

CHARACTERIZATION OF GRANITIC AND PEGMATITIC
K-FELDSPARS FROM LAC DU BONNET, SOUTHEASTERN
MANITOBA AND DRYDEN, NORTHWESTERN ONTARIO BY
RAPID X-RAY DIFFRACTION AND CHEMICAL METHODS

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by

Catherine Rae McGregor

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ABSTRACT

A rapid x-ray diffraction method using single crystal precession photography has been developed for deriving twinning, phase nature and other characteristics of microcline feldspars not obtainable by x-ray powder diffractometry. Nine K-feldspars from the Lac du Bonnet granite, Manitoba, and 13 pegmatitic and 7 granitic specimens from Dryden, Ontario were analyzed by this method. Interpretations of their precession photos, particularly of those K-feldspar specimens with complex twinning patterns, were greatly enhanced by the addition of Gandolfi powder-type photos of the same crystal and powder diffractograms of the same sample. Along with these crystallographic investigations are chemical variations as determined by the electron microprobe on the same single crystals which were supplemented with partial chemical analyses supplied by Ucakuwun (1981). Qualitative optical characteristics were derived from thin sections.

There are four main characteristics observed and interpreted by the above methods: (1) triclinicity; (2) nature and number of K-feldspar phases; (3) twinning pattern; and (4) chemical composition. The K-feldspars may be classified into three crystallographic groups based on reciprocal interaxial angle τ^* as measured in precession photos and complemented with the triclinicity $\Delta = 12.5(d_{131} - d_{1\bar{3}1})$ (range 0 to 1)

from powder diffractograms and Gandolfi powder-type photos:

(1) metrically monoclinic (orthoclase/sanidine) with $\gamma^* = 90^\circ$ and $\Delta = 0$; (2) intermediate microcline with $90^\circ < \gamma^* \leq 92^\circ 0'$ and $0 < \Delta \leq 0.85$; and (3) maximum microcline with $92^\circ 0' < \gamma^* \leq 92^\circ 18'$ and $0.85 < \Delta \leq 1$. No monoclinic K-feldspars (orthoclase) were found in any of the author's specimens.

All 16 granitic K-feldspars comprise one of two major K-feldspar groups. ^{The first group} / consists of single-phase maximum microclines (all perthitic) with one of four different twinning patterns as interpreted in precession photos: (1) untwinned (3 specimens); (2) albite-twinned (8); (3) pericline-twinned (1); and (4) albite- + pericline-twinned (4). They exhibit five different types of reflections which indicate different types of interface boundaries: (1) simple and sharp reflections; (2) diffuse streaks between strong albite- and strong pericline-twin reflections; (3) diffuse streaks between strong albite- and weak pericline-twin reflections (or vice versa); (4) streaks between transitional triclinic phases; and (5) untwinned intergrowth reflections. These microclines have Na_2O that ranges from 0.59 to 1.46 wt % (analyzed by electron microprobe).

The second group consists of pegmatitic K-feldspars (also perthitic) where precession photos have indicated that they are of four different types of microclines: (1) mixture of a largely untwinned intermediate microcline ($\gamma^* = 90^\circ 10'$ -

90°30' and $0.10 < \Delta < 0.25$) and a minor albite-twinned maximum microcline component (seven specimens; in powder diffractograms/photos, most of these multiple-phase specimens appear to contain a monoclinic phase as well as a maximum microcline phase although some diffractograms/photos show only monoclinic phase). All seven specimens show one type of reflection: monoclinic-triclinic transitional streak; (2) single or multiple phase intermediate microcline showing either sharp or diffuse streaks (2); (3) single phase maximum microcline with reflections similar to granitic K-feldspars (2); and (4) single phase maximum microclines showing diagonal association (2). They have Na_2O that ranges from 0.48 to 1.32 wt % (from electron microprobe) and Rb_2O from 1.04 to 2.24 wt % (from partial chemical analyses) except for the two specimens that are single phase maximum microclines similar to granitic K-feldspars which are low in Rb_2O (0.24 to 0.26 wt %).

There seems to exist a difference in the twinning patterns between the Lac du Bonnet (largely albite-twinned) and the Dryden (largely albite- + pericline-twinned) granitic K-feldspars. This may be due to the different cooling rates of the related plutonic rock types that generated K-feldspars of high and nearly consistent triclinicity. The present study casts doubt on Laves' hypothesis that albite- + pericline-twinned (maximum) microcline must have had a monoclinic precursor in all cases. The pegmatitic K-feldspars, on the other

hand, are greatly variable in terms of chemical composition, phase types, triclinicity, and twinning patterns. These variations may be attributed to the high Rb content of the pegmatites studied.

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The author wishes to acknowledge the supervision of Dr. R. B. Ferguson of the Department of Earth Sciences and the extensive time he has spent in discussing the ideas in the thesis and reviewing early drafts of it.

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TABLE OF CONTENTS

	Page
ABSTRACT	iv
ACKNOWLEDGEMENTS	viii
LIST OF TABLES	xiv
LIST OF FIGURES	xvii
CHAPTER I. INTRODUCTION	
(A) CHEMICAL COMPOSITION	1
(B) CRYSTAL STRUCTURE	1
(C) Si/Al ORDER/DISORDER	4
(D) NATURE OF STUDY	8
(E) GEOLOGICAL SETTING OF THE K-FELD- SPARS FROM THE TWO STUDY AREAS: LAC DU BONNET, MANITOBA AND DRYDEN, ONTARIO	10
(1) Descriptions of rock units and source of specimens from the Lac du Bonnet area	13
(2) Descriptions of rock units and source of specimens from the Dryden area	15
(a) Granitoid rocks	15
(b) Pegmatites	17
CHAPTER II. X-RAY DIFFRACTION: PROCEDURES	
(A) INTRODUCTION	20
(B) SEPARATION OF K-FELDSPARS	20
(C) PRECESSION PHOTOGRAPHY	23
(1) Introduction	23
(2) Selection and mounting of crystal	23
(3) Orientation procedures	24
(4) Other required orientation: precessing around z-axis	33
(5) Other possible orientations	35
(6) Standard setting and zero- level photos for the orient- ation procedures	37
(D) GANDOLFI POWDER-TYPE PHOTOGRAPHY	60
(E) X-RAY POWDER DIFFRACTOMETRY	61

	Page
CHAPTER III. X-RAY DIFFRACTION: INTERPRETATIONS	
(A) PRECESSION PHOTOGRAPHS	63
(1) Introduction	63
(2) Indexing of reflections	63
(3) Twinning	65
(4) Results	69
(a) Introduction	69
(b) Zero-level around x-axis	69
(i) K-feldspars	69
(ii) Albites	71
(c) Zero-level around z-axis	74
(i) K-feldspars	74
(ii) Albites	76
(d) Types of reflections and streaks and the inter-face boundary	77
(5) Summary of results	91
(6) Discussion	97
(a) Distribution of observed phases among granitic and pegmatitic rocks	97
(b) Type of albite- + pericline-twinning	98
(c) Perpendicularity of the twin axes and planes	98
(d) Albite- vs. pericline-twin γ^* readings	102
(e) Mixed microclines	104
(f) Type of twinning mechanism	104
(g) Implications of diffused or smeared reflections	105
(h) Implication of pericline-twinning only microcline	106
(B) POWDER-TYPE GANDOLFI PHOTOGRAPHY	106
(1) Introduction	106
(2) Triclinicity	107
(3) Different K-feldspar phases	107
(4) Albite as second phase	113
(5) Cell refinement data	113

	Page
(C) X-RAY POWDER DIFFRACTOMETRY	114
(1) Introduction	114
(2) Cell parameters	114
(3) Triclinicity	120
(4) K-Na solid solution composi- tion	124
(5) Albite as a second phase	126
(D) SUMMARY AND COMPARISON OF RESULTS FROM THE THREE X-RAY DIFFRACTION METHODS	127
(1) Reciprocal cell angles	127
(2) Proportion of multiple phases	132
(3) Triclinicities	132
(4) K-Na solid solution composi- tion	139
(5) Amount of albite as a second phase	139
(6) Twinning	141
(E) CONCLUSIONS	142
 CHAPTER IV. CHEMICAL ANALYSIS	
(A) INTRODUCTION	143
(B) PROCEDURES	143
(1) Electron microprobe analysis	143
(2) Whole rock and partial chemi- cal analysis	145
(C) RESULTS AND DISCUSSIONS	146
(1) Introduction	146
(2) Electron microprobe results	152
(3) Correlations between probe and partial chemical analyses	153
(4) Whole rock analyses	153
 CHAPTER V . THIN SECTION STUDIES	
(A) INTRODUCTION	156
(B) K-FELDSPARS	158
(C) ALBITE PHASE IN K-FELDSPARS	165
(D) PLAGIOCLASES	171
(E) RELATIONSHIPS BETWEEN PLAGIOCLASES AND K-FELDSPARS	173
(F) CORRELATION BETWEEN THE K-FELDSPARS AND THE PLAGIOCLASES	179

	Page
CHAPTER VI. INTERRELATIONSHIPS OF K-FELDSPAR RESULTS	
(A) INTRODUCTION	181
(B) COMPARISONS OF VARIOUS RESULTS . .	181
(1) Chemistry	181
(2) Triclinicity	187
(3) Twinning of microclines . . .	189
(4) Orientation and twinning of albite intergrowths	190
(C) SUMMARY AND DISCUSSION	191
(1) Introduction	191
(2) Granites	192
(a) Summary	192
(b) Discussion	195
(i) Mode of formation of the perthitic intergrowth	195
(ii) Twinning characteristics of the microclines	195
(iii) Possible origin of the cross-hatched twinning in the microclines	197
(3) Pegmatites	198
(a) Summary	198
(b) Discussion	200
(i) Possible relationship between Rb-content of a K-feldspar and its triclinicity, twinning, and phase composition	200
(ii) Mode of formation of the perthitic intergrowth.	205
(D) CONCLUDING STATEMENTS	206
REFERENCES	208

LIST OF TABLES

Table		Page
1-1	Cell dimensions and space groups of principal alkali feldspar polymorphs.	3
1-2	Minerals identified in the three Dryden area pegmatites discussed in the text.	18
2-1	Extinction angles on cleavage planes of alkali feldspars.	24
2-2	Intensity, $d(\text{\AA})$, and $2p^*(\text{mm})$ values and indices hkl of the different reflections for the relevant principal axes of K-feldspar and albite as discussed later in the chapter.	28
2-3	Summary of precession photos listed in Figure 2-10 of precession around various axes involved in the orientation procedures discussed in the text.	40
3-1	Summary of twinning characteristics observed in precession photos of Lac du Bonnet granitic and Dryden pegmatitic/granitic single K-feldspar crystals and their K- and Na-feldspar components as discussed in text.	70
3-2	Precession photo data of K-feldspars and their albite phases as discussed in text.	73
3-3	Summary of twinning characteristics and type of reflections/streaks in all K-feldspar specimens.	92
3-4	Precession photo readings of the y_p -axes, the $(010)_a$ plane, the y_a^* -axes, the x_p^* -axes and some interaxial angles as discussed in text.	100

Table		Page
3-5	Average γ^* values and range for each albite-twinned individual and for each pericline-twinned individual of microclines and comparable values for α^* of albites.	103
3-6	Gandolfi photography data as discussed in text.	109
3-7	Refined unit cell parameters from powder diffractograms.	115
3-8	Closeness of key monoclinic (adularia) and triclinic reflections.	118
3-9	X-ray powder diffractogram data as discussed in text.	121
3-10	Approximate weight % of different K-feldspar components in the pegmatitic K-feldspars as determined by the three different x-ray diffraction methods.	133
3-11	Estimated wt % of albite as a second phase in K-feldspars by the three different x-ray diffraction methods.	140
4-1	Standards used to analyze each element.	146
4-2	Electron microprobe results of single crystals in oxide (wt %) (which also includes those of partial chemical analyses of Ucauwun (1981)), molecular %, and number of cations per 8 oxygens.	148
4-3	Whole rock analyses of Lac du Bonnet (Černý et al., 1981 (Table 8); Černý, pers. comm.) and Dryden (Ucauwun, 1981) granitic specimens.	150
5-1	Modal analyses, optical characteristics of K-feldspars, perthites, and plagioclases in Lac du Bonnet and Dryden granitic and pegmatitic rocks.	160

Table

Page

6-1

Summary of different characteristics of K-feldspars from the Lac du Bonnet granites, Dryden granites, and Dryden pegmatites as discussed in text.

182

LIST OF FIGURES

Figure		Page
1-1	Features of a feldspar structure.	2
1-2	A projection onto (001) of the T atoms in the feldspar framework.	5
1-3	Location of the Lac du Bonnet and Dryden study areas in western Superior of the Precambrian Shield.	11
1-4	Two domains of the English River Subprovince in which the two study areas (Lac du Bonnet and Dryden) are located.	12
1-5	Geology of study area #1, Lac du Bonnet area: Distribution of rock types and sample locations.	14
1-6	Geology of study area #2, Dryden area: Distribution of rock types and sample locations.	16
2-1	Experimental set-up for the staining technique as described in text.	22
2-2	Ideal crystal size (0.5 mm) and shape (two good cleavages (010) and (001)).	25
2-3	Goniometer head with a crystal viewed through a collimator lens (the crystal is greatly enlarged here).	25
2-4	Example of monoclinic lattices projected along the y- and y*-axes showing the relationship between the direct (space) lattice (solid lines) and the reciprocal lattice (broken lines) where $p_{100} \propto 1/d_{100}$ and $p_{100}^* \propto 1/d_{100}^*$.	27
2-5	Precession setting photographs of a K-feldspar crystal for rotation about y* to illustrate the procedure for orienting the crystal to the required position as described in text.	31

Figure		Page
2-6	Buerger orientation error chart for precession method.	32
2-7	Direct lattice (solid lines) and reciprocal lattice (broken lines) projection along the y/y^* axis showing the xz and x^*z^* planes to illustrate the two axes making approximately 116° to x -axis.	36
2-8	Similar set-up as Figure 2-7 except that the x-ray beam is parallel to the z -axis.	38
2-9	Similar set-up as Figure 2-7 except that the x-ray beam is perpendicular to the (001) of the crystal.	39
2-10	Precession photos of various axes involved in the orientation procedures as discussed in text.	41
2-11	Positions of the crystal on the goniometer head in relation to the orientation procedure as discussed in text.	59
3-1	Diagrammatic representations of zero-level precession photos around (a) x -axis (y^*z^* plane) and (b) z -axis (y^*x^* plane) of a triclinic K-feldspar.	64
3-2	Comparable diagrams to Figure 3-1 of twinning patterns of K-feldspars as described in text.	66
3-3	"M-twinning" microcline with albite-twinning individuals A_1 and A_2 and pericline-twinning individuals P_1 and P_2 of the reflection 590 of Figure 3-2d.	68

Figure		Page
3-4	Drawings and photos of the various types of reflections and streaks and their interface boundaries which are discussed in text.	79
3-5	Plot of γ^* vs. α^* of K-feldspars from precession photo data.	93
3-6	Plot of γ^* vs. α^* of albite phase in microclines from precession photo studied.	96
3-7	Diagrammatic representation of the axes on a zero-level precession photo around z to explain certain inter-axial angles.	99
3-8	Standard Gandolfi powder-type photographs.	108
3-9	Gandolfi powder photos of pegmatitic K-feldspars that show other than maximum microcline.	111
3-10	Plot of α^* vs. γ^* of K-feldspars from cell refined powder diffractometer data.	117
3-11	Plots of the K-feldspar data on partial Stewart & Wright (1974) b-c diagrams of alkali feldspars.	119
3-12	131 and $\bar{1}\bar{3}1$ microcline peaks (denoted as T) and 131 orthoclase peak (denoted as M) in the vicinity of 29° and 30° at a scanning speed of $1/4^\circ/2\theta$ for $\text{CuK}\alpha$ radiation.	122
3-13	Plot of γ^* from powder diffractogram cell refinement data vs. γ^* from precession photos.	129
3-14	Plot of α^* from powder diffractogram cell refinement data vs. α^* from precession photos.	131
3-15	Three plots showing the relationships of Δ from precession photos, Gandolfi photos, and cell refinements.	135

Figure		Page
3-16	Maximum microcline (HG-01) powder diffractogram pattern between 29° and 30° at $1/4^{\circ}/20_{\text{mm}}$ showing that the $1\bar{3}1$ peak is at least three times as high as the 131 peak.	138
4-1	Na_2O (wt %) vs. K_2O (wt %) of electron microprobe analyses.	149
4-2	$\text{Ab} (+\text{An})^2$ wt % vs. $\text{Or} (+\text{Cn})^1(+\text{Rb}+\text{Cs}+\text{Li-feldspars})^2$ wt % where Na, K, and Ba^1 are from electron microprobe data and ^2Ca , Rb, Cs and Li are from partial chemical analyses (see Table 4-2).	151
4-3	% weight K_2O from electron microprobe analyses vs. partial chemical analyses.	154
5-1	Example of a typical K-feldspar (PG-24) in granitic rocks that is interstitial, shows no alteration, and has well-developed cross-hatched twinning with different widths of lamellae.	161
5-2	Example of a typical pegmatitic K-feldspar (MLP/NZ 30).	161
5-3	Example of the association of untwinned and cross-hatched K-feldspars in a granite (MLG-01).	163
5-4	Example of the association of untwining and cross-hatched twinning in a K-feldspar (MLG-01).	164
5-5	Example of incipient cross-hatched twinning with the presence of inclusions of quartz and albite strings (AEC-20).	164
5-6	Example of cross-hatched twinning being intensified with the presence of inclusions (in this case, muscovite) in a K-feldspar (PG-121).	166

Figure		Page
5-7	Example of a microperthite (HG-01) showing variable thickness of lamallae of both albite and pericline twinnings.	166
5-8	Example of the four textural perthitic types common in Lac du Bonnet and Dryden granitic and pegmatitic K-feldspars.	168
5-9	Example of albite strings.	168
5-10	Example of albite blebs in K-feldspar.	169
5-11	Example of albite rods in microperthite (HG-01).	169
5-12	Example of flame-type perthite (CG-03).	170
5-13	Example of albite rods in K-feldspar (MLP/NZ 01) showing twinning in the same crystallographic orientation as the twinning in the microcline.	170
5-14	Example of albitic rims in optical continuity with the plagioclase crystal.	174
5-15	Example of a rare simple twinned (presumably albite-twinned) albitic rims within the plagioclase (of GPG-22).	174
5-16	Example of a rare twinned bulb myrmekite at the contact between microcline (dark grey) and plagioclase (AEC-26).	177
5-17	Example of fresh cross-hatched microcline in granitic rock (GPG-22) attacking extensively-altered plagioclase.	177
5-18	Example of a granitic microcline (the perthitic units are twinned) attacking and replacing the plagioclase grains (GPG-22).	178
5-19	Example of a pegmatitic K-feldspar (MLP/NZ 01) attacking the albite laths.	178

Figure		Page
5-20	An % of plagioclase as separate crystals vs. the ratio of plagioclases to total feldspars (plagioclases and K-feldspars) from modal analyses of Lac du Bonnet and Dryden granites/pegmatites.	180
6-1	Or wt % from powder data using Orville curve vs. Or wt % from electron microprobe data for 27 microclines.	183
6-2	Or wt % from partial chemical analysis vs. Or wt % from probe data.	186
6-3	Coarseness of twin lamellae.	194
6-4	Wt % Na_2O vs. wt % K_2O from partial chemical analyses of Ucauwun (1981) and Lenton (1979).	202
6-5	Or wt % from powder data using Orville curve vs. Or wt % from probe data for 11 Rb-rich microclines showing the monoclinic and maximum microcline components of the mixed microclines.	203

CHAPTER I. INTRODUCTION

(A) CHEMICAL COMPOSITION

Feldspars may be represented by the general composition MT_4O_8 where $M = K, Na, Ca, (Rb, Sr, Pb, Cs, Ba, Mg)$

$T = Si, Al, (B, Fe^{3+}, Fe^{2+}, P, Ti)$

with minor and trace-elements shown in brackets (Ribbe, 1975).

This thesis is mainly concerned with the alkali feldspars:

microcline/orthoclase $KAlSi_3O_8$

albite $NaAlSi_3O_8$

perthites $(K, Na) AlSi_3O_8$

In the present study, only Rb, Ca, Ba, and Cs are important.

(B) CRYSTAL STRUCTURE

All feldspars have the same basic structural arrangement, in which all the tetrahedra share corners in a continuous 3-dimensional framework with the M cations in large cavities (Figure 1-1(a)). Each T atom is surrounded by four oxygen atoms in a tetrahedral arrangement, and each oxygen is linked to two T atoms. The four-membered rings of the TO_4 tetrahedra, with alternate pairs of vertices pointing in opposite directions, share corners with similar rings to form double crankshaft-like chains parallel to a (Figure 1-1 (b)).

The unit cell contains four formula units of MT_4O_8 ,

which means that there are 16 T atoms distributed over the available tetrahedral sites. Variations in tetrahedral occupancy and M cation sizes give rise to both monoclinic and triclinic structure types; these are discussed in the next section. The cell dimensions and space groups of the principal alkali feldspars are listed in Table 1-1.

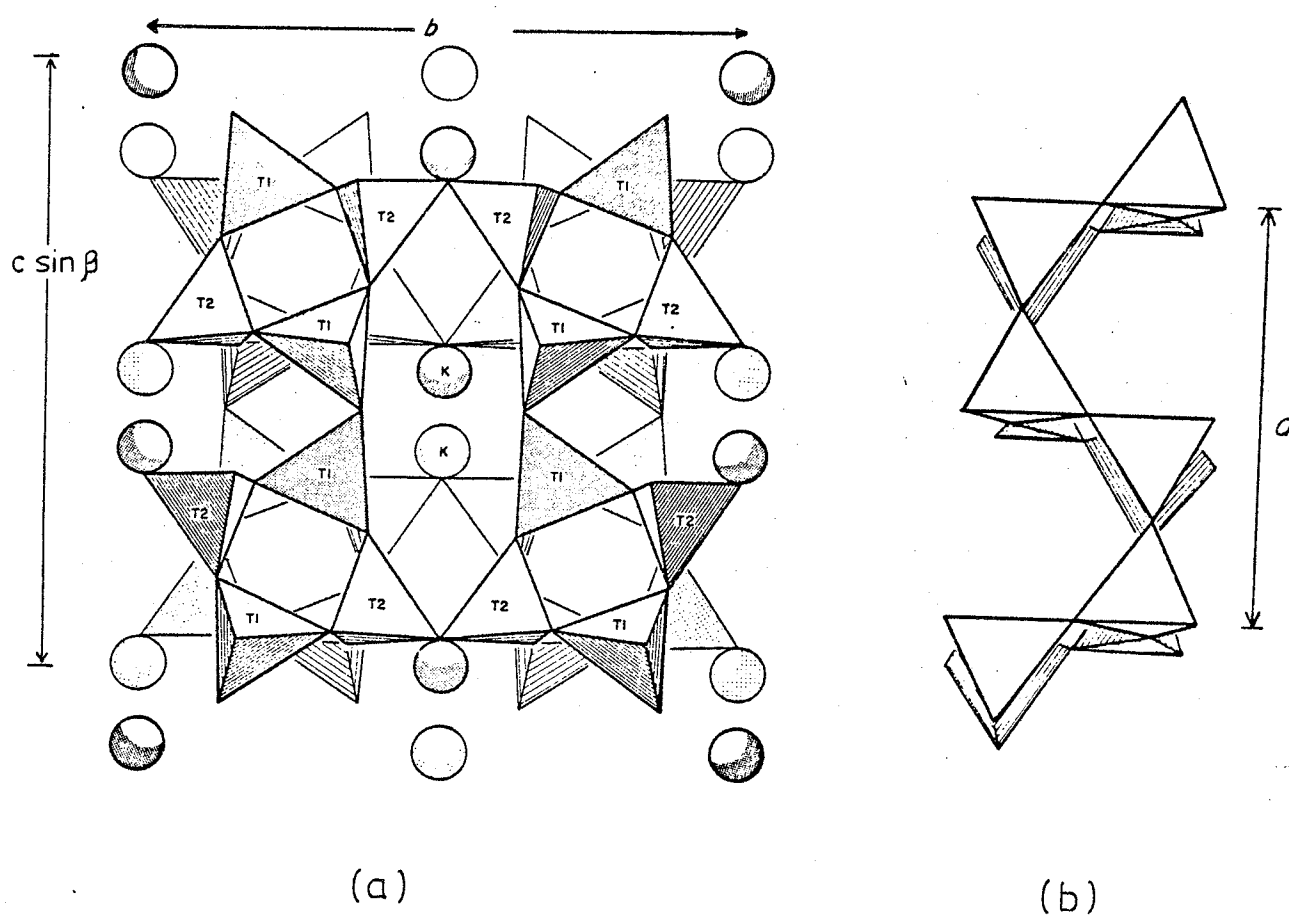


Figure 1-1. Features of a feldspar structure. (a) Projection along X of the sanidine structure with the K atoms in the large cavities. (b) Chains parallel to X formed from four-membered rings (after Papike & Cameron, 1976).

Table 1-1. Cell dimensions and space groups of principal alkali feldspar polymorphs.

NAME	CHEMICAL FORMULA	SYSTEM	a(Å)	b(Å)	c(Å)	α	β	γ	α^*	β^*	γ^*	SPACE GROUP
SANIDINE ¹	KAl Si ₃ O ₈	monoclinic	8.60	13.03	7.18	90° 00'	116° 00'	90° 00'	90° 00'	64° 00'	90° 00'	C 2/m
MAXIMUM MICROCLINE ²	KAl Si ₃ O ₈	triclinic	8.56	12.96	7.22	90° 39'	115° 50'	87° 42'	90° 28'	64° 02'	92° 14'	Cī
LOW ALBITE ³	Na AlSi ₃ O ₈	triclinic	8.14	12.78	7.16	94° 20'	116° 34'	87° 42'	86° 20'	63° 32'	90° 28'	Cī
HIGH ALBITE ³	Na AlSi ₃ O ₈	triclinic	8.16	12.88	7.11	93° 22'	116° 18'	87° 39'	86° 06'	63° 39'	88° 01'	Cī

¹Smith (1974); ²Ferguson (1981); ³Ferguson et al. (1958).

(C) Si/Al ORDER/DISORDER

A feldspar is said to be Si/Al disordered when the two kinds of atoms are randomly distributed over the available T sites. This is exemplified by the high temperature sanidine and high albite, in which the three Si and one Al atoms are randomly distributed over the two pairs of different, and four different, tetrahedral sites available respectively (Figure 1-2(a)). An ordered structure occurs when the Si and Al atoms are largely or completely segregated such that Al has a certain preference for specific positions (Figure 1-2(b)). In the corresponding low temperature forms, maximum microcline and low albite, most or all of the Al atoms are concentrated at one of the four T sites and most or all of the Si atoms in the other three sites (Ferguson, 1979) (Figure 1-2(b)).

There are two main interpretations of the Al/Si ordering process in alkali feldspars:

(1) The Si/Al FULL ORDERING theory proposed by Laves (1952 a,b) and Goldsmith & Laves (1954 a,b) is generally accepted by most feldspar workers. At high temperatures, there is a complete disorder of Si and Al atoms and with cooling, the atoms order themselves until they are completely ordered at the lowest temperatures. Low albite and maximum microcline are interpreted as fully ordered and regarded as the most stable low temperature forms; partly ordered

intermediate albite and orthoclase are regarded as intermediate-temperature forms that are metastable at ordinary temperatures.

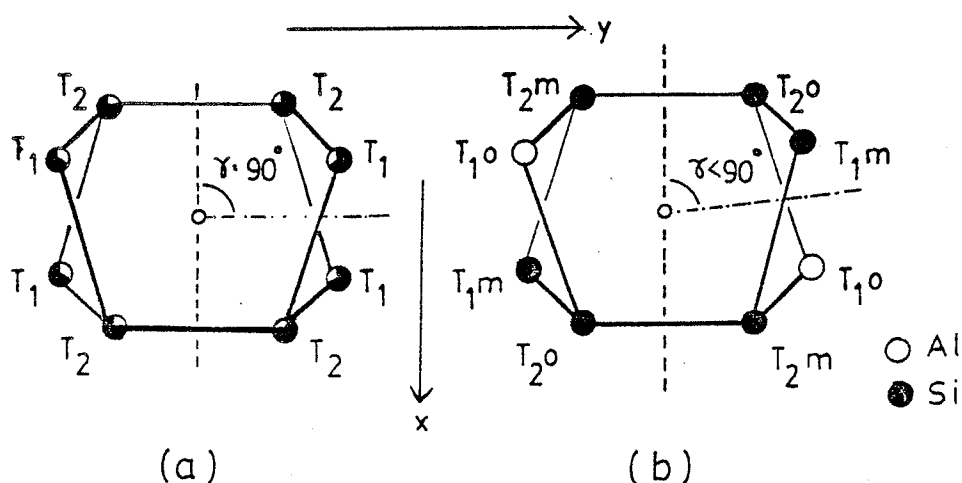


Figure 1-2. A projection onto (001) of the T atoms in the feldspar framework. The amount of Al/Si filling the T sites is diagrammatic. The small o is the center of symmetry. (a) Undistorted monoclinic feldspar structure when both T_1 and T_2 tetrahedra have the same occupancies of Al and Si, for example, orthoclase or sanidine. The dashed line is the trace of the mirror plane across which the corresponding T sites on the left side are related to the corresponding T sites on the right side. (b) Ordered feldspar structure in which Al occupies the T_{1o} site resulting in a distortion to triclinic symmetry, for example, maximum microcline and low albite. The dashed line is the trace of the pseudo-mirror plane. (after Putnis & McConnell, 1980; Ribbe, 1975).

(2) The BOND STRENGTH theory proposed by Ferguson (1960, 1979) which is based on Pauling's second rule or the electrostatic valency principle: in a stable structure, each

anion such as oxygen would be expected to received from all its neighbouring cations a total bond strength equal to its negative charge or valence of 2 (See for example Bloss, 1971). Upon slow cooling, the Si^{+4} and Al^{+3} ions in the high-temperature Al-Si disordered polymorphs tend to rearrange themselves to the extent that the bond strengths to the O^{2-} anions from the cations are ideal and the resultant structure is considered to be low-temperature form for that particular composition. According to this theory, largely ordered low albite and partly ordered orthoclase are considered to be the low temperature stable Na- and K-feldspars respectively, and largely ordered maximum microcline is considered to have formed from some type of Na-rich precursor such that it is observed as a stable low-temperature Na-poor K-feldspar.

Both theories agree with high albite ordering to low albite. Both structures are triclinic and the ordering only involves Al,Si migration, which is extremely sluggish. In addition, because Na^+ is small (as compared to K^+), the triclinic nature of albite is preserved upon cooling. Monoclinic albite (monalbite) has been produced in laboratory experiments at 1105°C (Prewitt et al., 1976) but it can exist only above that temperature. Upon cooling, it readily collapses to a triclinic (high albite) structure below 1105°C . Monalbite does not occur in nature.

As the K^+ cation is larger than the Na^+ cation, it

distends the framework and tends to make the feldspar structure monoclinic. Both theories agree that sanidine is a high temperature disordered monoclinic structure. The full ordering theory, however, implies that, as Si and Al proceed to order with cooling, their distribution will presently become asymmetric and the structure triclinic with two pairs of equivalent monoclinic T sites being split into four non-equivalent T sites (Putnis & McConnell, 1980) (Figure 1-2). Putnis & McConnell (1980) also state that on the basis of the large size of K^+ , the monoclinic K-feldspar should maintain a monoclinic structure upon cooling; this opinion conflicts with the full-ordering theory.

On the other hand, according to the bond strength theory, in a potassium-rich environment, a temperature-dependent series exists from high-temperature Al-Si disordered monoclinic sanidine to low-temperature partly ordered monoclinic orthoclase in which each oxygen receives an ideal oxygen bond strength of 2. In sanidine, the large K^+ ion distributes its bond strength symmetrically across (010), so that the resulting low temperature Al-Si distribution is also symmetrical and the structure monoclinic. This theory also indicates that there exists a low-temperature K-feldspar series that varies with increasing Na-feldspar: K-feldspar ratio in the original environment from monoclinic orthoclase through triclinic intermediate microclines to maximum microcline formed in a K-poor Na-rich environment. This series is

a consequence of the assumption that the triclinic nature of microcline was imposed upon it by an abundance of Na^+ ions randomly distributed in the K-feldspar structure (Ferguson, 1981) during the stage of Si/Al (partial) ordering.

(D) NATURE OF PRESENT STUDY

The primary purpose of this study is to establish a rapid procedure for properly characterizing K-feldspars for petrologic purposes. Specimens from a suite of granite rocks from Lac du Bonnet, Manitoba and another suite of granitic/pegmatitic rocks from Dryden, Northwestern Ontario were donated by Dr. Petr Černý, Department of Earth Sciences, University of Manitoba; K-feldspar analyses and detailed field and geochemical data were available. The techniques used in the present study may be summarized as follows:

(1) Crystallography as determined by single-crystal x-ray precession photography and powder diffractometry to give:

- (a) single K-feldspar component or multiple components
- (b) triclinicity of K-feldspars
- (c) twinned characteristics of K-feldspars
 - (i) untwinned
 - (ii) albite-twinned
 - (iii) pericline-twinned
 - (iv) albite- + pericline-twinned
 - (v) gradational

(d) presence or absence of albite phase

- (i) amount in K-feldspar
- (ii) untwinned
- (iii) albite-twinned
- (iv) pericline-twinned
- (v) albite- + pericline-twinned

(2) Chemical composition as determined by:

(a) electron microprobe analysis of single crystal
K-feldspars

(b) chemical analysis of K-feldspars

(c) whole rock analysis

(3) Thin section study to determine:

(a) presence/absence and nature of observable twinning in K-feldspars

(b) characteristics of K-feldspars and their perthitic albites

(c) nature of non-perthitic plagioclases and their relationship to the K-feldspars.

(E) GEOLOGICAL SETTING OF THE K-FELDSPARS
FROM THE TWO STUDY AREA: LAC DU BONNET,
MANITOBA AND DRYDEN, ONTARIO

The Dryden and Lac du Bonnet study areas are in the western Superior Province of the Canadian Precambrian Shield (Figure 1-3). The Lac du Bonnet area is part of the English River Subprovince (Figure 1-4), which is characterized by metasedimentary sequences, and gneissic and plutonic granitoid rocks (Breaks et al., 1978). The Dryden area straddles the boundary of the English River Subprovince and the Wabigoon Subprovince; the latter is made up of greenstone belts separated by abundant granitoid gneisses and granodiorite intrusions (Breaks et al., 1978) (Figure 1-4). Both the Lac du Bonnet and part of the Dryden study areas are in the southern plutonic domain, one of the two domains of the English River Subprovince (Figure 1-4), where they are generally metamorphosed to amphibolite facies (Breaks et al., 1978). Portions of the Dryden study area that are in the Wabigoon Subprovince are metamorphosed to greenschist facies with amphibolite and hornblende hornfels facies adjacent to batholithic intrusions (Ayres, 1978).

Although preliminary x-ray powder diffractograms by the author show little triclinicity variation in the K-feldspars (all maximum microclines) within the Lac du Bonnet granite, the fact that the area had been subjected to detailed geological and geochemical studies and that the

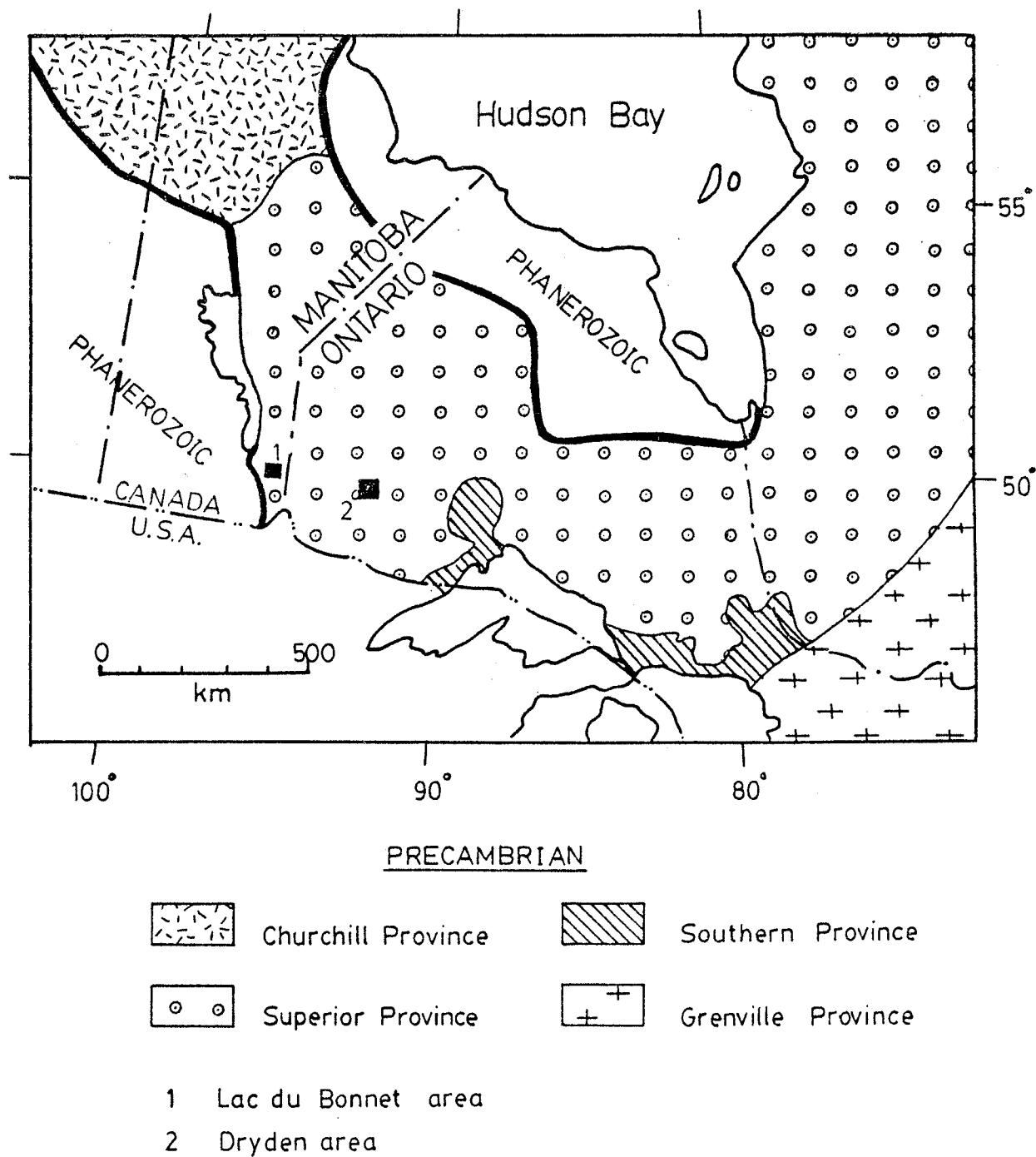


Figure 1-3. Location of the Lac du Bonnet and Dryden study areas in western Superior Province of the Precambrian Shield (after Cerný et al. (1981), McCrank et al. (1981)).

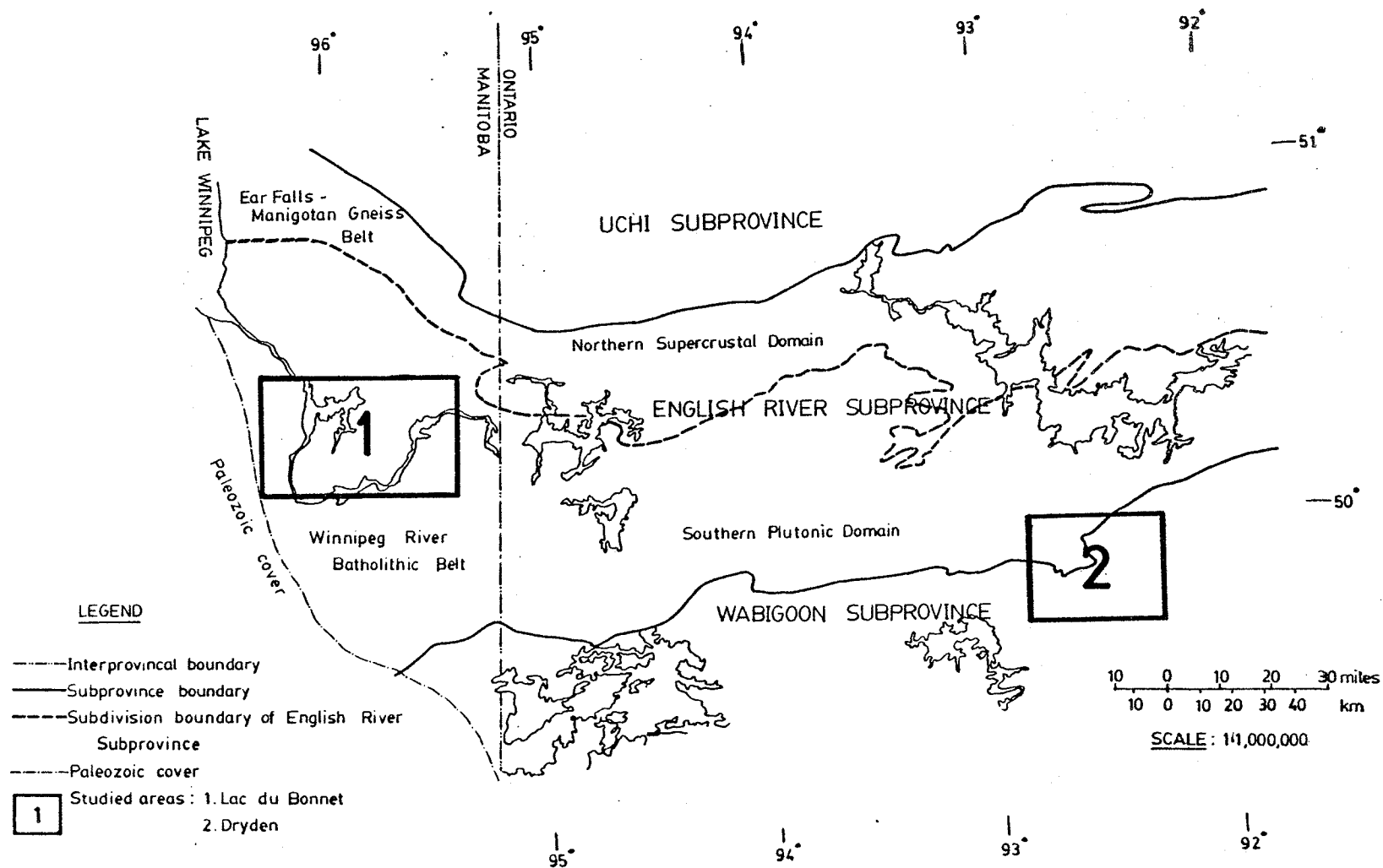


Figure 1-4. Two domains of the English River Subprovince in which the two study areas (Lac du Bonnet and Dryden) are located (after Černý et al. (1981), McCrank et al. (1981), Breaks et al. (1978)).

samples were immediately available, made it attractive to do detailed single crystal work for possible crystallographic variations. The Dryden pegmatitic K-feldspars were chosen because of their variable triclinicities reported by Ucakuwun (1981). A number of samples from the surrounding granites in the Dryden area were selected to provide K-feldspars for single crystal analysis to compare with those chosen from the pegmatites and the Lac du Bonnet granite. An adularia (Department of Earth Sciences, University of Manitoba, Mineralogy Museum Specimen no. 313-3) from Fierstal near Iegishan, Switzerland, was selected as a representative standard of a monoclinic K-feldspar.

(1) Descriptions of rock units and sources of specimens from the Lac du Bonnet area

Figure 1-5 shows the location of the specimens and their corresponding rock types. Intensive studies by Černý et al. (1981) document five major phases in the batholith. In order of decreasing relative ages, these are:

(a) Hornblende-biotite tonalite (specimen no. AEC-20) is a mesocratic equigranular gneissic rock. The sample studied is coarse-grained with abundant biotite and pink to white euhedral feldspars.

(b) Porphyritic hornblende-biotite granodiorite (specimen nos. SR-97, SR-148) is a grey mesocratic gneissic rock with quartz, biotite, feldspars, and abundant pink to white

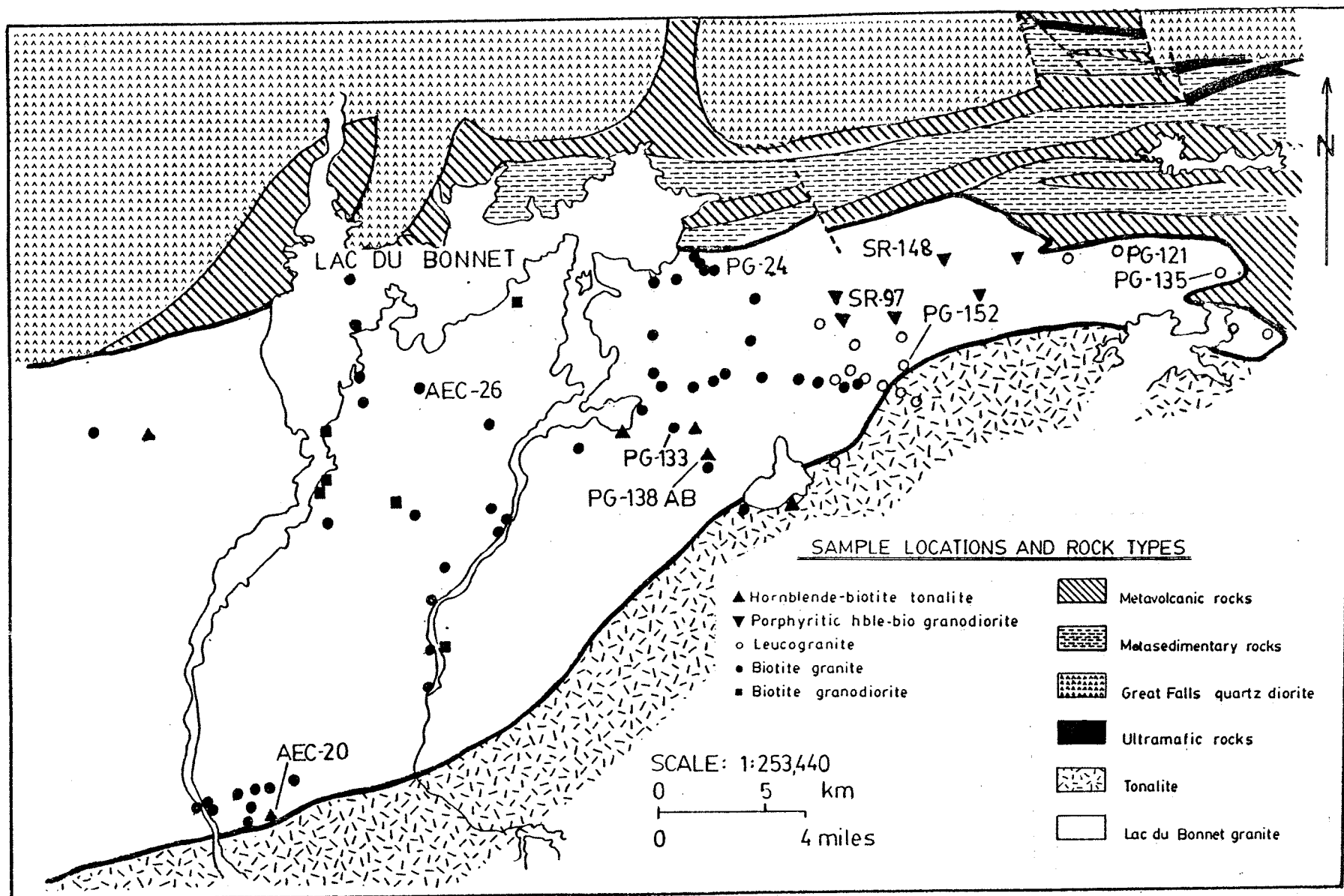


Figure 1-5. Geology of study area #1, Lac du Bonnet area: Distribution of rock types and sample locations (after Černý et al. (1981), McRitchie (1971)).

euohedral feldspar phenocrysts.

(c) Leucogranite (specimen nos. PG-121, PG-152, PG-135) is a medium-to coarse-grained rock with quartz, biotite, feldspars and a subordinate amount of pink to white feldspar phenocrysts.

(d) Biotite granite (specimen nos. PG-24, AEC-26, PG-133) is largely rusty pink, equigranular, fine to medium-grained and is composed of quartz, biotite and feldspars with an occasional feldspar phenocryst.

(e) Biotite granodiorite is a fine-grained porphyritic mesocratic rock and is composed of quartz, biotite, plagioclase, minor amount of hornblende and abundant K-feldspar phenocrysts. No specimens from this rock unit were studied by the author.

(2) Description of rock units and source of specimens from the Dryden area

(a) Granitoid rocks

The granitoid rocks are divided into four units by Ucauwun (1981) (Figure 1-6):

(i) Biotite ± hornblende quartz diorite rocks (specimen nos. SG-01, HG-01), from which the analyzed K-feldspars were taken, are weakly foliated and coarse-grained with small amounts of quartz and biotite and abundant pinkish blocky feldspars.

(ii) Biotite granite batholith (specimen no.

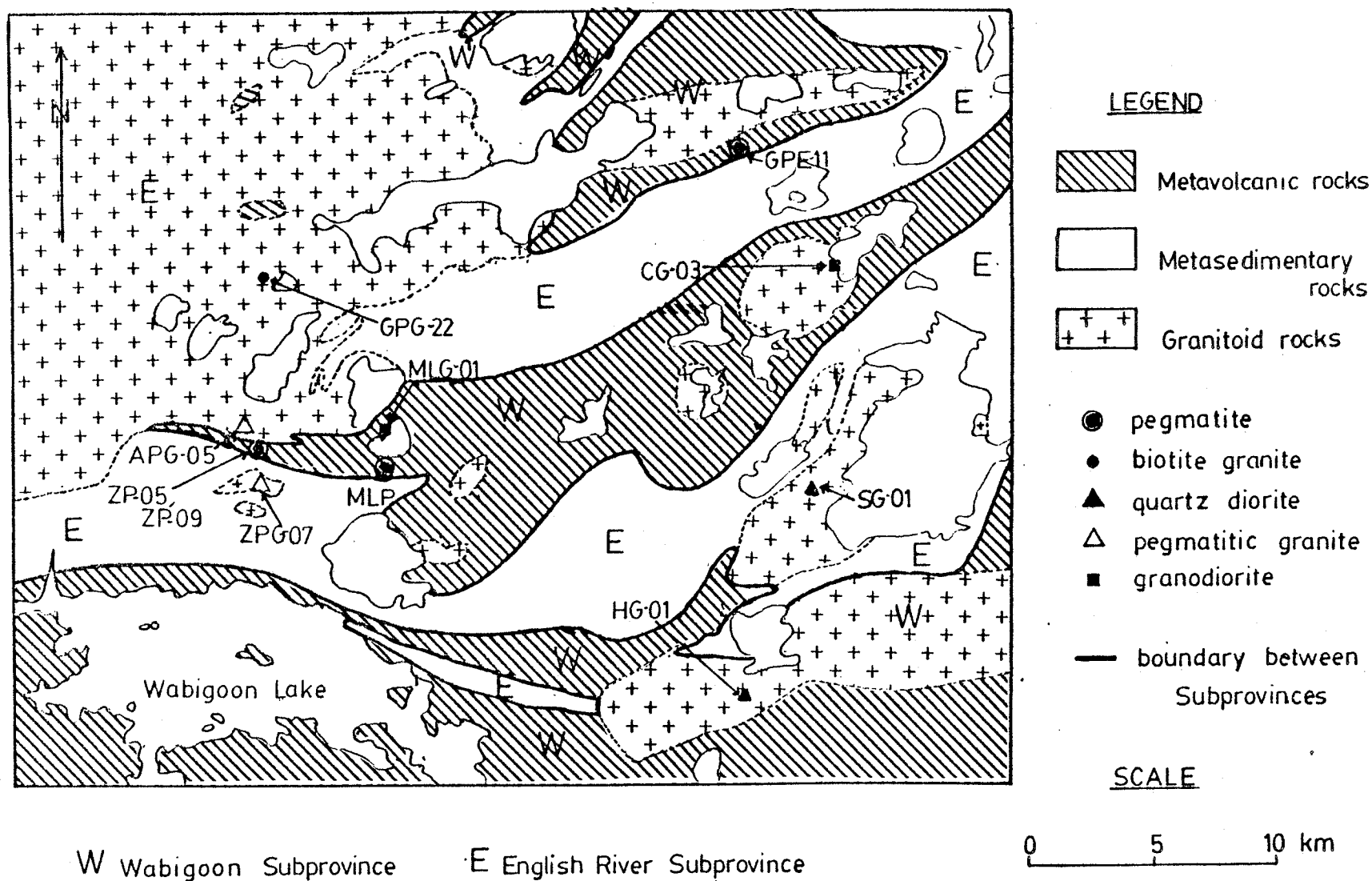


Figure 1-6. Geology of study area #2, Dryden area: Distribution of rock types and sample locations (after Ucakuwun, 1981).

GPG-22) with granites of variable properties; the sample studied is from an equigranular, light grey, coarse-grained rock with biotite, quartz and feldspars.

(iii) Discrete biotite granodiorite plutons (specimen no. CG-03, MLG-01) where the K-feldspars studied are from medium- to coarse-grained rocks with blocky feldspar crystals and subordinate amounts of quartz, biotite and epidote.

(iv) Leucocratic pegmatitic granites (specimen nos. APG-05, ZPG-07). The samples studied are from rocks that are creamy white with abundant feldspars and quartz, and a subordinate amount of biotite.

(b) Pegmatites

Three pegmatites in this study area were studied by Ucakuwun (1981):

(i) The Zealand pegmatite (specimen nos. ZP-05, ZP-09) has quartz, blocky K-feldspar and saccharoidal albite as the major constituents, with accessory garnet, beryl, tourmaline and apatite (Table 1-2).

(ii) The Mavis Lake pegmatite dykes (specimen nos. MLP/NZ 01, MLP/NZ 02, MLP/NZ 05, MLP/NZ 23, MLP/NZ 24, MLP/NZ 30, MLP/NZ 42, MLP/NZ 47, MLP/SZ 06, MLP/SZ 10) are divided into two zones: Mavis Lake North Zone (MLP/NZ) and Mavis Lake South Zone (MLP/SZ). The mineral assemblages of both zones are irregularly distributed in terms of

Table 1-2. Minerals identified in the three Dryden area pegmatites discussed in the text (after Ucakuwun, 1981).

MINERAL	PEGMATITE			
	ZEALAND	MAVIS LAKE		TOT LAKE
		NORTH ZONE	SOUTH ZONE	
QUARTZ	x	x	x	x
K-FELDSPAR	x	x	x	x
ALBITE	x	x	x	x
SPODUMENE	-	x	x	x
MUSCOVITE	-	x	x	x
TOURMALINE	x	x	x	x
BERYL	x	x	-	x
GARNET	x	-	-	x
POLLUCITE	-	-	-	x
HOLMQUISTITE	-	x	x	x
COLUMBITE-TANTALITE	-	x	-	x
APATITE	x	x	x	x
SPHALERITE	-	-	-	x

paragenesis, grain size and location. Quartz, blocky grey to pink K-feldspar, spodumene, albite and secondary muscovite are the major constituents (Table 1-2). Preliminary data showed a wide range of triclinicities in the K-feldspars, and ten specimens (8 from NZ and 2 from SZ) were studied by the present author.

(iii) The Tot Lake pegmatite (specimen no. GPE-11) has quartz, spodumene, K-feldspar, albite and primary muscovite as the major constituents (Table 1-2).

CHAPTER II. X-RAY DIFFRACTION: PROCEDURES

(A) INTRODUCTION

The bulk of this chapter is devoted to the single crystal precession method because of its importance in deriving the type of twinning and types of intergrowth characteristics that are not recorded by other x-ray methods. The precession method is used by only a few mineralogists as compared to powder x-ray methods. For the present investigation, a procedure for single crystal precession photography was established, and a step-by-step procedure for using precession photography was designed for use by interested geologists with little background in x-ray methods.

It was found desirable to take Gandolfi photos of the same single crystals used for the precession photos. The Gandolfi method is a modification of the more common Debye-Scherrer powder camera. X-ray powder diffractometry of powdered samples is widely used to characterize K-feldspars and the data in Chapter III are used to compare the results with those of single crystal precession and Gandolfi photos.

(B) SEPARATION OF K-FELDSPARS

Separation of K-feldspars from other minerals in the coarse-grained pegmatitic specimens was done manually under a binocular microscope (Ucakuwun, 1981). For the finer-

grained specimens of the granites, a different method was used:

- (1) A rock was crushed in an automatic crusher and then ground in a steel percussion mortar (also known as "shatter-box") for 10 seconds or less.
- (2) The resulting grains, which range in size from very fine powder to pebble-size, were sieved so that grains of 0.5ϕ (0.71 mm), that is, medium- to coarse-sand size, were collected for the steps discussed below.
- (3) With the selected grains thinly spread out along the bottom of a shallow plastic dish, the dish was placed inside a covered plastic beaker (Figure 2-1) that was half-full of hydrofluoric acid.
- (4) After the grains were etched by the hydrofluoric acid for 15 minutes, they were put into a sodium cobaltinitrite solution (1 gram of $\text{Na}_3\text{Co}(\text{NO}_2)_6$ in 4 ml of distilled water (Van der Plas, 1966)) for one minute.
- (5) The solution was rinsed off with water until clear and the grains were set aside to dry.
- (6) The K-feldspars could then be manually separated from other grains under the binocular microscope by the fairly strong yellow stain on the surface of the K-feldspars.
- (7) Some samples needed to be stained again when the K-feldspars had not been stained enough to distinguish them from the other minerals.

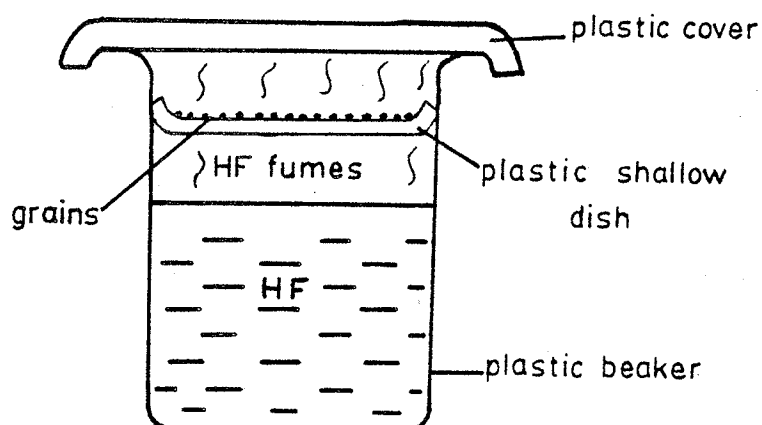


Figure 2-1. Experimental set-up for the staining technique as described in text.

This method was recommended by Petr Černý (personal communication) although it has been previously proposed by Kaneko (1974). Separation of K-feldspars by heavy liquids is used as a standard procedure by many feldspar workers but the staining technique described above is much more convenient and less time consuming.

The Lac du Bonnet and Dryden granitic K-feldspar crystals chosen for single crystal x-ray work were subhedral and colourless, whereas the pegmatitic K-feldspars were usually euhedral and cloudy white. All the crystals chosen were about 0.5 mm in size.

(C) PRECESSION PHOTOGRAPHY

(1) Introduction

Single crystal precession method was used here because it gave detailed information about the crystallographic variations in K-feldspars including their twinning and intergrowth characteristics. This method is described in detail in such works as Nuffield (1966), Buerger (1964), Azaroff (1968) or Henry et al. (1960).

(2) Selection and mounting of crystal

(a) Under a binocular microscope, a crystal about 0.5 mm long showing two well-developed cleavages $\sim 90^\circ$ to each other (Figure 2-2) is selected. Larger crystals produce large spots whose centres may be difficult to measure precisely. Fragments with poorly developed cleavage faces make orientation very difficult and sometimes impossible to do.

(b) Under polarized light on a petrographic microscope, the crystallographic orientation of the crystal is determined by observing the extinction angles on the two prominent cleavages. The extinction angles on the two cleavages for the principal alkali feldspars are listed in Table 2-1.

(c) The crystal is mounted such that the rotational axis is along y^* and the x-axis is parallel to the x-ray beam. The crystal is mounted on a glass rod using vaseline, such that the (010) face is normal to the glass rod, the

(001) face is parallel to one of the rockers (Figure 2-3), and the x-axis is parallel to the other rocker.

Table 2-1. Extinction angles on cleavage planes of alkali feldspars (from Kerr, 1959).

MINERAL	EXTINCTION ANGLES ON:	
	(001)	(010)
MAXIMUM MICROCLINE	15°	5°
ORTHOCLASE	0°	5-12°
SANIDINE	0°	5°
LOW ALBITE	3-5°	15-20°

(3) Orientation procedures

(a) The crystal is oriented such that the rotational axis (the presumed reciprocal axis, y^*) is exactly horizontal and the precession axis (the presumed direct axis, x) is exactly parallel to the x-ray beam. These required orientations are made by three instrumental angular adjustments:

(i) drum reading on the instrument that controls the principal vertical axis on the film;

(ii) vertical rocker of the goniometer head which controls the angular deviation of the approximately horizontal reciprocal axis from the true horizontal line;

(iii) horizontal rocker of the goniometer head which controls the fore and aft orientation of the reciprocal axis in the horizontal plane.

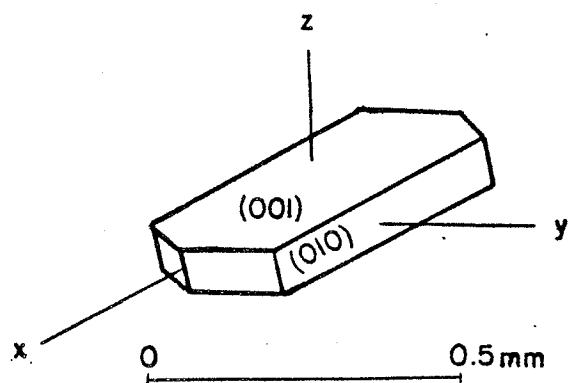


Figure 2-2. Ideal crystal size (0.5 mm) and shape (two good cleavages (010) and (001)) (after Deer, Howie, and Zussman, 1962).

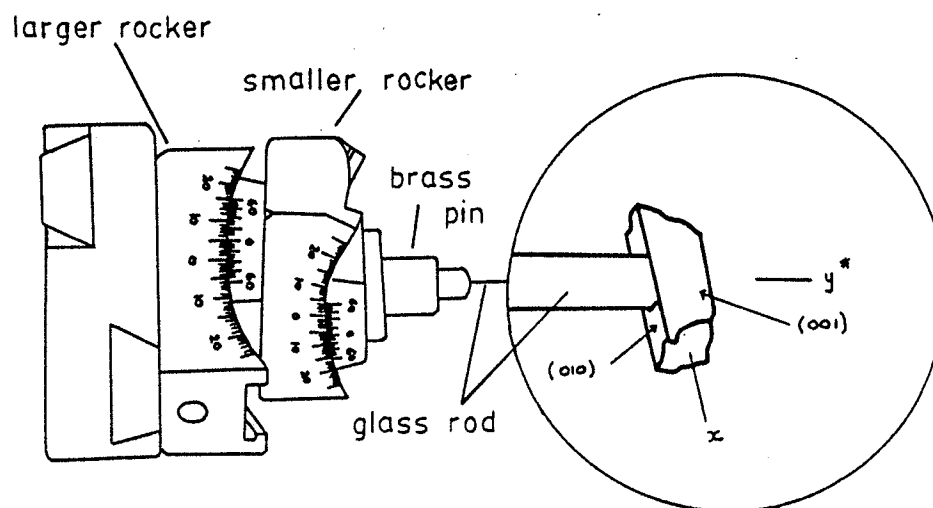


Figure 2-3. Goniometer head with a crystal viewed through a collimator lens (the crystal is greatly enlarged here). The (010) face is perpendicular to the glass rod and the (001) face is parallel to the larger rocker. The x- axis is parallel to the smaller rocker.

(b) A Polaroid camera (Land diffraction cassette #57-2 (XR-7) with 4" x 5" Land Polaroid film type 57 high speed (ASA 3000) is preferred because of the faster time (commonly) exposed to the unfiltered x-rays for 5 to 10 minutes) compared with a standard ordinary x-ray film (1 hour) such as Kodak no-screen x-ray film. The preferred x-radiation is usually short wavelength x-radiation such as MoK.

(c) Initially, the first picture will normally produce two principal axes in two positions that are approximately horizontal and vertical (i.e. Figure 2-5, p. 31). Identification of the two principal axes is determined by measuring the distance between pairs of two corresponding reflections across the centre of the film, i.e. $2p^*$, and halving it to give p^* (Figure 2-4) and the d of the reflections are derived and compared to the closest computed d value of an alkali feldspar listed in Table 2-2. The axes of the precession photos shown later in this chapter were identified by this means.

(d) Any axes may be identified by the procedure described in (c), but a set of standard precession photos, used for comparison purposes, described in the end of this chapter, makes this identification by measurement unnecessary. If comparisons do not show any similarities to the photos, that is, the rotational axis is not identified as y^* , z^* , or x^* , the crystal is best discarded. When the rotational axis

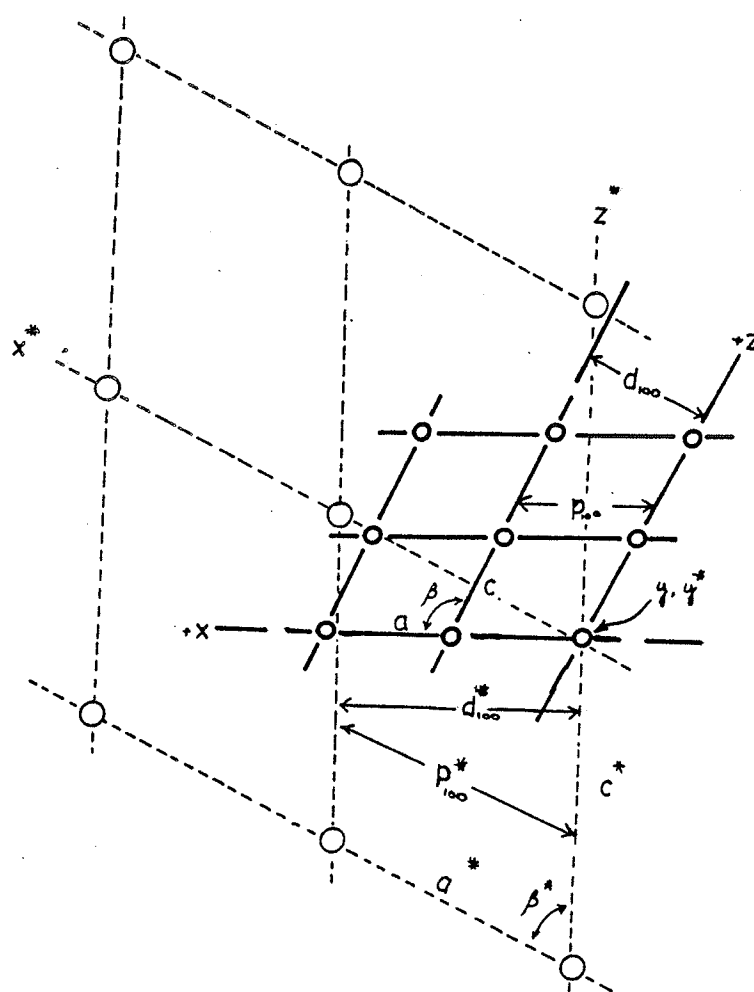


Figure 2-4. Example of monoclinic lattices projected along the y - and y^* -axes showing the relationship between the direct (space) lattice (solid lines) and the reciprocal lattice (broken lines) where $p_{100}^* \propto 1/d_{100}$ and $p_{100} \propto 1/d_{100}^*$ (the scales are arbitrary) (after Nuffield, (1966)). In this investigation, where $\text{MoK}\alpha$ radiation with wave-length $\lambda = 0.711 \text{ \AA}$ was used and $F = 60 \text{ mm}$, the relationship is $p_{hkl}^* = \lambda F / d_{hkl} = 42.66 / d_{hkl}$ where p^* is the reciprocal lattice distance on the film in mm.

Table 2-2. Intensity, $d(\text{\AA})$ and $2p^*$ (mm) values and indices hkl of the different reflections for the relevant principal axes of K-feldspar and albite as discussed later in the chapter. The majority of the d values were obtained from Borg & Smith (1969) and the rest including $2p^*$ were calculated by the author. The intensities were estimated from the precession photographs and for these the designations are v=very, w=weak, m=moderate, s=strong.

RECIPROCAL AXIS	ORTHOCLASE-MICROCLINE				LOW ALBITE		
	hkl	Intensity	$d, \text{\AA}$	$2p^*, \text{mm}$	Intensity	$d, \text{\AA}$	$2p^*, \text{mm}$
$x^* =$ [100] [*]	200	VW	3.850	22.2	VW	3.620	23.6
	400	M	1.925	44.3	W	1.820	46.9
	600	VW	1.283	66.5	VW	1.213	70.5
$y^* =$ [010] [*]	040	VS	3.238	26.3	VS	3.188	26.8
	060	S	2.159	39.5	W	2.125	40.1
	080	W	1.619	52.7	VW	1.594	53.5
	0100	VW	1.295	65.9	VW	1.275	64.0
$z^* =$ [001] [*]	002	VS	3.247	26.3	VS	3.194	26.7
	003	VW	2.165	39.4	VW	2.129	40.1
	004	VW	1.623	52.6	VW	1.597	53.4
	005	VW	1.299	65.8	VW	1.278	66.8
[101] [*]	$\bar{2}02$	VS	3.286	26.0	VS	3.214	26.6
	$\bar{4}04$	VW	1.643	51.9	VW	1.607	53.1
[102] [*]	$\bar{2}01$	VS	4.213	20.3	VS	4.027	21.2
	$\bar{4}02$	VW	2.106	40.5	VW	2.014	42.4
	$\bar{6}03$	VW	1.404	60.9	VW	1.342	63.6
[203] [*]	$\bar{4}03$	VW	1.910	44.7	M	1.849	46.1
	$\bar{6}04$	VW	1.409	60.6	VW	1.352	63.1

is identified as the y^* - axis, a vertical reciprocal axis, presumably the z^* - axis, is recorded. The angle between y^* - axis and the vertical axis is measured and if the angle is between 92° and 94° (i.e. $90^\circ \pm 2-4^\circ$), the crystal is identified as a plagioclase (usually albite) and is discarded if it is not being studied. If the measured angle is between 90° and 92° (i.e. $90^\circ \pm 2^\circ$), the crystal is a K-feldspar and the vertical axis must be identified. The axis is usually z^* but if it is not, then the crystal is rotated around the drum axis every 15° in order to locate the z^* -axis. Another crystal can be quickly chosen and remounted on the goniometer head within a few minutes after discarding the previous crystal.

(e) Orienting the face (001) instead of (010) normal to the glass rod gives a picture oriented 90° to the required orientation. To correct this, the goniometer head is removed from the camera and by checking the photo the crystal is carefully turned 90° around the x-axis to its original position under the binocular microscope.

(f) Initially, the y^* -axis of the crystal will not be exactly horizontal. There are a series of steps as discussed below that are necessary to bring the y^* -axis in line with the rotational axis of the instrument and the z^* -axis is along the plane of the film such that the crystal is precessing around the x-axis.

(i) Figure 2-5(a) shows the initial orientation.

The rotational axis, that is 12° off the true horizontal line, is identified as the y^* -axis. However, the so-called vertical principal axis is too far off to be identified properly. The crystal is then reoriented so that the y^* -axis is exactly horizontal. This is done by measuring the correction to be made on the vertical rocker Δr_v between the y^* -axis and the horizontal line (parallel to the border of the photo as the camera is exactly perpendicular to the x-ray beam) through the centre of the photo with a measuring device.

(ii) Figure 2-5(b) shows that, in comparison to Figure 2-5(a), the crystal is closer to the horizontal line and as well as to the vertical line. The vertical principal axis was determined to be z^* . At this stage, all three instrumental angular adjustments are used. The y^* -axis is 4.0° off the true horizontal line, that is, $\Delta r_v = 4.0^\circ$. Both the horizontal rocker, Δr_h , and the drum, Δd , are measured and plotted on the Buerger error chart in Figure 2-6. For example, for the correction on the drum reading, the difference between the intersection of y^* and z^* axes to the outermost streak on one side, z_2 , and to the other side, z_1 , is measured to be 7 mm which means an angular correction (plotted from Figure 2-6) of 1.7° . The angular correction for the horizontal rocker is very similar to that for the drum and is found to be 9° .

(iii) Generally speaking, if there are two or three large instrumental errors, it is difficult to

Figure 2-5. Precession setting photographs of a K-feldspar crystal for rotation about y^* to illustrate the procedure for orienting the crystal to the required position as described in text. The conditions for the photographs are: $F=60$ mm, no screen, $\mu=10^\circ$, and unfiltered Mo radiation ($\text{MoK}\alpha+\beta$). Designation below: d =drum reading, r_h =horizontal rocker, r_v =vertical rocker; all are in degrees.

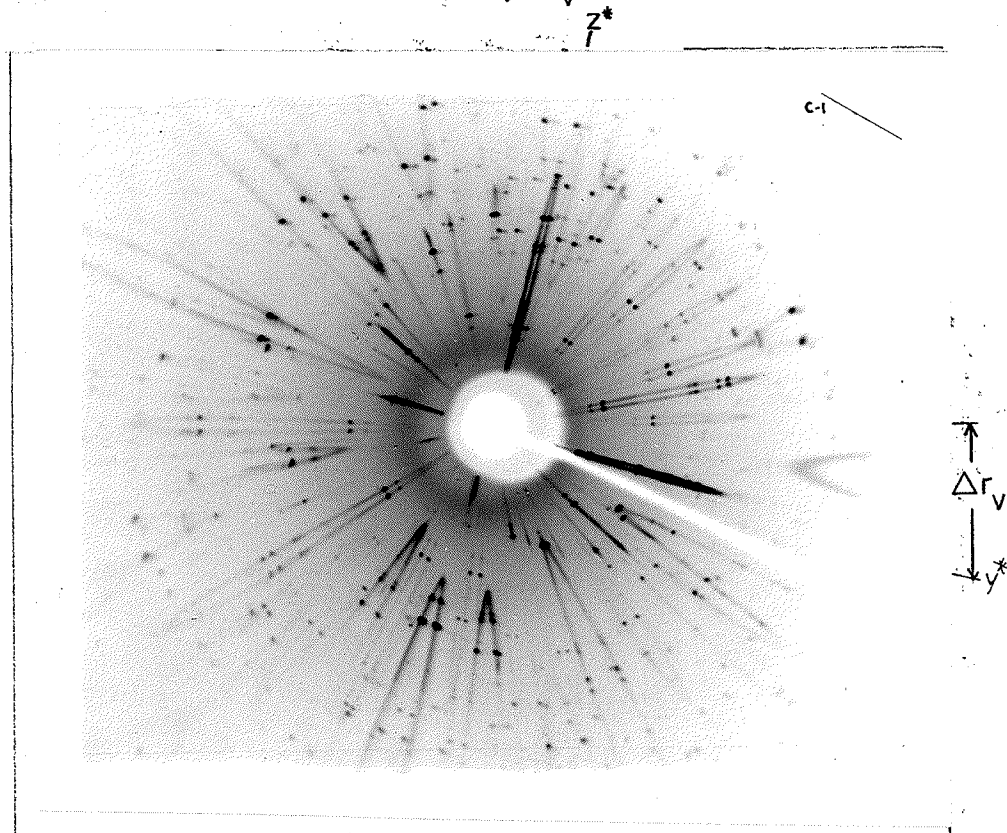


Figure 2-5(a) Setting photo I. $d=271.2^\circ$, $r_h=0.0^\circ$, $r_v=0.0^\circ$. Correction: $\Delta r_v=12.0^\circ$.

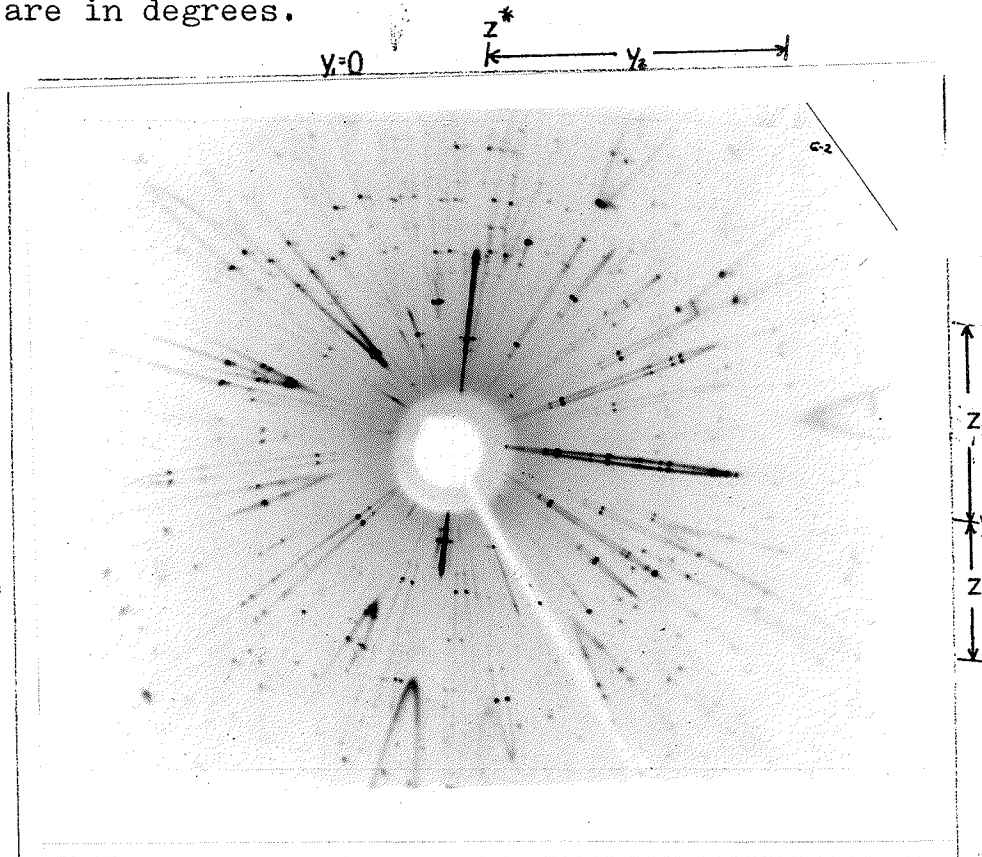
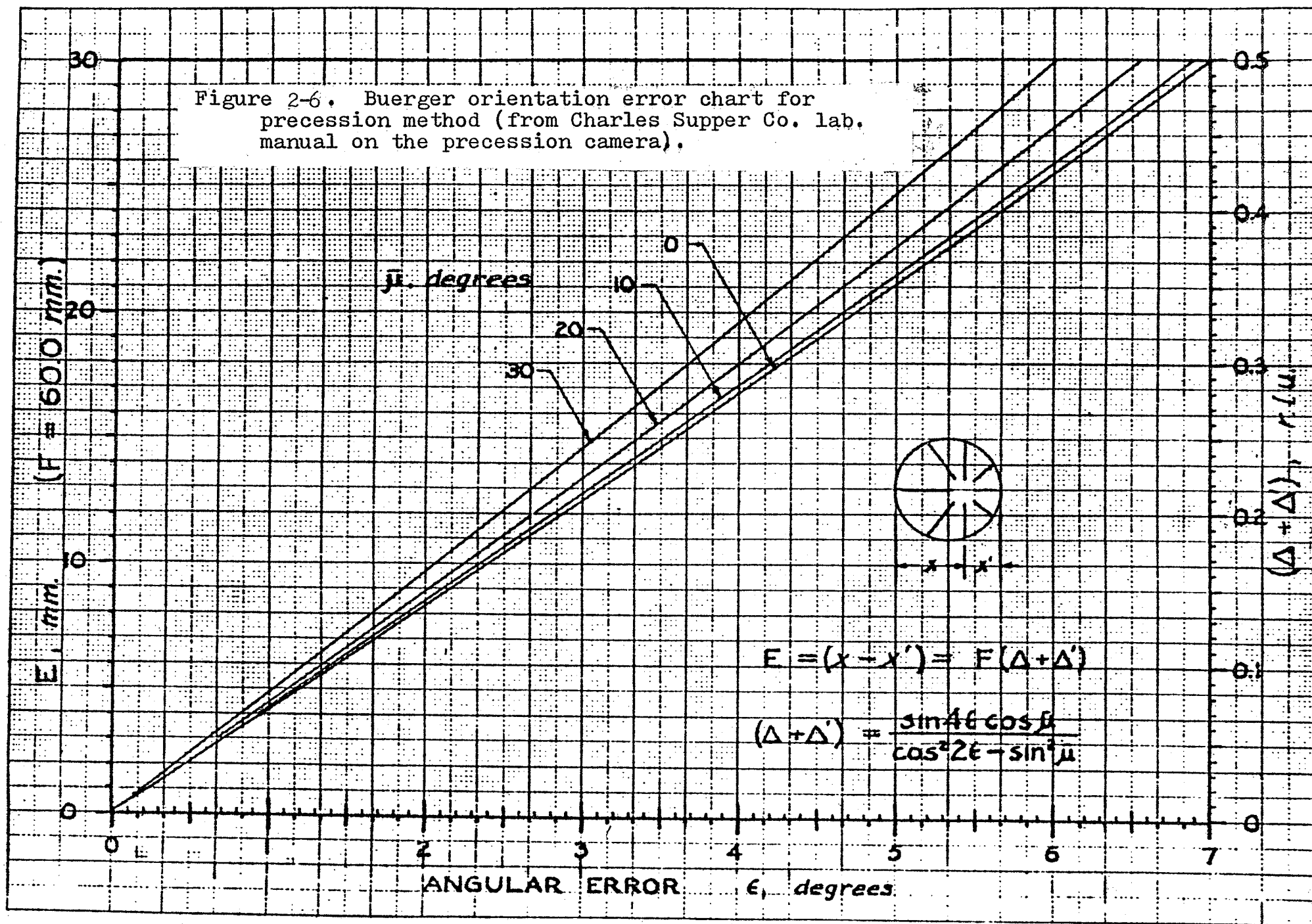


Figure 2-5(b) Setting photo II. $d=271.2^\circ$, $r_h=0.0^\circ$, $r_v=12.0^\circ$. Correction: $\Delta r_v=4.0^\circ$; $E_z=z_2-z_1=25-18=7$ mm (from Buerger chart $\Delta d=1.7^\circ$); $E_y=y_2-y_1=37-0=37$ mm (from Buerger chart $\Delta r_h=9.0^\circ$).

Figure 2-6. Buerger orientation error chart for precession method (from Charles Supper Co. lab. manual on the precession camera).



achieve perfect orientation with only one set of corrections. The writer found that it was more satisfactory to do each correction as a separate step. Figure 2-5(c) shows that the crystal is closer to the required orientation. The vertical rocker is now corrected and the other two instrumental angular adjustments (Δr_h and Δd) have small corrections to be made. Because of this, the two corrections were made simultaneously in the same fashion as described in 6(ii).

(iv) The crystal in Figure 2-5(d) is now exactly oriented as required, with y^* horizontal and z^* vertical. This means that the crystal is precessing about the direct axis x . The crystal is ready for the zero-level photo as described in (g).

(g) At this stage, it is necessary to make several instrumental changes in order to take the type of photo, namely a zero-level precession photo, that will provide the maximum amount of information about the structural characteristics of the crystal in question. In this case, the zero-level photo will be one about x that will record the $0kl$ reflections.

(4) Other required orientation: precessing around z-axis

To precess around the z axis, (i.e. to record the $hk0$ reflections), the crystal is rotated through the β angle of the K-feldspar crystal of 116° on the drum (as shown later in Figure 2-11). There are two possible orientations after

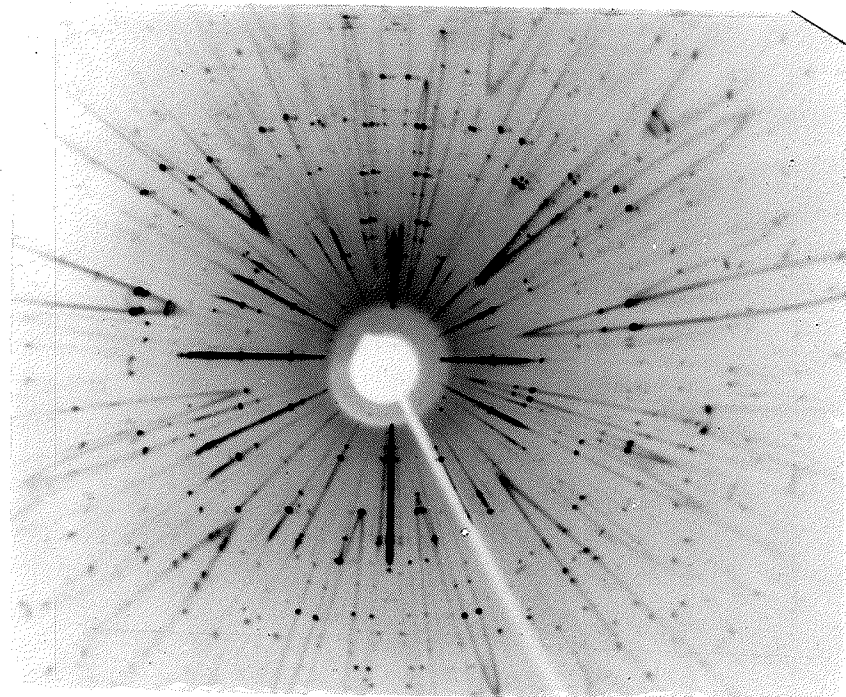
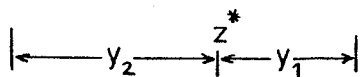


Figure 2-5(c) Setting photo III. $d=269.5^\circ$,
 $r_h=9.0^\circ$, $r_v=16.0^\circ$. Correction: $E_z =$
 $z_2 - z_1 = 27 - 17 = 10 \text{ mm } (\Delta d = 2.3^\circ)$; $E_y = y_2 - y_1 =$
 $28 - 18 = 10 \text{ mm } (\Delta r_h = 2.3^\circ)$.

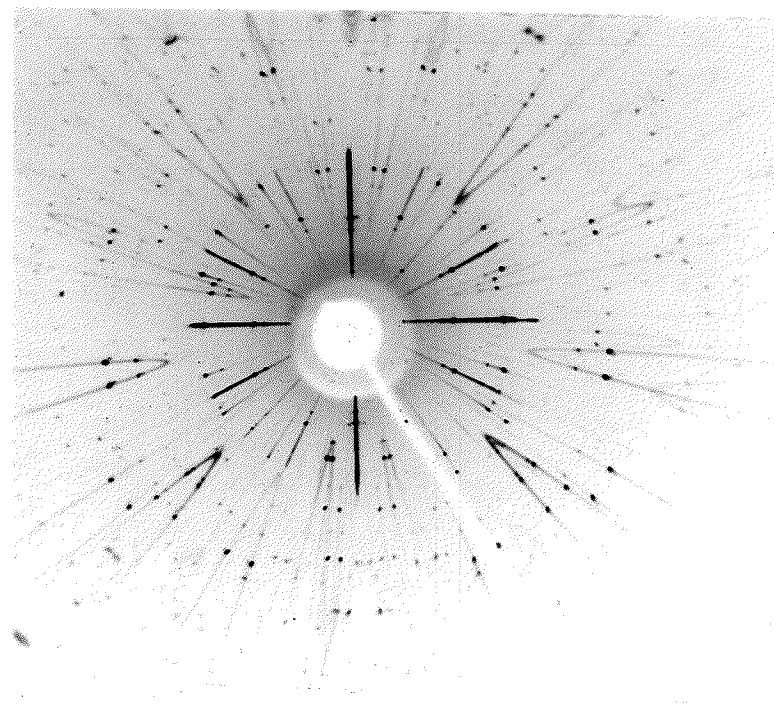


Figure 2-5(d) Setting photo IV. $d=271.8^\circ$,
 $r_h=6.7^\circ$, $r_v=16.0^\circ$.

rotating the drum through 116° . If the rotation is in one sense (say clockwise) then the required z-axis will be oriented parallel to the x-ray beam. However, if the rotation is in the opposite sense (counter-clockwise), then the axis $[203]$ happens to be nearly parallel to the x-ray beam as shown in Figure 2-7 and later in Figure 2-11. As the orientation photo is readily recognized in the setting picture with single or double V-shaped streaks of $[\bar{3}02]^*$ axis as seen in Figure 2-10 (p. 58), there is no need to take a zero-level photo to distinguish the $y^* [\bar{3}02]^*$ plane from the $y^* x^*$ plane.

(5) Other possible orientations

(a) It is possible to precess initially around the z-axis (by mistake) rather than the x-axis (this happened to the author at least 3 times). This resulted from mistakenly orienting the wrong rocker, the one not parallel to x, along the x-ray beam with the result that an axis roughly perpendicular to x was parallel to the beam. In some circumstances, this axis could be sufficiently close to z (despite $\beta = 116^\circ$) that the z-axis was actually the roughly oriented precession axis. If this is the case, then rotating the crystal 64° ($180^\circ - \beta$) one way results in x being the precession axis and the other way, because of geometry of the crystal, $[101]$ being the precession axis (Figure 2-8 and shown later in Figure 2-11). Care must be made in identifying setting and

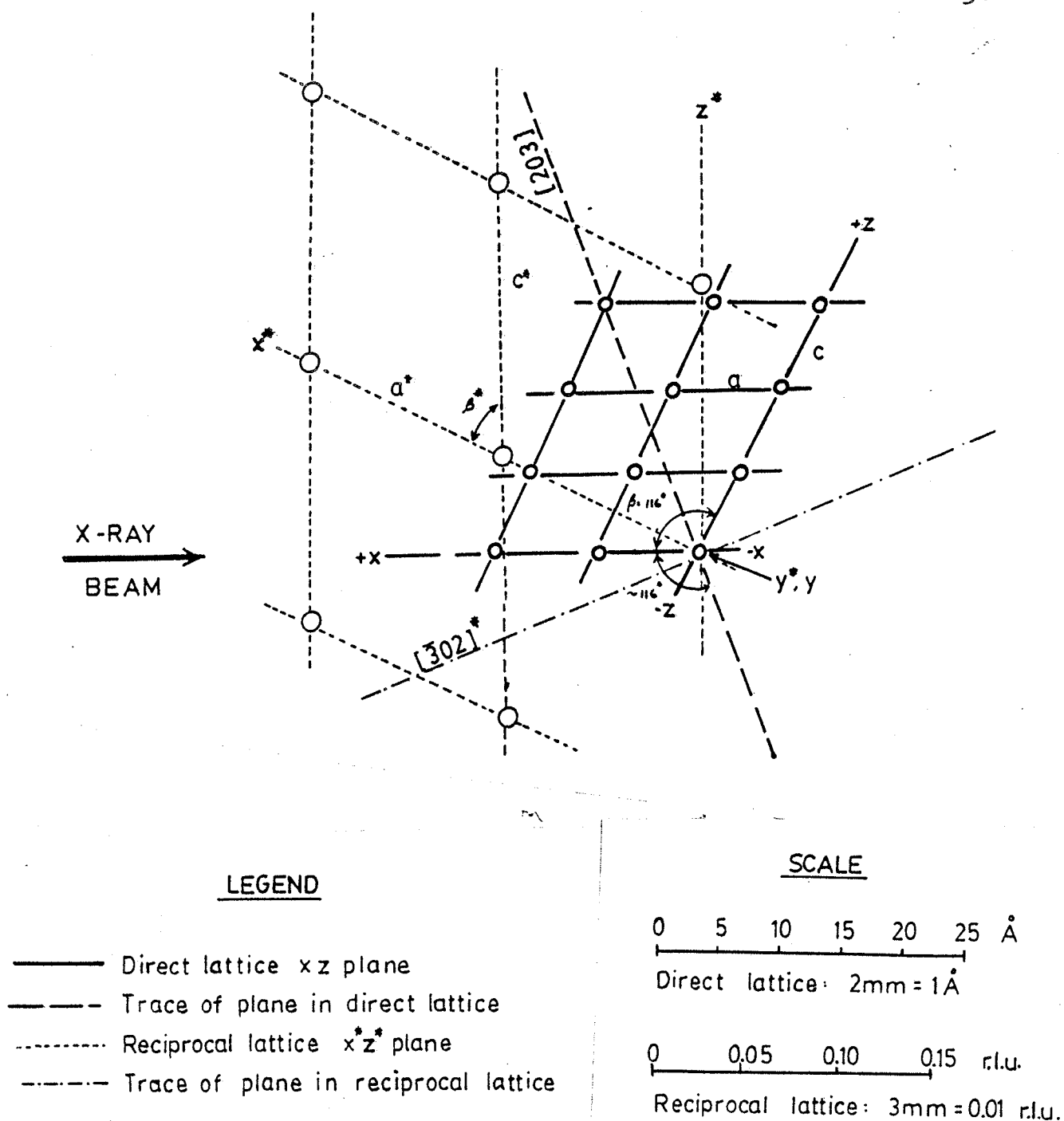


Figure 2-7. Direct lattice (solid lines) and reciprocal lattice (broken lines) projection along the y/y^* axis showing the xz and x^*z^* planes to illustrate the two axes making approximately 116° to x -axis. The x -axis of the crystal is parallel to the x -ray beam. Rotating approximately 116° in the one direction gives the direct axis $[203]$ whose normal gives $[\bar{3}02]^*$ in reciprocal space. Rotating 116° ($=\beta$) in the other direction gives the required z -axis.

zero-level photos taken around the $[101]$ axis as they are very similar to the corresponding photos around the x-axis in both setting and zero-level pictures (Figure 2-8). To differentiate the zero-level photos about the x-axis and the $[101]$ axis, note that the former shows reflections in a square pattern whereas the latter shows a diamond-shaped pattern.

(b) Another mistaken orientation that may occur is illustrated in Figure 2-9. If the crystal is exactly parallel to both rockers but the wrong rocker is parallel to the x-ray beam, that is, the (001) face of the crystal is perpendicular to the x-ray beam, the geometry is such that the $[102]$ axis is obtained with the vertical axis on the photo being $[\bar{2}01]^*$ (Figure 2-11). The setting photo for precession around $[102]$ axis is very similar to that for the x-axis, but the zero-level photo around $[102]$ shows a distinctly different arrangement of reflections more similar to the zero-level around the z-axis than that of the x-axis. When this is recognized, the crystal is rotated 90° so that the x-axis is exactly parallel to the x-ray beam.

(6) Standard setting and zero-level photos for the orientation procedures

The setting and zero-level photos shown in Figure 2-10 constitute a fundamental part of the orientation procedures, and are summarized in Table 2-3. Repetition is avoided when two or more photos of different kinds of crystal

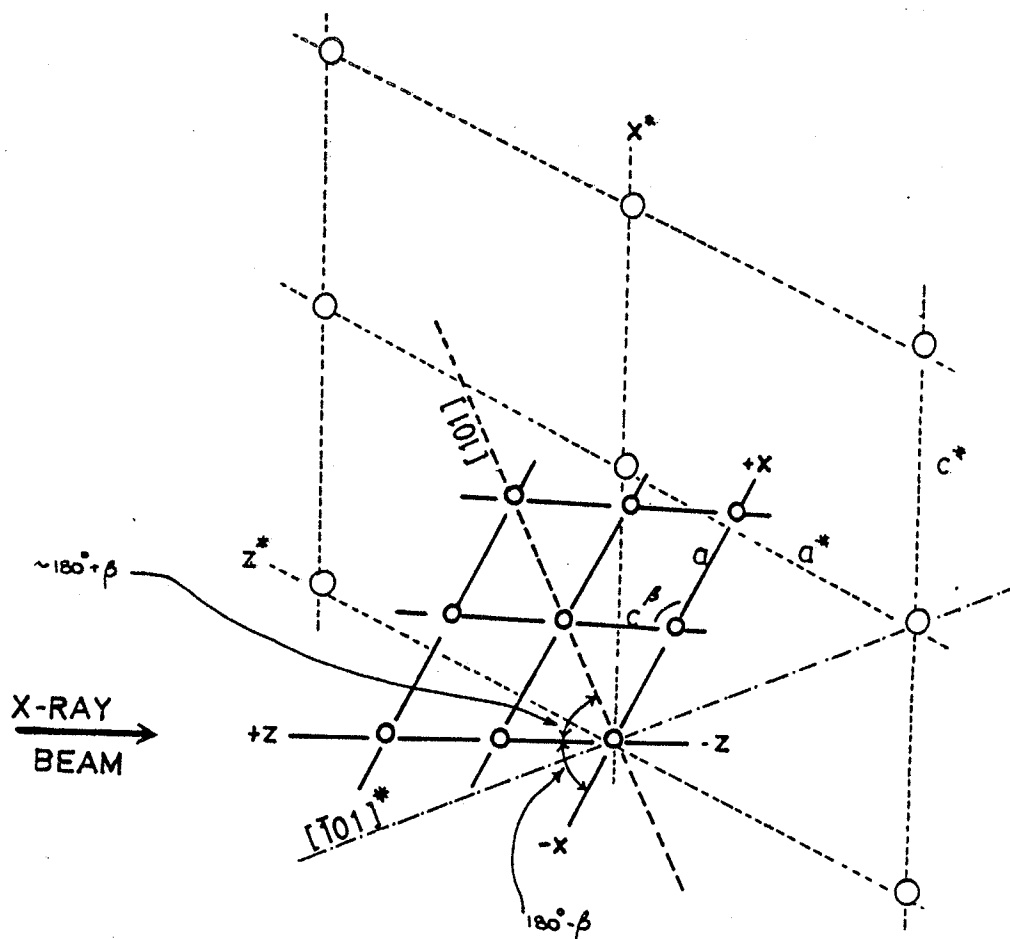


Figure 2-8 . Similar set-up as Figure 2-7 except that the x-ray beam is parallel to the z-axis. Rotating $(180^\circ - \beta)$ results in $[101]$ axis which means that $[101]^*$ axis of the reciprocal lattice is recorded. Rotating $180^\circ - \beta$ in the other direction gives the required x-axis. Scale of drawing same as Figure 2-7.

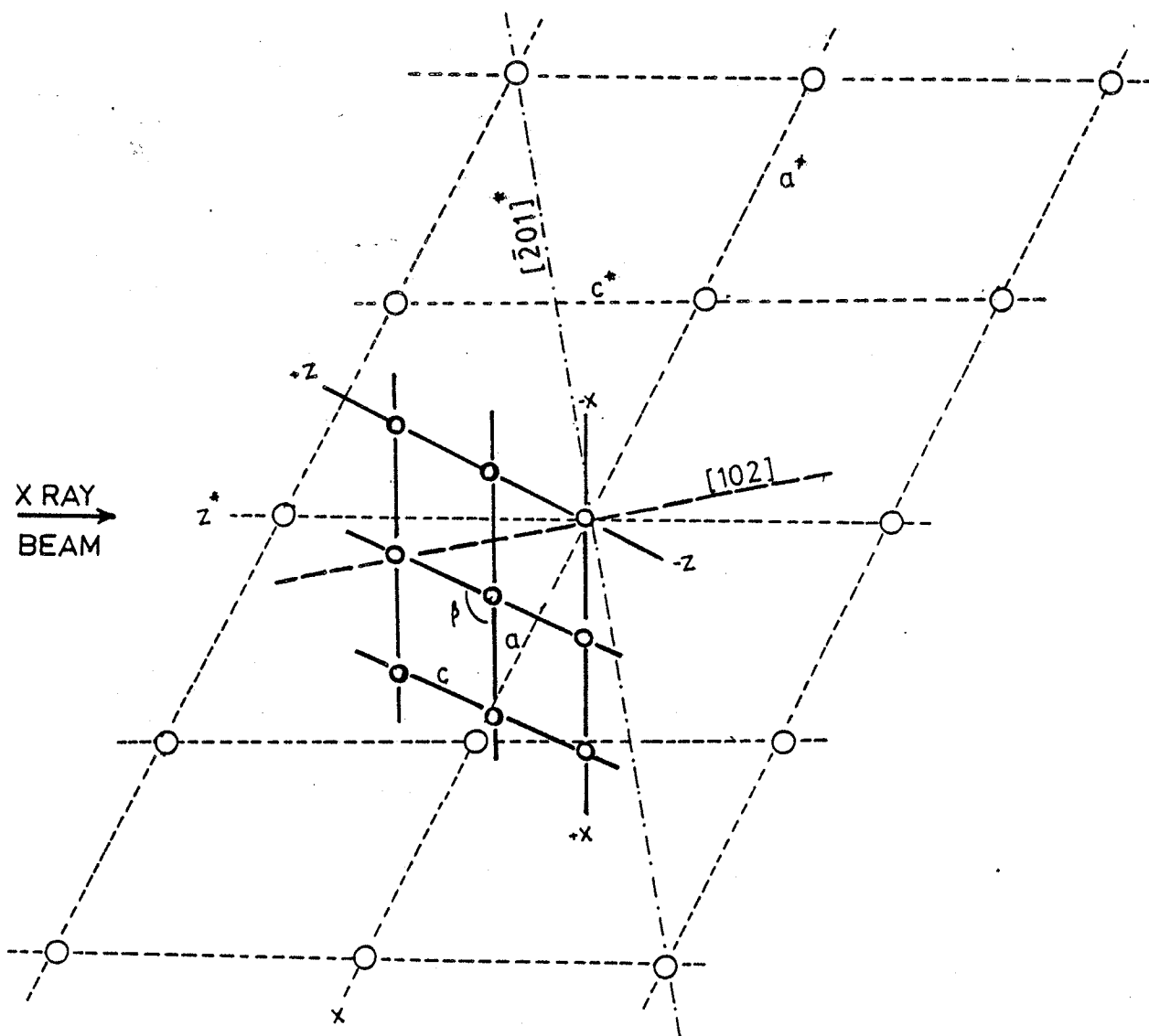
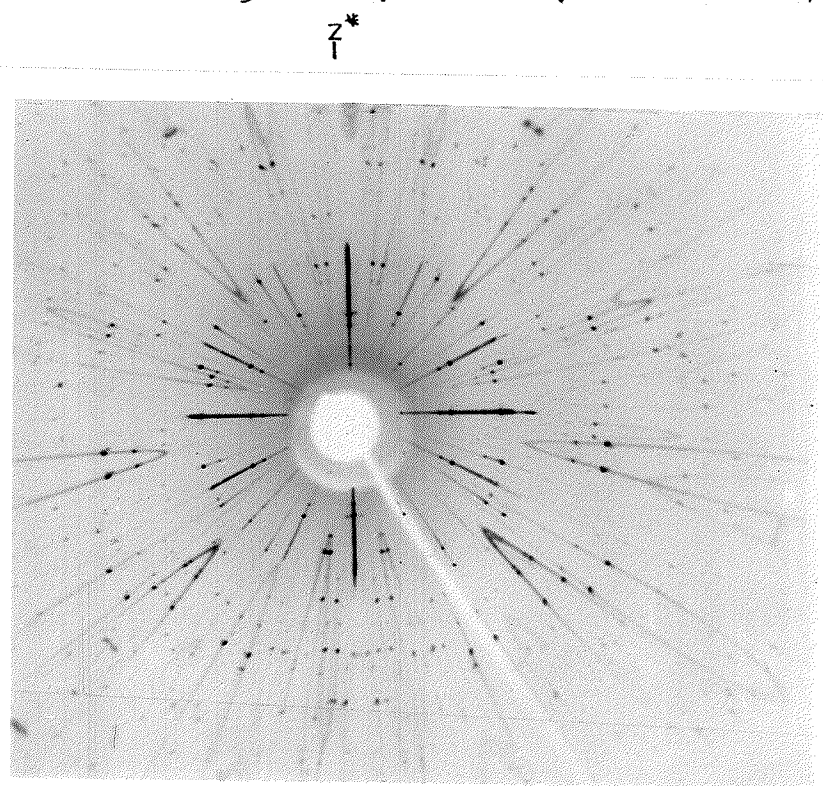


Figure 2-9. Similar set-up as Figure 2-7 except that the x-ray beam is perpendicular to the (001) face of the crystal. This results in orientation of $[102]$ which means that the $[201]^*$ axis of the reciprocal lattice is recorded. Rotating the 90° either way gives the required x-axis orientation. Scale of drawing is the same as Figure 2-7.

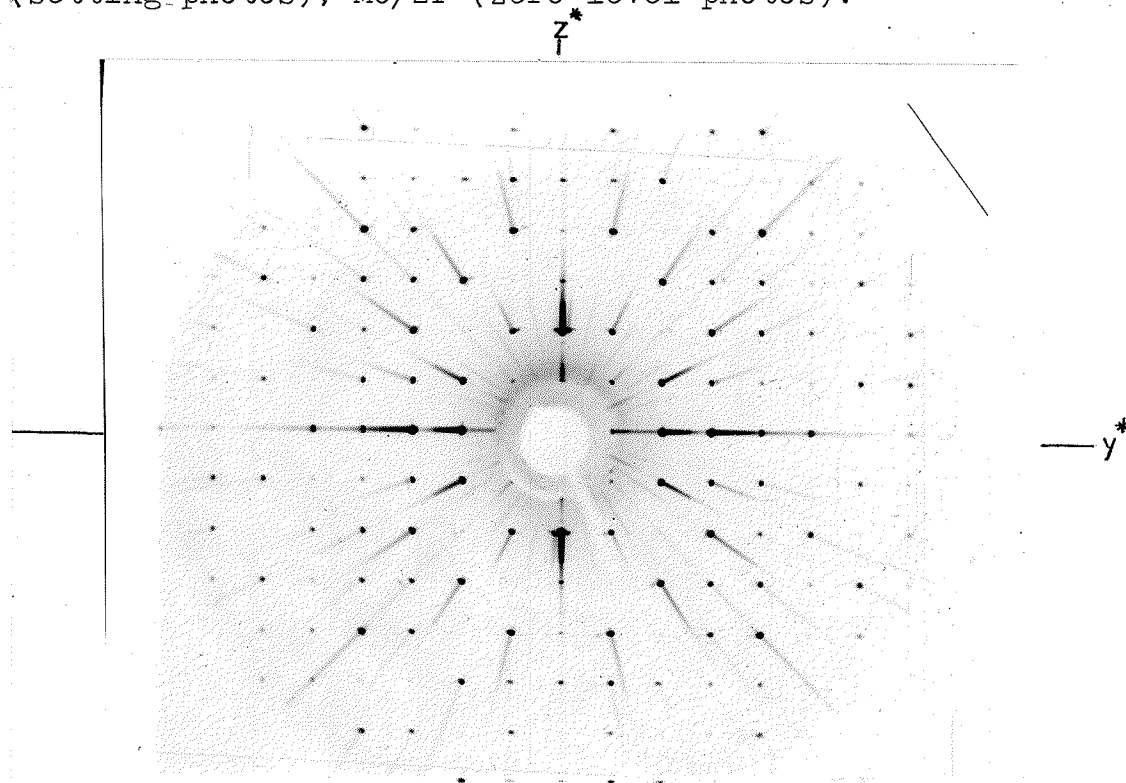
Table 2-3. Summary of precession photos listed in Figure 2-10 of precession around various axes involved in the orientation procedures discussed in this text. The numbers in brackets are specimen numbers.

Crystal	Precessing Direct Axis Reciprocal Lattice Plane	x[100] y* z*	z[001] y* x*	[101] y* [$\bar{1}$ 01]*	[102] y* ($\bar{2}$ 01)*	[203] y* [$\bar{3}$ 02]*
MONOCLINIC K-FELDSPAR		Figure 2-10 (a) (CG-03)	(d) (MONO)	(k) (PG-133)	(o) (MLG-01)	(s) (CG-03)
MAXIMUM MICRO- CLINE	UNTWINNED		(e) (PG-121)			
	ALBITE-TWINNED		(f) (CG-03)			
	PERICLINE-TWINNED		(g) (SR-148)			
	ALBITE + PERICLINE		(h) (APG-05)	(i) (APG-05)	(p) (APG-05)	
LOW	UNTWINNED	(b) (CG-03 AB)	(j) (CG-03 AB)	(m) (CG-03 AB)	(q) (CG-03 AB)	
ALBITE	ALBITE-TWINNED	(c) (PG-138 AB)		(n) (PG-138 AB)	(r) (PG-138 AB)	

Figure 2-10. Precession photos of various axes involved in the orientation procedures as discussed in text. The settings for the photos are as follow: $\mu=25^\circ$, $r_s=15$ mm, $s=32.6$ mm, $F=60$ mm, radiation Mo/ γ -(setting photos); Mo/Zr (zero-level photos).



(i)



(ii)

Figure 2-10 (a) Precessing around direct axis x (reciprocal lattice plane $y^* z^*$) of maximum microcline/ monoclinic K-feldspar. (i) Setting and (ii) zero-level photos.

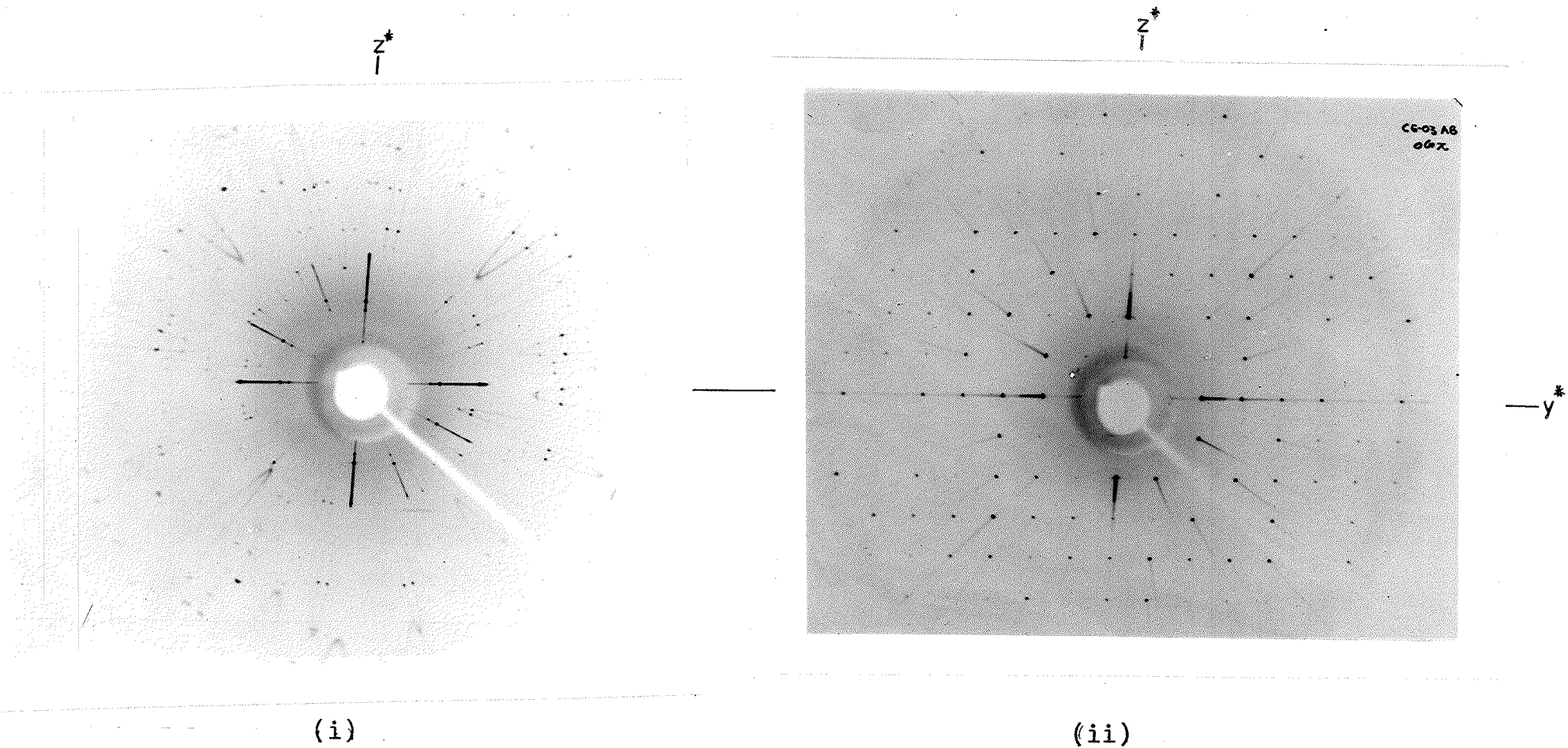
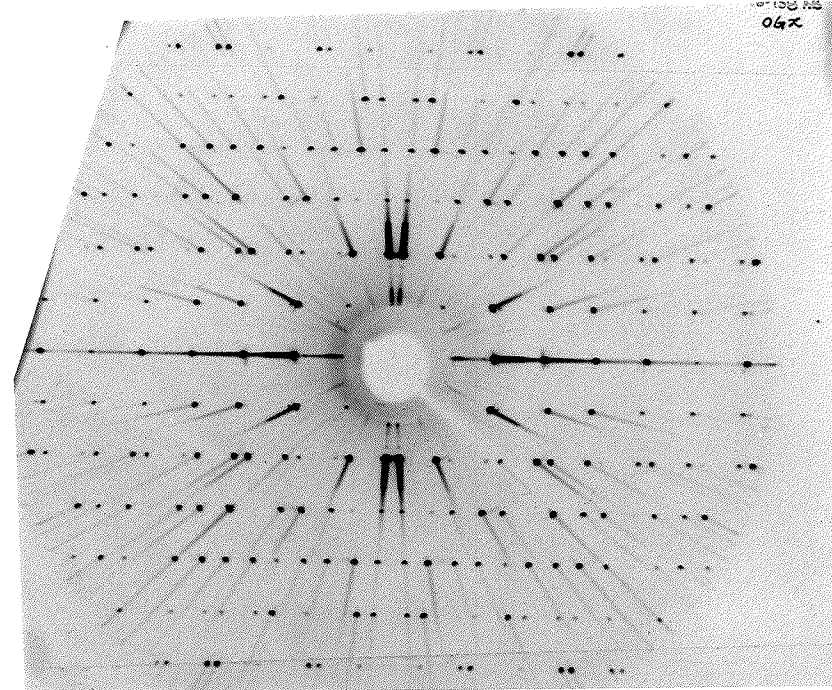
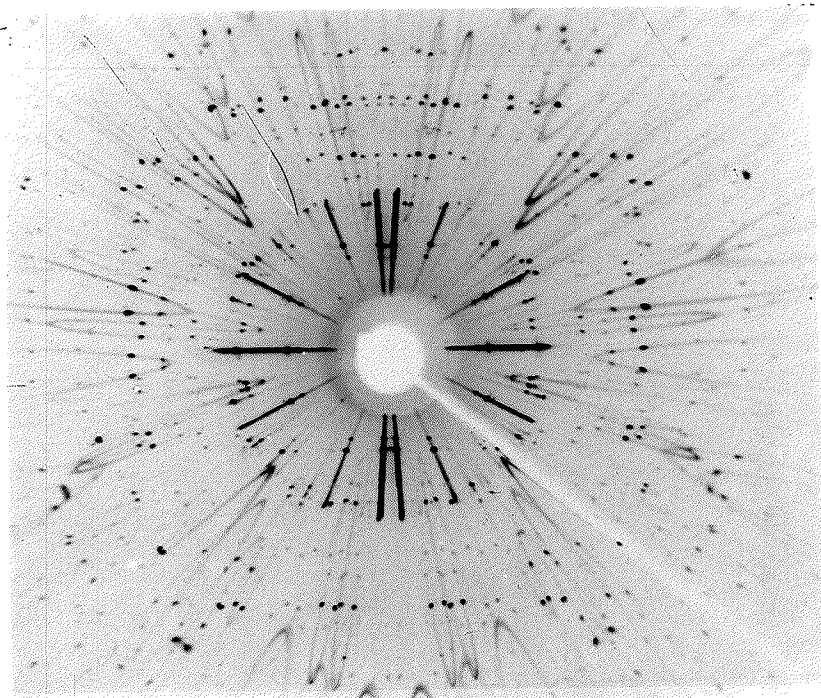


Figure 2-10 (b) Precessing around direct axis x (reciprocal lattice plane $y^* z^*$) of untwinned low albite. (i) Setting and (ii) zero-level photos.

$$\begin{matrix} z_a^* & z_a^* \\ | & | \end{matrix}$$

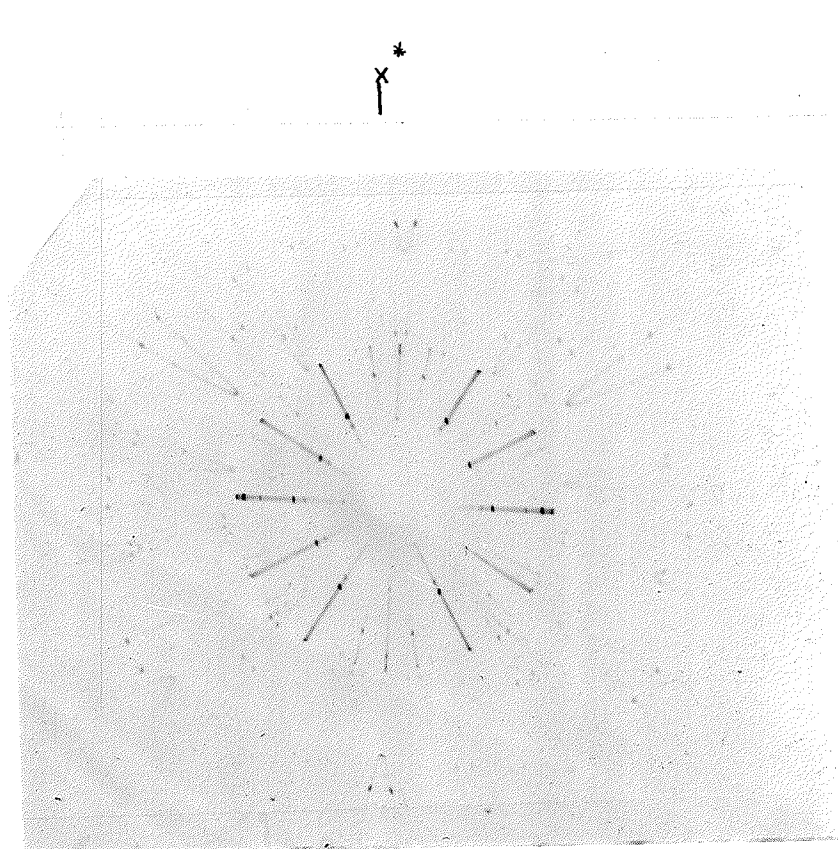
$$\begin{matrix} z_a^* & z_a^* \\ | & | \end{matrix}$$


$$-y_a^*$$

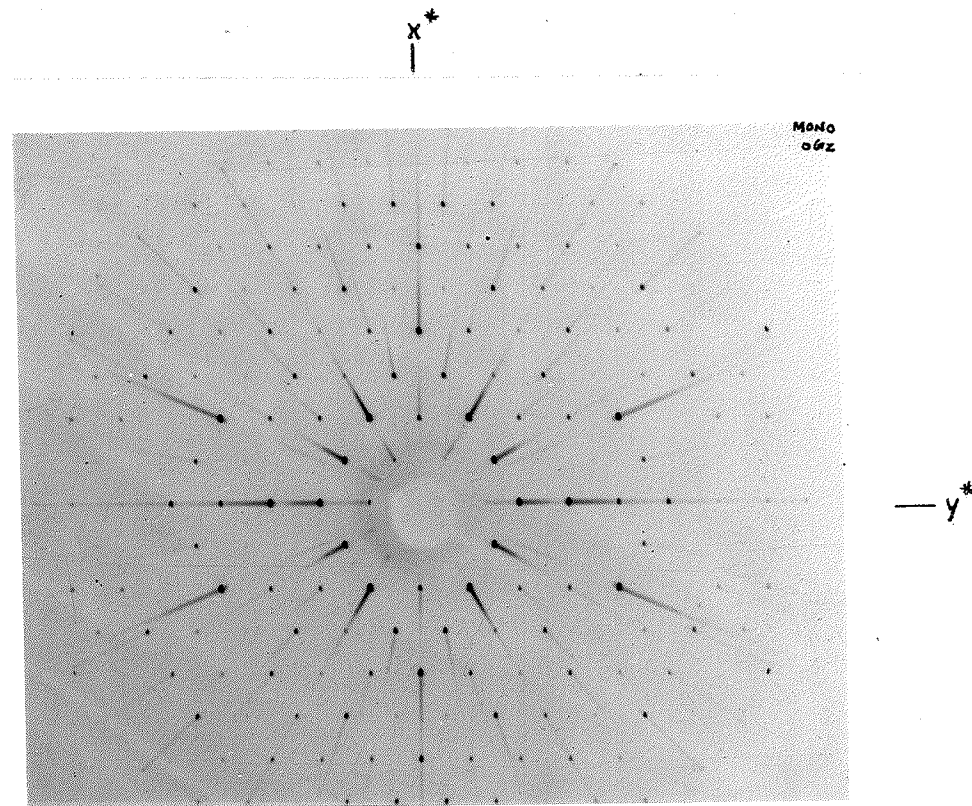
(i)

(ii)

Figure 2-10 (c) Precessing around direct axis x (reciprocal lattice plane y^*z^*) of albite-twinned low albite. (i) Setting and (ii) zero-level photos.



(i)



(ii)

Figure 2-10 (d) Precessing around direct axis z (reciprocal lattice plane y^*x^*) of monoclinic K-feldspar. (i) Setting and (ii) zero-level photos.

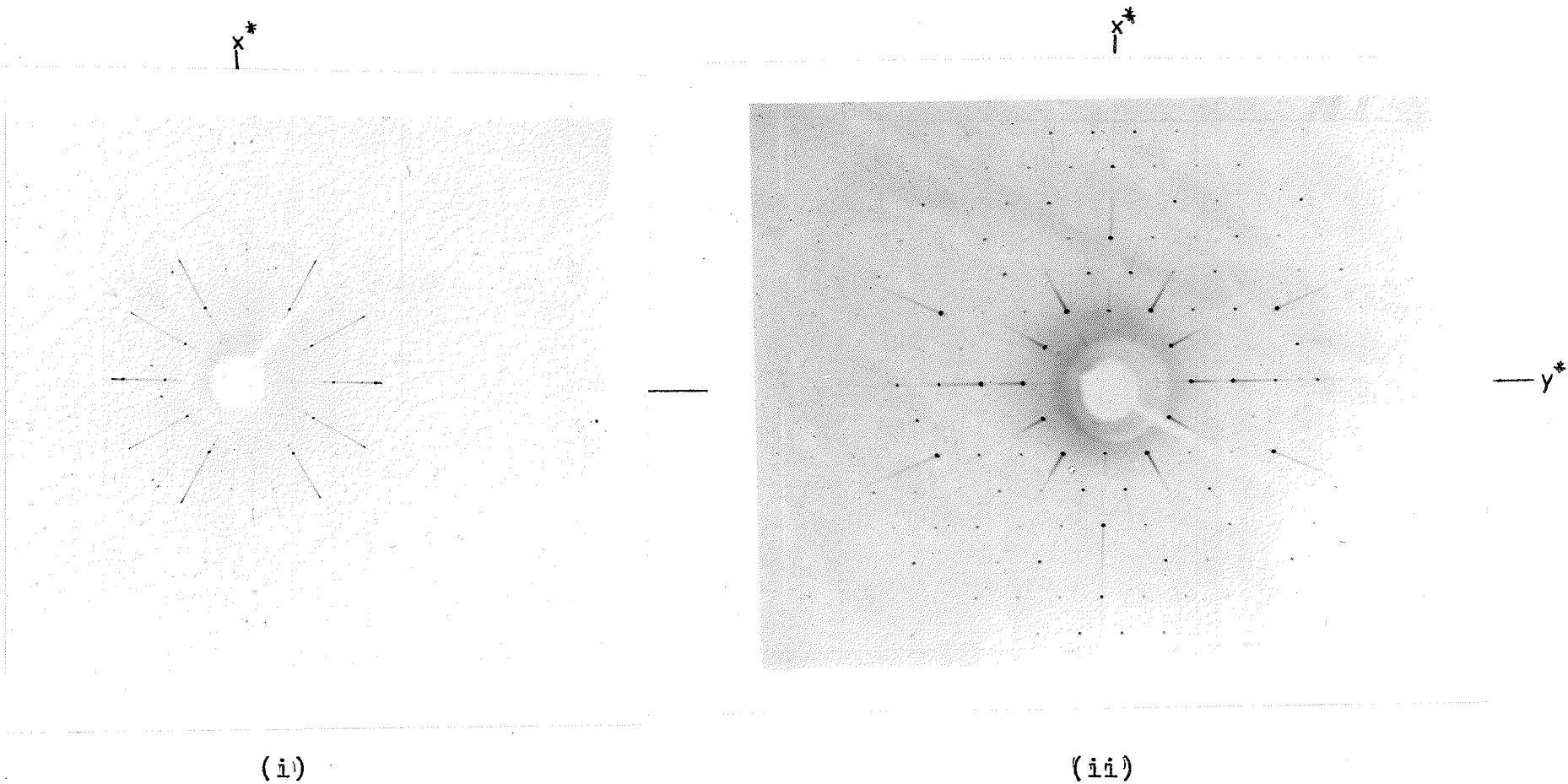
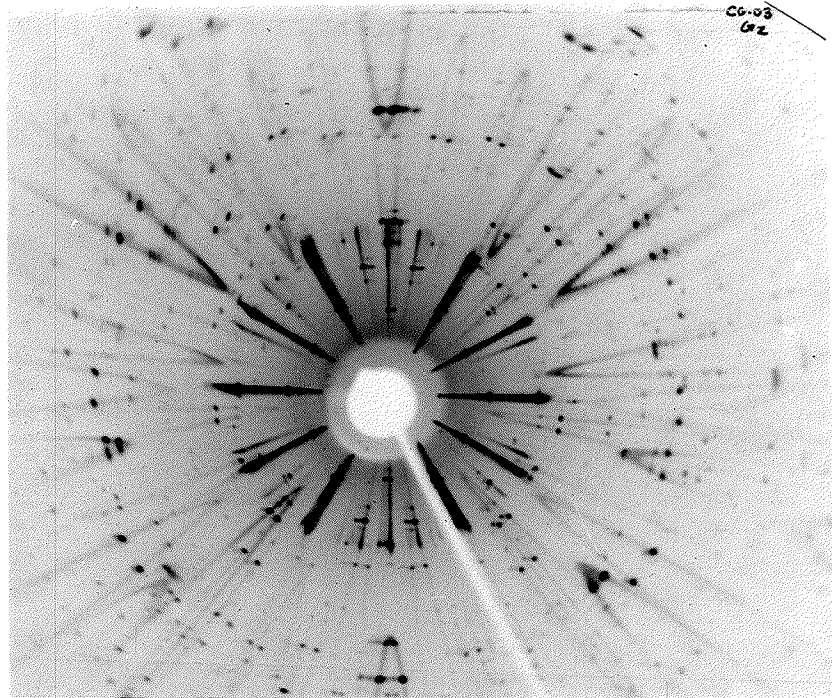
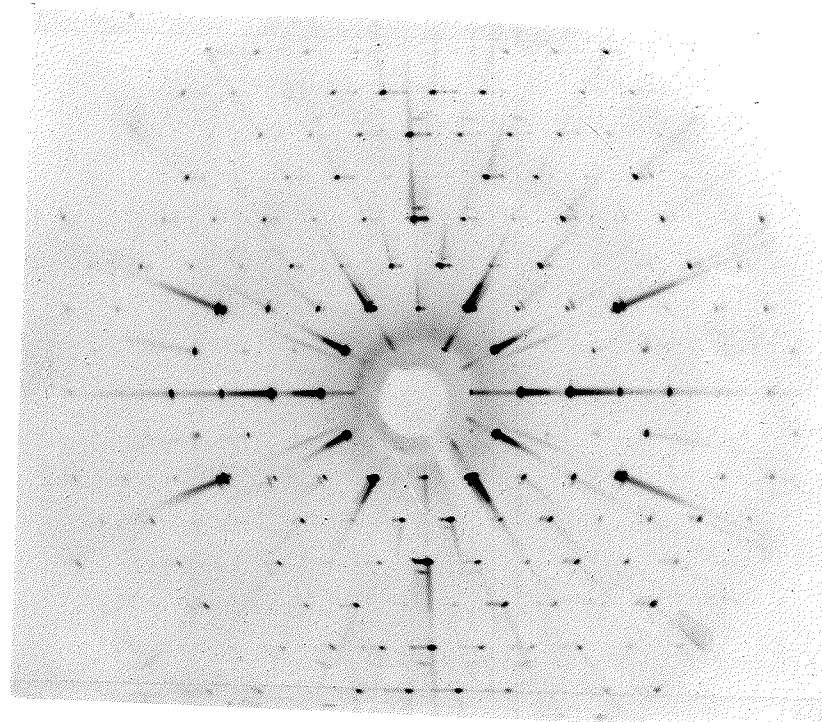


Figure 2-10 (e) Precessing around direct axis z (reciprocal lattice plane y^*x^*) of untwinned maximum microcline. (i) Setting and (ii) zero-level photos.

$$\begin{matrix} X_a^* & X_a^* \\ | & | \end{matrix}$$


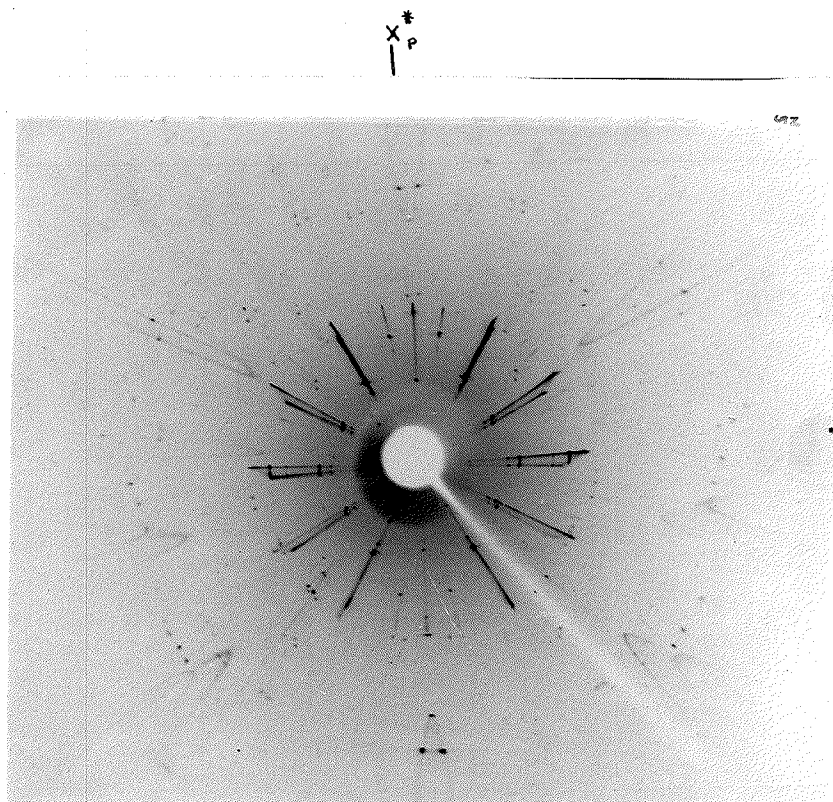
(i)

$$\begin{matrix} X_a^* & X_a^* \\ | & | \end{matrix}$$


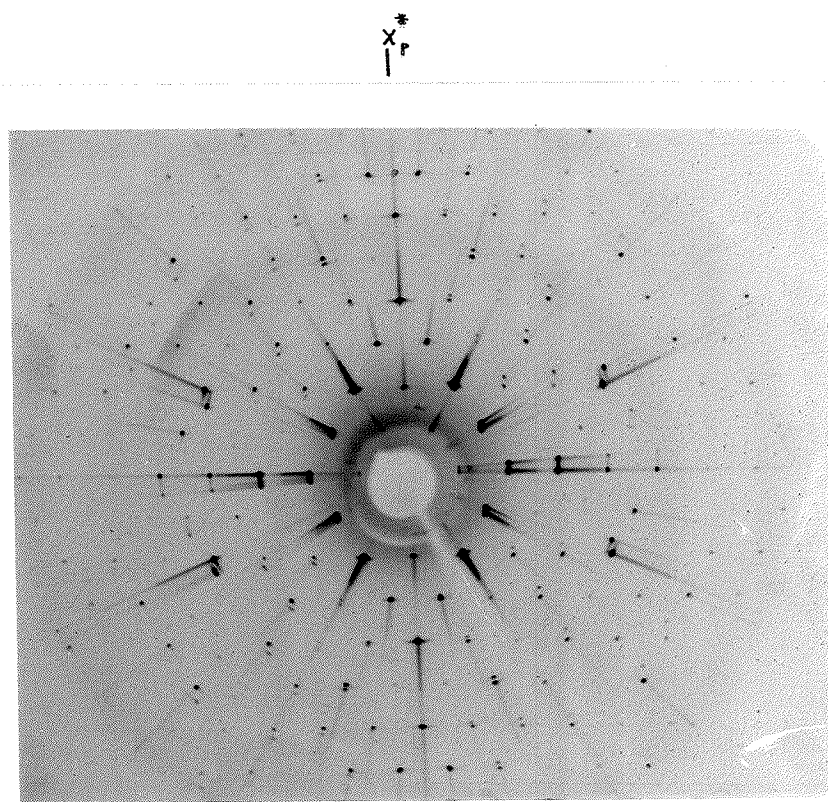
(ii)

Figure 2-10 (f) Precessing around direct axis z (reciprocal lattice plane y^*x^*) of albite-twinned maximum microcline. (i) Setting and (ii) zero-level photos.

$-y_a^*$



(i)

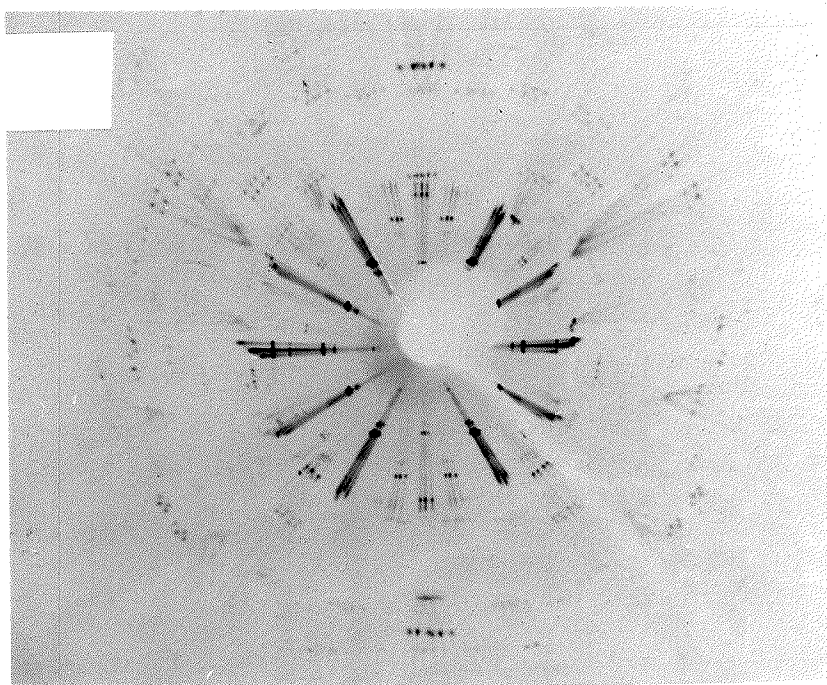


(ii)

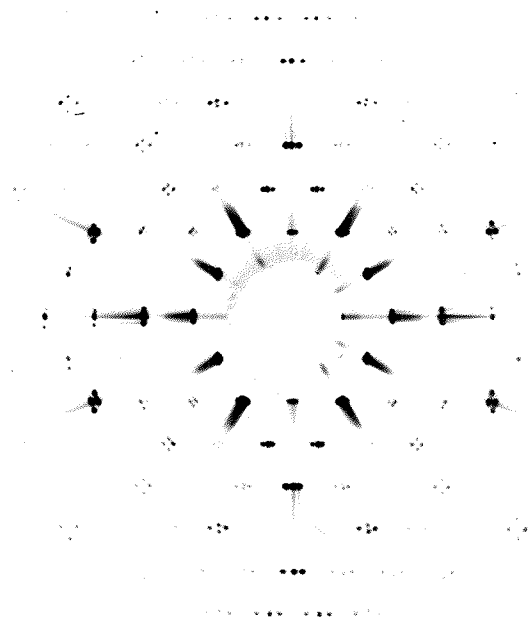
Figure 2-10 (g) Precessing around direct axis z (reciprocal lattice plane $y^* x^*$) of pericline-twinned maximum microcline. (i) Setting and (ii) zero-level photos.



AP-95
062

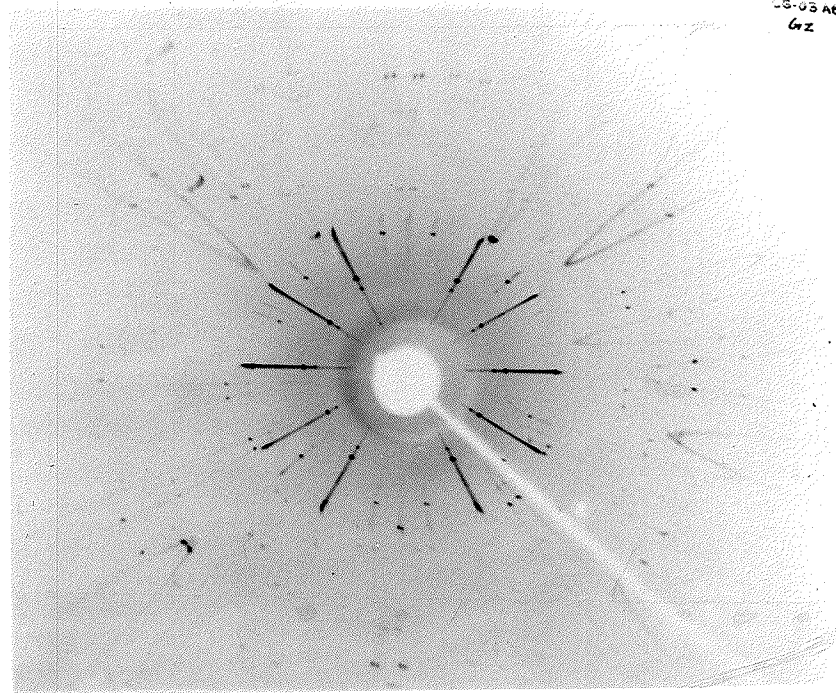


(i)

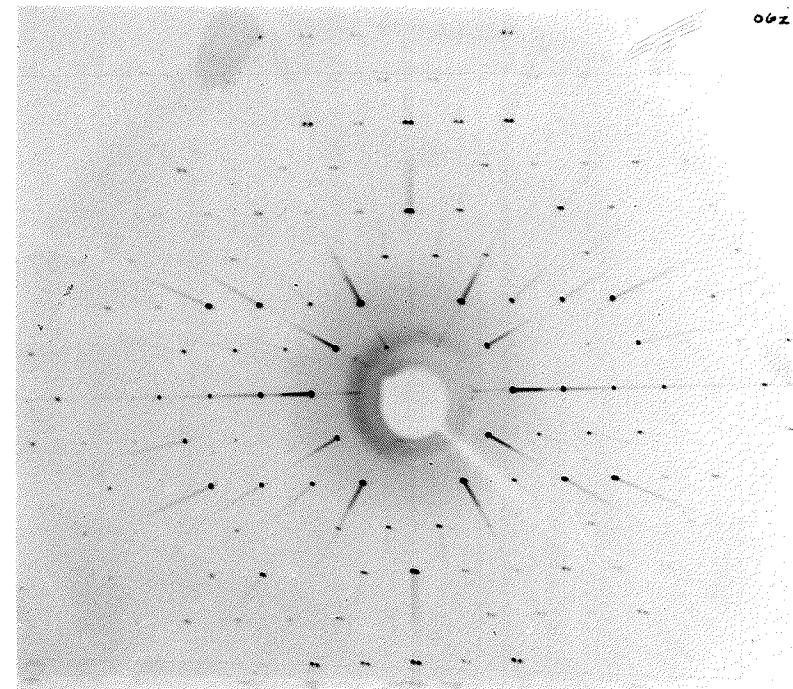


(ii)

Figure 2-10 (h) Precessing around direct axis z (reciprocal lattice plane $y^* x^*$) of albite- + pericline- twinned maximum microcline. (i) Setting and (ii) zero-level photos.



(i)



(ii)

Figure 2-10 (j) Precessing around direct axis z (reciprocal lattice plane $y^* x^*$) of low albite. (i) Setting and (ii) zero-level photos.

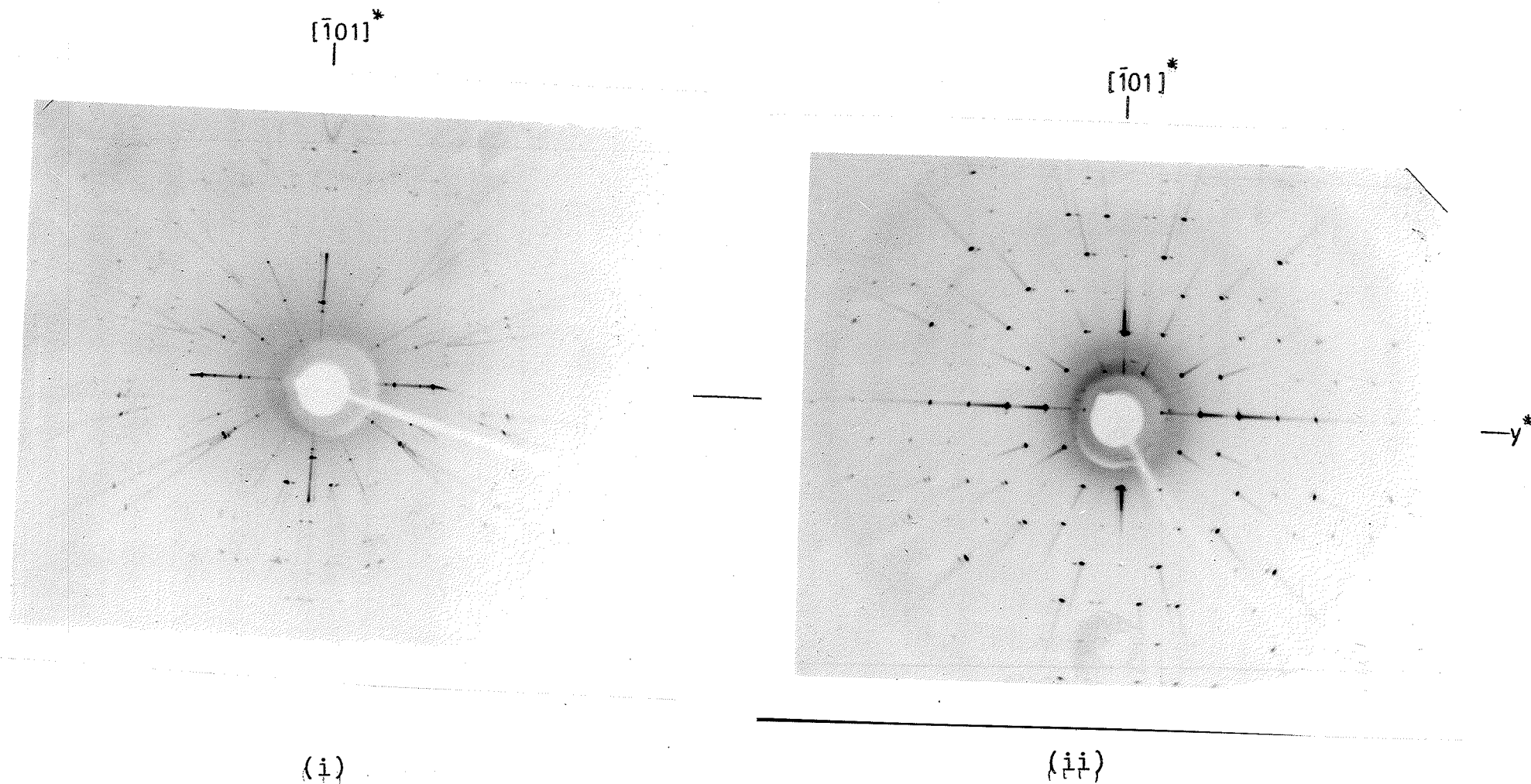
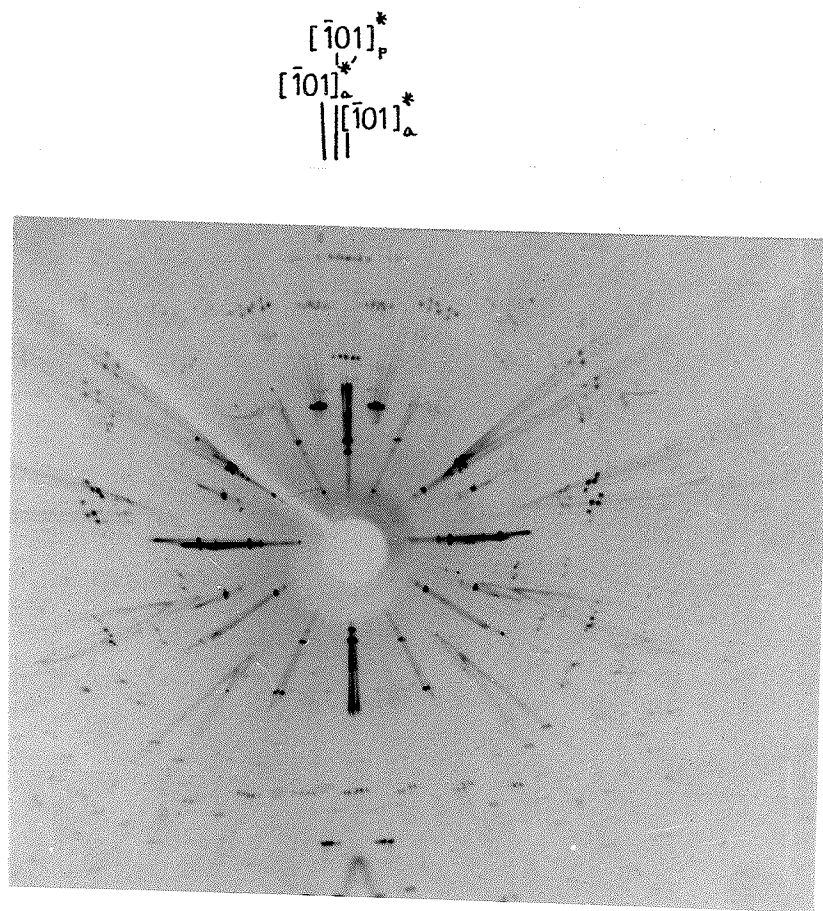
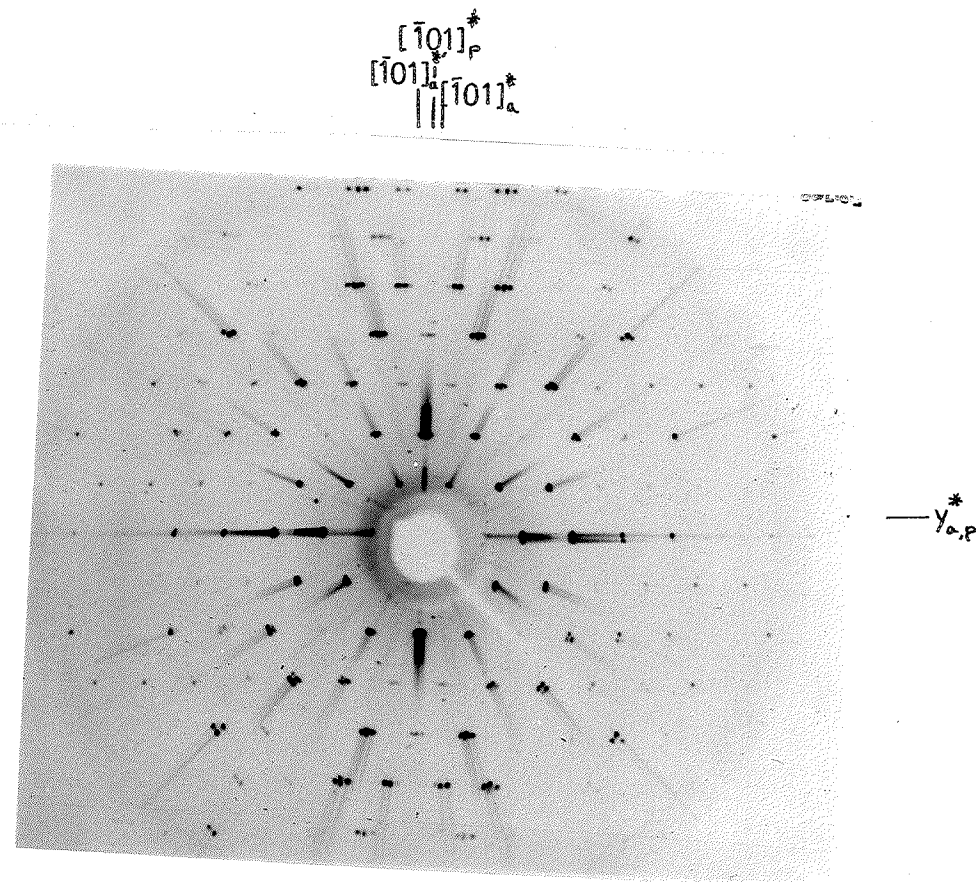


Figure 2-10 (k) Precessing around direct axis $[101]$ (reciprocal lattice plane $y^*[101]^*$) of maximum microcline. (i) Setting and (ii) zero-level photos.



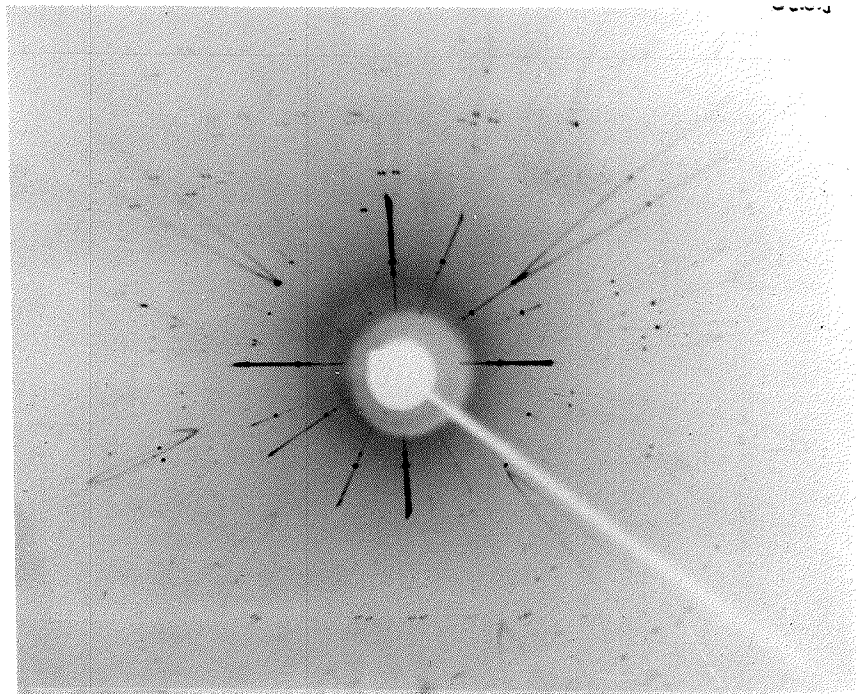
(i)



(ii)

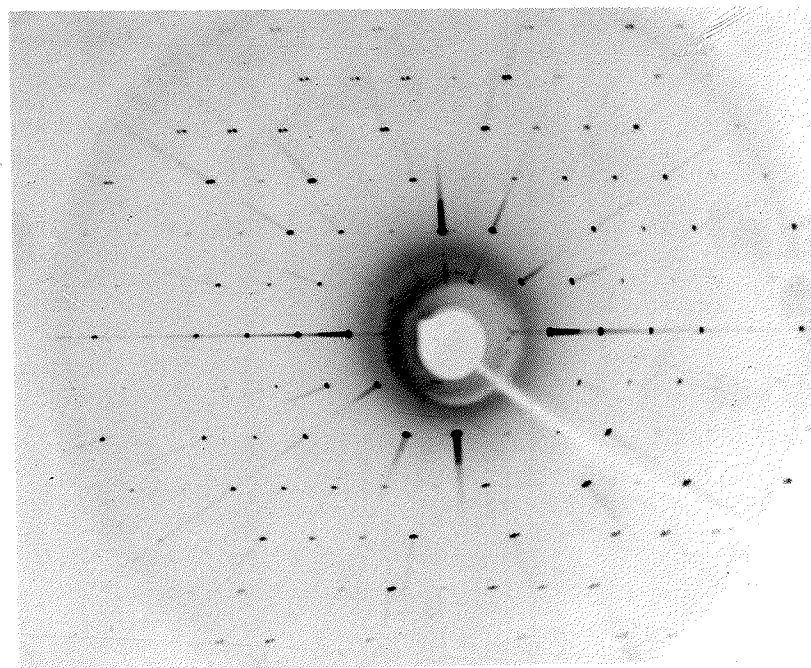
Figure 2-10 (1) Precessing around direct axis $[101]$ (reciprocal lattice plane $y^* [101]^*$) of albite- + pericline-twinned maximum microcline. (i) Setting and (ii) zero-level photos.

$[\bar{1}01]^*$



(i)

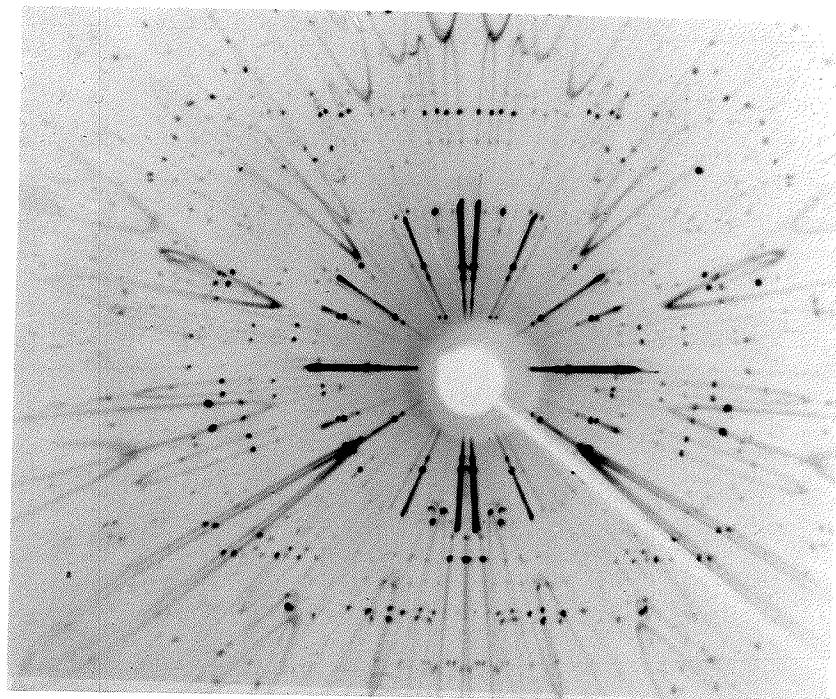
$[\bar{1}01]^*$



(ii)

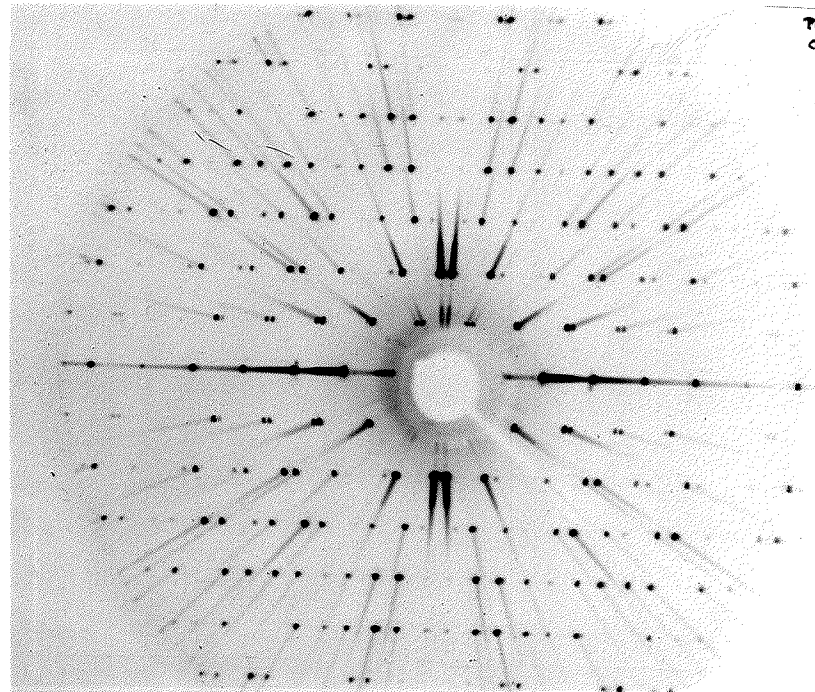
Figure 2-10 (m) Precessing around direct axis $[101]$ (reciprocal lattice plane $y^*[\bar{1}01]^*$) of untwinned low albite. (i) Setting and (ii) zero-level photos.

$[\bar{1}01]_a^*$
|
 $[\bar{1}01]_a^*$



(i)

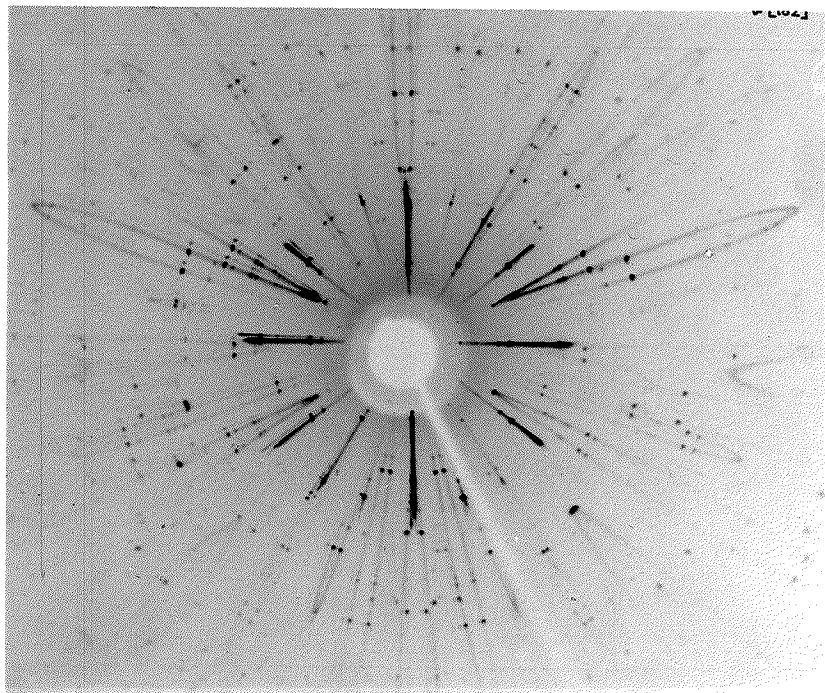
$[\bar{1}01]_a^*$
|
 $[\bar{1}01]_a^*$



(ii)

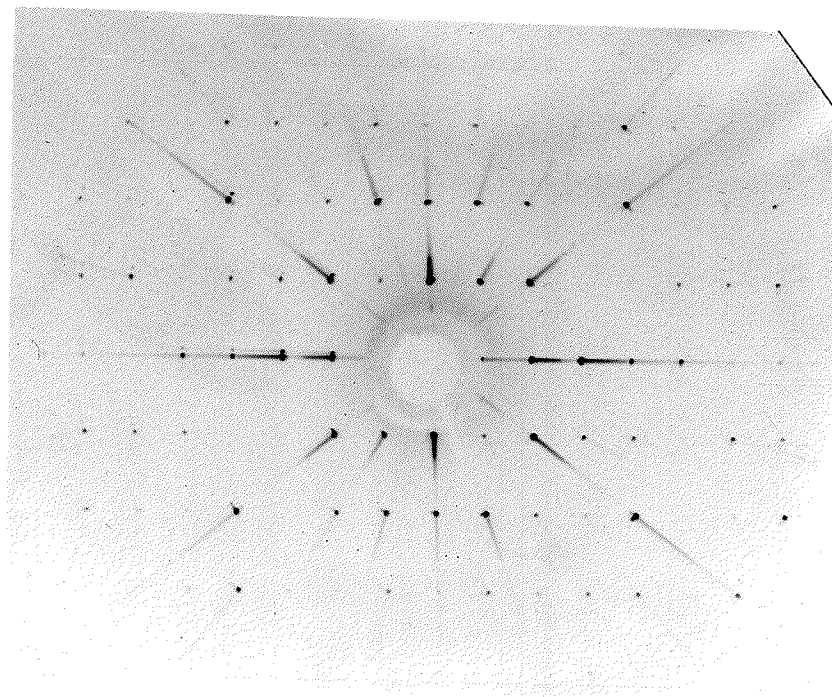
Figure 2-10 (n) Precessing around direct axis $[101]$ (reciprocal lattice plane $y^*[\bar{1}01]^*$) of albite-twinned low albite. (i) Setting and (ii) zero-level photos.

$[\bar{2}01]^*$
|



(i)

$[\bar{2}01]^*$
|



(ii)

Figure 2-10 (o) Precessing around direct axis $[102]$ (reciprocal lattice plane $y^*[\bar{2}01]^*$) of maximum microcline. (i) Setting and (ii) zero-level photos.

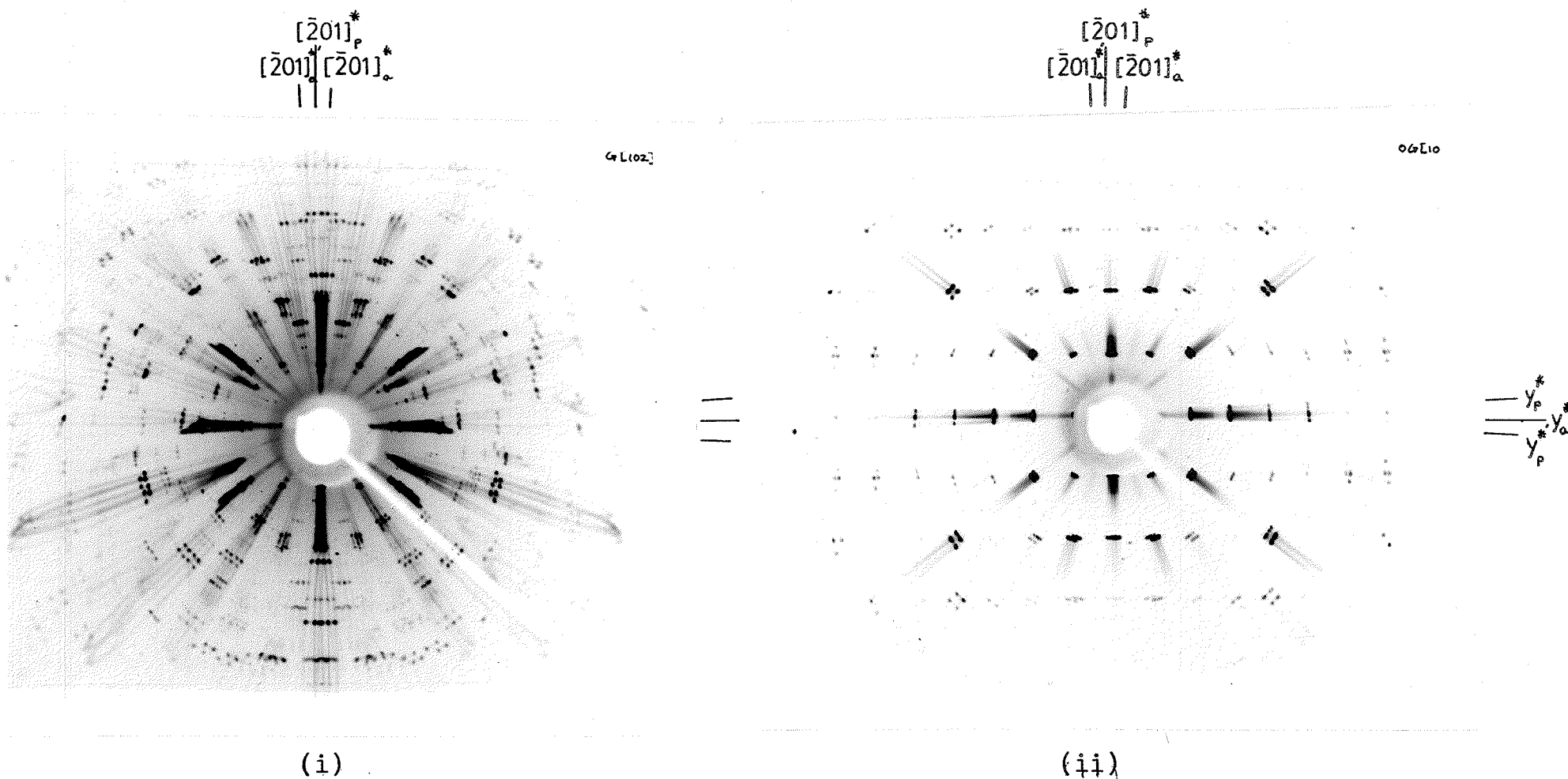
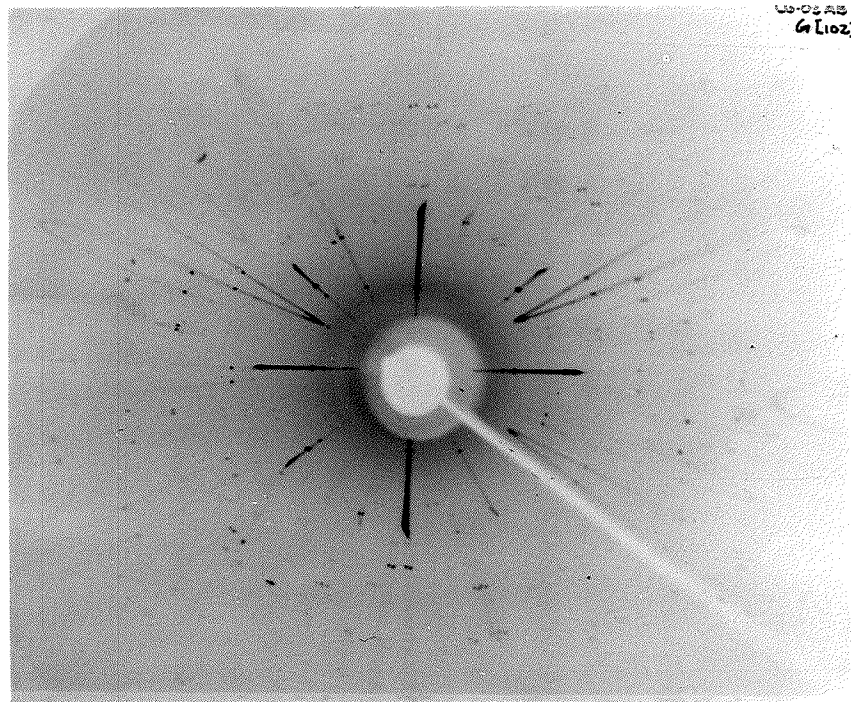


Figure 2- 10 (p) Precession around direct axis $[102]$ ((reciprocal lattice plane $y^* [201]^*$) of albite- + pericline-twinned low albite. (i) Setting and (ii) zero-level photos.

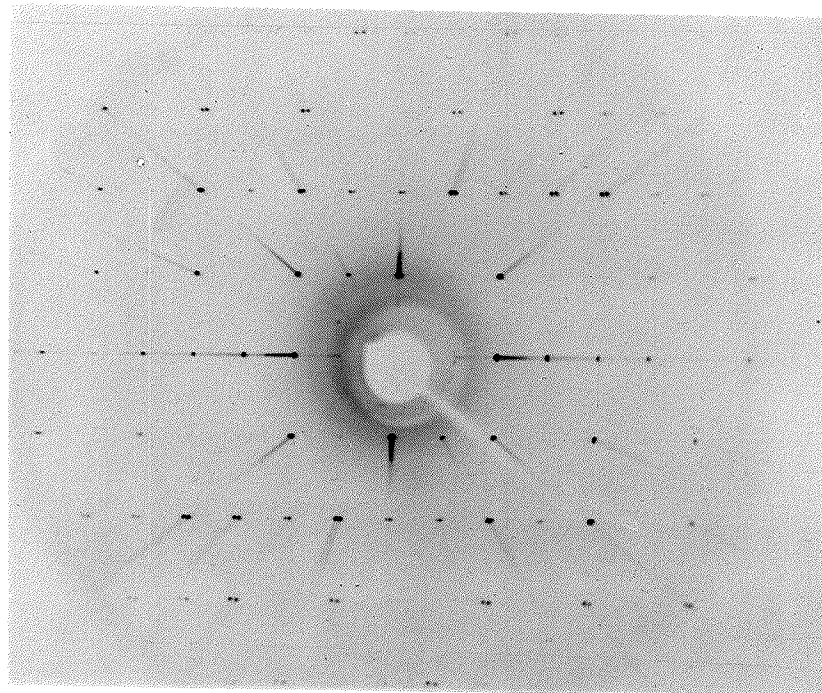
$[\bar{2}01]^*$
|

100-03 AS
6 [102]



(i)

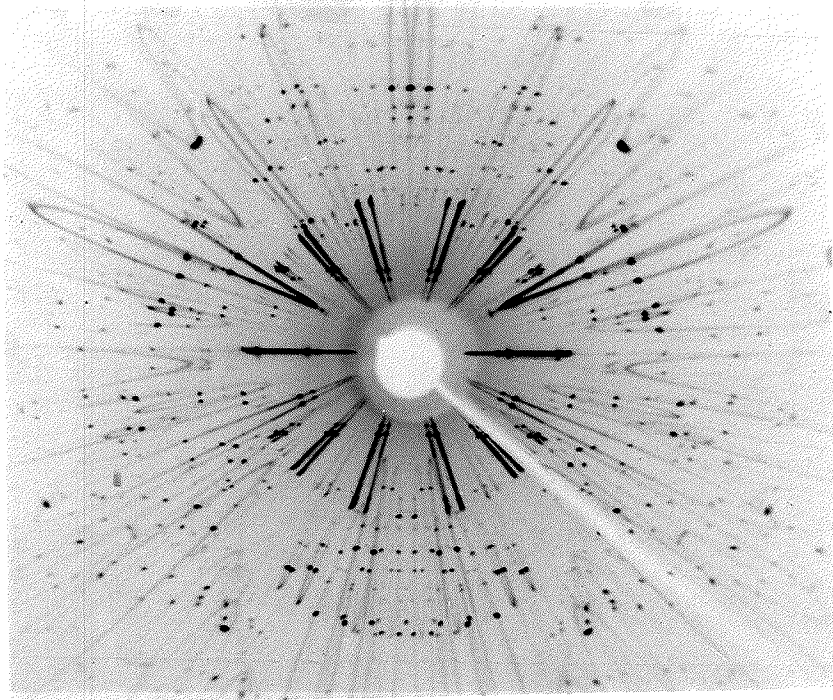
$[\bar{2}01]^*$
|



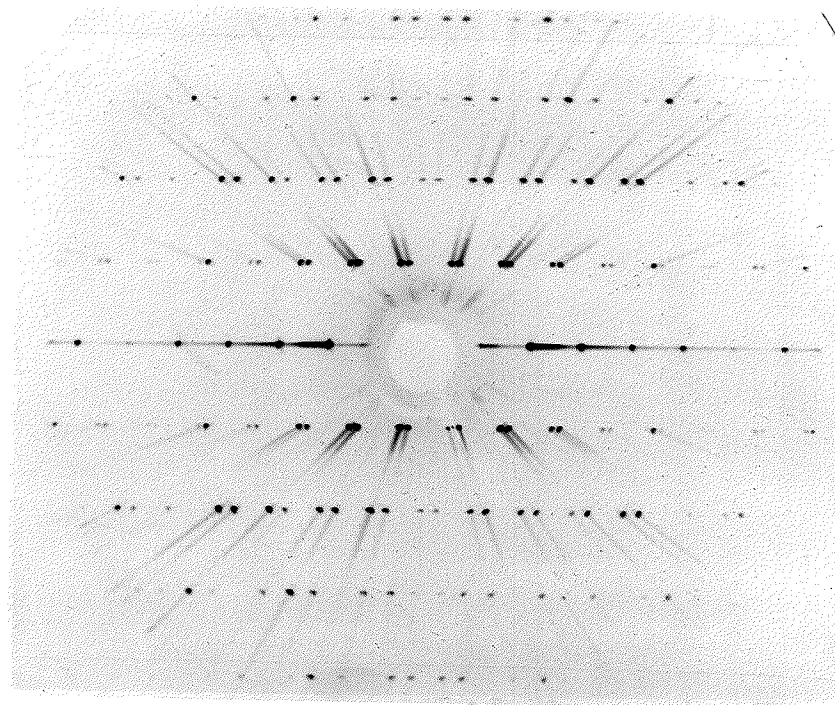
y^*

(ii)

Figure 2-10 (q) Precessing around direct axis [102] (reciprocal lattice plane $y^*[\bar{2}01]^*$) of untwinned low albite. (i) Setting and (ii) zero-level photos.

$$\begin{array}{c} [201]_a^* \\ | \\ [201]_a^* \end{array}$$


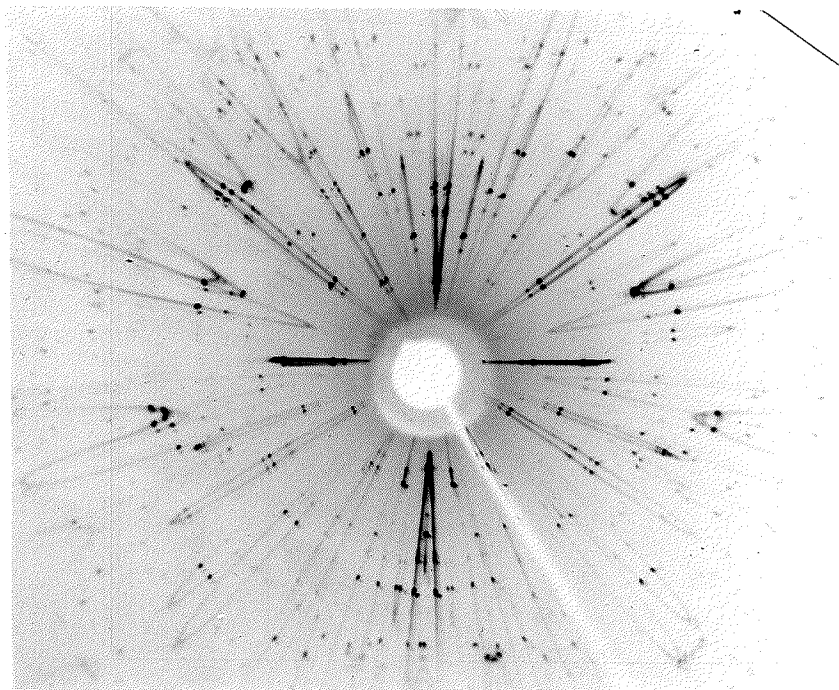
(i)

$$\begin{array}{c} [201]_a^* \\ | \\ [201]_a^* \end{array}$$


(ii)

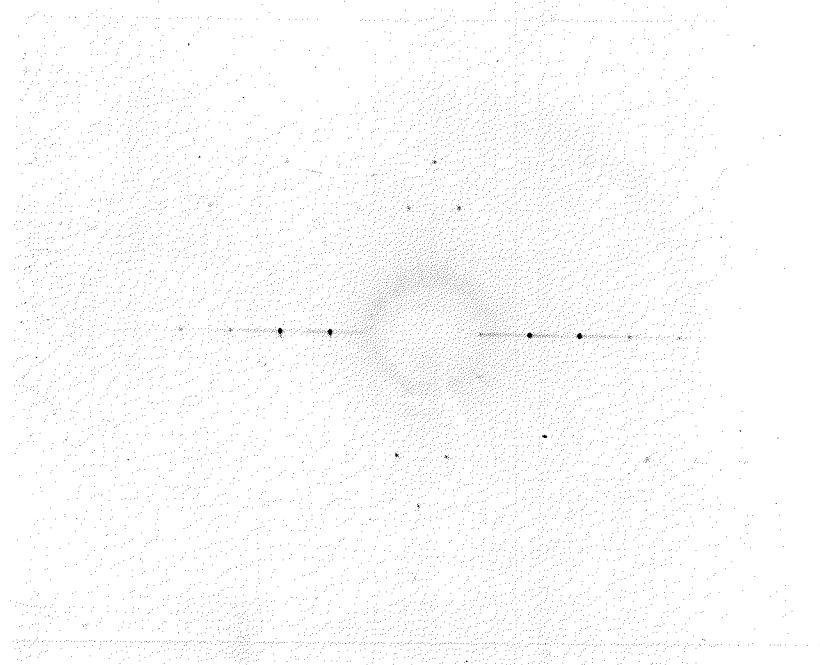
Figure 2-10 (r) Precessing around direct axis $[102]$ (reciprocal lattice plane $y^*[\bar{2}01]^*$) of albite -twinned low albite. (i) Setting and (ii) zero-level photos.

$[\bar{3}02]^*$



(i)

$[\bar{3}02]^*$



(ii)

— y^*

Figure 2-10 (s) Precessing around direct axis $[203]$ (reciprocal lattice plane $y^*[\bar{3}02]^*$) of alkali feldspar. (i) Setting and (ii) zero-level photos.

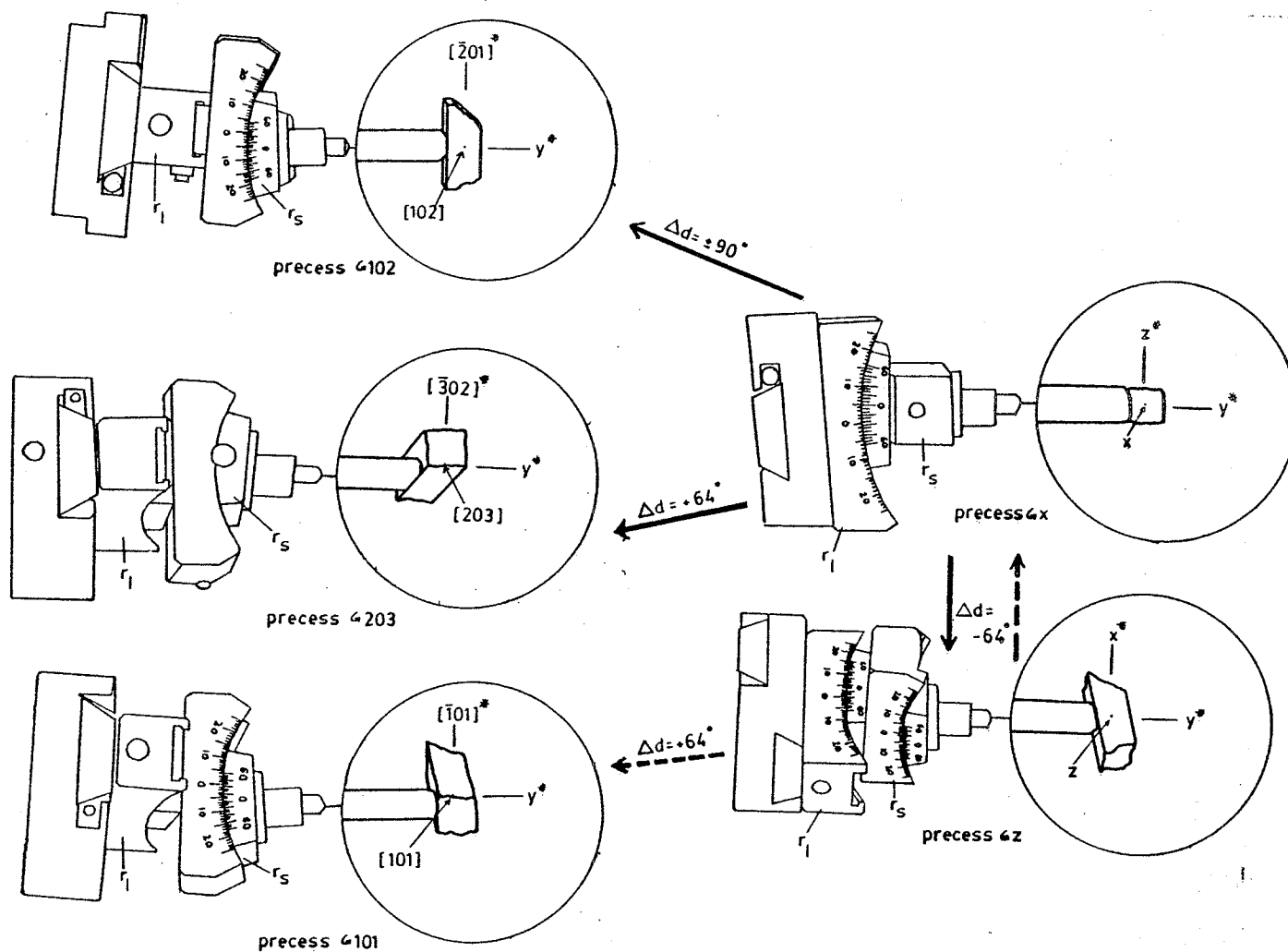


Figure 2-11. Positions of the crystal on the goniometer head in relation to the orientation procedure as discussed in text. Designations are: r_s =small rocker; r_l =large rocker; d =change in drum; + and - signs are arbitrary and relative.

twinning are nearly similar and only one is reproduced here as in the case of precession of all samples around [203]. The various positions of the crystal in the orientations listed in Table 2-3 are shown in Figure 2-11. Classification of K-feldspars on the basis of twinning patterns is discussed in Chapter III.

(D) GANDOLFI POWDER-TYPE PHOTOGRAPHY

To augment the single crystal precession data, Gandolfi photos were taken of the same single crystal to provide an x-ray powder diffraction record of each K-feldspar. The small size of the crystals ruled out powder diffractogram and conventional Debye-Scherrer photography. However, the modification of the latter known as the Gandolfi attachment has made possible powder-type patterns from single crystals. The reader is advised to consult Gandolfi (1967) on the theory of Gandolfi photography .

Ideally, the single crystal is mounted in such a way that it has random orientation to record all reflections as smooth bands. In practice, however, for feldspars and other minerals that have low symmetry (monoclinic or triclinic), not all different crystallographic lattice planes are recorded by this mechanism for one crystal mount. It is necessary to take a second exposure of the same Gandolfi film with the crystal 90° to its original position so that the reflections

are continuous bands rather than broken lines. Second exposures are not needed if crushed grains are used instead of single crystals but this could not be done because the single crystals were later used for electron microprobe studies.

The 29 K-feldspar crystals were analyzed by the Gandolfi method using CuK_α radiation and an exposure time of 10 hours. The photos and results are discussed in the next chapter.

(E) X-RAY POWDER DIFFRACTOMETRY

The powders of each K-feldspar used for the diffraction were the K-feldspars stained and separated from the other minerals by the separation procedure described earlier in this chapter. One K-feldspar crystal was set aside for single crystal analyses. The 29 powder and three standard powder samples were analyzed on a Philips x-ray powder diffractometer system with CuK_α radiation under high resolution operating conditions. For albites, Cu (purified electrolytic copper metal dust) was used instead of CaF_2 because of slight overlap of peaks at around $28^\circ 2\theta$. The reflections of the feldspars were then corrected for 2θ against the standards (values obtained from the Powder Diffraction File) (see References) and the unit cell parameters were refined by the least squares self-indexing computer program of

Appleman and Evans (1973). Several powder diffractograms are reproduced in part, and all the results are described below in Chapter III.

CHAPTER III. X-RAY DIFFRACTION: INTERPRETATIONS

(A) PRECESSION PHOTOS

(1) Introduction

Interaxial angles α , γ , α^* , and γ^* show significant variations in both the K-feldspar and the Na-feldspar structure among different polymorphs (Table 1-1). As discussed in Chapter II, the K-feldspar crystal is oriented so that the y^* -axis is along the rotational axis of the precession instrument. To record the two reciprocal interaxial angles α^* and γ^* , the crystal is oriented to precess around the x and z axes respectively.

(2) Indexing of reflections

Figure 3-1 shows a diagrammatic representation of the 0kl and hk0 reflections of a triclinic K-feldspar. These are similar to those of monoclinic K-feldspar and triclinic Na-feldspar, except that the triclinic feldspars have no mirror plane, unlike the monoclinic K-feldspars. All the K-feldspar and Na-feldspar polymorphs have a C-lattice (Table 1-1); thus the hkl reflections are present only with $(h + k) = 2n$. The diagram in Figure 3-1 shows the indexing of the reflections in two quadrants. Because the triclinic K-feldspars do not have a mirror plane (just a centre of symmetry), the two quadrants indexed represent the smallest reciprocal unit (known as the asymmetric unit) that, when

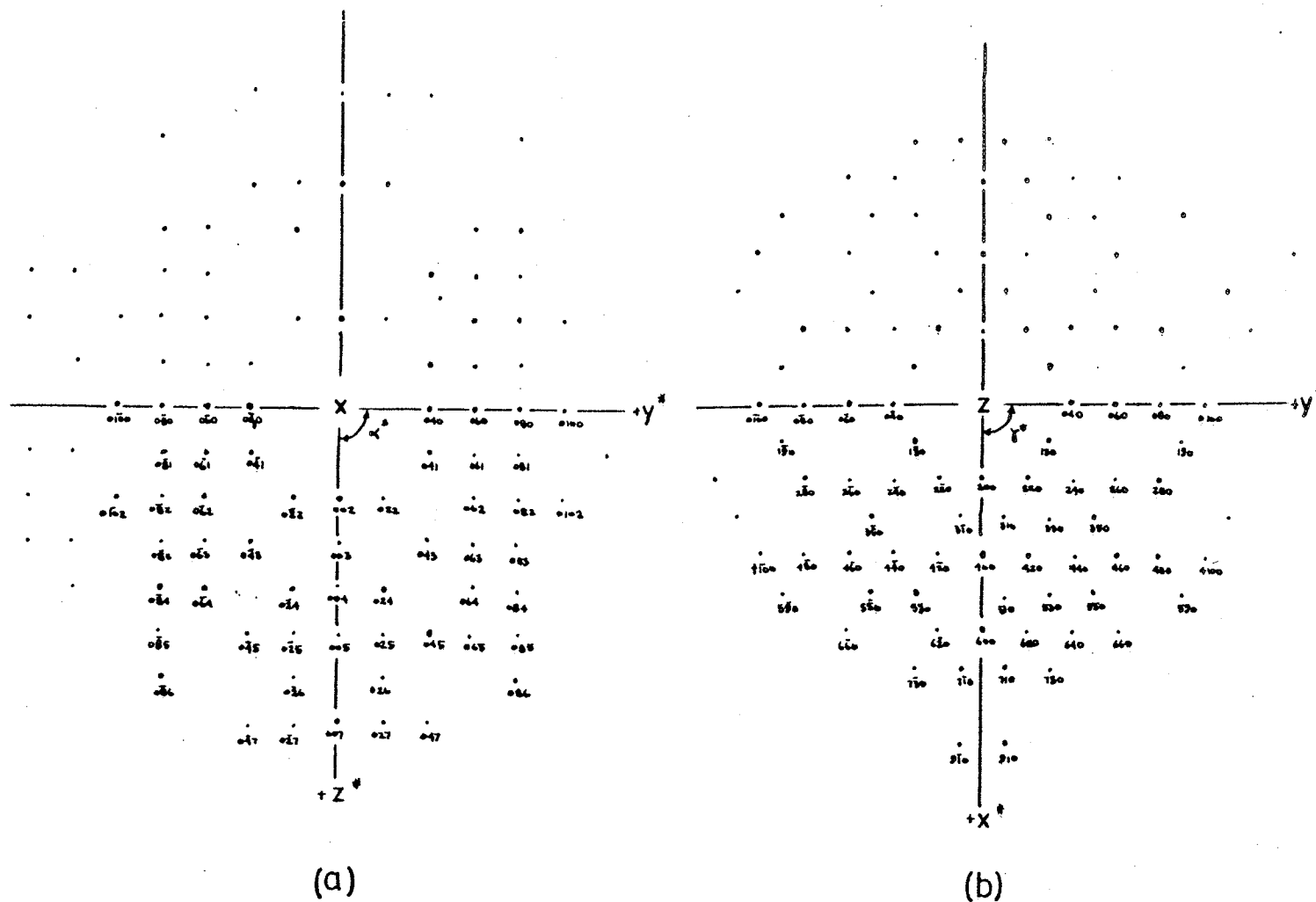


Figure 3-1. Diagrammatic representations of zero-level precession photos around (a) x-axis (y^*z^* plane) and (b) z-axis (y^*x^* plane) of a triclinic K-feldspar. The reflections of one asymmetric unit (as described in text) are indexed.

repeated by the symmetry, will reproduce the whole reciprocal lattice. So in the case of a monoclinic K-feldspar, only one quadrant needs to be indexed, as the other quadrant is related to it by the mirror plane.

(3) Twinning

There are four types of twinning patterns (including untwinned) that are found in the triclinic alkali feldspars. Monoclinic crystals may also be twinned, but not by the albite or pericline laws as there is a mirror plane parallel to 010 and a 2-fold axis parallel to y. The triclinic twinning patterns are:

- (a) Untwinned crystals with γ^* up to $\sim 2\frac{1}{2}^\circ$ off 90° (Figure 3-2a);
- (b) Twinning by Albite Law: reflection across (010), resulting in the superposition of the pair of y^* axes (y_a^*) (Figure 3-2b);
- (c) Twinning by Pericline Law: 180° rotation about a 2-fold axis parallel to y, resulting in the superposition of the pair of x^* axes (x_p^*) (Figure 3-2c);
- (d) Twinning by combined Albite and Pericline Laws (Figure 3-2d). This is the common type that produces the characteristic cross-hatched twinning used by petrographers to identify microclines. A first glance at precession photos of this type suggests that the middle reflections halfway between both pairs of twinned x^* and y^* axes are due to a monoclinic phase because the γ^* angle is ideally 90° .

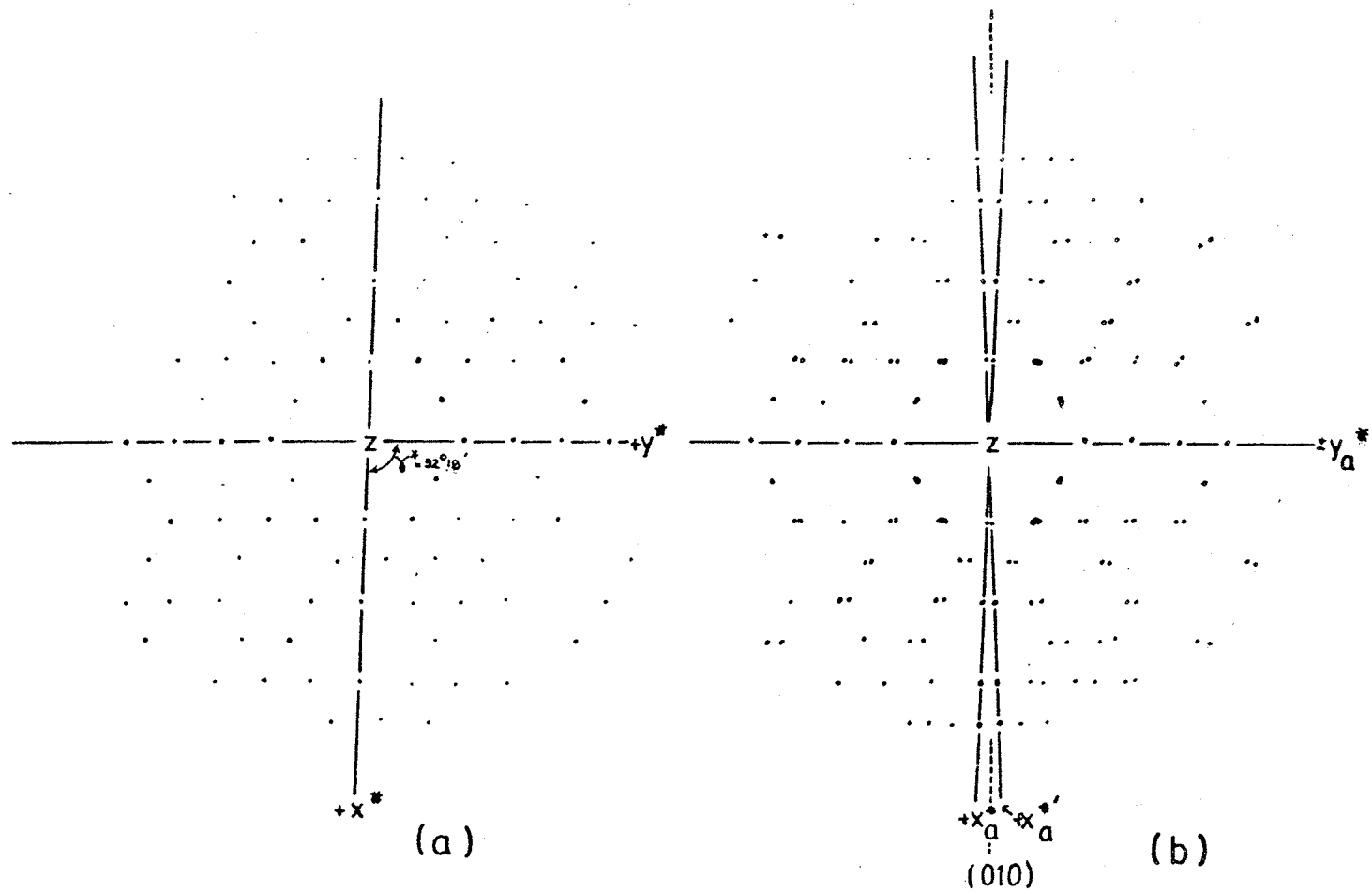


Figure 3-2. Comparable diagrams to Figure 3-1 of twinning patterns of K-feldspars as described in text. (a) untwinned, (b) albite-twinned, (continued ...)

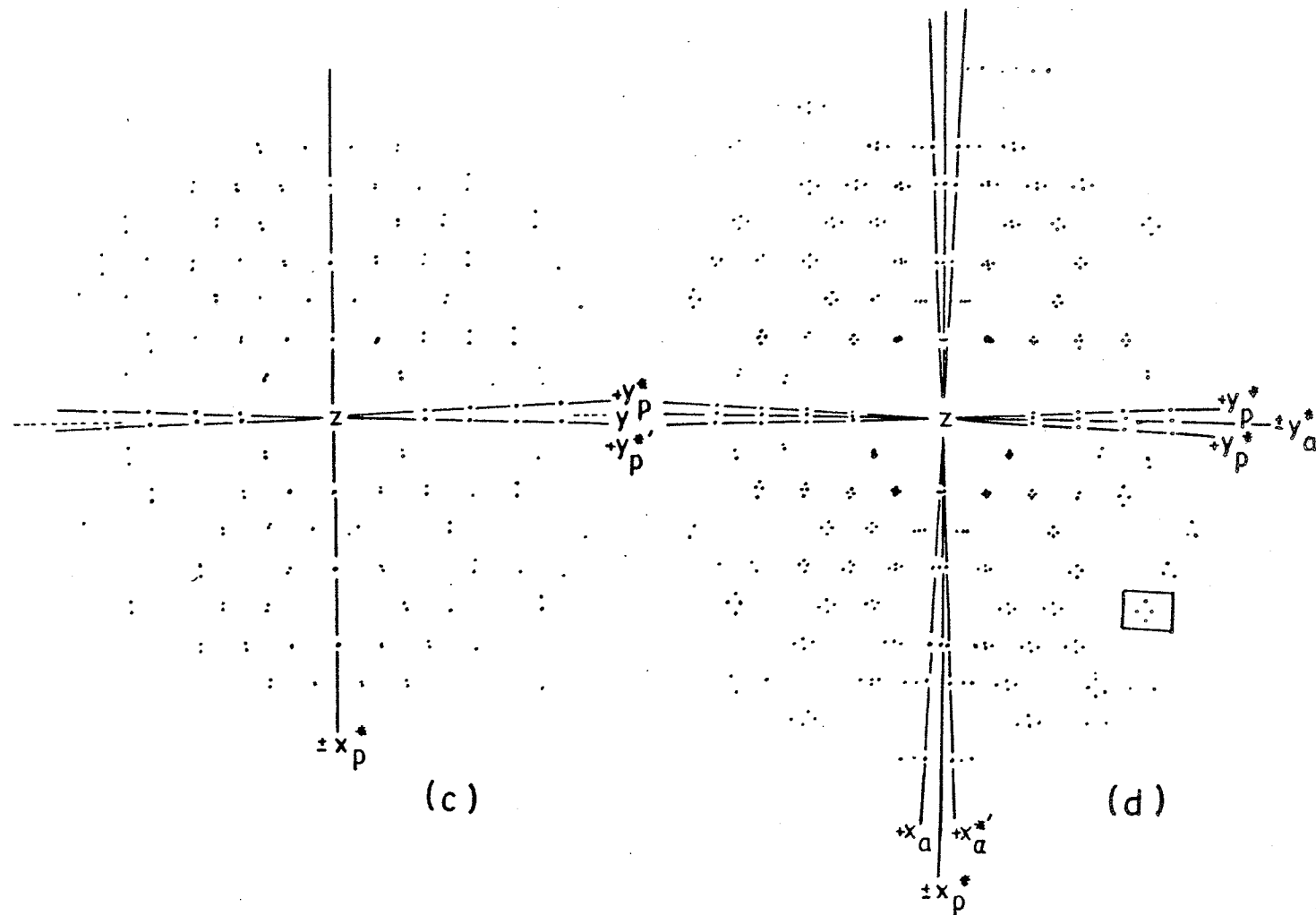


Figure 3-2 (... continued) (c) pericline-twinning, (d) albite- + pericline- twinning.
The block refers to reflection 590 which is discussed in details in Figure 3-3.

However, the twins act independently of each other and it is the superposed x_p^* and y_a^* axes (in zero-level around z-axis photos) that make an angle of 90° .

The outer non-axial reflections have four components (Figure 3-3a); two are albite reflections and two are pericline reflections. Laves (1950), Smith & MacKenzie (1958) and Smith (1974a) have made similar observations and called this M-twinned microcline (originally named by Smith & MacKenzie (1958) to denote a monoclinic-derived microcline). There are also other twinning patterns reported in the literature, as observed from other single crystal methods: a "T" type twinning (to denote a triclinic-derived microcline) with 3 components arranged in the form of a figure "7" as observed by Smith & MacKenzie (1958) and a "T" type twinning with 4 components in a "Z" form as observed by Pieri & Quarenzi (1972).

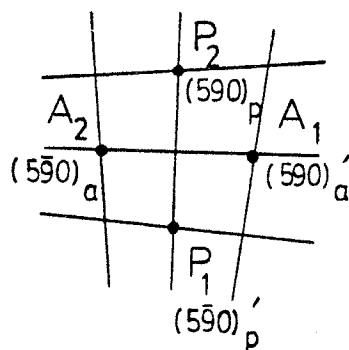


Figure 3-3. "M-twinned" microcline with albite-twinning individuals A_1 and A_2 and pericline-twinning individuals P_1 and P_2 of the reflections 590 and $\bar{5}90$ of Figure 3-2d.

(4) Results

(a) Introduction

Twentynine K-feldspars from the Lac du Bonnet granite and the Dryden granites/pegmatites were analyzed by precision photography. Twenty-seven of them have minor intergrowths of albite, and some of the K-feldspars have multiple K-feldspar components. The zero-level photos around x record the α^* angle of K-feldspar and of Na-feldspar. The types of twinning of albite are also recorded. The zero-level photos around z record the τ^* angles of both feldspars and the twinning types, microcline (triclinicity) groups, and types of reflections and streaks in the K-feldspar crystals. All of these are examined in detail below and Table 3-1 summarizes the results.

(b) Zero-level around x-axis

(i) K-feldspars

As the deviation from 90° is very small, measurements of α^* between y^* and z^* had to be made very carefully as the maximum separation between the z^* axes of a pair of albite twins is 1° or less. In some cases, when the maximum separation was less than 1° , strong reflections (002) and (003) were used, rather than the outer reflections which are sometimes blurred and difficult to read. Zero-level photos around the z-axis of the same crystal were used to check whether or not the crystal was twinned. If the crystal was

Table 3-1. Summary of twinning characteristics observed in precession photos of Lac du Bonnet granitic and Dryden pegmatitic/granitic single K-feldspar crystals and their K- and Na-feldspar components as discussed in text.

AREA AND ROCK TYPE	TWINNING CHARACTERISTICS	
	K-FELDSPAR COMPONENT	CORRESPONDING ALBITE COMPONENT
Lac du Bonnet granite	2 untwinned max. micro. 1 pericline- " " twinned 6 albite-twinned " "	2 untwinned 1 albite-twinned 2 albite-twinned, 2 both twinned, 2 not measured*
Dryden granites	1 untwinned max. micro. 2 albite-twinned " " 3 both twinned " " 1 both-twinned max. micro. & untw. max. micro.	1 untwinned 2 albite-twinned 3 albite-twinned 1 albite-twinned
Dryden pegmatites	1 untwinned int. micro. 1 albite-twinned max. micro. 1 albite-tw. int. micro. & untw. int. micro. 5 both-twinned max. micro. 7 albite-twinned " " & untw. int. micro.	1 untwinned 1 albite-twinned 1 albite-twinned 4 albite-twinned, 1 not measured* 5 albite-twinned, 2 untwinned

* the albite reflections are either unobserved or too weak to be measured.

twinned, then on the zero-level photos around x , the separation had to be measured on the outside of the middle of both twinned reflections, because if the middle part was measured, α^* came very close to 90° . The author found that, after the corresponding τ^* readings had been made, plotting the results on the diagram of α^* vs. τ^* in Figure 3-7, as shown later, would reveal whether or not the point lay close enough to the best straight line derived from a large number of single crystal studies to accept the α^* value as valid. If the point was off the line by more than $15'$, then α^* was measured again until consistent values were obtained. The observed values range from a low of nearly 90° to a high of $90^\circ 30'$. The α^* values of the microclines listed in Table 3-2 are the averages of two readings because of the twinning effect. Instrumental error is assumed to be $\pm 10'$, as discussed later.

(ii) Albite

If the albite intergrowth is untwinned or albite-twinned, the y^* -axis coincides with the y^* -axis of the microcline. If the albite is pericline-twinned, the y^* -axis does not coincide with that of the microcline. Along the z^* -axis, the albite intergrowth is seen as $00l$ albite-twinned reflections in precession photos, with the K-feldspar reflections in the middle or as untwinned $00l$ reflections beside the K-feldspar reflections, because the c^* -period of both albite and K-feldspar is very similar (Table 1-1). Because the amount of

albite is very small, as verified later by Gandolfi photography, only the reflections 002 and rarely 004 along the z^* -axis and the 040 and rarely 060 along the y^* -axis are recorded.

The results for Na-feldspars (in Table 3-2, as discussed later) show that albites exhibit three types of twinning characteristics; untwinned, albite-twinned, and combined albite- and pericline-twinned. Six of the 27 albite intergrowths are untwinned (see Table 3-1). Eighteen of the albites are albite-twinned. The y^* -axes in all albite-twinned albites coincide with the y^* -axes of the K-feldspars, indicating that the (0k0) planes of both Na- and K-feldspars are parallel to each other in the direct lattice. As implied by the constants given in Table 2-2, the corresponding microcline and albite 0k0 reflections along y^* are superimposed on the precession photos. There are only two specimens in which pericline twinings of albite do occur together with K-feldspars, and these are accompanied by albite-twinings of albite. In the similar fashion to the albite- + pericline-twinned microcline discussed earlier (section 3(c) of this chapter), the y_a^* -axis of the albite-twinned albite coincides with the y^* -axis of the microcline, and the z_p^* -axis of the pericline-twinned albite coincides with the z^* -axis of the microcline.

Although extreme care was taken with the measurement

Table 3-2. Precession photo data of K-feldspars and their albite phases as discussed in text. The albites as separate minerals and a monoclinic K-feldspar are also included in the table for comparative results.

ROCK TYPE	SAMPLE NO.	K-FELDSPARS								Na-FELDSPARS AS SECOND PHASE					
		ESTIMATED AMOUNT OF EACH K-FELDSPAR COMPONENT (WT %)	TWINNING/ INTERGROWTH	TYPE OF REFLECTIONS/ STREAKS	α* (0Gz)	γ* (0Gz)			ESTIMATE AMOUNT (WT %)	TWINNING/ INTERGROWTH	TYPE OF REFLECTIONS/ STREAKS	α* (0Gz)		γ* (0Gz)	
						UNTWINNED COMPONENT	TWINNED COMPONENT	WEIGHTED VALUES FOR MIXTURES				TRICLINICITY Δ K-FELDSPAR	UNTWINNED COMPONENT		TWINNED COMPONENT
K-FELDSPARS															
LAC DU BONNET GRANITE	PG-121	100% untwinned max. micro.	untwinned	sharp	90°25'(10)'	92°25'(9)'	-	-	1.00	-	-	-	-	-	-
	PG-135	100% twinned max. micro.	weak albite	diffused; strong albite, weak pericline	90°25'(8)'	-	92°22'(6)'	-	1.00	1	-	-	-	-	89°30'(20)'
	PG-152	" "	"	sharp	90°22'(8)'	-	92°12'(6)'	-	0.91	1	-	-	-	-	-
	SR-97	" "	"	diffused; strong albite, weak pericline	90°23'(8)'	-	92°20'(8)'	-	1.00	2	both	sharp	-	86°40'(10)'	88°30'(10)'
	SR-148	" "	pericline	diffused; strong pericline, weak albite	90°25'(8)'	-	92°13'(8)'	-	0.98	1	"	"	-	86°20'(15)'	89°15'(10)'
	PG-133	" "	weak albite, intergrowth	sharp	90°25'(8)'	-	92°13'(10)'	-	0.98	1	albite	diffused	-	86°22'(8)'	-
	PG-24	" "	albite	diffused; strong albite, weak pericline	90°25'(6)'	-	92°09'(6)'	-	0.95	1	"	"	-	86°20'(10)'	89°12'(13)'
	AEC-26	" "	weak albite	sharp	90°20'(10)'	-	92°15'(6)'	-	0.99	1	"	"	-	86°25'(6)'	89°35'(20)'
AEC-20	100% untwinned max. micro.	untwinned intergrowth	"	90°25'(10)'	92°28'(12)'	-	-	1.00	1	untwinned	sharp	86°15'(8)'	-	89°40'(8)'	
DRYDEN GRANITES	ZPG-07	100% twinned max. micro.	both	"	90°25'(8)'	-	92°25'(9)'	-	1.00	1	albite	diffused	-	86°17'(10)'	89°40'(6)'
	APG-05	" "	"	"	90°20'(8)'	-	92°24'(8)'	-	1.00	1	"	"	-	86°27'(10)'	-
	GPG-22	" "	"	"	90°25'(6)'	-	92°16'(6)'	-	1.00	1	"	sharp	-	86°25'(6)'	89°50'(8)'
	HG-01	50% " " 50% untwinned max. micro.	"	diagonal	90°27'(6)'	92°00'(6)'	92°23'(7)'	-	1.00	2	"	"	-	86°22'(6)'	89°15'(6)'
	MLG-01	100% " "	untwinned intergrowth	sharp	90°25'(8)'	92°22'(8)'	-	-	1.00	1	untwinned	"	86°20'(8)'	-	89°15'(13)'
	CG-03	100% twinned max. micro.	albite	triclinic transitional	90°23'(8)'	-	92°17'(6)'	-	1.00	2	albite	"	-	86°28'(8)'	89°17'(10)'
	SG-01	" "	weak albite	diffused; weak albite, weak pericline	90°25'(10)'	-	92°27'(11)'	-	1.00	1	"	diffused	-	86°25'(10)'	88°00'(15)'
DRYDEN PEGMATITES	MLP/NZ 01	30% " " 70% untwinned int. micro.	albite	monoclinic-triclinic transitional	90°15'(10)'	90°30'(10)'	92°18'(10)'	91°02'	0.45	1	untwinned	sharp	86°25'(15)'	-	-
	MLP/NZ 02	60% " " 40% twinned max. micro.	weak albite	"	90°15'(8)'	90°20'(8)'	92°25'(9)'	91°07'	0.49	1	albite	"	-	86°30'(8)'	89°20'(10)'
	MLP/NZ 05	30% " " 70% untwinned int. micro.	albite	"	90°15'(10)'	90°10'(10)'	92°03'(10)'	90°44'	0.34	3	"	"	-	86°25'(6)'	89°35'(10)'
	MLP/NZ 23	100% twinned max. micro.	both	diagonal	90°30'(8)'	-	92°26'(10)'	-	1.00	-	-	-	-	-	-
	MLP/NZ 24	40% " " 60% untwinned int. micro.	weak albite	monoclinic-triclinic transitional	90°15'(8)'	90°30'(8)'	92°00'(10)'	91°06'	0.48	1	albite	sharp	-	86°20'(8)'	89°30'(15)'
	MLP/NZ 30	60% " " 40% twinned max. micro.	albite	"	90°15'(8)'	90°20'(8)'	92°13'(10)'	91°05'	0.48	1	"	diffused	-	86°15'(8)'	-
	MLP/NZ 42	30% " " 70% untwinned int. micro.	"	"	90°10'(10)'	90°15'(8)'	92°23'(10)'	90°58'	0.38	1	"	"	-	86°08'(10)'	-
	MLP/NZ 47	55% " " 45% twinned max. micro.	"	"	90°15'(10)'	90°20'(8)'	92°20'(15)'	91°14'	0.53	1	untwinned	sharp	86°35'(8)'	-	-
	MLP/SZ 10	100% untwinned int. micro.	untwinned intergrowth	sharp	90°15'(8)'	91°30'(10)'	-	-	0.66	1	"	"	86°36'(10)'	-	88°52'(20)'
	MLP/SZ 06	40% " " 60% twinned int. micro.	weak albite	diffused; strong albite, weak pericline	90°20'(10)'	91°40'(10)'	91°40'(10)'	-	0.73	1	albite	"	-	86°18'(10)'	89°15'(10)'
	ZP-09	100% twinned max. micro.	both	sharp	90°25'(10)'	-	92°20'(6)'	-	1.00	1	"	diffused	-	86°18'(6)'	89°25'(6)'
	ZP-05	" "	albite, intergrowth	"	90°25'(6)'	-	92°27'(11)'	-	1.00	1	"	sharp	-	86°30'(6)'	88°55'(10)'
	GPE-11	" "	both	diagonal	90°20'(10)'	-	92°09'(6)'	-	0.95	1	"	diffused	-	86°30'(10)'	-
MONOCLINIC STANDARD	MONOCLINIC	100% monoclinic	-	sharp	90°00'(6)'	90°00'(6)'	-	-	0	-	-	-	-	-	-
ALBITES															
LAC DU BONNET GRANITE	PG-138 AB	3% K-feldspar	albite	diffused	90°10'(10)'	-	-	-	-	100	albite	sharp	-	86°37'(10)'	89°03'(6)'
DRYDEN GRANITE	CG-03 AB	-	-	-	-	-	-	-	-	"	-	"	86°20'(6)'	-	89°25'(6)'

of α^* angles between the y^* and z^* axes of these albite reflections, the results were rather ambiguous as only the 002 (and 004) were observable. Overlapping of 002 reflections of albite with those of microcline does occur frequently. The α^* angles range from $86^\circ 15'$ to $86^\circ 37'$ (Table 3-2). In many cases, the reflections are smeared, and these are discussed later.

(c) Zero-level around z-axis

(i) K-feldspars

For classification purposes, the author has arbitrarily divided the K-feldspars into three groups based on the γ^* angle: 1) metrically monoclinic K-feldspar with $\gamma^* = 90^\circ 00'$ to $90^\circ 05'$ (i.e. 90° within the range of error); 2) intermediate microcline with $\gamma^* = 90^\circ 06'$ (above instrumental error) to $91^\circ 59'$; and 3) maximum microcline with $\gamma^* = 92^\circ 00'$ to $92^\circ 18'$.

(1) Monoclinic K-feldspars ($\gamma^* = 90^\circ 00' - 90^\circ 05'$)

There are three more or less distinct monoclinic K-feldspar polymorphs: sanidine, adularia, and orthoclase. Sanidine is a high-temperature, volcanic, quenched, Al-Si disordered structure, and adularia is a late stage polymorph with a distinctive wedge-shaped habit. These two polymorphs are not expected among the granitic/pegmatitic K-feldspars being studied here. The third monoclinic K-feldspar polymorph is orthoclase. The term 'orthoclase' has been given

different meanings by different authors. None of the Lac du Bonnet and Dryden specimens contain orthoclase as defined by this classification scheme.

(2) Intermediate microclines ($\gamma^* = 90^\circ 06' - 91^\circ 59'$)

These microclines may be conveniently subdivided according to the presence or absence of albite- and/or pericline-twinning (see Table 2-3) as follows (with the number of the author's specimens shown in brackets):

- (a) untwinned (8)
- (b) albite-twinned (1)
- (c) pericline-twinned (0)
- (d) albite- + pericline-twinned (0)

Eight of the specimens (Table 3-2) show an untwinned intermediate microcline component with γ^* ranging from $90^\circ 15'$ to $90^\circ 30'$, and are mostly associated with albite-twinned maximum microclines in the Mavis Lake pegmatite. The one albite-twinned intermediate microcline specimen ($\gamma^* = 91^\circ 40'$) occurs with an untwinned intermediate microcline with the same γ^* angle in slightly different orientation (Table 3-1).

(3) Maximum microclines ($\gamma^* = 92^\circ 00' - 92^\circ 18'$)

The limiting value of γ^* of $92^\circ 18'$ for maximum microcline is that proposed by Ferguson (1982). Like intermediate microclines, these maximum microclines have been divided into the same four groups according to their twinning characteristics (Table 2-3) (the number of author's specimens are

shown in brackets):

- (a) untwinned (4)
- (b) albite-twinned (15)
- (c) pericline-twinned (1)
- (d) albite- + pericline-twinned (7)

The total of 27 of the 29 specimens (Table 3-2) are in this group, indicating that maximum microcline predominates over intermediate microclines and orthoclase; this is a typical situation in most Precambrian areas (Petr Černý, private communication, 1982; Marfunin, 1966). The γ^* values of the microclines listed in Table 3-2 are the averages of two readings if they are albite- (or pericline-) twinned, or four readings if they are albite- + pericline-twinned.

The presence of the one pericline-twinned microcline contradicts the observation made by Laves (1950) that pericline twinning is not found alone and that it is always associated with albite twinning. This has implications for the possible origin which is discussed later.

(ii) Albites

Again, as in the zero-level precession photos around the x-axis, the y^* -axis and the 0k0 reflections of the albite coincide with those of microcline, but the x^* -axis of albite is distinctly separated from that of microcline because the γ^* angle is smaller and the a^* period is longer than the corresponding values in microclines. A pair of albite-twinned

h00 reflections in albite is similar to a pair of albite-twinning 001 reflections in microcline on an x-axis photo in that the maximum separation between a pair of albite-twinning reflections is 1° or less. However unlike microcline, the albite reflections are not distinctly separated, but are rather smeared; this is discussed later.

(d) Types of reflections, streaks and the interface boundary

There are different types of reflections that are interpreted as dependent on the nature of the interface boundary between two twinned individuals. These reflections are sharp distinctive spots, strongly diffused streaks or weakly diffused streaks. Both types of streaks are of two types: parallel to y^* and parallel to x^* . The different kinds of reflections may occur in both the K-feldspars and the Na-feldspars, and are listed in Table 3-2. As K-feldspars are the main interest here, the observations and interpretations given below deal exclusively with K-feldspars, although the same observations and interpretations may also be applied to albites.

The different kinds of reflections may be classified into six categories:

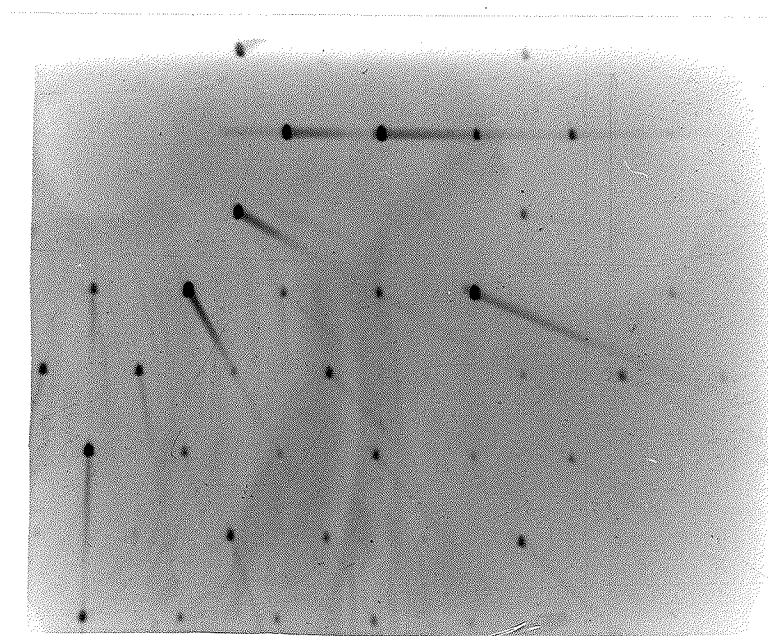
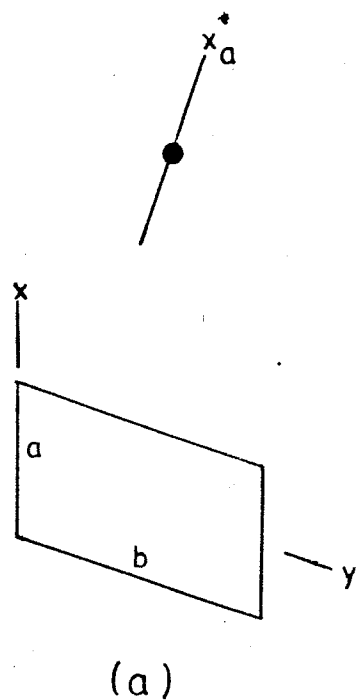
- (i) simple and sharp reflections
- (ii) diffuse streaks between strong albite-
and strong pericline-twinning reflections

- (iii) diffuse streaks between strong albite-reflections and weak pericline-twinned reflections (or vice versa)
- (iv) triclinic-monoclinic transitional streaks
- (v) triclinic transitional streaks
- (vi) untwinned intergrowth reflections

(i) Simple and sharp reflections (Figure 3-4a)

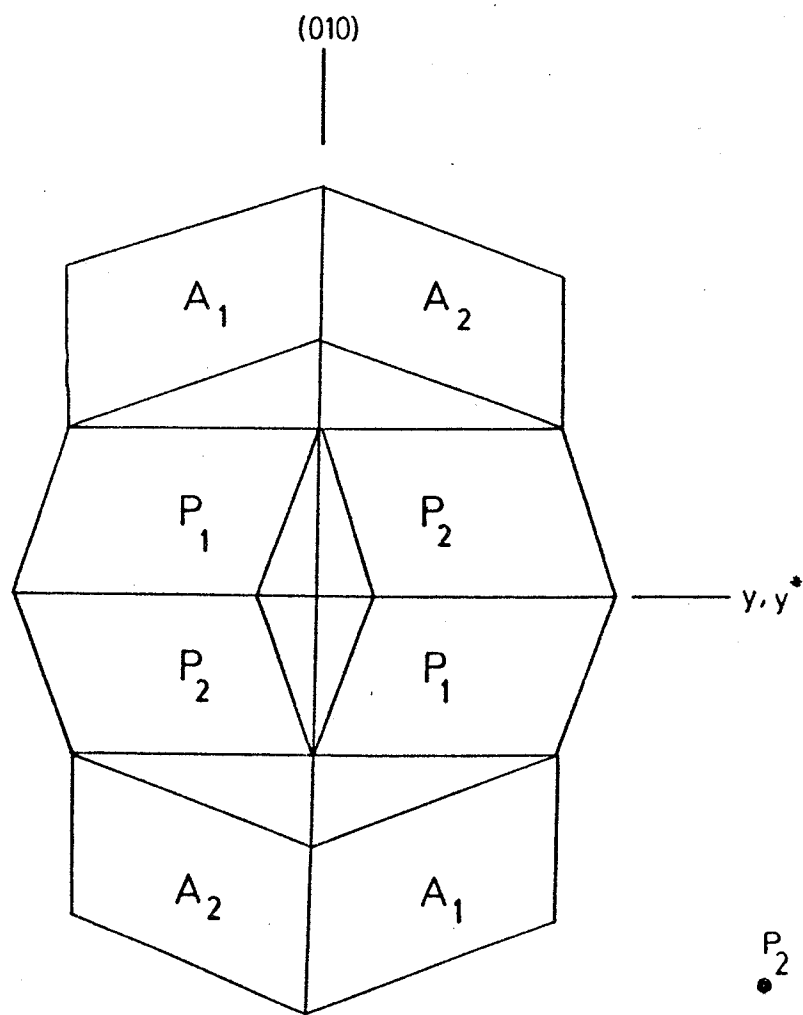
are characteristic of most untwinned crystals. For twinned crystals, there is evidence of a sharp well-defined boundary between two twinned individuals; such a boundary is known as an incoherent boundary. Of the 29 K-feldspar specimens examined here, all the untwinned microclines (both intermediate and maximum) and monoclinic K-feldspar (standard) have simple sharp reflections and also some twinned microclines for a total of 12 specimens. The albite + pericline-twinned microclines that show sharp reflections are interpreted as separate blocks of twinned individuals with incoherent boundaries (Figure 3-4b). In most cases, the reflections from both twinned individuals are of equal intensity, although there are also some cases where pairs are of unequal intensity implying that the volume of one twinned component is greater than that of the other. This may be interpreted as one albite lamella being wider than the other lamella (Figure 3-4c). Smith (1974b) called this "inequality" between units of the same twin law.

Figure 3-4. Drawings and photos of the various types of reflections and streaks and their interface boundaries which are discussed in text. The photos are enlarged parts of the lower right quadrant of each precession photo. The scales of the drawings are arbitrary. Designations: x_a^* = x-axis of one albite twin; x_a^* = x-axis of the other albite twin; A_1, A_2 = albite-twinned reflections; P_1, P_2 = pericline-twinned reflections; M = "monoclinic" (intermediate microcline) component; S = sharp; T = transitional.



(PG-121)

Figure 3-4 (a). Simple and sharp reflections.



(b)

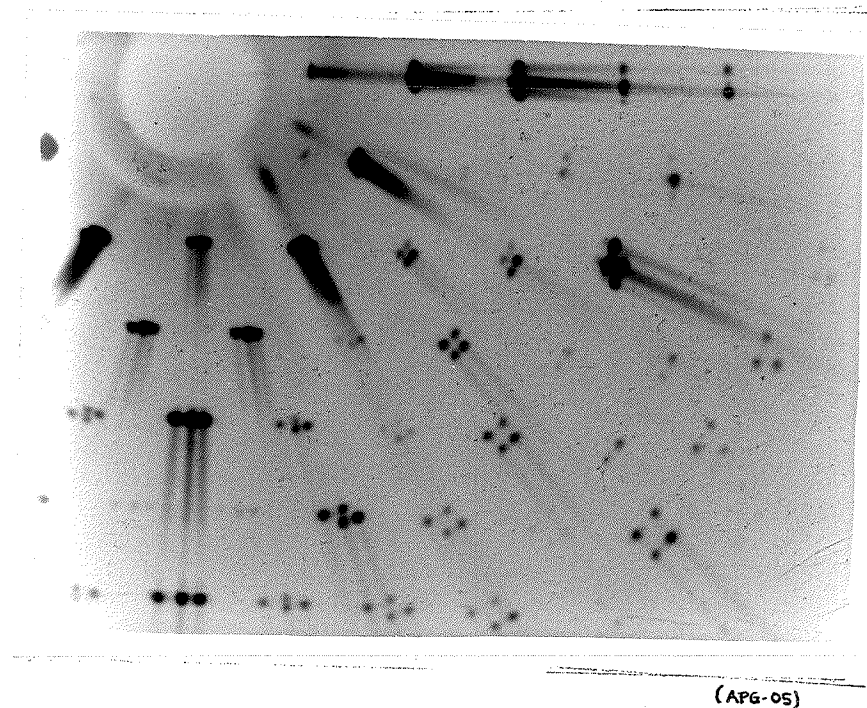
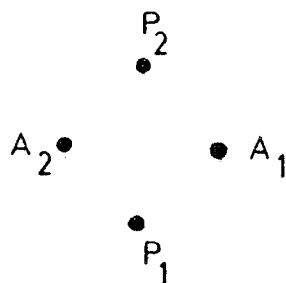
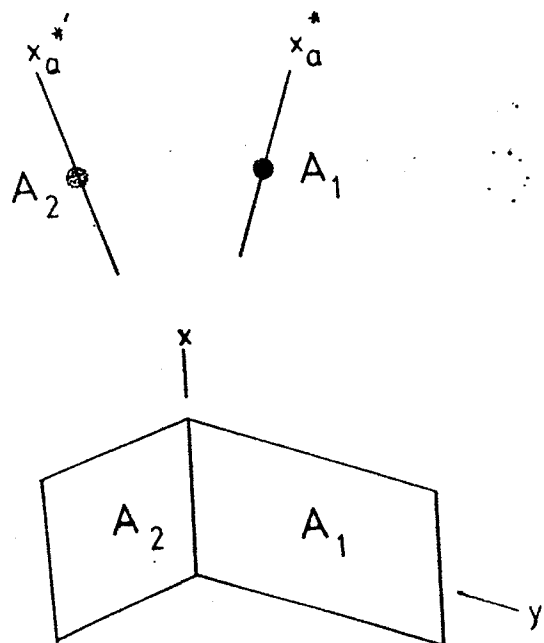
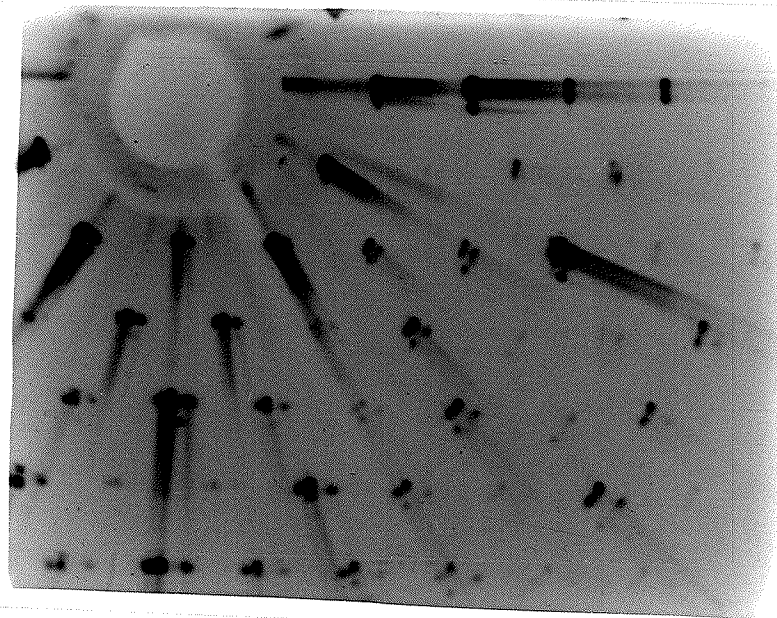


Figure 3-4 (b). Albite + pericline-twinning sharp reflections suggest separate blocks of twinned individuals with incoherent boundaries.



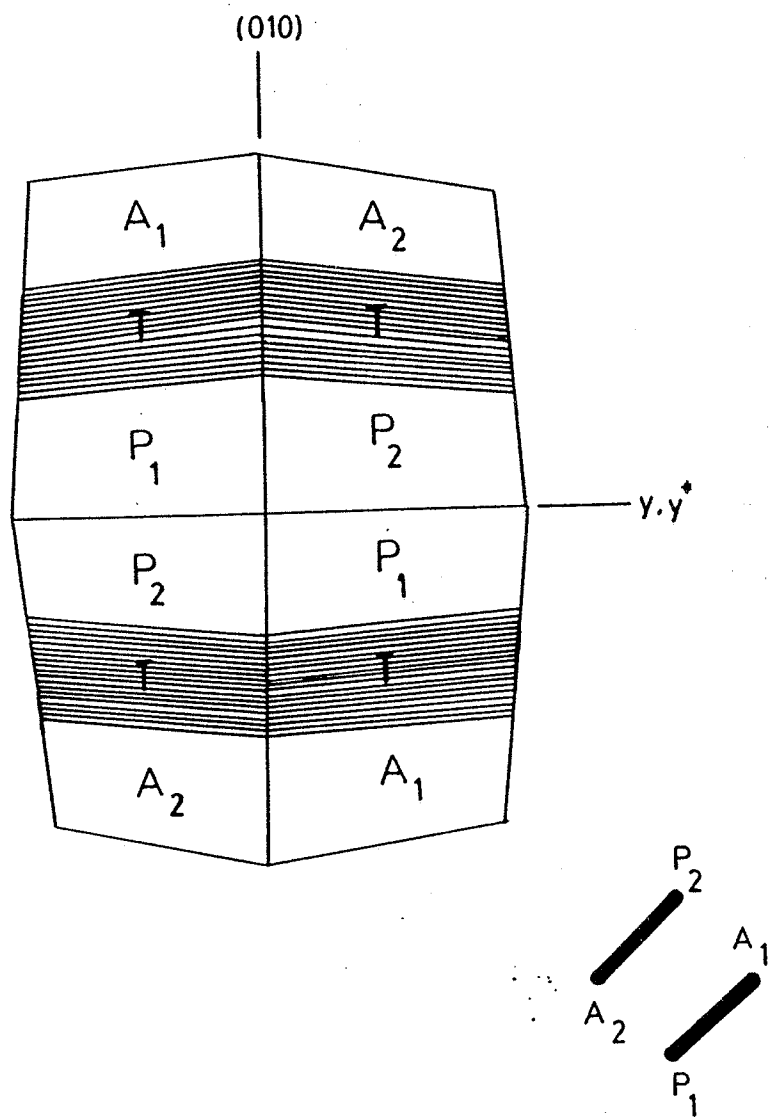
(c)



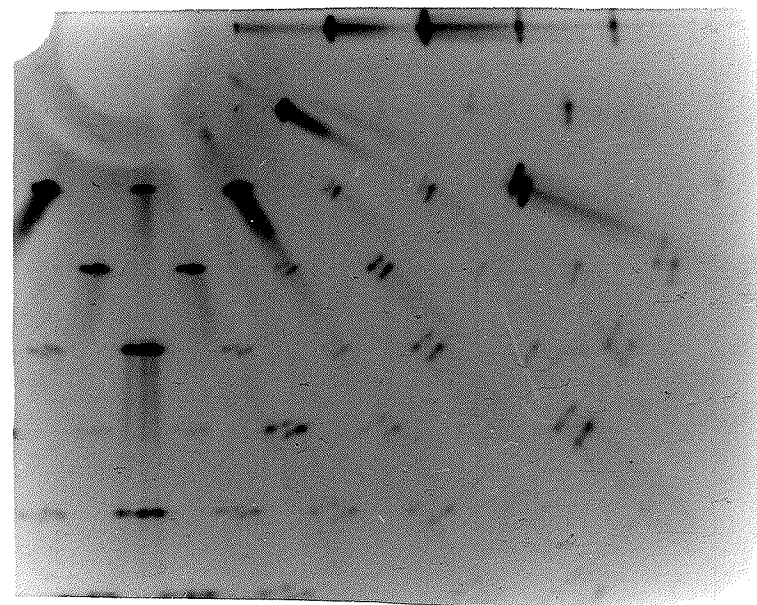
(GPG-22)

Figure 3-4 (c). Pairs of reflections of unequal intensity denoting one lamella (albite) being wider than the other lamella.

(ii) Diffuse streaks between strong albite- and strong pericline-twinning reflections (Figure 3-4d) are seen in three Lac du Bonnet and Dryden K-feldspars. Instead of three sharp axial reflections along both y^* - and x^* -axes (Figure 3-4b), there is only one streak across an axis such that the streak is parallel to either x^* of the pericline twins or to y^* of the albite twins. Similarly, instead of four twinned non-axial reflections, there are two parallel streaks (connecting A_1 to P_1 and A_2 to P_2) which are diagonal with respect to the axes. For both axial and non-axial reflections, the streaks are connecting an albite reflection to a pericline reflection (i.e. A_1 to P_1); they do not connect two albite or two pericline reflections. This suggests that the crystal is not composed of separate blocks of twinned individuals and that it is slightly twisted to accommodate both albite and pericline twins together. The boundary between albite and pericline reflections is coherent where it is diffuse rather than sharp (however, the boundary between the two albite reflections or between the two pericline reflections is incoherent). The streaks may also be interpreted as due to regions of transitional structure between albite and pericline twins. The fact that the two parallel streaks are strong and continuous from A_1 to P_1 and A_2 to P_2 indicates that the cell volumes of the transitional structure between the end members A_1 and P_1 , which have the



(d)



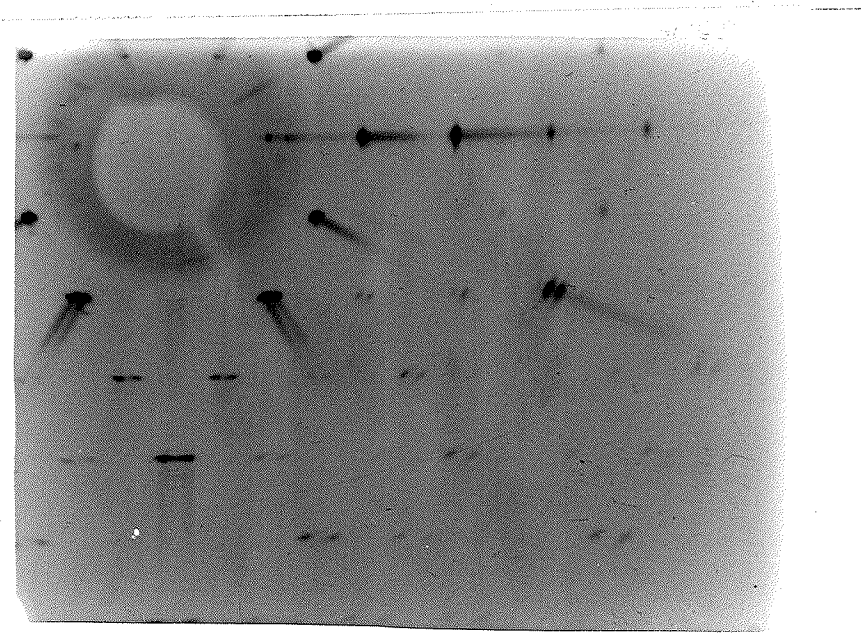
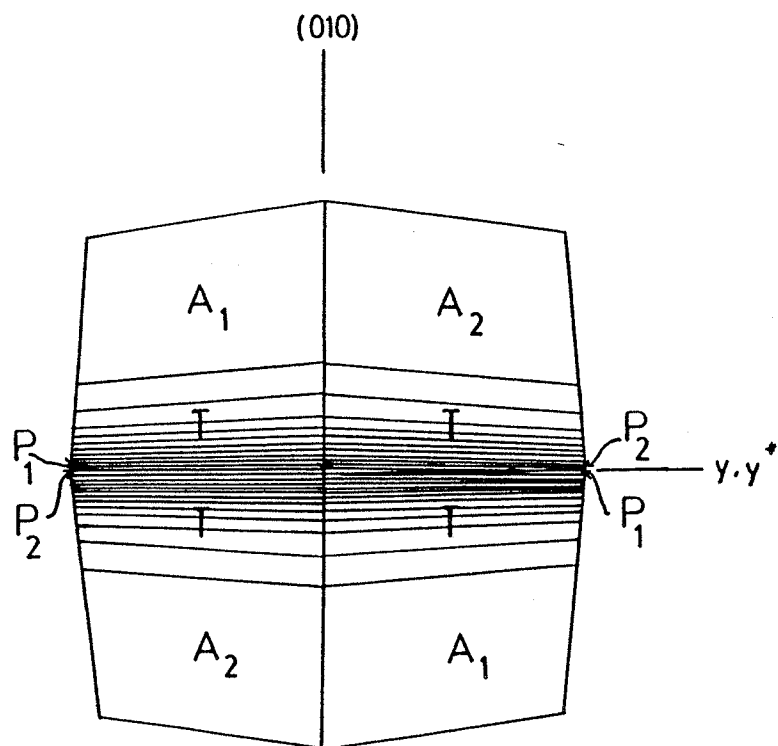
(GRE-II)

Figure 3-4 (d). Diffuse streaks between strong albite- and strong pericline-twins denote a coherent boundary. Both twin volumes are the same.

same volumes, has to be the same as the volume of one end member (i.e. A_1).

(iii) Diffuse streaks between strong albite- and weak pericline-reflections (or vice versa) (Figure 3-4e) are very similar to those described above. The major difference lies in the different cell volumes of albite- and pericline-twins. Strong albite- and weak pericline-twinning reflections (as seen in five K-feldspars) show weak diffuse streaks across the axes and weak diagonal streaks. The diagonal streaks are strongest in intensity at A_1 and A_2 , gradually decreasing towards and disappearing at P_1 and P_2 respectively. This suggests that the volumes of the pericline twins are much smaller than those of the albite twins. This interpretation may also be applied to those K-feldspars showing diffuse streaks between strong pericline- and weak albite-twins as seen in one of the specimens.

(iv) Triclinic-monoclinic transitional streaks (Figure 3-4f), which are seen in seven K-feldspar specimens, are similar to the two previous types of streaks in that they appear along the principal axes parallel to x^* of the pericline twins and y^* of the albite twins. However, the non-axial streaks are completely different: those that connect two albite-twinning reflections with the monoclinic reflection in the middle are parallel to the y^* axes for all non-axial reflections. The pericline-twinning reflections are



(SR-97)

(e)

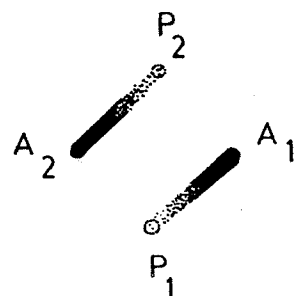
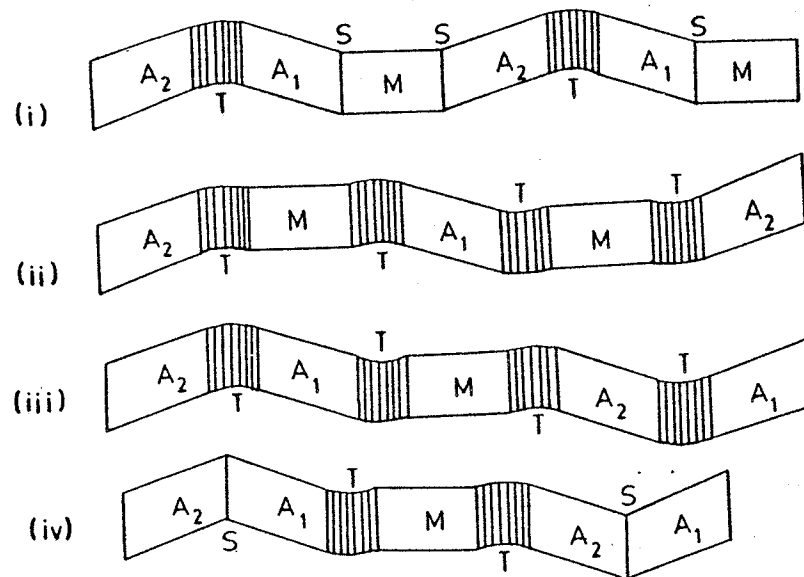


Figure 3-4 (e). Diffuse streaks between strong albite- and weak pericline-twins suggest larger albite-twin volumes than pericline twin volumes.

present, particularly along the y^* -axis, but away from the axis they disappear and so they are considered as a very minor component here. The K-feldspar crystal is interpreted as a transitional structure in which the maximum microcline component is connected to the monoclinic component by a large number of twinned intermediate microclines with geometries that range from nearly maximum microcline to nearly monoclinic. The intermediate microclines are of smaller cell volumes than either the maximum microcline or the monoclinic components. The boundaries between the two albite individuals and the monoclinic component can be interpreted in four different ways:

- (1) coherent between each maximum microcline albite-twinned individual (i.e. transitional with a large number of intermediate microclines that also include a small cell volume of a monoclinic geometry between the pair of albite twins) and incoherent between maximum microcline and the monoclinic component (Figure 3-4f(i));
- (2) coherent between one albite-twinned maximum microcline individual and the monoclinic component, and again coherent between the monoclinic component and the other albite-twinned individual (Figure 3-4f(ii));
- (3) coherent between each albite-twinned maximum microcline individual and coherent between maximum microcline and the monoclinic component (Figure 3-4f(iii));



A₂ M A₁

(f)



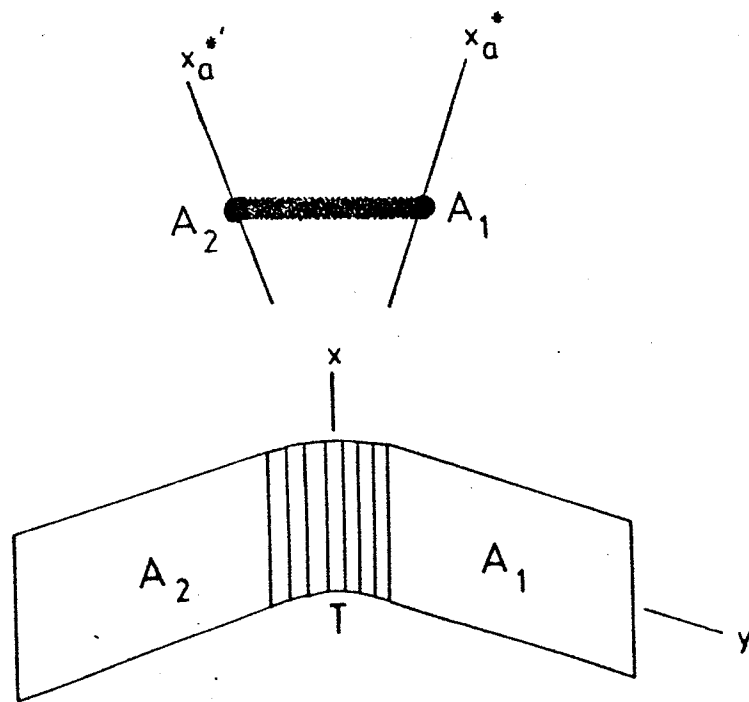
(MLP/NZ 02)

Figure 3-4 (f). Triclinic-monoclinic transitional streaks suggest that the microcline is a transitional structure between maximum microcline to nearly monoclinic phase. The boundary is either one of the four illustrate above.

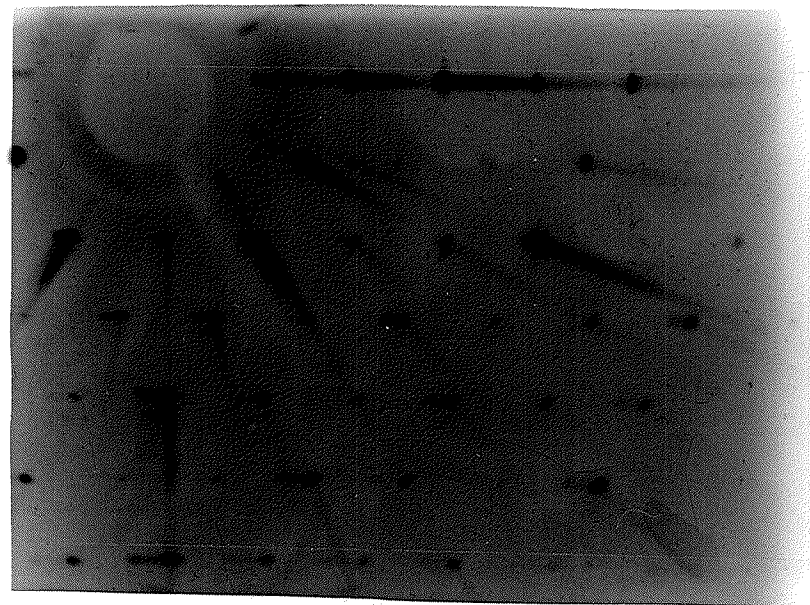
(4) incoherent between a pair of albite-twinned maximum microcline individuals and coherent between maximum microcline and the monoclinic component (Figure 3-4f(iv)).

(v) Triclinic transitional streaks (Figure 3-4g) are very similar to the triclinic-monoclinic transitional streaks where both types of streaks show both axial and non-axial streaks parallel to the y^* -axis of the albite twins. The difference lies in the absence of the monoclinic component in the triclinic transitional streaks. The streaks are composed of a large number of twinned intermediate microclines with geometries that range from nearly maximum microcline to monoclinic. Again, the cell volumes are smaller than those of maximum microcline. The boundary between the albite-twinned maximum microcline individuals is interpreted to be coherent. This type of streak is not common as only one of the 29 K-feldspar specimens studied shows this feature.

(vi) Untwinned intergrowth reflections (Figure 3-4h) were observed in five of the specimens in which regular splitting of the y^* - and x^* -axes could not be reasonably interpreted as due to any type of twinning. Such reflections were interpreted as due to large quasi-parallel blocks of structure with the same geometry. The structures were shifted, perhaps by some mechanical forces. Pieri & Quarenì (1972) have observed the same characteristics in some of their anorthoclase specimens, and attributed this to a particular type of growth process which persisted through high

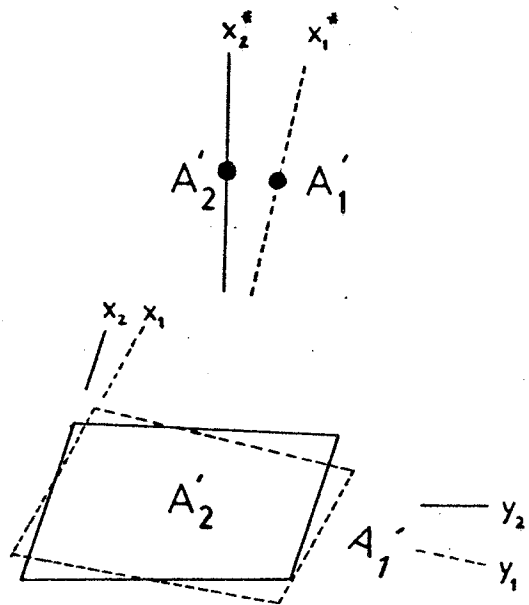


(g)

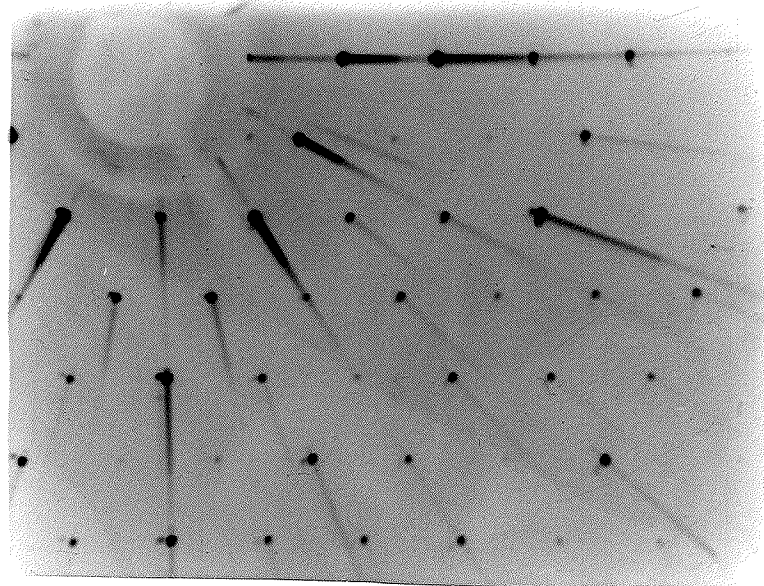


(CG-03)

Figure 3-4 (g). Triclinic transitional streaks which result from a large number of twinned intermediate microclines that range from nearly maximum microcline to nearly monoclinic K-feldspar.



(h)



(MLG-01)

Figure 3-4 (h). Untwinned intergrowth reflections denote large blocks of quasi-parallel structure.

temperatures ($\sim 850^{\circ}\text{C}$).

(5) Summary of results

The five main characteristics of K-feldspars observed in precession photos- (a) twinning and type of reflections/streaks; (b) nature and number of K-feldspar phases; (c) reciprocal cell angles; (d) triclinicity; and (e) albite as a second phase are summarized in Table 3-2.

(a) Twinning and type of reflections/streaks

The twinning and type of reflections/streaks of each K-feldspar specimen have been discussed in detail earlier in this chapter. They are summarized further in Table 3-3.

(b) Nature and number of K-feldspar phases

Twenty K-feldspars studied are single phase maximum microclines; two are intermediate microclines (one is single phase and the other is two-phase) and the other seven microclines are multiple phase microclines of a dominantly untwinned intermediate microcline component and a minor albite-twinned maximum microcline component (Table 3-2).

(c) Reciprocal cell angles γ^* , α^* of K-feldspars

Figure 3-5, which is a plot of α^* versus γ^* for the K-feldspar phase, shows that there is a good agreement, within the experimental error, of all data. The plot also shows three distinct groups: (1) maximum microclines; (2) intermediate microclines; and (3) mixed microclines.

As seen earlier in Table 3-2, there are two γ^* values

TABLE 3-3. Summary of twinning characteristics and type of reflections/streaks in all K-feldspar specimens.

TWINNING CHARACTERISTICS	# OF SPECIMENS	TYPE OF REFLECTIONS/STREAKS	# OF SPECIMENS
UNTWINNED	4	Simple & sharp reflections	12
ALBITE-TWINNED	9	Diffuse streaks between strong albite and (diagonal microclines)	3
ALBITE- + PERICLINE-TWINNED	6	Diffuse streaks between strong-albite and weak pericline reflections	5
MIXED: TWO K-FELDSPAR COMPONENTS			
(a) UNTWINNED WITH ALBITE-TWINNED	8	Diffuse streaks between weak albite and strong pericline reflections	1
(b) UNTWINNED WITH ALBITE- + PERICLINE-TWINNED	1	Triclinic-monoclinic transitional streaks	7
		Triclinic transitional streaks	1
		Untwinned intergrowth reflections	5

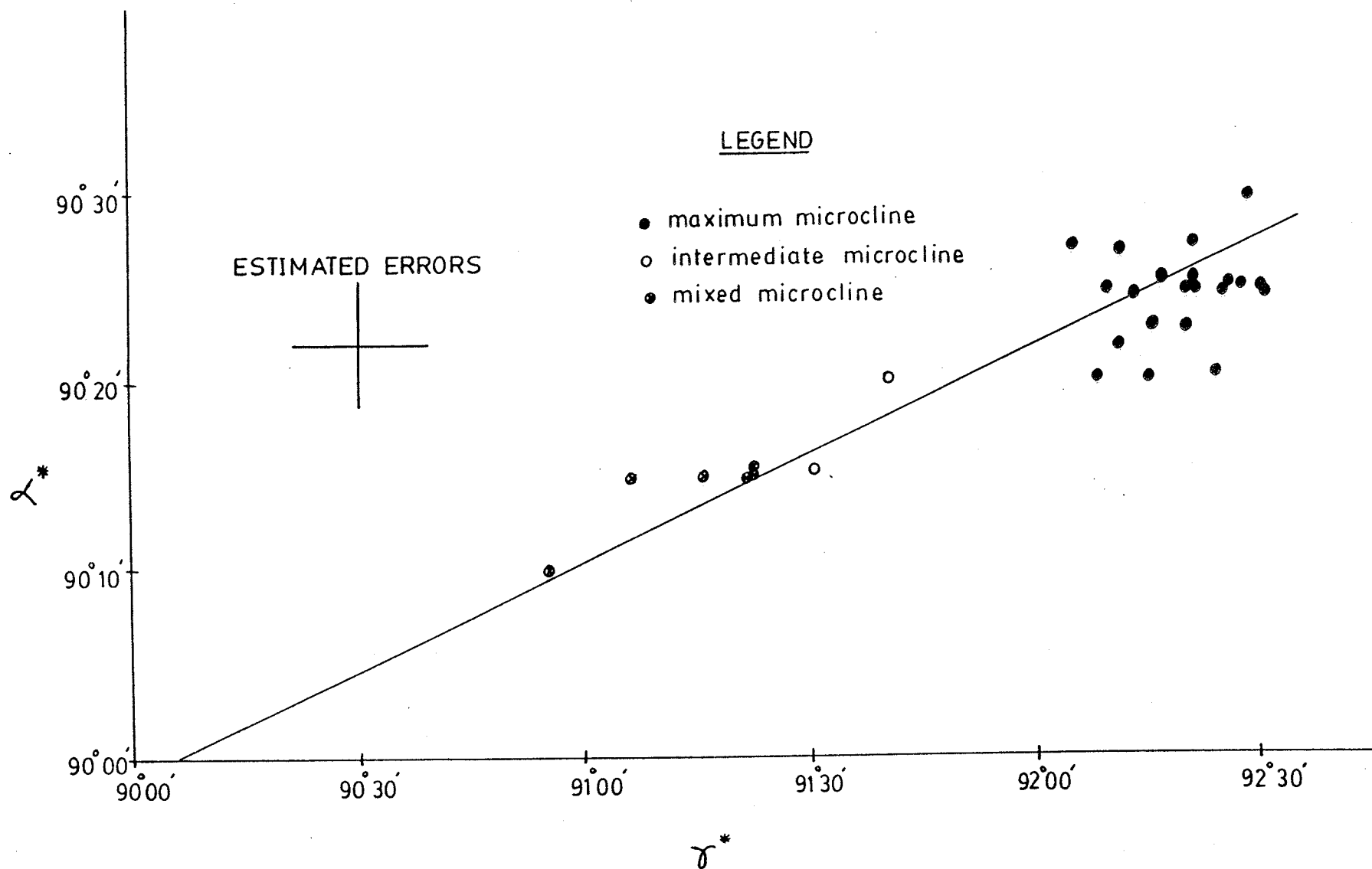


Figure 3-5. Plot of α^* vs. γ^* of K-feldspars from precession photo data. The values for the mixed microclines are weighted values as discussed later in the text. The solid line is the linear regression for a number of microclines that have been refined and listed in Ferguson (1980, 1982); the equation for this line is $\alpha^* = 0.198 \gamma^* + 72.183$. The bar is the estimated error which is $\pm 08'$ for both α^* and γ^* . The solid line does not go through 90° , presumably due to experimental error.

and only one α^* for each microcline. These were originally plotted on the γ^* vs. α^* diagram of microclines (Figure 3-5) but fell well off the regression line. Hence it was necessary to give the weighted γ^* value for every α^* value. The γ^* values plotted on the diagram in Figure 3-5 are weighted according to the relative amounts of both triclinic phases. For instance, the γ^* angle used for specimen MLP/NZ 01 is 70% of $90^\circ 30'$ + 30% of $92^\circ 18'$ to give $91^\circ 02'$. The γ^* angles for the other specimens showing two triclinic phases are: $91^\circ 07'$ for MLP/NZ 02; $91^\circ 05'$ for MLP/NZ 30; $90^\circ 58'$ for MLP/NZ 42; $90^\circ 44'$ for MLP/NZ 05; $91^\circ 06'$ for MLP/NZ 24; and $91^\circ 14'$ for MLP/NZ 47. The γ^* values along with the corresponding α^* values lie close to the straight line of Figure 3-5.

(d) Triclinicity Δ

The triclinicity of K-feldspars is easily calculated by the ratio below:

$$\Delta = \frac{\gamma^* \text{ of a given K-feldspar} - 90^\circ}{\gamma^* \text{ of an ideal maximum microcline } (92^\circ 18') - 90^\circ}$$

For example, a K-feldspar with $\gamma^* = 91^\circ 30'$ would have $\Delta = \frac{1^\circ 30'}{2^\circ 18'} = 0.66$. The triclinicity of all single phase maximum microclines as seen in precession photos ranges from 0.91 to 1.00 and 0.65 to 0.75 for intermediate microclines (Table 3-2). Since the mixed microclines have two γ^* values, there are two ranges of triclinicity values: $0.10 < \Delta < 0.25$ for the untwinned component and $0.87 < \Delta < 1.00$ for the twinned component. Table 3-2 gives the weighted Δ value of each

mixed microcline.

(e) Albite as a second phase

Each albite intergrowth appears to be very weak as compared to the associated microcline. The amount of albite, which is visually estimated by comparing the albite reflections with the corresponding microcline reflections, ranges from non-observable to 3%. Table 3-2 shows that 5 of the albite phase are untwinned, 18 are albite-twinned, 2 are albite- + pericline-twinned, and 4 are not determined. Table 3-2 also shows that there are two types of reflections: sharp (15 specimens) and diffuse (10 specimens).

Figure 3-6 shows a plot of α^* vs. γ^* of the albite phase in microclines. It was found that γ^* may be plotted as either obtuse or acute. Upper level photography would show the correct γ^* angles but there was insufficient time available to do it. The γ^* angles have been arbitrarily plotted as acute because they then fit closer to the lines plotted on the diagram of Figure 3-6. The results are in the range intermediate between low albite and high albite (known as intermediate albites in terms of geometry). As seen later in Chapter IV, electron microprobe analysis of some of these albitic phases show them to be Ca-poor, and this can be taken as further evidence that they are intermediate albites. There are no distinct albite groups.

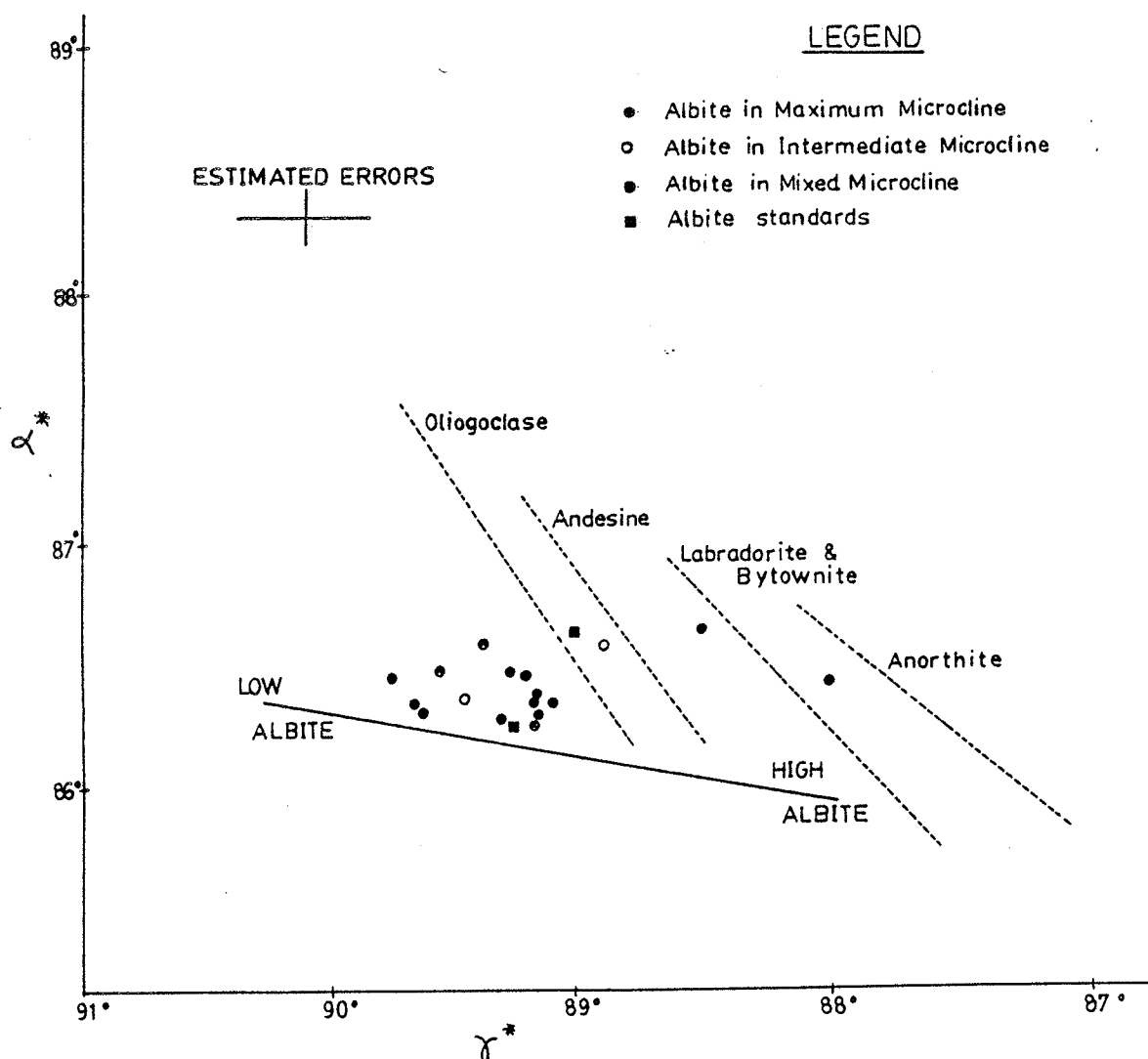


Figure 3-6. Plot of α^* vs. γ^* of albite phases in 18 of the microclines from precession photos plus two albite standards (after Smith, 1974a, Figure 7-52d, p. 335). The γ^* values for all specimens have been arbitrarily taken as acute as discussed in text. The bar is the estimated error which is $\pm 09'$ for α^* and $\pm 15'$ for γ^* . One sample had a low γ^* value that may be due to an incorrect γ^* reading.

(6) Discussion

(a) Distribution of observed phases among granitic and pegmatitic rocks

Twenty-six samples analyzed (Table 3-1) out of a total of the 29 specimens are intermediate and/or maximum microclines with an albite phase. Fifteen of the samples show both microcline and albite phases with the same twinning characteristic. Most of the untwinned microclines (both intermediate and maximum) and untwinned albite phases tend to be associated together in perthites. Similarly, most of the albite-twinned albite phases are commonly associated with albite-twinned microclines. Barth (1969) postulated that primary twins are frequent in metamorphic rocks, in which the mechanism of growth may be influenced by an early pre-existing crystal. Smith (1962) also observed the same behavior. Smith (1974b) named this mechanism "epitaxial inheritance". This suggests that albite and microcline formed an epitaxial relationship. For example, an albite exsolved from sodium in solid solution in a twinned microcline (i.e. albite-twinned) may be also be twinned (albite-twinned) in the same crystallographic orientation as the microcline. If the microcline is untwinned, it is possible that albite may also be untwinned. Fifteen out of the 29 specimens give strong support for this growth mechanism.

(b) Type of albite- + pericline-twinning

Of the three different types of albite- + pericline-twinning (M-twinning, T-twinning and Z-twinning) discussed earlier in this chapter, all the microclines examined in this study show only M-twinning, although some show diagonal streaks similar to Figure 3-4d. Blasi & Blasi (1980) have made similar observations on their microperthite specimens which are all M-twinning microclines with diagonal streaks similar to Figure 3-4d. All the names of different types of albite- + pericline-twinning described earlier have been given to single crystals that were recorded by b-axis x-ray oscillation photography (Smith & Mackenzie, 1955). Unlike precession photography, oscillation photos show distorted reciprocal lattices of single crystals. Some of the precession photos show all four components having uneven intensities such that one component may be so faint that it give a false appearance of a "T"-type twinning. Up to the present time, there has been no evidences of different albite- + pericline-twinning other than M-twinning recorded in precession photos.

(c) Perpendicularity of the twin axes and planes

In Figure 3-7, the angle γ_{t_2} between the common x^* axes of a pair of pericline-twins (x_p^*) and the common y^* axes of a pair of albite-twins (y_a^*) deviates from 90° by the same amount (within experimental error) as the angle γ_{t_1} ,

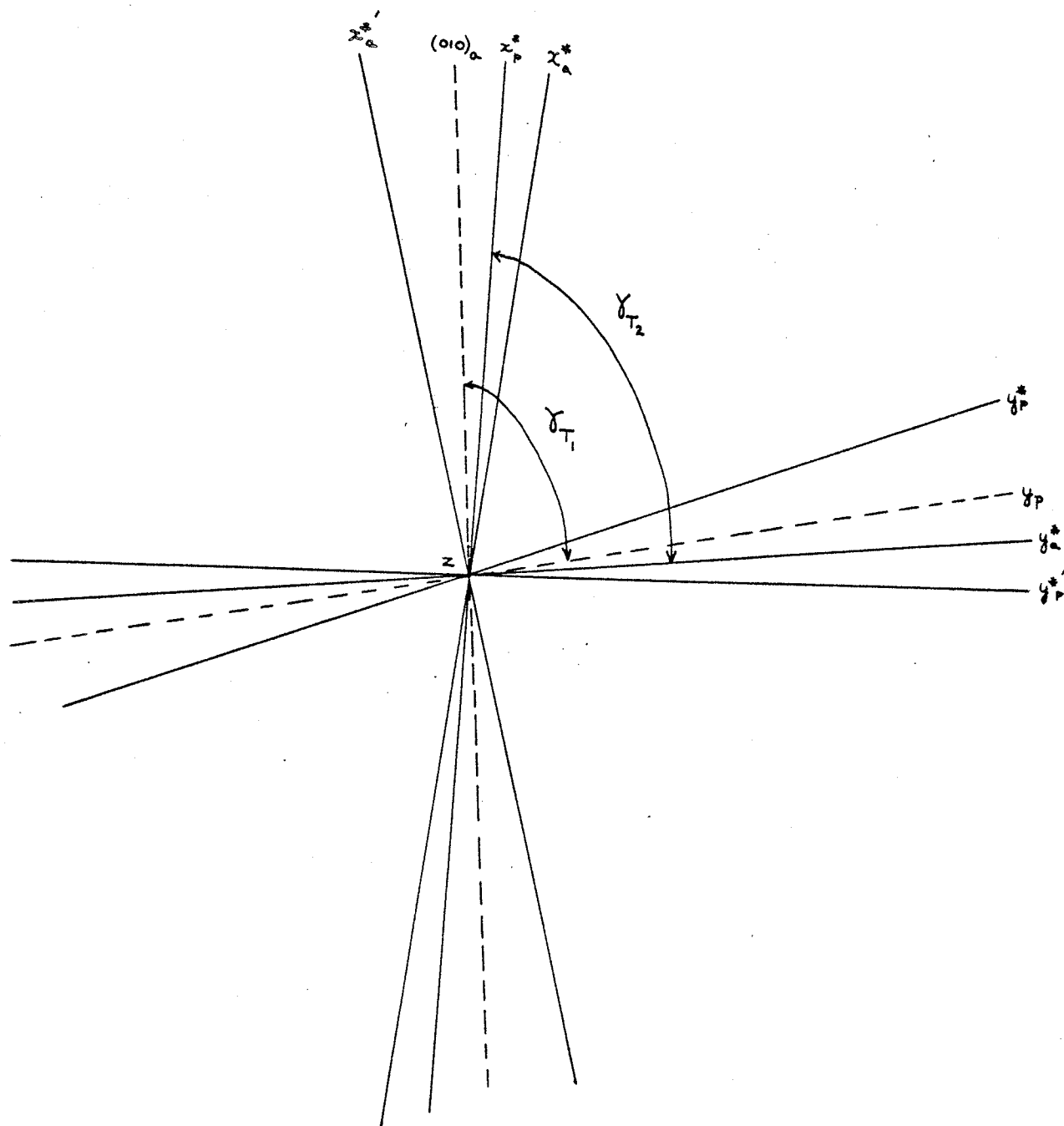


Figure 3-7. Diagrammatic representation of the axes on a zero-level precession photo around z to explain certain interaxial angles. The angles between certain of the axes are slightly exaggerated for this albite- + pericline-twinned microcline. For further explanations, see text.

Table 3-4. Precession photo readings of the y_p -axes, the $(010)_a$ plane, the y_a^* -axes, the x_p^* -axes and some interaxial angles as discussed in text. The angle between y_p -axis and x_p^* -axis and between $(010)_a$ plane and y_a^* -axis should be exactly 90° ; the deviation from 90° has been taken as the error of the reading.

SAMPLE		MIDLINES OF ALBITE + PERICLINE TWINS				x_p^* OF PERICLINE TWINS + y_a^* OF ALBITE TWINS			
		y_p -axis	trace of $(010)_a$ plane	angle	deviation from 90°	y_a^* -axis	x_p^* -axis	angle	deviation from 90°
ALBITE K-FELDSPARS (OGZ)	ZP-09	$180^\circ 05'$	$89^\circ 50'$	$90^\circ 15'$	$+15'$	$179^\circ 50'$	90°	$89^\circ 50'$	$-10'$
	GPE-11	$359^\circ 58'$	$89^\circ 57'$	$90^\circ 01'$	$+01'$	360°	$89^\circ 55'$	$90^\circ 05'$	$+05'$
	ZPG-07	$359^\circ 26'$	$90^\circ 08'$	$90^\circ 34'$	$+34'$	360°	$89^\circ 30'$	$90^\circ 30'$	$+30'$
	APG-05	$89^\circ 30'$	$179^\circ 55'$	$90^\circ 25'$	$+25'$	90°	$179^\circ 40'$	$89^\circ 40'$	$-20'$
	GPG-22	$270^\circ 53'$	$359^\circ 55'$	$89^\circ 02'$	$-58'$	270°	$360^\circ 50'$	$90^\circ 50'$	$+50'$
	HG-01	$270^\circ 15'$	$360^\circ 08'$	$89^\circ 53'$	$-07'$	270°	$360^\circ 15'$	$90^\circ 15'$	$+15'$
	MLP/NZ-23	$359^\circ 55'$	$270^\circ 03'$	$89^\circ 52'$	$-08'$	$360^\circ 10'$	270°	$90^\circ 10'$	$+10'$
	PG-152	$180^\circ 12'$	270°	$89^\circ 48'$	$-12'$	180°	$270^\circ 22'$	$90^\circ 22'$	$+22'$
	SR-97	$269^\circ 40'$	360°	$90^\circ 20'$	$+20'$	270°	$359^\circ 48'$	$89^\circ 48'$	$-12'$

between the y_p axis and the trace of $(010)_a$ plane within each sample. However, the trace of the $(010)_a$ plane does not coincide with the x_p^* axis, and the y_p axis does not coincide with y_p^* axis (Table 3-4). This information does not favour the monoclinic precursor theory but suggests rather that albite and pericline twinings act independently of each other.

For many of the albite- + pericline-twinned microclines examined in this study, the angle (γ_t in Figure 3-7) between $(010)_a$ and y_p is not exactly 90° . Of the seven microclines and two albite phases that are albite- + pericline-twinned, four are within or very close to the estimated error of $08'$. The deviations on both sides of 90° range from $15'$ to a maximum departure of $58'$. This deviation is equivalent to the angle between y -axis and y^* -axis of albite-twinned (y_a^*) microcline of Laves & Soldatos (1963) (their deviation from 90° ($20'$) for their seven specimens is less than those of the author's specimens). This seems to contradict the theory of a monoclinic precursor because if an albite- + pericline-twinned K-feldspar actually did derive from a monoclinic phase, then the $2/m$ symmetry elements could be expected to be preserved in the triclinic twinned assemblage such that the implied twin elements (010) and $y[010]$ would be mutually perpendicular. However, three of the specimens have deviation from 90° within the limit of error,

which suggests that a monoclinic precursor for these three specimens is a strong possibility. Laves & Soldatos (1963) acknowledged deviation from 90° above the limit of error in some of their specimens, and attempted to explain this deviation by a "distorted" -microcline twinning in order to support the monoclinic precursor theory. They suggested that this deviation from 90° resulted from accidental factors such as stress acting from outside the crystal to cause one twin domain to become dominant. Smith (1974b) suggested another factor: asymmetric mixing of albites from crypto-perthites.

(d) Albite- vs. pericline-twin γ^* readings

Table 3-5 shows that for albite- + pericline-twinned microclines and albites, there are significant differences between the γ^* values derived from the albite twins and those derived from the pericline twins (and similarly for the α^* values for albites). This can be taken as further disapproval of the monoclinic precursor theory because if the (010) twin plane is such that it is perpendicular to the y-axis, the albite twins and pericline twins could then be expected to influence each other in such way that one set of γ^* (and α^*) angles would be consistently higher than the other. This is not the case for the author's specimens. This is in conflict with Smith (1974b) who shows that the α^* angles of albite-twinned albites tend to be higher than those of

Table 3-5. Average γ^* values and ranges for each albite-twinned individual and for each pericline-twinned individual of microclines and comparable values for α^* of albites.

SAMPLE		ALBITE TWINS		PERICLINE-TWINS	
		MEAN OF PAIR OF γ^*	RANGE	MEAN OF PAIR OF γ^*	RANGE
K-feldspar γ^*	ZP-09	92° 25'	± 05'	92° 14'	0'
	GPE-11	92° 17'	± 08'	92° 02'	± 03'
	ZPG-07	92° 22'	± 08'	92° 28'	± 07'
	APG-05	92° 15'	± 05'	92° 14'	± 09'
	GPG-22	92° 20'	± 05'	92° 12'	± 03'
	HC-01	92° 27'	± 08'	92° 25'	0'
	MLP/NZ-23	92° 25'	± 05'	92° 27'	± 08'
Albite α^*	PG-152	86° 15'	0'	86° 22'	0'
	SR-97	86° 35'	0'	85° 25'	± 22'

pericline-twinning albites.

(e) Mixed microclines

Smith (1974b) compiled data from many sources, showing that a number of K-feldspars have monoclinic x-ray patterns with streaked reflections that he interpreted as indicating the presence of intimate domains with a triclinic distribution of Al and Si atoms. A great majority of them came from granitic pegmatites. Smith (1974b) suggests that when microcline and "monoclinic" K-feldspar coexist in single grains, they indicate an incomplete inversion to microcline from a monoclinic precursor.

(f) Type of twinning mechanism

Akizuki (1972) proposed that "microcline twins" (that is, albite plus pericline twins) may be formed by one or more of several mechanisms: during growth, by transformation, by recrystallization, by replacement, and by mechanical shear. According to Smith (1974b), a general factor concerning all twins is the energy associated with the twin boundary. No matter what the mechanism of twinning, a high energy across a potential twin boundary should inhibit twinning. Putnis & McConnell (1980) further added that the albite twin plane has a lower energy than the pericline twin plane and may be expected to be the more favourable. Such twinning is very common in albite and may also form during growth. Smith (1974b) observed that there have been no x-ray diffraction

studies of twins to determine whether the different possible mechanisms can be differentiated. He predicted that:

1) simple growth twins should obey strictly the orientation requirements of the twin law; 2) transformation twins should inherit the original symmetry elements as twin elements; 3) mechanical twins should show streaks and multiple diffractions resulting from lattice strain.

(g) Implications of diffuse or smeared reflections

It was observed earlier that the reflections of both microcline and albite phase range from sharp well-defined spots to diffuse spots. Diffuse reflections are particularly conspicuous in zero-level precession photos around the z-axis for microclines and around the x-axis for albites. Different interpretations have been made about these smeared or diffuse reflections.

In the case of microclines, Laves (1950) explained this feature as incomplete triclinic transformation from a monoclinic precursor, with intermediate states in intermediate positions or atomic arrangements. Smith (1974b) further added that the streaks might be due to a development of domains with microcline-like distribution of T atoms and a geometry distorted by clamping to neighbouring atoms.

On the other hand, the smeared or diffuse reflections of albite are interpreted by Smith (1974b) as a result of variable repeated distance of the twin boundaries across the

crystal. In addition, Laves (1952) proposed that this was a result of polysynthetic twinning with the twin boundaries spaced only a few unit cells apart.

(h) Implication of pericline-twinning only microcline

It was observed earlier that one of the microclines studied had diffuse streaks between strong pericline- and weak albite-twinning reflections. Because the albite reflections were so weak, the author considered this as pericline-twinning only microcline (sample no. SR-148). Up to the present time, there is no other data in the literature that reports a pericline-twinning only microcline. Laves (1950) observed that pericline twinning was not found alone and that it was always associated with albite twinning.

(B) POWDER-TYPE GANDOLFI PHOTOGRAPHY

(1) Introduction

Powder-type Gandolfi photos were taken of the same single crystals that were used in precession photography. Four main kinds of information are expected for K- and Na-feldspars from the Gandolfi photography: 1) triclinicity of the K-feldspars; 2) nature of different K-feldspar phases; 3) presence/amount of a Na-feldspar as a second phase; and 4) cell refinement data of K-feldspars.

The author has found that the Gandolfi photography is invaluable in the interpretations of precession photography

of the same crystal. Confusion in interpreting precession photos that show split reflections and diffuse streaks has been eliminated when associated with Gandolfi photos.

(2) Triclinicity

For K-feldspars, triclinicity (Goldsmith and Laves, 1954) is defined as $\Delta = 12.5 (d_{131} - d_{1\bar{3}1})$, where the minimum value is 0 for monoclinic K-feldspar and the maximum is 1 for triclinic maximum microcline. Alternatively, it may be expressed as $\Delta = 1.25 (2\theta_{131} - 2\theta_{1\bar{3}1})$, which is more convenient for interpreting Gandolfi photos. Although the monoclinic K-feldspar powder pattern is very similar to that of a triclinic one (Figure 3-8a), a monoclinic K-feldspar only has a single 131 reflection ($\Delta = 0$, see section on powder diffractometry), whereas a triclinic K-feldspar has 131 and $1\bar{3}1$ reflections ($0 < \Delta < 1$) (see Figure 3-8b). The triclinicity can be calculated from the photos by measuring the 2θ difference between a (131) and a ($1\bar{3}1$) reflection as shown in Figure 3-8b. In the author's procedures, Δ was measured twice and the range is given in Table 3-6. However, it must be noted that the triclinicity as determined by Gandolfi photography has a much higher error than that determined by powder diffractometry, because of the much lower resolution in the photographic method.

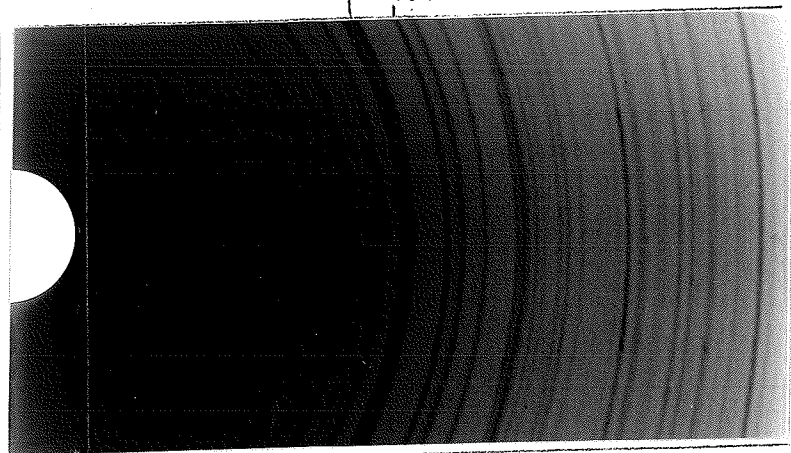
(3) Different K-feldspar phases

The different K-feldspar phases of a microcline

040,002 131

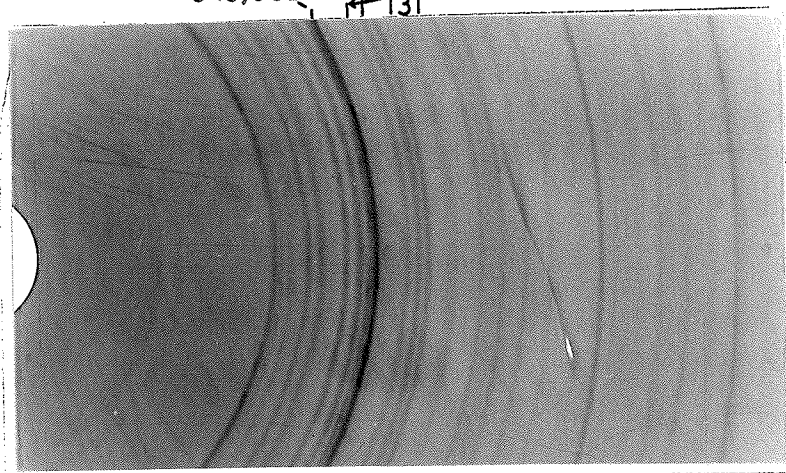
108

(a)



040,002 131 131

(b)



040,002

(c)

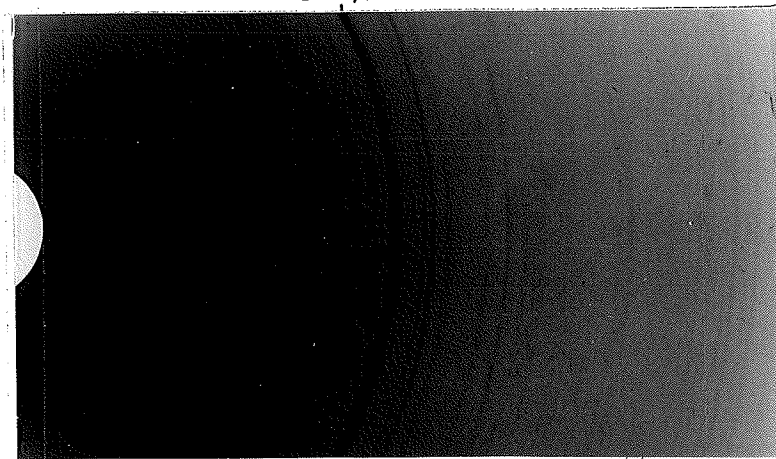


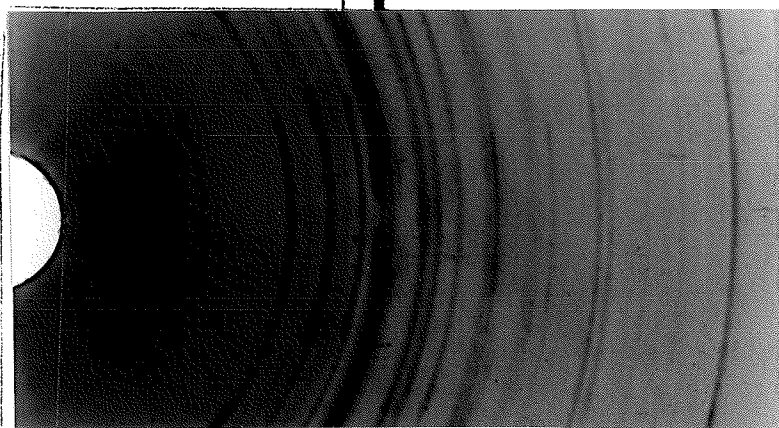
Figure 3-8. Standard Gandolfi powder-type photographs. Parts of each photo have been enlarged to show the differences in the major reflections. (a) monoclinic K-feldspar with single 131 reflection; (b) maximum microcline with sharp and well-defined 131 and $\bar{1}31$ reflections with a clear spacing between them; (c) albite which helps to identify the albite as a separate phase in microcline.

Table 3-6. Gandolfi photography data as discussed in text.

ROCK TYPE	SAMPLE NO.	TRICLINICITY Δ		% WT. Ab % AS SECOND PHASE (ROUGH ESTIMATION)	AMOUNT OF EACH K-FELDSPAR COMPONENT (WT. %) (ROUGH ESTIMATION)
		(EXTREME VALUES FOR MULTIPLE PHASES)	WEIGHTED VALUES FOR MIXTURES		
K-FELDSPARS					
LAC DU BONNET GRANITE	PG-121	1.05 $\pm$ 0.10		-	100% max. micro.
	PG-135	0.94 $\pm$ 0.01		-	"
	PG-152	1.06 $\pm$ 0.01		1	"
	SR-97	1.00 $\pm$ 0.01		2	"
	SR-148	1.00 $\pm$ 0.04		-	"
	PG-133	1.00 $\pm$ 0.03		-	"
	PG-24	1.01 $\pm$ 0.01		-	"
	AEC-26	1.00 $\pm$ 0.01		-	"
	AEC-20	1.05 $\pm$ 0.01		1	"
DRYDEN GRANITES	ZPG-07	0.99 $\pm$ 0.03		-	"
	APG-05	0.99 $\pm$ 0.01		-	"
	GPG-22	0.99 $\pm$ 0.03		1	"
	HG-01	0.96 $\pm$ 0.03		2	"
	MLG-01	1.00 $\pm$ 0.02		-	"
	CG-03	0.96 $\pm$ 0.01		2	"
	SG-01	0.95 $\pm$ 0.01		-	"
DRYDEN PEGMA- TITES		0			
	MLP/NZ 01	0.67 $\pm$ 0.04	0.47	-	30% mono, 70% max. micro.
		0			
	MLP/NZ 02	0.56 $\pm$ 0.04	0.22	$\frac{1}{2}$	" "
		0			
	MLP/NZ 05	0.47 $\pm$ 0.05	0.19	3	60% " 40% "
	MLP/NZ 23	0.98 $\pm$ 0.01		$\frac{1}{2}$	100% max. micro.
		0			
	MLP/NZ 24	0.73 $\pm$ 0.04	0.51	$\frac{1}{2}$	30% mono, 70% max. micro.
		0			
	MLP/NZ 30	0.69 $\pm$ 0.01	0.28	-	60% " 40% "
		0			
	MLP/NZ 42	0.64 $\pm$ 0.04	0.19	-	70% " 30% "
MLP/NZ 47	0.79 $\pm$ 0.01		-	100% int. micro.	
MLP/SZ 10	0.86 $\pm$ 0.03		$\frac{1}{2}$	" " "	
MLP/SZ 06	0.84 $\pm$ 0.03		-	" " "	
ZP-09	0.99 $\pm$ 0.03		-	" max. micro.	
ZP-05	0.99 $\pm$ 0.01		1	" " "	
GPE-11	1.05 $\pm$ 0.04		$\frac{1}{2}$	" " "	
MONOCLINIC STANDARD	Monoclinic	0		-	100% monoclinic
ALBITES					
LAC DU BONNET GRANITE	PG-138 AB	-		98	2% K-Feldspar
DRYDEN GRANITE	CG-03 AB	-		100	-

specimen can usually be recognized at the same time as the triclinicity is measured. Sixteen K-feldspars from the Lac du Bonnet and Dryden granites are maximum microclines ($\Delta=0.85$ to 1) with Gandolfi photos very similar to Figure 3-8b. They all have a single K-feldspar phase. However, 13 K-feldspars from the pegmatites show a range of triclinicities, from a low of 0.47 to a high of ~ 1 . Four of them are maximum microclines that have only one K-feldspar phase. The others are either intermediate microclines or have more than one type of microcline. Unlike the single phase maximum microclines, the microclines that show more than one K-feldspar phase are more complex, and the photos must be examined carefully. Examples of these multiple K-feldspar phases are shown in Figure 3-9. Three pegmatitic K-feldspars are single-phase intermediate microclines. Six multiple-phase K-feldspars show an extreme low for the monoclinic component and an extreme high for the triclinic component which in most cases is maximum microcline as shown in Table 3-6. The reflections ($1\bar{3}1$ of monoclinic, 131 and $1\bar{3}1$ of triclinic microcline) are very broad (Figure 3-9a-d) such that there is a continuous band across all three reflections. The monoclinic component is recognized by its weaker or stronger intensity. The broad bands of all three reflections suggests a structural continuity from the monoclinic to the triclinic structure. This is known as transitional structure,

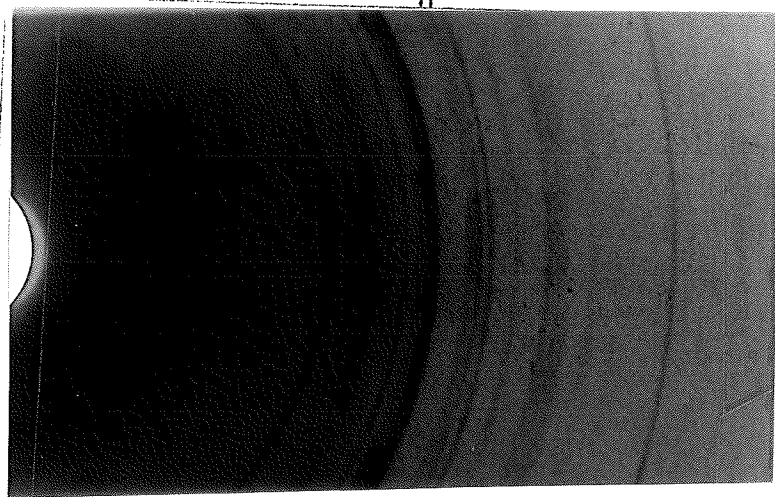
131+131



(a)

(MLP/SZ 06)

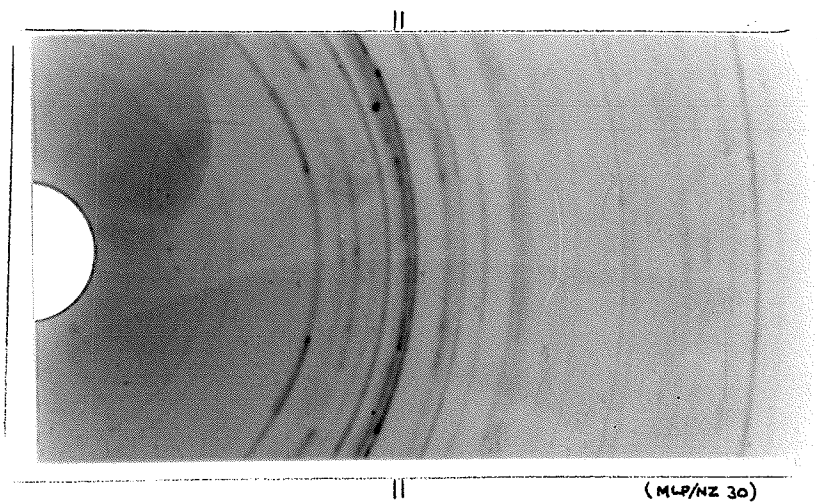
thin band of 002, 040 albite
reflection



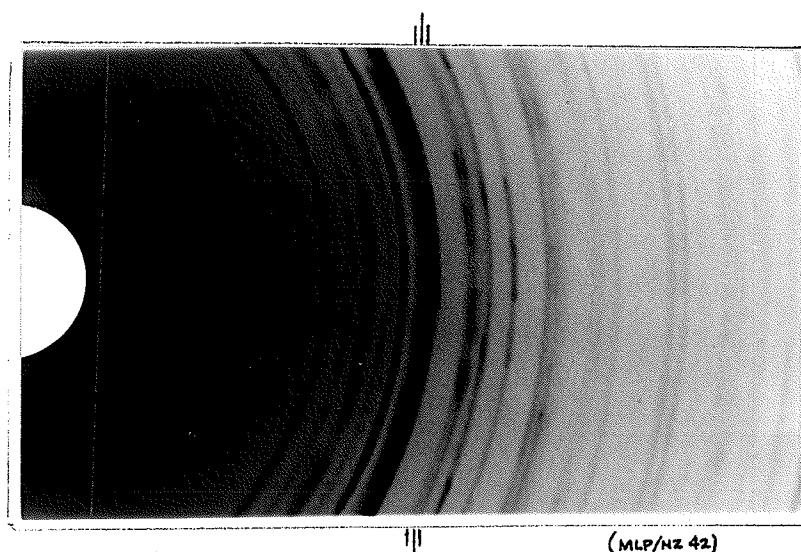
(b)

(MLP/NZ 01)

Figure 3-9. Gandolfi powder photos of pegmatitic K-feldspars that show other than maximum microcline. (a) intermediate microcline (100 %) that shows two rather thick bands almost to the point where they are merging into single band; (b) two rather distinct bands with slightly lighter shading in between them which may suggest a possible monoclinic ("M") component (continued...)



(c)



(d)

Figure 3-9. (...continued) (c) two broad bands that are intermediate microcline with a darker band in between them that suggests an "M" component; (d) there are actually three lines: a 131 "M" component that is rather sharp and strong with two broad slightly weaker bands that are diffused almost to the point where they merge. They have been enlarged in the similar fashion as Figure 3-8. The thick bands are due to the large size of the crystal and the broken lines to the crystal's low symmetry.

as discussed earlier in the precession photography section.

(4) Albite as a second phase

Gandolfi photos can give an idea of the amount of albite occurring as a second phase in microclines. The thick dark band made up of the 040,002 reflection of monoclinic and triclinic K-feldspars has a lower 2θ value (27.52° -Borg & Smith, 1969) than albite (27.96°) as shown in Figure 3-8. Thus albiteⁱⁿ microcline is seen as a band that is usually weak and thin just outside of the 040,002 microcline reflection (see for example, Figure 3-9a). The amount of albite present (which is roughly estimated in weight %) in each K-feldspar crystal is listed in Table 3-6. Most of the microclines analyzed show no albite as a second phase but the ones that do show presence of albite do not show more than a few % (by weight). One of the two albites analyzed shows the presence of a small amount of microcline as a thin and very weak band inside the 040,002 albite reflection (Table 3-6).

(5) Cell refinement data

Gandolfi photos were taken of the same K-feldspar crystals that were used in precession photography. However, most of the crystals were too large for Gandolfi photography, as the resultant photos show broad reflections rather than sharp lines. This gives appreciable error in reading the 2θ values. Cell refinement was attempted on about 12

specimens, but because of the errors in 2θ , no satisfactory results were obtained. A possible remedy would be to crush part of the crystal into smaller fragments but this was not done. The author was not able to attempt these alternative method because the crystals were later utilized in electron microprobe studies.

(C) X-RAY POWDER DIFFRACTOMETRY

(1) Introduction

X-ray powder diffractometry is commonly used to provide petrogenetic information through measurement of the cell dimensions and triclinicity of K-feldspars which gives its structural state and composition (in terms of Or % content).

(2) Cell parameters

Table 3-7 lists the refined cell parameters derived from powder diffractograms of larger powder samples taken from the hand samples of the 29 K-feldspars from the Lac du Bonnet and Dryden areas. Twenty K-feldspars are single-phase maximum microclines (as observed in the powder diffractograms). The remaining nine K-feldspars are either intermediate microclines or mixtures of different microcline phases. The latter gave difficulties in interpreting their diffractograms (as discussed in the next paragraph) and hence in refining their cell parameters. This observation has been reported by many researchers (i.e. Smith (1974a), Yund & Ackermund (1979)).

Table 3-7. Refined unit cell parameters from powder diffractograms.

ROCK TYPE	SAMPLE	DIRECT CELL PARAMETERS						RECIPROCAL CELL PARAMETERS					
		a, Å	b, Å	c, Å	α	β	γ	a*, Å ⁻¹	b*, Å ⁻¹	c*, Å ⁻¹	α^*	β^*	γ^*
K-FELDSPARS													
LAC DU BONNET GRANITE	PG-121*	8.564(9)	12.959(4)	7.220(2)	90°41'(4)	115°54'(2)	87°33'(4)	0.1299(1)	0.07724(3)	0.15396(4)	90°25'(3)	64°06'(2)	92°23'(4)
	PG-135*	8.58(1)	12.945(6)	7.199(7)	90°37'(6)	115°41'(7)	87°39'(4)	0.129(3)	0.0773(4)	0.154(1)	90°27'(5)	64°19'(7)	92°18'(3)
	PG-152*	8.578(8)	12.950(8)	7.214(3)	90°39'(4)	115°55'(4)	87°42'(4)	0.1298(1)	0.07729(5)	0.15412(8)	90°24'(4)	64°05'(4)	92°15'(3)
	SR-97*	8.56(1)	12.964(8)	7.222(5)	90°43'(5)	115°54'(5)	87°33'(5)	0.1299(1)	0.07720(5)	0.15392(9)	90°23'(4)	64°07'(5)	92°22'(5)
	SR-148*	8.563(4)	12.959(4)	7.215(3)	90°44'(2)	115°48'(2)	87°32'(2)	0.12981(6)	0.07723(3)	0.15395(5)	90°23'(3)	64°13'(2)	92°23'(2)
	PG-133*	8.559(6)	12.944(7)	7.213(3)	90°40'(4)	115°56'(3)	87°34'(4)	0.13004(9)	0.07732(4)	0.15417(6)	90°26'(4)	64°04'(3)	92°23'(4)
	PG-24*	8.567(9)	12.962(4)	7.220(3)	90°35'(2)	115°55'(3)	87°38'(3)	0.1299(1)	0.07721(2)	0.15399(4)	90°30'(2)	64°05'(3)	92°21'(2)
	AEC-26*	8.564(6)	12.964(3)	7.220(2)	90°42'(3)	115°58'(2)	87°35'(2)	0.12994(7)	0.07721(2)	0.15401(4)	90°24'(3)	64°05'(2)	92°21'(2)
	AEC-20*	8.56(1)	12.949(8)	7.215(4)	90°44'(6)	115°57'(4)	87°36'(7)	0.1306(2)	0.07729(5)	0.15414(8)	90°21'(5)	64°04'(4)	92°18'(6)
DRYDEN GRANITES	ZPG-07*	8.564(8)	12.982(9)	7.221(5)	90°39'(6)	115°57'(5)	87°44'(3)	0.1299(2)	0.07709(5)	0.1540(1)	90°22'(6)	64°03'(5)	92°12'(4)
	APG-05*	8.55(1)	12.94(1)	7.216(5)	90°38'(6)	115°49'(5)	87°41'(6)	0.1300(2)	0.07737(7)	0.1539(1)	90°25'(5)	64°11'(5)	92°16'(6)
	GPG-22*	8.56(1)	12.961(7)	7.215(4)	90°40'(5)	115°56'(4)	87°45'(5)	0.1299(1)	0.07721(4)	0.15411(9)	90°21'(4)	64°05'(4)	92°11'(4)
	HG-01*	8.560(4)	12.931(5)	7.209(3)	90°42'(3)	115°57'(2)	87°35'(2)	0.13002(6)	0.07740(3)	0.15427(5)	90°24'(3)	64°04'(2)	92°21'(2)
	MLG-01*	8.570(4)	12.951(5)	7.216(3)	90°38'(3)	115°56'(2)	87°42'(3)	0.12986(6)	0.07728(3)	0.15409(6)	90°24'(3)	64°04'(2)	92°14'(3)
	CG-03*	8.563(6)	12.964(4)	7.220(2)	90°41'(3)	115°50'(2)	87°41'(3)	0.12984(8)	0.07720(2)	0.15390(5)	90°21'(3)	64°10'(2)	92°14'(3)
	SG-01*	8.57(1)	12.950(5)	7.214(3)	90°36'(3)	116°02'(4)	87°44'(4)	0.1299(1)	0.07703(3)	0.15429(9)	90°26'(3)	63°58'(4)	92°14'(4)
DRYDEN PEGMATITES	MLP/NZ 01	8.57(2)	12.95(2)	7.22(1)	90°25'(12)	116°06'(9)	88°43'(19)	0.1299(3)	0.0772(1)	0.1542(1)	90°10'(6)	64°54'(9)	91°14'(17)
	MLP/NZ 02	8.571(8)	12.961(9)	7.218(4)	90°13'(4)	116°07'(4)	89°07'(4)	0.1299(1)	0.07716(6)	0.15429(7)	90°12'(5)	63°54'(4)	90°53'(4)
	MLP/NZ 05	8.60(2)	12.95(1)	7.210(6)	90°02'(7)	116°07'(6)	89°32'(7)	0.1295(2)	0.07723(6)	0.1544(1)	90°11'(6)	63°53'(6)	90°30'(7)
	MLP/NZ 23*	8.568(6)	12.950(5)	7.218(2)	90°35'(3)	115°56'(2)	87°49'(3)	0.12987(8)	0.07727(3)	0.15405(4)	90°24'(3)	64°04'(2)	92°08'(2)
	MLP/NZ 24	8.57(2)	12.95(1)	7.214(5)	90°27'(13)	116°01'(4)	88°32'(18)	0.1298(2)	0.07727(7)	0.15426(8)	90°13'(7)	63°59'(4)	91°25'(15)
	MLP/NZ 30	8.57(1)	12.95(1)	7.216(5)	90°25'(7)	115°58'(5)	88°36'(18)	0.1299(2)	0.07724(8)	0.1541(1)	90°13'(9)	64°02'(5)	91°21'(19)
	MLP/NZ 42	8.58(1)	12.981(8)	7.203(4)	90°11'(6)	116°02'(4)	89°27'(7)	0.1297(1)	0.07704(5)	0.15450(8)	90°03'(5)	63°58'(4)	90°31'(7)
	MLP/NZ 47	8.60(1)	12.960(6)	7.211(4)	90°24'(4)	115°55'(6)	88°18'(6)	0.1293(2)	0.07720(4)	0.1542(1)	90°23'(5)	64°05'(7)	91°42'(6)
	MLP/SZ 10	8.61(1)	12.964(6)	7.212(3)	90°28'(4)	115°09'(3)	88°27'(7)	0.129(2)	0.0772(4)	0.1543(6)	90°14'(3)	64°01'(3)	91°30'(7)
	MLP/SZ 06	8.59(1)	12.945(8)	7.216(5)	90°24'(7)	116°01'(5)	88°22'(8)	0.1295(2)	0.07718(5)	0.154(5)	90°21'(7)	63°59'(5)	91°37'(8)
	ZP-09*	8.580(6)	12.966(8)	7.217(3)	90°42'(5)	115°53'(4)	87°41'(5)	0.12965(9)	0.07719(5)	0.15402(7)	90°20'(4)	64°07'(4)	92°14'(5)
	ZP-05*	8.573(6)	12.953(5)	7.219(3)	90°35'(3)	116°03'(4)	87°44'(2)	0.12992(9)	0.07726(3)	0.1542(1)	90°28'(3)	63°57'(4)	92°14'(2)
	GPE-11*	8.600(4)	12.943(4)	7.218(3)	90°43'(3)	116°00'(2)	87°42'(3)	0.12946(6)	0.07732(3)	0.15413(5)	90°19'(3)	64°00'(2)	92°12'(3)
MONOCLINIC STANDARD	MONOCLINIC	8.528(7)	12.980(4)	7.188(3)	90°00'	115°51'(3)	90°00'	0.13030(8)	0.07704(3)	0.15459(6)	90°00'	64°08'(3)	90°00'
ALBITES													
LAC DU BONNET GRANITE	PG-138 AB	8.129(5)	12.810(9)	7.154(5)	94°18'(3)	116°27'(4)	87°26'(6)	0.13740(6)	0.07829(5)	0.15641(9)	86°28'(4)	63°39'(3)	90°43'(6)
DRYDEN GRANITE	PG-03 AB	8.140(6)	12.81(2)	7.150(4)	94°20'(3)	116°32'(3)	87°54'(6)	0.1373(1)	0.0782(1)	0.15666(8)	86°13'(3)	63°32'(3)	90°12'(6)

* - maximum microcline

For the mixed microcline samples, the actual or near overlapping of most of the reflections made it impossible to refine two different sets of data. It was only feasible to derive one set of unit cell parameters (presumably the weighted mean for the two phases), but it was difficult to choose a realistic set of 2θ 's that would give, upon refinement, a reasonable set of (weighted) cell parameters. The author used two criteria to choose the best set of data: 1) the speed of convergence and 2) the fit of the results on the α^* vs. γ^* graph of Figure 3-10 (which is similar to Figure 3-5). The α^* and γ^* angles are used in the same fashion as in the precession photo interpretations, in which the α^* and γ^* angles of a given cell are plotted on the graph of Figure 3-10. If the angles in a given case plotted well off the regression line (as determined by the 12 microclines that have been refined (Ferguson, 1981) as discussed previously), then the reflections listed in Table 3-8 were changed until the α^* and γ^* were found to plot reasonably close to the straight line. In the refinement of the powder diffraction data, triclinic solutions were used for the nine K-feldspars with intermediate structural states. A monoclinic solution was tried, as was done by Collerson (1976), for one of the specimens that showed a very strong monoclinic peak (MLP/NZ 42) but it was unsatisfactory. A triclinic solution was tried, with satisfactory results. Only one set of cell

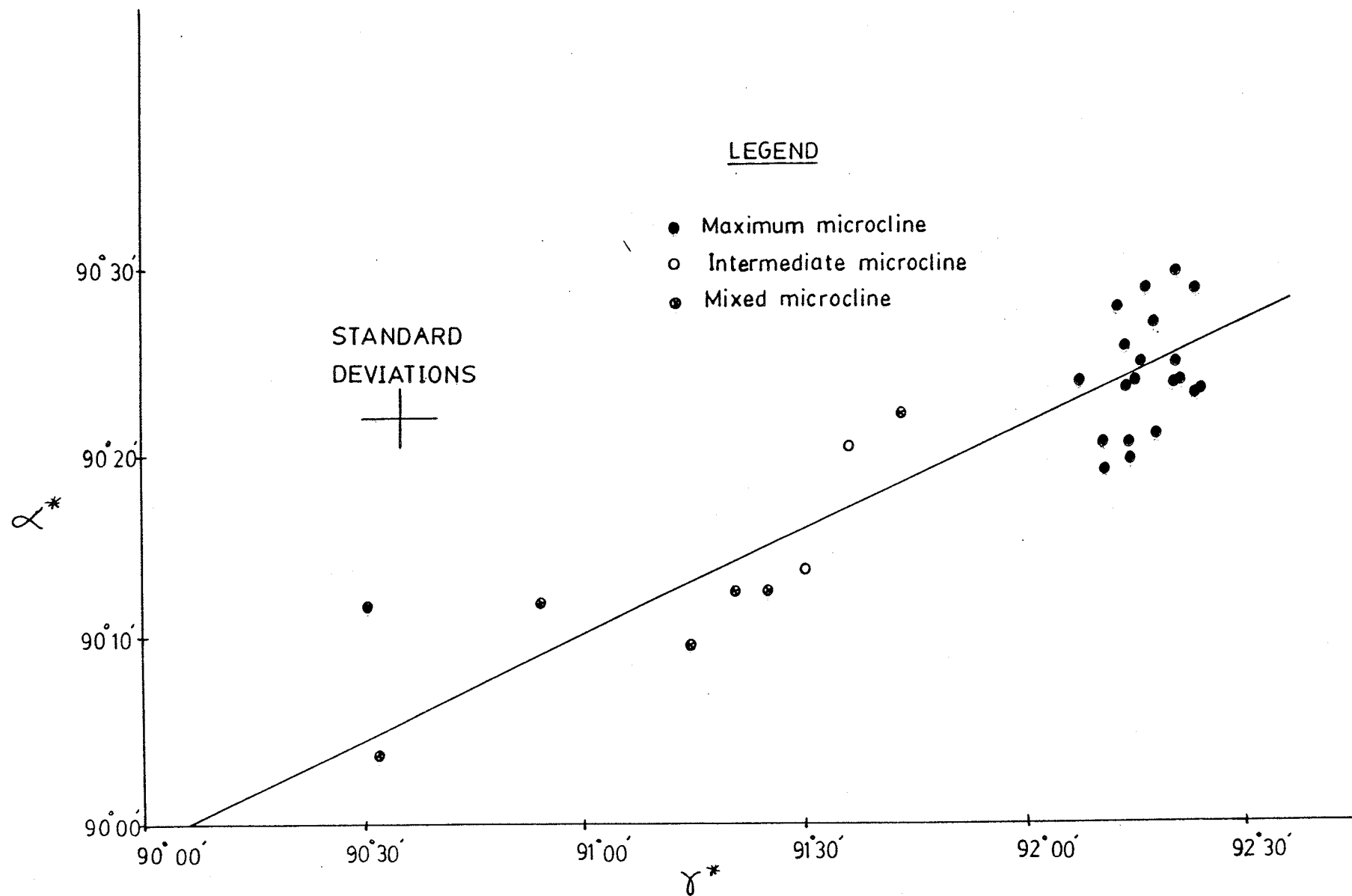


Figure 3-10. Plot of α^* vs. γ^* of K-feldspars from cell refined powder diffractometer data. The regression line is the same as in Figure 3-5. The bar is the standard deviation which is $\pm 02'$ for α^* and $\pm 03'$ for γ^* .

parameters is given (Table 3-7) for the microclines that have mixed triclinicities, for the reasons given above.

It can be seen in Table 3-7 that α and γ (and as well as α^* and γ^*) are the most sensitive cell parameters for differentiating one microcline from the other. The final refined α^* and γ^* values for the 29 feldspars are plotted in the α^* vs. γ^* diagram (Figure 3-10); within the experimental error, they all fall on the regression line.

ANGLE OF 2 θ (Cu K α)		hkl REFLECTIONS	
MONOCLINIC	TRICLINIC	MONOCLINIC	TRICLINIC
22.53	22.64	111	$1\bar{1}1$
25.64	25.55	$\bar{1}12$	$\bar{1}\bar{1}2$
30.81	30.73	041	0 $\bar{4}1$
58.72	58.68	024	0 $\bar{2}4$

Table 3-8. Closeness of key monoclinic (adularia) and triclinic reflections. Although only four are listed here, they can affect the cell dimensions of a given K-feldspar to a considerable degree. Both 2θ and hkl values are from Borg & Smith (1969).

A plot of the b and c cell edges for both K- and Na-feldspars was developed by Wright & Stewart (1968) and Stewart & Wright (1974) to identify the type of alkali feldspar, to estimate the Or content and to determine the strain in perthitic feldspars (Stewart, 1975). Substitution of Na in K-feldspars causes both b and c to decrease (Smith, 1974a). The results of all the K-feldspars studied here are shown in

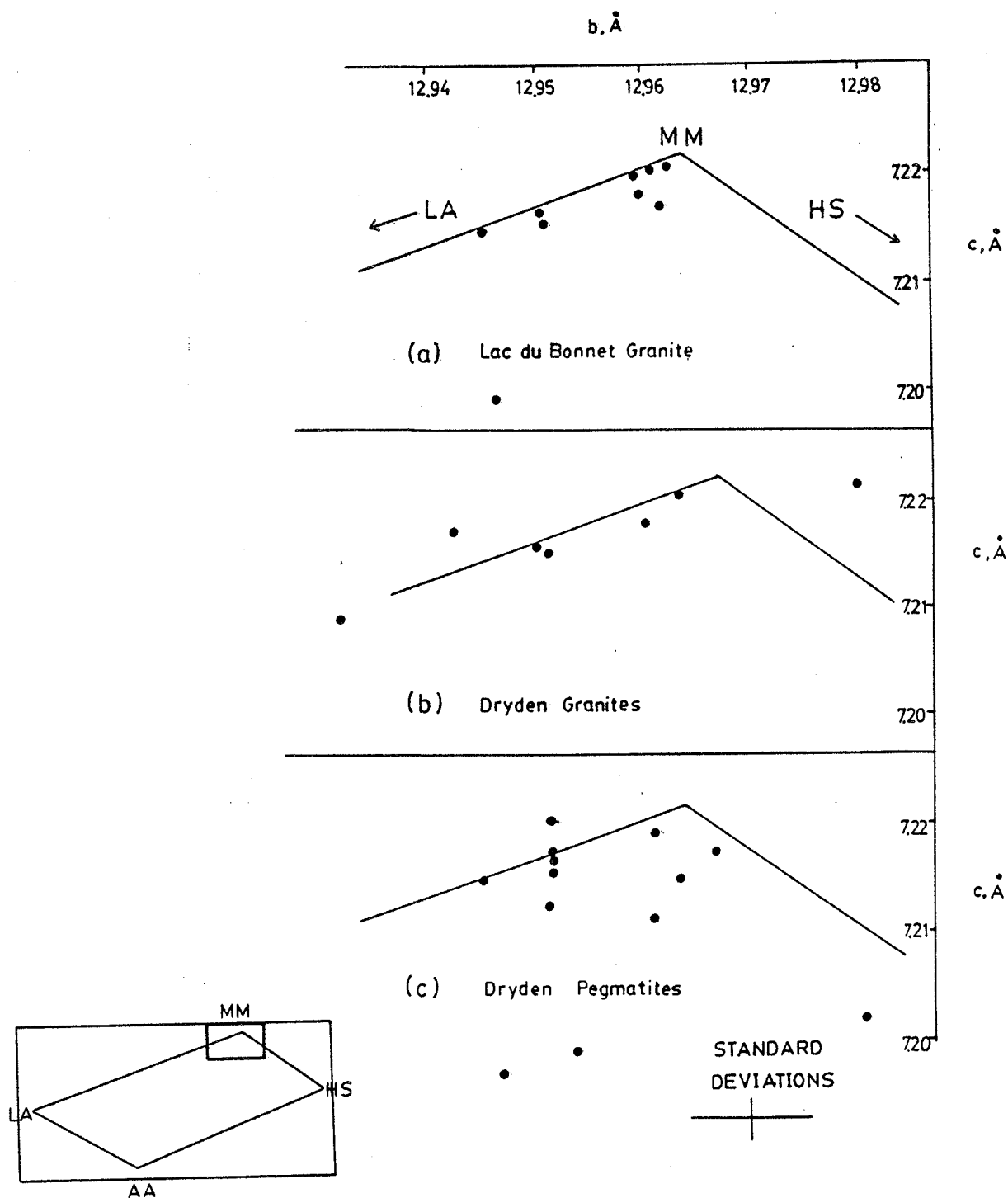


Figure 3-11. Plots of the K-feldspar data on partial Stewart & Wright (1974) b-c diagrams of alkali feldspars. (a) K-feldspars from Lac du Bonnet granite; (b) K-feldspars from Dryden granites; (c) K-feldspars from Dryden pegmatites. The bar is the standard deviation which is $\pm 0.0007 \text{ \AA}$ for b and $\pm 0.0004 \text{ \AA}$ for c. The smaller diagram shows the portion on the b-c diagram. Designations: MM-maximum microcline, HS-high sanidine, LA-low albite, AA-analbite.

Figure 3-11. All the specimens lie in the field of maximum microcline with little sodium feldspar in solid solution. In qualitative terms, Lac du Bonnet K-feldspars show little variation in the b and c cell dimensions (and hence in composition), whereas the Dryden granitic K-feldspars show greater range of composition and the pegmatitic K-feldspars a still slightly wider range of composition.

(3) Triclinicity

The triclinicities measured from the powder diffractograms of all 29 K-feldspars are given in Table 3-9. Twenty of these K-feldspars are maximum microclines with $0.85 < \Delta < 1.0$ as defined earlier (Table 3-9); they are from granites of both the Lac du Bonnet and Dryden areas. The 131 and $1\bar{3}1$ peaks of most maximum microclines are very similar to that of Figure 3-12b, that is the peaks are narrow, sharp and well-defined (although the 131 and $1\bar{3}1$ peaks are not always of the same intensity). Some maximum microclines show wider peaks with rather flattened tops (particularly the $1\bar{3}1$ peak) as shown in Figure 3-12c (Table 3-9). Smith (1974a) noted that some K-feldspars give blurred $1\bar{3}1$ peaks that can be interpreted as due to the superposition of K-feldspars with different triclinicities.

For some microclines, there are problems in determining the triclinicity because of the presence of different phases of microclines and albites. This is especially true for the

Table 3-9. X-ray powder diffractogram data as discussed in text.

ROCK TYPE	SAMPLE	ESTIMATED AMOUNT OF EACH K-FELDSPAR COMPONENT (WT %)	ESTIMATED AMOUNT OF ALBITE AS SECOND PHASE	TRICLINICITY Δ OF K-FELDSPAR	131 PEAK (DIFFUSED)	WT. % Or IN SOLID SOLUTION (ORVILLE, 1967)		
LAC DU BONNET GRANITE	PG-121	100% max. micro.	5	1.01		95		
	PG-135	" "	20	0.99	x	94		
	PG-152	" "	20	0.95		95		
	SR-97	" "	15	0.99		91		
	SR-148	" "	15	0.99		92		
	PG-133	" "	<5	1.02		91		
	PG-24	" "	<5	1.03		93		
	AEC-26	" "	<5	0.99		93		
	AEC-20	" "	<5	0.95		91		
DRYDEN GRANITES	ZPG-07	" "	20	0.93	x	93		
	APG-05	" "	25	0.97	x	89		
	GPG-22	" "	5	0.91	x	93		
	HG-01	" "	5	0.99		92		
	MLG-01	" "	5	0.96		94		
	CG-03	" "	25	0.93	x	92		
	SG-01	" "	15	0.96	x	95		
DRYDEN PEGMA-TITES	MLP/NZ 01	30% mono, 70% ^{max.} micro	30	0.50	x	*84	100	89
	MLP/NZ 02	" "	10	0.39	x	*88	99	92
	MLP/NZ 05	40% " 60% "	25	0.25	x	*89	108	95
	MLP/NZ 23	100% max. micro.	20	0.92			94	
	MLP/NZ 24	35% mono, 65% ^{max.} micro	<5	0.63	x	*88	97	91
	MLP/NZ 30	20% " 80% "	<5	0.56	x	*88	102	93
	MLP/NZ 42	60% " 40% "	-	0.21	x	*90	102	94
	MLP/NZ 47	35% " 65% "	<5	0.75	x	*93	102	97
	MLP/SZ 10	100% int. micro.	20	0.62	x		98	
	MLP/SZ 06	100% " "	30	0.71	x		101	
	ZP-09	" max. micro	15	0.93	x		96	
	ZP-05	" " "	20	0.98			96	
	GPE-11	" " "	20	0.91			101	
MONOCLINIC STANDARD	MONOCLINIC	100% monoclinic		0		85		

* The first column refers to the Or% for the maximum microcline component, the second to the "monoclinic" component, and the third to the total weighted value in Or% of both components.

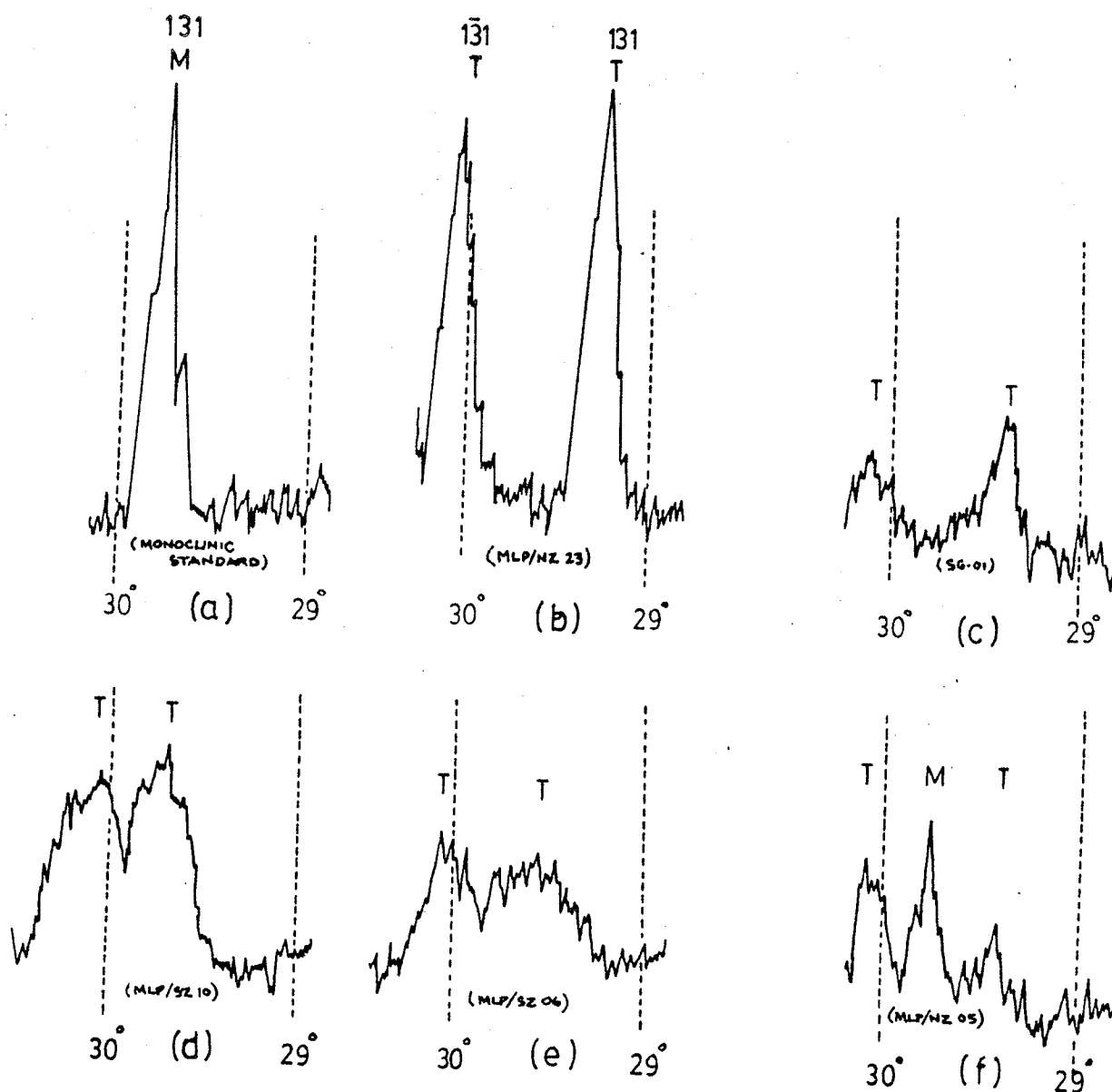


Figure 3-12. 131 and 131 microcline peaks (denoted as T) and 131 orthoclase peak (denoted as M) in the vicinity of 29° and 30° at a scanning speed of 1/4°/2θ/min. for CuK_α radiation; (a) orthoclase; (b) maximum microcline; (c) maximum microcline with lower peak intensities; (d) & (e) intermediate microclines; (f) mixture of "monoclinic" K-feldspar and maximum/intermediate microcline (continued...)

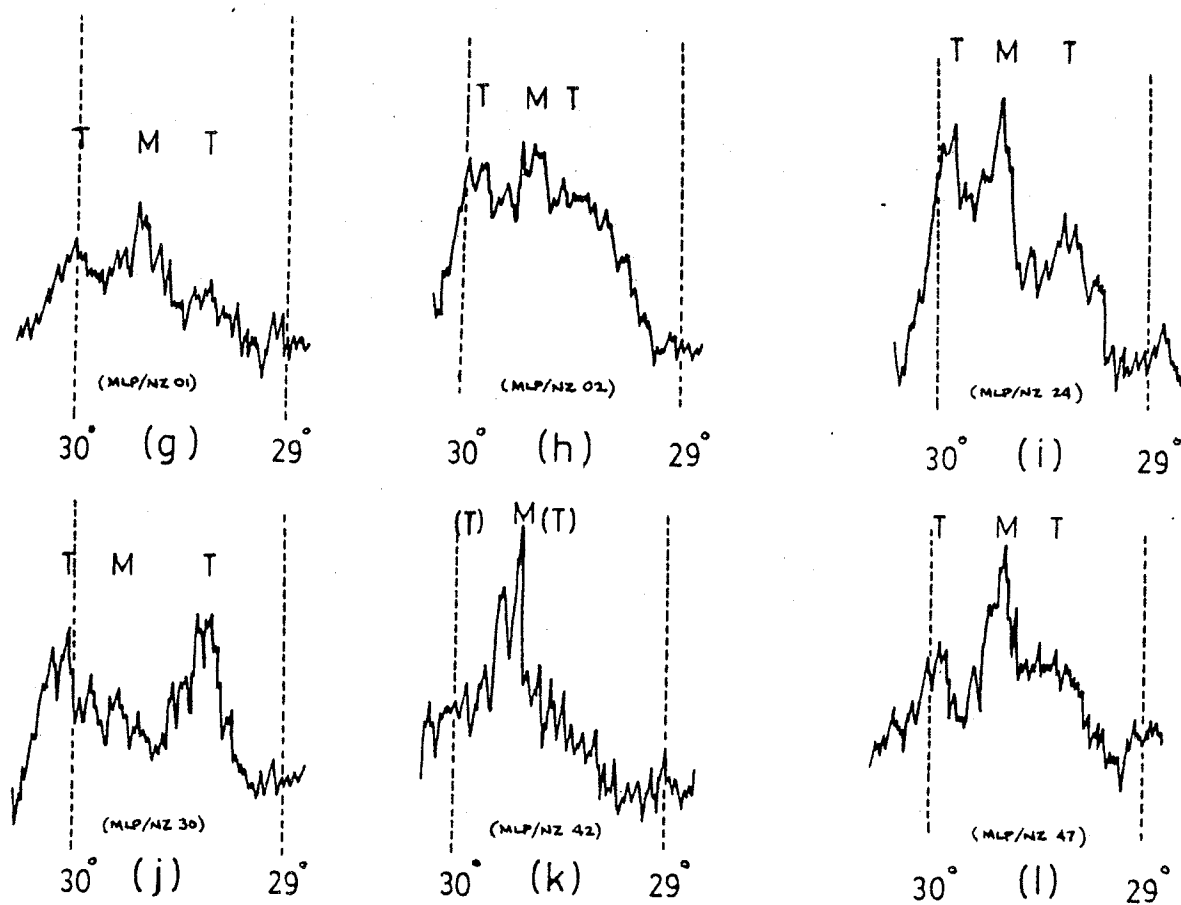


Figure 3-12. (...continued) (g) to (l) mixtures of "monoclinic" K-feldspars and maximum/intermediate microclines.

nine remaining K-feldspars that are all from the Mavis Lake pegmatite. These pegmatitic K-feldspars show an interesting variety of triclinicities. Two of them are intermediate microclines (Figures 4-12d & e), whereas the others are mixtures of a "monoclinic" K-feldspar and a maximum microcline (Figures 4-12f to 1). The "monoclinic" peak is usually sharp and well-defined (although some specimens show a split "monoclinic" peak (Figure 4-12i) as compared to the corresponding maximum microcline peak. The relative proportion of the different K-feldspar phases in each specimen were visually estimated by comparison with the artificial mixtures of orthoclase and microcline of Steiger & Hart (1967) and they are listed in Table 3-9.

(4) K-Na solid solution composition

The K/Na solid solution composition of alkali feldspars can be calculated from the d value of $\bar{2}01$, and is expressed as orthoclase (Or) content. This method is based on the fact that the a cell dimension changes with varying composition, thus changing $d_{\bar{2}01}$ (Jones et al., 1969). The method was first introduced by Bowen & Tuttle (1950) (for synthetic alkali feldspars) as a means of obtaining the composition of the phases in their hydrothermal experiments on the granite system. Orville (1963) used alkali-exchanged microclines and albites to establish a new determinative curve for the "natural" system microcline-low albite, based

on artificial single phase specimens over the whole range from maximum microcline to low albite. This is probably more applicable to natural low temperature feldspars than that of Bowen & Tuttle (1950) which applies to high temperature forms. This method is used commonly by petrologists and mineralogists (i.e. Wright, 1968; Ragland, 1967) even though Or % content of over 100 % have been observed by some workers; these have been explained as the result of strain due to exsolved perthite lamellae (Jones et al., 1969).

Wright (1968) has calculated the regression curve of Orville (1967) to be $\text{Or \%} = -92.19 [2\theta(\bar{2}01) \text{ feldspar}] + 2031.77$. However, Orville (1967) noted that his data conform not to a single straight line but rather to two straight lines that intersect at $\text{Or}_{45}\%$. The present author has calculated these two regression curves, expressed as wt Or %, to be:

$$\text{above Or}_{45} \% = -103.10 [2\theta(\bar{2}01)\text{feldspar}] + 2263.41$$

$$\text{below Or}_{45} \% = -79.69 [2\theta(\bar{2}01)\text{feldspar}] + 1759.14$$

As the alkali feldspars of the Lac du Bonnet and Dryden areas show Or contents much greater than 45 % regardless of which $\bar{2}01$ curve is used, the first of the above regression curves (above $\text{Or}_{45} \%$) was used. Table 3-9 lists the Or % contents deduced from the corrected Orville curve. A comparison of these results with the probe results is given in

Chapter VI.

(5) Albite as a second phase

The amount of albite occurring as a separate phase in microclines may be roughly estimated by the ratios of the heights of their strongest 040,002 peaks. Insufficient time was available for the author to set up a proper determinative curve. Instead, a rather crude technique for calculating the ratio (by visual estimate) of albite phase/microcline in a known mixture was used. Two mixtures were prepared and x-rayed: 90 % maximum microcline (Mc) + 10 % low albite (Ab) and 70 % Mc + 30 % Ab (the powders of each feldspar were accurately weighed to get the correct proportions for each ratio) and the ratio of peak heights were calculated. For example, with settings of 400 counts/sec, 2 sec time constant, 0 zero suppressor, and $1^{\circ}20'$ /min. scanning speed and using the older Philips powder diffractometry system in the author's department, the Mc/Ab ratio of the 90 % Mc + 10 % Ab mixture was calculated to be 5 and 70 % Mc + 30 % Ab to be 1. The other Mc/Ab compositions of 5 %, 15 %, 20 %, and 25 % Ab calculated to the ratios 6, 4, 3 and 2 respectively. However, it must be noted that the ratio does not take into account the amount of albite phase that was already present in the microcline that was used for this experiment.

The 29 K-feldspars were examined by this method. Because peak heights are subject to a fairly large error due

to sample orientation and instrumental error, the errors in the ratios were minimized by x-raying each K-feldspar sample three times on the same glass slide but in different positions and averaging the results. Table 3-9 shows that the amounts of albite phase in these microcline specimens range from 5 % to 30 %. There is no correlation between the amount of albite phase and the granitic/pegmatitic rock type. The results are discussed in Chapter VI.

(D) SUMMARY AND COMPARISON OF RESULTS FROM THE THREE X-RAY DIFFRACTION METHODS

The results for the 29 K-feldspar samples obtained by the three different x-ray diffraction methods may be summarized and compared in six categories:

- (1) reciprocal cell angles
- (2) proportions of multiple phases
- (3) triclinicities
- (4) K-Na solid solution composition
- (5) amount of albite as a second phase
- (6) twinning

(1) Reciprocal cell angles

As α^* and γ^* are the most sensitive cell parameters of alkali feldspars, the α^* and γ^* values obtained from the refinements of the powder diffractometer data will be the only cell parameters to be considered in this section, and will be compared with the α^* and γ^* obtained from the

precession photos.

Figure 3-13 shows a plot of γ^* from the refinement of the powder data against γ^* measured on precession photos. There is generally good agreement with most of the K-feldspars. Single phase maximum and intermediate microclines give good to excellent agreement but multiple-phased microclines, in general, give poor agreement because, as explained earlier, the γ^* values from both the cell refinement data and precession photo data are average results.

Figure 3-14 is a plot α^* from the refinement of powder data vs. α^* measured on precession photos and it shows similar features to those in Figure 3-13. However, α^* of a K-feldspar shows little departure from 90° as compared to γ^* ; because of the small departure of α^* from 90° ($\sim 30'$), values of α^* from the precession photos fall into seven groups due to the limit of measurement ($\sim \pm 08'$) whereas the cell refinement data show a wider range of values.

Both Figures 3-13 and 3-14 show three more or less separate groups of microclines: maximum microclines, intermediate microclines and mixed microclines, but because of its greater sensitivity, the γ^* diagram illustrates more clearly the division into the three groups. Both figures also show that the precession data gives a higher error ($\pm 08'$) than the cell refinement data ($\pm 03'$ for γ^* and $\pm 02'$ for α^*). This does not necessarily mean that the powder data

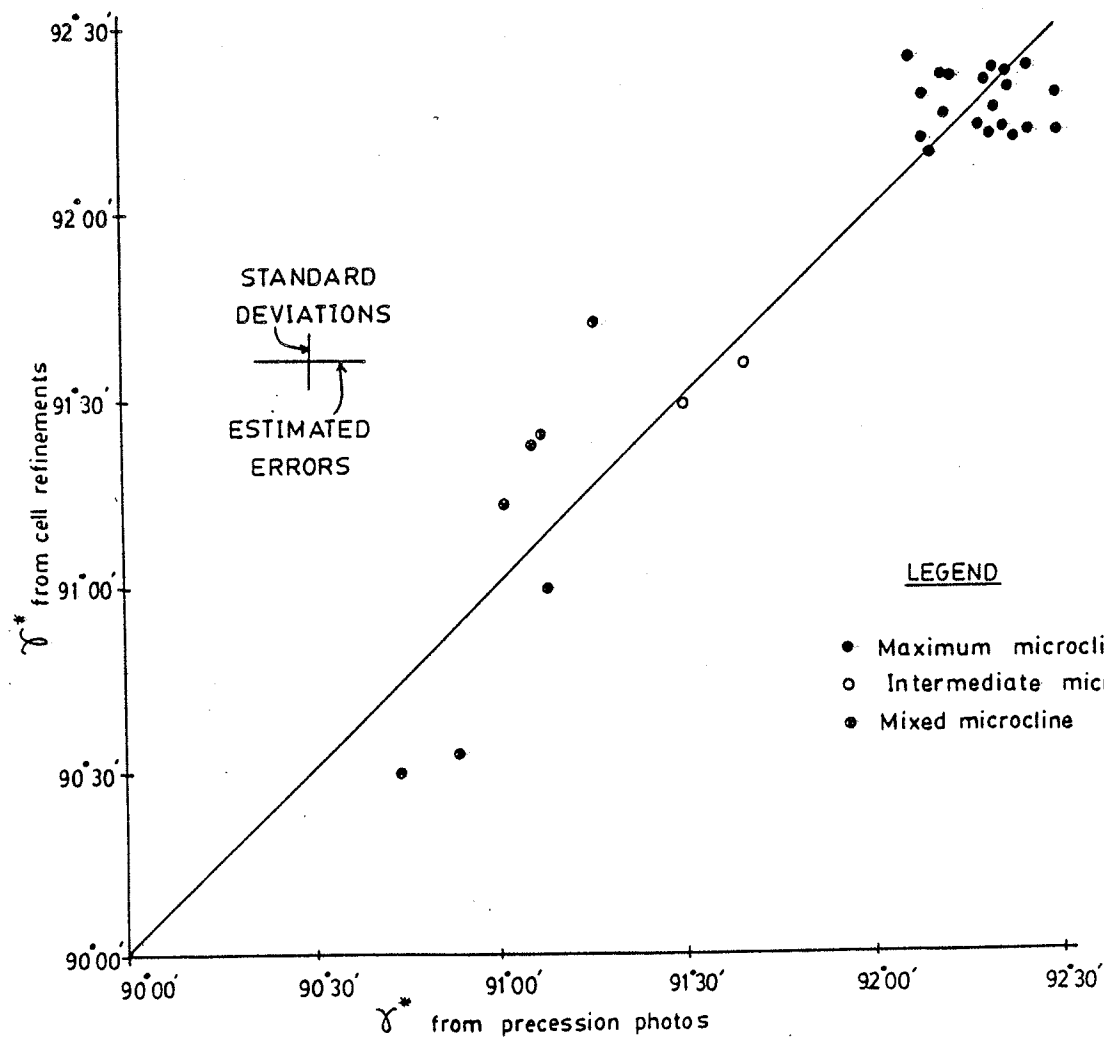


Figure 3-13. Plot of γ^* from refinement of powder data vs. γ^* from precession photos. The bar is the standard deviation ($\pm 03'$) for cell refinements and the estimated error ($\pm 08'$) for precession photos.

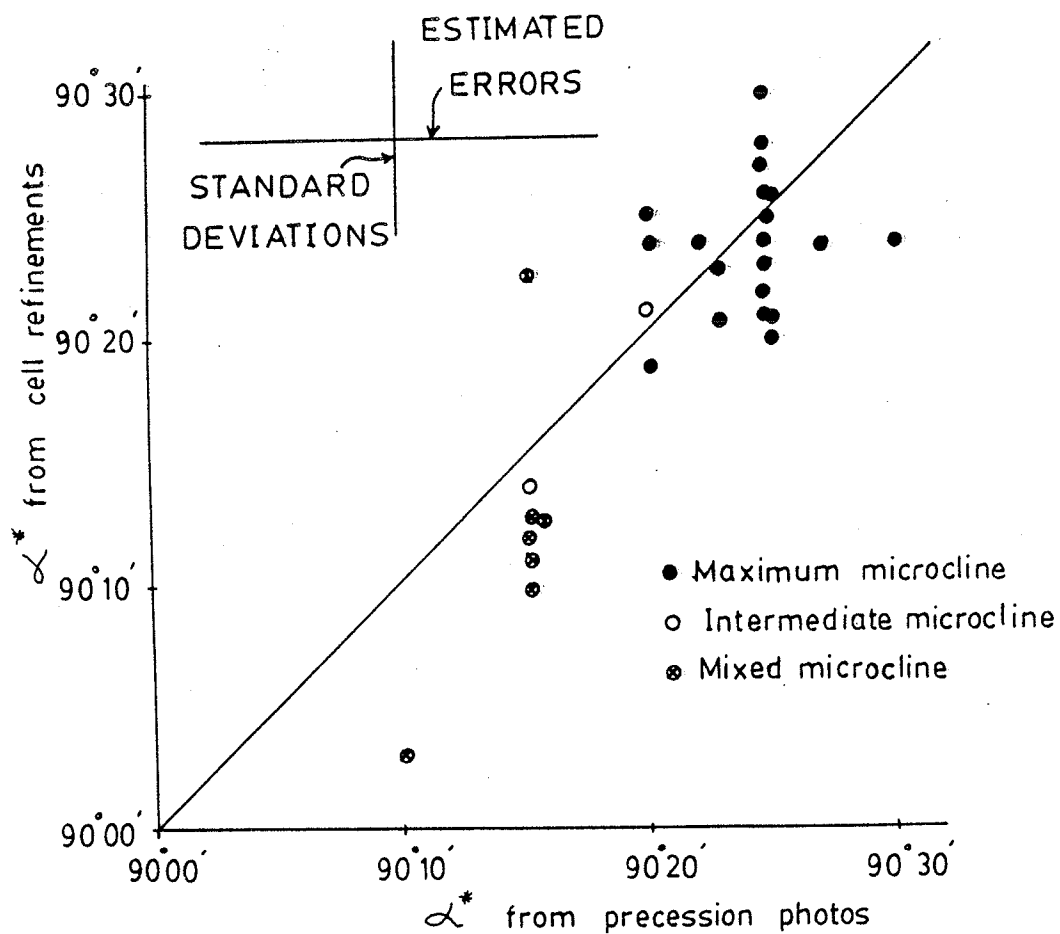


Figure 3-14. Plot of α^* from powder diffractogram cell refinement data vs. α^* from precession photos. The bar is the standard deviation ($\pm 03'$) for cell refinements and the estimated error ($\pm 08'$) for precession photos.

are more accurate because, in the case of mixed microclines, it was difficult to choose a reliable set of 2 θ data as explained earlier whereas in precession photos, γ^* was easily determined.

(2) Proportion of multiple phases

It was seen earlier that the pegmatites, particularly the Mavis Lake pegmatite, contain some K-feldspars that have more than one K-feldspar component. The results of the three x-ray diffraction methods confirm this observation. However, the observed amount of each K-feldspar component within a given K-feldspar varies with each x-ray diffraction method (Table 3-10), probably because they were all visually estimated rather than measured by densitometer (for both precession and Gandolfi photos) or by peak area (for powder diffractograms). Obviously much more work is required to give meaningful comparable results by the three methods.

(3) Triclinicities Δ

Figure 3-15 shows three plots of the triclinicities from precession photos, Gandolfi photos and cell refinements of powder diffractograms. There is a fairly good correlation among the maximum microclines as determined by the three x-ray diffraction methods but not among the intermediate microclines and mixed microclines. The two main reasons for the disparity of these results are that the

Table 3-10. Approximate weight % of different K-feldspar components in the pegmatitic K-feldspars as determined by the three different x-ray diffraction methods.

SAMPLE	PRECESSION PHOTOS		GANDOLFI PHOTOS		POWDER DIFFRACTOGRAMS	
	UNTWINNED INT. MICROCLINE	TWINNED MAXIMUM MICROCLINE	"MONOCLINIC"	MAXIMUM MICROCLINE	MONOCLINIC	MAXIMUM MICROCLINE
MLP/NZ 01	70	30	30	70	30	70
MLP/NZ 02	60	40	30	70	30	70
MLP/NZ 05	70	30	60	40	40	60
MLP/NZ 24	60	40	30	70	35	65
MLP/NZ 30	60	40	60	40	20	80
MLP/NZ 42	70	30	70	30	60	40
MLP/NZ 47	55	45	—	100	35	65

proportion of multiple phases in precession and Gandolfi photos was visually estimated, and that the triclinicities in the cell refinement data were average values as there were too many reflections in the powder diffractograms to be individually indexed as explained earlier.

It was observed earlier that, on the basis of the 131 and $1\bar{3}1$ reflections on the powder diffractograms, some of the pegmatitic K-feldspars were interpreted as having a monoclinic component (see Figure 3-12 and accompanying text). As the precession photos show an untwinned intermediate microcline rather than a monoclinic component, it is possible that, in the diffractogram, the component that is interpreted as a monoclinic component, is really a 131 and/or a $1\bar{3}1$ peak(s) of an intermediate microcline. As only one of the two peaks is present, there are three possibilities for the absence of the second peak: 1) it was overlapped by the 131 or $1\bar{3}1$ peak of maximum microcline; 2) it may be an intermediate microcline with an extremely low Δ value such that the 131 and $1\bar{3}1$ reflections lie very close to each other almost to the point of merging ; 3) the second peak lies within the background level. The relative heights of the 131 and $1\bar{3}1$ peaks of any triclinic K-feldspar can vary widely. One example of a maximum microcline is shown in Figure 3-16. The $1\bar{3}1$ peak is at least three times as high as the 131 peak, and as the peak height of the monoclinic component in some

Figure 3-15. Three plots showing the relationships of Δ from precession photos, Gandolfi photos, and cell refinements. The bar is the estimated error for precession and Gandolfi photos (both ± 0.03) and the standard deviation (± 0.05) for cell refinements.

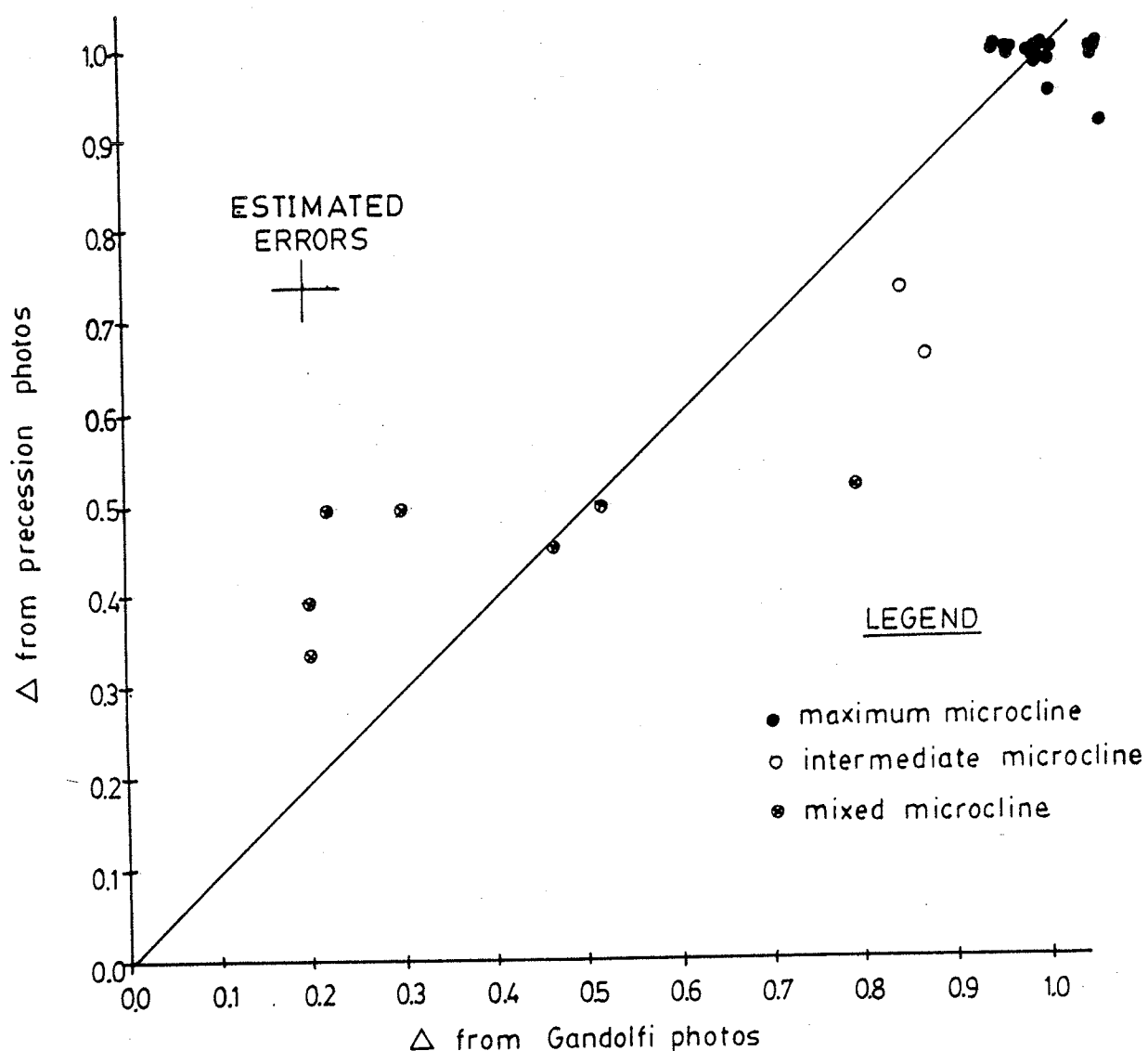


Figure 3-15 (a). Δ from precession photos vs. Δ from Gandolfi photos.

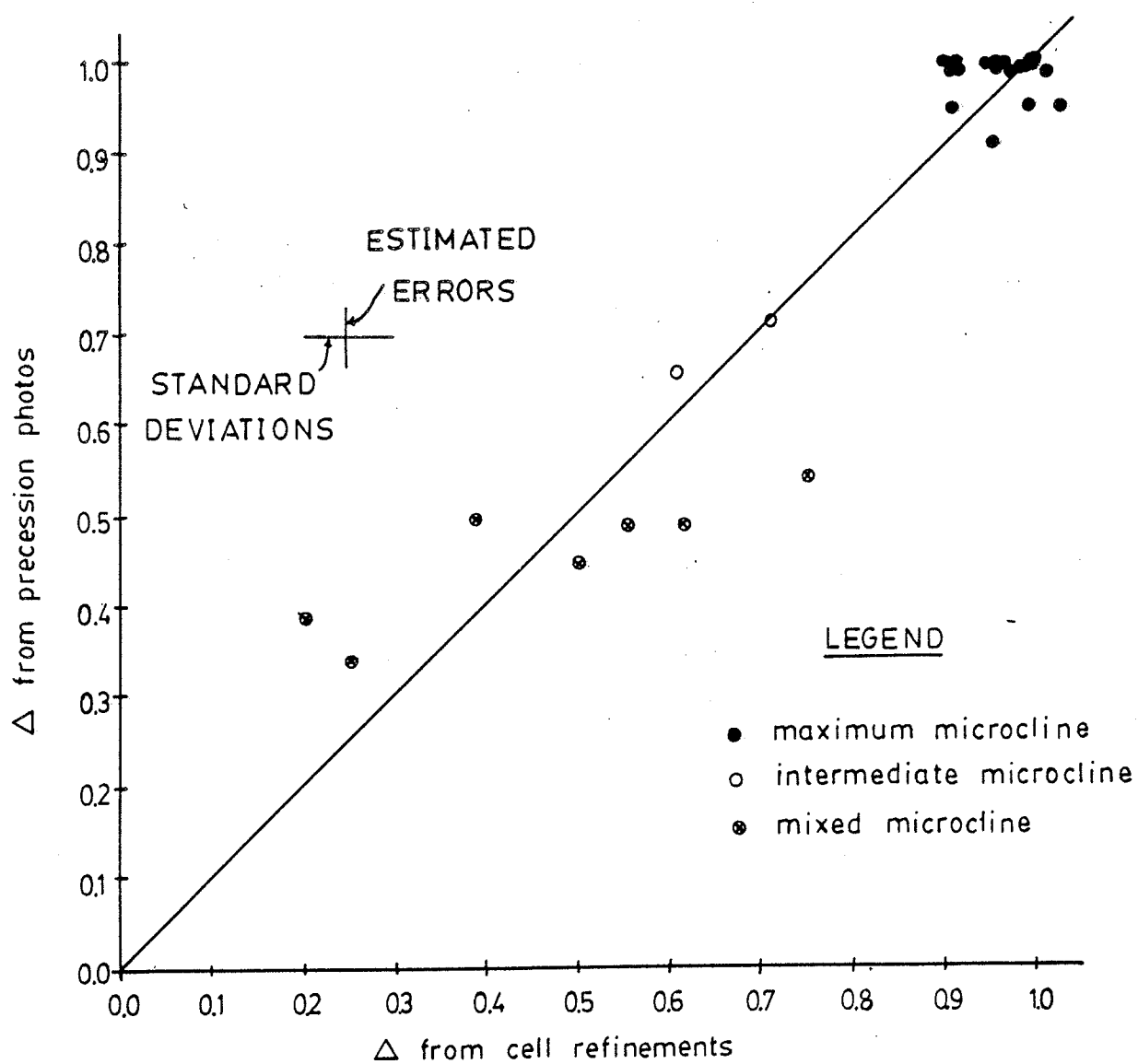


Figure 3-15 (b). Δ from precession photos vs. Δ from cell refinements.

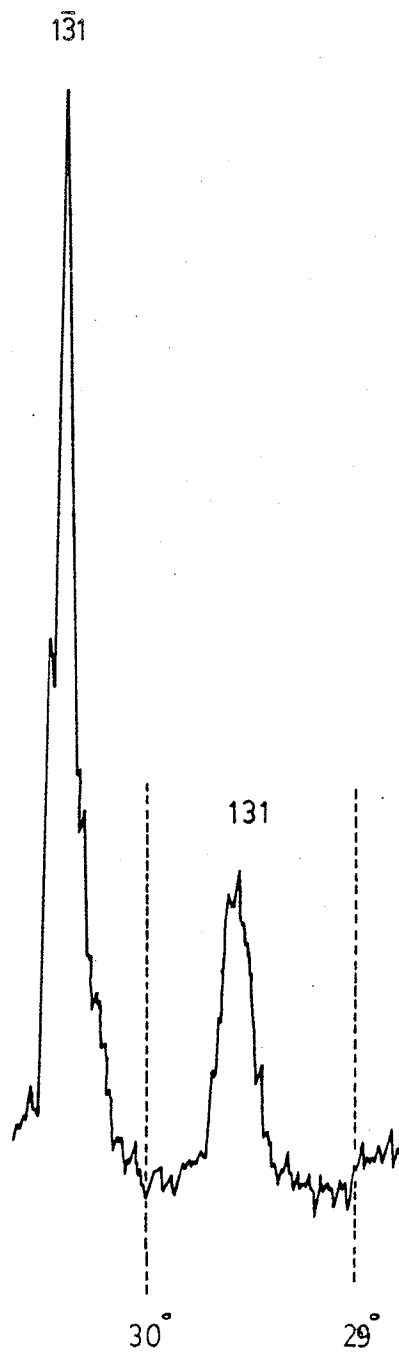


Figure 3-16. Maximum microcline (HG-01) powder diffraction pattern between 29° and 30° at $1/4^\circ/2\theta/\text{min}$. showing that the $\bar{1}\bar{3}1$ is at least three times as high as the 131 peak.

pegmatitic K-feldspars is very low (as compared to the peaks in Figure 3-16), the corresponding 131 or $1\bar{3}1$ peak would be within the background level, that is, if the monoclinic component is interpreted as an intermediate microcline.

(4) K-Na solid solution composition

The K-Na in solid solution composition was determined only from the powder diffractograms (as obtained from the $\bar{2}01$ spacing). It can not be determined accurately from the precession photo data because the photos do not use an internal standard. The compositions expressed in wt % Or are listed in Table 3-9. The values are compared with the electron microprobe data in Chapter VI.

(5) Amount of albite as a second phase

Table 3-11 summarizes the amounts of second phase albite as deduced by the three different diffraction methods. The results from both precession and Gandolfi data are closely related, as expected as they are from the same crystal. The albite reflections were sometimes not observable in the Gandolfi photos of the 15 microclines, even though they are present in the corresponding precession photos; this presumably result from the shorter exposure times when compared to the precession photos. The powder diffraction data give a higher wt % of albite (as a second phase in microclines) than do the two single crystal methods. This is possibly due to the fact that the powder method

Table 3-11. Estimated weight % of albite as a second phase in K-feldspars by the three different x-ray diffraction methods.

ROCK TYPE	SAMPLE	SAME SINGLE CRYSTAL		POWDERED SAMPLE
		PRECESSION PHOTOS	GANDOLFI PHOTOS	POWDER DIFFRACTOGRAMS
LAC DU BONNET GRANITE	PG-121	-	-	5
	PG-135	$\frac{1}{4}$	-	20
	PG-152	1	1	20
	SR-97	2	2	15
	SR-148	$\frac{1}{4}$	-	15
	PG-133	$\frac{1}{2}$	-	<5
	PG-24	$\frac{1}{2}$	-	<5
	AEC-26	$\frac{1}{4}$	-	<5
	AEC-20	1	1	<5
DRYDEN GRANITES	ZPG-07	$\frac{1}{2}$	-	20
	APG-05	$\frac{1}{2}$	-	25
	GPG-22	1	1	5
	HG-01	2	2	5
	MLG-01	$\frac{1}{2}$	-	5
	CG-03	2	2	25
	SG-01	$\frac{1}{2}$	-	15
DRYDEN PEGMATITES	MLP/NZ 01	$\frac{1}{4}$	-	30
	MLP/NZ 02	$\frac{1}{2}$	$\frac{1}{2}$	10
	MLP/NZ 05	3	3	25
	MLP/NZ 23	-	$\frac{1}{2}$	20
	MLP/NZ 24	$\frac{1}{2}$	$\frac{1}{2}$	<5
	MLP/NZ 30	$\frac{1}{4}$	-	<5
	MLP/NZ 42	$\frac{1}{4}$	-	-
	MLP/NZ 47	$\frac{1}{4}$	-	<5
	MLP/SZ 10	$\frac{1}{2}$	$\frac{1}{2}$	20
	MLP/SZ 06	$\frac{1}{2}$	-	30
	ZP-09	$\frac{1}{2}$	-	15
	ZP-05	1	1	20
	GPE-11	$\frac{1}{2}$	$\frac{1}{2}$	20

used larger K-feldspar (powdered) material which could contain more albite as a second phase than did the small single crystal. These results are further discussed and compared with other information in Chapter VI.

(6) Twinning

Of the three x-ray diffraction methods used here, only precession photos show the type of twinning and the nature of the interphase boundaries. However, although the powder diffraction method cannot record twinning information, it can provide valuable help in interpreting the nature and type of twinning and intergrowths observed in precession photos. The albite- + pericline-twinned microcline (particularly of the maximum type) in precession photos was initially interpreted by the author and her supervisor as albite- + pericline-twinned maximum microcline with a monoclinic component; however, the interpretation was changed to a simple albite- + pericline-twinned maximum microcline when the Gandolfi photo of the same crystal showed a purely maximum microcline. They realized that the central y^* and x^* axes with interaxial angle of 90° are a consequence of the albite- and pericline-twinning with or without a (pseudo-) monoclinic intergrown phase. Similarly, the Gandolfi photos also helped to interpret untwinned intergrowth reflections. The powder diffractograms also helped in the interpretation of the precession photos, particularly the streaks. Initially,

some of the K-feldspars were interpreted as having a transitional structure, due to streaks connecting twinned individuals. However, powder diffractograms of the same K-feldspar samples showed only simple maximum microclines. The interpretations of the precession photos of these K-feldspars were changed to the type of twinning and twin boundaries as discussed earlier.

(E) CONCLUSIONS

Precession photography of single K-feldspar crystals can show a wealth of information about the characteristics of that K-feldspar. However, interpretation of the precession photos is greatly clarified with the addition of Gandolfi powder-type photos of the same crystal, and of diffractograms of powder samples of the same K-feldspars.

CHAPTER IV. CHEMICAL ANALYSIS

(A) INTRODUCTION

It is important to supplement the x-ray diffraction data with chemical data in order to develop a broader understanding of the possible origin of the K-feldspars and of the pegmatitic and granitic rocks of both study areas.

The author and her supervisor felt that it might be possible to correlate microprobe analyses of the single crystals with their crystallographic characteristics (triclinicity, phases, streaks, twinning) and these possible correlations will be discussed later in Chapter VI. Partial chemical analyses from Ucakuwun (1981) on larger amounts of material from the same samples used for the single crystal studies of the K-feldspars supplement the author's electron microprobe data, particularly in elements that were not possible to analyze by electron microprobe. Whole rock analyses of the rock from which the single crystals and powders came were provided by P. Černý (private communication) some of which appear in Černý et al., 1981 (Table 18).

(B) PROCEDURES

(1) Electron microprobe analysis

The method used to mount the crystals for microprobe

analysis is as follow:

(a) With the edge of the probe mount thinly coated with epoxy and placed on a foil paper that is absolutely flat on a glass slide, the probe mount is partially filled with epoxy and heated on a hot plate set at 350° F until the epoxy has hardened.

(b) After the mount has cooled off and with the foil paper peeled off, the epoxy surface is ground by a diamond abrasive wheel until the surface is flat and smooth.

(c) Under a binocular microscope, indentations deep and wide enough for each crystal are made on the epoxy surface with a needle.

(d) A crystal is placed in the hole using a glass rod. However, finer adjustments of the size and depth of the hole are frequent.

(e) The crystal is then adjusted so that it is flat in relation the epoxy surface and very close to the surface.

(f) Another glass rod that has a tiny drop of liquid epoxy is rubbed against the edge of the hole to fill it and to seal the crystal to the probe mount. The position of the crystal is noted.

(g) The steps (no. c to f) are repeated for a number of crystals (in the author's case, 6).

(h) The probe mount is then placed in an oven set at 350° F until the epoxy in the hole hardens.

(i) The crystals are checked under the microscope and the holes are refilled with epoxy where necessary. It is important that the depression around a crystal is completely filled, otherwise it becomes very difficult to see the crystal in the microprobe (under reflected light).

(j) The procedure is repeated until the probe mount accommodated the maximum number of crystals (~ 18).

(k) The surface of the mount is polished on a wheel covered with a polishing cloth that has been coated with wet 0.3 micron polishing powder until the crystals are absolutely flat and have good reflectivity.

(l) The surface of the probe mount is finally given the required carbon coating before being analyzed by the microprobe.

A MAC-5 electron microprobe operating in the energy dispersive mode was used to analyze 31 single crystals with an accelerating voltage of 20 kV, a sample current of 4.5 namps., and a collecting time of 100 seconds. The data was reduced by MAGIC IV computer program (J.W. Colby, Kenex Corp., Foster City, Calif.). The standards used to analyze the feldspars are listed in Table 4-1.

(2) Whole rock and partial chemical analysis

The standard analytical procedures for the whole rock and partial chemical analyses of both the Lac du Bonnet and Dryden specimens are listed in Černý et al. (1981) and

Ucakuwun (1981). The accuracy and precision of all the elements are given in Černý et al. (1981, Table 2) and Ucakuwun (1981, Table 3-2).

Table 4-1. Standards used to analyze each element. The standards were purchased from Charles M. Taylor Co., Stanford.

ELEMENT	STANDARD(S)	ELEMENT	STANDARD(S)
K	orthoclase	Fe	orthoclase
Na	albite, orthoclase	Ba	K253 (glass)
Al	" "	P	apatite
Si	" "	Ca	pyrope

(C) RESULTS AND DISCUSSIONS

(1) Introduction

Twenty-seven K-feldspars (2 crystals were lost during polishing) were probed for six elements: K, Na, Si, Al, Ba, and P. It was not possible to probe for minor elements Rb, Sr and Ca because their peaks were overlapped by the strong K and Si peaks. It is common to find overlapping peaks in the spectra of many minerals and the K-feldspars are no exception. The L_{α} of Rb in K-feldspars overlaps the strong K_{α} peak of Si (in most K-feldspars the Rb is so low that the K_{α} of Rb is too weak to be detected above the background). Similarly the weak CaK_{α} peak overlaps the stronger KK_{β}

peak but probably over 0.1 % Ca may be detected (R. Chapman, personal communication). The $\text{SrL}\alpha$ also overlaps the $\text{SiK}\alpha$ peak. The probe results are listed in Table 4-2.

The relevant partial chemical analyzes from Ucauwun (1981) are reproduced in Table 4-2. Unfortunately Ba and Sr were not included in the analyses. Two specimens (MLP/NZ 02 and MLP/NZ 05) were not chemically analyzed by Ucauwun (1981) but were probed by the present author. Rb, Ca, Cs, Li are not included for these two specimens.

As explained earlier, not all elements in a given K-feldspar could be analyzed by the electron microprobe method. However, effective totals were derived by the unorthodox procedure of combining the writer's probe results with Ucauwun's (1981) partial chemical results to complement these "missing" elements (as oxides), namely Rb_2O , CaO , Cs_2O and Li_2O . Because Rb, Cs and Li are concentrated in the K-feldspar and Ca in a plagioclase in the bulk sample used for the partial chemical analyses, the Rb, Cs and Li amounts in Table 4-2 represent minima and the Ca amounts maxima, in the K-feldspars (Mason, 1982). These same elements are included in the molecular %'s of feldspar end-members in Table 4-2: Rb-feldspar, Cs-feldspar, etc.

cal analyses of Ucakuwun numbers are probe re-
artial chemical analyses.

See text for explanations. Designations: nd = not determined, ²⁰⁵ Pb present, ¹³⁷ Cs, ¹³⁸ U present.																									
ROCK TYPE	SAMPLE NO.	OXIDE (WT. %)										MOLECULAR %						NUMBER OF CATIONS PER 8 OXYGENS FROM PROBE							
		K ₂ O	Na ₂ O	Al ₂ O ₃	SiO ₂	BaO	Rb ₂ O	CaO	Cs ₂ O	Li ₂ O	Σ probe	Ab	An	Rb-feld	Li-feld	Cs-feld	Cn	K	Na	Ba	Σ M	Al	Si	Σ T	Σ CATIONS
LAC DU BONNET GRANITE	PG-121	16.59	0.75	18.15	64.61	-	-	-	-	-	100.10	6.43	-	-	-	-	-	0.9806	0.0675	-	1.0481	0.9915	2.9944	3.9859	5.0339
	PG-135	15.45	0.85	19.05	64.05	-	-	-	-	-	99.40	7.71	-	-	-	-	-	0.9136	0.0768	-	0.9907	1.0423	2.9707	4.0127	5.0035
	PG-152								nd																
	SR-97	16.44	0.59	18.40	63.92	0.64	-	-	-	-	99.99	5.05	-	-	-	-	2.23	0.9772	0.0545	0.0117	1.0434	1.0105	2.9783	3.9888	5.0323
	SR-148	15.77	0.77	19.13	64.66	-	-	-	-	-	100.33	6.90	-	-	-	-	-	0.9251	0.0687	-	0.9938	1.0368	2.9740	4.0108	5.0046
	PG-133								nd																
	PG-24	16.05	1.22	18.70	64.02	-	-	-	-	-	99.99	10.36	-	-	-	-	-	0.9492	0.1100	-	1.0592	1.0218	2.9689	3.9967	5.0499
	AEC-26	15.17	1.29	18.72	64.57	0.29	-	-	-	-	100.03	11.32	-	-	-	-	1.03	0.8933	0.1152	0.0160	1.0245	1.0188	2.9811	3.9999	5.0137
	AEC-20	15.41	0.88	19.01	64.19	0.36	-	-	-	99.85	7.88	-	-	-	-	1.28	0.9088	0.0790	0.0065	0.9943	1.0351	2.9735	4.0086	5.0028	
DRYDEN GRANITES	ZPG-07	15.30	1.01	19.01	64.68	-	(0.06)	(0.07)	-	-	100.28	9.05	0.70	0.20	-	-	-	0.8991	0.0903	-	0.9892	1.0315	2.9791	4.0107	4.9998
		11.90	3.01	-	-	-	0.06	0.07	-	-															
	APG-05	15.41	0.97	18.58	65.04	-	(0.19)	(0.08)	(0.064)	-	100.00	8.51	0.70	0.54	-	0.11	-	0.9054	0.9863	-	0.9917	1.009	2.9953	4.0043	4.9960
		13.10	2.41	-	-	-	0.19	0.08	0.064	-															
	GPG-22	13.74	1.46	19.39	64.95	0.46	-	-	-	-	100.00	13.68	-	-	-	-	1.74	0.8034	0.1302	0.0083	0.9419	1.0473	2.9770	4.0243	4.9661
	HG-01	15.09	1.01	19.71	64.19	-	-	-	-	-	100.00	9.24	-	-	-	-	-	0.8862	0.0898	-	0.9760	1.0691	2.9542	4.0233	4.9993
	MLG-01	17.01	0.62	18.50	63.77	present	-	-	-	-	99.90	5.46	-	-	-	-	-	1.0162	0.0555	-	1.0717	1.0158	2.9702	3.9860	5.0577
	CG-03	15.83	0.79	18.90	63.88	0.60	-	-	-	-	100.00	6.88	-	-	-	-	2.11	0.9373	0.0712	0.9110	1.0195	1.0345	2.9665	4.0010	5.0205
	SG-01	15.32	1.09	19.52	64.06	-	-	-	-	99.99	9.77	-	-	-	-	-	0.9014	0.0973	-	1.0481	1.0614	2.9542	4.0156	5.0144	
DRYDEN PEGMATITES	MLP/NZ 01	15.48	0.56	18.77	64.11	-	(1.10)	(0.09)	(0.017)	(0.03)	98.82	4.95	0.88	3.24	0.55	0.05	-	0.9207	0.0511	-	0.9718	1.0274	2.9865	4.0139	4.9857
	MLP/NZ 02	13.85	1.56	-	-	-	(<u>n.d.</u>)	(<u>n.d.</u>)	(<u>n.d.</u>)	(<u>n.d.</u>)	98.29	6.36	-	-	-	-	-	0.9236	0.0624	-	0.9860	1.0184	2.9525	3.9709	4.9867
	MLP/NZ 05	14.67	0.76	18.13	64.00	-	(<u>n.d.</u>)	(<u>n.d.</u>)	(<u>n.d.</u>)	(<u>n.d.</u>)	97.98	7.32	-	-	-	-	-	0.8752	0.0685	-	0.9437	0.9995	2.9937	3.9932	4.9535
		15.03	0.99	18.86	64.00	-	(1.04)	(0.16)	(0.022)	(0.01)															
	MLP/NZ 23	14.25	1.14	-	-	-	1.04	0.16	0.022	0.01	98.88	8.68	1.57	3.04	0.16	0.05	-	0.8926	0.0901	-	0.9836	1.0341	2.9787	4.0128	4.9956
		15.28	0.64	18.64	63.62	-	(1.77)	(0.10)	(0.047)	(0.07)															
	MLP/NZ 24	13.75	1.20	-	-	-	1.77	0.10	0.047	0.07	98.18	5.51	0.96	5.08	1.23	0.11	-	0.9145	0.0574	-	0.9652	1.0306	2.9840	4.0146	4.9866
		14.61	1.14	20.03	62.95	-	(1.12)	(0.11)	(0.017)	(0.02)															
	MLP/NZ 30	13.30	1.83	-	-	-	1.12	0.11	0.017	0.02	98.73	10.04	1.09	3.28	0.38	-	-	0.8685	0.1032	-	0.9717	1.0994	2.9325	4.0319	5.0036
		14.37	1.32	20.63	61.62	-	(1.59)	(0.12)	(0.030)	(0.03)															
	MLP/NZ 42	13.25	1.54	-	-	-	1.59	0.12	0.030	0.03	97.94	11.48	1.13	4.58	0.54	0.05	-	0.8618	0.1206	-	0.9834	1.1433	2.8970	4.0403	5.0226
		15.08	0.48	18.55	64.39	-	(1.47)	(0.14)	(0.025)	(0.04)															
	MLP/NZ 47	13.85	1.47	-	-	-	1.47	0.14	0.025	0.04	98.50	4.29	1.39	4.40	0.72	0.06	-	0.8965	0.0430	-	0.9395	1.0191	3.008	4.0199	4.9594
		14.60	0.76	17.97	63.16	-	(2.24)	(0.05)	(0.088)	(0.05)															
	MLP/SZ 10	13.70	1.43	-	-	-	2.24	0.05	0.088	0.05	96.96	6.75	0.50	6.59	0.93	0.16	-	0.8809	0.0701	-	0.9591	1.0015	2.9873	3.9888	4.9588
		15.00	0.76	18.48	64.22	-	(1.46)	(0.08)	(0.054)	(0.03)															
	MLP/SZ 06	13.65	1.40	-	-	-	1.46	0.08	0.054	0.03	98.46	6.77	0.72	4.29	0.55	0.11	-	0.8928	0.0685	-	0.9613	1.0162	2.9975	4.0137	4.9750
		15.61	0.73	19.21	64.11	-	(0.24)	(0.04)	(0.009)	(0.01)															
ZP-09	12.75	2.83	-	-	-	0.24	0.04	0.009	0.01	99.66	6.56	0.39	0.72	0.17	-	-	0.9214	0.0657	-	0.9871	1.0479	2.9673	4.0152	5.0023	
	16.32	0.77	18.44	64.20	-	(0.26)	(0.03)	(0.005)	(0.01)																
ZP-05	12.50	2.81	-	-	-	0.26	0.03	0.005	0.01	99.73	6.60	0.27	0.75	0.16	-	-	0.9676	0.0694	-	1.0370	1.0099	2.9833	4.0032	5.0303	
	14.60	0.73	17.60	65.08	-	(2.09)	(0.09)	(0.317)	(0.04)																
GPE-11	13.00	1.50	-	-	-	2.09	0.09	0.317	0.04	98.01	6.48	0.88	6.15	0.71	0.61	-	0.8697	0.0657	-	0.9354	0.9686	3.0397	4.0083	4.9437	
MONOCLINIC STANDARD	MONOCLINIC	15.75	0.80	19.39	64.07	-	-	-	-	-	100.00	-	-	-	-	-	-	0.9277	0.0711	-	0.9988	1.0553	2.9588	4.0141	5.0129

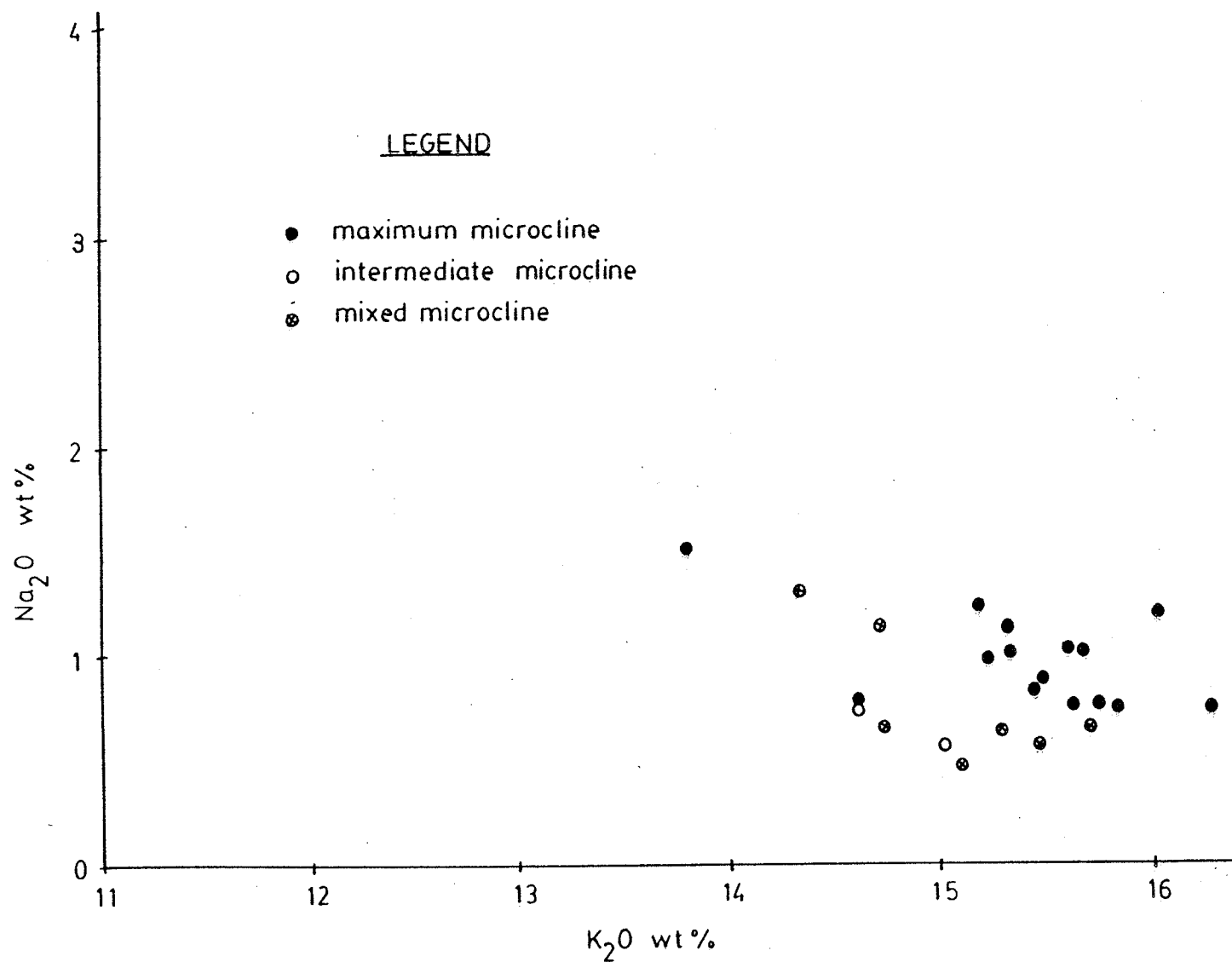


Figure 4-1. Na₂O (wt. %) vs. K₂O (wt. %) of electron microprobe analyses. See text for explanations.

Table 4-3 Whole rock analyses of Lac du Bonnet (Černý et al., 1981, Table 8 and Černý, 1980 private communication) and Dryden (Ucakuwun, 1981) granite specimens

OXIDE IN WT % ELEMENT IN PPM	LAC DU BONNET								DRYDEN					
	LEUCOGRANITE			BIOTITE GRANITE			HORNBLende BIOTITE TONALITE	PORPHYRITIC HORNBLende BIOTITE GRANODIORITE	BIOTITE GRANITE		GRANODIORITE		QUARTZ DIORITE	
	PG-121	PG-152	PG-135	PG-24	AEC-26	PG-133	AEC-20	SR-97	SR-148	GPG-22	CG-03	MLG-01	HG-01	SG-01
SiO ₂	76.85	76.50	77.05	72.55	72.55	73.40	67.30	64.10	69.60	73.55	70.20	75.50	76.60	65.45
TiO ₂	0.08	0.16	0.09	0.26	0.27	0.11	0.38	0.73	0.48	0.14	0.20	0.12	0.07	0.50
Al ₂ O ₃	12.20	11.49	11.76	14.54	14.12	13.62	16.23	14.62	13.94	15.18	16.28	13.62	13.40	16.12
Fe ₂ O ₃	0.83	1.31	0.82	0.96	0.87	0.97	1.68	3.40	2.23	0.10	0.93	0.18	0.25	2.35
FeO	0.72	1.16	0.58	0.76	0.90	0.72	1.72	2.60	1.30	0.48	0.36	0.66	0.19	1.40
MnO	0.02	0.03	0.02	0.02	0.04	0.03	0.04	0.01	0.07	0.01	0.01	0.01	0.01	0.06
MgO	0.02	0.14	0.04	0.44	0.58	0.45	1.20	2.15	1.18	0.21	0.48	0.26	0.06	1.78
CaO	0.40	0.48	0.43	1.41	1.07	1.06	3.90	3.98	2.28	1.62	2.03	0.79	0.46	3.60
Na ₂ O	3.46	3.32	3.74	3.78	3.70	3.56	4.50	3.48	3.30	4.32	6.40	4.60	4.70	5.84
K ₂ O	4.59	4.96	4.95	4.43	5.10	5.63	1.60	3.27	4.70	4.08	1.79	3.78	3.92	1.86
P ₂ O ₅	0.02	0.02	0.02	0.08	0.09	0.08	0.21	0.27	0.14	0.07	0.10	0.06	0.03	0.25
H ₂ O	0.37	0.29	0.46	0.31	0.44	0.35	0.74	0.87	0.54	0.36	0.83	0.37	0.23	0.60
CO ₂	0.03	0.06	0.06	0.05	0.12	0.04	0.10	0.07	0.05	0.08	0.18	0.06	0.04	0.04
Totals	99.59	99.92	100.02	99.59	99.85	100.02	99.60	99.64	99.81	100.20	99.79	100.01	99.96	99.85
Li(ppm)	29	34	47	81	32	57	30	91	19	10	14	52	3	33
Rb	277	166	217	212	232	231	48	91	121	92	37	84	90	36
Cs	5	1	1	7	2.3	4	2.4	0.7	1.1	1.8	1.4	3.2	1.9	3.4
Be	5	2	4	3	1.4	2	2.2	1.5	1.5	1.7	1.4	1.4	1.6	1.7
Sr	10	28	24	143	149	225	423	470	330	450	393	348	218	1040
Ba	111	1049	176	625	635	926	593	1504	1060	1145	666	635	231	926
Pb	10	9	14	28	18	22	7	13	22	34	8	21	17	13
Ga	35	22	31	33	34	28	27	29	23	11	23	23	30	29
Y	83	nd	54	nd	12	nd	3	33	17	nd	nd	nd	nd	12
Zr	211	382	203	190	242	212	198	259	193	41	62	51	35	182
Sn	9	nd	10	1	13	5	10	6	9	4	16	10	14	6
Th	39	nd	32	14	19	16	13	7	22	nd	nd	1	4	9
U	10	6	11	7	6	2	nd	nd	5	nd	nd	nd	nd	nd

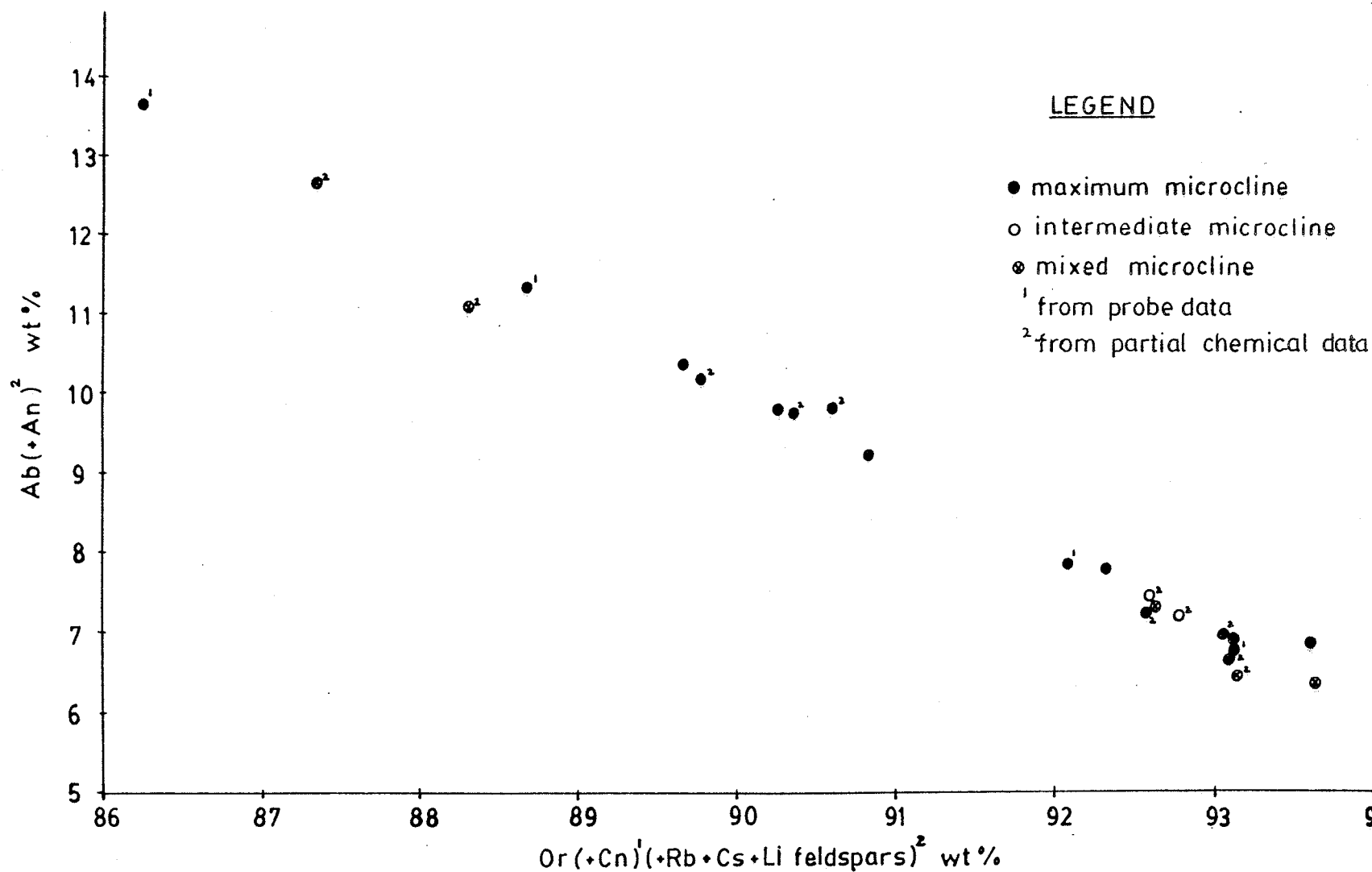


Figure 4-2. Ab (+An)² wt % vs. Or (+Cn)¹(+Rb+Cs+Li-feldspars)² wt % where Na, K, and Ba¹ are from electron microprobe data and ²Ca, Rb, Cs and Li are from partial chemical analyses (see Table 4-2).

Whole rock analysis in weight % oxide along with trace elements in ppm of 14 granitic rocks from both Lac du Bonnet source and Dryden source areas are listed in Table 4-3.

(2) Electron microprobe results

As seen in Table 4-2, of the three elements K, Na, Ba analyzed by the probe, K is dominant as expected. Although the sodium content is generally low (up to 1.47 wt % Na_2O), it is inversely correlated with K_2O (Figure 4-1). Figure 4-2 shows that all the points fall close to a straight line which can be taken as evidence that the probe results are dependable.

Thirteen K-feldspar crystals show traces of Ba and/or P in the probe analyses. It was found that Ba and P in each K-feldspar crystal, particularly in those that were analyzed twice, were present in either the first or the second analyses but rarely both. The reason for this is that the electron microprobe beam is much smaller than the crystals and so the beam in both analyses (first and second) hit different spots of the same crystal. Six of the K-feldspars which show presence of Ba (of which 5 were analyzed) are from granitic rocks whereas 7 K-feldspars show presence of P are from pegmatitic rocks. It is possible that Ba is incorporated in the K-feldspar structure and that P is possibly part of a small apatite exsolved from P that was probably incorporated in the K-feldspar structure (Simpson, 1977). Cs was observed in one sample only (GPE-11) but could not be quantitatively analyzed because ✓

there were no standards for Cs available at that time.

(3) Correlations between probe and partial chemical analyses

As the partial chemical analyses were on the same material used for the powder diffractograms, and the single crystals were also derived from the same material before crushing, it is desirable to compare the partial chemical analyses and probe analyses.

Figure 4-3 shows a plot of K_2O from partial chemical analysis against K_2O from microprobe analysis and it shows that the K_2O values from the probe analyses are much higher than those from the partial chemical analysis. The most likely interpretation is that the probe analyses are of small areas of the K-rich microclines that contain little Na in solid solution or as microperthitic albite whereas the chemical analyses are of a much larger microcline volume which is more likely than a small K-feldspar area to contain appreciable (micro-)perthitic albite.

Partial chemical analyses show very low Cs_2O in all microclines except GPE-11; this is the only specimen in which Cs was detected by microprobe analysis.

(4) Whole rock analyses

The electron microprobe analyses show that six single K-feldspar crystals contain detectable Ba. This corresponds to those granitic rocks that have Ba contents of 550 ppm and higher (see Table 4-3). However, five other rocks also

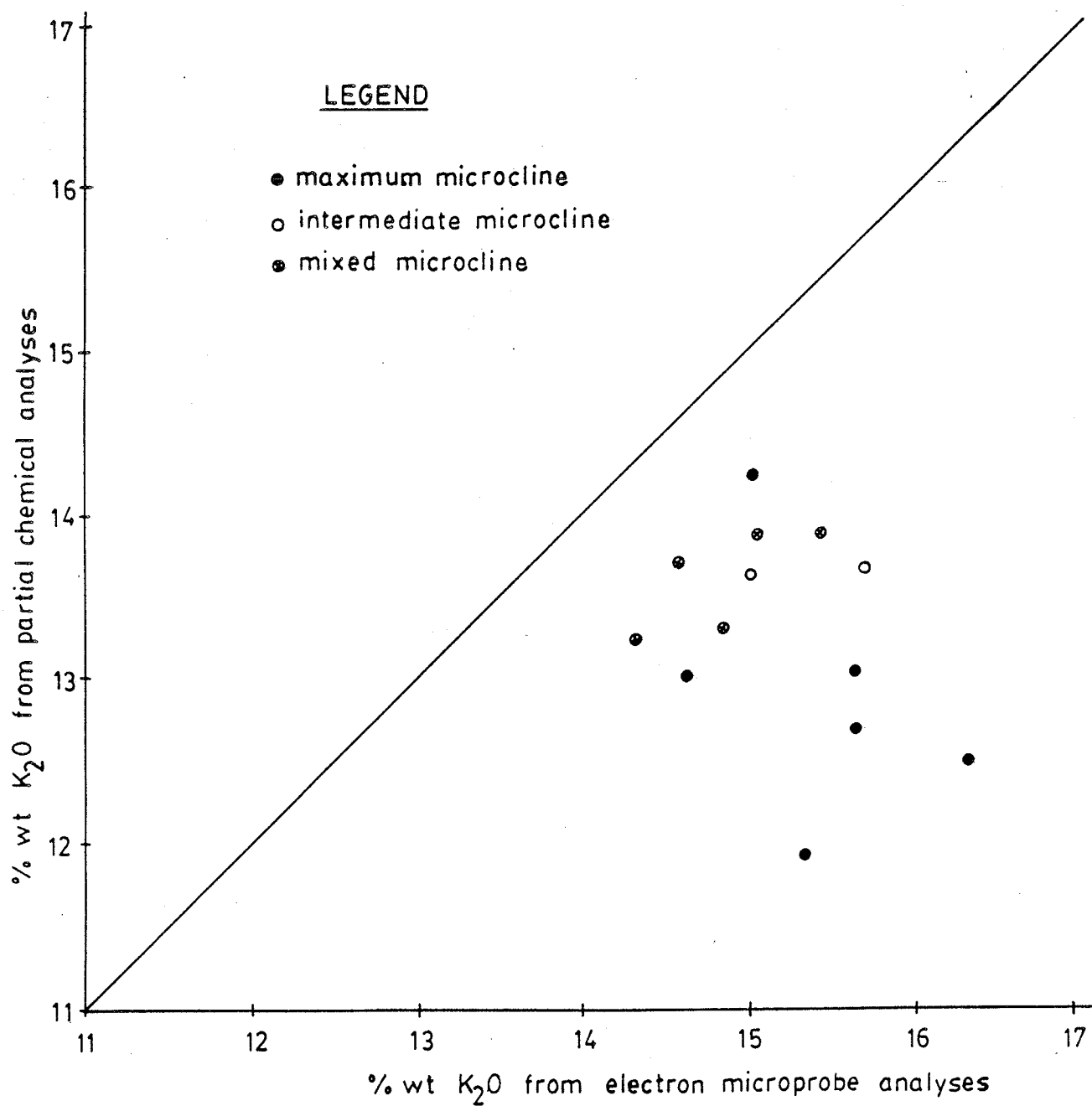


Figure 4-3. % weight K_2O from electron microprobe analyses vs. partial chemical analyses. See text for explanations.

show high Ba contents but the probe analyses did not reveal Ba in the single crystals. There are several possible reasons for this: (1) the Ba is probably concentrated in other minerals although several workers such as Rhodes (1969) have observed that most of the Ba in granites is concentrated in the K-feldspars and (2) Ba is preferably incorporated in the K-feldspar structure in randomness and detailed probing of a crystal is needed to detect Ba.

Rb, Cs, Sr, and Li are all very low (less than 500 ppm) in the whole rock analyses, and, in agreement, they were below the limits of detectability for electron microprobe analyses of the K-feldspars.

CHAPTER V. THIN SECTION STUDIES

(A) INTRODUCTION

Along with the structural characteristics as interpreted from the precession photos, Gandolfi photos and powder diffractograms and the chemical variations as analyzed by the electron microprobe (and supplemented by the partial chemical analysis), the textural characteristics of the K-feldspars were examined in thin sections. The characteristics observed included their crystal size in relation to the other minerals within the thin sections, their shape, their twinning habit and their degree and products of alteration. The albite as a second phase in microclines is easily recognized in thin sections and is known as perthite. The optical characteristics of perthites are recorded in terms of abundance, size, shape and in some cases, composition as determined by universal stage methods.

Because of their unique relationship with the K-feldspars, the textural characteristics of the plagioclases are also described in a similar fashion to the K-feldspars as outlined above. The plagioclases in thin sections appear in two forms: as separate crystals and as inclusions within the microclines. These plagioclases are treated separately from the Na-rich feldspars that occur as perthitic intergrowths in microclines and as rims around the plagioclases.

In some cases, the intimate association of plagioclases and K-feldspars gives rise to albitic rims and myrmekites and their qualitative relative amounts in thin sections and their compositions (from universal-stage measurements) were also observed. Modal analyses of all the minerals with plagioclase and albite undifferentiated were made of each thin section for possible correlations between the K-feldspars and the plagioclases.

A total of 15 thin sections were studied by the author: five from the Lac du Bonnet granitic specimens (AEC-20, PG-24, AEC-26, PG-121, SR-148), four from the Dryden granites (GPG-22, MLG-01, HG-01, CG-03), one from a Dryden pegmatitic granite (APG-05), and five from the Mavis Lake pegmatite (MLP/NZ 01, MLP/NZ 24, MLP/NZ 30, MLP/NZ 42, MLP/NZ 47). This represents half of the number of K-feldspar samples studied by x-ray diffraction and chemical methods. The thin sections were taken from the same part of the hand sample from where the single crystals and powder samples were taken. The results from the thin section studies are correlated and compared with those from x-ray diffraction methods and chemical analyses in Chapter VI.

Although optical methods such as optic axial angle measurements were the principal basis for describing and classifying alkali feldspars, particularly the K-feldspars, into different structural groups prior to 1950 (Smith, 1974a),

the author did not do any optical measurements on the K-feldspars because they have very low birefringence permitting a low accuracy of 2V measurement. The orientation of the indicatrix is also hard to determine with any reliable accuracy. Structural and chemical variations of each K-feldspar were accurately measured and so it was unnecessary to include optical measurements with larger errors. Many petrographers have noted that variations in 2V within a K-feldspar is common. For example, Marfunin (1966) reported a change in 2V from 55° to 84° for a single pegmatitic K-feldspar. However, the composition of the plagioclases (both as a separate mineral and as inclusions in K-feldspars) and Na-feldspars (as rims of plagioclase and as second phases in K-feldspars) were determined by the universal stage methods (Fedorow method for low-temperature plagioclases) because the accuracy, in contrast to K-feldspars, is within 2 % of the An content. However, it was not possible to probe or to x-ray the plagioclases as there was not enough time to do them and the emphasis of the thesis is on the K-feldspars rather than the plagioclases.

(B) K-FELDSPARS

K-feldspars are major constituents in all the 15 granitic and pegmatitic rocks examined in thin sections. Modal analyses (Table 5-1) have revealed that K-feldspars

range from a low of 9 % to a high of 87 % due to the different rock types as expected. Both the Lac du Bonnet and Dryden granites (which also included leucogranites, granodiorites, and tonalites) show variable K-feldspar content whereas the pegmatites show consistently high K-feldspar contents as expected.

In granitic rocks, the K-feldspars are observed as fine-to coarse-grained and interstitial with no definite crystal outline (Figure 5-1). They are largely unaltered (Figure 5-1) although some are slightly altered to epidote and sericite (Table 5-1).

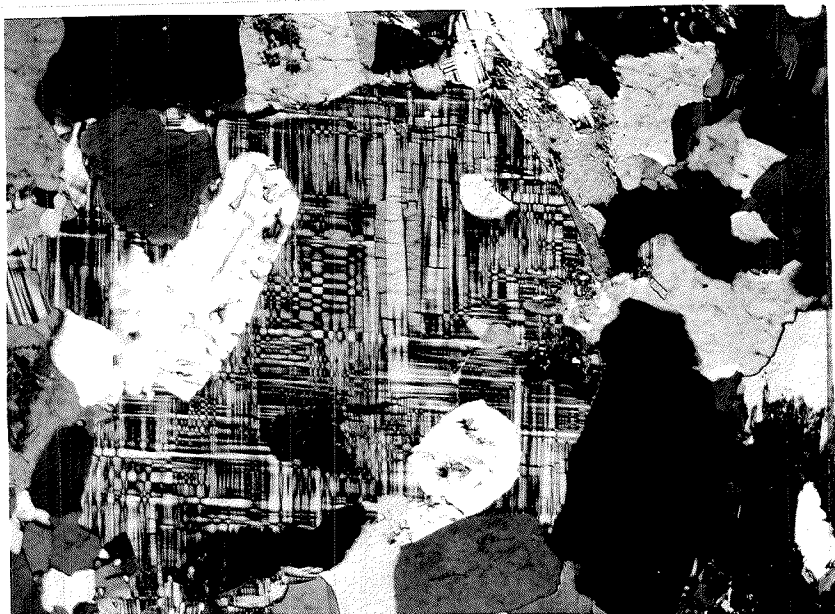
Pegmatitic K-feldspars are massive and show moderate to extensive patchy alteration to epidote and some sericite (Figure 5-2). They are also characterized by heavy iron staining.

The presence of cross-hatched twinning, the well-known combination of albite and pericline twinings, is, in general, the most important criterion used by petrographers to classify K-feldspars as microclines. Orthoclases have been optically described by many petrographers as those K-feldspars in granitic type rocks that do not display any twinning. However, there are several reasons for the K-feldspar to appear as untwinned: (1) all granitic feldspars in a given thin section are in random orientation and a K-feldspar that is actually albite- or pericline-twinned may

Table 5-1. Modal analyses, optical characteristics of K-feldspars, perthites, and plagioclases in Lac du Bonnet and Dryden granitic and pegmatitic rocks. Designations: Comp'n = Composition, K-spar = K-Feldspar, plag = plagioclase, bio = biotite, hble = hornblende, chl = chlorite, epi = epidote, musc. = muscovite, seri. = sericite, ext. = extensive, ab = abundant

ROCK TYPE	SAMPLE NO.	ROCK NAME (FROM Chapter 2)	FIGURES IN TEXT OF PHOTOS	MODAL ANALYSES (VOL. %)									K-FELDSPARS					
				K-SPAR	PLAG.	QTZ.	BIO.	HBLE	CHL.	EPI.	OXIDES	MUSC	PERTHITIC CHARACTERISTICS	SIZE	SHAPE	DEGREE OF ALTERATION	ALTERATION PRODUCTS	TWINNING
LAC DU BONNET GRANITE	PG-121	Leucogranite	6-5	31	25	42	1	1	-	-	1	1	non-perthitic to mod. perth.	fine-med grained	intersti- tial	slight	seri.,epi	cross- hatched
	SR-148	Porphyritic Hble. Bio. Granodiorite	-	9	48	26	12	1	>1	3	1	-	non to slightly perth.	v.f. grained	"	"	bio, oxides epi.	both
	PG-24	Bio. Granite	6-1, 6-8 7-5a	36	32	20	6	-	2	2	-	2	perthitic	fine- coarse	"	none	-	"
	AEC-26	"	6-15	16	42	34	5	-	>1	1	1	>1	non-to slightly perth.	med-coarse	"	"	-	"
	AEC-20	Hble-Biotite Tonalite	6-4	22	48	25	3	-	1	1	-	>1	perthitic	coarse	"	"	-	"
DRYDEN GRANITES	APG-05	Pegmatitic Granite	-	76	23	-	-	-	-	-	-	1	"	massive	"	slight	musc, epi	one twin
	GPG-22	Bio. Granite	6-13, 6-14, 6-16, 6-17, 7-5b	29	45	22	2	-	>1	>1	-	>1	slightly perth.	med-coarse	"	none	-	both
	HG-01	Quartz Diorite	6-6, 6-10	62	6	31	-	-	-	>1	-	>1	perthitic	coarse	"	slight	seri,epi	"
	MLG-01	Granodiorite	6-3	32	39	24	3	>1	1	-	-	-	non-to mod.perth	"	"	none	-	"
	CG-03	"	6-11	10	69	16	-	-	-	4	-	>1	non to slightly perth.	med-coarse	"	"	-	-
DRYDEN PEGMA- TITES	MLP/NZ 01	Pegmatite	6-12, 6-18	70	27	2	-	-	-	-	-	-	perthitic	massive	"	mod	epi. iron	"
	MLP/NZ 24	"	6-9	54	44	1	-	-	-	-	-	-	"	"	"	mod-ext.	epi, iron,seri	"
	MLP/NZ 30	"	6-2	71	28	>1	-	-	-	-	-	-	slightly perth.	"	"	"	iron	"
	MLP/NZ 42	"	7-5c	68	5	26	-	-	-	1	-	1	non-mod. perth.	"	"	"	epi, iron,seri	"
	MLP/NZ 47	"	-	87	10	4	-	-	-	-	-	-	non-perthitic	"	"	"	epi, iron	"

ROCK TYPE	SAMPLE NO.	PERTHITES					PLAGIOCLASES						PLAGIOCLASE INCLUSIONS IN K-FELDSPARS		ALBITIC RIMS		MYRMEEKITES	
		MACRO/MICRO/CRYPTO	ALBITE SHAPE	AMT. OF STRINGS	AMT. OF RODS & BLEBS	COMP'N OF RODS	SIZE	SHAPE	DEGREE OF ALTERATION	ALTERATION PRODUCTS	TWINNING/ZONING	An%	AMT.	COMP'N	AMT.	COMP'N	AMT.	COMP'N
LAC DU BONNET GRANITE	PG-121	micro	coarse-grained blebs	-	moderate	-	fine to med. gr.	prism. to anhedral	slight	musc., calcite epi, chl.	both	An ₉	few	-	-	-	-	
	SR-148	"	strings	ab.	-	-	coarse gr. to 'porphyritic'	anhedral	mod. to ext.	musc., epi., chl, bio.	"	An ₁₅₋₂₅	"	-	few	-	few	
	PG-24	"	strings, fine-grained rods, few c.g. blebs	"	few	-	fine to coarse	"	ext.	seri, chl. epi, oxides	untwinned zoned	An ₁₂	ab.	-	"	An ₂	ab.	
	AEC-26	"	few strings, f.g. rods, very f.g. blebs	few	"	-	coarse	"	"	seri, epi, cc	both	An ₁₈₋₂₂	mod	An ₀	"	An ₀	ab.	
	AEC-20	"	coarse-gr. rods grad. into flame	"	mod.	-	"	"	mod to ext	seri, epi., oxide	"	An ₁₁₋₁₅	few	-	"	-	-	
DRYDEN GRANITES	APG-05	macro	strings, c.g. rods and blebs	ab.	ab.	An ₆₋₉	-	-	none	-	untw.	-	mod.	-	-	-	-	
	GPG-22	micro	strings, c.g. blebs	"	few	-	coarse	anhedral	mod to ext	seri, epi, chl	both	An ₅	ab.	An ₂₋₉	ab.	-	ab.	
	HG-01	"	c.g. rods	-	ab.	An ₂	fine	"	slight to mod.	epi, seri.	"	An ₉	few	-	-	-	-	
	MLG-01	"	c.g. rods & blebs	-	-	An ₉	fine-med.	"	mod.	seri, epi	untw.	An ₁₀	"	-	few	-	ab.	
	CG-03	"	c.g. rods graded into flame	-	few	An ₃	coarse	pris. to anhedral	ext.	epi, seri.	both	An ₂₅	"	-	ab.	-	-	
DRYDEN PEGMATITES	MLP/NZ 01	micro-macro	strings c.g. rods & blebs, strings	ab.	ab.	An ₅	med.	both	slight	epi, cc.	zoned	-	few	An ₂	-	-	-	
	MLP/NZ 24	micro	f.g. blebs	-	"	An ₂	med-coar.	"	"	epi, seri.	both	An ₇	mod.	An ₉	-	-	-	
	MLP/NZ 30	"	"	few	-	-	"	"	none	-	"	An ₆	"	An ₀	-	-	-	
	MLP/NZ 42	macro	c.g. rods & blebs	-	ab.	An ₀	fine-med.	"	"	-	"	An ₀	-	-	-	-	-	
	MLP/NZ 47	"	-	-	-	-	"	"	"	-	twinned	-	mod.	An ₃₋₁₀	-	-	-	



0 0.5 mm

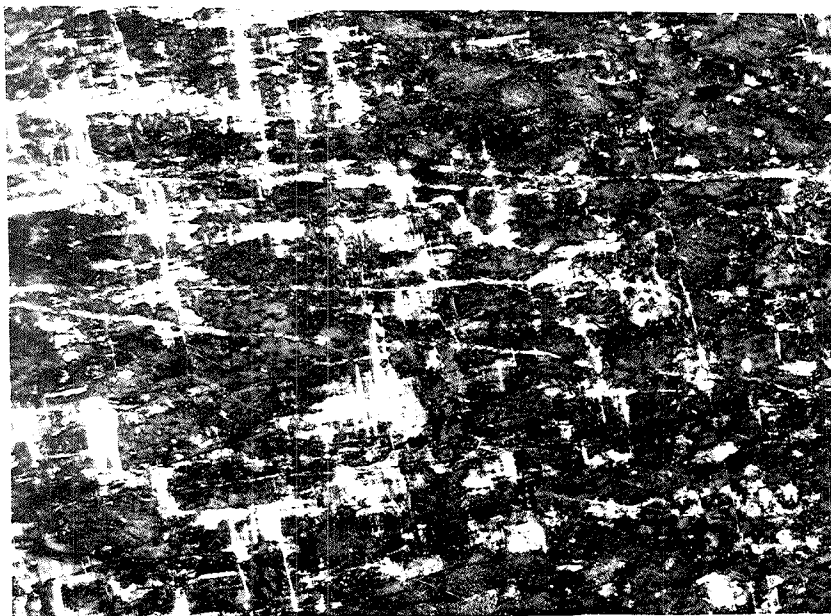
Figure 5-1. Example of a typical K-feldspar (PG-24) in granitic rocks that is interstitial, shows no alteration, and has well-developed cross-hatched twinning with different widths of lamellae. It also contains myrmekite as an inclusion.



0 10 mm

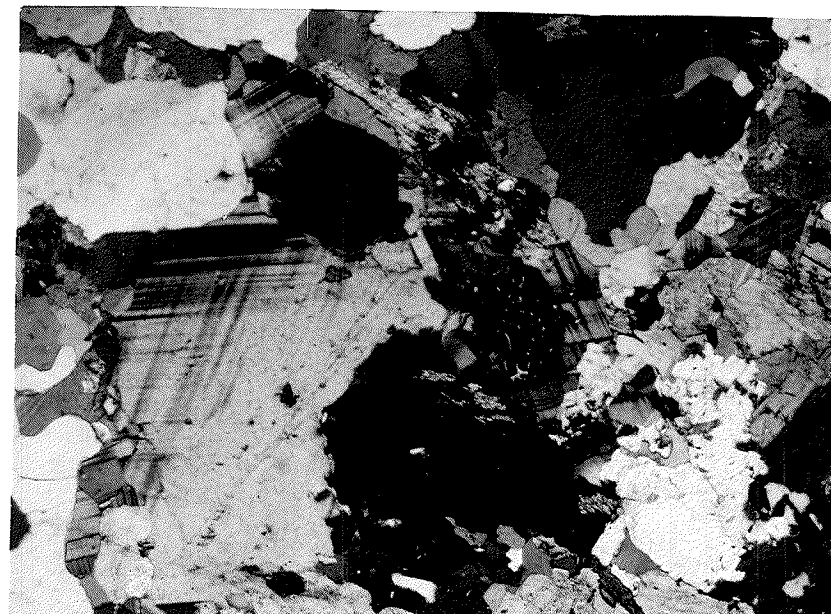
Figure 5-2. Example of a typical pegmatitic K-feldspar (MLP/NZ 30). (a) Under plane-polarized light shows a very "blotchy" appearance of alteration products and heavy iron staining (continued ...)

appear to be untwinned in a given orientation; (2) the K-feldspar may actually be untwinned; (3) a pegmatitic K-feldspar may be of a size such that only one twinned individual is seen in thin section as untwinned; and (4) Laves (1950), other feldspars workers and the author have observed untwinned K-feldspar in the optical microscope that precession photos show to be albite- + pericline-twinned maximum microcline. Hence, a K-feldspar in thin section that does not show any twinning is not necessarily an orthoclase. In the thin sections described here, those that show no optically visible twinning are called "untwinned" K-feldspars. Both cross-hatched twinning and "untwinning" are common in granitic and pegmatitic K-feldspars but cross-hatched twinning is by far the most (Figure 5-3). Cross-hatched twinning and untwinning are usually associated within the same K-feldspar crystal (Figures 5-3 and 5-4). In an untwinned K-feldspar, cross-hatched twinned areas appear to be associated with inclusions (Figure 5-5). Similarly, a largely untwinned microcline crystal may show cross-grating at one edge of the crystal where it is common to find one set of lamellae becoming thicker towards a contact with a non-K-feldspar crystal, particularly quartz (Figure 5-4). Cross-hatching tends to be well-developed in a crystal in the area of inclusions, whether they be plagioclase, quartz, other minerals or even perthitic albite (Figure 5-6). In the pegmatitic



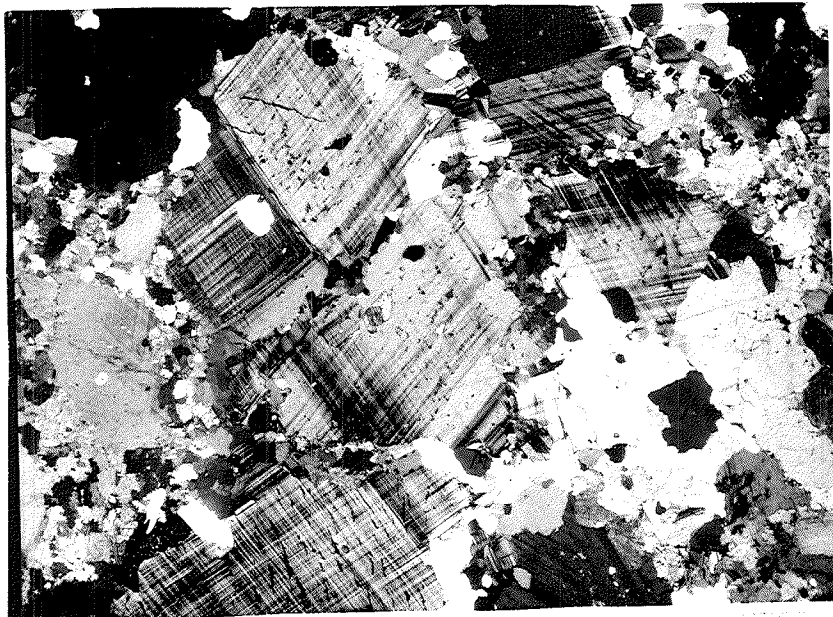
0 10mm

Figure 5-2 (...continued) (b) Same as (a) but in crossed nicols. The cross-hatched twinning is fairly well-developed in the areas free of alteration and staining.



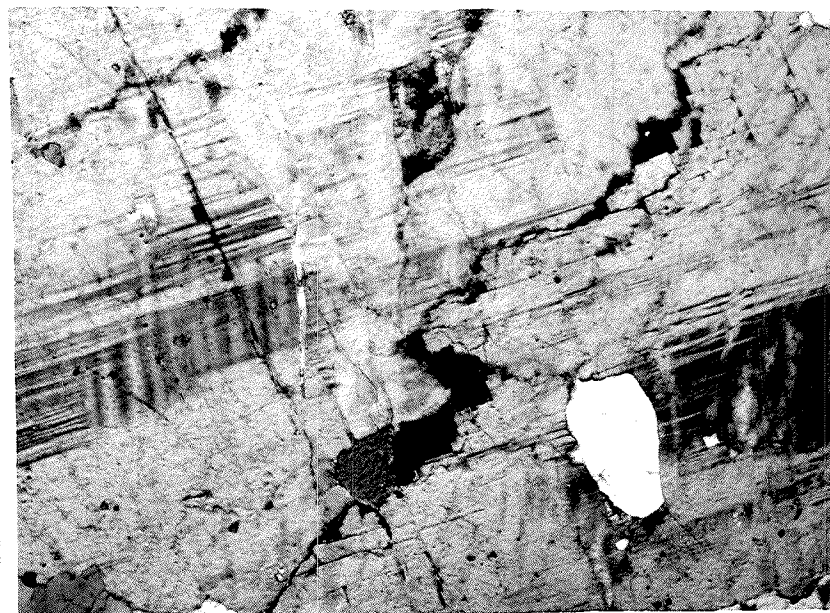
0 5.0mm

Figure 5-3. Example of the association of untwinned and cross-hatched K-feldspars in a granite (MLG-01). It can be seen that cross-hatched twinning predominates untwinning.



0 10 mm

Figure 5-4. Example of the association of untwinning and cross-hatched twinning in a K-feldspar (MLG-01). The K-feldspar is largely untwinned with cross-hatched twinning at the edge of the grain in contact with quartz.



0 1.0 mm

Figure 5-5. Example of incipient cross-hatched twinning with the presence of inclusions of quartz and albite strings (AEC-20).

K-feldspars, cross-hatched twinning is well-developed and prominent in patchy areas where little or no epidote alteration and iron staining occur (Figure 5-2b). In both granitic and pegmatitic K-feldspars that contain cross-hatched twinning, both sets of twin lamellae are usually of different widths and in addition, a single twin lamella is not, in general, continuous throughout a whole K-feldspar crystal (Figure 5-7).

(C) ALBITE PHASE IN K-FELDSPARS

Most of the K-feldspars are actually perthites, that is, they contain albite as a second phase. Many classification schemes have been proposed to divide perthites into groups; the following one proposed by Laves and Soldatos (1963) is commonly used by many petrographers today (Smith, 1974b):

- (1) Macroperthites with albite bands thicker than 0.05 mm and visible with a hand lens.
- (2) Microperthites are those smaller than 0.05 mm and recognizable in an optical microscope.
- (3) Cryptoperthites have intergrowths not visible in the optical microscope that can be detected only by x-ray diffraction methods.

All three kinds of groups are present in the Lac du Bonnet and Dryden granites and pegmatites (Table 5-1). It

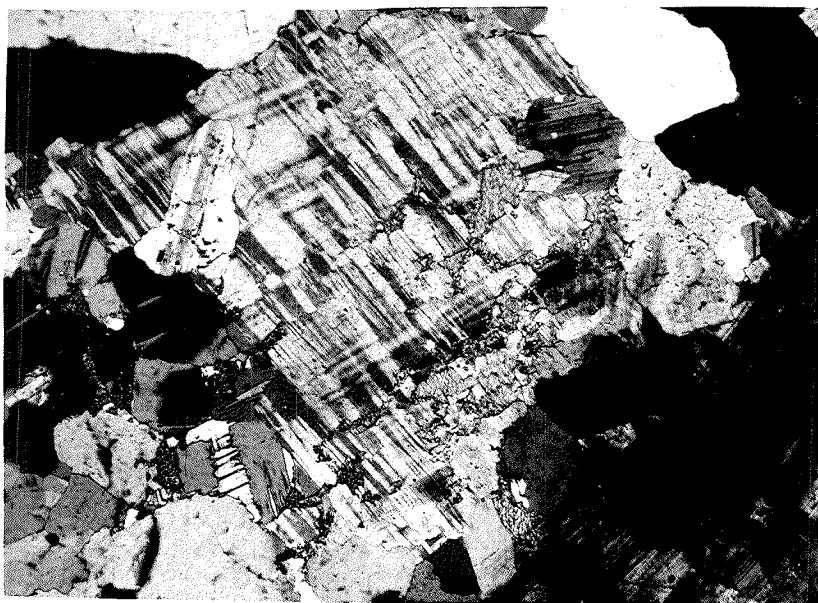


Figure 5-6. Example of cross-hatched twinning being intensified with the presence of inclusions (in this case, muscovite) in a K-feldspar (PG-121).

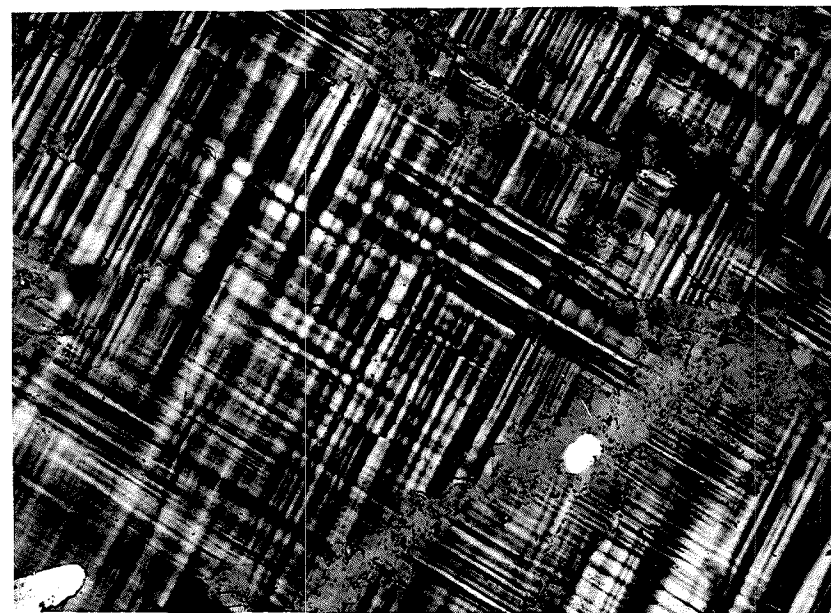


Figure 5-7. Example of a microperthite (HG-01) showing variable thickness of lamellae of both albite and pericline twinnings. It can be seen that both sets of lamellae are discontinuous, that is, they tend to show incoherent boundaries. The light grey mineral that is untwinned and contains dusty inclusions is albite rod.

must be noted that those microclines listed in Table 5-1 as non-perthitic may be, in fact, cryptoperthites. X-ray diffraction data in Tables 3-2 and 3-9 indicate that all these microclines are perthites.

Smith (1974b) listed many specific names given to perthites of different textural habits. However, he noted that the shapes and orientation of perthitic units are not easy to describe as the shape may be different with the orientation of the thin section cut. For the purpose of this thesis, the perthites are categorized into the broad terms: strings, rods, blebs (which may sometimes be rods in cross-section), and flame (Figure 5-8). These different textural types are given in Table 5-1 for each specimen. In granitic rocks, it is common for the different microclines in a given thin section to have different perthitic types (see Table 5-1). For example, non-perthitic microclines (presumably cryptoperthites) are usually associated with microperthitic microclines. The perthitic units, particularly strings and rods in K-feldspars, show various degrees of parallelism to each other. Parallel groups of rods tend to orient themselves at some angle to the microcline twins (Figure 5-11); on the other hand, the strings show strong crystallographic parallelism with one of the crystallographic directions of the cross-hatched twinning of microclines (Figure 5-9). Albite as a second phase in microclines is

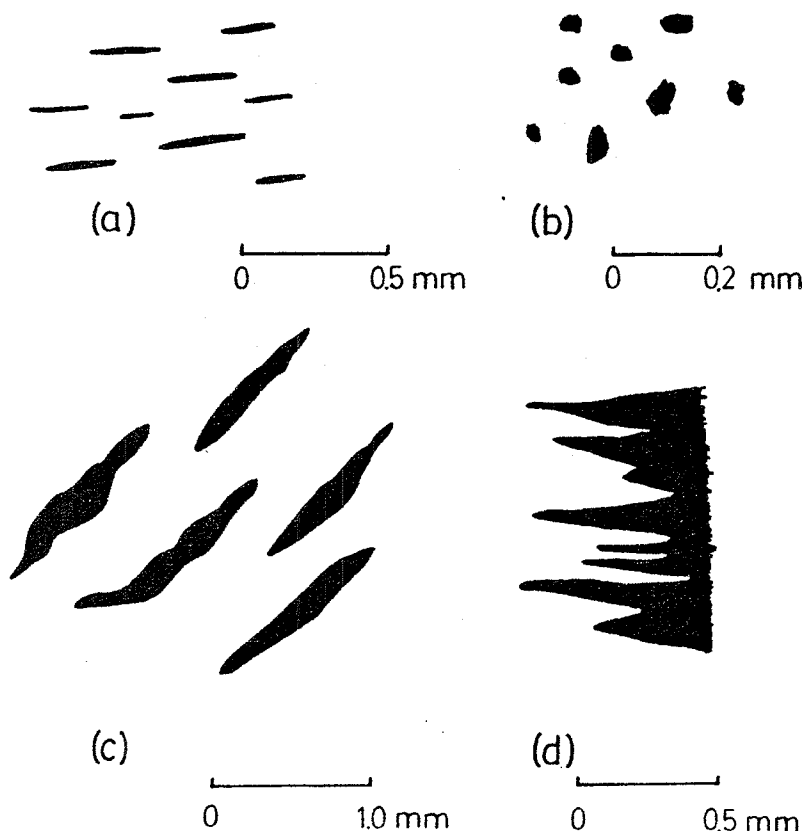


Figure 5-8. Example of the four textural perthitic types common in Lac du Bonnet and Dryden granitic and pegmatitic K-feldspars. (a) strings (photo is shown in Figure 5-9); (b) blebs (Figure 5-10); (c) rods (Figure 5-11); and (d) flame (Figure 5-12) (after Smith, 1974b).

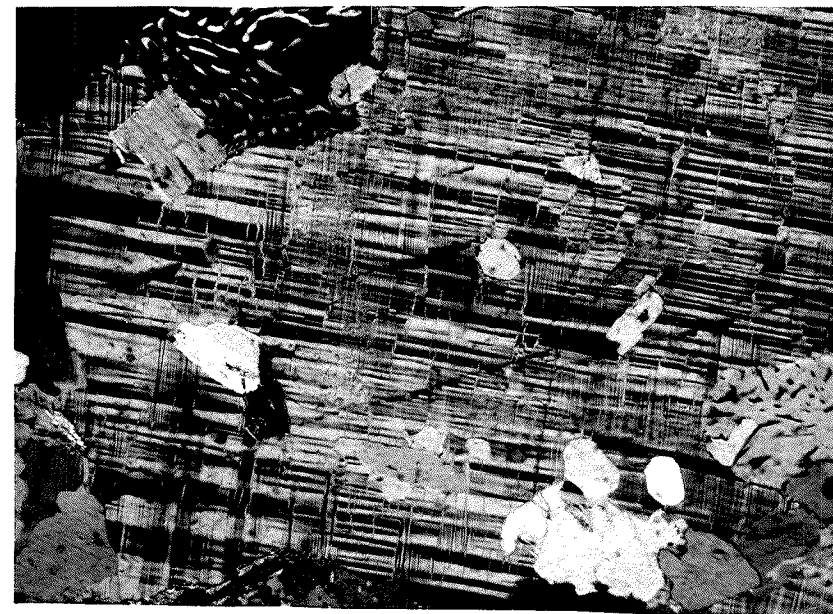


Figure 5-9. Example of albite strings. They show strong crystallographic parallelism with the one set of twinings in the microcline (PG-24). Some of the twin lamellae of the microcline become thicker towards the inclusions. Bulbous myrmekites intrude into the microcline. (The albite strings are seen in the photo as vertical with respect to this page).

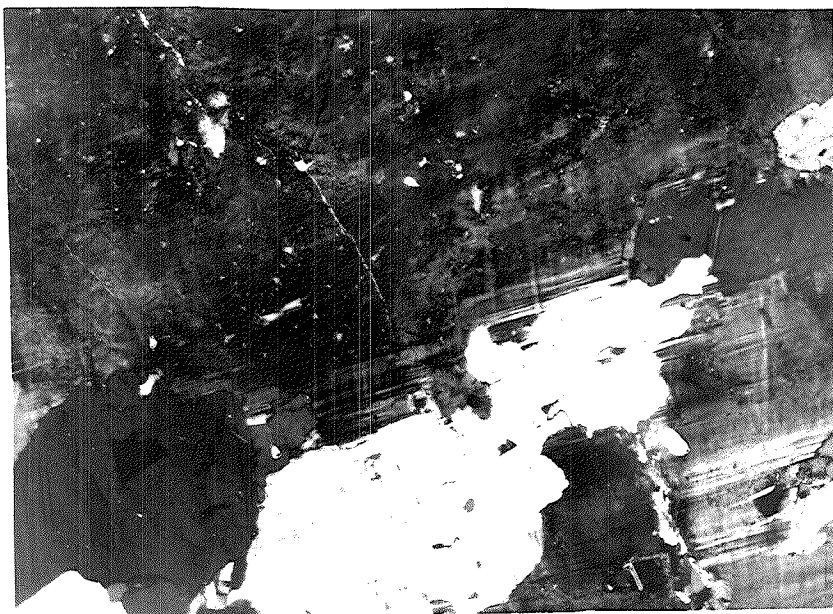
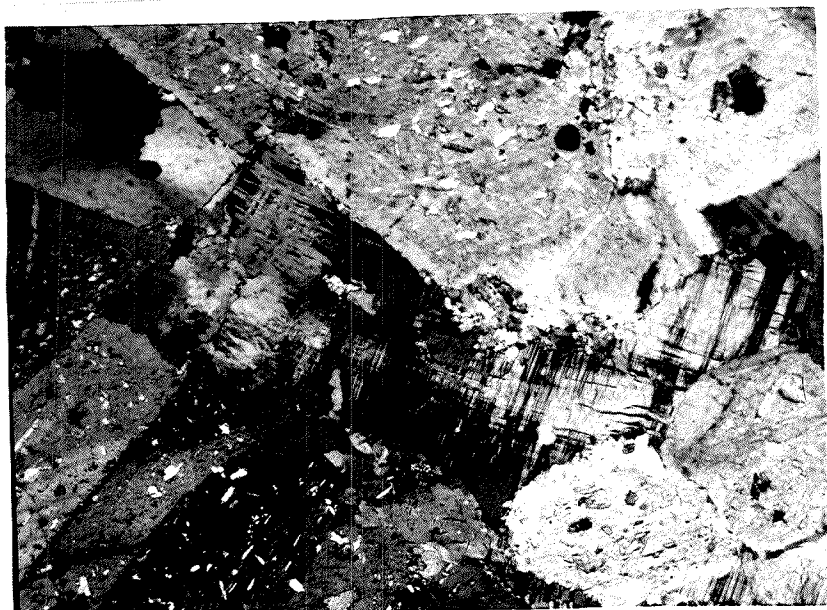


Figure 5-10. Example of albite blebs in K-feldspar (very dark). The albite laths in pegmatite (MLP/NZ 24) are being replaced by the K-feldspar where it becomes non-perthitic and free of alteration and staining products. It is also possible that the K-feldspar is being replaced by albite.



Figure 5-11. Example of albite rods in microperthite (HG-01). The rods show slight crystallographic orientation with respect to the associated microcline. The plagioclase inclusion shows very thick albitic rims.



0 10 mm

Figure 5-12. Example of flame-type perthite (CG-03). It is interstitial among the larger plagioclase grains that are extensively altered, show fresh albitic rims and have very corroded edges.



0 10 mm

Figure 5-13. Example of albite rods in K-feldspar (MLP/NZ 01) showing twinning in the same crystallographic orientation as the twinning in the microcline.

commonly seen in thin sections on the microscope stage as untwinned (Figure 5-7) with a rare crystal being twinned (Figure 6-13). The perthitic albite units within a K-feldspar grain are either all untwinned or all twinned but not as both. However, many of these apparent untwinned albites of all thin sections studied were checked by the universal stage methods and some appear to be twinned with the twins oriented in the same crystallographic orientation as one set of cross-hatched twinning of the associated microclines (presumably along those twinned by Albite law). Some of the implications of these observations are discussed in Chapter VI.

Some of the albites in microclines of both Lac du Bonnet and Dryden granites and pegmatites were analyzed for their An % content by universal stage methods (Table 5-1). They are albitic in composition with a range of An 2 to 9 % as expected.

(D) PLAGIOCLASES

Plagioclases are present in all Dryden and Lac du Bonnet granitic and pegmatitic samples as separate plagioclase crystals and as inclusions in microclines. Modal analyses (Table 5-1) have shown that plagioclases, like K-feldspars, are present in variable amounts; from a low of 6 % to a high of 69 %. The Lac du Bonnet granite shows a rather

consistent plagioclase content as compared to the Dryden granite. The pegmatitic specimens show variable plagioclase content from a low of 5 % to a high of 44 %.

In granitic rocks, the plagioclases are seen as fine- to coarse-grained (see Table 5-1), sometimes porphyritic, and prismatic but usually anhedral with corroded edges and corners. All but one of the specimens are also moderately to extensively altered (Figure 5-12) to epidote, sericite (or muscovite), calcite, chlorite, and sometimes biotite and oxides (hematite, magnetite as identified by reflected light). Sample PG-121, which is a leucogranite from Lac du Bonnet, contains plagioclases that are only slightly altered to similar minerals as described earlier. The compositions, as determined by universal stage methods, show a range from a low of 5 % to a high of 25 % An (Table 5-1). The plagioclase inclusions are more sodic in composition (An 0-10 %) than the separate crystals (An 0-22 %).

Plagioclases in the pegmatitic rocks, on the other hand, are seen as fine- to coarse-grained lath-shaped crystals (Figure 5-10). They are commonly observed as inclusions within the microclines although they also occur in fractures and cracks in the microclines. They are fresh (Figure 5-10) or slightly altered to epidote, sericite, and calcite compared to those from granitic rocks and they are albitic in composition (0 to 10 % An).

Twinning is almost universal in both granitic and pegmatitic plagioclases which are generally albite-twinned and zoned. Detailed studies of the various types of zonings and twinings of the plagioclases were beyond the scope of the present study and these features are not discussed further.

(E) RELATIONSHIPS BETWEEN PLAGIOCLASES
AND K-FELDSPARS

The relationships between plagioclases and microclines have generated much interests among petrographers because many interpretations of the petrogenesis of the feldspars and their associated rocks are based on their affinities. Three characteristics of these relationships are: albitic rims, myrmekites, and replacement features and they all deal with the contact between a plagioclase grain and a microcline grain. It is relevant that the observations made by the author show that the albitic rims and myrmekites are always at the contact between plagioclase and microcline grains.

Albitic rims consist of sodium-rich plagioclase (as determined later by universal stage methods) that is in optical continuity with the associated plagioclase grain at the contact with a microcline grain (Figure 5-14) but not with any other mineral (i.e. quartz). Albitic rims are common in granitic rocks. Table 5-1 shows that seven out of the ten Lac du Bonnet and Dryden granites contain

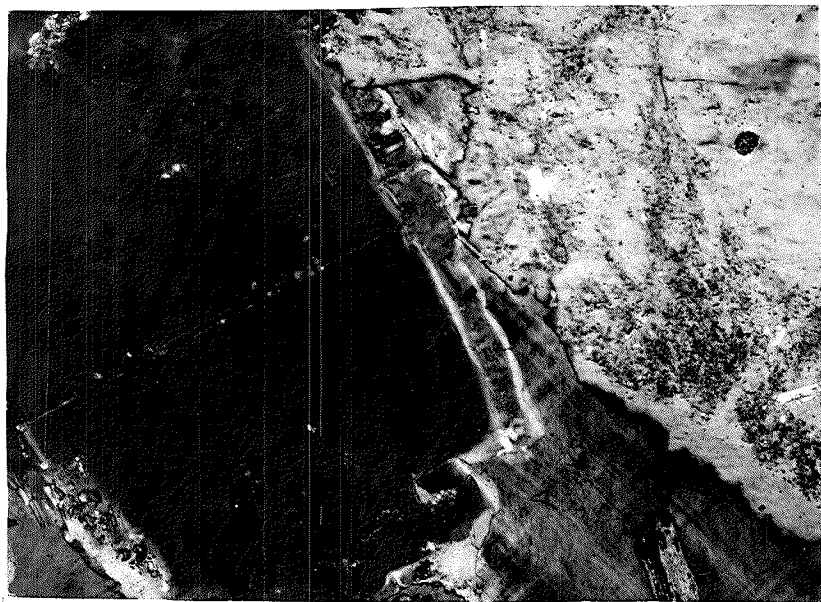


Figure 5-14. Example of albitic rims in optical continuity with the plagioclase crystal (dark grey). Fringe-like myrmekite is beginning to form within the albitic rims (of GPG-22).

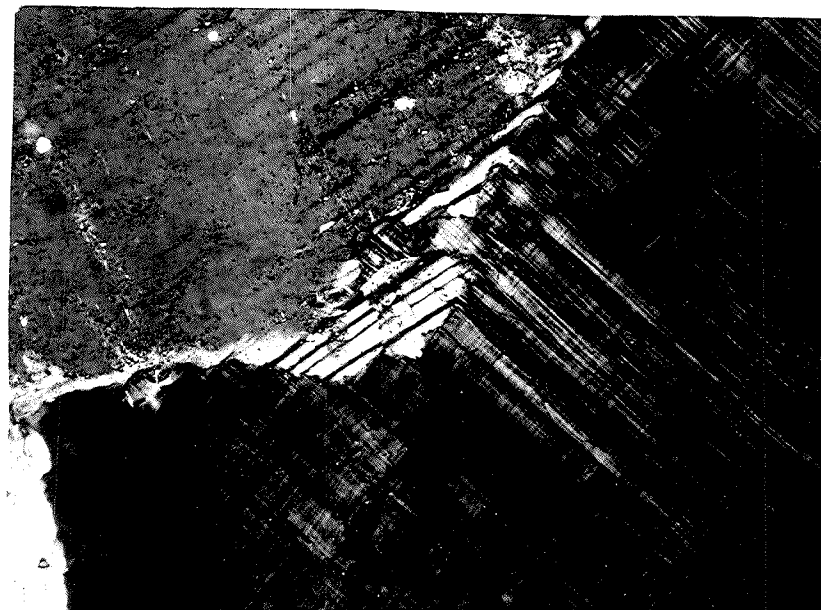


Figure 5-15. Example of a rare simple twinned (presumably albite-twinned) albitic rims within the plagioclase (of GPG-22). The contact between the albitic rim and the microcline is highly irregular.

plagioclases displaying thin albitic rims in various amounts. The pegmatitic specimens do not display this characteristic.

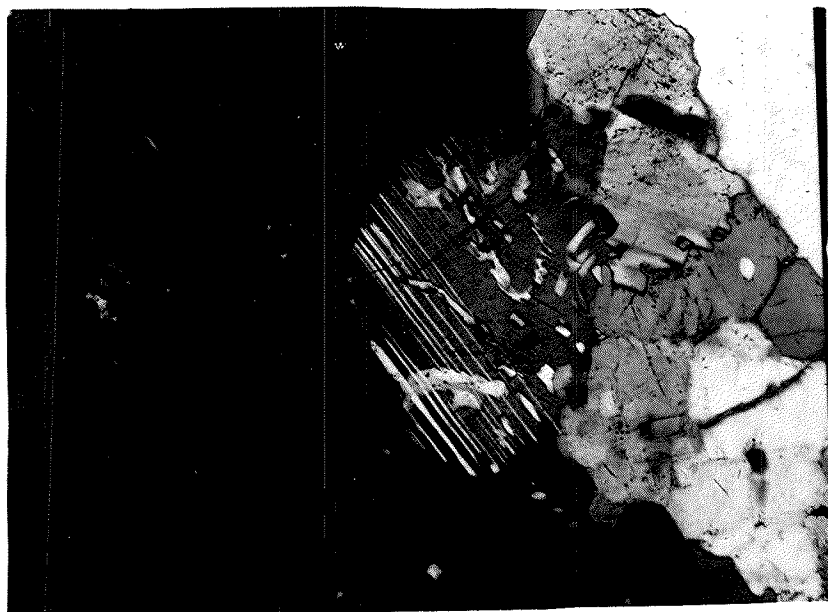
Albitic rims are similar to second -phase albites in perthites in that they are usually untwinned (Figure 5-14) on the microscope stage and rarely as twinned (Figure 5-15). However, as in the previous case, some of the untwinned albitic rims on microscope stage appear to be twinned in universal stage. Universal stage examination of two albitic rims have determined the composition of them to be almost pure albite (0-2 % An, Table 5-1). The rims also show no alteration whereas the associated plagioclase is extensively altered (Figure 5-15). Some plagioclase inclusions also show albitic rims, but in contrast to those at the contact between a separate plagioclase grain and a microcline grain, they are more conspicuous, wider and more complete (Figure 5-11).

Myrmekites are defined by Smith (1974b) as vermicular intergrowths of quartz enclosed in sodic plagioclases. They are similar to albite rims in that they are common in granites (Figure 5-9); six out of ten granitic rocks studied showed this characteristic but it was not observed in any of the author's pegmatitic rocks. However, Marmo (1971) observed that myrmekites are common in pegmatites. Myrmekites occur in a variety of sizes and forms but are commonly bulbous (Figure 5-9) and fringe-like (Figure 5-14). The plagioclase

of myrmekites is usually untwinned (Figure 5-9) and only rarely twinned (Figure 5-16).

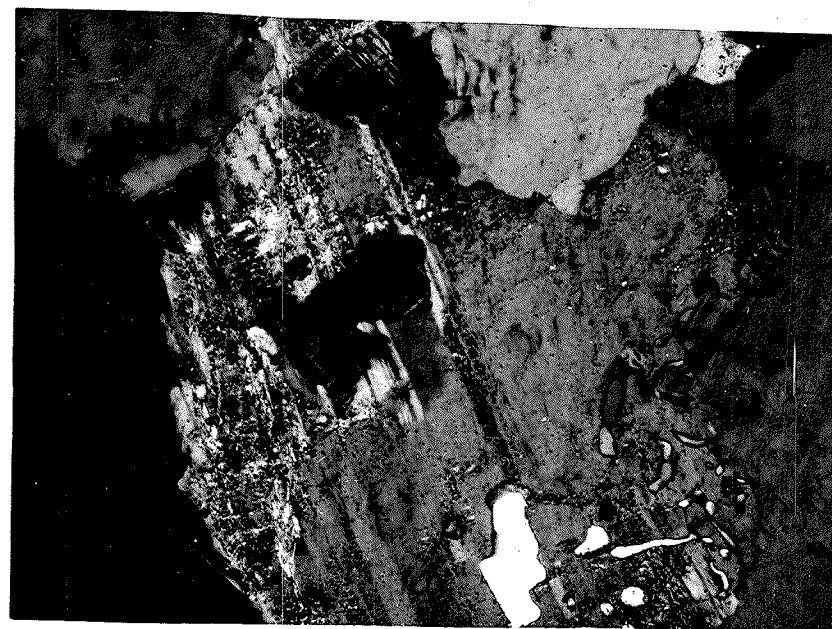
Myrmekites are intimately associated with plagioclases and K-feldspars particularly at the contacts between these two feldspars although they sometimes occur within K-feldspar grains (Figure 5-1) in association with the plagioclase. The plagioclase of the myrmekites have compositions very similar to those of separate plagioclases. For example, as seen in Table 5-1, the myrmekites in AEC-26 have a composition of 15 % An which is very similar to the plagioclase composition range of An₁₈₋₂₂. The other two myrmekites analyzed by universal stage methods have compositions of 13 % and 18 % (Table 5-1) which are also very similar to the plagioclase composition of 10 % and 12 % respectively. Myrmekites are sometimes closely associated with albite rims (i.e. Figure 5-14).

In all the granitic and pegmatitic rocks studied in thin section, the K-feldspar appears to be replacing the plagioclase crystals that are in various stages of alteration (Figures 5-17 and 5-18). Albite laths in pegmatitic K-feldspars are fresh as compared to the associated microclines (i.e. Figures 5-10 and 5-19), and seem to replace the microcline although the reverse may be possible. The presence of alteration products in a given feldspar does not necessarily mean that it is older than another feldspar



0 0.5 mm

Figure 5-16. Example of a rare twinned bulbous myrmekite at the contact between microcline (dark grey) and plagioclase (AEC-26).



0 10 mm

Figure 5-17. Example of fresh cross-hatched microcline in granitic rock (GPG-22) attacking extensively-altered plagioclase. Highly irregular albitic rims are seen within the plagioclase at the contact with a microcline. Myrmekite is also seen at the top of the photo.



0 0.5mm

Figure 5-18. Example of a granitic microcline (the perthitic units are twinned) attacking and replacing the plagioclase grains (GPG-22).



0 0.5mm

Figure 5-19. Example of a pegmatitic K-feldspar (MLP/NZ 01) attacking the albite laths.

that is free of alteration products (Petr Černý, personal communication).

(F) CORRELATION BETWEEN THE K-FELDSPARS AND
THE PLAGIOCLASES

Only one correlation was established between the different characteristics of the K-feldspars and plagioclases. It was found that the An % content of separate plagioclase grains generally increases regularly with increasing ratio of plagioclase to total feldspars (Figure 5-20). This is to be expected as the more plagioclase-rich rock (i.e. granodiorite) is, the higher the Ca (or An %) will be.

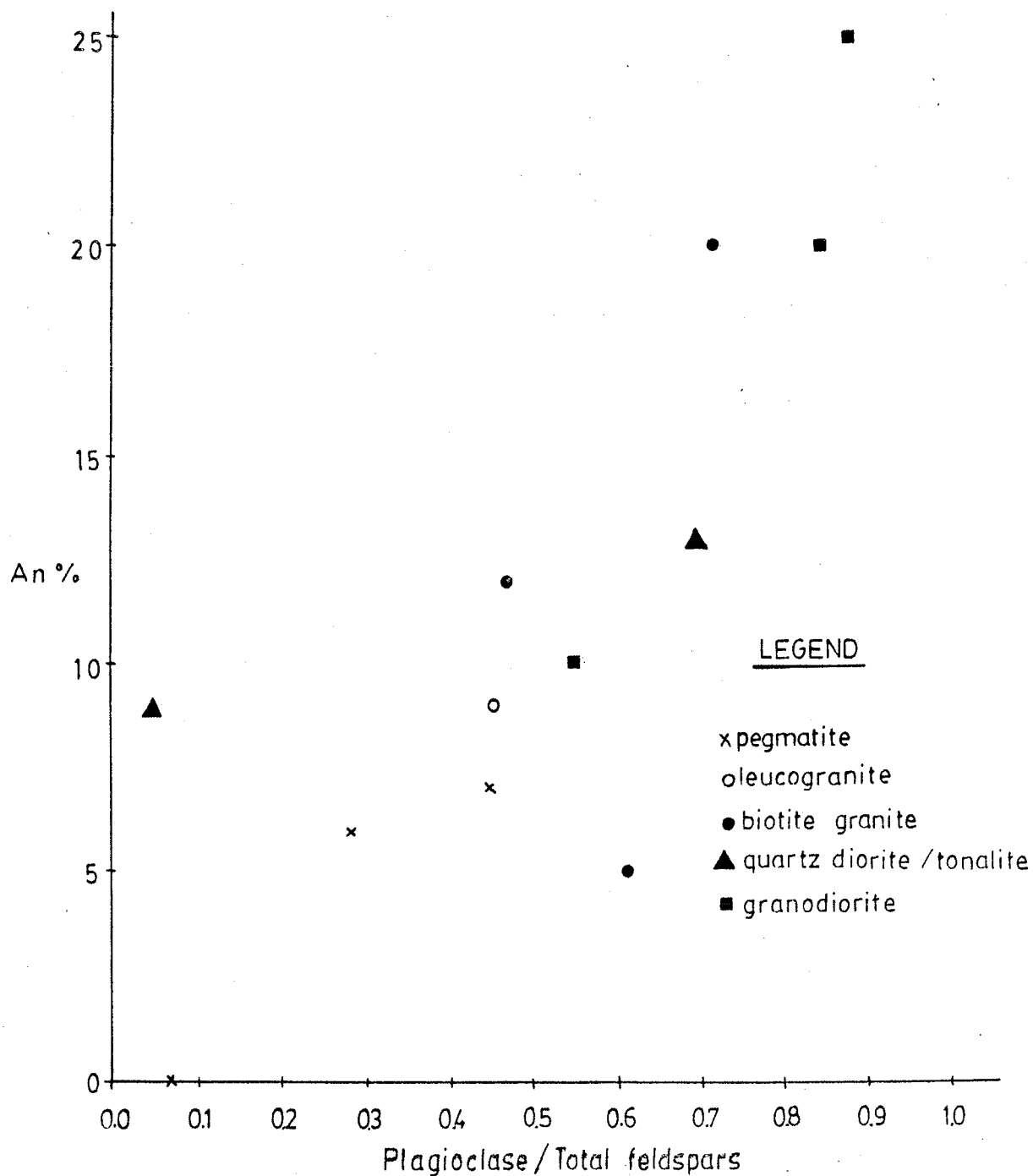


Figure 5-20. An % of plagioclase as separate crystals vs. the ratio of plagioclases to total feldspars (plagioclases and K-feldspars) from modal analyses of Lac du Bonnet and Dryden granites/pegmatites.

CHAPTER VI. INTERRELATIONSHIPS OF K-FELDSPAR RESULTS

(A) INTRODUCTION

In this chapter, the chemistry, triclinicity, and twinning from the three types of experimental methods are compared separately, and then possible correlations are examined. These correlations are briefly considered in relation to the possible origin of the K-feldspars from the Lac du Bonnet granite and the Dryden granites/pegmatites.

(B) COMPARISONS OF VARIOUS RESULTS

(1) Chemistry

The compositions of K-feldspars were determined in this study by three methods; electron microprobe analysis, partial chemical analysis, and powder diffractogram data. For the powder diffractograms, the composition of a K-feldspar is expressed only in Or %, based on the $2\theta_{201}$ values, whereas electron microprobe and partial chemical analysis expresses the different elements present as oxides, from which Or % may be calculated.

Figure 6-1 (Table 6-1) is a plot of Or % from x-ray powder data vs. those calculated from electron microprobe data. The majority of maximum microclines fall close to the ideal 1:1 curve. In other words, the results of the two sets of data are in good agreement. This suggests that Na found in the probe

Table 6-1. Summary of different characteristics of K-Feldspars from the Lac du Bonnet granites, Dryden granites, and Dryden pegmatites as discussed in text.

ROCK TYPE	SAMPLE NO.	# OF K-FELDSPAR PHASES	WT % Or FROM PROBE	WT % Or FROM PART. CHEM.	WT % Or FROM POWDER DATA	ESTIMATED AMOUNT OF EACH K-SPAR COMPONENT (WT %)	OTHER ELEMENTS PRESENT IN PROBE AND PART CHEM.	PRECESSION			PHOTOS	APPEARANCE OF SINGLE CRYSTALS
								TRICLINICITY Δ (FROM PREC.)	TWINNING (SINGLE PHASE MAX-MICRO)	TWINNING (MULTIPLE PHASES & INT. MICRO)		
LAC DU BONNET GRANITE	PG-121	1	94	-	95	100% max. micro.	-	1.00	untwinned	-	sharp	clear, transparent
	PG-135	1	92	-	94	"	-	1.00	albite-tw.	-	diffused	"
	PG-152	1	-	-	95	"	-	0.91	"	-	sharp	"
	SR-97	1	93	-	91	"	BaO	1.00	"	-	diffused	"
	SR-148	1	93	-	92	"	-	0.98	pericline tw.	-	"	"
	PG-133	1	-	-	91	"	-	0.98	albite tw.	-	sharp	"
	PG-24	1	90	-	93	"	-	0.95	"	-	diffused	"
	AEC-26	1	88	-	93	"	BaO	0.99	"	-	sharp	"
	AEC-20	1	91	-	91	"	BaO	1.00	untwinned	-	"	"
DRYDEN GRANITES	ZPG-07	1	90	72	93	"	-	1.00	both	-	sharp	clear, transparent
	APG-05	1	90	77	89	"	-	1.00	"	-	"	"
	GPG-22	1	85	-	93	"	BaO	1.00	"	-	"	"
	HG-01	1	91	-	92	"	-	1.00	"	-	diagonal	"
	MLG-01	1	94	-	94	"	BaO	1.00	untwinned	-	sharp	"
	CG-03	1	91	-	92	"	BaO	1.00	albite tw.	-	tric. trans.	"
	SG-01	1	90	-	95	"	-	1.00	"	-	diffused	"
DRYDEN PEGMATITES	MLP/NZ 01	2	90	83	*84 100 89	*70 int. 30 max. micro. micro.	P ₂ O ₅ , Rb ₂ O	0.45 ⁺	-	untwinned/ albite tw.	mono-tri. trans.	turbid, cloudy
	MLP/NZ 02	2	94	-	*88 99 92	*60 " 40 " "	P ₂ O ₅	0.49 ⁺	-	"	"	"
	MLP/NZ 05	2	93	-	*89 108 95	*70 " 30 " "	P ₂ O ₅	0.34 ⁺	-	"	"	"
	MLP/NZ 23	1	86	85	94	100% max. micro.	Rb ₂ O	1.00	both	-	diagonal	"
	MLP/NZ 24	2	87	81	*88 97 91	*60 int. 40 max. micro. micro.	P ₂ O ₅ , Rb ₂ O	0.48 ⁺	-	untwinned/ albite tw.	mono-tri. trans.	"
	MLP/NZ 30	2	85	79	*88 102 93	*60 " 40 " "	Rb ₂ O	0.48 ⁺	-	"	"	"
	MLP/NZ 42	2	82	80	*90 102 94	*70 " 30 " "	P ₂ O ₅ , Rb ₂ O	0.38 ⁺	-	"	"	"
	MLP/NZ 47	2	89	81	*93 102 97	*55 " 45 " "	P ₂ O ₅ , Rb ₂ O	0.53 ⁺	-	"	"	"
	MLP/SZ 10	1	85	79	98	100% int. micro.	Rb ₂ O	0.60	-	untwinned	sharp	clear, transparent
	MLP/SZ 06	2	88	81	101	*40 int. 60 int. micro. micro.	Rb ₂ O	0.73	-	alb.tw/untw.	diffused	turbid, cloudy
	ZP-09	1	92	74	96	100% max. micro.	-	1.00	both	-	sharp	clear, transparent
	ZP-05	1	92	74	96	" " "	-	1.00	albite-tw.	-	"	"
	GPE-11	1	85	78	101	" " "	Rb ₂ O, Cs ₂ O	0.95	both	-	diffused	turbid, cloudy

*The first column refers to the Or% for the maximum microcline component, the second to the "monoclinic" component, and the third to the total weighted value in % Or of both components. ⁺The triclinicity values are in weighted values (See Table 5-2 for the triclinicity for each K-Feldspar component).

*The first column is the untwinned intermediate microcline component and the second is the albite-twinned maximum microcline component.

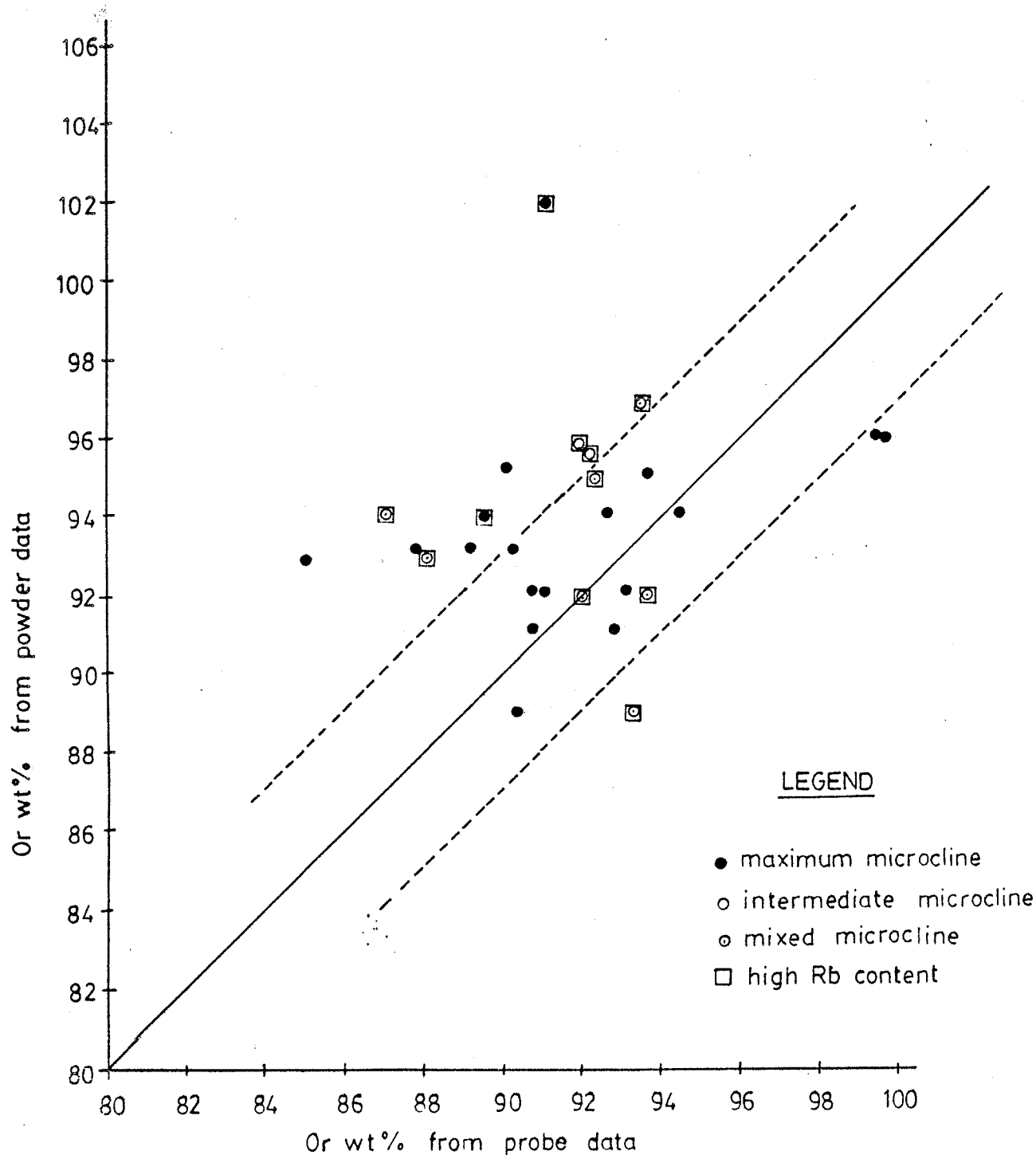


Figure 6-1. Or wt % from powder data using Orville curve vs. Or wt % from electron microprobe data for 27 microclines. The broken lines on either side of the ideal 1:1 curve is the limit of error set by the powder diffractogram data; the limit of error for the probe data can not be estimated. See text for explanations.

analyses is in solid solution and not in second phase albite. However, some of the maximum microclines have lower Or % from the probe data than that from the powder data which suggests the possibility that Na in the probe analyses of these microclines is in second phase albite. Originally, the Or % of the mixed microclines were also calculated from the Orville maximum microcline-low albite curve and the plotted results initially fell way off the ideal 1:1 curve. There are several reasons for the disparities of these microclines: (1) they each contain a "monoclinic" (as determined from powder diffractograms) component along with a maximum microcline component; (2) they are high in Rb (two maximum microcline specimens and two intermediate microcline specimens are also high in Rb). A method was developed in order to correct for these disparities. As the maximum microcline-low albite Orville curve is valid for the maximum microcline component but is invalid for the "monoclinic" component, the Wright (1968) orthoclase curve was used instead. Five out of the seven mixed microclines show split $2\theta_{201}$ peaks on the powder diffractograms, and the lower $2\theta_{201}$ value was assigned to the maximum microcline component, whereas the higher $2\theta_{201}$ was assigned to the "monoclinic" component. The other two mixed microclines only have one 201 peak and the same $2\theta_{201}$ value was used for both curves. Because the Or % results from the electron microprobe for each K-feldspar crystal are averaged values, the final Or % values from the powder diffractograms of each K-feldspar used in the

plot in Figure 6-1 is the weighted value based on the estimated amount of each K-feldspar component within a crystal (Table 6-1). As the $\bar{2}01$ peak does not differentiate Rb-rich microclines from those that are Rb-poor, the Rb-feldspar % is added on to the Or % from the electron microprobe analysis. Figure 6-1 shows the resultant plot. The mixed microclines fall reasonably close to the ideal 1:1 curve. For the intermediate microclines, the Or % content was averaged from that obtained from the maximum microcline and with the same $\bar{2}01$ value from the orthoclase curve. Again, they fall reasonably close to the 1:1 line. The one maximum microcline with a high Rb content falls significantly away from the regression curve. The reason for this is not clear. The results suggest that one should be cautious about using these curves for Rb_2O containing K-feldspars.

Both Figure 6-2, which is a plot of wt % Or from partial chemical analyses vs. wt % Or from electron microprobe analyses, and Table 6-1 show that the Or contents deduced by partial chemical analyses are much lower than the Or % contents deduced by electron microprobe (and by powder diffractogram as seen in Table 6-1). The likely reason is that the partial chemical analyses were done on bulk samples and hence do not differentiate albite in second phase from that in solid solution in the K-feldspars. On the other hand, electron microprobe analysis (of very small single K-feldspar

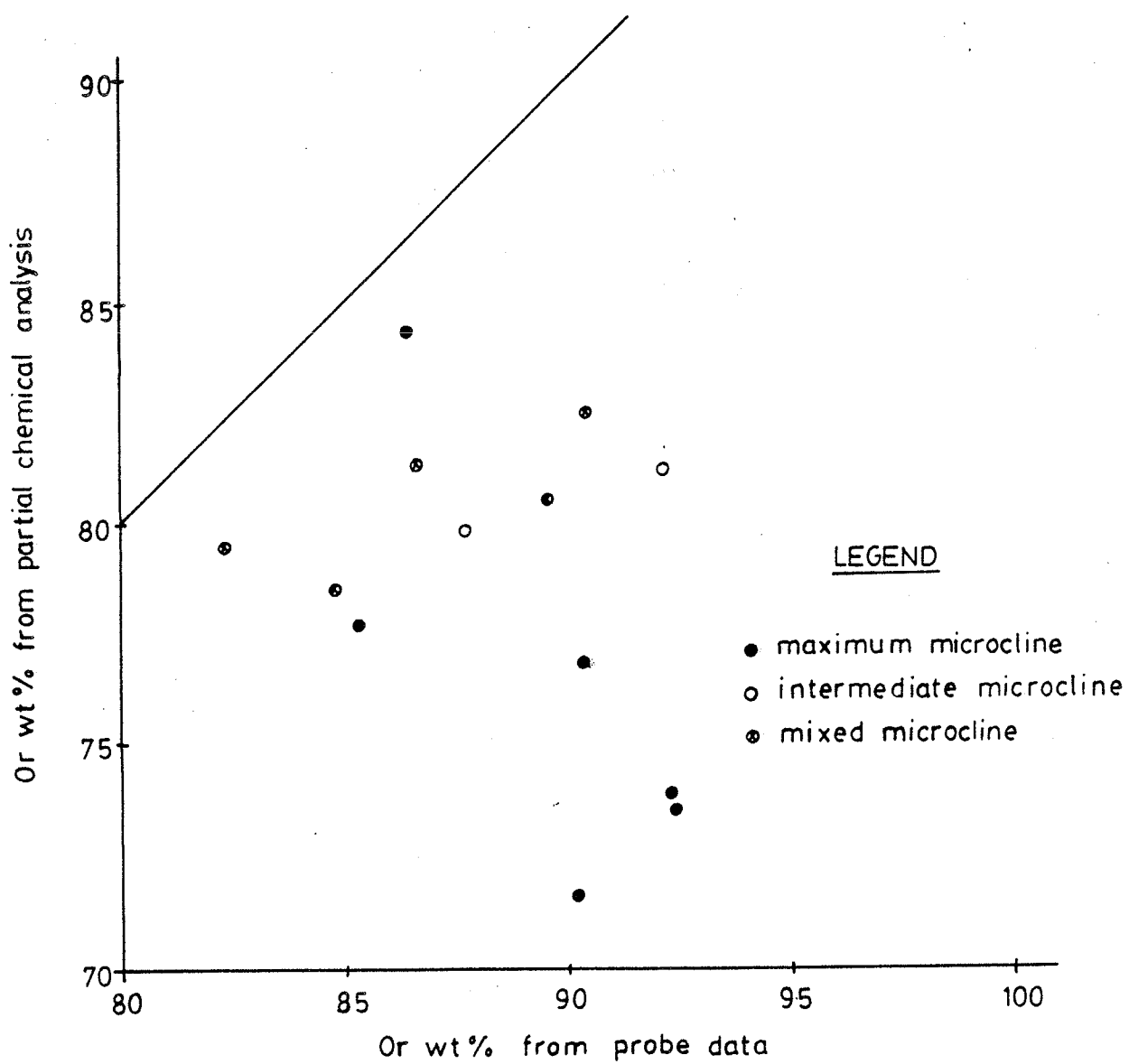


Figure 6#2. Or wt % from partial chemical analysis vs Or wt % from probe data. See text for explanations.

crystals) and powder diffractogram data relate to the K-feldspar component only and hence give the amount of Na in solid solution.

(2) Triclinicity

Triclinicities were obtained from all three of the x-ray diffraction methods used in this study. It is not possible to determine the triclinicity of K-feldspars from thin sections; one can only conclude from the presence of cross-hatched twinning that the K-feldspar is triclinic.

Twenty K-feldspar specimens seem to be single phase maximum microclines in both powder diffractograms and Gandolfi photos. However, the precession photos show 19 single phase maximum microclines and one multiple phase consisting of two quasi-parallel maximum microcline crystals. For those maximum microclines that are albite- + pericline-twinned, it was necessary to take a Gandolfi photo of the same single crystal used for the precession photo in order to be sure that the crystal is a single phase K-feldspar and not a mixed microcline.

Of the remaining nine K-feldspar specimens, seven are mixed microclines, that is, K-feldspars with multiple phases and triclinicities. Both powder diffractograms and Gandolfi photos show two components: a "monoclinic" component and a maximum microcline component. On the other hand, precession photos indicate that the "monoclinic" component

is actually an untwinned intermediate microcline with a very low triclinicity ($0.10 < \Delta < 0.25$), and that the maximum microcline has a high triclinicity. For one specimen, the Gandolfi photo indicates an intermediate microcline, but the precession photo and the powder diffractogram both showed it to be a mixed microcline. The other two K-feldspar specimens seemed on powder diffractograms and Gandolfi photos to be intermediate microclines; precession photos confirmed that one is an untwinned single-phase intermediate microcline, but indicated that the other is a multiple phase, consisting of untwinned and twinned intermediate microclines of the same triclinicity. For the maximum microclines, all three x-ray diffraction methods give consistent Δ values ($\Delta = 0.85-1.00$). For the mixed microclines ($\Delta = 0.10-0.75$) however, powder diffractograms may give better triclinicity values than either precession or Gandolfi photos, because the amount of each K-feldspar phase is easily measured but in the other two methods, it is visually estimated. This is true if the sample is a simple mixture and consequently the powder diffractogram shows simple mixture but if the mixture is very complex, the precession photos would give better results. Minor K-feldspar components may not be detected by powder diffractograms but are easily seen in precession photos. Hence, a powder diffractogram supplemented with a corresponding single crystal precession photo

gives the maximum information about the triclinicity of a given K-feldspar and its phase components.

(3) Twinning of microclines

Microclines are easily recognized in thin section by their characteristic cross-hatched twinning. Most of the thin sections studied show well-developed cross-hatched twinning in the majority of the K-feldspars. It is also common to see untwinned K-feldspars (that is, no twinning is visible in the optical microscope) in association with those that are cross-hatched twinned. In many instances, a K-feldspar may show some twinned areas and some untwinned areas. Untwinned K-feldspars in granitic rocks are often interpreted as orthoclase, but the precession photos in this work show them to be maximum microclines. There was no orthoclase among the author's granitic specimens, even though many K-feldspars were not twinned in thin section. Some precession photos are of untwinned microcline, so it is likely that some of the optically untwinned crystals are truly untwinned. It is possible that untwinned and twinned areas of a given K-feldspar crystal represent variations in triclinicity. A systematic study is needed to show whether there are variations in triclinicity in such crystals. Thin sections of pegmatitic feldspars show optically twinned and untwinned areas together within a single K-feldspar (similar to granitic feldspars), but precession photos show untwinned

intermediate microcline with a low triclinicity and maximum microcline with a high triclinicity.

It is possible to differentiate by optical methods albite-twinned and pericline-twinned microcline if the twin lamellae are coarse enough to measure the orientation of the principal optical directions X, Y, Z (J. Macek, personal communication). However, x-ray precession photography is more rapid. Of the feldspars studied here (Table 3-3), four are untwinned, nine are albite-twinned, one is pericline-twinned, six are albite- + pericline-twinned and eight are mixed microclines where one component is albite-twinned and the other is untwinned. Furthermore, precession photos give information on the character of interface boundary, that is, incoherent (sharp reflections) and coherent (diffuse reflections). It can be seen that, in general, precession photos give much more information about twinning than do optical methods.

(4) Orientation and twinning of albite intergrowths

Most K-feldspars examined (27 out of 29 specimens) are perthitic. In thin section, the albite is commonly seen as rods showing twinning in the same orientation as one of the microcline twins. Precession photos show albite in microcline, having the y^* -axis (of albite-twinned and untwinned individuals) parallel to the y^* -axis of the microcline. This observation suggests an epitaxial relationship

which will be discussed later. Eighteen out of 25 albites in microclines proved to be albite-twinned, five untwinned, and two albite- + pericline-twinned. As the amount of albite in microcline as determined from precession photos is very low, the type of interface boundary is less certain than the microclines themselves. As shown in Chapter V (Table 5-1), seven albite rods in microclines from 15 thin sections were analyzed by universal stage methods; resultant compositions ranged from An_0 to An_9 .

(C) SUMMARY AND DISCUSSION

(1) Introduction

The results from the different types of investigation that were discussed separately earlier in this chapter are here summarized and then compared for possible correlations. Even though the K-feldspar specimens are from the same general region (the Superior Province) and are of similar metamorphic grade (amphibolite facies), they are from two different provenances- granites and pegmatites. As a consequence, the different characteristics of the K-feldspars, notably twinning patterns, triclinicity, nature and number of phases, and chemical composition, are considered separately under the headings "granite" and "pegmatite". Certain features of the two K-feldspar groups are discussed, and then some possible correlations between the different characteristics of each

of the two groups of K-feldspars are considered. However, desirable as it would be to be able to correlate the observed detailed crystallographic and chemical characteristics of the K-feldspars with the chemical compositions and likely paragenesis of the granitic and pegmatitic rocks in which they occur, sufficient information and understanding are not yet available to do this, and so such correlations are not considered here.

(2) Granites

(a) Summary

-all nine Lac du Bonnet and seven Dryden granitic specimens are single-phase maximum microclines

-all show little variation in cell parameters and triclinicities

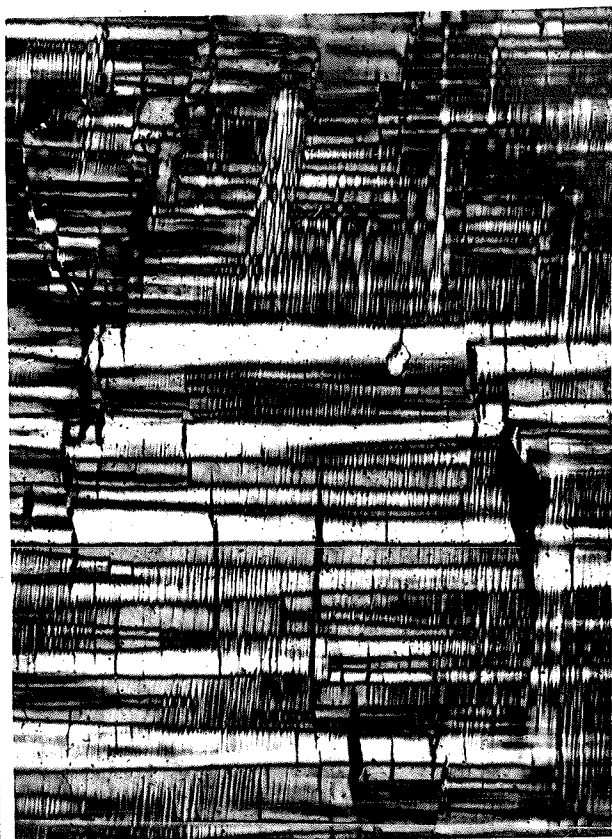
-in precession photos they show four types of twinning patterns with characteristic types of reflection and streaks:

(see also Table 3-2):

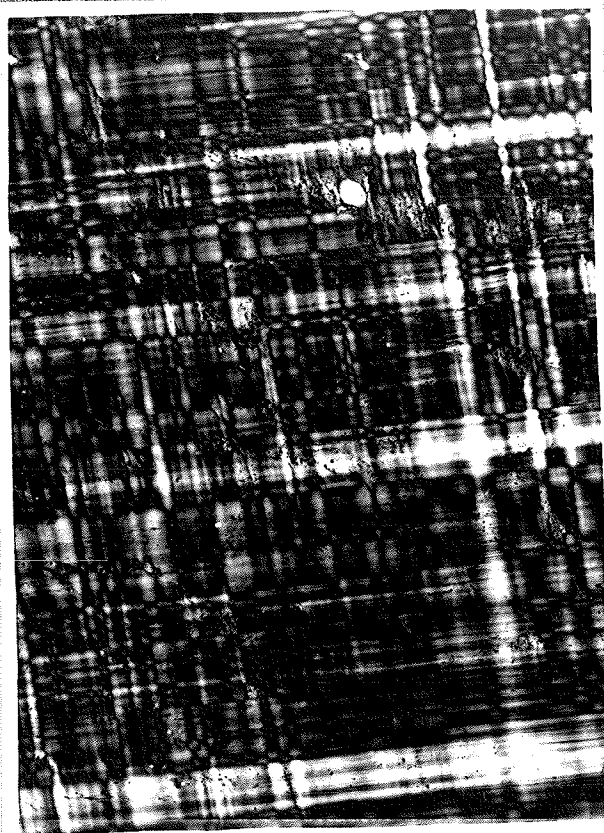
- (i) untwinned showing sharp reflections (3 specimens)
- (ii) albite-twinned (8 specimens); 3 show sharp reflections, 4 showing diffuse reflections (strong albite, weak pericline), and one showing triclinic transitional streaks
- (iii) pericline-twinned (1 specimen) showing diffuse reflections (strong pericline, weak albite)

- (iv) albite- + pericline-twinned (4 specimens);
3 show sharp reflections; 1 show diffuse
reflections (strong albite, strong pericline)

- most show variable twinning patterns within a given thin section
- all are perthitic as indicated by all three x-ray methods and from thin section studies
- some perthitic albites are seen in precession photos twinned, with their composition planes parallel to one set of composition planes in the cross-hatch twinned host microclines, indicating that the albite and microcline form an epitaxial relationship
- Na_2O contents from microprobe analyses vary from 0.59 to 1.46 wt %.
- all are low in Rb_2O contents ranging from undetectable (microprobe) to 0.19 wt % (partial chemical analysis)
- detectable Ba in microprobe analyses of six specimens
- single crystals studied all clear and transparent
- unaltered in thin section (plagioclases are extensively altered)
- interstitial in thin section
- in thin section, cross-hatched twin lamellae tend to be rectangular (rather than lenticular) (Figure 6-3).



(a)



(b)

0 10 mm



(c)

Figure 6-3. Coarseness of twin lamellae. All are of the same scale.
 (a) Lac du Bonnet granitic K-feldspar (PG-24);
 (b) Dryden granitic K-feldspar (GPG-22);
 (c) Dryden pegmatitic K-feldspar (MLP/NZ 42).

(b) Discussion

(i) Mode of formation of the perthitic inter-growth

The characteristics listed in the above summary suggest that the perthitic and rimming albites in the granitic K-feldspars may have formed as a result of exsolution and recrystallization of an original (K,Na)-feldspar precursor containing not more than 30 % Na-feldspar in solid solution. When the alkali feldspar cooled, some of the sodic material would have migrated, according to this model, to the edge of the K-feldspar and then crystallized on the nearest most suitable nucleus - a plagioclase grain- as albitic rims, while at the same time, most of the other sodic material would have exsolved from the K-feldspar host to form epitaxial perthitic albite within the K-feldspar host. Experiments have shown that plagioclase offers a better nucleating surface than K-feldspar and quartz for Na-feldspar exsolved from a (K, Na)-feldspar (Smith, 1974b). The microcline in the final stage would, by this model, contain little Na-feldspar (< 15 mol. % - Tables 3-9 and 4-2). The myrmekites observed in the author's specimens may also have originated by exsolution, an origin for myrmekites suggested by some authors.

(ii) Twinning characteristics of the microclines

The Lac du Bonnet and Dryden granitic K-feldspars are

all maximum microclines, and they show generally similar twinning characteristics. This could result from the fact that both areas are of amphibolite facies metamorphic grade, and both probably have similar intrusive temperatures and cooling histories associated with emplacement at the same crustal level regardless of differences in location and geological age (P. Černý, pers. comm.).

Small differences do exist in the twinning characteristics between the Lac du Bonnet and the Dryden microclines. Precession photos show that six out of nine Lac du Bonnet granitic K-feldspars are albite-twinned maximum microclines (including those that show strong albite- and weak pericline-twinning), and four out of seven Dryden granitic K-feldspars are albite- + pericline-twinned maximum microclines. One possible explanation for the difference in the observed x-ray twinning lies in the coarseness of the twin lamellae. Figure 6-3 shows that there is a significant difference in the twin lamellae (as viewed perpendicularly to (001) where both albite and pericline twins are ^{seen} in thin sections) of the Dryden and Lac du Bonnet K-feldspars. The latter (Figure 6-3a) shows one set of lamellae wider than the other whereas the former (Figure 6-3b,c) have both twin lamellae of about the same size and on a smaller scale. Thus one might expect the Dryden single crystal to show both albite- + pericline-twinning in precession photos, as a majority of them do. In

contrast, one might expect the Lac du Bonnet single crystals to show untwinning or a single twin type in precession photos, as, again, a majority of them do. However, against this possible explanation is the fact that the single crystals that were x-rayed were ~ 0.5 mm across whereas all lamellae in the three photos in Figure 6-3 are $\ll 0.2$ mm wide. A 0.5 mm crystal taken from any of the three sections shown in Figure 6-3 would be reasonably expected to show both albite- + pericline-twinning. One may conclude that a single crystal of that size to show only untwinning or albite- or pericline-twinning alone would have to come from a crystal with untwinned or single-twinned volumes > 0.5 mm across.

(iii) Possible origin of the cross-hatched twinning in the microcline

Laves (1950) proposed, on crystallographic grounds, that albite- + pericline-twinning in microclines can only arise by inversion with cooling of a monoclinic precursor. Two crystallographic observations of the present author appear to refute this origin for twinned microcline. Firstly, the monoclinic precursor theory implies that the perpendicularity of the symmetry axis and plane of the original monoclinic K-feldspar should be preserved in the albite- + pericline-twinned (maximum) microcline as a mutually perpendicular twin plane of the albite twin and twin axis of the pericline twin. For six out of the nine albite- +

pericline-twinned maximum microclines, the twin planes and axes in precession photos are not mutually perpendicular (see Chapter III). Secondly, Laves' theory implies that pericline-twinning should always be associated with albite- at least on the scale of the crystal used for precession photos, twinning whereas one of the author's microclines is pericline-twinned only. In the author's opinion, there is no crystallographic reason why pericline-twinning alone cannot occur in microcline. The author is aware of no other case reported in the literature of a microcline that is only pericline-twinned.

It can also be pointed out that there is no experimental evidence to suggest that a monoclinic K-feldspar inverts to a triclinic form (microcline) during cooling. Microcline can be inverted into a monoclinic form upon heating at temperatures as low as $375^{\circ} \pm 50^{\circ} \text{C}$ but the reverse has not been demonstrated (Marmo, 1971). Microcline can be made by potassium exchange (or potassium metasomatism) of low albite under hydrothermal conditions (Orville, 1967; Laves, 1950), but triclinic K-feldspar has never been synthesized in the true sense. Monoclinic K-feldspar (orthoclase, sanidine) under all conditions experimentally available remains monoclinic with cooling.

(3) Pegmatites

(a) Summary

-nine specimens (all from the Mavis Lake pegmatite) are

multiple-phase microclines and single phase intermediate microclines with variable triclinicities and cell parameters

-four specimens (one from Mavis Lake, two from Zealand, and one from Tot Lake pegmatites) are single-phase maximum microclines with little variation in triclinicities and cell parameters

-in precession photos, these microclines are seen to be of four types:

(i) largely untwinned intermediate microcline with low triclinicity ($0.10 < \Delta < 0.25$) ("monoclinic" phase) combined with a minor albite-twinned maximum microcline component showing monoclinic-triclinic transitional streaks (seven specimens)

(ii) single or multiple-phase intermediate microclines showing either sharp reflections or diffuse streaks (two specimens)

(iii) single-phase maximum microclines with sharp reflections (two specimens)

(iv) single-phase maximum microclines showing 'diagonal association' reflections (two specimens)

-all are perthitic as indicated by all three x-ray methods and from thin section studies

-Na₂O contents vary from 0.48-1.32 wt % (from microprobe)

-all are relatively high in Rb₂O (1.04-2.24 wt %; minimum based on partial chemical analyses) with the exception of the two type (iii) microclines that are low in Rb₂O (0.24-0.26 wt %)

- seven of the mixed microclines specimens showed erratic distribution of P in the microprobe analyses (possibly due to apatite inclusions; see Chapter IV)
- all single crystals studied were turbid and cloudy except for the two of type (iii) which are clear and transparent
- in thin section, all these microclines except for the two of type (iii) were extensively altered and deeply iron-stained; the two exceptions were unaltered
- in thin section, cross-hatched twin lamellae of the mixed microclines tend to be lenticular (rather than rectangular); (Figure 6-3)
- the other types of microclines were not studied in thin sections

(b) Discussion

(i) Possible relationship between Rb-content of a K-feldspar and its triclinicity, twinning, and phase composition

In contrast with the granitic K-feldspars, the Dryden pegmatitic K-feldspars show variations in crystallographic, structural and chemical characteristics. However, four of the pegmatitic K-feldspars studied are single-phase maximum microclines. The same was observed on 12 other Mavis Lake, and seven Zealand and Tot Lake specimens studied by Ucakuwun (1981). This is typical of most pegmatites from the Canadian Precambrian Shield (Petr Černý, pers. comm.). The fact that some of the Dryden pegmatitic (particularly Mavis Lake) K-feldspars are mixed microclines suggests that they are unusual.

The differences between the various microclines will be discussed

in detail.

(1) Mixed microclines (including intermediate microclines):

As shown earlier in the summary, all mixed microclines and intermediate microclines contain higher Rb content than the maximum microclines of type (iii). Gordienko & Kamentsev (1969) observed a correlation between the low structural state of K-feldspars from pegmatites and the increased content of Rb and Cs. It is well known that Rb^+ and Cs^+ have larger ionic radii than K^+ and so a K-feldspar that contains an appreciable amount of Rb may have modifications of its structure (monoclinic) relative to one that is Rb-free. This is suggested in precession photos of these mixed microclines by diffuse streaks between a nearly monoclinic phase and a maximum microcline phase. However, preliminary work by the author has shown that Rb in mixed microclines might possibly be preferred by the maximum microcline component. Figure 6-4, which is a plot of wt % Na_2O vs. wt % K_2O from partial chemical analyses, also shows that Rb-rich maximum microclines are commonly associated with Rb-rich mixed microclines which suggests that Rb does not influence the structural state of K-feldspars (as also observed by Cerny & Macek, 1972).

Figure 6-5 compares the chemical compositions of Rb-rich K-feldspars as determined by powder diffractogram and electron microprobe analysis. For the mixed microclines, the two components, "monoclinic" K-feldspar and maximum microcline, are

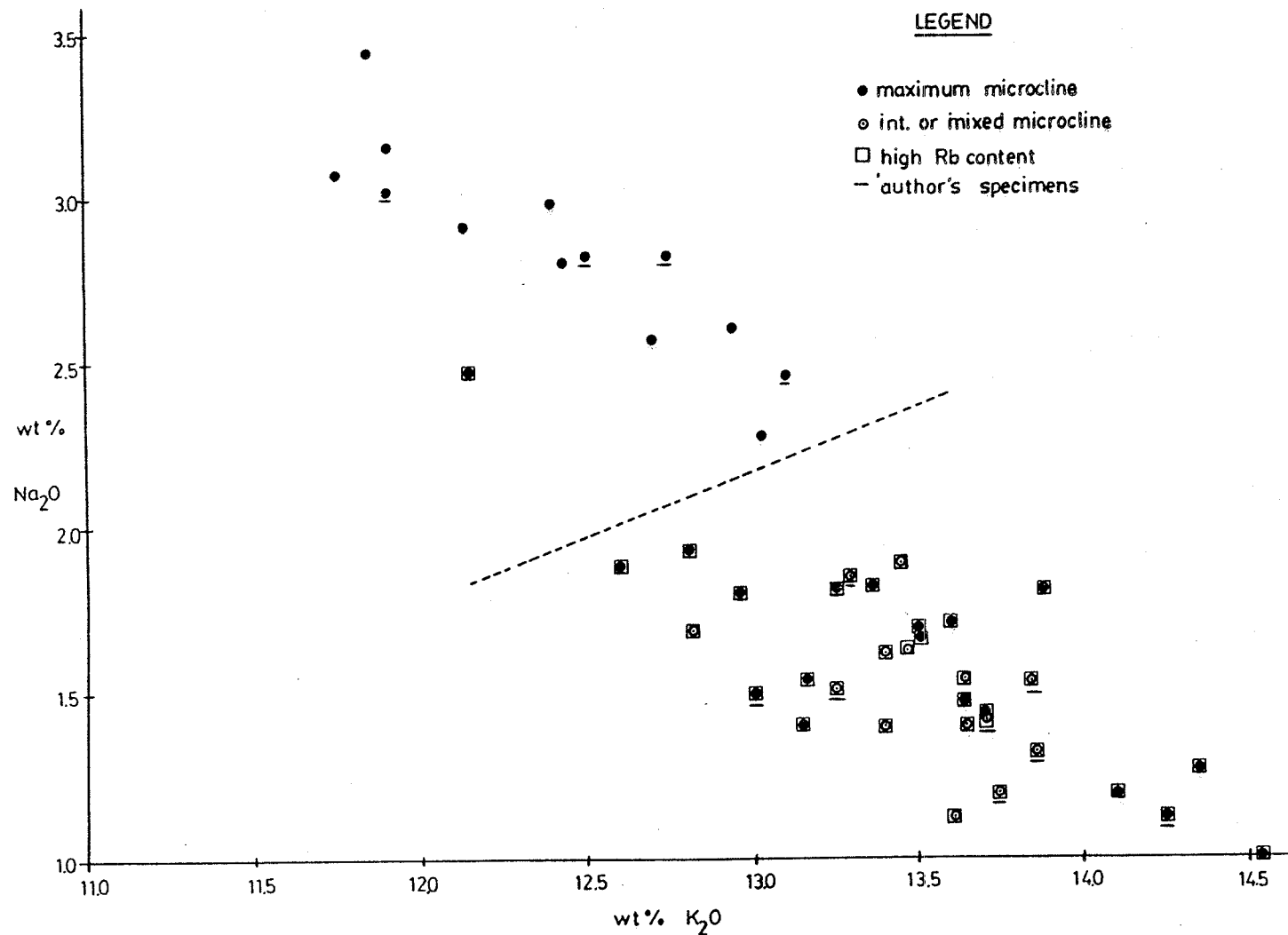


Figure 6-4. Wt % Na_2O vs. wt % K_2O from partial chemical analyses of Ucakuwun (1981) and Lenton (1979). The broken line is the arbitrary dividing line between Rb-poor, high Na_2O , low K_2O microclines and Rb-rich, low Na_2O , high K_2O microclines. See text for explanations.

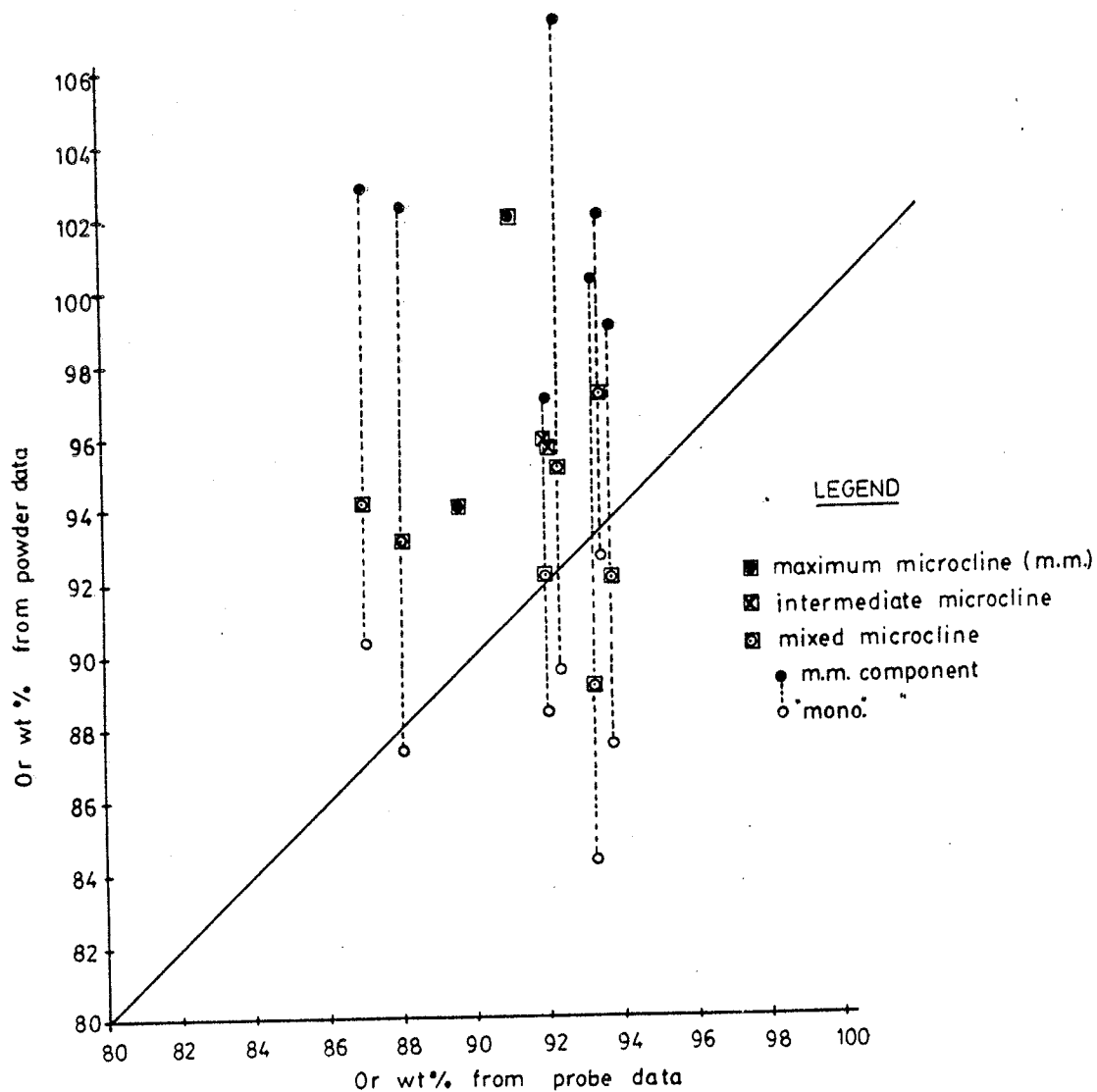


Figure 6-5. Or wt % from powder data using Orville curve vs. Or wt % from probe data for 11 Rb-rich microclines showing the monoclinic and maximum microcline components of the mixed microclines. See text for explanations.

also plotted along with their weighted values (as discussed earlier in this chapter). The maximum microcline components are significantly further from the regression line than the "monoclinic" component. This suggests that Rb may be preferred by the maximum microcline component in mixed microclines. However, it is still not known whether or not Rb is preferably concentrated in one phase. Detailed electron microprobe studies are needed to determine the distribution of Rb in the K-feldspar components.

(2) Single-phase maximum microclines:

Two of the four pegmatitic single-phase maximum microclines are high in Na_2O (2.81-2.83 wt % from partial chemical analyses) and low in Rb_2O (0.24-0.26 wt %). They show in precession photos, twinning and interphase boundaries characteristics typical of granitic K-feldspars. In contrast, the other two pegmatitic single-phase maximum microclines are lower in Na_2O (1.0-2.5 wt %) and higher in Rb_2O (1.04-2.24 wt %) and show diagonal association. As discussed earlier, Rb-rich maximum microclines are common as compared to Rb-rich mixed microclines (Figure 6-4). The two Rb-rich maximum microclines showing diagonal association may provide slight evidence that other Rb-rich maximum microclines may have significantly different crystallographic characteristics than Rb-poor maximum microclines. It was observed in Chapter III that albite-twinned microcline may consist of strong

albite-twinned and weak pericline-twinned reflections. Because the albite-twinned maximum microcline component of the mixed microclines only makes up 30 - 40 wt % of the total K-feldspar crystal and pericline-twinning is commonly weak, it is possible that diagonal association is too weak to be recorded by precession photos. This suggests the possibility of all Rb-rich microclines, single-phase or multiple-phase, to show diagonal association. Detailed precession photography of many Rb-rich maximum microclines is needed in order to assess any possible differences between Rb-rich and Rb-poor maximum microclines.

(ii) Mode of formation of the perthitic inter-growth

There are several different characteristics listed in the summary that strongly suggest that exsolution had taken place within the pegmatitic K-feldspars while they were cooling. The low amount of albite in solid solution within the K-feldspars as revealed by electron microprobe studies (4.29-11.48 % Ab) of highly fractionated pegmatites is the result of extensive exsolution of albite from an original homogeneous alkali feldspar that was Na-poor from the beginning of crystallization (as a consequence of its lower temperature of crystallization than that for a typical granitic K-feldspar) (Petr Černý, pers. comm.). Similarly, the heavy iron staining of the untwinned component in mixed microclines could have resulted from the exsolution of iron oxides upon cooling (Smith, 1974b)

or it could have occurred in the last stage of recrystallization (Černý & Macek, 1972).

(D) CONCLUDING STATEMENTS

According to McLaren (1978), the structural type and unit cell dimensions of a particular feldspar are a function of its chemical composition, temperature of crystallization and subsequent thermal history. This statement of McLaren agrees with the observations listed above where the two major groups of microclines, granitic and pegmatitic, were formed under different geochemical conditions and were subjected to different thermal regimes during crystallization and cooling. The twinning pattern may be a function of the cooling rate of a K-feldspar. It seems possible that the differences in twinning patterns between the Lac du Bonnet and the Dryden granitic K-feldspars reflect primarily on the different cooling rates in otherwise related plutonic rock types that generated K-feldspars of high and relatively uniform triclinicity. The properties of the pegmatitic K-feldspars, however, are greatly variable in terms of chemical composition, phase composition, triclinicity, and twinning patterns. The limited suite of examined specimens does not permit any conclusive interpretations; the only suggestion that may be made is a possible association of multiple-phase microclines with Rb-rich pegmatites in the Dryden area. The results of the present study indicate, however, that the properties of pegmatitic K-feldspars

are much more diversified and complex than realized previously and further work on a broader sampling basis is warranted.

The availability of a rapid x-ray diffraction method using single crystal precession photography may encourage geologists with a limited background in crystallography to carry out systematic studies of K-feldspars to correlate twinning, triclinicity, number of K-feldspar phases and chemical composition with each other and possibly with the genesis of the rock types studied.

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