A STUDY OF THE POTASSIUM FELDSPARS
IN SOME IGNEOUS AND METAMORPHIC ROCKS
FROM THE MOAK-THOMPSON MAP AREA, MANITOBA

A Thesis
Submitted to
The Faculty of Graduate Studies and Research
University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Lowell Thomas Trembath
1961

TABLE OF CONTENTS

CHAPTER PAGE

ACKNOWLEDGEMENTS.............................. i

ABSTRACT...................................... ii

I INTRODUCTION.................................. 1

II NATURE OF THE PRESENT STUDY................... 5

Object of the Study........................... 5

Description of Rock Types..................... 5

Experimental Techniques....................... 8

III EXPERIMENTAL RESULTS OF THE PRESENT STUDY...... 9

Relation of Obliquities to Na:K Ratios in the K Feldspars............................ 9

Relation of Obliquities to Na:K Ratios in the Rocks................................. 10

IV INTERPRETATION OF RESULTS..................... 21

A Proposed Orthoclase-Low Albite Phase Diagram............................... 21

A Proposed Microcline Series-Low Albite Phase Diagram......................... 28

The Effect of High Pressure on the Proposed Microcline Series-Low Albite Phase Diagram.. 36

V RELATION OF OBLIQUITY TO AREAL DISTRIBUTION AND ROCK TYPE................................ 40

APPENDIX...................................... 47

REFERENCES.................................... 51

LIST OF TABLES

TABLE PAGE

1 Chemical Compositions and Obliquities of Microclines.................................. 11

2 Alkali Contents of Rocks and Obliquities of Corresponding K Feldspars...................... 14

3 Reciprocal Cell Dimensions of Synthetic High-Temperature Alkali Feldspars............. 20

4 Obliquities of K Feldspars From the Moak-Thompson Map Area........................ 43

LIST OF ILLUSTRATIONS

FIGURE

1 Plot of Obliquity versus Mole % $KAlSi_3O_8$ to Total Alkali Feldspar in the K Feldspar Specimens.................................. 13

2 Plot of Obliquity versus Mole % $KAlSi_3O_8$ to Total Alkali Feldspar in the Rock Specimens... 16

3 Plot of the Ratio Na Feldspar:K Feldspar versus Obliquity........................ 20

4 Proposed Orthoclase-Low Albite Phase Diagram.. 26

5 Proposed Microcline Series-Low Albite Phase Diagram.................................. 31

6 Proposed Microcline Series-Low Albite Phase Diagram at Very High Water Pressures......... 37

ACKNOWLEDGEMENTS

The writer is particularly indebted to Dr. R. B. Ferguson, Professor of Mineralogy at the University of Manitoba, for suggestion of this research project and for invaluable help in the preparation of the thesis.

Thanks are due to J. M. Patterson, a fellow graduate student, for his interest and helpful discussion. Specimens, thin sections and notes being used in the preparation of the Manitoba Department of Mines and Natural Resources report on the Moak-Thompson area (J. M. Patterson, to be published) were made available to the writer with the permission of J. F. Davies, Chief Geologist, Manitoba Department of Mines and Natural Resources.

D. Brown, Manitoba Department of Mines analyst, assisted with the flame photometer analysis of 18 microclines.

Expenses of the investigation were partially defrayed by a National Research Council research grant to R. B. Ferguson and a studentship to the writer.

ABSTRACT

Sodium and potassium contents of 35 igneous and metamorphic rock specimens from the Moak-Thompson area were determined by flame photometer. Potassium feldspars were separated from the rocks and obliquities (triclinicities) of the minerals estimated from X-ray powder photographs. For a number of specimens an increase in obliquity may be correlated with an increase in the ratio K feldspar:total alkali feldspar with a monoclinic K feldspar occurring in a rock with ~ 23 mole % K feldspar of the total alkali feldspar and a maximum microcline in a rock with ~ 67 mole % K feldspar of the total alkali feldspar. It is suggested that there is a microcline series extending over the composition range ~ 23 - 67 mole % K feldspar of the alkali feldspar diagram, and a phase diagram is proposed.

A modification of the phase diagram for very high water pressures is proposed to account for the occurrence of microclines with a given obliquity in igneous rocks of differing alkali compositions. An orthoclase-low albite phase diagram is proposed to account for the orthoclase-cryptoperthite series.

Sodium and potassium contents and obliquities of 37 microclines were determined but no simple relationship was found between mineral composition and obliquity.

The study suggests a possible way of distinguishing between igneous and metamorphic rocks.

CHAPTER I

INTRODUCTION

Feldspars are the most abundant minerals in the earth's crust and thus are of particular importance to petrologists. Members of the feldspar group are closely related in form and physical properties. Laboratory studies have indicated that at high temperatures there is complete solid solution between K feldspar and Na feldspar and between Na feldspar and Ca feldspar and only limited solid solution between K feldspar and Ca feldspar. Thus the common rock forming feldspars are divided into two series, the plagioclase series (Na-Ca) and the alkali series (Na-K), the latter series being the one considered in this thesis.

In natural feldspars polymorphism and limited solubility of the low-temperature forms complicate the picture. K feldspar occurs in several polymorphic forms. Sanidine is a monoclinic high-temperature polymorph commonly found in volcanic rocks. Orthoclase, a second monoclinic variety, is found in igneous and metamorphic rocks as well as in pegmatites. Microcline, a triclinic polymorph is unusual in that the reciprocal lattice angles α^* and γ^* may range in value from 90° for a monoclinic member to $90^\circ 25'$ and $92^\circ 20'$ respectively. Microcline is a common K feldspar in igneous and metamorphic rocks and pegmatites. Adularia is the name given a morphologically monoclinic form with a distinctive crystal habit that is commonly found in low-temperature veins.

Two sodium feldspar polymorphs have been observed in natural specimens. High-temperature albite is found in volcanics and high-temperature veins. Low-temperature albite is the common Na feldspar in igneous and metamorphic rocks and pegmatites.

At low temperatures solid solutions intermediate between the potassium and sodium end members exsolve into an intergrowth of potassium- and sodium-rich solid solutions. These intergrowths are termed perthites if the K-rich solid solution predominates or anti-perthites if the Na-rich solid solution predominates.

Barth (1934) suggested that the potassium feldspar polymorphs differ by the degree of order or disorder of the Si and Al atoms, with low-temperature forms showing a high degree of ordering (Al concentrated in one site) and high-temperature forms showing a lesser degree of ordering.

Goldsmith and Laves (1954b) demonstrated that a maximum microcline heated at high temperatures undergoes a progressive change in lattice geometry from a maximum microcline through intermediate values of obliquity* to a monoclinic feldspar. They interpreted this as reflecting a change in the degree of Al-Si ordering with maximum microcline being fully ordered and monoclinic sanidine being disordered. They concluded that

---

* "Obliquity" is used here in place of the more common "triclinicity" because the writer regards it as the more precise term. See Appendix 1.

obliquity is a function of temperature with maximum microcline the low-temperature form, intermediate microcline the intermediate-temperature form and monoclinic sanidine the high-temperature form. They suggested that "common orthoclase" consists of triclinic units twinned on a sub-X-ray scale to simulate monoclinic symmetry, and thus they do not regard it as a true polymorph.

Goldsmith and Laves (1954b) also showed that microcline heated under water pressure was changed to sanidine with no evidence of a progressive change in lattice geometry. They interpreted this as "a hydrothermal synthesis of sanidine, the microcline acting as source material".

In recent years a number of detailed structure analyses have been completed confirming the idea that the feldspar polymorphs differ by the degree of Al-Si ordering. In the Na feldspars, Ferguson et al (1958) found that in high albite the Al-Si atoms are disordered and in low albite most but not all of the Al is concentrated in one site. In the K feldspars, Cole et al (1949) found that monoclinic sanidine is completely disordered; Jones and Taylor (1961) found that monoclinic orthoclase is partially ordered; and Bailey and Taylor (1955) found an intermediate microcline (triclinic) to be partially ordered in a complex way. It is probable that maximum microcline is more highly ordered than the intermediate microcline (Goldsmith and Laves, 1954).

Although the structural evidence confirms the idea that the feldspar polymorphs are related by differences in degrees of ordering, Ferguson et al (1958) and Ferguson (1960), as a result of structural work, disagree with Goldsmith and Laves (1954b) that the low-temperature form of an alkali feldspar is the one most highly ordered with respect to Al-Si. Rather they suggest that the alkali feldspars behave as ionic compounds with the low-temperature forms having, in general, the Al-Si distribution that leads to the most satisfactory charge balance. In none of the alkali feldspars is this distribution likely a fully ordered one. By means of the ionic theory, the authors are able to offer explanations for the particular (not fully ordered) Al-Si distributions observed in low albite, intermediate microcline and orthoclase. Details of their theory are given in Ferguson et al (1958) and in Ferguson (1960).

MacKenzie (1954) suggested that the range of lattice parameters in the microcline series was due to the Na feldspar in solid solution in the K feldspar. Difficulty is encountered in testing this theory because chemical methods are unable to differentiate between Na feldspar in solid solution and Na feldspar exsolved as perthitic intergrowth.

Ferguson et al (1958) suggested that sodium is essential to the crystallization of microcline, and that microcline forms as the result of exsolution of an alkali feldspar that contained appreciable sodium at higher temperatures. The K feldspar itself is the result of a more or less complete exsolution process, and thus it may not contain as much Na at low temperatures as it did before exsolution. The most highly triclinic potassium feldspar would be maximum microcline with the same Al-Si distribution as low albite, corresponding to a potassium feldspar crystallizing from a high sodium melt.

CHAPTER II

NATURE OF THE PRESENT STUDY

OBJECT OF THE STUDY

The aim of this study was to examine, for a series of rocks from one area, the possible relation of the obliquities ("triclinicities") of the K feldspars to:

i) the Na and K content of the potassium feldspars,
ii) the Na:K ratios in the respective rocks, and
iii) areal distribution and rock type.

DESCRIPTION OF ROCK TYPES

A suite of granitic rocks from the Moak-Thompson map area of Northern Manitoba was readily available for such a study as a fellow graduate student, J. M. Patterson, was studying the geology of the area for the Manitoba Government as well as for his own doctoral thesis. Detailed rock descriptions and a geological map are to be published in a Manitoba Department of Mines and Natural Resources' Report on the Moak-Thompson area by J. M. Patterson.

The specimens studied have been divided into five groups according to rock type by the Manitoba Mines Branch.

Red Granite

In outcrop this unit is massive to slightly foliated, medium to coarse grained, and locally porphyritic. Typical specimens are composed of red perthitic microcline (50%), sodic plagioclase An_{20-25} (20%), quartz (25%), and biotite (5%). The plagioclase is commonly sericitized. Minor amounts of muscovite, apatite, zircon and iron oxides are present in some rocks.

Grey Granodiorite

This rock is massive to foliated. The average specimen contains plagioclase (60%), quartz (25%), potassium feldspar (15% or less but locally up to 30%), and biotite (5%). The relationship of this unit to the granite gneiss and red granite is not known.

Granite Gneiss

In general this is a well foliated to moderately well banded grey, white or pink rock. It is intruded by the red granite. Many of the contacts with adjacent sedimentary gneiss and granitic rocks are gradational. In some areas a mixture of granite gneiss, sedimentary gneiss and granitized gneiss are included in this unit. Basic inclusions and basic bands are common.

This unit includes a wide range of compositions. The major minerals are plagioclase An_{20-25} (40-60%), potassium feldspar (0-40%), quartz (25-40%), and biotite (0-10%). Plagioclase is commonly highly sericitized in the specimens with a high alkali content, or altered to epidote in the more basic rocks. Apatite, zircon, sphene and iron oxides are common accessories.

Sedimentary Gneiss

This unit is characterized by fine persistent banding. Locally broad bands (or sills) of amphibolite and/or pegmatites accentuate this fine banding.

The important minerals in these rocks are plagioclase (40-60%), quartz (20-40%), and biotite (0-15%) with potassium feldspar locally making up 50% of the rock. Garnet and amphibole are important in some zones. Chief accessories are apatite, zircon, iron oxide and sphene. Pyroxene, sillimanite, cordierite, staurolite and kyanite are found in many of the rocks. Plagioclase is commonly sericitized in the rocks high in alkali or altered to epidote in the more basic rocks, and either of these conditions made it impossible to obtain reliable compositions of the original plagioclase by the usual optical methods.

Pyroxene Granulite or Charnockite

The charnockites are well foliated to poorly banded rocks. A wide range of compositions is included in this unit. Plagioclase An_{30-40} (30-50%), quartz (30-50%), and potassium feldspar usually less than 15% but in places up to 30%. Coarse perthite and antiperthite are common. Locally pyroxene constitutes 30% of the rock but averages 5%. Hypersthene is the common pyroxene although both hypersthene and clinopyroxene are found in some specimens. Combinations of biotite, chlorite, amphibole, magnetite, antigorite and serpentine are pseudomorphs after pyroxene.

In studying the natural feldspar system it is desirable to consider both the alkali and the plagioclase feldspars. Calcium contents of the rocks should have been determined in addition to the alkalies, but no ready method of determination was available. As optical studies indicate that Ca is present in the plagioclases, it is necessary to regard the system as a pseudobinary join between K feldspar and a sodic plagioclase.

EXPERIMENTAL TECHNIQUES

The potassium feldspars were separated from the rocks by standard heavy liquid procedures. Sodium and potassium contents of both the potassium feldspar and the rock specimens were determined with a flame photometer. Obliquities (triclinicities) were determined from X-ray powder photographs of the K feldspar specimens taken with 114.53 mm cameras. The alkali compositions of the feldspars were determined with a Philips diffractometer using the $(\bar{2}01)$ spacing on the powder patterns (Bowen and Tuttle, 1950; Orville, 1957). Details of experimental techniques are given in Appendix 1.

CHAPTER III

EXPERIMENTAL RESULTS OF THE PRESENT STUDY

RELATION OF OBLIQUITIES TO Na:K RATIOS IN THE K FELDSPARS

Thirty-seven K feldspars were selected for chemical analysis in an attempt to establish any possible relationship between alkali ratio and obliquity. Powder photographs were taken of these samples before analysis. The strongest line of albite (a combination of the 002, 040, 220 and $2\bar{2}0$ reflections) was visible on nearly all of the patterns indicating that these specimens contained appreciable exsolved albite. The samples were selected to include the whole range of obliquities. Intermediate values (obliquity = 0.4 - 0.5) were rare. It was difficult to obtain samples with low obliquities in a pure form because such grains are highly irregular in outline (best described as interstitial), and they only make up small percentages of the rocks in which they occur.

Compositions were determined with a flame photometer. As a check on the flame photometer determinations, the potassium-sodium contents of the feldspars were estimated by the $\bar{2}01$ method (Bowen and Tuttle, 1950; Orville, 1957). For this purpose the specimens were first heated at 1050°C for 140 hours.

Results of the analyses by both the flame photometer and the $\bar{2}01$ methods, and the obliquities, are given in Table 1. For 19 of the specimens the K feldspar contents determined by the $\bar{2}01$ method are within 4 mole % of the flame photometer values. For ten specimens the two methods yielded results differing by

5-10 mole % K feldspar. In general the diffractometer results indicate higher K feldspar contents suggesting that these specimens were not completely homogenized by the heat treatment.

The potassium contents in mole % of the K feldspars (using the flame photometer values) are plotted versus obliquities in Figure 1. If there is a simple relationship between obliquities and the alkali compositions of the K feldspars, it is not evident in this suite of minerals. It is evident that a K feldspar with a given obliquity may have a range in compositions. Whether the sodium is present in solid solution within the potassium feldspar or as a separate phase cannot be determined by chemical analysis. As noted above the X-ray powder photographs indicate that at least part of the sodium is present as a separate albite phase in most of the specimens.

RELATION OF OBLIQUITIES TO Na:K RATIOS IN THE ROCKS

The obliquities of the K feldspars and the potassium-sodium contents (determined by flame photometer) of the rocks are listed in Table 2. Sodium and potassium have been recalculated to mole % feldspar of the total alkali feldspar. The data given in Table 2 and plotted in Figure 2 show that for a large number of specimens there is an increase in obliquity corresponding to an increase in the ratio K feldspar:total alkali feldspar of the rock.

In interpreting this diagram it must be remembered that the obliquities are measurable within ± 0.05 under the most favourable condition (obliquities greater than 0.4). In the

TABLE I

CHEMICAL COMPOSITIONS AND OBLIQUITIES OF MICROCLINES

			Flame Photometer			Diffractometer ($\bar{2}01$ method)
Specimen Number	Rock Type*	Obliquity	K_2O (wt.%)	Na_2O (wt.%)	K feldspar (mole %)	K feldspar (mole %)
M-113-58	GG	0.77	13.58	1.75	83.6	-
M-336-58	GG	0.81	-	-	-	84.9
M-361-58	GG	0.96	-	-	-	86.6
P-364-58	PG	0.79	-	-	-	77.5
P-511-58	PG	0.50	13.54	1.84	82.9	87.0
P-588-58	PG	$\begin{bmatrix}0.70\\0.00\end{bmatrix}$	13.57	1.83	83.0	85.3
P-621-58	PG	0.00	13.48	2.13	80.6	-
A-1-3-59	RG	0.90	14.44	1.34	87.6	89.0
A-4-1-59	GG	0.00	10.81	2.88	71.2	-
A-6-59	GG	0.35	11.43	2.43	75.6	-
A-7-59	GG	0.35	12.93	3.19	72.7	-
A-8-59	RG	0.80	9.94	2.74	70.5	-
A-11-59	RG	0.96	14.11	1.94	82.7	85.7
A-20-59	RG	0.87	-	-	-	99.8
A-32-59	RG	0.82	-	-	-	87.0
A-55-2-59	GG	0.87	-	-	-	90.7
A-57-59	GG	0.72	15.06	1.09	90.1	96.5
A-65-59	GG	0.65	11.30	1.48	83.4	-
A-110-59	RG	0.96	14.88	1.23	88.8	90.7
A-173-59	RG	0.81	14.04	1.58	85.4	90.7
A-276-59	GG	0.86	-	-	-	88.2

---

* Abbreviations for rock types.

RG - Red granite

GGd - Grey granodiorite

GG - Granite gneiss

SG - Sedimentary gneiss

PG - Pyroxene granulite

TABLE I cont'd.

CHEMICAL COMPOSITIONS AND OBLIQUITIES OF MICROCLINES

			Flame Photometer			Diffractometer ($\bar{2}01$ method)
Specimen Number	Rock Type*	Obliquity	K_2O (wt.%)	Na_2O (wt.%)	K feldspar (mole %)	K feldspar (mole %)
A-356-59	GG	0.20	11.70	1.38	84.8	-
A-445-59	SG	0.64	13.45	1.68	84.0	80.0
A-468-59	GGd	0.89	-	-	-	80.8
A-490-59	SG	0.10	12.10	1.33	85.7	-
A-548-59	SG	0.30	13.86	1.25	87.9	93.2
A-635-1-59	SG	0.81	-	-	-	91.1
A-682-59	SG	0.87	14.15	1.36	87.2	90.3
A-807-59	SG	0.61	14.43	1.22	88.6	92.8
B-48-1-59	GG	0.74	13.38	1.74	83.5	88.2
B-84-3-59	GG	0.85	13.48	1.50	85.5	90.3
B-87-1-59	RG	0.86	10.12	3.80	63.7	71.8
B-113-1-59	RG	0.59	13.70	1.42	86.4	82.4
B-184-59	RG	0.89	14.45	1.48	86.5	86.5
B-233-59	GG	0.20	14.45	1.73	84.6	83.2
B-338-59	GG	0.69	13.60	1.57	85.1	83.2
B-370-59	RG	0.86	14.13	1.46	86.4	95.7
B-403-1-59	SG	0.00	12.26	1.97	80.4	89.9
B-448-1-59	GGd	0.81	13.93	1.32	87.4	90.7
B-459-59	GG	0.69	13.32	1.63	84.3	86.6
B-465-59	GG	0.90	13.61	1.93	82.3	82.4
B-591-59	GG	0.87	-	-	-	82.2
B-692-59	SG	0.98	14.95	1.13	89.7	89.9
B-701-59	SG	0.90	13.55	1.82	83.4	90.7
B-768-59	GG	0.86	-	-	-	86.1
C-103-59	RG	0.80	10.92	3.71	65.9	82.4
C-179-1-59	GGd	0.85	14.25	2.14	81.4	91.1
C-288-4-59	SG	0.30	-	-	-	85.7
C-506-59	SG	0.51	14.55	1.51	86.4	99.9

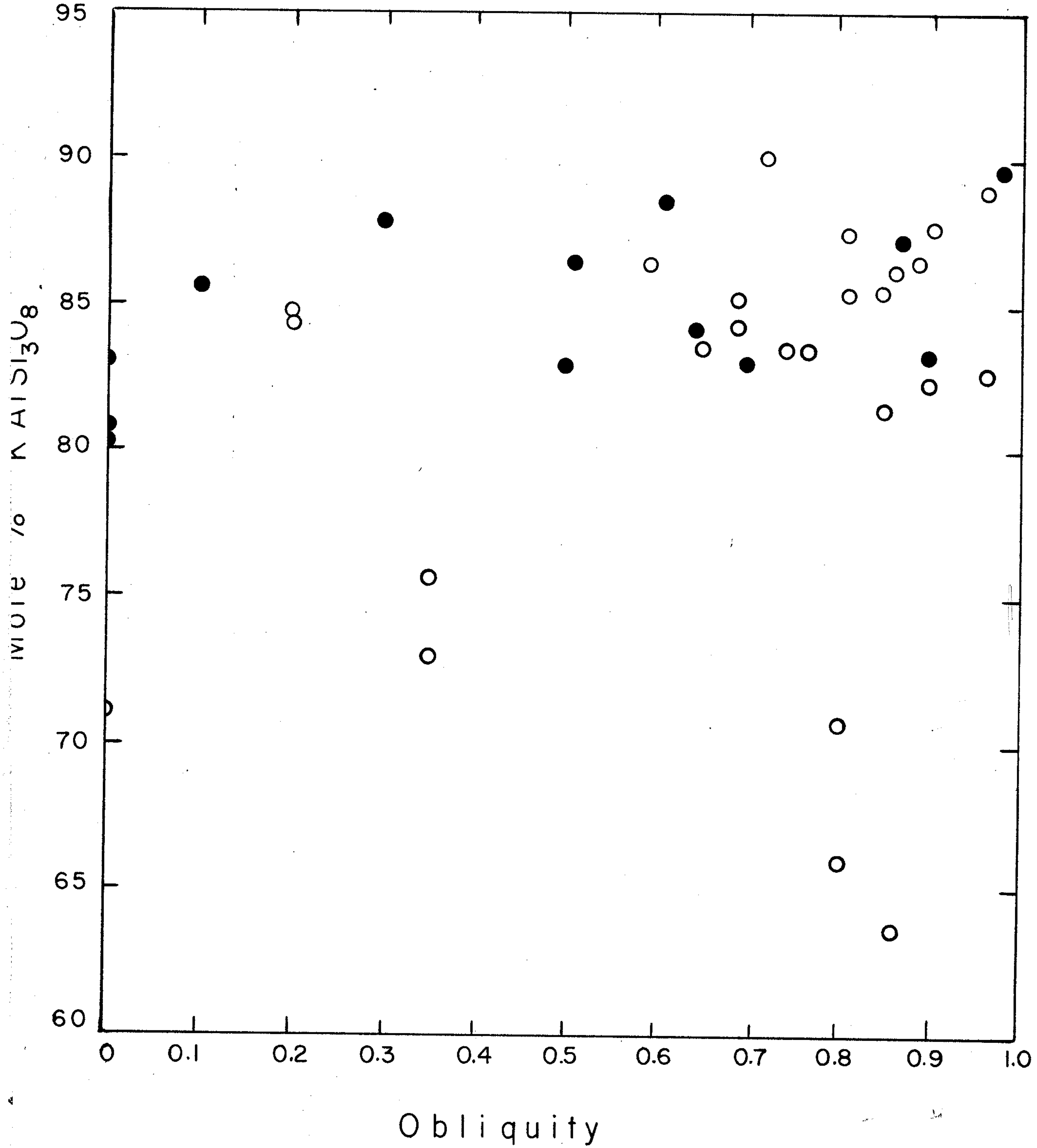


Figure 1. Plot of obliquity versus mole % $KAlSi_3O_8$ to total alkali feldspar in the K feldspar specimens. Open circles denote rocks of probable igneous origin. Closed circles denote rocks of probable metamorphic origin.

TABLE II

ALKALI CONTENTS OF ROCKS AND OBLIQUITIES OF K FELDSPARS

Chemical Compositions by Flame Photometer

Specimen Number	Rock Type*	Obliquity	K_2O (wt.%)	Na_2O (wt.%)	K feldspar mole %	$\frac{\text{Moles } Na_2O}{\text{Moles } K_2O}$
M-113-58	GG	0.77	4.28	4.25	39.9	1.51
P-324-58	PG	0.10	2.47	3.84	29.7	2.36
P-340-58	PG	0.25	1.37	3.48	20.6	3.86
P-511-58	PG	0.50	5.89	3.96	49.6	1.03
P-588-58	PG	[0.70 0.00]	4.41	3.06	48.9	1.05
P-621-58	PG	0.00	1.91	4.54	21.7	3.61
A-4-1-59	GG	0.00	4.18	3.57	43.5	1.30
A-6-59	GG	0.35	1.80	6.06	16.4	5.12
A-7-59	GG	0.35	3.96	4.77	35.3	1.83
A-8-59	RG	0.80	3.85	5.07	33.3	2.00
A-11-59	RG	0.96	7.13	3.46	57.6	.74
A-57-59	GG	0.72	3.84	4.97	33.7	1.97
A-61-59	SG	0.10	2.17	4.11	25.8	2.88
A-65-59	GG	0.65	2.95	4.76	29.0	2.45
A-110-59	RG	0.96	4.02	4.82	35.4	1.82
A-173-59	RG	0.81	8.43	3.60	60.6	.65
A-356-59	GG	0.20	2.56	3.63	31.7	2.15
A-445-59	SG	0.64	4.76	3.81	46.5	1.15
A-490-59	SG	0.10	2.92	4.52	29.8	2.35
A-548-59	SG	0.30	3.72	4.27	36.4	1.74

---

* Abbreviations for rock types.

RG - Red granite
GGd - Grey granodiorite
GG - Granite gneiss
SG - Sedimentary gneiss
PG - Pyroxene granulite

TABLE II cont'd.

ALKALI CONTENTS OF ROCKS AND OBLIQUITIES OF K FELDSPARS

Chemical Compositions by Flame Photometer

Specimen Number	Rock Type*	Obliquity	K_2O (wt.%)	Na_2O (wt.%)	K feldspar mole %	$\frac{\text{Moles } Na_2O}{\text{Moles } K_2O}$
A-682-59	SG	0.87	6.38	3.21	56.7	.76
A-807-59	SG	0.61	5.90	3.45	53.0	.89
B-48-1-59	GG	0.74	4.00	4.38	37.5	1.66
B-113-1-59	RG	0.59	3.96	4.86	34.9	1.86
B-233-59	GG	0.20	3.11	4.73	30.3	2.31
B-338-59	GG	0.69	4.71	3.63	46.1	1.17
B-403-1-59	SG	0.00	1.79	3.90	23.2	3.31
B-448-1-59	GGd	0.81	5.28	2.95	54.1	.85
B-459-59	GG	0.69	1.71	5.76	16.3	5.12
B-465-59	GG	0.90	6.39	2.64	61.4	.63
B-692-59	GG	0.98	6.00	2.65	59.8	.67
B-701-59	SG	0.90	6.23	2.24	64.7	.55
C-103-59	RG	0.80	3.47	5.24	30.4	2.29
C-179-1-59	GGd	0.85	3.96	4.56	36.4	1.75
C-506-59	SG	0.51	6.07	4.12	49.2	1.03

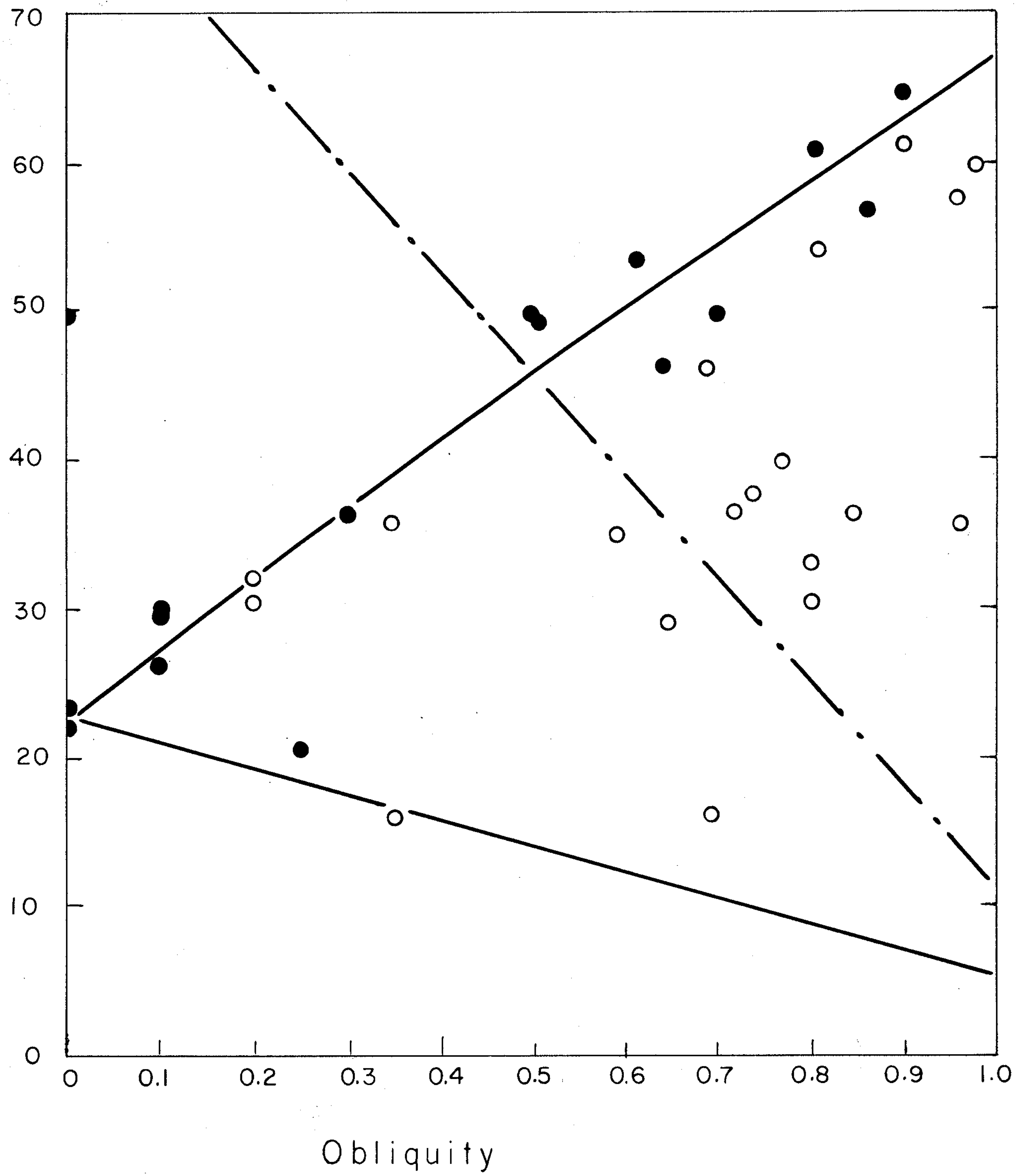


Figure 2. Plot of obliquity versus mole % $KAlSi_3O_8$ to total alkali feldspar in the rock specimens. Significance of the solid and chained lines is discussed in the text.

Open circles denote rocks of probable igneous origin.

Closed circles denote rocks of probable metamorphic origin.

case of lower obliquities the values given are estimates of line widths, and they may be less accurate although the relative values are probably significant.

If a nearly straight line is drawn from 22 mole % K feldspar for a monoclinic feldspar (obliquity = 0) to 67 mole % K feldspar at the maximum microcline side (obliquity = 1) a large number of the points fall close to the line. All rock types (including some of probable igneous origin) included in this study are represented by these points. Removed from, but mainly below, this line there is a scattered group of points representing rocks of probable igneous origin. A discussion of possible reasons for the obliquities of this group not being simply related to the compositions will be given after consideration of a possible alkali feldspar phase diagram.

Figure 2 shows that in some rocks the obliquity of the K feldspar may be correlated to the total alkali composition. In general an increase in obliquity may be correlated with an increase in potassium content. If we consider a given composition, for example 35 mole % K feldspar, Figure 2 indicates that the K feldspar may have an obliquity equal to or greater than 0.3. Thus the line drawn may represent the <u>minimum</u> obliquity that a K feldspar may possess if it crystallizes and cools to ordinary temperatures at or near equilibrium conditions assuming that obliquity is, in some way, determined by the total alkali in the rock.

This does not mean that it is impossible to have K feldspars that would plot above the line. The heating experiments of Goldsmith and Laves (1954b) showed that if a specimen is strongly heated the obliquity can be reduced. However it should be pointed out that these heating experiments were carried out on fairly pure K feldspars that have been removed from the alkali feldspar system of which they are a part. If a microcline in a rock were heated after the Na feldspar had exsolved out (into separate grains) the obliquity would be reduced. The resulting K feldspar would have an obliquity which was not related to the total alkali content of the rock.

Specimen P-588-58 (48.7 mole % K feldspar) was found to contain two K feldspar phases -- a microcline with obliquity = 0.70 and a monoclinic phase. This is interpreted as a partial change of the microcline to a monoclinic feldspar. Water was probably present during the transition for the original pyroxene in the rock has been replaced by a number of hydrous minerals. The reaction was probably similar to that carried out by Goldsmith and Laves (1954b) in their hydrothermal-treatment of microcline. In order to obtain obliquities intermediate between the original value and the monoclinic member the K feldspar would have to be heated in a dry environment.

Table 2 and Figure 2 also suggest that in alakali feldspar systems containing less than 23 mole % K feldspar the K feldspar will form a microcline. Only three specimens were found which contain less than 23 mole % K feldspar, and these are all intermediate microclines. This is very little evidence to offer in support of a second microcline series but such a series may exist.

The data given in Table 2 and Figure 2 are plotted in a different manner in Figure 3. Here the ratio $\frac{\text{Na-Feldspar mole \%}}{\text{K-Feldspar mole \%}}$ is plotted against the obliquity. This curve is important because it indicates that the Na:K ratio approaches a lower limit for most triclinic K feldspars. This limit corresponds to an Na:K ratio of ~ 1:2. It is suggested that perhaps maximum microcline represents the limiting composition of the triclinic microclines. It is unfortunate that rocks containing more potassium than this ratio were not encountered in this study.

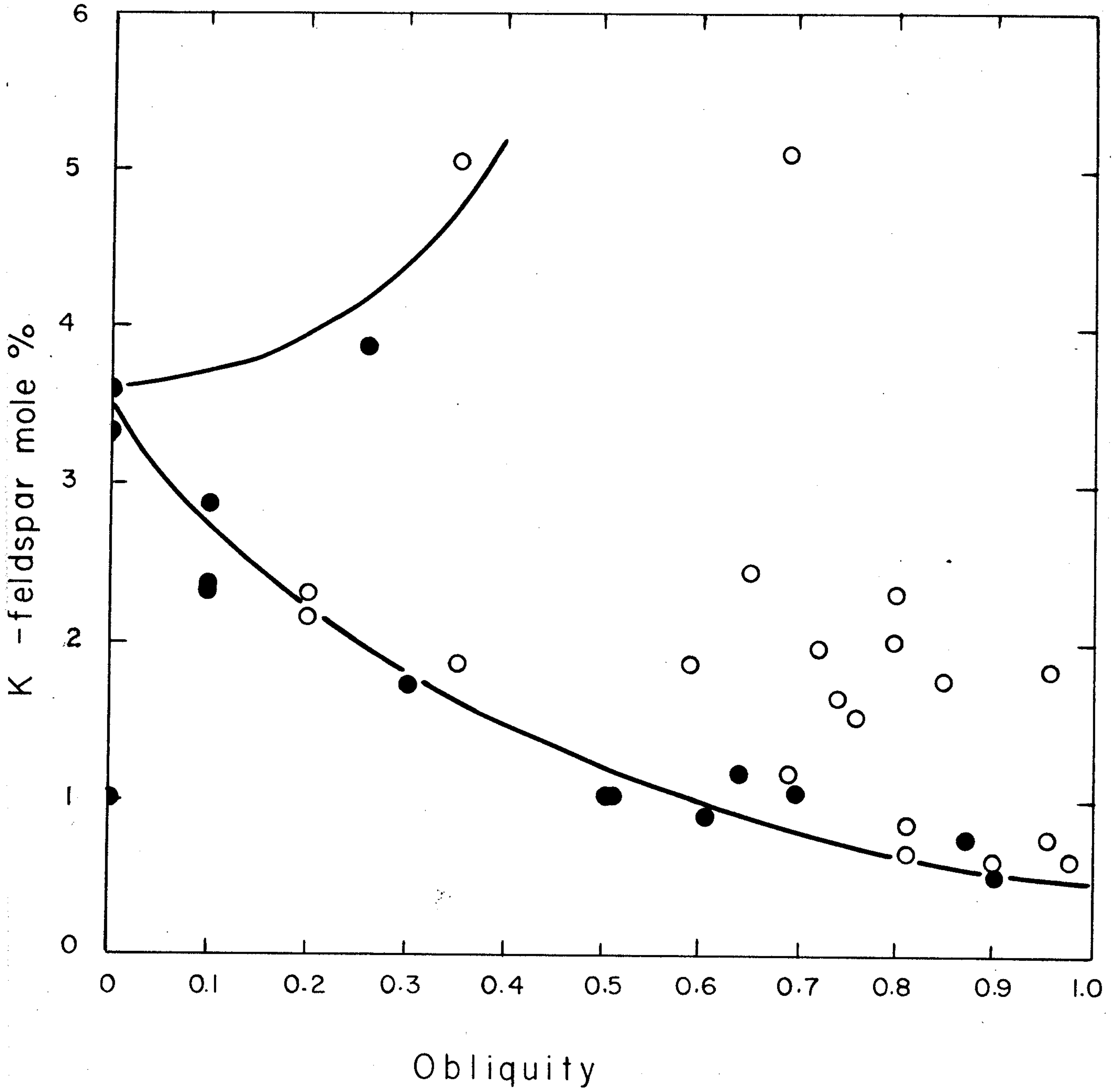


Figure 3. Plot of the ratio Na feldspar:K feldspar versus obliquity, in the rock specimens.
Open circles denote rocks of probable igneous origin.
Closed circles denote rocks of probable metamorphic origin.

CHAPTER IV

INTERPRETATION OF THE RESULTS

A PROPOSED ORTHOCLASE-LOW ALBITE PHASE DIAGRAM

Bowen and Tuttle (1950) synthesized a complete solid solution series of alkali feldspars at temperatures near the solidus-liquidus. Donnay and Donnay (1952) worked out cell dimensions from diffractometer patterns of Bowen and Tuttle's synthetic specimens and found a change in lattice geometry which could be directly related to the chemical composition. Reciprocal lattice angles of representative members of the series are given in Table 3. Examination of this high-temperature feldspar series reveals that the deviation of the angles α^* and γ^* from 90° is a function of composition. Compositions with greater than ~ 33 mole % K feldspar were found to be dimensionally monoclinic and the remainder triclinic. Whether or not these dimensionally monoclinic compounds are structurally triclinic could not be determined from the powder diffraction data.

MacKenzie (1952) has shown that the composition at which the change from triclinic to dimensionally monoclinic symmetry takes place in the synthetic high-temperature specimens is dependent upon temperature. If this change in symmetry were a true phase change there would have to be a region in which monoclinic and triclinic feldspars could co-exist. As they did not find such a region, Donnay and Donnay (1952) concluded that for all practical purposes there is a complete series of solid solutions at high temperatures.

TABLE III

RECIPROCAL CELL DIMENSIONS OF SYNTHETIC HIGH-TEMPERATURE ALKALI FELDSPARS

(after Donnay and Donnay, 1952, Table 5, Page 122)

mole % Ab	$\alpha^{*\circ}$	$\beta^{*\circ}$	$\gamma^{*\circ}$
Or	90	63.92	90
20.97	90	64.05	90
41.44	90	63.95	90
51.49	90	63.89	90
61.42	90	63.83	90
66.34	90	63.79	90
67.32	90.00	63.76	90.00
71.24	88.48	63.73	89.22
80.94	87.46	63.68	88.60
90.52	86.49	63.57	88.29
Ab	85.82	63.48	87.96

Petrological studies had indicated the presence of a solvus in natural low-temperature alkali feldspars. Bowen and Tuttle (1950) established an exsolution curve for the synthetic high-temperature alkali feldspars, but the low-temperature alkali feldspar exsolution curve may, because of difference in physical and chemical conditions differ considerably from that of the synthetic feldspars.

The low-temperature alkali feldspar diagram is complicated by Al-Si ordering. MacKenzie (1957) investigated the high-albite - low-albite transformation by X-raying albites synthesized at different temperatures. McConnell and McKie (1960) analysed MacKenzie's data and concluded that the Al-Si ordering is a rate process in which ordering takes place over a temperature range with the most rapid rate at around 600°C. Although no comparable work has been done on the K feldspars, structure determinations have demonstrated that low-temperature K feldspars are ordered to some degree with orthoclase possessing partial monoclinic ordering (Jones and Taylor, 1961) and intermediate microcline partial triclinic ordering (Bailey and Taylor, 1955).

Thus Al-Si ordering apparently takes place at some temperature or range in temperatures, and this temperature may not necessarily be the same for all Na:K ratios. Also, the extent to which an alkali feldspar of a given composition may order is probably dependent on that composition as Ferguson et al (1958) and Ferguson (1960) propose in their ionic picture of the alkali feldspars. In the following discussion it will be assumed that Al-Si ordering takes place over a range of temperatures near 600°C regardless of composition. The region of ordering will be represented by a horizontal band on the phase diagram.

The existence of a low-temperature ordered (or partially ordered) form implies either that the phase crystallized at a high temperature and then cooled slowly through the critical temperature range for Al-Si ordering (probably with water present) or possibly that crystallization took place at a temperature below the critical temperature range in which Al-Si ordering may take place.

The microcline series as determined by this study corresponds to the composition range $Or_{67} - Or_{23}$. Tuttle (1952) has proposed an orthoclase cryptoperthite series over the composition range $Or_{100} - Or_{40}$ and probably to Or_{20}. This proposed series is based on a fairly regular variation of 2V with alkali composition of the <u>mineral</u> specimen (not the <u>rock</u> specimen). There is doubt in the writer's mind as to whether Tuttle's mineral compositions do, in fact, represent original alkali compositions of the rock because the composition of the mineral specimens in the present study obviously do not. However, if we accept Tuttle's mineral compositions to represent a true low-temperature series then the writer's microcline series from $\sim Or_{67} - Or_{23}$ corresponds in composition to part of Tuttle's orthoclase cryptoperthite series $Or_{100} - Or_{20}$. Thus one series could be interpreted as the low-temperature modification of the other with the microcline series probably the lower temperature series. However when the feldspar structures are considered the picture is more complicated. In the region of mineral composition $Or_{50}Ab_{50}$ orthoclase cryptoperthites are exsolved into two phases, monoclinic orthoclase and triclinic low albite (MacKenzie and Smith, 1955). Jones and Taylor (1961) found that orthoclase has partial monoclinic Al-Si ordering whereas Ferguson et al (1958) found that low albite has most of the Al concentrated in one triclinic site. Thus such cryptoperthites are composed of two feldspar phases with apparently different Al-Si distributions. A possible explanation for the existence of such a combination is that the Al-Si ordering took place after the mineral had exsolved into two phases. Figure 4 is a diagrammatic representation of the proposed phase diagram in which orthoclase and low albite are the two low-temperature end members and orthoclase low-albite cryptoperthites (and possibly orthoclase + low albite) are the subsolvus phases. Note that in potassium-rich compositions ordering would take place before exsolution, and in this region the exsolved sodium-rich phase would have an Al-Si distribution similar to monoclinic orthoclase. Such an albite would have lattice parameters somewhat similar to those of high-temperature albite. In this potassium-rich region the phase relations are exactly the same as those proposed by Ferguson (1960) who suggested the name "maximum albite" for the sodium phase that would crystallize with the orthoclase. The sense in which this phase diagram differs from that proposed by Ferguson (1960) is in the interp~~ret~~enetration of the solvus and the region of Al-Si

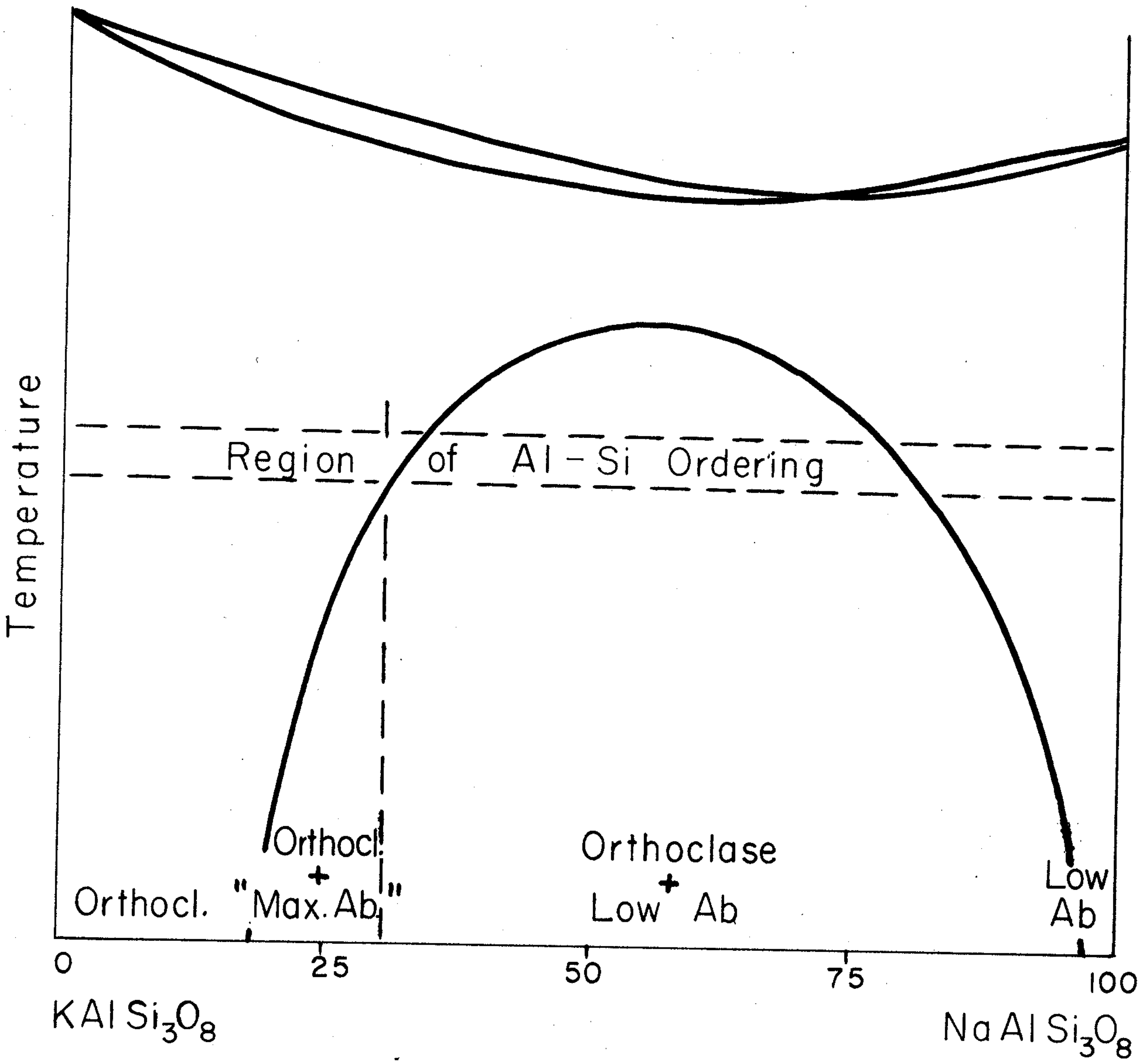


Figure 4. Proposed orthoclase - low albite phase diagram.

ordering. Ferguson suggests that, on the basis of crystal chemical considerations, the region of Al-Si ordering is likely to be higher than the region of K-Na exsolution although he was not, under this assumption, able to offer an explanation for the co-existence of structurally different orthoclase and low albite.

This proposed phase diagram thus implies some kind of discontinuity in the high potassium region. Detailed work by several feldspar investigators has pointed to the possibility of a discontinuity at Or_{60-70}. Spencer (1937) heated a number of orthoclase cryptoperthites to 850°C and then observed the change in specific gravity and refractive index. From these changes Spencer concluded that a maximum of 30% Na feldspar may be taken into the orthoclase lattice at 800 - 850°C. Thus if an alkali feldspar contains 30% or less sodium feldspar all the sodium can be taken into the lattice. If more than 30% of the alkali feldspar is sodium feldspar the system unmixes into two feldspars.

MacKenzie and Smith (1955) studied a number of Spencer's orthoclase cryptoperthites by the single-crystal X-ray method. They found that in specimens with less than 60% K feldspar the unmixed sodium phase had lattice angles corresponding to low-temperature albite. Specimens more potassium-rich than $Or_{60}Ab{+}An_{40}$ have sodium phases described as "pericline type superstructure", pericline twinned, or an "albite twin type superstructure". The difference in the accompanying sodium phase may also indicate a structural break.

Bowen and Tuttle (1958) conducted a series of heating experiments using the same orthoclase cryptoperthite specimens as MacKenzie and Smith. They found that specimens containing more than 60% potassium feldspar could be homogenized and that those with less would melt before homogenization.

If exsolution is to take place before ordering, as this proposed phase diagram requires, the exsolution curve (solvus) would have to be raised with respect to the region of Al-Si ordering. Addition of calcium to the system would raise the exsolution curve because calcium has a very limited solubility in K feldspar. This phase diagram would have to represent comparatively low water pressures because the solidus-liquidus curves would likely intersect the solvus at higher pressures and result in the crystallization of two phases (Bowen and Tuttle, 1950). Hence the orthoclase cryptoperthite may represent crystallization in a relatively dry environment that has appreciable calcium present.

A PROPOSED MICROCLINE SERIES-LOW ALBITE PHASE DIAGRAM

Study of the synthetic alkali feldspar solid solution series showed that it is possible to have a feldspar series with variable lattice geometry determined by composition. The present study indicates that the obliquity (lattice geometry) of a group of microclines in the composition range $\sim$ Or_{67} - Or_{23} may be correlated with the sodium-potassium content of the rock. This would be essentially the sodium-potassium content of the alkali feldspar system if the feldspars all interacted with each other at higher temperatures. The fact that there is a simple correlation for many of the specimens between obliquity of the microcline and the ratio K feldspar:total alkali feldspar suggests that in these rocks the feldspars did in fact all interact at higher temperatures. Thus it seems reasonable to postulate a microcline series based on the comparative feldspar composition of the rock. If the degree of ordering (not necessarily to full ordering) reflected in the obliquity of the K feldspar is correlated with the proportion of K feldspar to total alkali feldspar it is probable that the ordering took place before exsolution. At high temperatures the alkali feldspar system would be represented by a single phase with the lattice geometry determined by its composition. Potassium-rich compositions would be monoclinic and sodium-rich compositions triclinic, the transition occurring at roughly 67% Or (Donnay and Donnay, 1952). Cooling would result in Al-Si ordering with the degree of ordering depending upon composition.

These considerations are those proposed by Ferguson (1960) to account for the known Al-Si distributions in the alkali feldspars, and it was these considerations that in fact suggested the present research work, namely, the comparison of the obliquities of a group of microclines with the ratios K feldspar:total feldspar in the rock. As Figure 2 shows, for many of the writer's specimens there does appear to be a correlation between obliquity and composition (solid line on Figure 2), but as the chained line in the figure also shows, this relationship is almost the opposite to that proposed by

Ferguson. As Figures 2 and 3 in Ferguson (1960) show, his low-temperature potassium phases change from orthoclase through intermediate microcline to maximum microcline from the pure potassium to the high-sodium region on the phase diagram. Thus in general his picture associates increasing obliquity of the K feldspar with increasing total sodium in the rock. It is this relationship which appears to be reversed by the writer's findings and he therefore offers a new phase diagram to explain his findings.

This new diagram is shown in Figure 5. The picture proposed here is similar to Ferguson's (1960) in that it assumes the Al-Si distribution in a low-temperature alkali feldspar to be a function of the overall alkali composition at high temperatures (above the solvus), but it differs from Ferguson's in the important respect that obliquity does not, in general, increase with original sodium content. In fact, the obliquity decreases from that of maximum microcline at $\sim$ Or_{67} to a monoclinic member at $\sim$ Or_{23}.

Melts more sodium-rich than Or_{67} exsolve into a microcline and a sodium phase. Figure 2 indicates that the microcline series appears to approach a limiting Na:K atomic ratio of 1:2 with maximum microcline, and this suggests that a discontinuity might occur at $\sim$ 67% K feldspar. Since the most potassic rock studied contained $\sim$ 67% K feldspar it was impossible to extend the study to these compositions.

However, considerable data have accumulated concerning the natural high-temperature alkali feldspar series and the

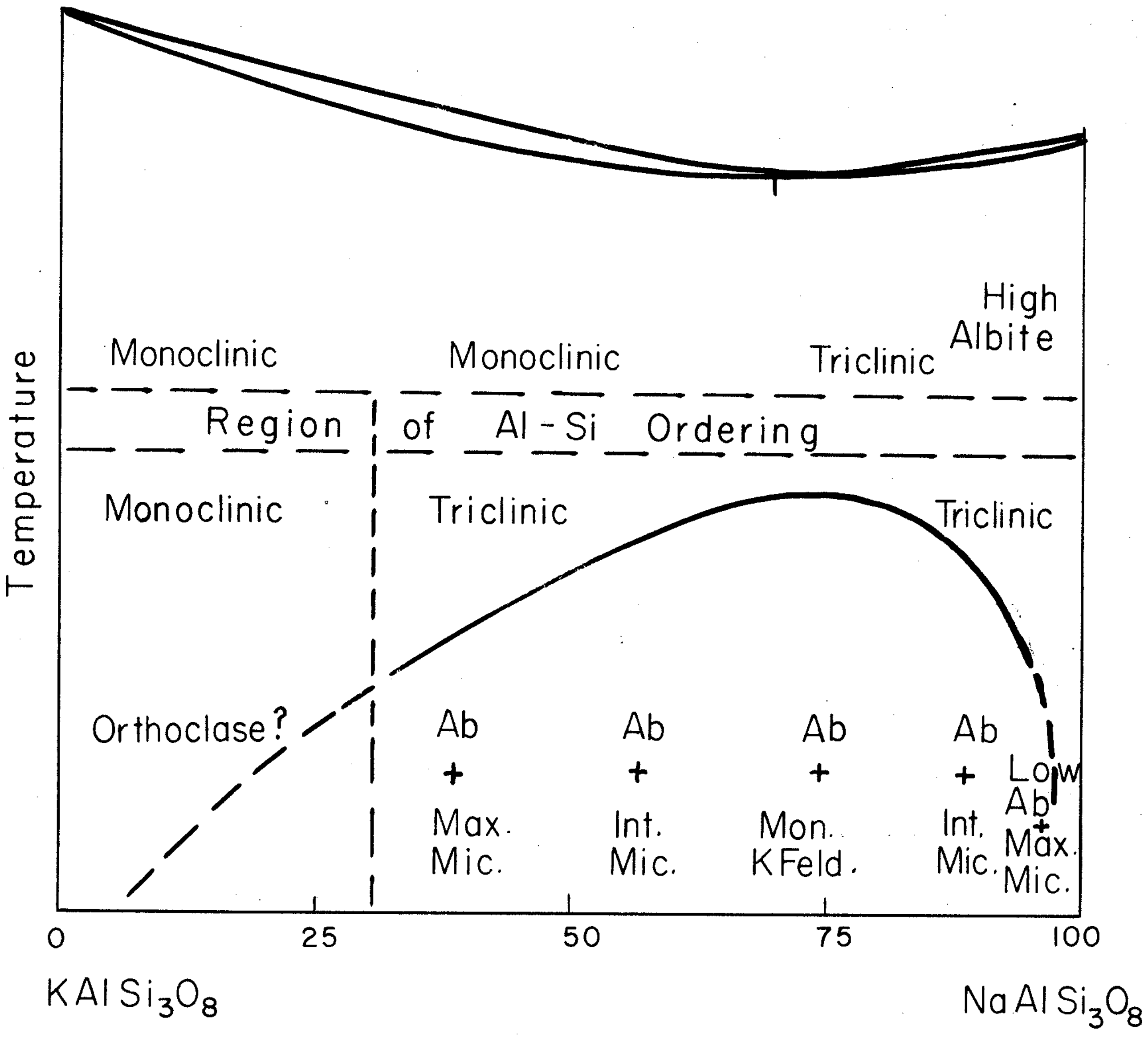


Figure 5. Proposed microcline series - low albite phase diagram.

orthoclase cryptoperthite series. It should be remembered that the chemical data for both these series represent grain compositions and not necessarily total rock compositions. These mineral specimens occur either as homogeneous minerals or as cryptoperthites so it may be assumed that these feldspars crystallized as a single feldspar and later exsolved into two phases.

MacKenzie and Smith (1956) used X-ray and optical methods to study natural high-temperature alkali feldspars. Their conclusions indicate a discontinuity in the high-temperature series at a composition of $Or_{60}(Ab+An)_{40}$. Their findings are summed up in the following quotation(p. 420):

"With respect to the effect of heating at 900°C this series of feldspars can be divided into three groups. Specimens with more than 60% potassium feldspar in their bulk composition show a slight but measurable decrease in the mean value of the optic angle. Feldspars in the compositional range $Or_{60}(Ab+An)_{40}$ (approx.) show an increase in the mean value of the optic angle, and this increase reaches its maximum value in the most sodium-rich specimens. Alkali feldspars with less than 40% potassium feldspar show a very slight increase or no change in the mean value of the optic angle as a result of this heat treatment.

" It is now fairly well established that any natural potassium-rich feldspar, if heated for a sufficiently long period at about 1050°C, is changed to the high-sanidine form by a decrease in the optic angle and rotation of the optic plane into a position parallel to the symmetry plane[10] (Spencer, 1937;

"[10] Some microclines are not changed to the high-sanidine form even after heating for 6 months at 1050°C but it is believed that longer heating will effect this change (personal communications from Dr. F. Chayes)."

Tuttle, 1952a). The reduction of the optic angle in the potassium-rich specimens as a result of heating at 900°C is the effect which would be expected since the change is in the direction of a high-sanidine, but the heat treatment has not been sufficient to convert any of the specimens completely to the high-sanidine form. ...

"Specimens in the compositional range $Or_{60}(Ab+An)_{40}$ to $Or_{40}(Ab+An)_{60}$ (approx.) do not show a tendency to change to the high-sanidine form as a result of heating at 900°C for 24 hours since the mean value of the optic angle increases. Additional evidence for a discontinuity in the effect of heat treatment at the composition $Or_{60}(Ab+An)_{40}$ is given by the results of prolonged heating at 1030°C. Heating a number of specimens at 1030°C for seven months showed that specimens more potassium-rich than $Or_{60}(Ab+An)_{40}$ were changed to the high-sanidine form but more sodium-rich specimens were not thus changed. ..."

MacKenzie and Smith (1956) found that sanidines more sodium-rich than Or_{60} were unmixed. Hewlett's (1959) single-crystal X-ray study of natural high-temperature feldspars indicated that compositions more potassium-rich than Or_{68} were unmixed. These two studies indicate that natural high-temperature monoclinic feldspars more potassic than Or_{68} may retain all the sodium in solid solution.

Several workers have found evidence in the orthoclase cryptoperthite series for discontinuity near Or_{67}. If this discontinuity is significant for the orthoclase cryptoperthite series, it is also possible that it is significant for the writer's proposed microcline series - low albite phase diagram (Figure 5) as the orthoclase - low albite phase diagram (Figure 4) may be regarded as a special case. Thus the discontinuity required by the writer's phase diagram is shown in Figure 5 as a vertical dashed line at roughly Or$_{67}$.

It is proposed here that the monoclinic orthoclase structure is the stable low-temperature modification for compositions more potassic than Or$_{67}$. For more sodium-rich compositions the triclinic microcline-low albite series will be the stable low-temperature series in the manner shown in Figure 5.

The microcline series suggested by this study ranges from a maximum microcline at $\sim$ Or$_{67}$ to a monoclinic member at $\sim$ Or$_{23}$. Three specimens with less than 23 mole % K feldspar were examined in the present study and these contained intermediate microclines. This suggests that intermediate microclines may form as a result of exsolution of compositions on either side of Or$_{23}$. For this reason the crest of the solvus is placed at Or$_{23}$ corresponding to the monoclinic potassium feldspar. The obliquities of the K feldspars resulting from each composition (obliquities taken from the solid line on Figure 2) are placed at the bottom of the phase diagram.

Thus an intermediate microcline with an obliquity of 0.30 could result from the exsolution of alkali feldspar compositions of $\sim$ Or$_{35}$ or $\sim$ Or$_{16}$. This suggests that a maximum microcline could result from the exsolution of either an alkali feldspar composition of $\sim$ Or$_{67}$ or a nearly pure albite. A microcline exsolving from an alkali feldspar with a large excess of Na over K probably would have the same Al-Si distribution as low albite and would correspond to the maximum microcline of Ferguson (1960). However this proposed phase diagram differs from Ferguson's in that maximum microcline could also result from exsolution of an alkali feldspar of composition $\sim Or_{67}$. There might be a difference between two such microclines in that the high sodium feldspar almost certainly would be triclinic before ordering whereas the microcline exsolving from composition Or_{67} would almost certainly be dimensionally monoclinic before ordering. Probably detailed structure analyses would be required to determine if the structures of the two maximum microclines and the corresponding sodium phases were identical.

The general relationships of the proposed phase diagram are best illustrated by an example. Consider the cooling of a liquid of composition Or_{40}. One feldspar of composition Or_{40} would crystallize from the melt. Further slow cooling would result in ordering of the Al-Si atoms with the degree of ordering depending upon the total alkali feldspar composition in some manner. At lower temperatures the alkali feldspar would exsolve into two phases - an intermediate microcline and a sodium phase with the same Al-Si distribution in the two phases. Similarly exsolution of an alkali feldspar of composition Or_{67} would result in a maximum microcline and a sodium phase with the same Al-Si distributions.

THE EFFECT OF HIGH PRESSURE ON THE PROPOSED MICROCLINE SERIES - LOW ALBITE PHASE DIAGRAM

Some interesting relationships are brought out if the effect of pressure on the proposed microcline series - low albite diagram is considered.

Bowen and Tuttle (1958) showed that if the water pressure is increased sufficiently in the $NaAlSi_3O_8$ - $KAlSi_3O_8$ - H_2O system, the solidus-liquidus curves will likely be lowered to temperatures at which they will intersect the solvus.

When considering metamorphic rocks, the reactions, by definition, must take place in the solid state so there are no complications due to intersection of the solidus-liquidus and the solvus. With igneous rocks two additional possible relationships must be considered. Depending upon the manner in which the solidus-liquidus intersects the solvus, the freezing point may exhibit either a transition point or a eutectic point. Both of these are possible, but the eutectic relation seems much more probable because the solidus-liquidus minimum as determined by Bowen and Tuttle (1958) is at a composition near Or_{30} and the writer's work suggests the crest of the microcline solvus is at $\sim Or_{23}$.

In Figure 6 the solidus-liquidus intersects the solvus with the melting point exhibiting a eutectic point. Low-temperature ordered (or partially ordered) feldspars could crystallize directly from the melt, for crystallization would be taking place at temperatures either below or within the range of temperatures at which ordering may take place.

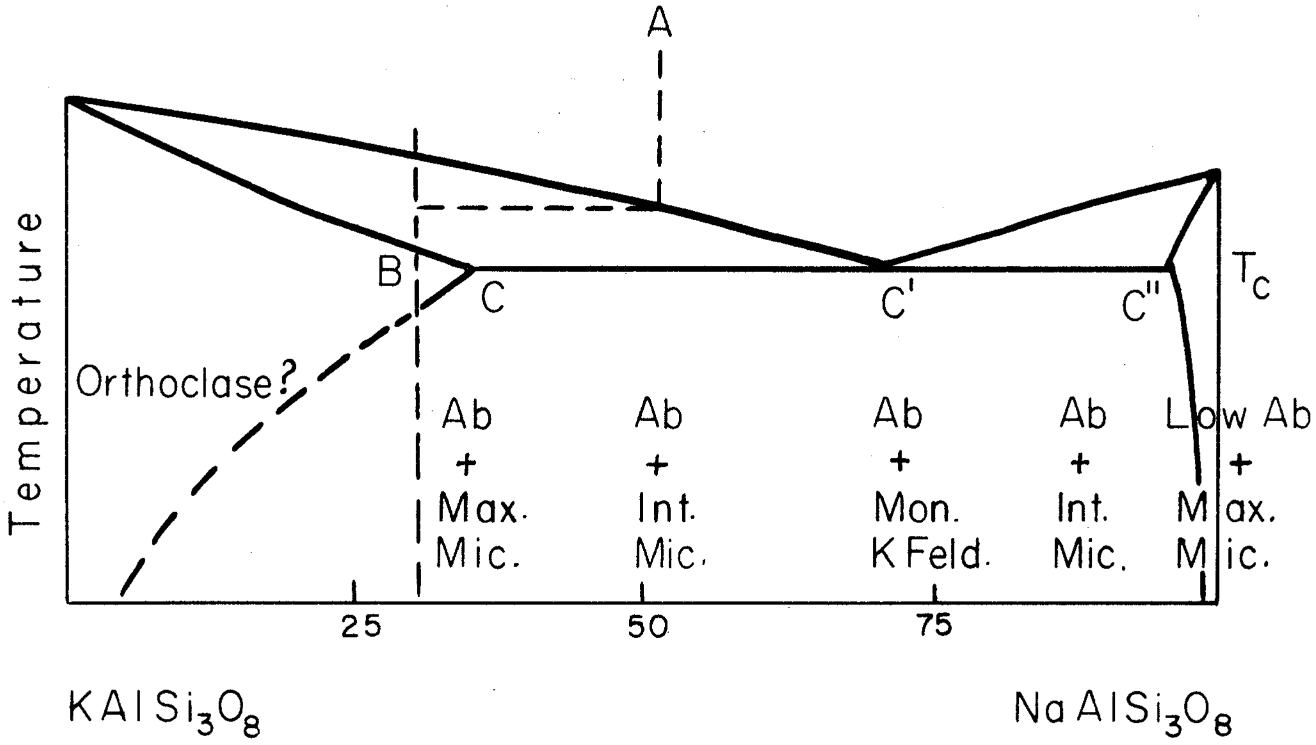


Figure 6. Proposed microcline series - low albite phase diagram at very high water pressures.

If we consider cooling a liquid of composition A, the first phase to appear would be a K feldspar with composition B. As the temperature is lowered, the liquid would change composition toward C' and the potassium feldspar phase would change toward composition C. Presumably the Al-Si order of the potassium phase must change as the composition changes toward C providing cooling is slow enough for the solid phase to react with the liquid. At temperature T_C the potassium phase and the liquid interact and two solid solutions would crystallize (maximum microcline). On Figure 6 composition C would be maximum microcline and C" would be low albite. Further cooling would result in exsolution of these two phases to form a perthite and an anti-perthite.

Figure 6 indicates that at the water pressure represented by this diagram, melts with compositions within the range C to C" would all finally crystallize as the same solid solutions of compositions C and C". Thus a whole range of compositions would result in potassium feldspars with the same obliquity. If two feldspars crystallized out at the same time then the obliquity of the resultant microcline would depend on the alkali composition of the high potassium phase and not upon the total alkali feldspar composition. In Figure 2, it is evident that K feldspars with a given obliquity do occur in rocks with a range of alkali compositions. For example, K feldspars with obliquities of 0.80 occur in rocks containing $\sim$ Or_{60} or less. Thus it is probable that the specimens which plot below the solid line of Figure 2 represent rocks in which two feldspars have crystallized. In general this would result in a potassium feldspar having a greater obliquity than it would have if only one feldspar phase crystallized from the melt.

Figure 6 also indicates that microclines with intermediate and low obliquities cannot crystallize under the physical conditions (water pressure) represented by this diagram. A series of constant pressure diagrams could be drawn for the proposed microcline series-low albite phase diagram. With decreasing pressure in relation to Figure 6 the composition range C C" within which the same two solid solutions crystallize would become smaller and the obliquity of the microcline C would decrease with the shift of composition C. These considerations imply that a rock with a given Na:K ratio would contain a microcline of only one obliquity. However they show that several rocks with the same Na:K ratio could have K feldspars with different obliquities if the rocks had crystallized at different pressures. Figure 2 indicates that for a given Na:K ratio there is a minimum obliquity and this minimum obliquity is interpreted as corresponding to the water pressure at which this composition is the point C on a phase diagram of the type shown in Figure 6.

Thus, if the writer's interpretation is the correct one, with increasingly high pressures only increasingly high obliquities could occur. Hence, the study of the microcline series may make it possible to estimate the water pressure under which a given rock crystallized. Perhaps relationships such as this would account for the comparative rarity of microclines with low and intermediate obliquities.

CHAPTER V

RELATION OF OBLIQUITY TO AREAL DISTRIBUTION AND ROCK TYPE

Previous chapters have shown that for a large number of specimens an increase in obliquity of the K feldspar may be correlated with an increase in the ratio K feldspar:total alkali feldspar. This relationship is shown by the specimens which plot near the solid line of Figure 2. An examination of thin sections and the field relationships indicate that most of the specimens plotting near the solid line belong to either the pyroxene granulite or the sedimentary gneiss units. These are probably metamorphic rocks. If the obliquity is related to the relative alkali composition then the areal distribution of the obliquities should reflect the ratio K feldspar:total alkali feldspar. The analysed specimens from these rock types were too scattered to show any pattern on a map. It would be desirable to sample these units on a closely space grid system.

Field relations indicate that the red granite is an igneous rock and that the grey granodiorite and granite gneiss may be of igneous origin. Obliquities of K feldspars from these three rock types do not, in general, fall near the solid line of Figure 2. These are, however, restricted to a limited area. Thus the experimental observations appear to bear out the field relations in that the obliquities of the K feldspars from the presumed igneous rocks have a different pattern on Figure 2 than those from the presumed metamorphic rocks. Furthermore, the interpretation of the obliquities for the presumed igneous microclines requires the crystallization of two feldspars from a melt. This does not imply that all igneous rocks must crystallize two feldspars.

As in the case of the metamorphic rocks, no simple pattern was found in the areal distribution of the obliquities. This is probably due to the widely spaced sampling. Pyke (1958) determined the distribution of the K feldspar obliquities in a closely sampled granodiorite mass at Moir Lake, Saskatchewan. This oval-shaped body of rock was interpreted as being igneous on the basis of field relations and thin section studies. The obliquities, in terms of the $2\theta_{(131)} - 2\theta_{(1\bar{3}1)}$ separations, for the K feldspars were plotted to coincide with the specimen location within the granodiorite body and the values contoured. Obliquities of the central portion are intermediate values with the obliquities gradually increasing outward to maximum obliquities near the margins. Pyke interpreted the pattern in terms of an inversion from high temperature monoclinic K feldspar to low temperature triclinic feldspar. However, in view of the present study the writer suggests that any interpretation should involve a consideration of the Na:K ratios in the rocks. Pyke's point count analyses and his K feldspar obliquities confirm the writer's findings that the K feldspars in the igneous granitic rocks all fall within the limited area shown on Figure 2.

In summary, the present work suggests strongly that the obliquities of the K feldspars together with Na:K ratio may be used to distinguish between two groups of rocks. Igneous rocks crystallizing above the solvus and many metamorphic rocks would plot near the solid line of Figure 2. Igneous rocks crystallizing at temperatures below the solvus (2 feldspar granites) plot in the area outlined by the solid lines and probably would be concentrated in the high obliquity region of Figure 2.

TABLE IV

OBLIQUITIES FOR K FELDSPARS FROM THE MOAK-THOMPSON MAP AREA

Specimen Number	Rock Type**	Obliquity	Sodium-Potassium Analyses Mineral	Sodium-Potassium Analyses Rock
M-36-58	GG	0.81		
M-113-58	GG	0.77	*	*
M-122-1-59	GG	0.82		
M-266-58	GG	0.40		
M-336-58	GG	0.81	*	
M-361-58	GG	-	*	
M-745-58	GG	-		
M-654-58	PG	-		
P-166-58	GG	0.84		
P-266A-58	SG	-		
P-269-58	SG	-		
P-304-58	GG	0.86		
P-310-58	SG	0.87		
P-324-58	PG	0.10		*
P-340-58	PG	0.25		*
P-364-58	PG	0.79	*	
P-388-58	PG	0.20		
P-511-58	PG	0.50	*	*
P-520-58	PG	-		
P-535-58	PG	0.10		

** Abbreviations for rock types.

RG	Red granite	SG	Sedimentary gneiss
GGd	Grey granodiorite	PG	Pyroxene granulite
GG	Granite gneiss		

* Analyses given in Tables I or II.

\- No K feldspar.

TABLE IV cont'd.

OBLIQUITIES FOR K FELDSPARS FROM THE MOAK-THOMPSON MAP AREA

Specimen Number	Rock Types**	Obliquity	Sodium-Potassium Analyses	
			Mineral	Rock
P-588-58	PG	[0.70 0.00]	*	*
P-621-58	PG	0.00	*	*
A-1-3-59	RG	0.90	*	
A-3-1-59	Dyke Gd	–		
A-4-1-59	GG	0.00	*	*
A-6-59	GG	0.35	*	*
A-7-59	GG	0.36	*	*
A-8-59	RG	0.80	*	*
A-9-1-59	RG	–		
A-11-59	RG	0.96	*	*
A-20-59	RG	0.87	*	
A-32-59	RG	0.82	*	
A-55-2-59	GG	0.87	*	
A-57-59	GG	0.72	*	*
A-61-59	SG	0.10		*
A-65-59	GG	0.65	*	*
A-110-59	RG	0.96	*	*
A-173-59	RG	0.81	*	*
A-268-59	GG	?		
A-273-59	GG	–		
A-276-59	GG	0.86	*	
A-356-59	GG	0.20	*	*
A-390-59	GG	–		
A-407-59	SG	–		
A-431-59	SG	–		
A-445-59	SG	0.64	*	*
A-468-59	GGd	0.89	*	
A-490-59	SG	0.10	*	*
A-510-59	GGd	?		

TABLE IV cont'd.

OBLIQUITIES FOR K FELDSPARS FROM THE MOAK-THOMPSON MAP AREA

Specimen Number	Rock Types**	Obliquity	Sodium-Potassium Analyses	
			Mineral	Rock
A-548-59	SG	0.30	*	*
A-561-59	SG	-		
A-568-59	SG	-		
A-581-59	SG	-		
A-629-59	SG	?		
A-635-1-59	SG	0.81	*	
A-682-59	SG	0.87	*	*
A-807-59	SG	0.61	*	*
B-16-59	GG	0.82		
B-48-1-59	GG	0.74	*	*
B-84-3-59	GG	0.85	*	
B-87-1-59	RG	0.86	*	
B-92-2-59	RG	-		
B-113-1-59	RG	0.59	*	*
B-121-1-59	GG	-		
B-184-59	RG	0.89	*	
B-224-59	GG	-		
B-233-59	GG	0.20	*	*
B-277-59	GG	-		
B-278-59	GG	-		
B-338-59	GG	0.69	*	*
B-370-59	RG	0.86	*	
B-385-59	GG	-		
B-393-59	GG	-		
B-403-1-59	SG	0.00	*	*
B-427-59	GG	-		
B-448-59	GGd	0.81	*	*
B-449-59	GG	Trace		
B-459-59	GG	0.69	*	*
B-465-59	GG	0.90	*	*

TABLE IV cont'd.

OBLIQUITIES FOR K FELDSPARS FROM THE MOAK-THOMPSON MAP AREA

Specimen Number	Rock Types**	Obliquity	Sodium-Potassium Analyses	
			Mineral	Rock
B-591-59	GG	0.87	*	
B-692-59	SG	0.98	*	*
B-701-59	SG	0.90	*	*
B-768-59	GG	0.86	*	
C-103-2-59	RG	0.80	*	*
C-179-1-59	GGd	0.85	*	*
C-279-59	SG	-		
C-288-59	SG	0.30	*	
C-506-1-59	SG	0.51	*	*
M-14-1-59	RG	0.82		
M-53-59	GG	-		
M-85-59	GG	-		
M-154-59	GG	-		
W-70-59	GG	-		
W-143-59	GG	-		
W-287-59	GG	-		
W-365-59	GG	-		
B-199-60	PG	0.94		
B-207-60	PG	0.89		
G-513-60	PG	0.40		
G-611-60	PG	0.40		
M-190-60	PG	0.10		
M-198-2-60	PG	0.30		
M-239-60	SG	0.20		
M-274-60	SG	0.10		
M-510-60	PG	0.20		
M-530-60	PG	0.30		
P-207-3-60	PG	0.70		
P-341-60	PG	0.58		

APPENDIX I

ANALYTICAL METHODS

POTASSIUM FELDSPAR EXTRACTION

Rock samples were crushed in a steel mortar and passed through Tyler Standard screens. Grains that passed through a 100 mesh screen and were retained on the 200 mesh screen were separated into two fractions using heavy liquids.

The specific gravity of a bromoform-acetone solution was adjusted to hold orthoclase (SG=2.59) and microcline perthite (SG=2.59) chips in suspension and to allow quartz (SG=2.65) and cleavlandite (SG=2.62) to settle. As the specific gravity of potassium feldspars is the lowest of the common rock forming minerals, the separation is not difficult. After centrifuging, the fractions were transferred to filters and washed thoroughly with acetone to remove all bromoform. The potassium feldspar fraction was reseparated two or more times in an effort to obtain pure fractions.

Perthitic material with a range in specific gravity was encountered in a few of the samples. The range in specific gravity probably reflects a range in the amount of sodium feldspar in different grains.

SODIUM AND POTASSIUM DETERMINATION

Rock samples were crushed to pass through a 100 mesh screen. K feldspar samples were those separated by heavy liquids as described above.

Sodium and potassium were determined using a Coleman Flame Photometer and a Coleman Junior Spectrophotometer.

About 0.5 grams of powdered sample were weighed into a 150 ml Teflon beaker and 10 ml concentrated HF and 3 ml concentrated H_2SO_4 added. After digestion on a hot plate at about $125^\circ C$ the solution was evaporated to about 3 ml, cooled, and 1 ml concentrated HNO_3 added. Evaporation was continued to strong white fumes, and the beaker filled with water. The solution was filtered and transferred to a 250 ml flask, and diluted to volume. The flame photometer utilized propane gas, and oxygen at 13 lbs./in^2. Samples were diluted to give galvanometer deflections in the range 30 - 70 on a 100 scale. The following procedure was used in making the determinations. NaCl and KCl standard solutions were used to establish working curves.

1. The instrument was adjusted to read roughly 0 and 100 for the blank and most concentrated solutions respectively (the most concentrated solution used was 100 ppm K_2O).

2. Rough analyses of the unknown solutions were made to determine if dilutions were necessary.

3. A working curve was established with standard solutions, checking for instrument drift with the blank and full scale standard after determining the deflection for each standard solution.

4. The unknown samples were determined.

5. The working curve was checked.

6. Samples were redetermined.

7. The working curve was rechecked.

The three curves were averaged in drawing up the final working curve. If at any time either the blank or full scale standard drifted by 0.5 scale divisions the readings were discarded. All readings were thus reproducible to within 0.5 scale divisions.

X-RAY DETERMINATION OF OBLIQUITIES

Pairs of reflections such as (130) $(1\bar{3}0)$, (111) $(1\bar{1}1)$ and (131) $(1\bar{3}1)$ have the same spacing in monoclinic patterns but are in general split into doublets in triclinic patterns.

MacKenzie (1952) suggested that these pairs could be used to describe the triclinic nature of microclines. Goldsmith and Laves (1954b) used the difference in spacing of the 131 and $1\bar{3}1$ reflections on the powder patterns to estimate the degree of "triclinicity" of potassium feldspars. They proposed the use of a Δ value as a quantitative expression of the "triclinicity" or deviation from 90° of the angles α^* and γ^*. A microcline with the maximum observed values ($\alpha^* = 90^\circ 25'$, $\gamma^* = 92^\circ 20'$) was arbitrarily given a "triclinicity" of unity, and a monoclinic feldspar would of course have a "triclinicity" of 0. The angular deviations from 90° are small, and therefore a linear relation was assumed between the "triclinicity" and $(d_{(131)} - d_{(1\bar{3}1)})$, that is $\Delta = k\ (d_{(131)} - d_{(1\bar{3}1)})$. For a microcline with the maximum deviation from 90° $d_{(131)} - d_{(1\bar{3}1)} = 0.08$.

$$\text{Thus } 1=k\ (0.08)$$

$$\text{and } k=12.5.$$

The expression for the "triclinicity" may thus be stated as

$$\Delta = 12.5\ (d_{(131)} - d_{(1\bar{3}1)}).$$

MacKenzie (1960) has proposed that the term "triclinicity" be replaced by "obliquity" because a structure may be either monoclinic or triclinic but strictly speaking cannot exhibit a degree of triclinicity. Obliquity is used throughout this thesis.

X-ray photographs were taken using a powder camera of 114.53 mm diameter and FeKα radiation, and $d_{(131)}$ and $d_{(1\bar{3}1)}$ were measured on the powder films. Obliquities in the range 0.0 - 0.5 had to be estimated from line widths because the two reflections overlap. (131) and $(1\bar{3}1)$ reflections are not well defined in the photographs of specimens A-445-59, C-506-59, P-511-58 and these specimens probably have variable obliquities. This may be true also for the specimens with obliquities less than 0.5, but this could not be ascertained from the powder patterns.

X-RAY DETERMINATION OF K FELDSPAR CONTENT

The proportions of K feldspar to total feldspar in the minerals were estimated using the X-ray method of Bowen andTuttle (1950). $2\theta_{(\bar{2}01)}$ was measured with a Philips diffractometer using smear mounts of powdered sample which had been heated at 1050°C for 140 hours. $KBrO_3$ was used to calibrate the diffractometer (Orville, 1957). Peak positions were determined by plotting fixed count times at intervals of $0.01^\circ 2\theta$.

REFERENCES

BAILEY, S. W., & TAYLOR, W. H. (1955): The structure of a triclinic potassium felspar, Acta Cryst., 8, 621-632.

BARTH, T. F. W. (1934): Polymorphic phenomena and crystal structure, Am. J. Sci., 27, 273-286.

BASKIN, Y. (1956): A study of authigenic feldspars, J. Geol., 64, 132-155.

BOWEN, N. L., & TUTTLE, O. F. (1950): The system $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O, J. Geol., 58, 489-511.

CHAO, S. H., SMARE, D. L., & TAYLOR, W. H. (1939): An x-ray examination of some potash-soda feldspars, Min. Mag., 25, 338-350.

COLE, W. F., SÖRUM, H., & KENNARD, O. (1949): The crystal structure of orthoclase and sanidinized orthoclase, Acta Cryst., 2, 280-287.

DONNAY, G., & DONNAY, J. D. H. (1952): The symmetry change in the high-temperature alkali-feldspar series, Am. J. Sci., Bowen Volume, pp. 115-132.

FERGUSON, R. B. (1960): The low-temperature phases of the alkali feldspars and their origin, Canadian Mineral, 6, 415-436.

FERGUSON, R. B., TRAILL, R. J., & TAYLOR, W. H. (1958): The crystal structures of low-temperature and high-temperature albites, Acta Cryst., 11, 331-348.

GOLDSMITH, J. R., & LAVES, F. (1954a): The microcline-sanidine stability relations, Geochim. Cosmochim. Acta, 5, 1-19.

REFERENCES cont'd.

GOLDSMITH, J. R., & LAVES, F. (1954b): Potassium feldspars structurally intermediate between microcline and sanidine, Geochim. Cosmochim. Acta, <u>6</u>, 100-118.

LAVES, F. (1950): The lattice and twinning of microcline and other potash feldspars, J. Geol., <u>58</u>, 548-571.

LAVES, F. (1952a): Phase relations of the alkali feldspars .1. Introductory remarks, J. Geol., <u>60</u>, 436-450.

LAVES, F. (1952b): Phase relations of the alkali feldspars .11. The stable and pseudo-stable phase relations in the alkali feldspar system, J. Geol., <u>60</u>, 549-574.

MACKENZIE, W. S. (1952): The effect of temperature on the symmetry of high-temperature soda-rich feldspars, Am. Jour. Sci., <u>Bowen Volume</u>, 319-342.

MACKENZIE, W. S. (1957): The crystalline modifications of $NaAlSi_3O_8$, Am. Jour. Sci., <u>255</u>, 481-516.

MACKENZIE, W. S. (1954): The orthoclase-microcline inversion, Min. Mag., <u>30</u>, 354-366.

MACKENZIE, W. S. (1960): The nomenclature of the feldspars, (Abstract of paper given at the Symposium on Feldspars, Copenhagen).

MACKENZIE, W. S., & SMITH, J. V. (1955): The alkali feldspars, 1: Orthoclase-microperthites, Am. Mineral, <u>40</u>, 707-732.

MACKENZIE, W. S., & SMITH, J. V. (1956): The alkali feldspars, 111: An optical and X-ray study of high-temperature feldspars, Am. Mineral, <u>41</u>, 405.-427.

REFERENCES cont'd.

McCONNELL, J. D. C., & McKIE, D. (1960): The kinetics of the ordering process in triclinic $NaAlSi_3O_8$, Min. Mag., 32, 436-454.

ORVILLE, P. M. (1957): Feldspar investigations, Annual report of the Director of the Geophysical Laboratory, Carnegie Inst. Washington Year Book, 57, 206-209.

PYKE, M. W. (1958): Microclines from a precambrian granodiorite, (unpublished thesis, University of Saskatchewan.

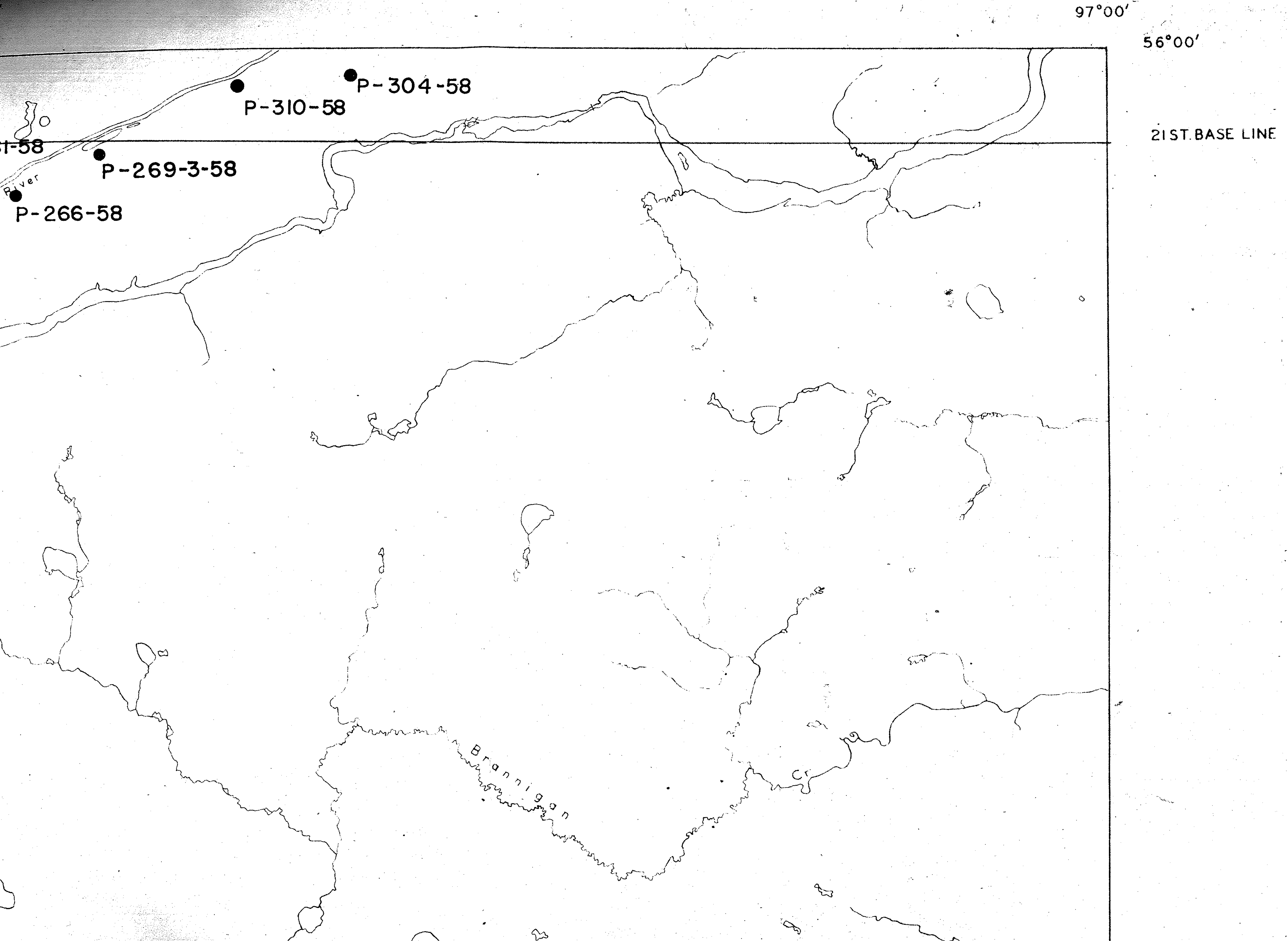
SMITH, J. V., & MACKENZIE, W. S. (1958): Alkali feldspars, IV: The cooling history of high-temperature sodium-rich feldspars, Am. Mineral, 43, 872-889.

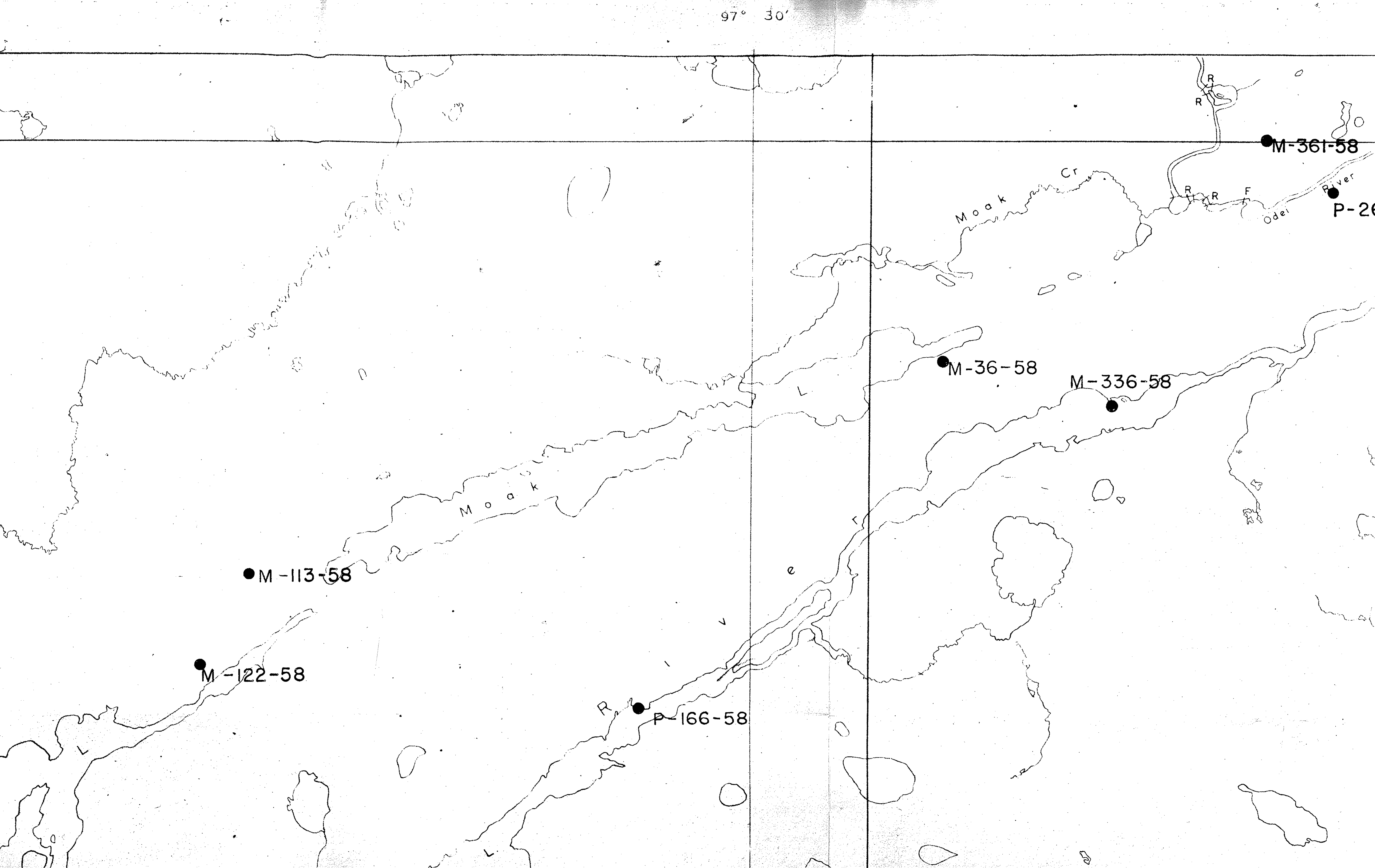
SPENCER, E. (1937): The potash-soda-felspars, 1: Thermal stability, Min. Mag., 24, 453-494.

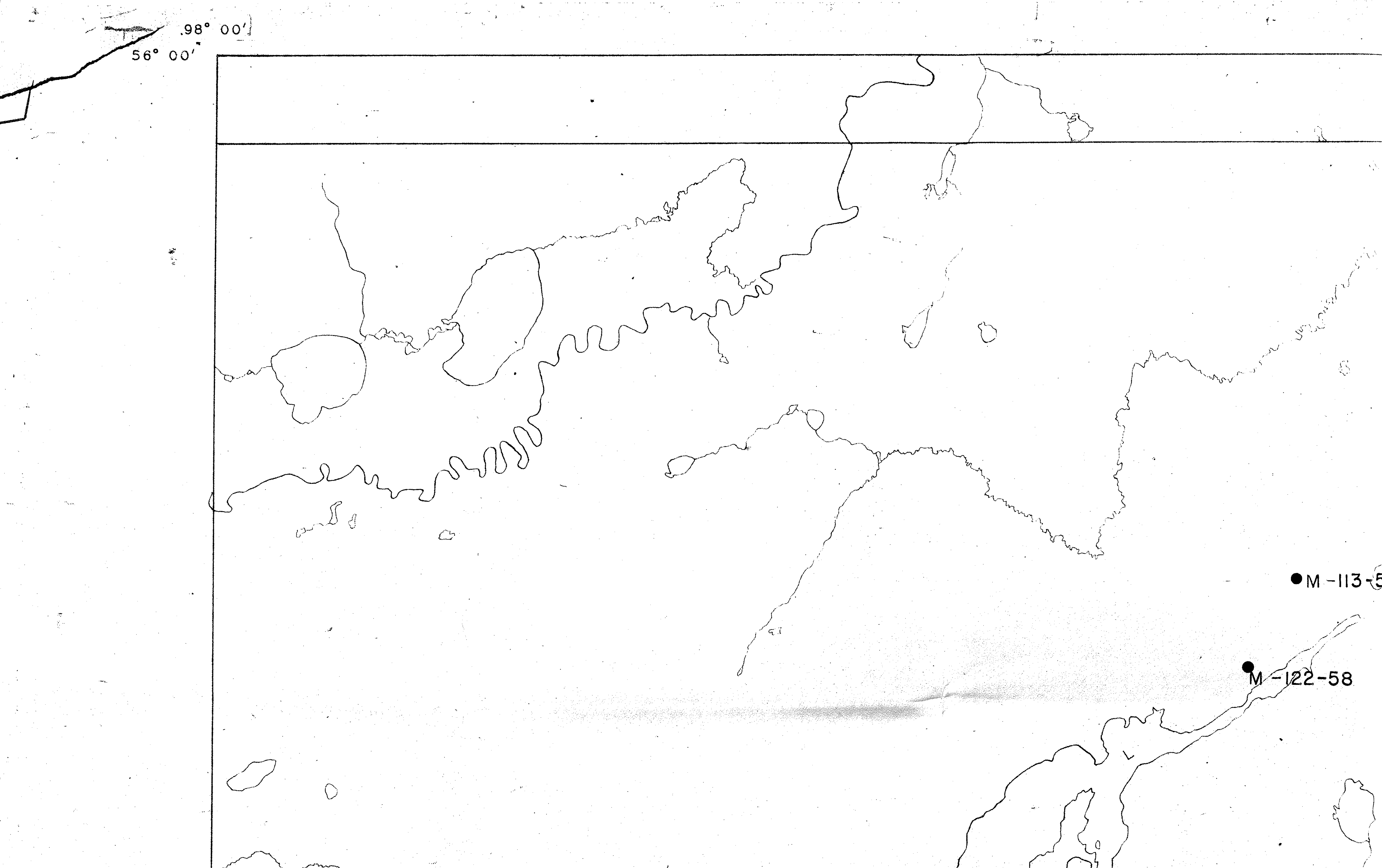
TUTTLE, O. F. (1952a): Optical studies on alkali feldspars, Am. J. Sci., Bowen Volume, 553-567.

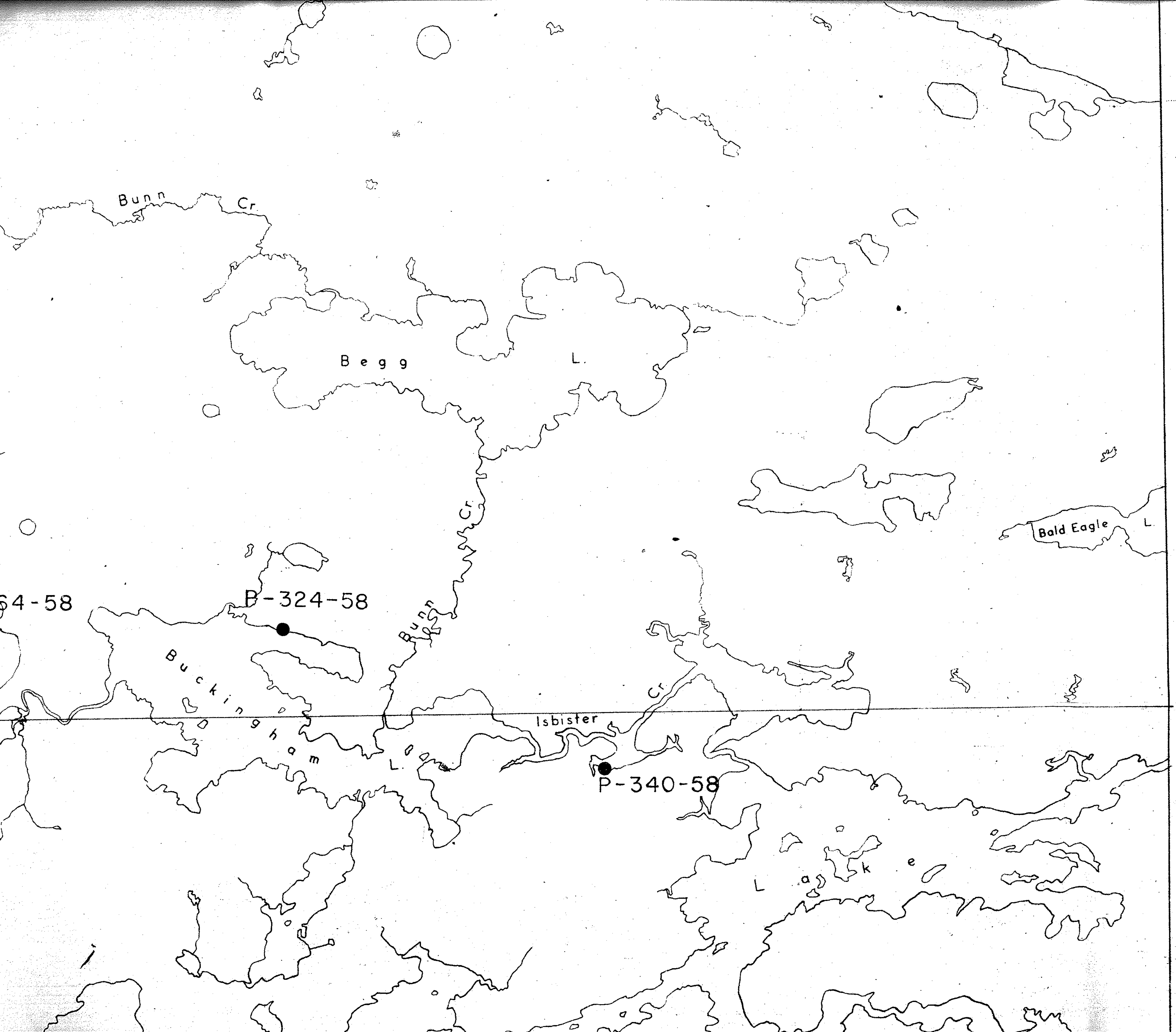
TUTTLE, O. F. (1952b): Origin of the contrasting mineralogy of extrusive and plutonic salic rocks, J. Geol., 60, 107-124.

TUTTLE, O. F., & BOWEN, N. L. (1958): Origin of granite in light of experimental studies, Geol. Soc. America Mem. 74.


97°00′
56°00′
21ST. BASE LINE
P-304-58
P-310-58
1-58
P-269-3-58
River
P-266-58
Brannigan
Cr.

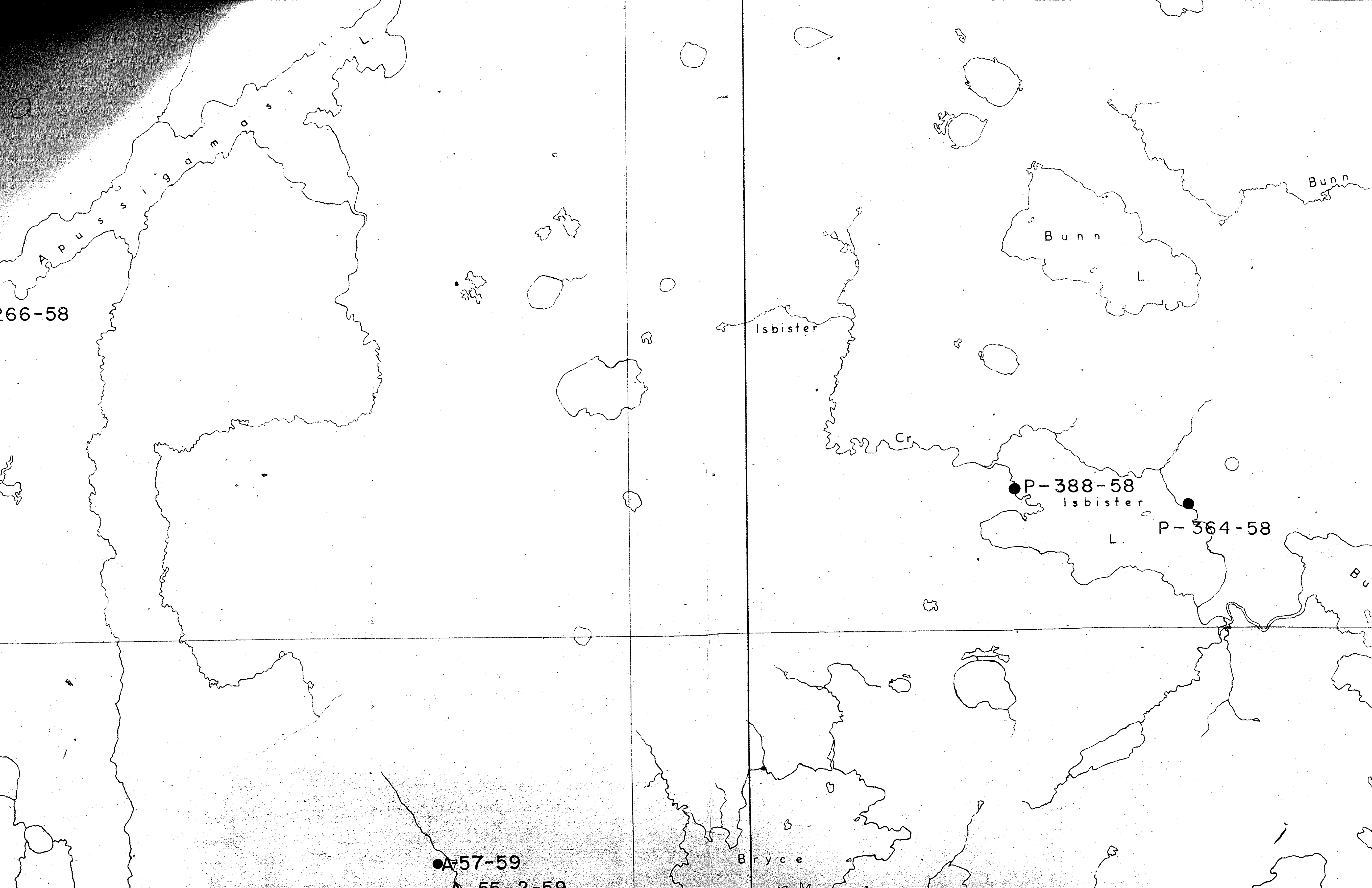

97° 30'
R
R
M-361-58
Moak Cr
R
R
F
Odei River
P-26
M-36-58
M-336-58
L
Moak
Moak
River
M-113-58
M-122-58
P-166-58
L
L

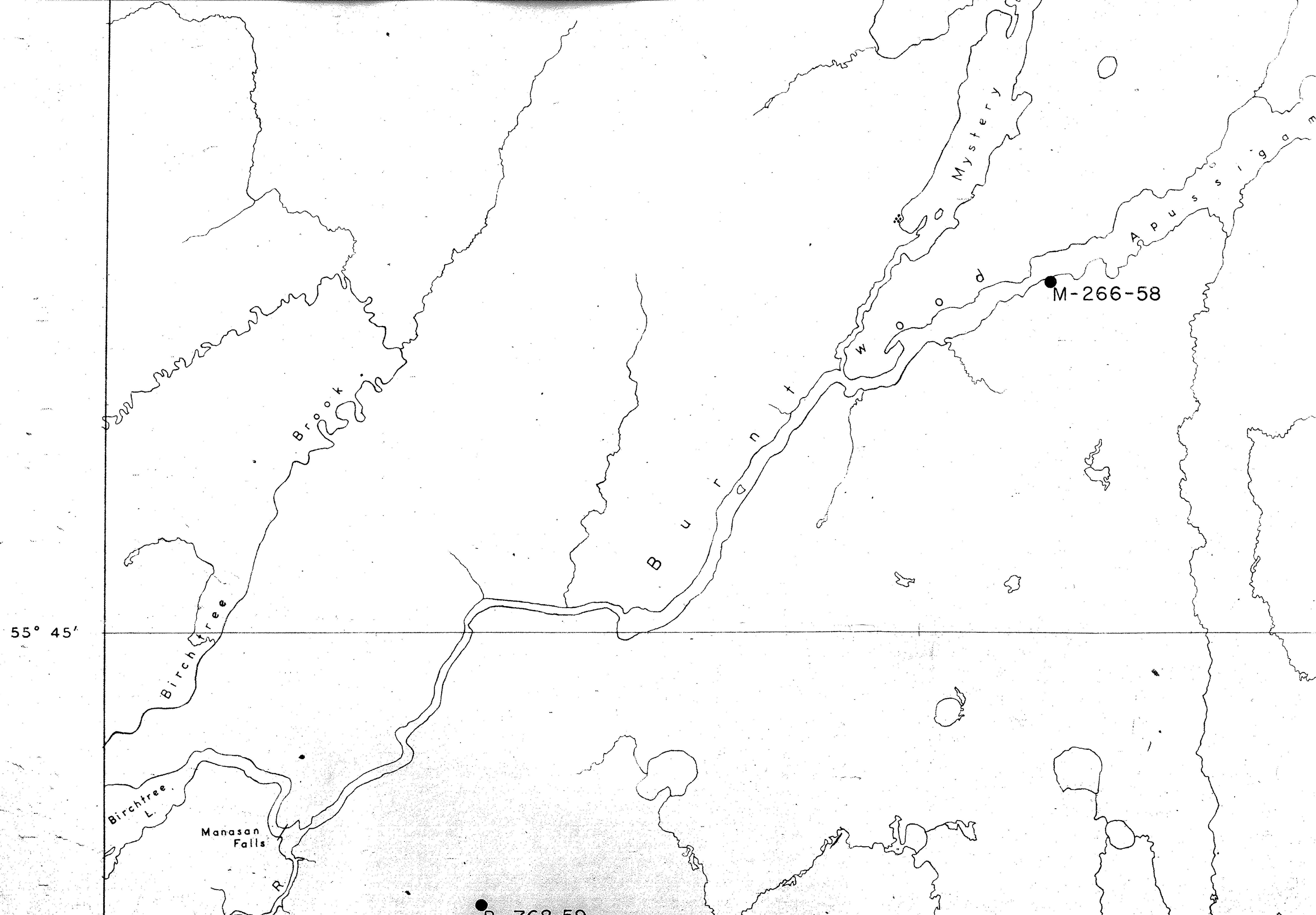

98° 00'
56° 00'
M-113-5
M-122-58

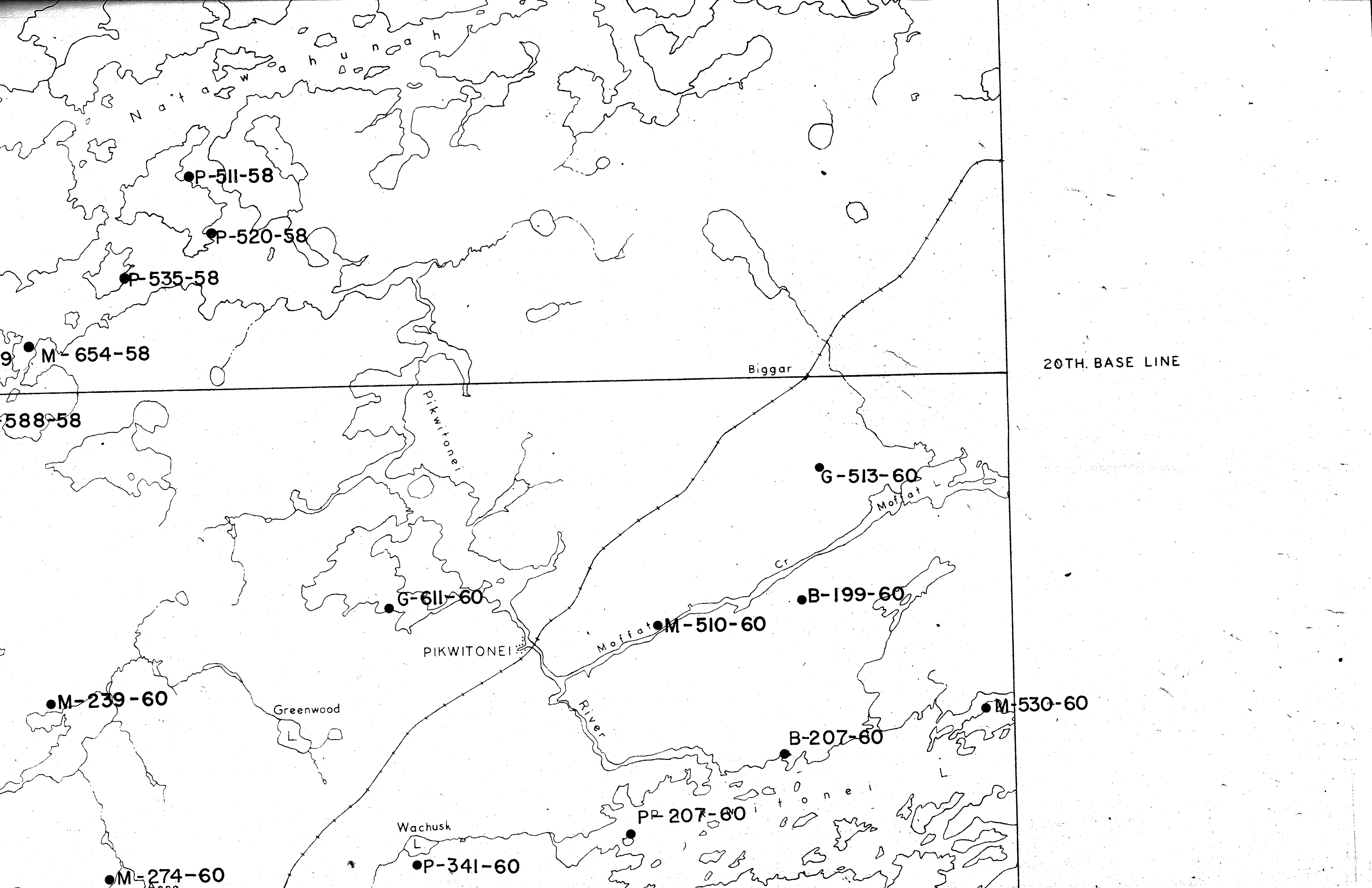


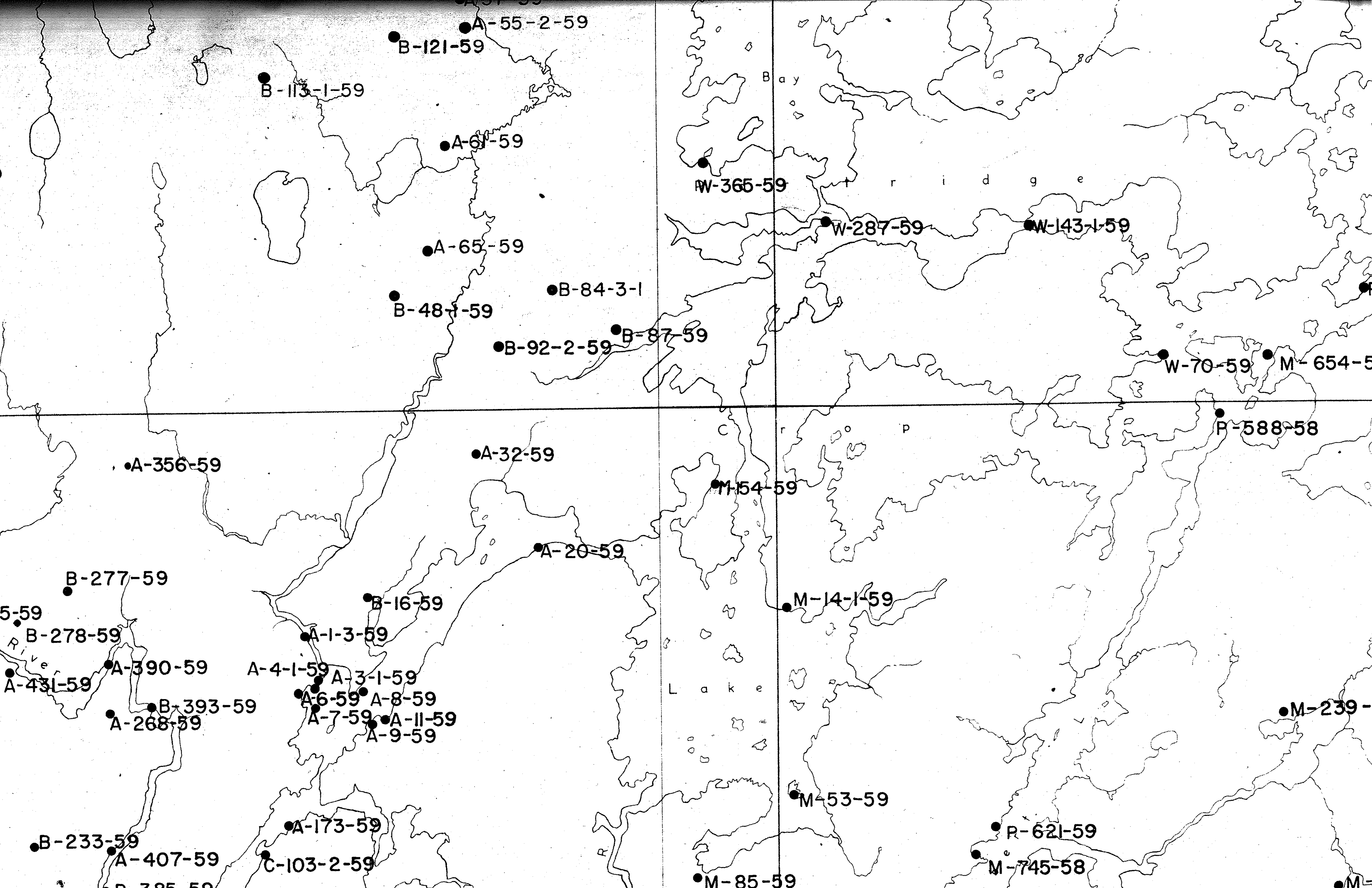
Moak-
Thompson
Area

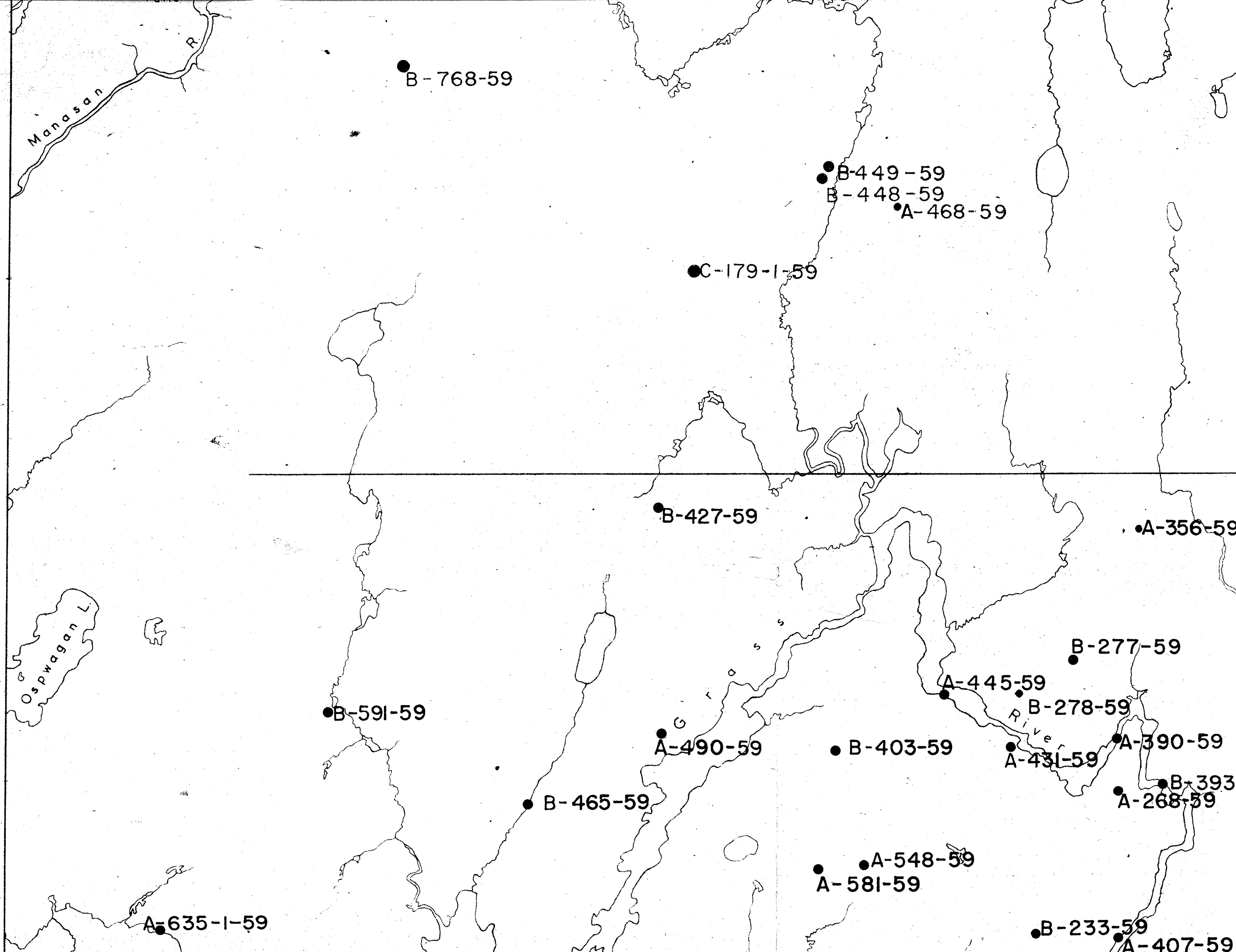
Specimen Map

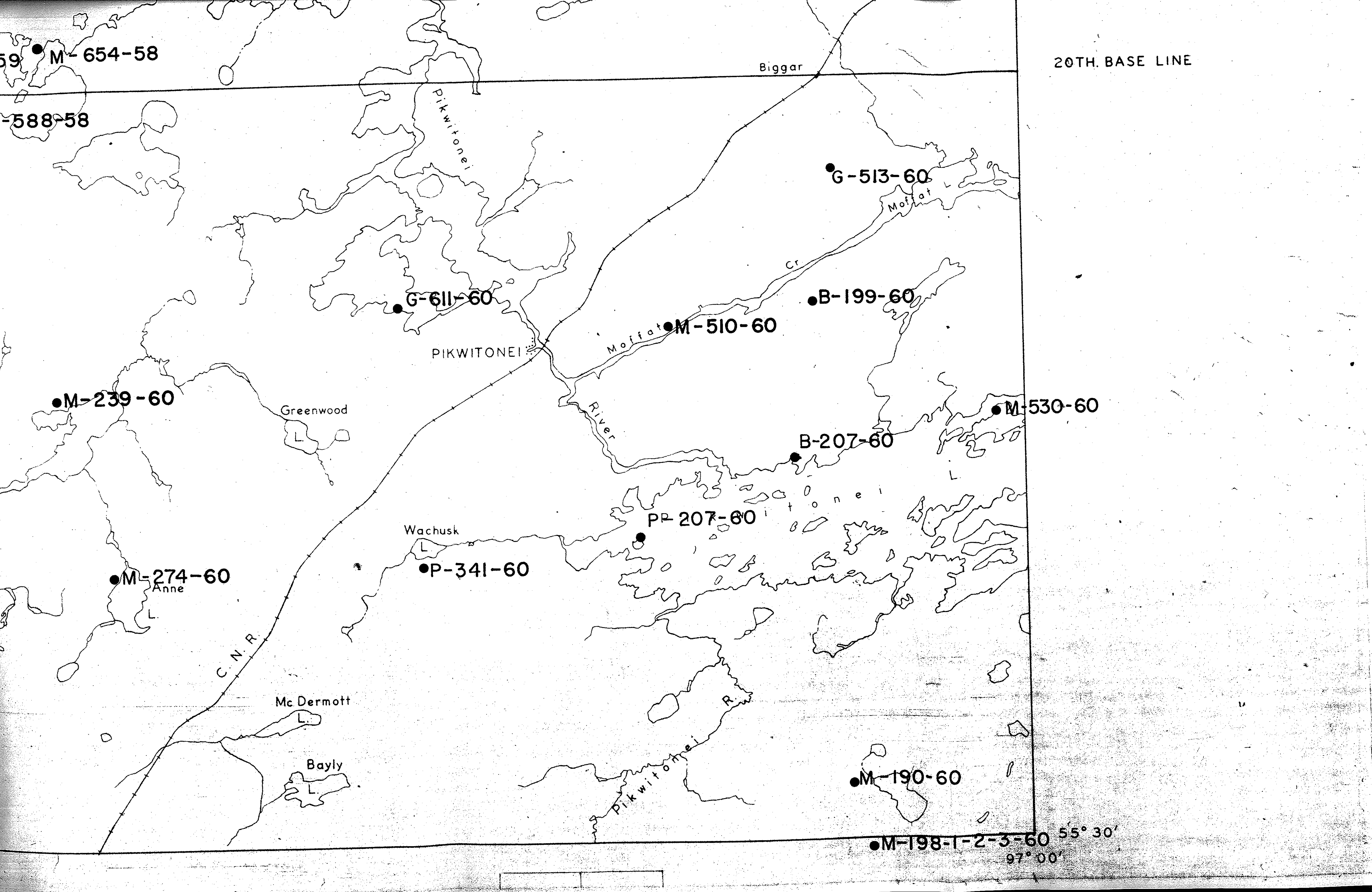

Apussigamasi L
266-58
Isbister
Bunn
Bunn L
Cr
P-388-58
Isbister L
P-364-58
Bu
A-57-59
55-2-59
Bryce


Mystery
Apussiga
M-266-58
Burntwood
Brook
Birchtree
55° 45′
Birchtree L.
Manasan Falls
R

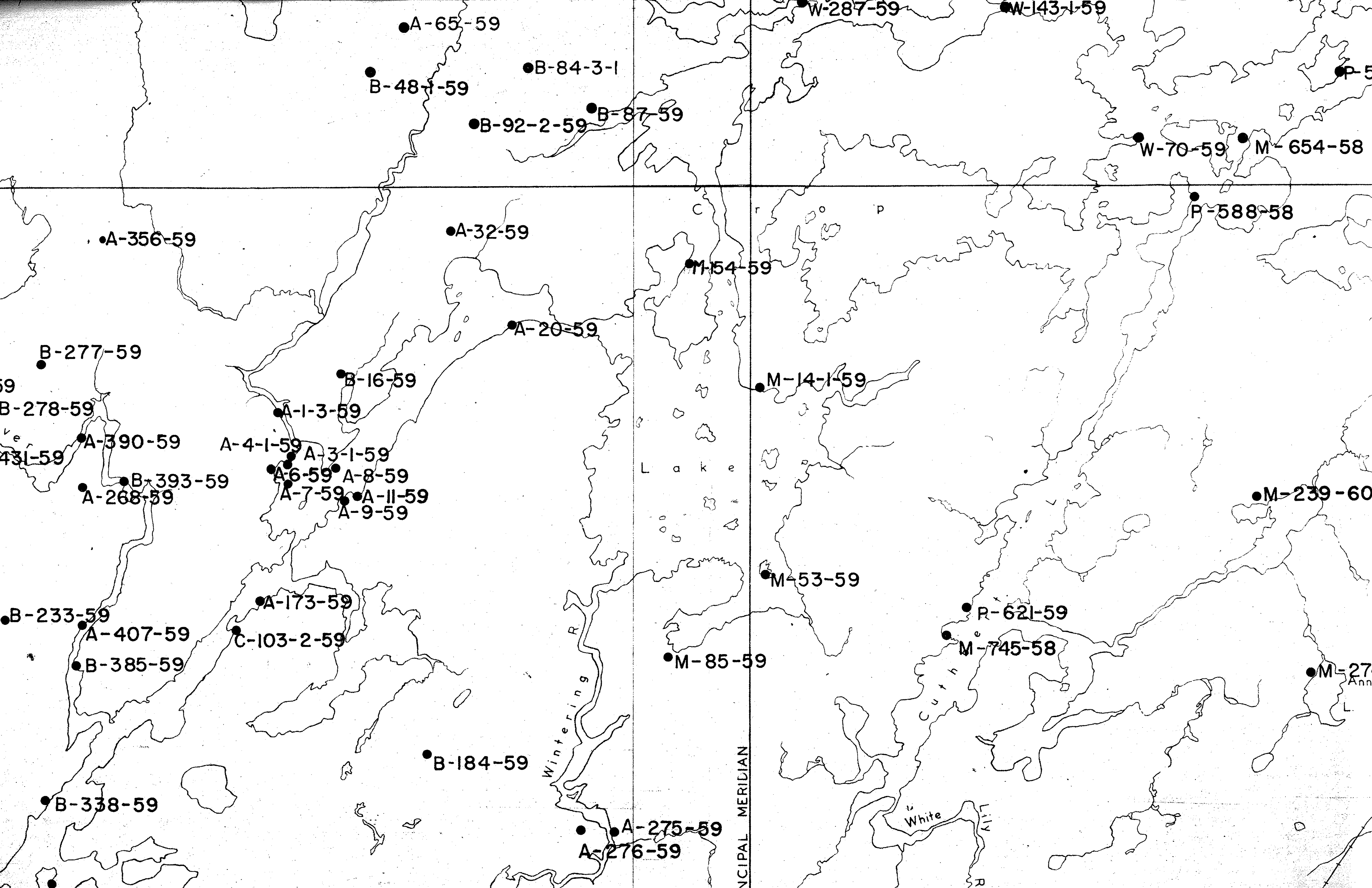

Natawahunah
P-511-58
P-520-58
P-535-58
9
M-654-58
588-58
Biggar
20TH. BASE LINE
Pikwitonei
G-513-60
Moffat L.
Cr.
B-199-60
G-611-60
M-510-60
Moffat
PIKWITONEI
M-239-60
Greenwood L.
River
M-530-60
B-207-60
tonei
L.
P-207-60
Wachusk L.
P-341-60
M-274-60

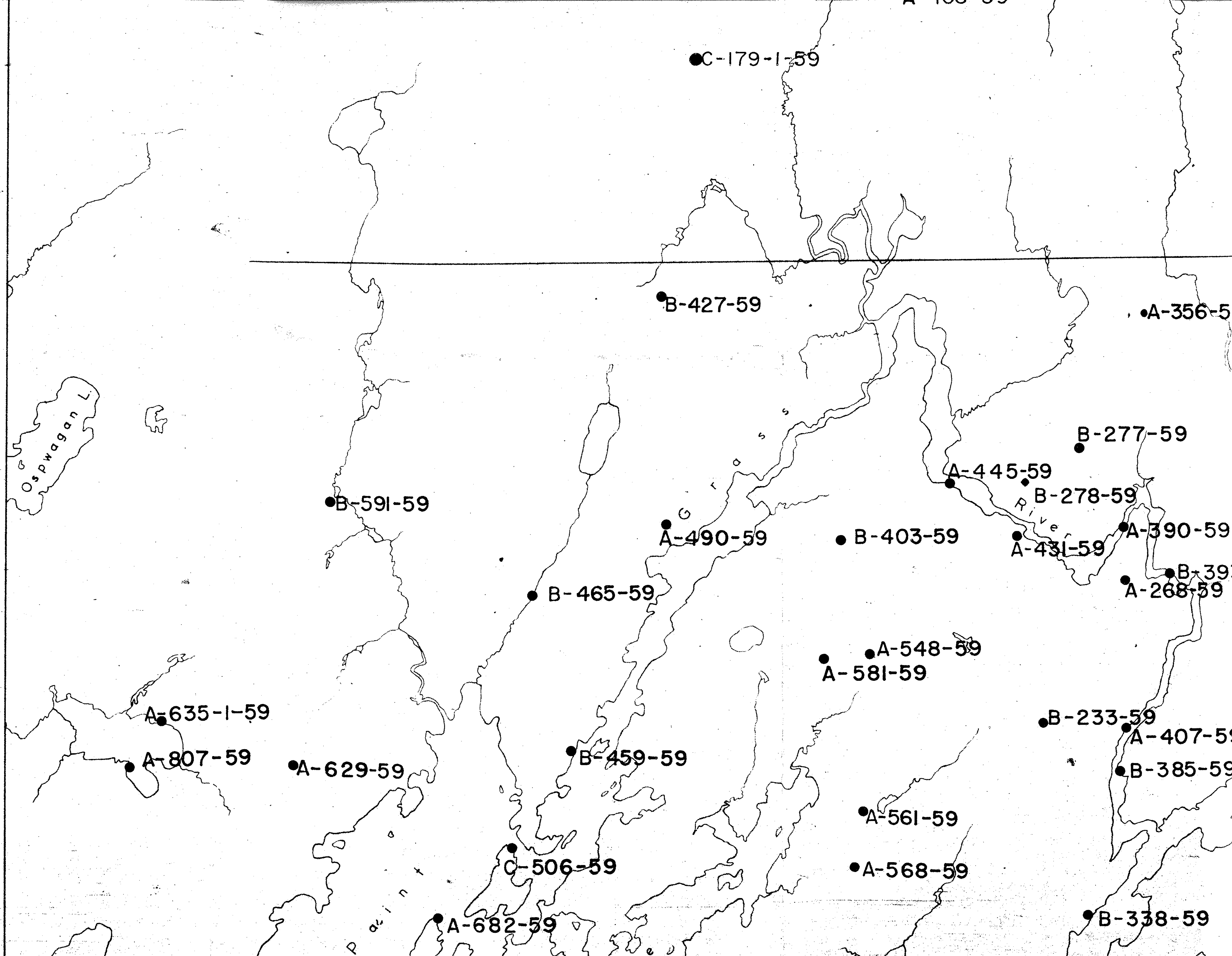

A-55-2-59
B-121-59
B-113-1-59
A-61-59
A-65-59
B-84-3-1
B-48-1-59
B-92-2-59
B-87-59
Bay
W-365-59
tridge
W-287-59
W-143-1-59
W-70-59
M-654-5
P-588-58
Crop
A-32-59
A-356-59
M-154-59
A-20-59
B-277-59
5-59
B-278-59
River
B-16-59
A-1-3-59
M-14-1-59
A-390-59
A-431-59
A-4-1-59
A-3-1-59
A-6-59
A-8-59
A-7-59
A-11-59
A-9-59
B-393-59
A-268-59
Lake
M-239-
M-53-59
A-173-59
B-233-59
A-407-59
C-103-2-59
P-621-59
M-745-58
M-85-59


Manasan R.
B-768-59
B-449-59
B-448-59
A-468-59
C-179-1-59
B-427-59
A-356-59
Ospwagan L.
Grass River
B-277-59
A-445-59
B-278-59
B-591-59
A-490-59
B-403-59
A-431-59
A-390-59
B-393
A-268-59
B-465-59
A-548-59
A-581-59
A-635-1-59
B-233-59
A-407-59



59
M-654-58
-588-58
20TH. BASE LINE
Biggar
Pikwitonei
G-513-60
Moffat L
Cr
G-611-60
B-199-60
Moffat
M-510-60
PIKWITONEI
River
M-239-60
Greenwood
L.
M-530-60
B-207-60
Pikwitonei
L
P-207-60
Wachusk
L.
P-341-60
M-274-60
Anne
L.
C.N.R.
Mc Dermott
L.
R.
Bayly
L.
Pikwitonei
M-190-60
M-198-1-2-3-60
55° 30′
97° 00′


W-287-59
W-143-1-59
A-65-59
B-84-3-1
B-48-1-59
P-5
B-87-59
B-92-2-59
W-70-59
M-654-58
P-588-58
C r o p
A-356-59
A-32-59
M-154-59
A-20-59
B-277-59
59
B-16-59
M-14-1-59
B-278-59
A-1-3-59
ver
A-390-59
A-4-1-59
A-3-1-59
431-59
B-393-59
A-6-59
A-8-59
L a k e
A-268-59
A-7-59
A-11-59
A-9-59
M-239-60
M-53-59
B-233-59
A-173-59
P-621-59
A-407-59
C-103-2-59
M-745-58
B-385-59
M-85-59
Wintering R.
Cuthe
M-27
Ann
L.
B-184-59
B-338-59
White
Lily
R.
A-275-59
A-276-59
NCIPAL MERIDIAN


C-179-1-59
B-427-59
A-356-5
Ospwagan L.
B-277-59
A-445-59
B-278-59
Grass
River
B-591-59
A-490-59
B-403-59
A-431-59
A-390-59
B-39
A-268-59
B-465-59
A-548-59
A-581-59
A-635-1-59
B-233-59
A-407-5
A-807-59
A-629-59
B-459-59
B-385-5
A-561-59
C-506-59
A-568-59
Paint
A-682-59
B-338-59