PETROLOGY AND CHEMISTRY OF A GRANODIORITE PLUTON, HELMCKEN LAND DISTRICT, VANCOUVER ISLAND, B.C.

PETROLOGY AND GEOCHEMISTRY OF A PLUTON OF THE SAANICH GRANODIORITE COMPLEX, HELMCKEN LAND DISTRICT, VANCOUVER ISLAND, B.C.

By

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ABSTRACT

The thesis pluton is part of the Saanich granodiorite batholithic complex on south-east Vancouver Island. The pluton is 11 Km by 2 Km, elliptical and trends NW-SE.

Petrographically its mineral composition is that of a granodiorite. Alteration is fairly intense as shown by plagioclase and potassium feldspar altering to sericite, as well as biotite and hornblende altering to chlorite. Deformation textures were observed in the form of strained quartz and bent cleavage in biotite.

From chemical analyses it was found that the granodiorite represents part of a fractionation process along a calc-alkaline trend. The magma was derived from partial melting of the lower crust.

ACKNOWLEDGEMENTS

Of the numerous people I have to thank, I would like to start with Mr. Brian Kotila, my boss and friend of this past summer. Through his encouragement and advice, this thesis was commenced. Tom Howarth deserves honourable mention for his aid with field work.

I would like to thank Dr. McNutt for being my advisor. His guidance and gentle prodding proved to be invaluable throughout the year.

For other people who assisted, I would first like to express appreciation to Len Zwicker for thin section cutting. His work is truly that of a craftsman. Ota Mudroch helped with the XRF machine and computer work. Jack Whorwood developed the photographs. Special thanks go to Mrs. Joyce Allen for typing the thesis on a last minute's notice. My friends Dale Rees, Mike Carr, Mark (Ziff) Hall, Ernie Meszaros, Cathy Capell, and George Cooper graciously assisted with the drafting at the drafting party.

Finally, I would like to thank my classmates of 4th year geology, friends, and relatives for their "good influence". Without these people this project probably would have been finished in February!

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CHAPTER 1

INTRODUCTION

1. LOCATION AND ACCESSIBILITY

The granodiorite pluton studied is located in the northern part of the Helmcken Land District, Shawnigan Lake area, Vancouver Island, B.C. The pluton is bounded by the latitudes $48^{\circ}40'$ and $48^{\circ}43'$N and longitudes $123^{\circ}41'$ and $123^{\circ}51'$W. The sampled area can be located on the Shawnigan Lake Sheet, compiled in 1965 by the Topographic Division, Surveys and Mapping Branch, Department of Lands and Forests, B.C., NTS reference 92 B/12. It can also be seen on the location map of this study (Figure 1).

The stock is part of the Saanich granodiorite complex of stocks and batholiths. These granodiorites intrude a thick sequence of basaltic flows. The pluton is 11.5 by 2.0 km in a NW-SE direction. This trend is typical for most of the Saanich granodiorite intrusions.

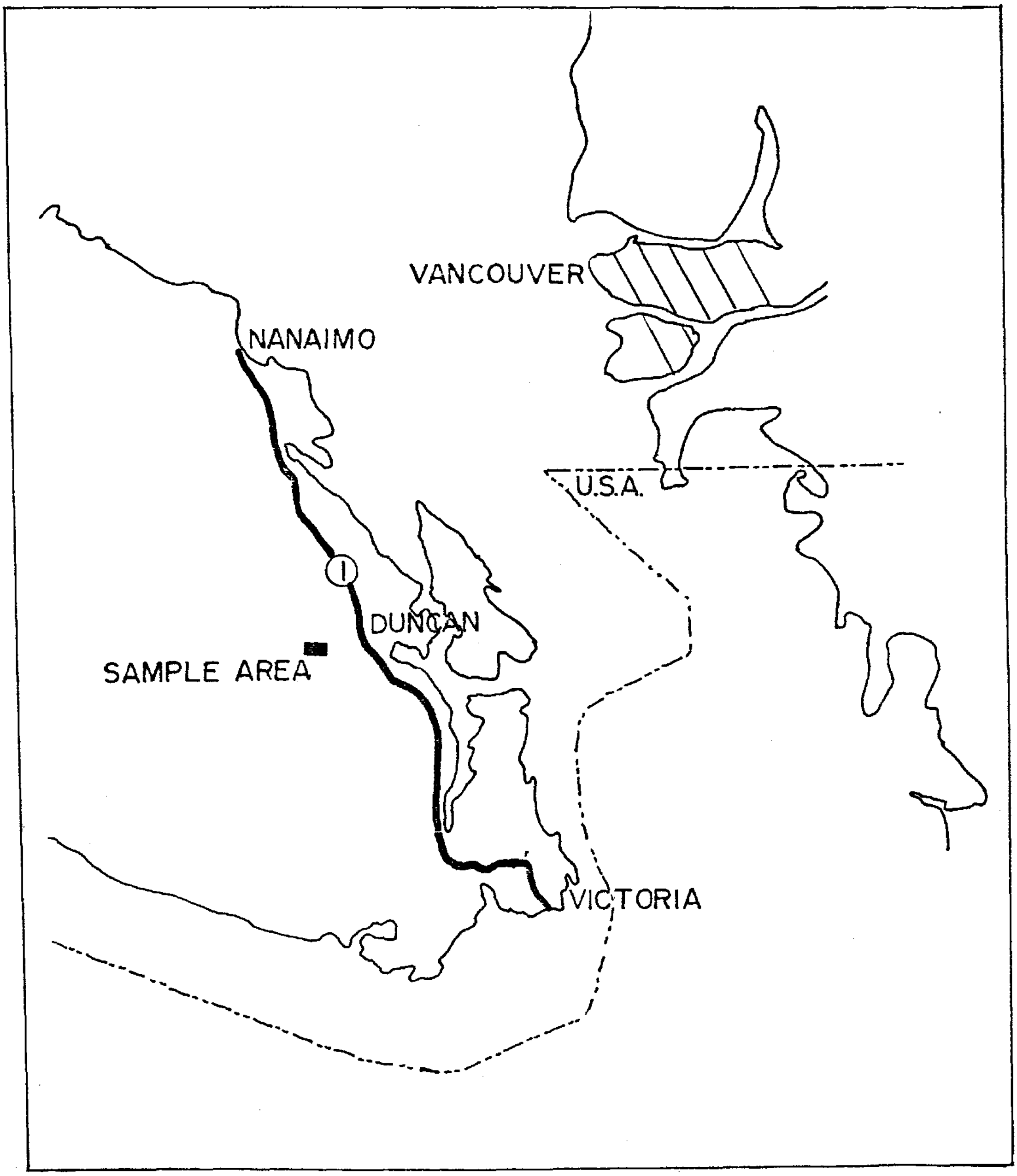


FIGURE 1 LOCATION MAP

The sample area is about 7 km SW of the town of Duncan, which itself is 70 km north of Victoria. The area is accessible via a series of dirt logging roads leading from Duncan, providing a four-wheel drive vehicle is available. The land is owned by the MacMillan-Bloedel forestry company and permission to use the roads or hike over the land has to be granted by the company. Unfortunately, the forest fire conditions were so hazardous during the course of the summer the land was inaccessible for the majority of the time available.

2. PREVIOUS WORK

The summary of previous work up until 1971 was taken from Carson (1972).

C.H. Clapp of the Geological Survey of Canada was the first to map the area and discover the granodiorite in 1912. He also named it the Saanich granodiorite after the Saanich Peninsula, a large protrusion of farmland north of Victoria. Clapp continued his mapping in 1913 and 1914, then again with Cooke in 1917.

Fyles (1955) of the B.C. Department of Mines studied the Saanich granodiorites with field mapping, petrographic and chemical analyses.

Carson (1968) studied the mineral deposits on Vancouver Island with the emphasis placed on plutonic rocks. He sampled plutonic rocks from the entire island and performed petrographic and geochemical analysis on them. In 1972, he produced a paper exclusively on the plutonic rocks of Vancouver Island. Although Carson has failed to find any mineralogic prospects associated with the Saanich granodiorite, his work has been valuable in understanding the rock stratigraphically, petrologically and chemically.

Muller (1977) has worked on Vancouver Island for almost 20 years and through his work and others he produced a geological map of the entire island. As part of this report, he describes the granodiorite and related rocks.

3. STATEMENT OF THE PROBLEM

The summer of 1979 was spent working for Gulf Minerals of Canada Ltd., under the supervision of B. Kotila. Through the encouragement of Mr. Kotila the author was persuaded to map and sample a granodiorite pluton and surrounding area, for the purpose of petrographic and geochemical analysis.

This pluton was chosen because of its good accessibility and its central location. Its dimensions also made it a good size to study for this project.

The main purpose of the study was to compare the results of this study with those of other authors on the Saanich granodiorite complex to see if indeed this pluton is part of the complex.

4. METHOD OF SAMPLING

Several days were spent during the summer and four days at the end of the summer accomplishing the task of sampling. The hazardous fire conditions provided a constant source of frustration for the author when trying to gain access to the area. Thus, detailed mapping was not possible due to a lack of time. A sample locality map with geology from others is provided.

Twenty-two samples were collected for thin section analysis. Of these, nineteen samples, all granodiorites, were prepared for chemical analysis. All granodiorite samples were stained with sodium cobaltinitrate for the purpose of identifying the potassium feldspar content.

It is important to note that the first three granodiorite samples collected are not from the thesis pluton. Sample No. VI-1 and VI-2 are from a Jurassic granodiorite pluton in the north part of the island and sample No. VI-4 is from a Saanich granodiorite pluton a few miles east of the thesis pluton. Although these samples cannot be used to prove any relationships between plutons, they were collected so as to observe any chemical or petrological similarities.

5. GENERAL GEOLOGY OF VANCOUVER ISLAND

Table 1 shows the geological history of Vancouver Island. In general, it consists of four periods of basaltic volcanism followed by periods of sedimentation. The Sicker volcanics (Fermian) were the first of these basaltic flows followed by the deposition of the Sicker sediments. The basalts and associated sediments of the Vancouver group were emplaced during the Triassic. Then came the Bonanza Volcanics and a thick sedimentary sequence through the rest of the Mesozoic. The final period of volcanism occurred in the Early Eocene in which the Metchosin Volcanics were erupted followed by deposition of the sedimentary sequences.

The Saanich granodiorites and other granodiorites have been observed to intrude all volcanics up to and including the Bonanza volcanics (Fyles, 1955; Muller, 1977). This would make the age of intrusions mid to late Jurassic. This corresponds to Carson's K-Ar ages of 141-181 m.y. for the plutons (Carson, 1968). This means that the Saanich granodiorite intrudes approximately 10,600 metres of volcanics and sediments.

Table 1. Generalized Geology of Vancouver Island (from Muller, 1977)

Era	Time Period	Lithologies	Thickness of Unit (metres)
Cenozoic	Eocene to Oligocene	Sedimentary Sequence - conglomerate, sandstone, siltstone, shale	1,500
	Early Eocene	Metchosin Volcanics - basaltic lava, pillow lava, breccia, tuff	3,000
Mesozoic	Cretaceous	Sedimentary Sequence - conglomerate, sandstone, siltstone, shale, coal, greywacke, argillite	3,650
	Mid-Late	Island Intrusions - granodiorite, quartz diorite, granite, quartz monzonite	
	Early Jurassic	Bonanza Volcanics - basaltic to rhyolitic lava, tuff, breccia minor argillite, greywacke	1,500
	Triassic	Vancouver Group - basaltic, lava, pillow lava, breccia, tuff limestone, calcareous siltstone, greywacke conglomerate, breccia	volcanics -4,500 sediments -1,700
Paleozoic	Pennsylvanian and Permian	Sicker Group - basaltic to rhyolitic metavolcanic flows, tuff, agglomerate - metagreywacke, argillite, schist, marble limestone, chert	volcanics -2,000 sediments -900
	Devonian	Intrusives - metagranodiorite, metaquartzdiorite, quartz feldspar gneiss, amphibolite	~

Contacts between the Jurassic granodiorites and country rock is usually straight regardless of topography which would indicate that the plutons are steeply dipping.

CHAPTER 2

PETROGRAPHY

1. LOCAL GEOLOGY AROUND PLUTON

The thesis pluton is in contact on the east and west sides with the volcanics of the Sicker group. These volcanics consist of slightly metamorphosed, tuffaceous basaltic volcanics. The contact was not exposed in outcrop. The geological map by Muller (G. S. C. open file publication 463, 1977) shows Sicker sediments bordering the south of the pluton. Again, outcrop was extremely poor ($<1\%$) so no Sicker sediments were observed at the contact. The northern part of the stock is unconformably overlain by E-W trending upper Cretaceous sediments which gradually pinch out to the south. The dominant rock type is a light brown feldspathic to arkosic sandstone.

2. THIN SECTION DESCRIPTION OF ROCK UNITS

A) Granodiorite

In the field the main texture observed was a medium- to coarse-grained equigranular hypidiomorphic rock. Plagioclase was

was by far the most predominant mineral seen, followed by hornblende, quartz, and minor amounts of biotite. Trace amounts of pyrite were observed in most samples. The rusty brown weathered appearance of the rock gave good evidence that pyrite was present.

In thin section the medium-grained hypidiomorphic equigranular texture was again dominant. Minerals in order of the abundance were plagioclase, quartz, hornblende, potassium feldspar, biotite, opaques, and accessories. Figure 2 shows a thin section of one of the more unaltered samples exhibiting a typical mineral assemblage and texture.

In general, the granodiorite is extensively altered (Fig. 3). The feldspars are altered to clays (Fig. 4) which have destroyed most twinning in both plagioclase feldspar and potassium feldspar. Hornblende and biotite are both partially altered to chlorite. Deformational textures are also prevalent as exhibited by strained quartz, strained twinned lamellae in the feldspar and the broken-up appearance of the hornblende and opaques. This is also seen by bent, even kinked cleavage in biotite (Fig. 5).

Plagioclase occurs as subhedral laths, 2-3 mm in length. When twins are present, they yield a composition range of An_{35} to An_{45}. This could be misleading because alteration and zoning could make the

FIGURE 2 - Representative photomicrograph of a granodiorite; sample VI-11; magnification 7X; X nicols.

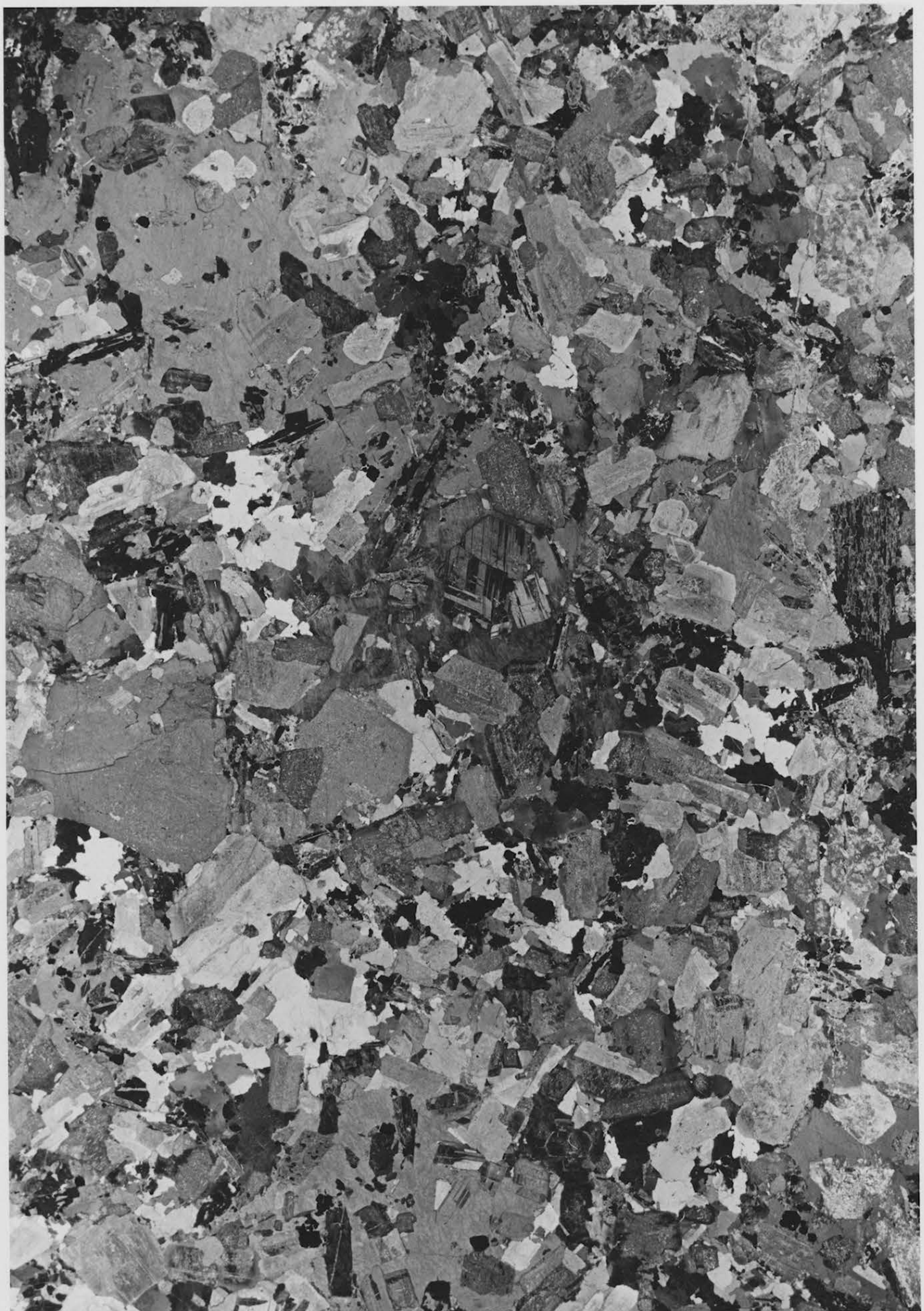


FIGURE 3 - Heavily altered granodiorite; sample VI-7; magnification 7X; X nicols.

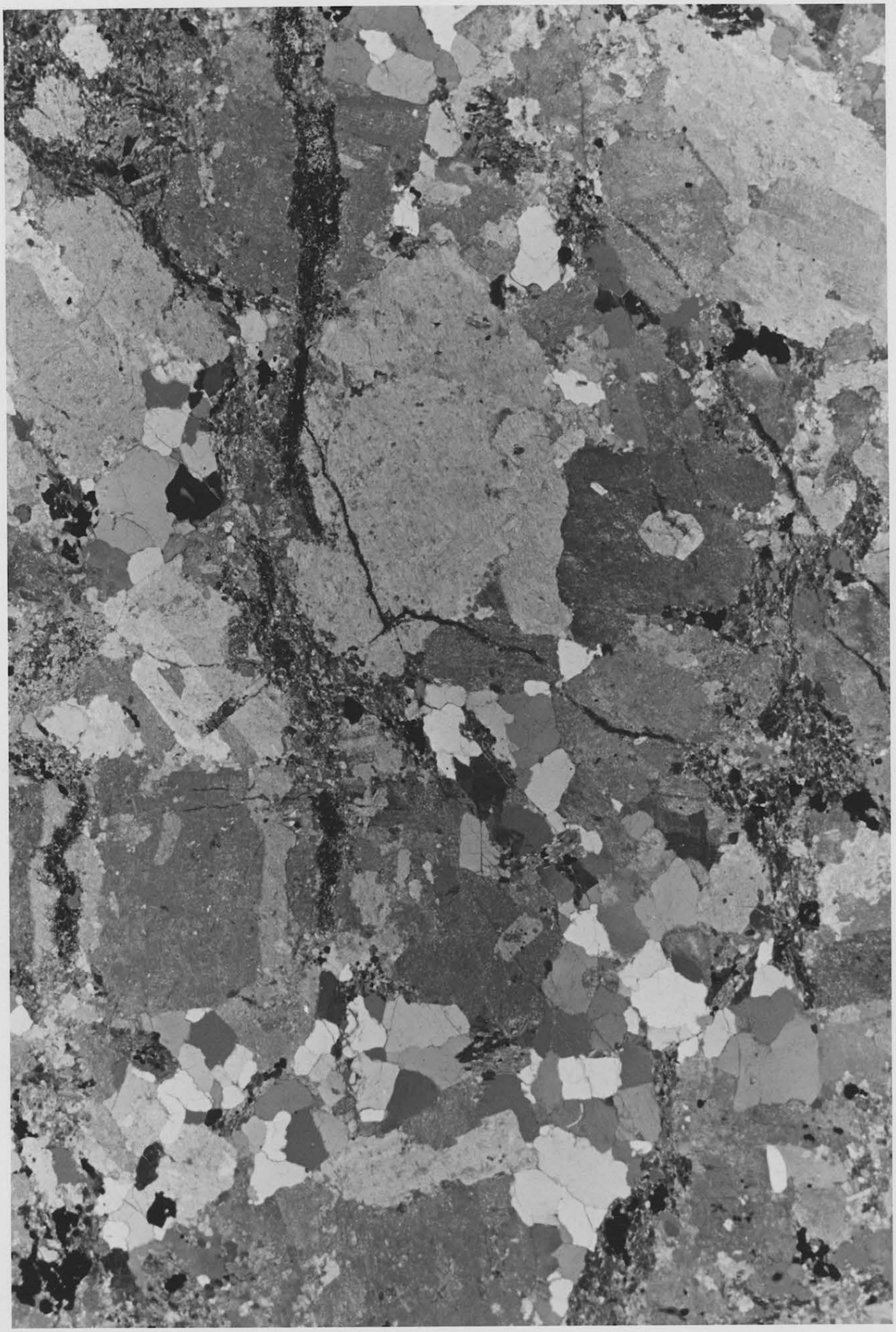
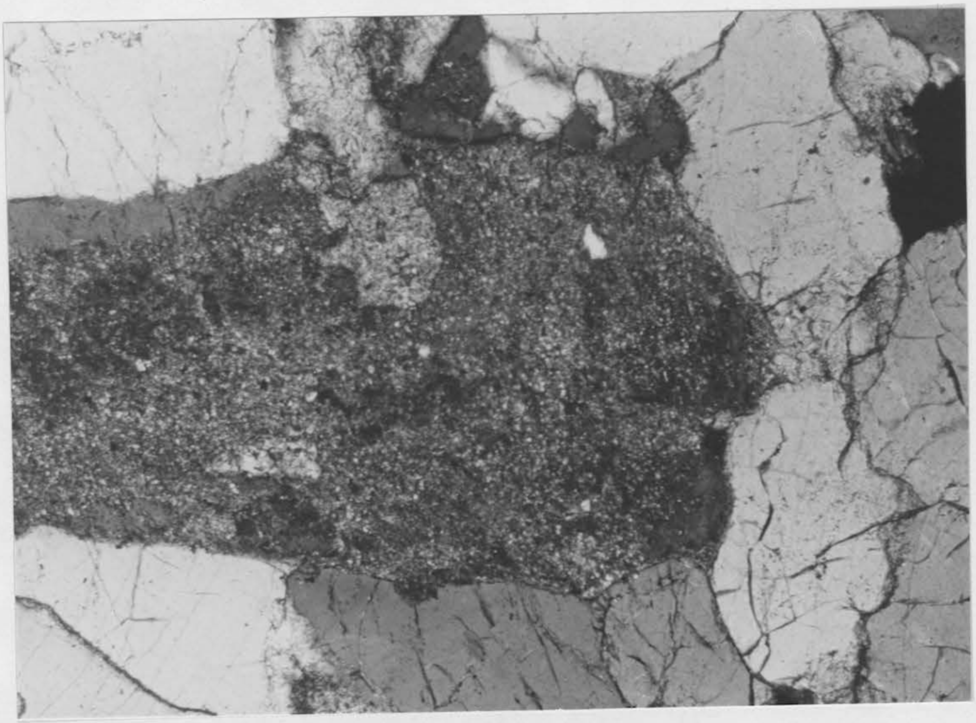
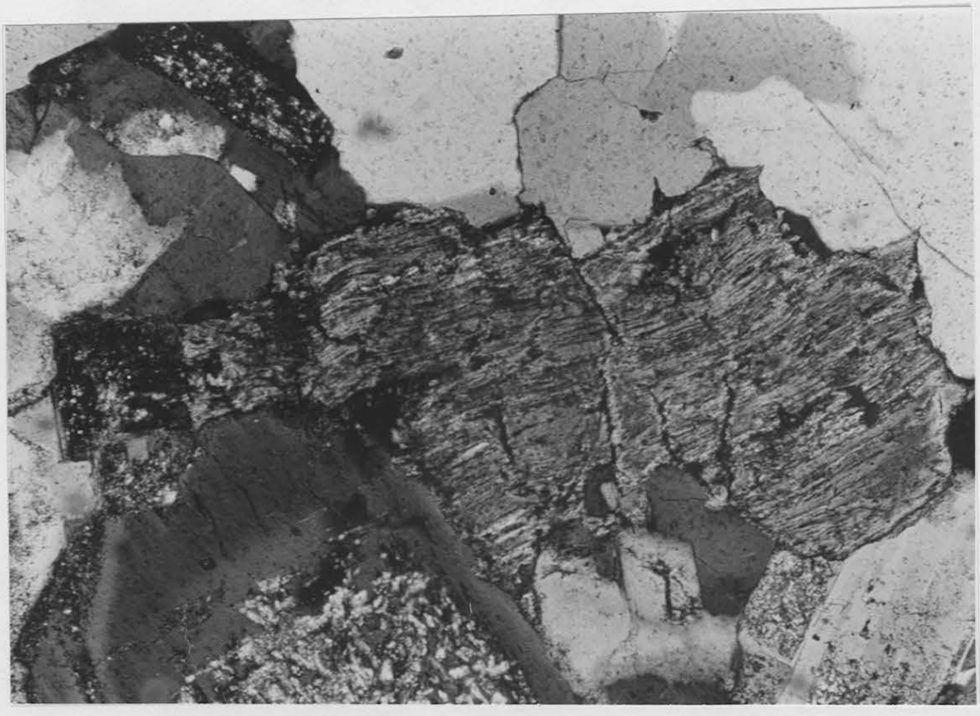


FIGURE 4 - Individual sericitized plagioclase grain; sample VI-7; magnification 63X; X nicols

FIGURE 5 - Bent cleavage in biotite; sample VI-11; magnification 63X; X nicols





Michel-Levy test inaccurate. Broken (discontinuous) twins and strained extinctions give evidence that this rock has been stressed. Zoning is a common feature showing a calcic inner core grading to a more sodic outer rim. Inclusions of smaller feldspar grains, hornblende, accessories and opaques are not uncommon.

The quartz content in these granodiorites is about 20-25%. It is always anhedral averaging 1-2 mm in diameter. It usually occurs in clusters or aggregates of interlocking grains. Almost every quartz grain showed strained, undulose extinction.

The most common mafic constituent is pleochroic, green to brown hornblende. Subhedral to euhedral basal sections give good 56^{o}-124^{o} cleavage. They usually contain inclusions of opaques and sometimes quartz. Small hornblende grains, which have broken away from the larger grains, leave holes, and give the appearance of "floaty" grains in the sections. Alteration to chlorite around grain boundaries is common and sometimes the hornblende is completely altered.

The biotite in these granodiorites is pleochroic light to dark brown with bent kinked cleavages. Biotite also is heavily altered to a pale green, low birefringence chloritic mineral.

Because of the lack of twins and unaltered grains, potassium feldspar was very difficult to find in thin section. Occasionally carlsbad twins could be seen which could be on K-spar grains. Hand specimens were stained with sodium cobaltinitrate to determine potassium feldspar percentage which was found to be about 10%. The K-spar was fine to medium-grained (approximately 1 mm in diameter), interstitial to larger plagioclase grains (Fig. 6). Microcline, showing polysynthetic twins, occurs in minor amounts.

Accessories observed were sphene (Fig. 7) and apatite (Fig. 8). Sphene occurs in almost all granodiorite sections whereas apatite is very minor. The sphene is light brown under both plain and crossed polarized light which is masking its extremely high birefringence.

An apparent anomaly to this general granodiorite was sample VI-8. In hand specimen it was fine-grained (<1 mm) and consisted of mainly felsic minerals. It also showed a sugary texture. Thin section analysis revealed the chief minerals in order of abundance were plagioclase, quartz and potassium feldspar. The mafic minerals, mostly chlorite, never exceed 10%. The sugary texture, fine-grained nature and mineralogy leads one to believe that this could be a dike rock, probably an aplite. The outcrop was very small, only about 1 m wide, so no dike contacts were observed.

FIGURE 6 - Potassium feldspar grain showing carlsbad twinning; sample VI-17; magnification 63X; X nicols.

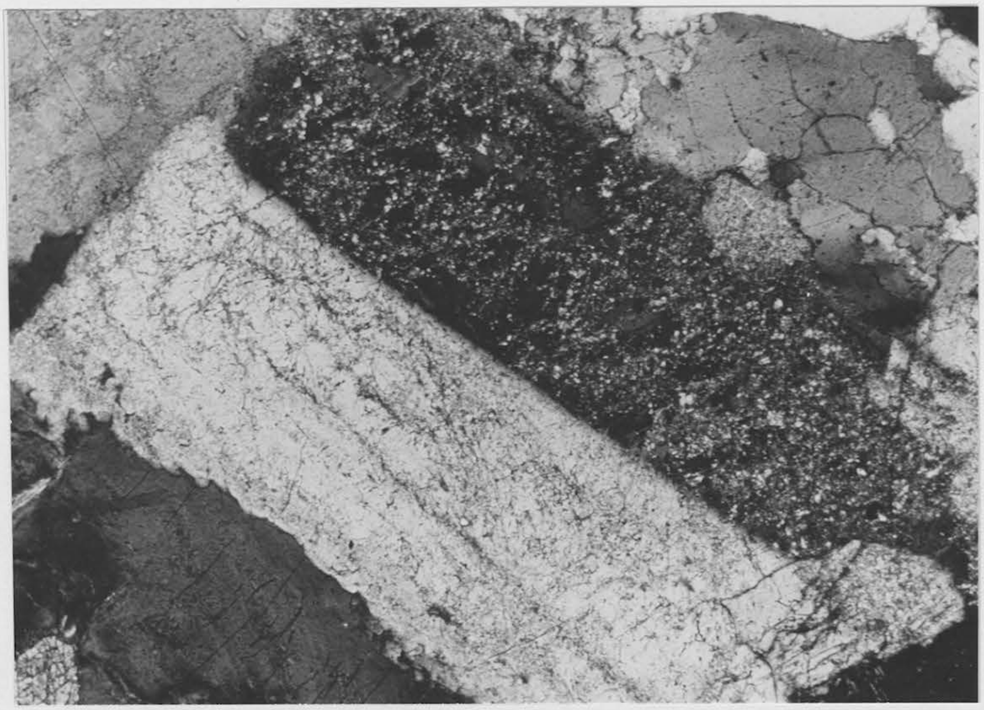
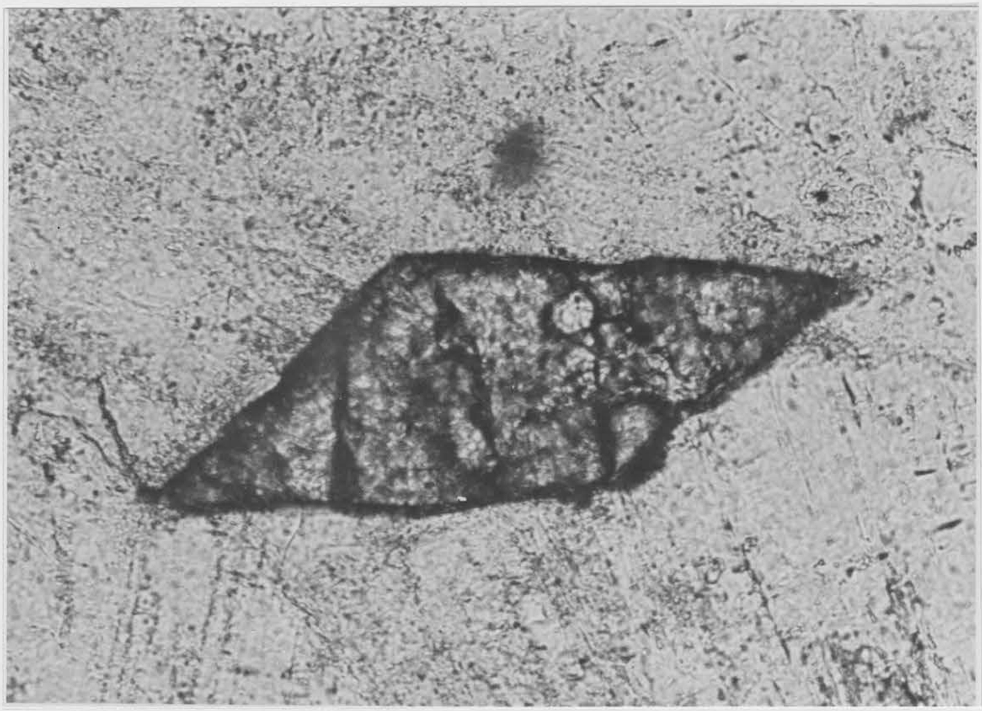
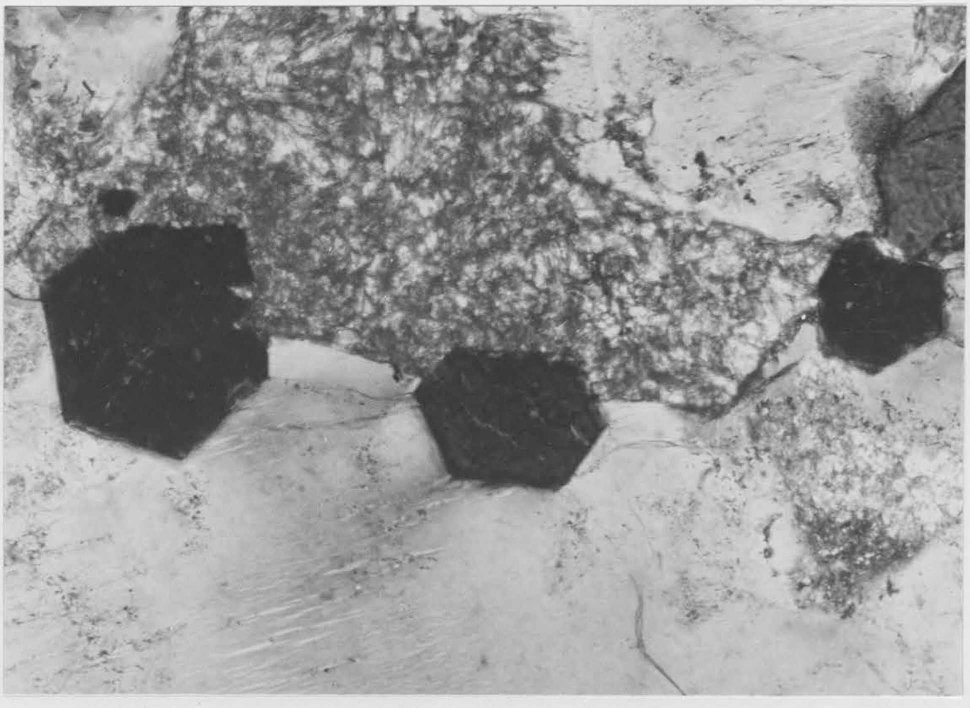


FIGURE 7 - Euhedral sphene crystal in granodiorite; sample VI-18; magnification 125X; X nicols

FIGURE 8 - Euhedral apatite crystals in granodiorite; sample VI-18; magnification 125X; X nicols





B. Xenoliths in the Granodiorite

Xenoliths (Fig. 9) are uncommon in these rocks (<<<1%). They were circular in shape and averaged 1.5 cm in diameter.

The mineralogy of the xenolith was found to be exactly the same as the granodiorite, the only difference being that the xenolith was fine-grained, .1 - .5 mm as opposed to 1-3 mm for the granodiorite. The proportion of mafics, hornblende and opaques, was approximately 25% compared to 15% in the host rock. The contact is quite sharp showing little evidence of resorption.

There is no country rock type near the pluton which remotely resembles the mineralogy of the xenolith, thus ruling out the country rock as a source. A more plausible explanation is that the xenolith represents part of the granodiorite which crystallized early as part of the roof rock and was then assimilated into the granodiorite magma as a xenolith.

C) Pyroclastics

Volcanic units of the Sicker formation outcrop west and east of the stock (Muller, 1977). Sample VI-3 was taken east of the pluton close to the inferred contact.

In the field this rock was medium gray, consisting of 50% tuffaceous to lapilli size fragments (Fig. 10), light gray in colour and

FIGURE 9 - Xenolith in granodiorite; sample VI-20B; magnification 7X; X nicols.

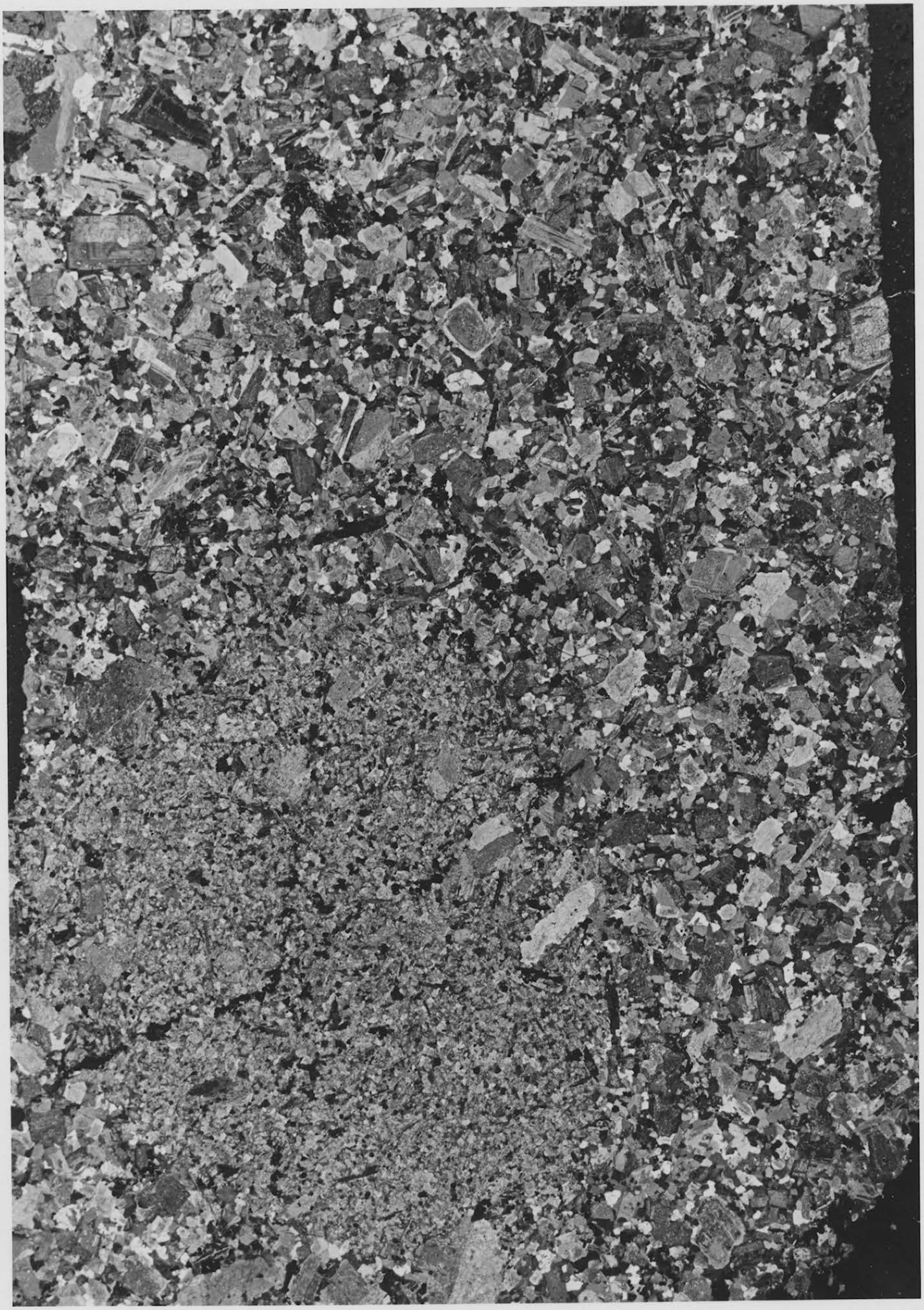
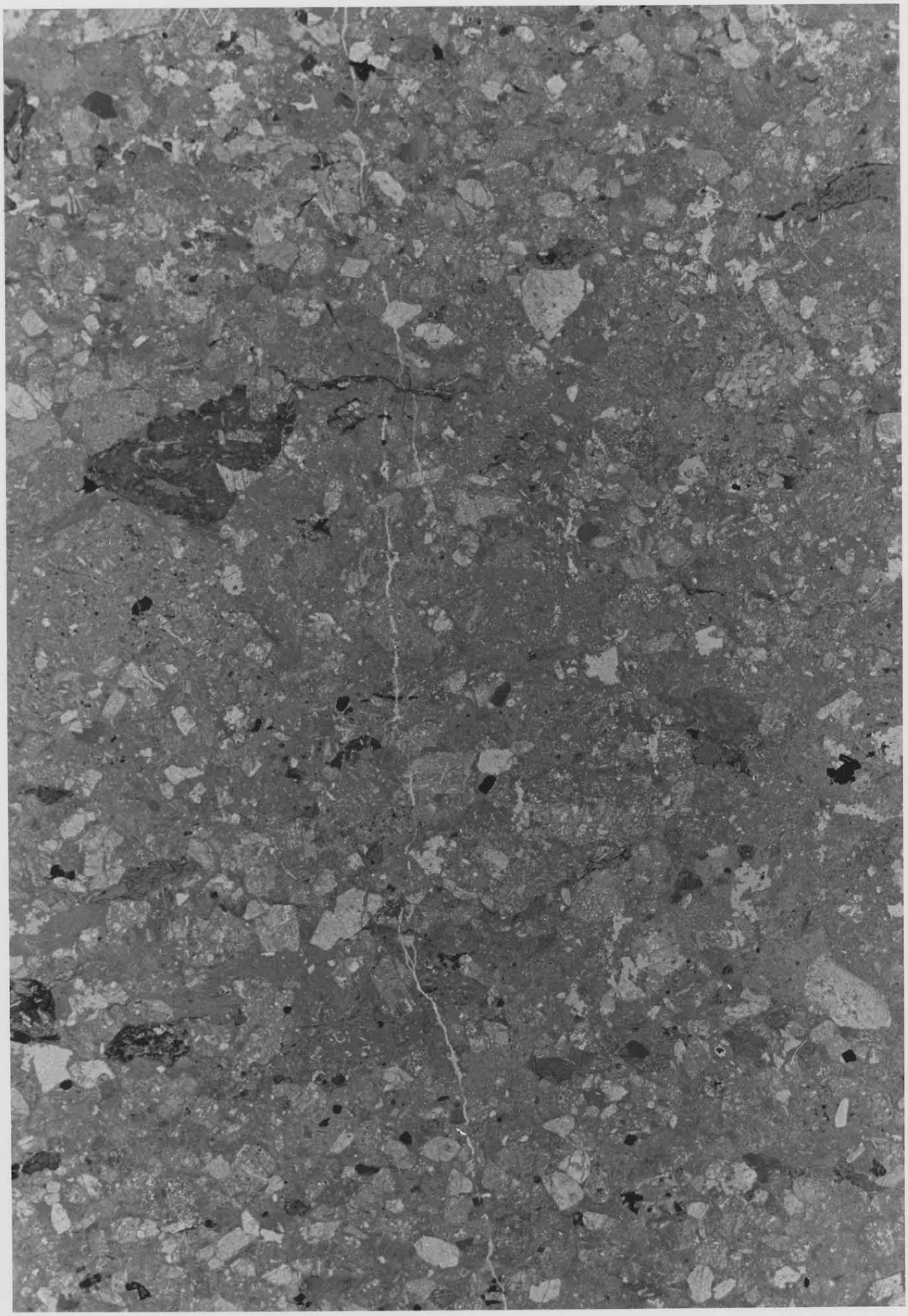


FIGURE 10 - Photomicrograph of a pyroclastic slide; sample VI-3; magnification 7X; X nicols.



subangular. The designated field name was andesite tuff.

In thin section this rock is composed of 50% fragments, 50% matrix. The matrix is too fine grained to discern any mineralogy. The majority of the fragments were anhedral plagioclase 1-2 mm in diameter. Twins are vague to absent in all grains due to alteration. Associated with all plagioclase is calcite. The calcite does not appear to be inclusions but an alteration.

Calcite also occurs as anhedral fragments and in veins throughout the rock. This calcite shows its typical good twinning and very high birefringence.

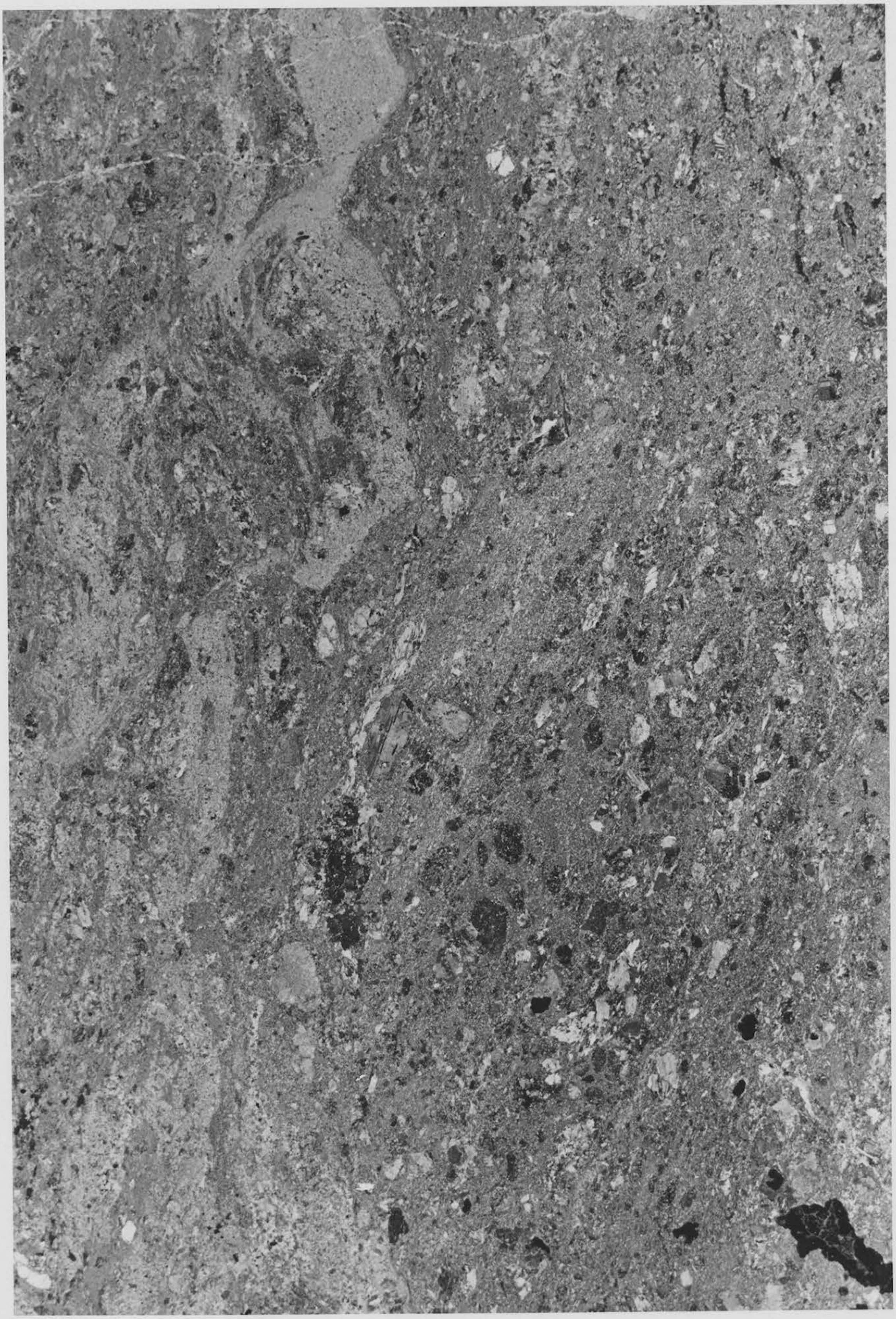
D) Southern Sediments

Permian sediments of the Sicker formation are in contact with the pluton to the south. Samples VI-12 (Fig. 11) and VI-19 were taken just south of the contact.

In hand specimen VI-12 shows vague bedding but is highly convoluted and faulted. Clasts of potassium feldspar and plagioclase (1-2 mm in diameter) sitting in a light gray fine-grained matrix constitutes approximately 40% of the rock.

Specimen VI-19 consists of alternating fine-grained (silt size) beds with sandy beds averaging .3-.5 mm. These beds are often displaced due to a large amount of faulting. Calcite veining is also very prominent throughout the rock.

FIGURE 11 - Metawacke showing the convoluted nature of bedding; sample VI-12; magnification 7X; X nicols.



Thin section analysis reveals that the clasts in VI-12 are potassium feldspar, plagioclase and epidote. The feldspars are equidimensional to elongate, subrounded and range from .5 mm to 2 mm in length. Twinning is sometimes present but the composition was not determined due to the broken up state and strained extinction of the twins.

Epidote shows the diagnostic pistachio green colour and good cleavage. It constitutes 20% of all the clasts. Its form is equidimensional, rounded and poorly sorted. Cleavages are often deformed due to stress.

The matrix which weaves around the clasts is difficult to analyze due to its fine-grained nature. It consists mainly of micaceous minerals such as biotite and chlorite but also very fine-grained quartz.

Calcite constitutes 10% of the rock and is in veins and aggregates throughout the rock.

Sample VI-19 has similar mineralogy but it does not contain the clasts and its bedding is far more competent. The more coarse-grained beds show a mineralogy of epidote, biotite, chlorite, quartz and feldspar, all about the same size.

Sample VI-12 would be classified as a metagreywacke. Sample VI-19 is an interbedded metagreywacke-metargillite rock.

E) Sandstone

Unconformably overlaying the northern part of the pluton is upper Cretaceous sandstones. This sandstone gradually pinches out going southward over the stock.

In hand specimen, the sandstone was medium brown, consisting of rounded grains .3 to .5 mm in diameter. White feldspar constitutes 40 to 50% of the rock, thus is arkosic. Mafic minerals, mostly biotite constituted most of the remaining mineralogy.

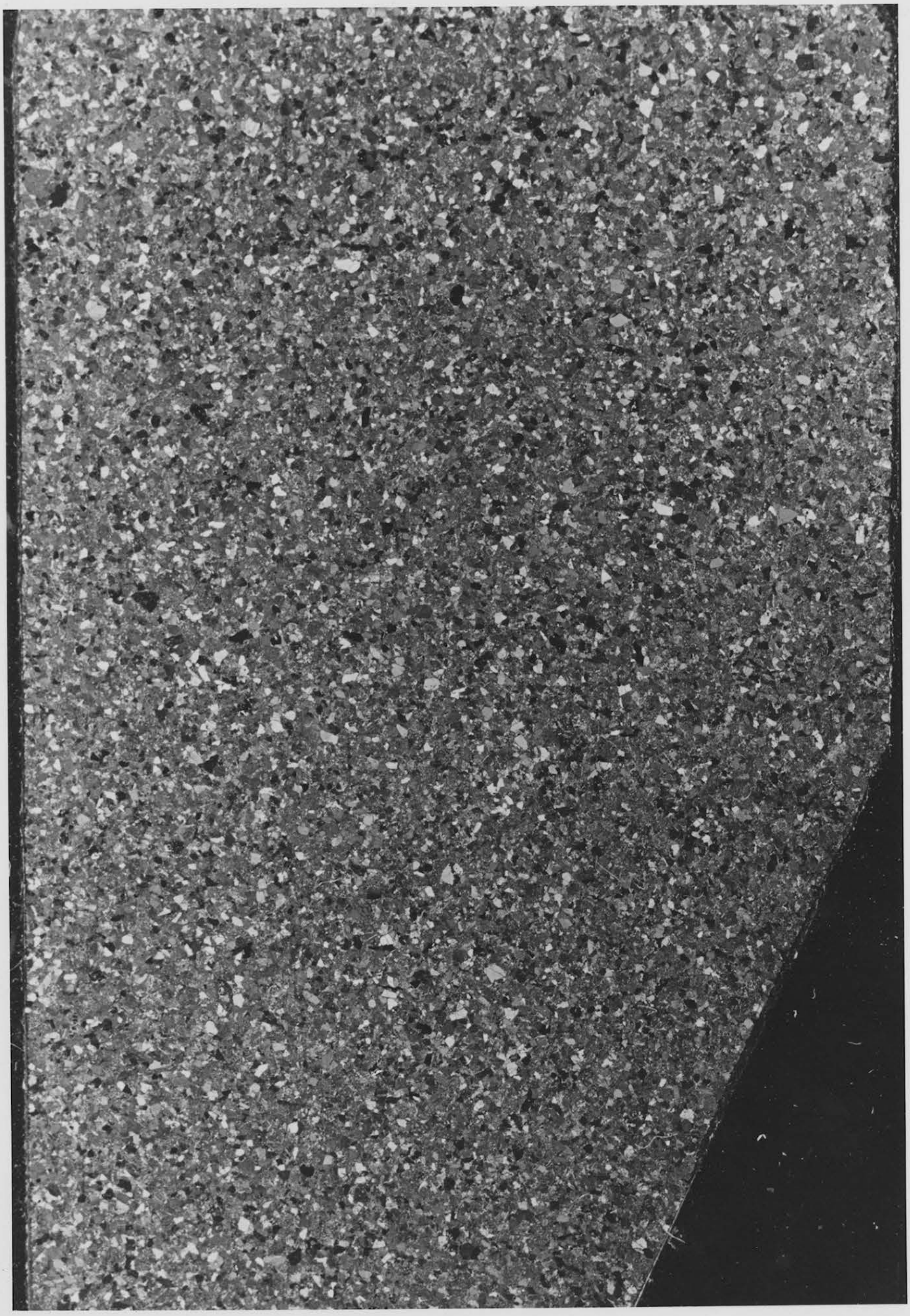
In thin section the sandstone was 90% clasts, 10% matrix (Fig. 12). The clasts consist of plagioclase, potassium feldspar, quartz and biotite. The matrix which binds the sandstone grains together was brown, probably Fe-rich, indicating it might have been derived from the breakdown of biotite.

Plagioclase grains are equidimensional, subangular to subrounded, .5 mm in diameter. Twin lamellae are mostly absent due to alteration to clays.

Quartz is equidimensional, subangular, approximately .5 mm in diameter. Strained extinction is almost always present. Some polycrystalline aggregates were also observed indicating evidence of stress. This stress was most likely subjected to the source rock because there was no evidence to suggest the sandstone was deformed.

FIGURE 12 - Arkosic sandstone; sample VI-5; magnification 7X;

X nicols.



Sorting of the clasts is poor. There is a wide variety of sizes and different types of clasts showing that transportation has been short.

"Arkoses are usually the product of deposition close to acid plutonic source rocks" (Knox, 1978). This sandstone could have been derived from the Jurassic granodiorite stocks. Evidence for this is that the mineralogy is similar to the granodiorite, i.e. strained quartz, alteration of plagioclase to clays.

Also the time relationship is right. Plutons intruded during the Jurassic could have shed sediments during the upper Cretaceous.

CHAPTER 3

GEOCHEMISTRY

1. ANALYTICAL METHODS

The rock powder used for making the fused and powder pellets was made using a Spex Industries Shatter Box. The rock samples were stripped of their weathered surfaces, crushed into small fragments and inserted into the Shatter Box. Vibrating tungsten carbide rings crushed the fragments to the desired rock powder.

A Philips, Model 1450 AHP, sequential X-ray fluorescence spectrometer, located within the Geology Department was used for whole rock and trace element analyses for all of the granodiorite samples. A 6:1 mixture of lithium tetraborate and lithium metaborate (flux) to rock powder was fused in Pt/Au crucibles for 3-5 minutes at 1200°C for major element, whole rock analyses. Minor and trace elements were analyzed using rock powder with Mowoil binder and pressed to 20 tons pressure. The major elements Si, Al, total Fe, Mg, Ca, Na, K, P, Mn, Ti as well as the trace elements Ni and S were analyzed using a Cr tube. Trace elements Cr, Co, Cu, Pb, As, Zn as well as Rb-Sr were run using a Mo tube. A programme for other trace elements Rb, Sr, Y, Zr, Nb, Ba, Ce, La, Nd, V, Ti was also run using a W tube.

2. RESULTS

Major element oxides of all granodiorite samples and the aplite sample (VI-8) are listed in Appendix D. Trace element data can be found in Appendix E. Cation mesonorms (Barth, 1962) were calculated using a computer programme (Birk, 1978) and the results can be found in Appendix F.

MAJOR ELEMENTS

Table 2 shows the major oxide range for the granodiorites compared to the average granodiorite composition (Nockolds, 1978) and to the aplite.

The figures for average granodiorites were consistent with the ranges for the pluton with the exception of total Fe_2O_3 and MgO. The thesis granodiorite had ranges for Fe_2O_3 and MgO just slightly higher than average compositions. This extra amount of Fe_2O_3 and MgO is reflected in the fact that the stock contains a high amount of hornblende and biotite.

The chemistry backs up the petrographic and textural evidence that VI-8 is an aplite. The amount of SiO_2 is very high, even higher than for granites. All oxides are lower than those for granodiorites with the exception of Na_2O. Its content is about the same as for a granodiorite. This is probably because there is a high amount of sodic feldspar in aplites.

MINOR ELEMENTS

The compositional ranges for some of the more important trace elements are listed in Table 3. These were chosen because they pertain to later discussion. The results for other trace elements and minor elements are in Appendix E.

The results for Rb were lower than average. The elements Sr and Ba both have wide compositional ranges and both are quite abundant for trace elements. The trace elements Zr, Y and Nb were about average. Values for the aplite agreed well with the granodiorites.

Table 2. Major Oxide Ranges compared to the Average Granodiorite Chemical Compositions

Oxide	Granodiorites from Pluton (Wt. %)	Average Granodiorite (Wt. %)	Aplite (Sample VI-8)(Wt. %)
SiO_2	60.76-67.15	66.88	73.14
TiO_2	0.41- 0.63	0.57	0.22
Al_2O_3	15.40-17.88	15.66	14.58
Fe_2O_3	Total Fe 4.28- 5.89	1.33	Total Fe 2.21
FeO		2.59	
MnO	0.07- 0.11	0.07	0.06
MgO	1.58- 2.38	1.57	0.70
CaO	3.14- 5.81	3.56	2.45
Na_2O	3.25- 4.86	3.84	3.78
K_2O	1.63- 4.49	3.07	2.79
H_2O^+	-	0.65	-
P_2O_5	0.10- 0.36	0.21	0.07

Table 3. Minor Element Ranges for Samples (in ppm)

Element	Granodiorite Range	Aplite
Sr	319-1322	803
Rb	23.8-72.5	45.7
Y	27-34	26
Zr	91-116	106
Nb	21-26	21
Ba	544-1852	1414
Rb/Sr	.016-.124	.057
K/Rb	268.4-563.8 ave.=426.3	503.5

CHAPTER 4

PETROGENESIS

1. INTRODUCTION

Much work has been researched as to how and where granitic magmas are formed. Although the debate continues, the following theories are summarized.

Orogenic granites can be generated either by complete or partial remelting of the mantle or lower crust, or as the end stage product of metamorphism (Pitcher, 1979). Wyllie et al. (1976) suggest that calc-alkaline rocks can be generated in deep continental, subducted ocean crust, or in a mantle wedge above a lithosphere slab.

The purpose of this chapter is to analyze the chemical trends and to develop a picture of how and where these granodiorites were formed.

2. CHEMICAL TRENDS OF MAJOR OXIDES VARIATION DIAGRAMS

Many variation diagrams have been implemented to find chemical trends in rocks which help to infer the genesis of the rock. The Differentiation Index (DI) makes use of wt. % normative quartz + orthoclase + albite + nepheline + leucite + kalsilite (Thorton & Tuttle, 1960), but because it is based on the CIPW norm which does not account for water, it is not applicable to granitoids. Other methods such as Crystallization Index, Mafic Index, and Iron Ratio will reflect early stages of differentiation and therefore is not applicable to granitoids.

A system which does reflect late fractionation so is applicable to granitoids, is the Larsen Index (L. I.) (Larsen, 1938). This sums the oxides 1/3 SiO_2+K_2O-MnO-CaO-FeO. This was later modified to represent the sum of the elements 1/3 Si+K-Ca-Mg (Nockolds and Allen, 1953). By plotting certain cations versus the modified Larsen factor (Fig. 13a-e), chemical trends which may or may not infer differentiation has occurred.

The cations Na, K, Al and Fe were plotted because they reveal the best results for granitoid rocks. The Felsic Index, $\left(\frac{(Na_2O + K_2O)}{CaO + Na_2O + K_2O}\right) \times 100$, was also plotted because if the magma is fractionating leaving the residual liquid more felsic, then the Felsic Index should increase.

For a calc-alkaline suite of rocks the trends are all consistent. Both K and Felsic Index increase which is to be expected since the residual magma should be enriched in the alkalies. Total Fe decreases which is also expected. Although Fe does not emerge from the liquid early in the differentiation process, it does emerge during an intermediate phase. By the time the residual liquid is enriched in alkalies, Fe should be showing a decreasing trend. The elements Na and Al showed a constant trend. Both Al and Na enter the feldspar structure and continue to do so until crystallization is complete. Therefore, their pattern should be constant.

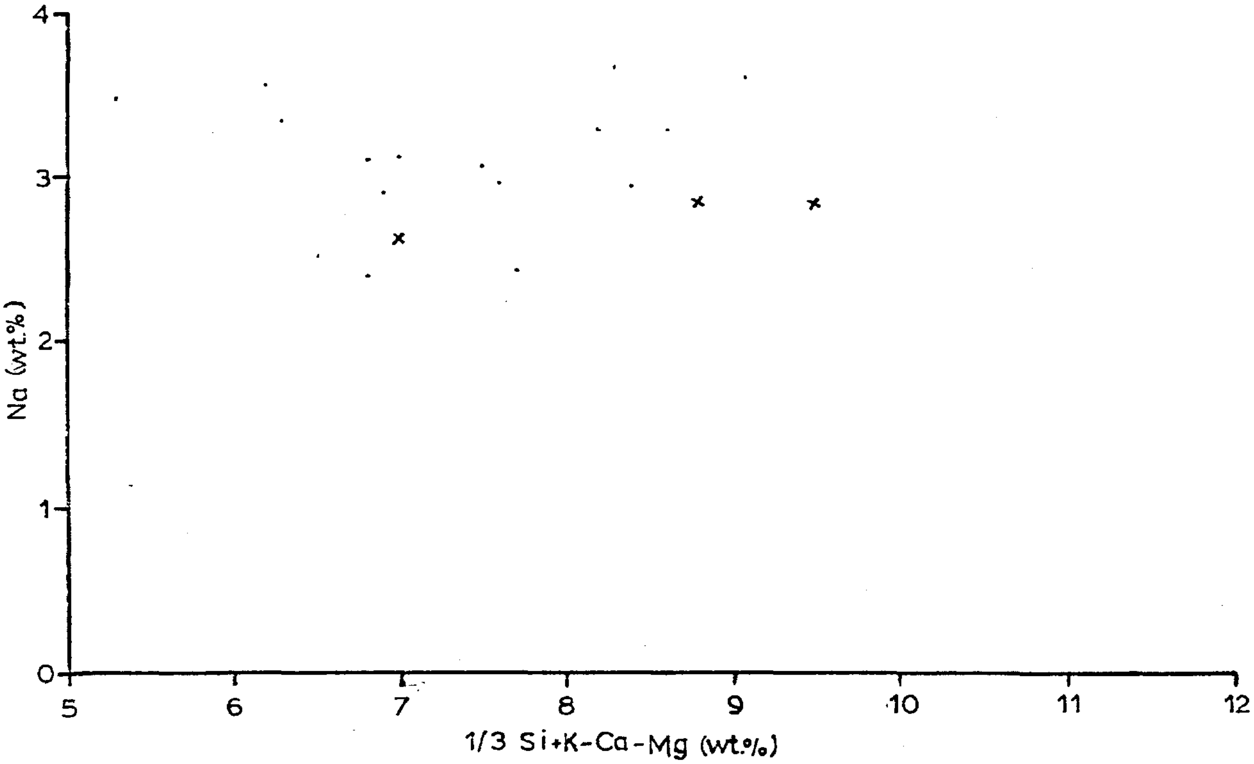
The chemical trends are consistent with those predicted for the calc-alkaline series of rocks (Larsen, 1938; Nockolds and Allen, 1953). They give a good indication that differentiation based on fractional crystallization, from a more mafic liquid to felsic liquid, has been occurring.

In all the plots, one sample does not fall into the main trend. This sample is VI-8, and the reason for this behaviour is its high SiO_2 content (73%). It could represent the residual magma left after the bulk of the granodiorite had crystallized.

FIGURE 13 - a) Na vs Modified Larsen Index.

Note: Crosses represent granodiorite samples not from pluton

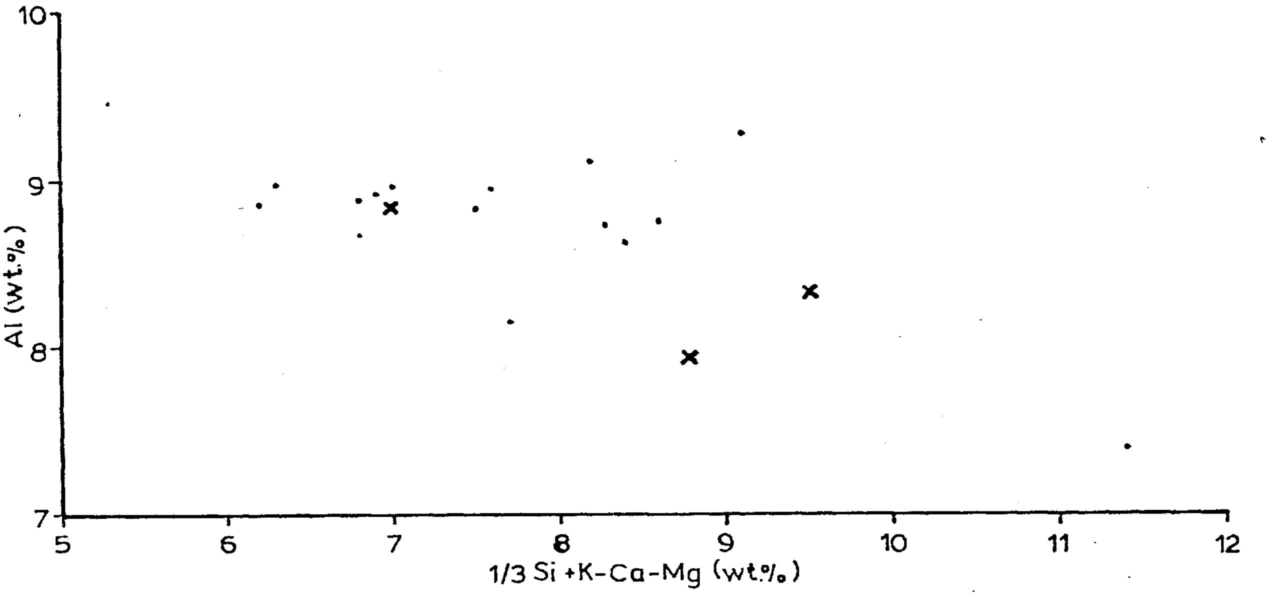
FIGURE 13 - b) K vs Modified Larsen Index.


4
3
2
1
0
Na (wt.%)
5
6
7
8
9
10
11
12
1/3 Si+K-Ca-Mg (wt.%)


4
3
2
1
0
K (wt.%)
5
6
7
8
9
10
11
12
1/3 Si +K-Ca-Mg (wt.%)

FIGURE 13 - c) Al vs Modified Larsen Index.

FIGURE 13 - d) Fe vs Modified Larsen Index.


10
9
8
7
Al (wt.%)
5
6
7
8
9
10
11
12
1/3 Si +K-Ca-Mg (wt.%)

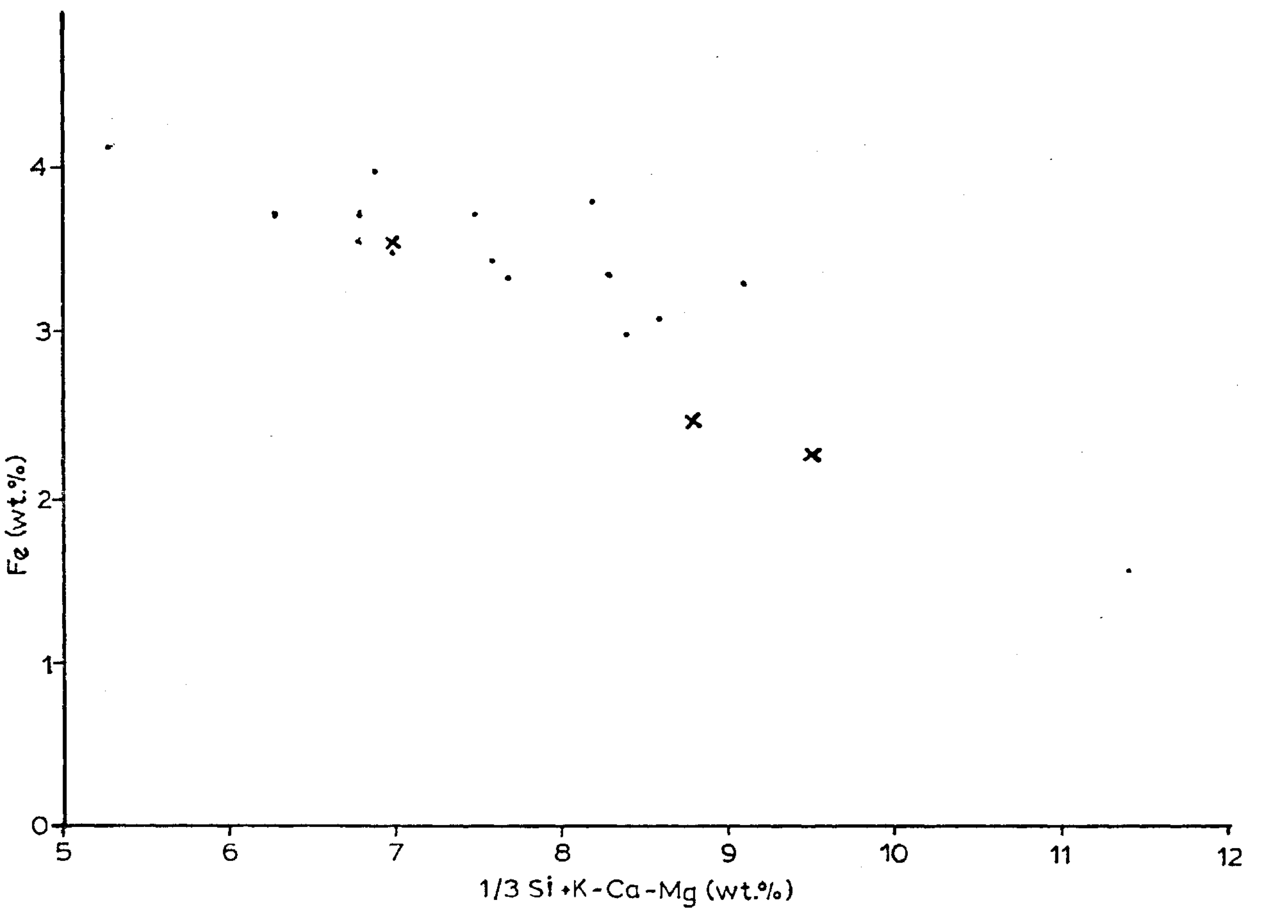

4
3
2
1
0
Fe (wt.%)
5
6
7
8
9
10
11
12
1/3 Si +K-Ca-Mg (wt.%)

FIGURE 13 - e) Felsic Index vs Modified Larsen Index.

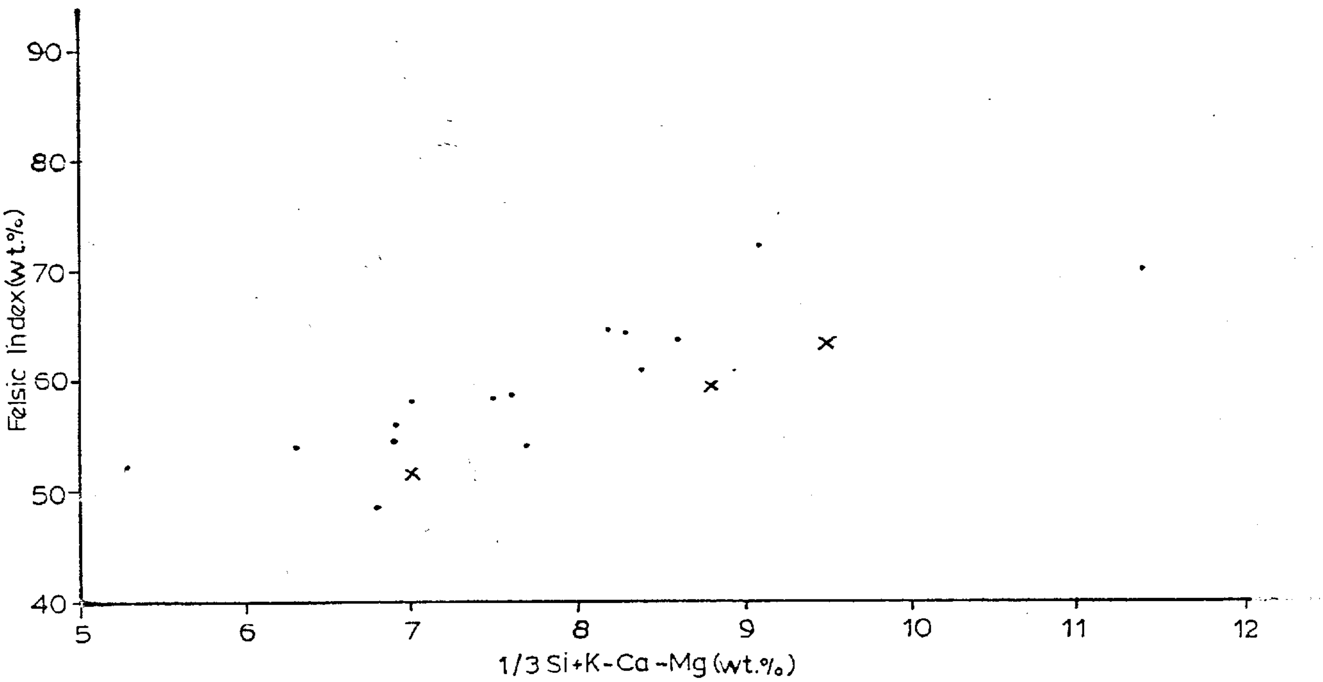

90
80
70
60
50
40
Felsic Index (wt.%)
5
6
7
8
9
10
11
12
1/3 Si+K-Ca-Mg (wt.%)

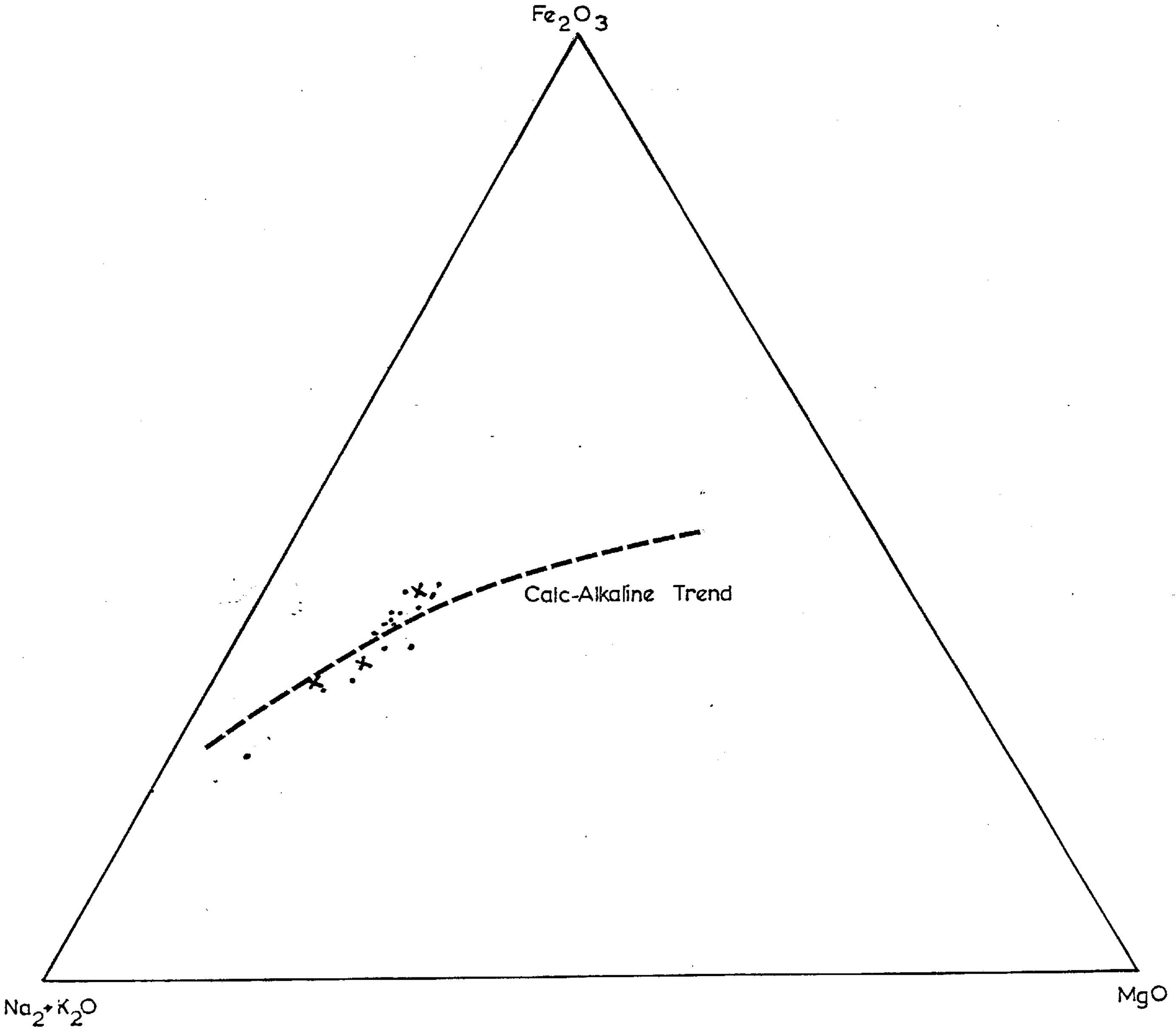
Figure 14 is an AFM plot, where A=N_2O+K_2O, $FeO+Fe_2O_3$ and M=MgO. The points show a trend towards the A corner and also plot along the calc-alkaline trend line (Carmichael et al., 1974). These findings are consistent with the variation diagrams, indicating that a fractionation process probably occurred.

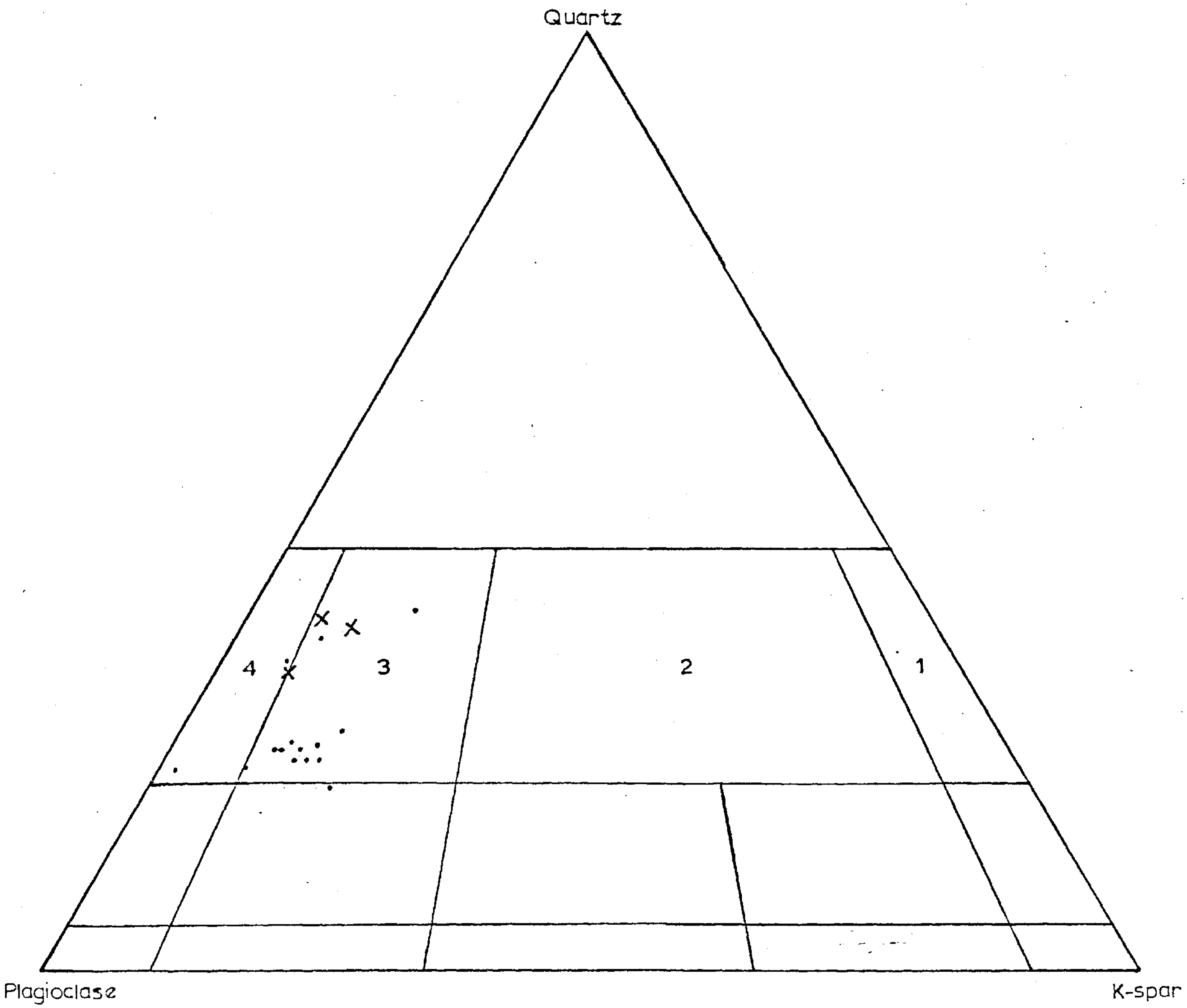
The next series of plots were all calculated from a mesonorm computer program (Birk, 1978). This program is good for granitoid rocks because it allows for the presence of water whereas the CIPW norm does not.

A Quartz-Plagioclase-Alkali feldspar plot is given in Figure 15. Lines and fields drawn on the diagram are according to the igneous rock classification by Streckeisen (1973). All samples plot well in the granodiorite field with the exception of VI-6 which has a low potassium feldspar proportion. This was also seen in hand specimen as K-spar only constituted 2%. This could be because the magma, the sample represented, fractionated earlier than the granodiorite and thus had a more dioritic composition.

The Ca-Na-K plot (Fig. 16) is very useful for granitoid rocks because it reflects feldspar fractionation (Green and Poldervaart, 1958) and also distinguishes magmatic granites from replacement granites (Raju and Rao, 1972). Fractional crystallization of feldspars

FIGURE 14 - AFM diagram showing the calc-alkaline trend (Carmichael *et al.*, 1974).


Fe2O3
Calc-Alkaline Trend
Na2+K2O
MgO


Quartz
4
3
2
1
Plagioclase
K-spar

will result in Ca being used up and the residual liquid being enriched in alkalies (Green and Poldervaart, 1958). This general trend is shown by plotting the calc-alkaline trend line (Nockolds and Allen, 1953). The points show a trend from calcic to more alkalic. Green and Poldervaart (1958) delineated a line from the Ca-apex to the 50% Na, 50% K point and called it the igneous trend line. They state that felsic volcanics should plot on the potassic side of the igneous trend line whereas intermediate and mafic rocks should plot on the sodic side. The transition from felsic to mafic means an increase in ferro-magnesium minerals and a tendency toward dark colours. Granodiorite rocks would be considered felsic and therefore, should plot on the potassic side of the igneous trend line, yet in practice they plot on the sodic side. This is to be expected since there is more Na than K in granodiorites. Acidity (amount of SiO_2) would probably be more appropriate than felsic and mafic. Raju and Rao (1972) studied 170 granitic samples of which 80 were magmatic, 90 replacement. Almost all magmatic samples fall within the field of Raju and Rao, outlined on the Ca-Na-K diagram (Fig. 16). All granodiorite samples fall within this field with the exception of three which are very close. This infers that the granodiorites are magmatic in origin.

FIGURE 16 - Ca-Na-K diagram showing calc-alkaline trend (Nockolds and Allen, 1953), igneous trend line (Green and Poldervaart, 1958) and the magmatic field of Raju and Rao (1972).

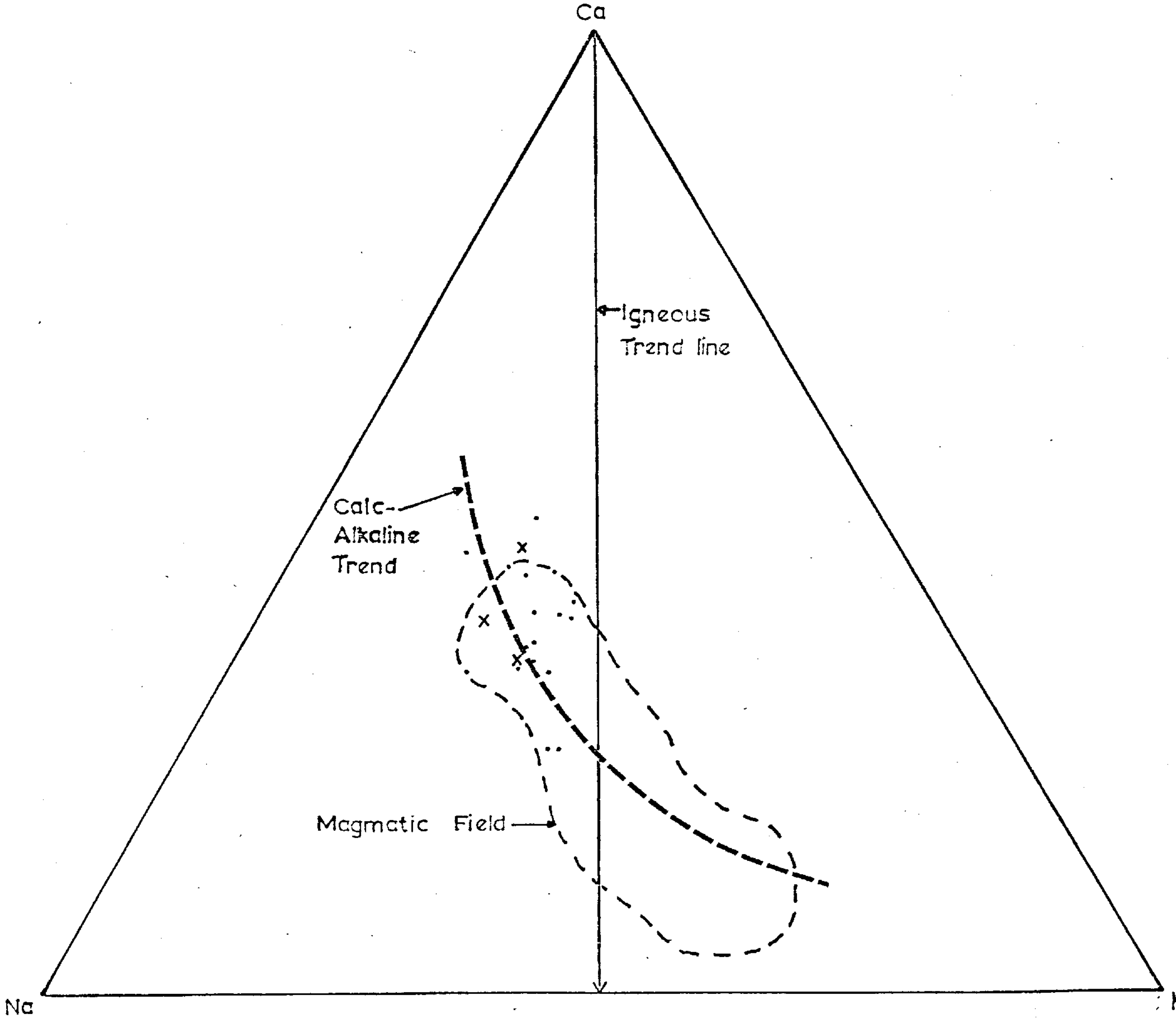

Ca
Igneous
Trend line
Calc-
Alkaline
Trend
Magmatic Field
Na

Figure 17 shows the Quartz-Albite-Orthoclase diagram (Tuttle and Bowen, 1958). Note that there is not a eutectic point until P_{H_2O} = 5000 Bars. Petrographic evidence suggests that a two-feldspar field was present since small potassium feldspar grains lie beside larger plagioclase grains. Probably plagioclase was first to crystallize from the melt, the crystallization path lead to a univariant line where quartz decreased. The path of the liquid then travelled along this univariant to the eutectic point where K-spar crystallized. For this to happen, P_{H_2O} = 5000 Bars. Hydrous minerals such as biotite and hornblende do show there was water present. Water content even in granites seldom exceeds 2% (Wyllie <u>et al</u>., 1976). Points on the plot mainly fall in the quartz field if we assume there is a eutectic which should not exist. The problem with this diagram is that it does not account for the anorthite component in the plagioclase.

This system is correct only when the ratio of Ab/An is infinity. With an Ab/An ratio of 2.9, the temperatures of the eutectic point will change considerably at different P_{H_2O} values (Winkler, 1974). The Ab/An ratio for the granodiorite sample is 2.1. This is sufficient anorthite to considerably reduce the P_{H_2O} at which the ternary eutectic occurred.

FIGURE 17 - Quartz-Albite-Orthoclase diagram with univariant lines corresponding to P_{H_2O} equal to 500, 1000, 3000 and 5000 bars respectively.

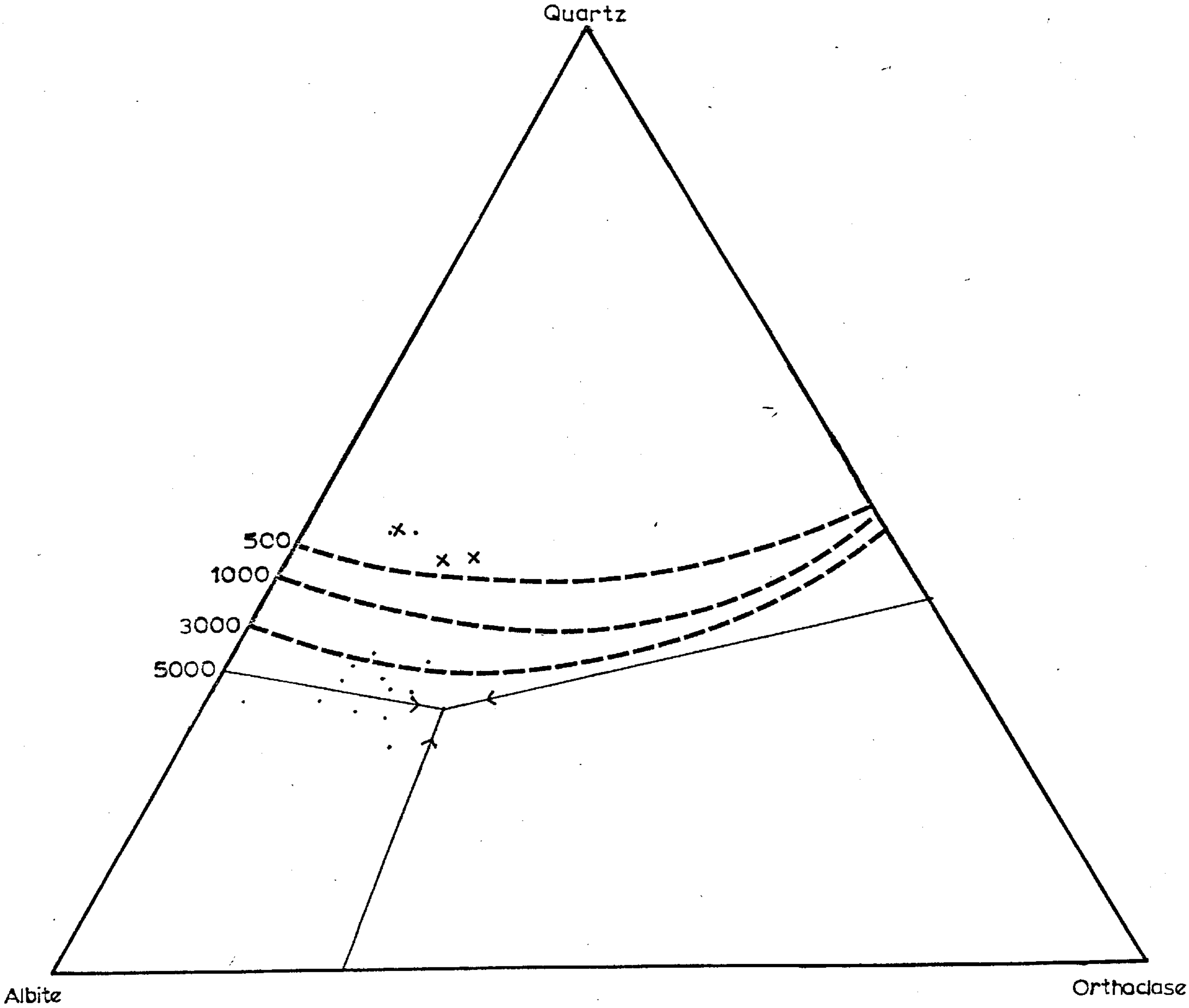

Quartz
500
1000
3000
5000
Albite
Orthoclase

Figure 18 is an Anorthite-Albite-Orthoclase plot which illustrates how much anorthite is present. Approximately 20-40% of all feldspars is anorthite. From this information the question of the applicability of the Quartz-Albite-Orthoclase diagrams for these types of rock should be raised.

3. TRACE ELEMENT TRENDS

Variation diagrams using trace element can also give chemical trends which imply differentiation. If fractional crystallization is proceeding, then it would be expected that Rb and Ba should increase since they remain in the residual liquid. Sr content should decrease during fractionation since it is consumed early (Ringwood, 1955).

Figures 19a-c show the concentration of Rb, Ba, Sr vs. the modified Larsen factor. Rb does not give any information due to scatter. Ba shows a vague increasing trend and Sr, a vague decreasing trend. These results are consistent if differentiation is occurring but the lack of a good trend means the data cannot be relied upon too heavily.

The Ba-Rb-Sr plot (Figure 20) has been suggested as a good model for differentiation, since the three elements occur mainly in the main silicates, not in accessories (McCarthy and Hasty, 1976; Bouseily and Sokkany, 1975). The granodiorite samples were plotted

FIGURE 18 - Anorthite-Albite-Orthoclase diagram

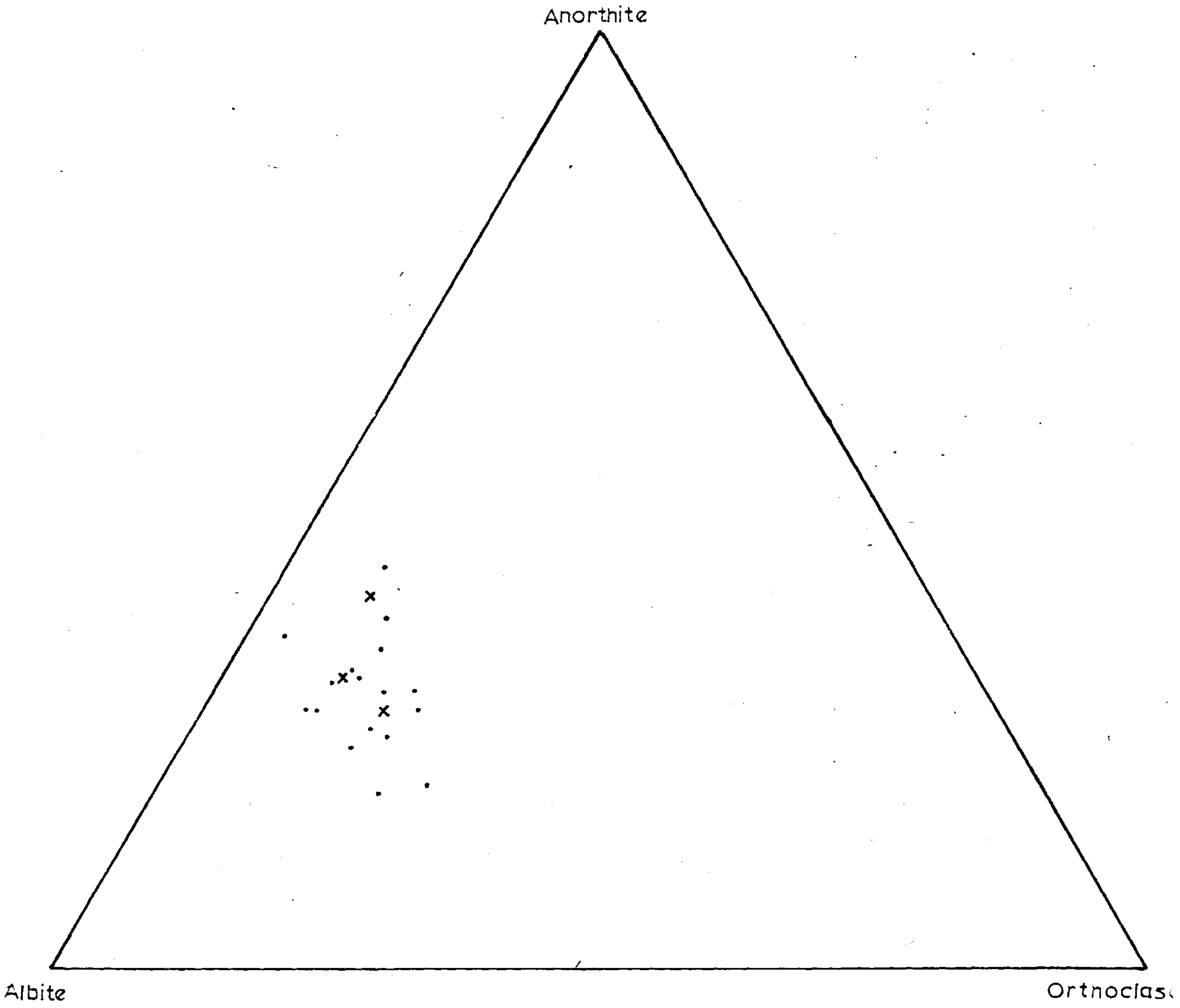
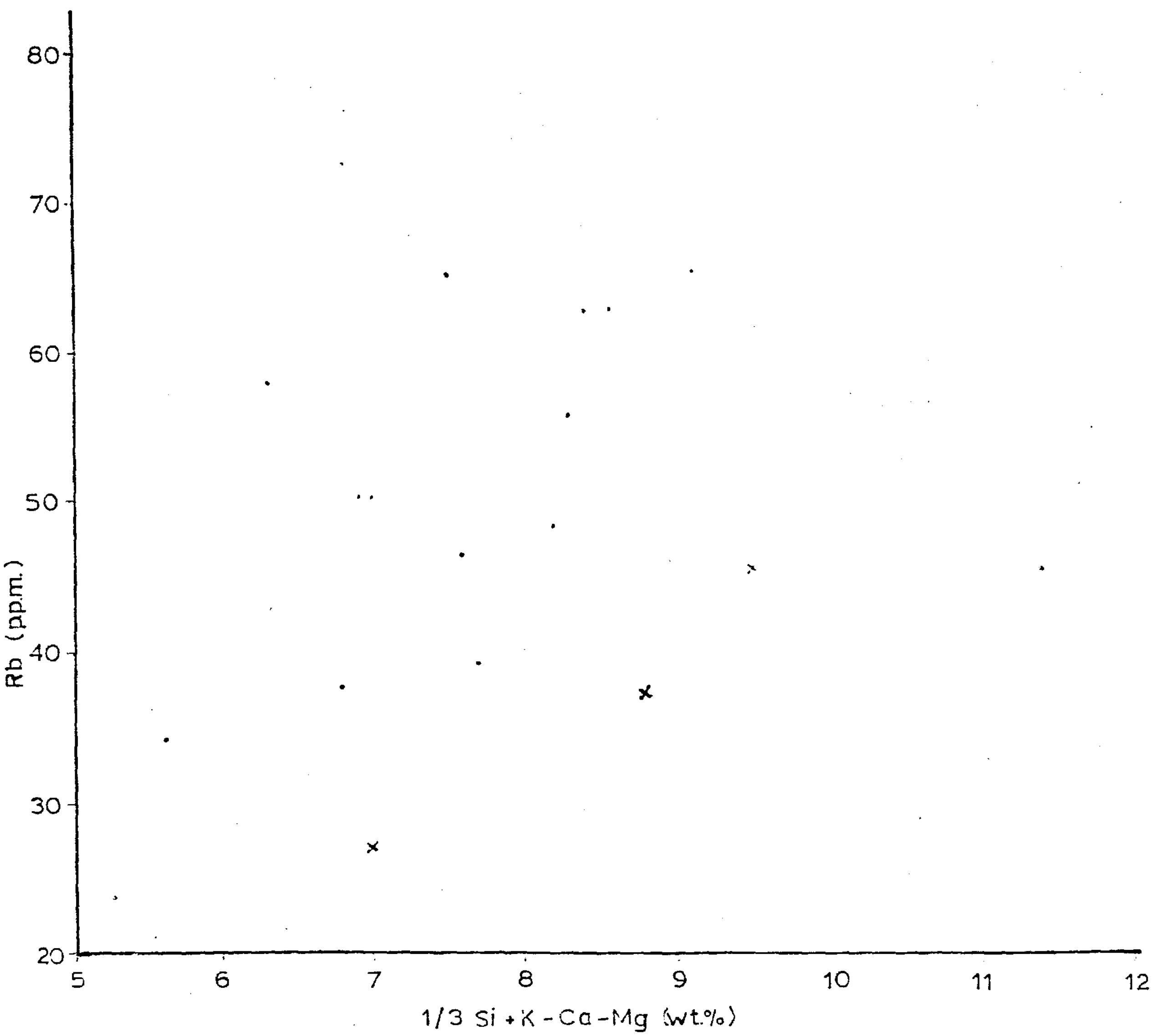

Anorthite
Albite
Ortnoclas

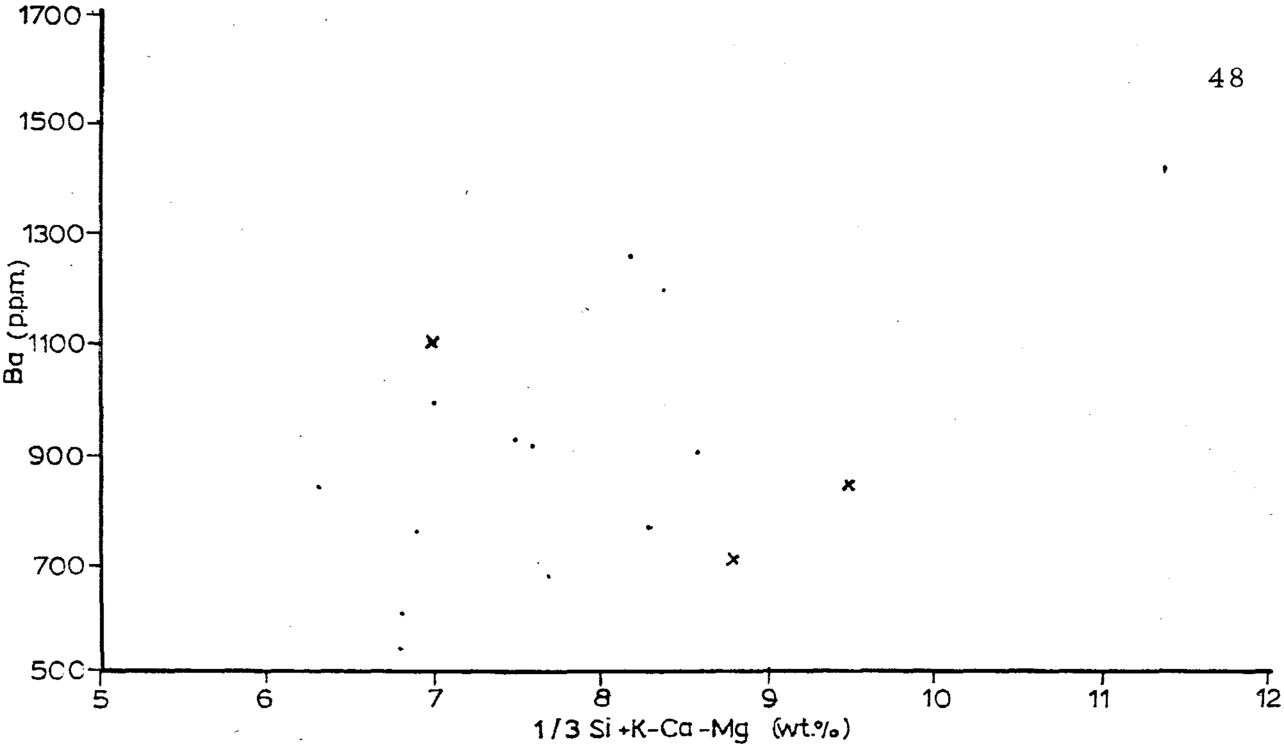
FIGURE 19 - a) Rb vs. Modified Larsen Index.



80
70
60
50
40
30
20
Rb (p.p.m.)
5
6
7
8
9
10
11
12
1/3 Si + K - Ca - Mg (wt.%)

FIGURE 19 - b) Ba vs. Modified Larsen Index.

FIGURE 19 - c) Sr vs. Modified Larsen Index.


1700
1500
1300
1100
900
700
500
Ba (p.p.m.)
5
6
7
8
9
10
11
12
1/3 Si +K-Ca -Mg (wt.%)

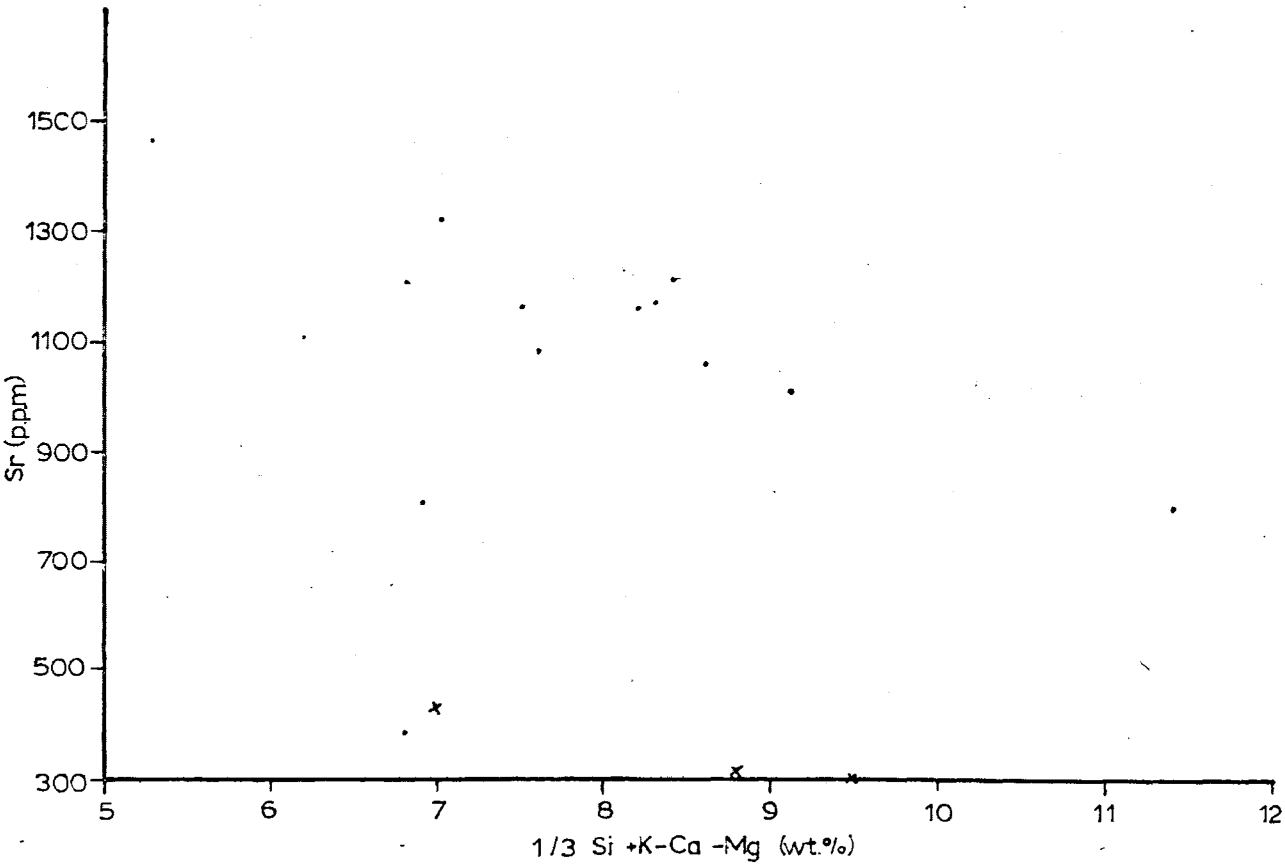

1500
1300
1100
900
700
500
300
Sr (p.p.m)
5
6
7
8
9
10
11
12
1/3 Si +K-Ca -Mg (wt.%)

FIGURE 20 - Ba-Rb-Sr diagram (McCarthy and Hasty, 1976; Bouseily and Sokkany, 1975). The trend the points give is delineated by the dashed area:

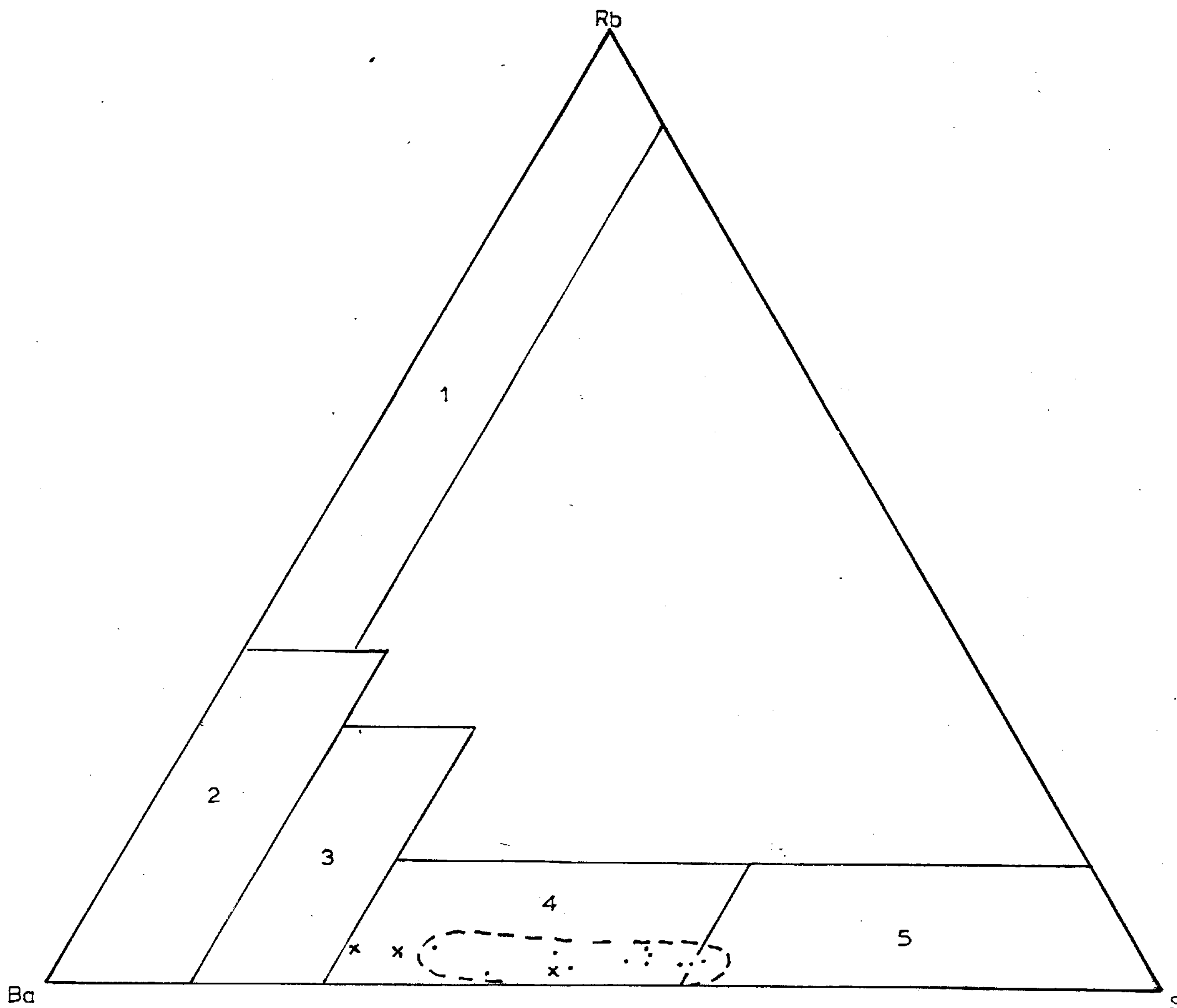
1 - strongly differentiated rocks

2 - normal granites

3 - anomalous

4 - granodiorites and quartz diorites

5 - diorites


Rb
1
2
3
4
5
Ba
S

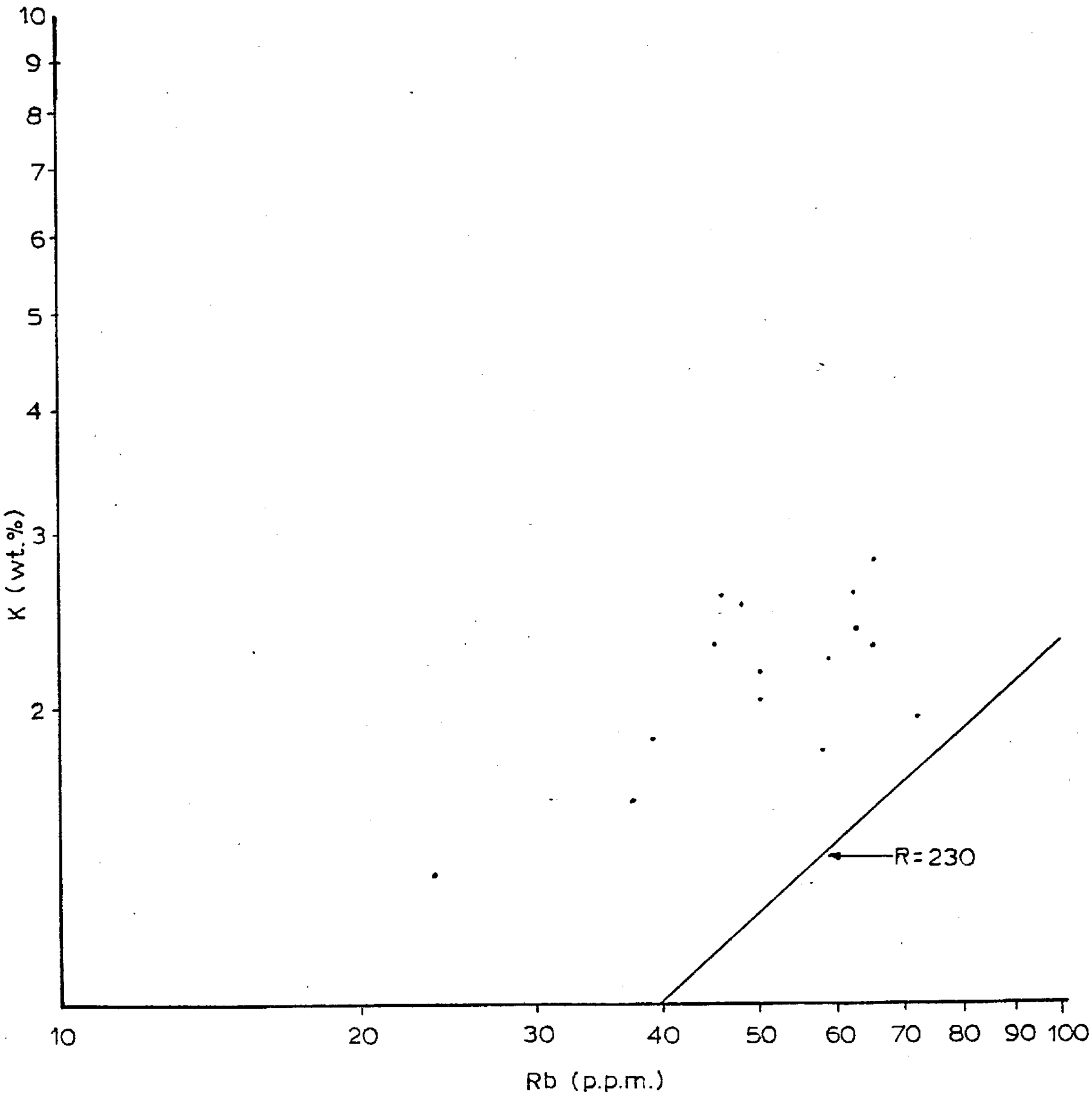
and all fell into the granodiorite field as delineated by Bouseily and Sokkany (1975). A trend shown by the dashed circle is elongate across the granodiorite field. This would be expected if the granodiorites had a differentiated sequence.

Many workers have used K/Rb values to infer differentiation and depth of origin of the magma. A statistical analysis was performed to see whether the K/Rb values (R) do decrease with differentiation (Shaw, 1967). Shaw suggests that the enrichment of Rb relative to K as differentiation proceeds could be due to: a) biotite accumulation since biotite is one of the main reservoirs for Rb; b) metasomatism after separation of aqueous fluids; c) crystallization and removal of hornblende.

Shaw delineated a main trend for igneous rocks with R=230. Ocean tholeiites which represent magma from the upper mantle were found to have an R value of over 1000. Pegmatites which are extremely fractionated rocks from the crust had R values less than 100.

The plot of log K vs. log Rb is shown in Figure 21. The points plot at much higher values than the main trend (R=230). The average R value of the granodiorites was 426 (Table 3). This high K/Rb value can explain the following mineral observations. Biotite was not

FIGURE 21 - Log K vs. Log Rb diagram shows main trend line; R = 230 (Shaw, 1967)


10
9
8
7
6
5
4
3
2
K (wt.%)
R=230
10
20
30
40
50
60
70
80
90
100
Rb (p.p.m.)

very abundant in the rocks. The Rb remained in the residual liquid as the granodiorite was cooling and did not come down until more biotite was crystallizing. The K went into hornblende, which is abundant and pushed the K/Rb value up.

The R value of 426 suggests a lower crustal origin for the magma. If the mantle was the origin, the rocks should have a high amount of Ni and other transition metals since they are concentrated in the mantle. The values of Ni, Cr, Pb, Zn, etc. were very low (Appendix E). An upper crustal origin can also be eliminated. Large ion lithophile elements such as Zn, Y, Nb, Rb, K are known to be concentrated in the upper crust. Values for the granodiorites are not high (Table 3), therefore the upper crust is an unlikely source of the magma.

4. SUMMARY

a) Variation diagrams using major and trace elements, along with various ternary plots show that the magma has differentiated with a calc-alkaline trend.

b) Water was present in the magma because of the presence of minerals such as hornblende and biotite. Care must be taken when interpreting the water pressure at which the magma crystallized from the Qtz-Ab-Orth diagram since there is considerable anorthite component present.

c) The average K/Rb ratio of 426 infers the depth of magma origin to be lower crustal.

If the above assertions are true, partial melting of the lower crust must have occurred which is one of the ways in which a granitic magma can be generated (Wyllie _et al._, 1976; Pitcher, 1979). The original composition of the magma could have been dioritic and was since fractionated into more alkaline residual liquids. Granodiorite samples from the thesis pluton represent an intermediate stage in the fractionation process.

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APPENDICES

APPENDIX A - ROCK SAMPLES AND CLASSIFICATION

VI-1	Granodiorite
VI-2	Granodiorite
VI-3	Andesite tuff
VI-4	Granodiorite
VI-5	Arkosic sandstone
VI-6	Granodiorite
VI-7	Granodiorite
VI-8	Aplite
VI-9	Granodiorite
VI-10	Granodiorite
VI-11	Granodiorite
VI-12	Metagreywacke
VI-13	Granodiorite
VI-14	Granodiorite
VI-15	Granodiorite
VI-16	Granodiorite
VI-17	Granodiorite
VI-18	Granodiorite
VI-19	Metargillite
VI-20	Granodiorite
VI-21	Granodiorite
VI-22	Granodiorite

APPENDIX B - MODAL ESTIMATE

	VI-1	VI-2	VI-3	VI-4	VI-5	VI-6	VI-7	VI-8	VI-9	VI-10	VI-11	VI-12	VI-13	VI-14	VI-15	VI-16	VI-17	VI-18	VI-19	VI-20	VI-21	VI-22
quartz	35	20	-	35	15	15	25	33	25	20	18	25	19	18	14	20	15	15	12	20	13	18
plagioclase	48	58	80	40	60	63	47	41	57	58	51	30	55	53	56	44	63	60	33	55	58	59
K-feldspar	3	7	-	8	10	2	10	12	5	4	9	13	7	10	5	21	7	10	8	5	12	4
amphibole	-	12	-	8	-	15	15	-	15	15	15	-	10	10	20	10	10	10	-	15	15	15
biotite	10	2	-	5	15	-	-	-	-	-	3	7	5	5	-	2	1	2	-	-	-	1
chlorite	-	-	2	-	-	1	-	10	-	-	-	10	-	-	-	-	-	-	12	2	-	-
epidote	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-	-	-	-	25	-	-	-
calcite	-	-	17	-	-	-	-	-	-	-	-	10	1	-	-	-	-	-	10	-	-	-
sphene	1	-	-	1	-	-	-	1	1	-	1	-	1	2	1	1	1	1	-	-	1	1
apatite	-	-	-	-	-	-	-	1	-	-	1	-	1	-	1	-	1	1	-	-	-	1
opaques	3	1	1	3	-	4	3	2	2	3	2	-	1	2	3	2	2	1	-	3	1	1

Note: K-feldspar estimates done using staining technique.

APPENDIX C - ACCURACY OF XRF DETERMINATIONS

The accuracy of the XRF results for major oxides was measured by running standards of known composition and comparing them to the recommended values (Abbey, 1973). For major oxide analysis, the standards GA, SY-3, NIM-G, and G-1 were run and gave the following results:

	NIM-G (unknown)	NIM-G (recommended)	SY-3 (unknown)	SY-3 (recommended)
SiO_2	75.50	75.72	61.10	59.68
Al_2O_3	12.10	12.09	11.34	11.80
Fe_2O_3	1.95	1.88	6.34	6.04
MgO	0.06	0.04	2.55	2.64
CaO	0.83	0.78	8.38	8.26
Na_2O	3.54	3.30	4.00	4.15
K_2O	4.89	5.00	4.24	4.24
TiO_2	0.10	0.09	0.16	0.15
MnO	0.03	0.02	0.33	0.33
P_2O_5	0	0.02	0.57	0.54

There is good agreement between the recommended and unknown values. Samples GA and G-1 also showed good results.

A separate program was run for Rb and Sr using the standards GSP-1, AGU-1, W-1 and BCR-1. The results were as follows:

	W-1 (unknown)	W-1 (recommended)	AGU-1 (unknown)	AGU-1 (recommended)
Rb	22.2	21.0	68.4	67.0
Sr	191.5	190.0	656.9	660.0

Results are within the limits of error.

A program for the trace elements Y, Zr and Nb using the standards GSP-1, NIM-S, SY-1 and Cr-1 yielded the following results:

	GSP-1 (unknown)	GSP-1 (recommended)	NIM-S (unknown)	NIM-S (recommended)
Nb	30.0	29.0	1.0	3.5
Y	28.0	32.0	2.0	3.0
Zr	517.0	500.0	19.0	45.0

Considering these trace elements are not very abundant, the error is reasonable.

The standards W-1, SY-1, BCR-1 and NIM-D were used for the elements Pb, Cu, Zn and Ni. The results obtained were the following:

	W-1 (unknown)	W-1 (recommended)	NIM-D (unknown)	NIM-D (recommended)
Ni	95.0	78.0	2100.0	2863.0
Cu	107.0	110.0	20.0	10.0
Pb	14.0	8.0	10.0	-
Zn	89.0	86.0	93.0	91.0

Ni was run using a different program than Cu, Pb, Zn. Similar results were obtained for the other samples.

APPENDIX D - WHOLE ROCK ANALYSIS (Normalized to 100%)

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Total
VI-1	70.32	14.98	3.49	1.29	3.81	3.83	1.77	0.29	0.11	0.09	100.00
VI-2	65.30	16.65	5.04	1.71	5.15	3.53	1.93	0.48	0.10	0.12	100.00
VI-4	70.13	15.70	3.22	0.98	3.50	3.79	2.20	0.32	0.09	0.07	100.00
VI-6	60.76	17.88	5.89	2.26	5.78	4.71	1.63	0.63	0.09	0.36	100.00
VI-7	62.99	17.20	5.41	1.81	4.10	4.44	3.07	0.58	0.10	0.30	100.00
VI-8	73.14	14.58	2.21	0.70	2.45	3.78	2.79	0.22	0.06	0.07	100.00
VI-9	67.15	15.40	4.74	1.85	4.71	3.29	2.23	0.42	0.08	0.10	100.00
VI-10	65.43	16.38	5.07	1.86	5.45	3.25	1.93	0.41	0.09	0.14	100.00
VI-11	65.25	16.28	4.28	1.77	4.53	3.96	3.12	0.48	0.08	0.26	100.00
VI-13	63.60	17.54	4.68	1.97	3.14	4.86	3.39	0.49	0.08	0.24	100.00
VI-14	63.35	16.65	5.31	1.91	4.89	4.14	2.77	0.57	0.11	0.30	100.00
VI-15A	62.50	16.94	5.30	1.81	5.72	4.55	2.16	0.59	0.11	0.32	100.00
VI-15B	62.24	16.75	5.30	1.87	5.81	4.80	2.20	0.59	0.10	0.33	100.00
VI-15C	62.60	16.48	5.34	2.00	5.72	4.68	2.17	0.59	0.10	0.33	100.00
VI-16	64.58	16.48	4.74	1.71	4.13	4.80	2.69	0.50	0.10	0.25	100.00
VI-17	65.27	16.52	4.37	1.58	4.13	4.45	2.87	0.49	0.10	0.24	100.00
VI-18	63.06	16.96	4.96	2.38	4.92	4.22	2.60	0.52	0.09	0.29	100.00
VI-20	63.13	16.87	5.66	1.80	5.28	3.92	2.44	0.51	0.11	0.28	100.00
VI-21	63.27	16.80	5.29	1.96	5.12	4.20	2.36	0.60	0.07	0.32	100.00
VI-22	63.17	16.91	4.87	2.00	4.97	4.02	3.11	0.54	0.09	0.32	100.00

APPENDIX E - TRACE ELEMENT ANALYSIS (ppm)

	Rb	Sr	Y	Zr	Nb	Pb	Cu	Zn	Ni
VI-1	37.2	312.9	27	89	20	44	12	0	36
VI-2	27.0	439.6	29	97	19	52	21	37	17
VI-4	45.7	305.5	29	100	23	58	13	0	21
VI-6	23.8	1465.3	33	116	20	27	12	23	25
VI-7	48.5	1168.3	29	107	24	25	17	15	31
VI-8	45.7	803.8	26	106	21	39	6	6	19
VI-9	39.5	319.2	34	102	22	31	16	7	15
VI-10	37.8	393.9	30	96	21	34	18	0	17
VI-11	62.9	1218.5	27	93	22	28	16	21	31
VI-13	65.6	1914.7	27	91	22	23	18	12	45
VI-14	65.1	1166.4	30	101	24	16	11	39	27
VI-15	58.1	1108.8	31	105	26	19	12	40	18
VI-16	59.1	1172.7	29	103	23	16	6	41	23
VI-17	63.0	1074.4	28	97	24	18	12	46	79
VI-18	50.4	1322.3	28	97	23	19	22	51	48
VI-20	50.5	808.0	30	104	24	20	10	34	177
VI-21	72.5	1211.2	27	97	26	16	7	40	24
VI-22	46.5	1079.9	27	103	22	20	10	25	161

APPENDIX F - MESONORMS

	QTZ	COR	OR	AB	AN	BI	WO	MT	TN	AP
VI-1	31.42	0.48	6.20	34.76	17.47	7.03	-	1.84	0.62	0.19
VI-2	25.30	0.32	5.62	32.06	23.31	9.47	-	2.66	1.01	0.25
VI-4	30.47	1.43	9.57	34.38	15.95	5.69	-	1.70	0.66	0.15
VI-6	15.28	-	2.25	42.19	22.81	11.81	0.50	3.08	1.31	0.76
VI-7	16.55	0.61	11.90	39.94	16.38	9.95	-	2.83	1.22	0.62
VI-8	33.32	1.49	14.14	34.21	11.05	4.00	-	1.17	0.47	0.15
VI-9	28.23	-	7.21	29.96	20.94	9.81	0.23	2.51	0.90	0.22
VI-10	26.50	-	5.22	29.58	24.71	10.04	0.11	2.68	0.87	0.30
VI-11	20.74	-	12.73	35.70	17.48	9.15	0.66	2.25	1.01	0.55
VI-13	15.26	1.43	13.63	43.42	12.30	10.03	-	2.43	1.02	0.49
VI-14	18.42	-	10.00	37.27	18.76	10.32	0.64	2.78	1.19	0.64
VI-15	16.61	-	6.57	40.87	19.46	9.90	1.90	2.78	1.24	0.68
VI-16	17.52	-	10.11	43.02	15.46	9.19	0.66	2.47	1.04	0.52
VI-17	19.25	-	11.59	39.93	16.68	8.53	0.21	2.29	1.01	0.51
VI-18	17.99	-	8.04	37.92	19.62	11.73	0.42	2.59	1.09	0.61
VI-20	19.70	-	8.19	35.45	21.36	10.12	0.56	2.98	1.06	0.59
VI-21	19.01	-	7.49	37.83	20.08	10.41	0.49	2.77	1.26	0.67
VI-22	17.57	-	11.96	36.10	18.93	10.63	0.75	2.55	1.12	0.66