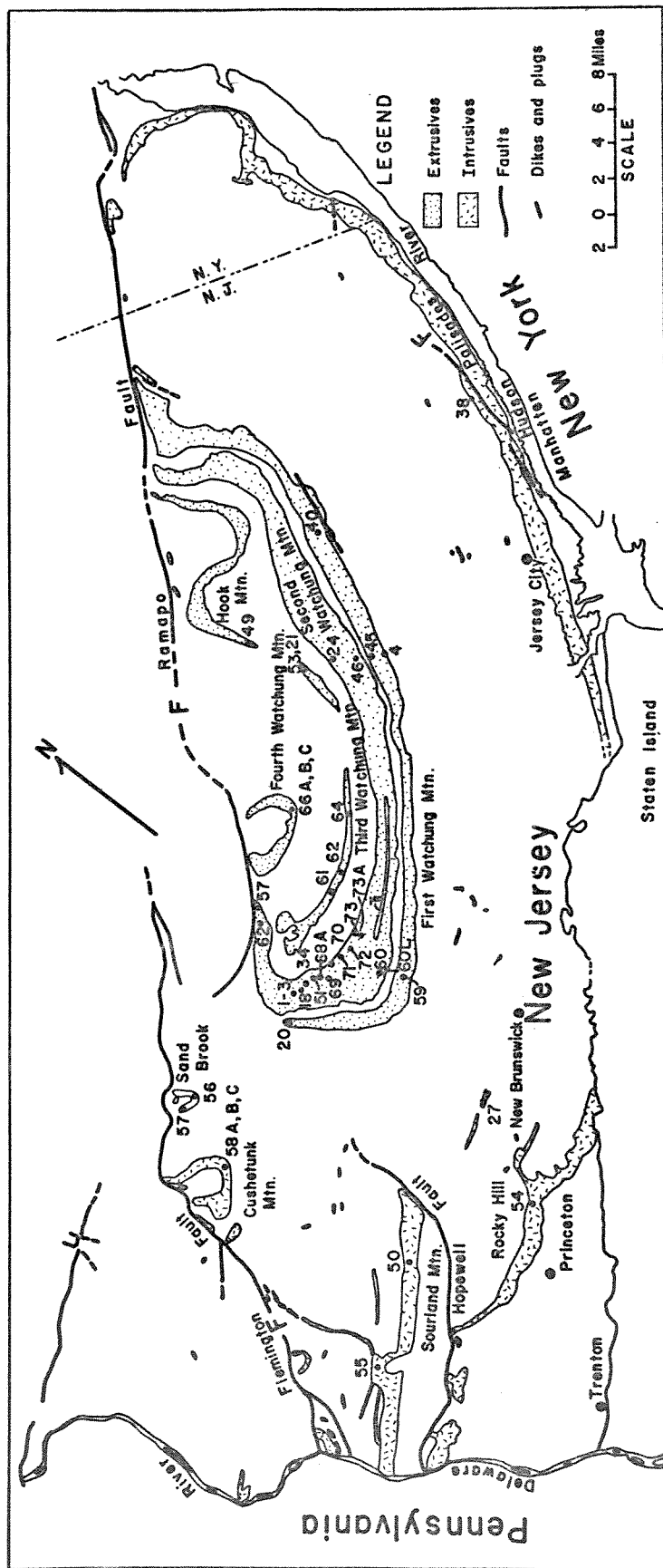
- Armstrong, R. L., Besancon, J.: A Triassic time scale dilemma: K-Ar Dating of Upper Triassic Mafic Igneous Rocks, Eastern U.S.A. and Canada, and Post-Upper Triassic Plutons, Western Idaho, U.S.A., *Eclogae Geologicae Helvetiae*, 63, p. 15-28, (1970).
- Bailey, E. B., Clough, C. T., Wright, W. B., Richey, J. E. and Wilson, G. V.: Tertiary and post-tertiary geol. of the Mull, Loch Aline, and Olson, Mem. Geol. Survey Scot., 445 pp., (1924).
- Burri, C.: Petrochemical Calculations, translated by A. Katz, Sivan Press, Jerusalem, 304 pp., (1964).
- de Boer, J.: Paleomagnetic differentiation and correlation of the late Triassic volcanic rocks in the central Appalachians, *Geol. Soc. Am. Bull.* 79, p. 609-626, (1968).
- Darton, N. H.: The relations of the traps of the Newark system in the New Jersey region, U. S. Geological Survey Bulletin No. 67, (1890).
- Dixon, W. J.: BMD Computer Programs, University of Calif. Press, Berkeley, Calif., 600 pp., (1968).
- Earl, A. J.: The terrestrial abundance relationship between K and Rb, In: L. H. Aherns (ed.), *Origin and Distribution of the Elements*, Ed.; Pergamon Press, Oxford, 1178 pp., (1968).
- Flanagan, F. J.: U. S. Geological Survey standards-II. First compilation of data for the USGS rocks, *Geochem, Cosmochem Acta*, 33, p. 81-120, (1969).
- Fairbairn, H. W. and Hurley, P.M.: Evaluation of X-ray fluorescence and Mass Spectrometric analyses of Rb and Sr in some silicate standards, *Geochem, Cosmochem Acta*, 35, p. 149-156, (1971).
- Gast, P. W.: Terrestrial Ratio of K to Rb and the Composition of the Earth's mantle, *Sci.*, 147, p. 147-149, (1965).
- _____: Trace element fractionation and the origin of tholeiitic and alkaline magma types, *Geochem, Cosmochem Acta*, 32, p. 1057-1086, (1968).

- Green, D. H. and Ringwood, A. E.: The genesis of basaltic magmas, *Contr. Mineral. Petrol.*, 15, p. 103-190, (1967).
- Jakes, P. and White, A. J. R.: K/Rb ratios of rocks from island arcs, *Geochem, Cosmochem Acta*, 34, p. 849-856, (1970).
- Kummel, H. B.: The Newark System-Report of progress, Report of the State Geologist, Trenton, New Jersey, (1897).
- Kuno, H.: High-Alumina basalts, *J. of Petrol.*, 1, p. 121-145, (1960).
- Lewis, J. V.: Petrography of the Newark Igneous Rocks of New Jersey, Annual Report of the State Geologist, p. 99-167, Trenton, New Jersey, (1907).
- McKee, E. D., Oreel, S. S., Kepner, K. B., MacLachlin, J. E., Goldsmith, J. W., McLachlin, J. C. and Mudge, M. R.: Paleotectonic maps of the Triassic system, U. S. Geol. Survey Misc. Geol., Inv. Map I 300, (1959).
- Manson, V.: Geochemistry of Basaltic Rocks: Major Elements, In: Hess, H. H., Poldervaart, A. (ed.), *The Poldervaart Treatise on Rocks of Basaltic Composition*, 1, Interscience, New York, 482 pp., (1967).
- MacDonald, G. A.: Comp. and Origin of Hawaiian lavas, in: R. R. Coats, R. L. Hay and C. A. Anderson (eds.), *Studies in volcanology*, *Geol. Soc. Am. Mem.*, 116, 477-522, (1968).
- Manspeizer, W.: Paleomagmatic structures in late Triassic basaltic lavas of the Newark basin, (abs.), in: *Abstracts with Programs*, Pt. 7, *Geol. Soc. Am.*, (1969).
- Nocholds, S. R.: Average chem. comp. of some igneous rocks, *Geol. Soc. Am. Bull.*, 65, p. 1007-1032, (1954).
- Osborn, E. F.: Role of Oxygen pressure in the crystallization and differentiation of basaltic magmas, *Am. J. Sci.*, 257, p. 609-647, (1959).
- Powers, H. A.: The lavas of the Modoc lava-bed quad., Calif., *Amer. Min.*, 17, p. 253-294, (1932).
- Ragland, P. C., Rogers, J. J. W. and Justus, P. S.: Origin and differentiation of Triassic dolerite magmas, N. C., U. S. A., *Contr. Mineral. Petrol.*, 20, p. 57-80 (1968).

- Ratcliffe, N. M.: Ramapo fault system in M. Y. and adjacent Northern N. J.: A cast of tectonic heredity, *Geol. Soc. Am. Bull.*, 82, p. 125-142, (1971).
- Rose, H. J., Adler, I. and Flanagan, F. J.: X-ray fluorescence analysis of the light elements in rocks and minerals, *App. Spectry.*, 17, p. 81-85, (1963).
- Schafer, H. M. S.: Determination of iron 2 (oxide) in silicate and refractory materials, *Analyst*, 91, p. 763-770, (1966).
- Stuber, A. M., Murthy: K-Rb Ratio in Ultramafic Rocks: *Diff. of Upper Mantle Sci.*, 153, p. 740, (1966).
- Tilley, C. E.: Some Aspects of Magmatic evolut., *Quart. J. Soc. Lond.*, 106, p. 37-61, (1950).
- _____: Differentiation of Hawiian basalts: Some variants in lava suites of dated Kilauean eruptions, *J. Petrol.*, 1, p. 47-55, (1960).
- Van Houten, F.: Late Triassic Newark Group, north central N. J. and adjacent N. Y. and Pa. In: S. Subitzky (ed.), *Geology of selected areas in New Jersey and Eastern Penn.*, p. 314-347, New Brunswick, N. J., Rutger's U. Press, (1969).
- Walker, F.: Differentiation of the Palisades diabase, N. J., *Geol. Soc. Am. Bull.*, 51, p. 1059-1106, (1940).
- Walker, K. R.: The Palisades Sill, New Jersey: A Reinvestigation, *Sp. Paper 111*, *Geol. Soc. Am.*, (1969).
- Weigand, P. W.: Major and trace element Geochemistry of the Mesozoic dolerite dikes from Eastern North America, Ph.D. thesis, University of North Carolina, (1970).
- Weigand, P. W. and Ragland, P. C.: Geochemistry of Mesozoic dolerite dikes from eastern North America, *Contr. Mineral. and Petrol.*, 29, p. 195-214, (1970).
- Yagi, K.: Silicate systems related to Basaltic Rocks, In: Hess, H. H., Poldervaart, A. (ed.), *The Poldervaart Treatise on Rocks of Basaltic Composition*, 1, Interscience, New York, 482 pp., (1967).
- Yoder, H. S. and Tilley, C. E.: Origin of basalt magmas: an experimental study of natural and synthetic rock systems, *J. Petrology*, 3, p. 342-532, (1962).

APPENDIX I
Analyzed Samples

Location refers to the sample's location as shown on Map 1.
Standard Norm calculated after Burri (1964).
nd refers to values not determined for a particular sample.



Appendix I: Analyzed Samples

Weight Percent Oxide

Sample Location	T Conn	W Conn	3rd Third	1				3 2nd	4 1st	18 1st
				2nd	2nd	2nd	2nd			
SiO ₂	50.90	52.50	47.90	51.60	54.60	51.20	49.00	52.30		
Al ₂ O ₃	13.50	13.80	11.50	14.30	11.10	13.60	9.20	13.40		
Fe ₂ O ₃	3.90	4.90	4.00	3.90	4.00	3.90	2.80	4.60		
FeO	11.40	6.40	11.10	9.30	9.60	9.40	6.80	8.90		
MnO	0.30	0.20	0.0	0.10	0.20	0.20	0.20	0.20		
MgO	4.80	5.90	4.20	5.50	5.00	5.90	9.20	3.96		
CaO	10.10	7.40	9.70	9.80	10.20	10.10	13.70	9.20		
Na ₂ O	3.10	3.40	2.40	3.80	3.10	3.20	2.90	3.35		
K ₂ O	0.10	0.90	0.0	0.20	0.20	0.20	0.10	0.30		
TiO ₂	1.10	1.50	1.40	1.00	1.00	1.00	1.00	1.60		
RB(ppm)	22	38	25	18	27	24	55	35		
SR	142	43	106	nd	nd	nd	379	138		
ZR	140	105	113	130	139	137	179	138		
NI	76	64	79	72	92	79	80	78		
Standard Norm										
Q	1.2	4.5	5.3	0.0	7.0	0.8	0.0	8.4		
OR	00.6	5.5	0.0	1.2	1.2	1.2	0.6	1.9		
AB	28.7	31.8	24.2	34.6	28.8	29.5	27.4	31.9		
AN	23.4	20.6	23.2	21.7	16.3	22.8	12.4	22.5		
DI	19.5	9.8	20.35	19.3	25.9	20.12	41.00	16.5		
EN	9.1	13.5	8.5	7.9	7.5	10.9	0.0	3.6		
HY	10.7	5.6	10.6	6.2	6.7	8.2	0.0	6.4		
FO	0.0	0.0	0.0	1.6	0.0	0.0	8.7	0.0		
FA	0.0	0.0	0.0	1.22	0.0	0.0	8.65	0.0		
MT	4.22	5.3	4.7	4.14	4.33	4.2	3.1	5.2		
TIT	2.4	3.3	3.3	2.1	2.2	2.2	2.2	3.6		

Appendix I: Analyzed Samples

Weight Percent Oxide

Sample Location	20C 1st	21 3rd	24 2nd	27 dike	34C 2nd	38 Palisades	39 1st	40 1st
SiO ₂	49.20	49.50	52.70	52.40	51.60	51.00	50.50	51.30
Al ₂ O ₃	13.50	12.20	13.50	13.20	12.20	12.60	13.80	13.60
Fe ₂ O ₃	4.40	7.40	1.66	3.80	5.70	1.70	3.80	2.30
FeO	8.69	8.30	7.98	5.35	5.60	8.40	5.20	7.30
MnO	0.20	0.20	0.20	nd	0.20	nd	0.10	0.10
MgO	6.91	4.70	4.80	6.50	8.00	7.80	6.60	6.44
CaO	10.00	6.90	5.70	10.80	7.60	9.80	10.70	10.50
Na ₂ O	2.65	3.60	4.50	1.70	3.80	2.40	2.70	2.70
K ₂ O	0.08	0.50	0.70	0.40	0.10	0.80	0.30	0.30
TiO ₂	0.90	1.30	1.50	1.20	0.70	1.10	0.90	1.00
RB(ppm)	38	40	25	34	19	38	32	19
SR	294	149	114	186	nd	186	154	nd
ZR	119	141	149	123	125	nd	132	nd
NI	104	93	78	89	62	86	81	55

Standard Norm

Q	0.0	4.6	2.12	9.80	2.80	0.85	3.95	3.94
OR	0.5	3.2	4.27	2.50	0.62	4.97	1.88	1.89
AB	45.3	35.1	41.71	16.15	35.69	22.63	25.74	25.78
AN	15.0	16.9	15.04	28.78	16.67	22.31	26.18	25.63
DI	0.0	12.2	7.01	18.78	16.18	19.78	21.50	16.20
EN	0.0	10.3	11.39	12.27	16.53	16.25	11.13	14.13
HY	0.0	6.4	5.92	4.86	3.75	8.93	3.40	7.65
FO	14.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FA	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MT	4.7	8.4	9.30	4.21	6.24	1.87	4.22	2.56
TIT	1.9	2.9	3.24	2.65	1.53	2.41	2.00	2.22

Appendix I: Analyzed Samples

Weight Percent Oxide

Sample Location	45 1st	46 2nd	49 3rd	50 Sourland	51 2nd	52 Jugtown Mt.	53 3rd	54 Rocky Hill
SiO ₂	50.80	53.00	49.30	52.50	59.00	52.20	49.70	50.20
Al ₂ O ₃	13.70	13.50	12.90	12.00	14.80	13.90	13.60	14.30
Fe ₂ O ₃	2.79	3.60	5.40	0.10	3.37	4.70	3.58	5.10
FeO	7.13	9.20	9.10	9.00	4.22	8.70	10.80	5.40
MnO	nd	nd	nd	0.20	nd	nd	nd	nd
MgO	7.50	4.70	3.90	6.90	1.28	3.10	4.58	7.60
CaO	10.60	9.40	9.80	11.30	4.15	9.20	9.75	10.20
Na ₂ O	2.00	2.50	2.00	3.10	3.30	2.30	2.06	1.90
K ₂ O	0.20	0.40	0.50	0.30	1.26	0.60	0.27	1.00
TiO ₂	1.10	1.10	1.30	0.80	1.10	1.50	1.65	1.70
RB (ppm)	39	31	29	26	61	37	11	20
SR	165	122	91	148	204	824	64	191
ZR	121	118	110	130	128	121	46	100
NI	89	73	88	75	41	90	56	86
Standard Norm								
Q	4.82	8.02	8.69	0.0	24.23	10.93	5.85	4.34
OR	1.24	2.49	3.26	1.84	11.58	3.82	1.72	6.14
AB	18.91	23.62	19.78	28.95	30.72	22.24	19.91	17.72
AN	29.29	25.71	27.26	18.66	20.72	27.82	29.14	28.61
DI	17.65	15.47	17.05	29.40	0.0	12.57	13.40	14.25
EN	15.69	9.61	7.52	10.05	3.67	6.36	10.47	16.02
HY	6.90	8.70	7.22	7.48	4.35	7.58	11.79	3.67
FO	0.0	0.0	0.0	1.02	0.0	0.0	0.0	0.0
FA	0.0	0.0	0.0	0.76	0.0	0.0	0.0	0.0
MT	3.07	3.96	6.23	0.11	3.66	5.30	4.03	5.54
TIT	2.42	2.42	2.99	1.74	0.38	3.38	3.71	3.69

Appendix I: Analyzed Samples

Weight Percent Oxide

Sample Location	60L 2nd	61A 3rd	62 3rd	64 3rd	64A 3rd	66A 4th	66B 4th	66C 4th
SIO2	50.00	47.00	47.50	50.40	49.70	50.98	47.80	49.20
AL2O3	12.40	12.50	12.70	12.20	11.40	13.50	13.30	13.50
FE2O3	2.09	4.73	4.50	3.50	2.80	2.90	3.20	3.40
FEO	9.33	9.70	10.20	11.30	11.30	11.80	11.70	11.00
MNO	nd	nd	nd	nd	nd	nd	nd	nd
MGO	5.21	4.37	5.10	3.50	4.50	3.60	3.90	3.80
CAO	8.50	9.33	7.10	9.30	9.50	9.80	9.50	9.40
NA2O	3.02	3.75	3.00	2.00	1.90	2.00	2.00	2.30
K2O	0.80	0.88	0.60	0.40	0.40	0.70	0.50	0.50
TIO2	1.12	1.33	1.30	1.40	1.50	1.40	1.50	1.40
RB (ppm)	18	29	16	29	25	26	39	27
SR	96	92	52	118	85	94	102	85
ZR	119	121	117	124	112	123	114	110
NI	55	79	63	84	78	66	84	83

Standard Norm

Q	1.63	0.0	1.55	9.52	7.44	7.53	4.21	4.90
OR	5.18	5.74	3.94	2.61	2.63	4.38	3.28	3.23
AB	29.69	29.81	29.93	19.80	19.00	19.03	19.92	22.57
AN	19.62	19.85	21.57	25.51	23.85	27.34	28.66	27.37
DI	17.83	20.88	10.03	16.00	18.28	15.22	14.26	14.63
EN	11.08	6.76	13.02	7.54	8.79	7.65	9.07	8.43
HY	10.01	6.57	11.71	11.76	12.26	12.52	13.40	11.79
FO	0.0	0.95	0.0	0.0	0.0	0.0	0.0	0.0
FA	0.0	0.92	0.0	0.0	0.0	0.0	0.0	0.0
MT	2.39	5.46	5.23	4.04	3.26	3.22	3.71	3.89
TIT	2.56	3.07	3.02	3.23	3.49	3.10	3.48	3.20

Appendix I: Analyzed Samples

Weight Percent Oxide

Sample Location	67 2nd	68 2nd	68A 2nd	69 2nd	70 2nd	71 2nd	71A 2nd	72 2nd
SiO ₂	49.40	50.30	51.00	51.70	49.60	51.50	51.40	50.30
Al ₂ O ₃	15.20	15.50	14.00	14.90	13.90	14.80	14.30	12.30
Fe ₂ O ₃	2.00	1.60	1.65	1.70	2.16	1.70	2.20	1.80
FeO	8.10	8.40	8.40	8.40	7.87	8.70	8.20	10.70
MnO	nd	nd	nd	nd	nd	nd	nd	nd
MgO	6.66	6.78	4.21	5.80	7.50	6.30	5.80	5.00
CaO	10.90	10.20	8.30	10.90	10.50	9.40	8.70	8.00
Na ₂ O	1.90	1.90	2.93	1.60	2.97	2.50	1.60	2.50
K ₂ O	0.30	0.40	0.95	0.30	0.28	0.30	0.40	0.70
TiO ₂	0.80	0.90	0.95	0.80	1.20	0.80	0.80	1.00
RB (ppm)	35	18	20	31	24	39	31	15
SR	133	118	119	175	116	714	95	90
ZR	121	116	99	133	119	161	114	115
NI	80	76	67	96	80	79	77	58
Standard Norm								
Q	1.49	2.51	3.98	7.35	0.0	3.50	10.04	3.48
OR	1.86	2.47	6.15	1.88	1.72	1.86	2.58	4.53
AB	17.88	17.82	28.82	15.21	27.78	23.57	15.67	24.58
AN	33.61	34.04	24.36	34.50	24.76	29.70	33.45	22.20
DI	16.13	12.44	13.69	15.84	20.12	13.09	8.48	17.87
EN	16.22	16.89	9.36	12.41	9.64	14.45	14.98	10.89
HY	8.86	10.11	9.58	9.17	4.98	10.21	10.45	12.09
FO	0.0	0.0	0.0	0.0	3.98	0.0	0.0	0.0
FA	0.0	0.0	0.0	0.0	2.06	0.0	0.0	0.0
MT	2.19	1.75	1.89	1.88	2.35	1.87	2.51	2.06
TIT	1.75	1.97	2.17	1.77	2.61	1.76	1.82	2.29

Appendix I: Analyzed Samples

Weight Percent Oxide

Sample Location	73A 2nd	73C 2nd	75B 2nd	I 2nd	II 2nd	III 2nd	IV 2nd	V 2nd
SiO ₂	51.80	51.00	49.50	54.70	47.80	49.60	55.40	47.90
Al ₂ O ₃	15.10	15.10	15.30	14.70	13.70	14.20	16.50	15.70
Fe ₂ O ₃	3.20	2.07	2.50	3.43	4.47	4.08	5.88	3.17
FeO	7.40	8.50	8.10	8.89	8.85	9.56	5.79	6.45
MnO	nd	nd	nd	nd	nd	nd	nd	nd
MgO	5.80	7.00	7.00	5.75	8.35	5.87	5.78	3.97
CaO	10.80	10.00	10.30	10.10	10.30	7.94	10.10	6.48
Na ₂ O	1.60	1.65	1.60	1.58	1.50	4.25	2.05	4.23
K ₂ O	0.30	0.55	0.40	0.45	0.21	0.47	0.40	1.37
TiO ₂	0.90	0.77	0.80	1.18	1.32	1.32	1.33	1.09
Rb (ppm)	17	16	16					
Sr	137	124	129					
Zr	119	111	115					
Ni	75	81	88					
Standard Norm								
Q	8.87	4.72	4.07	10.76	2.52	0.0	11.38	0.0
Or	1.87	3.40	2.50	2.71	1.31	2.87	2.34	8.96
Ab	15.12	15.51	15.22	14.45	14.20	39.42	18.25	42.01
An	34.87	33.69	35.38	32.29	31.67	18.88	34.35	21.91
Di	14.58	12.36	12.66	11.66	13.90	13.62	9.26	8.49
En	12.79	19.57	2.73	12.29	1.76	12.24	16.40	16.43
Hy	7.06	9.95	9.19	9.17	9.00	2.02	3.75	1.25
Fo	0.0	0.0	0.0	0.0	0.0	7.58	0.0	5.91
Fa	0.0	0.0	0.0	0.0	0.0	5.60	0.0	4.20
Mt	3.52	2.27	3.66	4.93	4.41	6.10	3.67	3.43
Tit	1.98	1.69	1.77	2.51	2.91	2.87	2.26	1.83

Appendix I: Analyzed Samples

Weight Percent Oxide

Sample Location	VII 2nd	VIII 2nd	IX 2nd	X	
				2nd	2nd
SiO ₂	55.30	56.70	53.70	51.20	51.20
Al ₂ O ₃	15.50	14.80	15.20	12.90	12.90
Fe ₂ O ₃	3.41	4.05	6.17	6.37	6.37
FeO	8.87	8.70	5.71	4.95	4.95
MnO	nd	nd	nd	nd	nd
MgO	7.02	8.86	6.81	3.47	3.47
CaO	7.72	8.86	6.81	3.47	3.47
Na ₂ O	4.21	1.80	1.80	1.60	1.60
K ₂ O	0.94	0.38	0.40	0.36	0.36
TiO ₂	1.01	1.05	0.91	0.76	0.76
Rb (ppm)					
Sr					
Zr					
Ni					
Q	0.0	6.88	10.05	Standard	Norm
Or	5.33	2.13	2.38	17.76	
Ab	36.30	15.35	16.27	2.41	
An	19.80	29.61	32.43	16.25	
Di	10.88	13.11	13.86	30.48	
En	10.45	18.68	13.36	18.55	
Hy	6.13	8.14	3.23	3.90	
Fo	3.56	0.0	0.0	1.32	
Fa	2.09	0.0	0.0	0.0	
Mt	3.43	4.02	6.50	0.0	
Tit	2.02	2.08	1.91	7.54	
				1.80	