1

MicroD

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

**GEOLOGY, GEOCHEMISTRY AND GENESIS OF STANNIFEROUS GRANITES
IN THE SOUTHERN PART OF THE KARAGWE-ANKOLEAN BELT,
NW TANZANIA**

by

JUSTINIAN RWEZAULA IKINGURA, B.Sc., M.Sc.

**A thesis submitted to the Faculty of Graduate Studies and
Research in partial fulfillment of the requirements of the
degree of Doctor of Philosophy**

**Department of Earth Sciences
Carleton University
Ottawa, Ontario**

March, 1989

Copyright 1989

Justinian R. Ikingura

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-315-51129-X

The undersigned hereby recommend to
the Faculty of Graduate Studies and Research
acceptance of the thesis:

**Geology, geochemistry and genesis of stanniferous granites
in the southern part of the Karagwe-Ankolean Belt, NW Tanzania**

submitted by

JUSTINIAN RWEZAULA IKINGURA, B.Sc., M.Sc.

in partial fulfillment of the requirements for the
degree of Doctor of Philosophy

.....
Chairman, Department of Earth Sciences

.....
Thesis Co-Supervisor

.....
Thesis Co-Supervisor

.....
External Examiner

Carleton University

April, 1989

ABSTRACT

Field studies, petrological, chemical and isotopic data are used to place constraints on the petrogenesis of stanniferous/post-orogenic and barren/syn-orogenic granites in the Karagwe-Ankolean belt, NW Tanzania. The granites are mainly two-mica granites that are locally surrounded by contact aureoles. Tourmaline-muscovite leucogranites occur only locally. Most of the stanniferous and barren granites consist of microcline, quartz and sodic plagioclase ($An_{<13}$), and accessory biotite, muscovite, tourmaline, apatite, ilmenite, monazite, xenotime and zircon. Garnet-bearing pegmatites and aplites are restricted to the stanniferous granites.

Both stanniferous and barren granites are characterized by evolved major element compositions and high contents of incompatible trace elements. They are mainly peraluminous, low-calcium granites, with low Fe, Mg and Ti contents, high K_2O relative to Na_2O , and restricted SiO_2 (71-76 %) compositions. The stanniferous granites show marked enrichment in Sn, Li and commonly F, and depletion of Ba, Sr and Zr relative to the barren granites. High Rb/Ba (>1.55), Rb/Zr (>10) and Li/Sr (>2), and low K/Rb (<110) and Sr/Rb (<0.15) ratios are associated mainly with the stanniferous granites. Low Zr (30-126 ppm) and high B (30-2000 ppm) contents in the stanniferous and barren granites, together with high $^{87}Sr/^{86}Sr$ initial ratios (0.732-0.807) and P_2O_5 contents (0.1-0.2 %) that are close to P saturation values in felsic magmas, suggest a crustal origin for the parent magmas. On the Rb vs. (Y+Nb) variation diagram, the data from the granites straddle the boundary separating syn-collision and within-plate granite fields. The Karagwe-Ankolean granites are thought to have formed from magmas generated by crustal anatexis of B-rich metapelites.

Major and trace element variation diagrams are consistent with a model that involves fractional crystallization of plagioclase, K-feldspar, biotite, Fe-Ti oxides and zircon. Chemical variations of Ca, F, Fe, Mg and Na in tourmaline from stanniferous leucogranites are also compatible with magmatic fractionation. Formation of the stanniferous granites is thought to be related to high degrees of fractional crystallization and Sn-enrichment in B- and/or F-rich granitic magmas. Shallow (≤ 2 kb) emplacement of the chemically specialized magmas, and brittle deformation of the country rocks enabled Sn-rich fluids to escape from the magmas and form exogranitic, hydrothermal tin deposits.

Subsolidus re-equilibration in both the syn-orogenic and post-orogenic granites was accompanied by the development of myrmekite and structurally more ordered microcline. Estimates of biotite-K-feldspar re-equilibration temperatures are between $570^{\circ}C$ and $590^{\circ}C$, based on Rb/K partitioning.

Whole-rock Rb-Sr isotopic data record at least two events of granite magmatism in the Karagwe-Ankolean belt at 1324 ± 23 Ma, 1088 ± 59 Ma and 1006 ± 44 Ma. These events may be correlated with igneous activities responsible for the formation of G1/G2, G3 and G4 granites, respectively, in other parts of the Karagwe-Ankolean/Kibaran orogen in Zaire, Burundi, Rwanda and SW Uganda. Tin mineralization in the Karagwe-Ankolean belt appears to be related to the latest granitic events. Rb-Sr and $^{40}Ar/^{39}Ar$

dates of biotite and muscovite from the granites are in the range 965 Ma to 685 Ma and represent resetting of micas by tectono-thermal events post-dating the Karagwe-Ankolean/Kibaran orogeny but contemporaneous with the Bukoban-Katangan cycle of Pan-African tectonism in western and eastern-central Africa.

ACKNOWLEDGEMENTS

This study would have been impossible without financial assistance from CIDA, IDRC and the universities of Carleton and Dar es Salaam. IDRC financial support enabled me to conduct field work in Tanzania and do laboratory studies in Canada. This support is greatly acknowledged. Financial support through Ontario Graduate Scholarship and Carleton University teaching assistantships is also gratefully acknowledged. I would like to thank my supervisors, Professors D.H. Watkinson and K. Bell, whose guidance, criticisms and encouragement were invaluable in accomplishing this thesis. Field supervision by Professor Watkinson laid the foundation for this research. Dr. Peter van Straaten of the University of Guelph was very instrumental in the planning and execution of the research project and editing the thesis manuscript. His contribution to the quality of this work is appreciated. Laboratory analyses were in part made possible by the operating and equipment grants from NSERC to Professors Watkinson and Bell. Professors K. Bell and J. Blenkinsop made Rb-Sr isotope laboratory facilities available and helped me through the analytical procedures. X-ray diffraction analytical facilities were provided by Dr. George Chao. Analytical work by X-ray fluorescence was accomplished with the assistance of Ron Hartree in the XRF laboratory at the University of Ottawa. The technical help provided by the various members of the Department of Earth Sciences at Carleton is appreciated. In particular I would like to thank Peter Jones for his help with microprobe analyses and computer data processing by BMDP, Ron Conlon for XRD work, Dan Marshal and Peter Mustard for helping me learn word processing on a computer, and Ross Taylor for preparing the thin sections and microprobe mounts. Technical help from Mrs Barbara Watkinson during the statistical analysis of chemical data on a mainframe computer is appreciated.

This research has benefited from useful discussions with Dr. R. P. Taylor who also provided some analytical data. Analytical facilities for $^{40}\text{Ar}/^{39}\text{Ar}$ were made available by Dr. P. Reynolds of the Geology Department at Dalhousie University. This assistance is much appreciated.

Mrs. Sally Hilly and Mr. Jack Hogg in the Department of Earth Sciences, made my stay at Carleton quite pleasant. Dr. David Farr, former director of Paterson Centre for International Programs at Carleton, is remembered for making the exchange program between Carleton and the University of Dar es Salaam successful, and providing a suitable study environment for the participants from Dar es Salaam. Mrs. Margaret Sheick of the Paterson Centre looked after my well-being for six years. Her generosity is appreciated. I wish to conclude the acknowledgement by expressing special thanks to my wife, Joyce K. Ikingura, for her love, support and understanding during the preparation of this thesis.

TABLE OF CONTENTS

	Page
THESIS TITLE	i
ACCEPTANCE FORM	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vi
 INTRODUCTION	 1
 CHAPTER 1 RESEARCH METHODOLOGY	
1.0.0 Introduction	5
1.1.0 Previous work	5
1.2.0 Objectives of the study	10
1.3.0 Field work	11
1.4.0 Laboratory studies	12
 CHAPTER 2 GENERAL GEOLOGY OF THE KARAGWE-ANKOLEAN BELT	
2.0.0 Introduction	13
2.1.0 Karagwe-Ankolean metasedimentary rocks	14
2.2.0 Structure and metamorphism	15
2.3.0 Basic and ultrabasic intrusions	17
2.4.0 Granitic intrusions	17
2.5.0 Mineralization	18
 CHAPTER 3 GEOLOGY AND PETROLOGY OF KARAGWE-ANKOLEAN GRANITES IN BUSHUBI	
3.0.0 Introduction	20
3.1.0 Syn-orogenic granites in the Bushubi batholith	21
3.1.1 Rulenge granites	22
3.1.2 Muyenzi granites	22
3.1.3 Bukiriro-Rwinyana granites	23
3.1.4 Kabanga granites	24
3.2.0 Post-orogenic granites	26
3.2.1 Nyamakombe pluton	27
3.2.2 Mumakera pluton	27
3.2.3 Mwibanda-Maleba pluton	28
3.3.0 Mineralogy and petrography	34
 CHAPTER 4 POST-MAGMATIC ALTERATION AND TIN MINERALIZATION	
4.0.0 Introduction	42
4.1.0 Tourmalinization	42
4.2.0 Albitization	48
4.3.0 Muscovitization and sericitization	52
4.4.0 Chloritization	52
4.5.0 Kaolinization	53
4.6.0 Tin mineralization	55

CHAPTER 5 CHEMISTRY OF KARAGWE-ANKOLEAN GRANITES AND RELATED ROCKS

5.0.0 Introduction	58
5.1.0 Major element chemistry	58
5.1.1 Whole-rock $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio analyses	62
5.1.2 Normative composition	64
5.1.3 Chemical classification of the granitic rocks	70
5.2.0 Trace element chemistry	77
5.3.0 Inter-element correlations	80
5.4.0 REE chemistry	100
5.5.0 Comparison of granite, xenolith and country rock compositions	109
5.6.0 Statistical analysis of chemical data from granitic rocks	114
5.6.1 Factor analysis	115
5.6.2 Discriminant analysis	118
5.7.0 Geochemistry of gabbroic intrusions	121

CHAPTER 6 MINERAL CHEMISTRY

6.0.0 Tourmaline composition	125
6.0.1 Results of microprobe analysis	127
6.1.0 Biotite composition	135
6.1.1 Results of microprobe analysis	136
6.2.0 White mica composition	144
6.3.0 Composition and structural state of alkali feldspars	151
6.3.1 Results of X-ray diffraction and microprobe analysis	153
6.4.0 Garnet composition	160
6.4.1 Results of microprobe analysis	161
6.5.0 Tin contents of various mineral phases	165

CHAPTER 7 Rb-Sr AND $^{40}\text{Ar}/^{39}\text{Ar}$ GEOCHRONOLOGY

7.0.0 Introduction	169
7.1.0 Rb-Sr dating method	169
7.1.1 Analytical procedure	171
7.1.2 Results of Rb-Sr isotopic analysis	171
7.2.0 $^{40}\text{Ar}/^{39}\text{Ar}$ dating method	178
7.2.1 Analytical procedure	181
7.2.2 Results of $^{40}\text{Ar}/^{39}\text{Ar}$ analysis	182
7.3.0 Significance of Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ ages	187
7.4.0 Petrological and geochronological correlations	189
7.5.0 Summary	194

CHAPTER 8 COMPARISON OF GRANITES FROM KARAGWE-ANKOLEAN BELT AND OTHER TIN PROVINCES

8.0.0 Introduction	196
8.1.0 Petrological comparison	196
8.2.0 Chemical comparison	201
8.2.1 Major element composition	202
8.2.2 Trace element composition	204
8.3.0 Style of tin mineralization	207

CHAPTER 9 PETROGENESIS OF KARAGWE-ANKOLEAN GRANITES

9.0.0 Mineralogical constraints	212
9.1.0 Geochemical constraints	216
9.2.0 Isotopic constraints	221
9.3.0 Concentration of tin during magmatic differentiation	224
9.4.0 Role of B and other volatiles	228
9.5.0 Source rock composition and the origin of the stanniferous and barren granitic magmas	232
9.6.0 Tectonic model	236

CHAPTER 10 SUMMARY AND CONCLUSIONS	238
---	------------

REFERENCES	242
-------------------------	------------

LIST OF TABLES

Table 4-1. Major and trace element changes due to alteration of granite in a quartz-tourmaline vein selvage, based on constant mass isocon	46
Table 4-2. Major and trace element changes in albitized granite, based on three isocon models	51
Table 4-3. Microprobe analyses of biotite and chlorite from an altered Maleba granite	54
Table 4-4. Hydrothermal mineralization and mineral paragenetic sequence in the Kyerwa and Maleba tin deposits	57
Table 5-1. Average chemical compositions of granite suites from the Karagwe-Ankolean Belt	60
Table 5-2. $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio analyses of some Karagwe-Ankolean granites	63
Table 5-3. Chemical comparison of I- and S-type granites (Chappell and White, 1974) with Karagwe-Ankolean granites	78
Table 5-4. Correlation matrix of the major and trace element data from the Karagwe-Ankolean granites	82
Table 5-5. REE analyses of some Karagwe-Ankolean granites	103
Table 5-6. Chemical analyses of country rocks and xenoliths from Karagwe-Ankolean granites	110
Table 5-7A. Principal factors and factor scores for major element variables in the stanniferous and barren granites	116
Table 5-7B. Principal factors and factor scores for trace element variables in the stanniferous and barren granites	116

Table 5-8. Chemical analyses of Nyakisasa gabbro	122
Table 5-9. Comparison of mean Nb, Sr, Ti, Y and Zr contents for Nyakisasa gabbro with those of basic volcanic rocks from different magma types and tectonic settings	122
Table 6-1. Chemical formulae of common tourmaline end-members	126
Table 6-2. Important chemical substitutions in tourmaline	126
Table 6-3. Microprobe analyses of optically zone tourmaline from tourmaline leucomonzogranite in the Maleba pluton	128
Table 6-4. Microprobe analyses of tourmaline from quartz- tourmaline veins in the Kabanga granites	129
Table 6-5. Comparison of Fe/(Fe + Mg) ratios for tourmaline from Karagwe-Ankolean granites, NW Tanzania, Oliver Creek tin occurrence, Canada (Emond, 1985), and Hub Kapong batholith, Thailand (Manning, 1982)	134
Table 6-6. Microprobe analyses of biotite from Maleba two-mica granite	137
Table 6-7. Microprobe analyses of biotite from Bukiro two-mica granite	138
Table 6-8. X-ray fluorescence analyses of biotite and K-feldspar from Maleba and Bukiro two-mica granites	143
Table 6-9. Distribution coefficients (K_D) for Rb/K in biotite- alkali feldspar and temperatures of "equilibration" in the Maleba and Bukiro two-mica granites	145
Table 6-10. Representative microprobe analyses of magmatic muscovite from Maleba granites	146
Table 6-11. Microprobe analyses of white mica in hydrothermally altered two-mica granite in the Maleba pluton	147
Table 6-12. Unit cell parameters of alkali feldspars from Karagwe-Ankolean granites	154
Table 6-13. $ a $ values calculated from "b" and "c" cell parameters of alkali feldspars	159
Table 6-14. Orthoclase contents of alkali feldspars determined from unit cell parameters and microprobe analysis	159
Table 6-15. Microprobe analyses of garnets from aplite dykes, expressed in terms of molar proportions of almandine, pyrope, spessartine and grossular	162

Table 6-16. Tin contents of whole-rocks and minerals from the Karagwe-granites	166
Table 6-17. Comparison of average tin contents (ppm) of micas from stanniferous granites from various localities	168
Table 7-1. Summary of Rb-Sr isotopic data from the Karagwe-Ankolean granites	172
Table 7-2. Summary of Rb-Sr ages of granites and minerals from the Karagwe-Ankolean belt	173
Table 7-3. Comparison of geochronological data of granites from various parts of the Kibaran Belt	190
Table 7-4. Main deformation phases of the Kibaran and Katangan orogenies in central and eastern Africa (Fig. 7-7); data obtained from Cahen et al. (1984) and Klerkx et al. (1987)	192
Table 8-1. Comparison of average chemical compositions of tin granites from selected tin provinces, including the Karagwe-Ankolean belt	203
Table 8-2. Petrological comparison of tin granitoids from Karagwe-Ankolean belt and other tin provinces	211
Table 9-1. Physical and chemical properties governing the crystal-chemical behaviour of Sn, Ti and Fe in minerals	224
Table 9-2. Comparison of trace element averages and H ₂ O content in sandstone and shale	233

LIST OF FIGURES

Figure 1-1. Map showing the location of the Kibaran-Karagwe-Ankolean orogenic belt (Kibarides) in central Africa	6
Figure 1-2. Map showing the localities of Karagwe Tinfield and Bushubi granites in the Karagwe-Ankolean belt, NW Tanzania	8
Figure 1-3. Map showing the location of Bushubi in the southern part of the Karagwe-Ankolean belt, and areas mapped (scale 1:10,000) during the present study	9
Figure 4-1. Isocon plot of chemical analyses of least altered and strongly altered granite samples from a quartz-tourmaline vein selvage in Kabanga granite	45
Figure 4-2. Isocon plot of chemical analyses of unaltered and albitized granite from the Maleba pluton	50

Figure 5-1. Triangular plot of Ab-Qz-Or normative compositions of Karagwe-Ankolean granites. Projections of haplogranitic minimum melt compositions and alkali feldspar-quartz cotectics determined by Tuttle and Bowen (1958) are also shown	65
Figure 5-2. Ab-Or-Qz projection of minimum melt compositions in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 , with or without anorthite (An), at 1 kb H_2O pressure. Data are from Tuttle and Bowen (1958) and James and Hamilton (1969)	67
Figure 5-3. Normative mineralogical data for Karagwe-Ankolean granites plotted on the (Ab-Or-Qz) ₉₇ An ₃ plane in the system Ab-Or-An-Qz- H_2O (James and Hamilton, 1969)	69
Figure 5-4. Plot of data from Karagwe-Ankolean granites on a Na_2O - K_2O -CaO chemical classification diagram. Field boundaries for various granitoids types are from Bell and Dodson (1981)	71
Figure 5-5. Classification of Karagwe-Ankolean granites using the Ab-Or-An diagram of O'Connor (1965)	72
Figure 5-6. Classification of granites and aplites from the Maleba pluton using the Ab-Or-An diagram of O'Connor (1965)	73
Figure 5-7. Classification of the Karagwe-Ankolean granites using the K_2O - Na_2O diagram. Field boundaries taken from Bell and Dodson (1981)	74
Figure 5-8. Rb vs. (Y+Nb) plot (Pearce et al., 1984) of data from the Karagwe-Ankolean granites	76
Figure 5-9. TiO_2 -Zr plot of data from Bukiriro (Buk), Maleba (Mal), Mumakera (Mum) and Muyenzi (Muy) granites	83
Figure 5-10. Fe_2O_3 -Zr plot of data from Bukiriro, Maleba, Mumakera and Muyenzi granites	84
Figure 5-11. MgO-Zr plot of data from Bukiriro, Maleba, Mumakera and Muyenzi granites	85
Figure 5-12. CaO-Zr plot of data from Bukiriro, Maleba, Mumakera and Muyenzi granites	86
Figure 5-13. SiO_2 -Zr plot of data from Bukiriro, Maleba, Mumakera and Muyenzi granites	87
Figure 5-14. Al_2O_3 -Zr plot of data from Bukiriro, Maleba, Mumakera and Muyenzi granites	88
Figure 5-15. K_2O -Zr plot of data from Bukiriro, Maleba, Mumakera and	

	Muyenzi granites	89
Figure 5-16.	Na ₂ O-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	90
Figure 5-17.	Ba-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	91
Figure 5-18.	Sr-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	92
Figure 5-19.	Y-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	93
Figure 5-20.	Rb-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	94
Figure 5-21.	Li-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	95
Figure 5-22.	Sn-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	96
Figure 5-23.	F-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	97
Figure 5-24.	B-Zr plot of data from Bukiro, Maleba, Mumakera and Muyenzi granites	98
Figure 5-25.	Rb-Ba-Sr triangular plot of the data from Karagwe-Ankolean granites	101
Figure 5-26.	Chondrite-normalized REE patterns for the two-mica granites from Bukiro, Mumakera and Maleba plutons	104
Figure 5-27.	Chondrite-normalized REE patterns for the Maleba granites	105
Figure 5-28.	Chondrite-normalized REE patterns for fresh granites (a) and their constituent minerals (b) from SW England (after Alderton et al., 1984)	108
Figure 5-29.	Histogram showing results of stepwise discriminant analysis for distinguishing the stanniferous granites from the barren granites using major element data	119
Figure 5-30.	Histogram showing results of stepwise discriminant analysis for distinguishing the stanniferous granites from the barren granites using trace element data	119
Figure 5-31.	Data from Nyakisasa gabbro plotted on Zr-Ti, Zr-Ti-Sr, and Zr-Ti-Y diagrams (Pearce and Cann, 1973) for discrimination of tectonic settings and magma types	123

Figure 6-1. Fe-Mg-Al triangular plot (in molecular proportions) of data from tourmaline from various rock types in the southern part of the Karagwe-Ankolean belt. Field boundaries taken from Henry and Guidotti (1985)	130
Figure 6-2A. FeO, MgO profiles across optically zoned tourmaline from a tourmaline-leucomonzogranite in the Maleba pluton	131
Figure 6-2B. Na ₂ O, CaO and F profiles across optically zone tourmaline in the tourmaline-leucomonzogranite from the Maleba pluton	132
Figure 6-3. Fe ²⁺ -Fe ³⁺ -Mg triangular plot (Eugster and Wones, 1962) for biotite from the Bukiro and Maleba two-mica granites	141
Figure 6-4. "b" versus "c" plot of unit cell parameters for alkali feldspars from Karagwe-Ankolean granites and aplite dykes	155
Figure 6-5. "b x c" versus "a" plot of unit cell parameters for alkali feldspars from Karagwe-Ankolean granites and aplites. Unstrained alkali feldspars normally plot in a narrow band while strained feldspars plot outside this band (Kroll and Ribbe, 1983)	157
Figure 7-1. Rb-Sr whole-rock isochron plot for the Bukiro granites	174
Figure 7-2. Rb-Sr whole-rock isochron plot for the Mumakera granites	176
Figure 7-3. Rb-Sr whole-rock isochron plot for the Maleba granites	177
Figure 7-4. Radioactivity decay scheme of ⁴⁰ K (after Dalrymple and Lanphere, 1969)	179
Figure 7-5. Argon age spectrum plots for muscovite (Mu) and biotite (Bi) from the Bukiro, Mumakera and Maleba plutons. Half-height of bars represent 1 sigma uncertainties. Total gas ages are given in parentheses. Whole-rock (W) Rb-Sr dates of the plutons are also shown	183
Figure 7-6. Argon age spectrum plots for muscovite (Mu) from Kaitambuzi granite (Kt-10) and pegmatite (Kt-5) in the Karagwe Tinfield	186
Figure 7-7. Map showing areas affected by the Kibaran, Bukoban (B)-Katangan (K) and other tectonic events in central and eastern Africa (After Cahen et al., 1984)	193

Figure 8-1. Diagrams showing average trace element contents in the stanniferous and barren granites from NW Tanzania and Nigerian Tin Province. Data for the Nigerian granites are from Imeokparia (1985)	205
Figure 8-2. Trace element patterns for stanniferous granites from NW Tanzania, Nigeria, and Thailand. The stanniferous/barren ratio was obtained by dividing the mean value of each element in Sn-mineralized granites to the corresponding value in the barren granites in each province	206
Figure 9-1. P-T stability fields for muscovite and other phases found in peraluminous granites and their relationship to the field of silicate melts (after Clarke, 1981)	215
Figure 9-2. Stability relationships of the Al_2SiO_5 polymorphs after Richardson et al. (1969; dotted lines) and Holdaway (1971; solid lines). P-T curve for H_2O -saturated granite solidus is also shown. (Diagram modified after White and Chappell, 1977)	217
Figure 9-3A. Valence states of Sn in hawaiite at various oxygen fugacities (Durasova et al., 1986)	226
Figure 9-3B. Solubility of Sn in magnetite as affected by temperature and oxygen potential (Durasova et al., 1986)	226
Figure 9-4. Liquidus phase relationships in the system Qz-Ab-Or at 1 kb H_2O pressure (Tuttle and Bowen, 1958) and with Li_2O , B_2O_3 , and F added under water-saturated conditions. (After Manning and Pichavant, 1988)	230
Figure 9-5. Schematic flow diagram showing possible ways by which ore-bearing and barren granites may originate based on source rock compositions	234
Figure 9-6. Cartoon diagrams showing the evolution of the Karagwe-Ankolean belt	237

LIST OF PLATES

Plate 3-1A. Rounded quartz-tourmaline intergrowths in the apical parts of a medium-grained Kabanga biotite-muscovite granite. Photo locality close to sample KA-24 (Map 2, Appendix 9)	33
Plate 3-1B. Tourmaline stringers bordered by leucocratic haloes in the Maleba monzogranite. Photo locality close to sample MA-18 (Map 4, Appendix 9)	33
Plate 3-1C. Tourmaline-bearing quartz-feldspar pegmatite dyke in the apical part of the medium-grained Kabanga biotite-muscovite	

granite. Photo locality same as sample KA-30 (Map 2, Appendix 9)	33
Plate 3-1D. Pegmatite pod in a coarse-grained Maleba biotite-muscovite granite. Photo locality same as sample MB-2 (Map 4, Appendix 9)	33
Plate 3-1E. Tourmaline-quartz-feldspar dykes (trending at 315°) cut by N50E-trending mesoscopic fault with sinistral displacement. Photo locality close to sample KA-30 (Map 2, Appendix 9)	33
Plate 3-1F. Cassiterite-bearing quartz vein in muscovite schist at Maleba tin mine. Photo locality same as sample MB-30 (Map 4, Appendix 9)	33
Plate 3-1G. Plan view of a cylindrical aggregate of biotite in a medium-grained biotite granite close to the Maleba tin mine (Map 4, Appendix 9)	33
Plate 3-1H. Cross-section of a cylindrical biotite aggregate shown in Plate 3-1G	33
Plate 3-2A. Myrmekite replacing microcline in a two-mica granite	41
Plate 3-2B. Subhedral xenotime (Xm) and monazite (Mz) crystals in the Bukiriro two-mica granite	41
Plate 3-2C. Euhedral apatite (Ap) and subhedral zircon (Zr) crystals in a two-mica granite from Bukiriro. Apatite crystals have cloudy, rounded, cores that are surrounded by euhedral apatite overgrowths	41
Plate 3-2D. Optically and chemically zoned (Fig. 6-2) tourmaline from Maleba tourmaline-leucomonzogranite (sample MA-19, Map 4, Appendix 9)	41
Plate 3-2E. Selective replacement of albite by tourmaline in a perthitic K-feldspar in the Nyamakombe granite	41
Plate 3-2F. Pervasively tourmalinized phyllite cut by a tourmaline vein containing coarse-grained tourmaline in the exocontact zone of the Nyamakombe pluton	41
Plate 3-2G. Euhedral garnet (57.5 % almandine, 41.2 % spessartine, 0.8 % grossular, 0.5 % pyrope) in a muscovite-tourmaline-bearing aplite dyke in the Maleba pluton (sample MB-12, Map 4, Appendix 9)	41
Plate 3-2H. Skeletal garnet (54.8 % almandine, 43.4 % spessartine, 1 % grossular, 0.8 % pyrope) in a biotite-muscovite-tourmaline-bearing aplite dyke in the Maleba pluton (sample	

LIST OF APPENDICES

APPENDIX 1. Normative Ab-Or-Qz plots for Karagwe-Ankolean granites from different plutons. Minimum melt compositions at 0.5, 1, 2 and 5 kb H ₂ O pressure, determined by Tuttle and Bowen (1958) and Luth et al. (1964) are shown on the plots. The quartz-feldspar and two feldspar cotectics in the plots are from James and Hamilton (1969), and are valid for compositions containing 3 % anorthite at 1 kb H ₂ O vapour pressure	 256
APPENDIX 2. Rb-Ba-Sr data from Karagwe-Ankolean granites from various plutons plotted on the triangular diagram of El Bouseily and El Sokkary (1975)	 259
APPENDIX 3. Sample preparation, analytical methods, accuracy and precision of geochemical data	 262
APPENDIX 4. Chemical analyses of Karagwe-Ankolean granites	 286
APPENDIX 5. Microprobe analyses of tourmalines from granites, aplites, hydrothermal veins, and tourmalinized country rocks. Other analyses are given in Tables 6-3 and 6-4 in Chapter 6.	 301
APPENDIX 6. Microprobe analyses of garnets from aplites dykes	 305
APPENDIX 7. Computer output of X-ray diffraction (XRD) data and unit cell refinement results for an alkali feldspar sample. Unit cell parameters for all 9 analysed feldspar samples are given in Table 6-12	 309
APPENDIX 8. Laboratory results of ⁴⁰ Ar/ ³⁹ Ar step-heating experiments for muscovite and biotite from Karagwe-Ankolean granites	315
APPENDIX 9. Geological maps for the Bukiriro, Kabanga, Nyamakombe, Mumakera and Maleba plutons. Sample locations are also shown on the maps	 326

INTRODUCTION

The spatial and temporal association of granites with tin deposits is well established and suggests that the granites and the deposits are genetically related (Taylor, 1979; Stemprok, 1979). Granites associated with tin deposits (i.e. tin granites) are known to range in age from Precambrian to Tertiary, although the bulk of tin production has come from Paleozoic and Mesozoic granites, such as the Hercynian granites of Europe and the Triassic granites of southeast Asia. Tin granites occur in a variety of continental geologic settings, ranging from convergent plate margins (e.g., Andean Tin belt; Sillitoe, 1976; Sawkins, 1984) to anorogenic settings (e.g., Nigeria Tin Province; Hutchison and Chakraborty, 1979; Sawkins, 1984).

Many studies in the literature have dealt mainly with the chemical characterization and discrimination of tin granites from barren granites with the purpose of developing effective methods for tin exploration. Granites associated with tin deposits have generally been found to be enriched in incompatible lithophile trace elements, such as Rb, Li, Be, F, Sn and W, and depleted in compatible trace elements, such as Sr and Ba, relative to barren granites (Lehmann, 1982; Imeokparia, 1984). The petrogenesis of tin granites is, however, not well understood. The diverse nature of tin deposits associated with the granites suggests that several processes are involved in their formation. Some tin deposits seem to have formed in boron-poor, fluorine-rich environments: e.g., East Kemptville, Canada (Richardson, 1988) whereas others appear to have formed in fluorine and/or boron-rich environments: e.g., South East Asian tin deposits (Manning, 1986) and those in Cornwall (Manning, 1986; Charoy, 1982).

In the present study, the geological, petrological and chemical aspects of stanniferous and barren granites in the Karagwe-Ankolean Belt have been investigated. Field and laboratory studies have been used, together with field and experimental data from granites elsewhere, to understand the petrogenesis of the stanniferous granites in northwestern Tanzania.

Definition of stanniferous granites

The tin content in granitic rocks has traditionally been used by many authors to distinguish tin-mineralized granites from unmineralized granites. The tin content has also been used to discriminate those granitic rocks which give rise to Sn deposits from those which do not give rise to Sn deposits. The average Sn abundance in calcium-poor granites is 3 ppm, while in calcium-rich granites and basaltic rocks the average is 1.5 ppm (Turekian and Wedepohl, 1961; Flinter, 1971). Several authors quote 5 ppm Sn as a cut-off value between "tin-poor" and "tin-rich" granitic rocks, while others give a value of 10 ppm as the cut-off limit (Flinter, 1971). In his review of "tin in acid granitoids", Flinter proposed the following definitions:

- a) **Barren granitoids:** granitoids which contain a certain amount of Sn but do not give rise to tin mineralization.
- b) **Stanniferous granitoids:** granitoids which contain a certain minimum value of Sn and may give rise to tin mineralization. The Sn may be present in dispersed form or as discrete tin minerals.
- c) **Mineralized granitoids:** stanniferous granitoids essentially containing discrete tin minerals (e.g., cassiterite).

Flinter proposed 10 ppm as a best figure for the cut-off limit between stanniferous granites and barren granites, and this seems to hold

for the granites in the Karagwe-Ankolean belt. The terms "barren" and "stanniferous" granites are adopted in the present study from Flinter (1971).

TERMS USED IN THE THESIS

The following are explanations of terms that are used in the thesis and are found in literature on granites and related mineral deposits.

Incompatible elements: Elements largely excluded from rock-forming minerals because of their ionic radius and/or charge, which are concentrated in residual magmas during igneous crystallization (e.g., F, Li, Rb, Sn)

Compatible elements: Elements largely taken in rock-forming minerals during igneous crystallization (e.g., Sr and Ba in feldspar).

"Ore-elements": Elements of valuable metals found in ore-deposits (e.g., Sn, W, Ta, U)

"Ore-fluids": Aqueous fluids containing valuable elements (e.g., Sn, W, Nb, U) and other elements such as F, Cl, Li and B which form soluble metal-complexes. Changes in pH, Eh, composition or temperature of such fluids by reaction with rocks or mixing with other fluids results in the precipitation of metals from solution to form mineral deposits.

"Volatiles": Refers to chemical components such as H₂O, Li, F, Cl and B which act as fluxes in granitic magmas or form volatile metal-complexes. They provide an efficient way of scavenging metals from H₂O-saturated granitic magmas and concentrating them in ore-fluids.

Reef: Cassiterite-rich quartz vein of large dimensions. In general usage the term "reef" refers to any kind of large vein, rich in ore-minerals.

"Fertile" magmas: Magmas which give rise to ore-bearing/mineralized granites, pegmatites, or hydrothermal veins.

"Barren" magmas: Magmas which do not give rise to ore-bearing granites.

Geochemically specialized granites: Granites strongly enriched in trace elements such as Sn, W, U, Ta and Nb, and other trace elements including F, B, or Li. Such granites are commonly associated with economic ore-deposits.

Kilobar (kb): Lithostatic or H_2O pressure expressed in kilobars ($1 \text{ kb} = 10^8$ Pascals).

CHAPTER 1

RESEARCH METHODOLOGY

1.0.0 Introduction

The Karagwe-Ankolean belt, also known as the NE Kibaran belt, is part of a Mid-Proterozoic orogenic belt that extends from Zaire in the southwest, through Burundi, Rwanda and NW Tanzania to SW Uganda in the northeast (Fig. 1-1). The thesis area is located in the Bushubi area (Figs. 1-2, 1-3) of Ngara district in the southern part of the Karagwe-Ankolean belt. The area is characterised by warm tropical climate, rainfalls, and the vegetation consists of bush and tall grasses. It is accessible by roads from the towns of Bukoba and Mwanza on the shores of Lake Victoria. Local accessibility in the study area is difficult. Two gravel roads cut across the area and a few, hardly motorable, tracks extend for short distances into the countryside from local townships and villages. The hilly and rugged topography of the area and tall grasses make traversing more difficult. Tropical weathering and thick soil cover have resulted in few outcrops being preserved, making mapping and correlation of geologic units difficult.

1.1.0 Previous work

The Karagwe-Ankolean rocks in northwestern Tanzania have been explored for tin and tungsten since the late 1920's. Exploration activities were concentrated in the northern part of the Karagwe-Ankolean belt, especially in the Karagwe district (Fig. 1-2). Several economic tin occurrences and a few tungsten deposits were discovered and active tin mining commenced in the late 1930's. Most of the tin production came from the Kyerwa mine during the

1. Tabular Upper Precambrian; 2. Folded Upper Precambrian; 3. Formations older than the Upper Precambrian affected by Upper Precambrian events; 4. Kibarides and Irumides; 5. Zones cratonized since at least 1800 Ma ago; 6. Lakes in the Eastern Rift.

Fig. 1-1. Location of the Kibaran belt in central and eastern Africa. (Original map by Cahen et al. (1984), modified by Klerkx et al. (1987)).

period 1938-1971. Proved ore reserves in the Kyerwa tin deposit are estimated at 350,000 tonnes, containing 0.04 % Sn (Saltikoff, 1977). A geological study of the northern part of the Karagwe-Ankolean belt (Fig. 1-2) was carried out by Stockley and Williams (1938) who mapped and compiled the geology of Degree Sheet No. 1: Karagwe Tinfields (Scale 1: 250,000). Although Stockley and Williams gave a comprehensive account of the metasedimentary rocks and the mineralized areas, the granites were only briefly described. Harris (1961) summarised the geology of economic mineral occurrences in Tanzania and described the tin deposits, while Harpum (1970) discussed the structural aspects of metasedimentary rocks and their bearing on the evolution of the Karagwe-Ankolean belt.

Although there are known tin occurrences in the southern part of the Karagwe-Ankolean belt, especially in Bushubi (Figs. 1-2, 1-3), this area has not been well explored or studied. A first reconnaissance traverse was carried out in the area by Combe (1926) who described briefly the metasedimentary rocks. Berryman (1941) and McConnell (1942) reported local tin mining operation near Maleba in the Bushubi area (Map 4, Appendix 9). Brief descriptions of the tin-bearing "quartz-reef" at Maleba were also made by Quennell and Booth (1953). Windelschmidt (1958) conducted a regional survey for tin and wolfram in the Bushubi Chiefdom and reported the sporadic occurrence of cassiterite in the alluvial sediments of the Nyabachencho flat. No economic cassiterite concentrations were found. Gray (1963) geologically surveyed the region and a Quarter Degree Sheet Map 29 & 29 W Ngara (Scale 1: 125,000) was published in 1967 by the Geological Survey of Tanzania. The geologic similarity and occurrence of economic nickel deposits in the neighbouring area in Burundi prompted the Tanzanian

Fig. 1-2. Map showing the localities of Karagwe Tinfield and Bushubi granites in the Karagwe-Ankolean belt, NW Tanzania.

Fig. 1-3. Map showing the location of Bushubi in the southern part of the Karagwe-Ankolean Belt, and areas mapped (scale 1:10,000) during the present study.

government, in 1975, to investigate the region for nickel and allied metallic sulfide deposits. A UNDP assisted project "Mineral Exploration in Northwest Tanzania" led to the discovery of a nickel-sulfide deposit associated with ultramafic intrusions at Kabanga in 1976 (van Straaten, 1984). The region was also explored for tin and tungsten, and concentrations of tin were confirmed near Maleba (Msanya, 1976; UNDP Report, 1977). The chemistry and the age relationships of the granitic and ultramafic rocks and the associated mineral deposits in Bushubi and other parts of the Karagwe-Ankolean belt in NW Tanzania have not been studied.

1.2.0 Objectives of the study

The objectives of this study were to :

1. map the Karagwe-Ankolean granites in selected areas,
2. study the mineralogical and chemical characteristics of the granites,
3. characterise and discriminate petrochemically the stanniferous granites from the barren granites, and establish suitable criteria for the recognition of potentially mineralized granites,
4. examine alteration haloes within and around the granites and evaluate their usefulness in distinguishing target areas for tin mineralization,
5. establish the time of the emplacement of the granites from isotopic studies, and
6. constrain the petrogenesis of the Karagwe-Ankolean granites and related tin deposits on the basis of field relationships, petrological and geochemical data.

1.3.0 Field work

The field work in NW Tanzania was conducted during the spring and summer of 1985 and 1987, and dealt mainly with geological mapping and sampling of granites in the Bushubi area (Figs. 1-2, 1-3) of the Karagwe-Ankolean belt. Traverses were also made in the northern part of the Karagwe-Ankolean belt in the Karagwe Tinfield (Fig. 1-2) for correlation purposes. In Bushubi, five key granite areas were chosen for detailed study based on:

- (i) availability of topographical base maps and aerial photographs
- (ii) amount of outcrop (iii) mineralogical and textural contrasts in the granites, (iv) the presence of tin deposits, and (v) the amount of time available for the field work. The granites investigated in detail are those in the Bukiriro, Kabanga, Nyamakombe, Mumakera and Maleba plutons (Fig. 1-3).

The Bukiriro and Kabanga granites in the Bushubi batholith (Fig. 1-3) consist mainly of foliated granites that were considered by Gray (1963) to be late-tectonic with respect to the structural and metamorphic evolution of the Karagwe-Ankolean belt. Granites of the Nyamakombe pluton, surveyed by Gray (1963), were originally thought to be composed of both, syn-tectonic and post-tectonic intrusions. But as will be shown later, all granites in the Nyamakombe pluton appear to be post-tectonic. The Mumakera and Maleba plutons were considered post-tectonic (Gray, 1963).

Granites in the various plutons were mapped on a scale of 1:10,000 (see Appendix 9), using base maps obtained by enlargement of the 1:50,000 topographical map sheet Nos. 29/1 and 29/2 from the Ministry of Lands and Survey, Tanzania. Samples collected during the mapping were shipped to

Carleton University for laboratory studies.

1.4.0 Laboratory studies

Laboratory work, undertaken mainly in the Ottawa-Carleton Geoscience Centre, dealt with petrographic studies and electron microprobe, chemical and isotopic (Rb-Sr, $^{40}\text{Ar}/^{39}\text{Ar}$) analysis of rock and mineral samples. Details of sample preparation and experimental procedures are given in Appendix 3. The chemical data base consists of 136 whole-rock analyses of Si, Al, Fe, Mg, Ca, Mn, Na, K, Ti, P, Rb, Sr, Ba, Y, Zr, and Nb. Analyses were made using X-ray fluorescence (XRF) at the University of Ottawa. One hundred fifteen granite samples, 2 xenoliths, 9 aplites, 4 gabbros, and 6 metasedimentary rocks were analysed by XRF. Some of the samples were also analysed for Sn by XRF at Bondar-Clegg, Ottawa, and for F, Li, B, and W by wet chemistry, atomic absorption, direct current plasma (DCP) and neutron activation (NA) methods, respectively, at the X-Ray Assay Laboratory (XRAL), Toronto. Ten granite samples were analysed by ICP for REE (La, Ce, Nd, Sm, Eu, Dy, Er, Yb and Lu) at "Centre de Recherches Petrographiques et Geochimiques" (C.R.P.G.) in France. In addition, at least 120 electron microprobe analyses of tourmaline, biotite, muscovite, feldspar, and garnet were obtained. All microprobe analyses were done in the Department of Earth Sciences at Carleton University with the exception of some tourmaline analyses done at CNRS-BRGM in France. Isotopic data consist of 23 Rb-Sr analyses and 9 $^{40}\text{Ar}/^{39}\text{Ar}$ analyses. Rb and Sr isotope analyses were obtained at Carleton University, and the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses at Dalhousie University. Analytical procedures, and details of the accuracy and precision for the various analyses are given in Appendix 3.

CHAPTER 2

GENERAL GEOLOGY OF THE KARAGWE-ANKOLEAN BELT

2.0.0 Introduction

The name "Karagwe-Ankolean System" was first proposed by Combe (1926) for the metasedimentary rocks belonging to the NE to NNW-trending Mid-Proterozoic orogenic belt in NW Tanzania and SW Uganda. The type localities were in Karagwe district in NW Tanzania and the Ankole district in SW Uganda. The Karagwe-Ankolean rocks were later correlated with the Kibaran rocks (Kibarides) in Zaire, and with the Burundian Supergroup in Burundi and Rwanda (Cahen and Snelling, 1966). The term "Kibaran" is commonly used in the literature to include the Kibarides and the Burundian and Karagwe-Ankolean Supergroups. In Tanzania, the term "Karagwe-Ankolean System" has been retained for local usage. In the present study, the term "Karagwe-Akolean System" has been replaced by "Karagwe-Ankolean Belt", bearing in mind that the word "System" is a stratigraphic term reserved for Phanerozoic strata deposited in a specific time period.

Kibaran rocks in Burundi, Rwanda and Zaire, studied by several workers (e.g., Cahen and Snelling, 1961; Cahen et al., 1984, Klerkx et al., 1987, Pohl, 1987), consist mainly of phyllites, schists and quartzites, intruded by granites and mafic and ultramafic plutons. Some volcanic rocks have been reported from Kibaran rocks in Zaire (Kampunzu et al., 1985) and Burundi (Klerkx et al., 1987).

In Uganda, the Karagwe-Ankolean (Kibaran) rocks have been described by Stheeman (1932) and Cahen and Snelling (1961), amongst others. The rocks

consist mainly of phyllites, schists and quartzites. The metasedimentary rocks were cut by several generations of granites, some of which host pegmatitic tin and tungsten deposits.

Rb-Sr dates for the granitic intrusions in the Kibaran belt range from ca 1350 Ma to ca 950 Ma (Cahen and Snelling, 1961; Cahen et al., 1984; Klerkx et al., 1987; Lehmann and Lavreau, 1987). The older granites, dating ca 1350-1200 Ma, are considered to be syn- or pre-tectonic and the younger (ca 1000-950 Ma), post-tectonic. Tin and tungsten deposits in the Kibaran rocks are thought to be associated only with the post-tectonic granites.

2.1.0 Karagwe-Ankolean metasedimentary rocks

The Karagwe-Ankolean metasedimentary rocks in NW Tanzania are composed mainly of sericite phyllites, muscovite schists, sericitic quartzites and massive quartzites. Carbonaceous sedimentary rocks have been metamorphosed to graphitic schists, and iron-rich sediments are represented by hematitic bands interlayered with red-brown ferruginous phyllites and quartzites. Cross-bedding and sedimentary lamination are still preserved in weakly metamorphosed sedimentary rocks. No volcanic rocks have been observed in the Karagwe-Ankolean belt of NW Tanzania.

The northern part of the Karagwe-Ankolean belt, in the Karagwe district (Fig. 1-2) was mapped and described in detail by Stockley and Williams (1938), who proposed the following stratigraphic sequence:

5. Kishanda Beds
(2010 m)	phyllites, flaggy, fine-grained, well-bedded sandstones and argillites.
4. Mtagata Quartzite
(1470 m)	bedded quartzites, current-bedded quartzitic sandstones, conglomerate.
3. Mabira Beds	phyllitic shales and ferruginized phyllites

(6210 m)	intercalated with psammitic bands, quartzite, argillites.
2. Kafulu Quartzite (1740 m)	mainly quartzite interlayered with phyllites and graphitic phyllites.
1. Arena Beds (1500 m)	highly tourmaliniferous mica schists, graphitic schists/phyllites, micaceous quartzite, fine-grained quartzite, white-mica schists/phyllites, current-bedded quartzite.

The Arena beds, which occur in the immediate contact of exposed granite cupolas, form the lower portion of the Karagwe-Ankolean metasedimentary succession. The localization of tourmaline in the Arena beds suggests metasomatism by B-rich fluids derived from the granites.

The total thickness of the Karagwe-Ankolean succession is not known because the base of the succession is not exposed, the top is not well known and the rocks are folded and faulted. Stockley and Williams (1938), however, estimated a maximum thickness of about 13,000 m. Others estimated the thickness to be between 5,000 and 10,000 m (van Straaten, 1984).

2.2.0 Structure and metamorphism

Two principal structural trends, defined either by foliation, lineation, folds, or faults and joints, are recognised in the Karagwe-Ankolean belt. Northeast-trending structures are more prevalent in the southern part of the Karagwe-Ankolean belt in Ngara district whereas NNE to NNW-trending structures are observed in the northern part in Karagwe district. A structural analysis of the major structures is given by Harpum (1970).

Folding and subsequent erosion have given rise to the highly rugged topography of the Karagwe-Ankolean belt. Quartzites commonly form prominent ridges whereas phyllites form steep-sided valleys with contorted contour

patterns. Deep preferential erosion of the metasedimentary rocks above granite cupolas has resulted into low-relief, topographical basins known as "arenas" (Stockley and Williams, 1938). The basins are surrounded by steep-sided hills of Karagwe-Ankolean phyllites and quartzites. Late Mesozoic and Cenozoic peneplanation surfaces (Gray, 1963), mantled by laterite and lateritic duricrusts, are well developed in some places.

The grade of metamorphism of Karagwe-Ankolean metasedimentary rocks varies from low to middle or upper greenschist facies. The predominant rock types are sericite phyllites, quartzites or quartzitic sandstones. Muscovite schists are found in contact aureoles adjacent to the granites or in the lower units of the metasedimentary succession. Shales, argillites and cross-bedded sandstones occur locally, particularly in the upper portions of the succession.

Chloritoid-bearing schists have been reported by Gray (1963) in the northern part of the Ngara district around Rusumo Falls. Chloritoid schists were also observed locally in the southern part of the Ngara district in Bushubi during this study. The preservation of chloritoid and quartz, coupled with the lack of garnet or staurolite in the country rocks, indicates that greenschist-amphibolite facies boundary was probably not reached during regional metamorphism. Winkler (1979) gives the following reaction isograds for the greenschist-amphibolite transition:

Local contact metamorphic aureoles occur in the metasedimentary rocks

around granite intrusions. The aureoles are commonly marked by the development of andalusite porphyroblasts in the mica schists, and quartzites have been strongly recrystallized, exhibiting coarse-grained, granoblastic textures. Tourmaliniferous schist, quartzite, and hornfels are localized along the granite contacts.

2.3.0 Basic and ultrabasic intrusions

A narrow linear belt of basic and ultrabasic intrusions extend from NW Tanzania to Burundi along the eastern margin of the Karagwe-Ankolean belt. In Tanzania, the basic intrusions occur mainly in the eastern and central part of the Karagwe-Ankolean belt, north and south of Rusumo Falls. Basic dykes and sills as well as extensive bodies of gabbroic rocks were intruded in the upper sequence of the Karagwe-Ankolean sedimentary rocks prior to the main folding (Gray, 1963). The formation of basic dykes and sills preceded the emplacement of the gabbroic intrusions. Ultrabasic rocks, including pyroxenites and peridotites, were discovered in the southern part of the Karagwe-Ankolean belt by geochemical and geophysical methods and drilling at Kabanga (UNDP Report, 1977; van Straaten, 1984).

2.4.0 Granitic intrusions

Granites outcrop in two main clusters in the Karagwe-Ankolean belt. The northern cluster includes granites of the Karagwe Tinfield, and the southern cluster consists of the Bushubi granites in Ngara district (Figs. 1-2, 1-3). Post-orogenic granites occur mainly in the northern and southern clusters, and syn-orogenic granites appear to be confined to the southern cluster. The present study deals mainly with the syn-orogenic and post-orogenic granites of the southern cluster.

2.5.0 Mineralization

Tin-tungsten and nickel deposits in the Karagwe-Ankolean belt are related to granitic and ultrabasic intrusions, respectively. The tin and tungsten deposits are restricted to the post-orogenic granites.

The primary tin deposits of the Karagwe Tinfield, described by Stockley and Williams (1938), Harris (1961) and Saltikov (1977), occur as cassiterite in quartz, or quartz-muscovite veins within tourmalinized mica schists and phyllites in the exocontact zone of granitic intrusions. No large workable deposits have been found within the granites themselves.

Most of the tin production in the Karagwe Tinfield has come from the Kyerwa mine, where cassiterite-bearing muscovite-quartz veins and stockworks occur in tourmalinized Karagwe-Ankolean metasedimentary rocks. Granite is not exposed, but the degree of metamorphism of the metasedimentary rocks in the mine area suggests that a granite body probably underlies the area at shallow depth (Harris, 1961).

Cassiterite is found disseminated in quartz reefs or in isolated pockets along the margins of otherwise barren massive quartz. Cassiterite-rich pockets are commonly found in coarse-grained white mica selvages, bordering quartz veins, and in mica-filled fractures along the strike of quartz veins. Alluvial and eluvial tin deposits are also found.

In the southern part of the Karagwe-Ankolean belt, cassiterite occurs in the Maleba area of Bushubi (Map 4, Appendix 9). Vein and alluvial cassiterite was mined in the Kigarama valley from 1938 to 1940 (Berryman, 1941). Recent exploration work of the Maleba tin occurrence by Musanya

(1976) and UNDP (1977) has indicated the presence of recoverable quantities of alluvial cassiterite in the Kigarama valley.

Tungsten occurrences are limited to the northern part of the Karagwe Tinfield, close to the Tanzania-Uganda border. Tungsten occurs as wolframite in quartz-hematite-mica veins enclosed in phyllitic country rocks (e.g., Karungu-Chamunyana area) or in quartz $\pm$ arsenopyrite reefs and greisen within the granite, e.g., the Ihunjere Arena (Harris, 1961).

Unlike the granites, the gabbroic intrusions are lacking any economic mineral deposits. Epigenetic pyrite-pyrrhotite veins have been reported in syn-orogenic gabbroic intrusions of Rusumo Falls and northern Bushubi (Gray, 1963), but no economic minerals have been found. Magmatic Cu-Ni sulfide deposit associated with ultrabasic intrusions, has recently been discovered at Kabaga (van Straaten, 1984) in the southern part of the Karagwe-Ankolean belt. This discovery has opened up new exploration targets for ultramafic-related mineral deposits in the Karagwe-Ankolean belt.

Alluvial gold of unknown origin occurs locally in some parts of the Karagwe-Ankolean belt. Deposits of commercial value have yet to be found.

Vermiform and pisolitic laterites of Late Mesozoic to Cenozoic age are well developed in the southern part of the Karagwe-Ankolean belt (van Straaten, personal communication). These laterites may be favourable for bauxite deposits.

CHAPTER 3

GEOLOGY AND PETROLOGY OF KARAGWE-ANKOLEAN GRANITES IN BUSHUBI

3.0.0 Introduction

The Karagwe-Ankolean granites in Bushubi (Fig. 1-3) have been briefly described by Gray (1963) who subdivided them into "older", lineated, gneissic biotite-muscovite granites and "younger", generally non-lineated muscovite-microcline granites and adamellites. The older granites are considered to be syn-orogenic, the younger post-orogenic. The latter have been correlated with granites of the northern domain in the Karagwe Tinfield where granites are known to be associated with several occurrences of tin $\pm$ tungsten deposits. No tin or tungsten deposits have been found associated with the syn-orogenic granites.

Gray's subdivision of the granites in Bushubi has been adopted in the present study. However, some granites originally classified as "older" on the basis of texture and field relationships were found to resemble the "younger" granites and vice-versa. This particularly applies to the Kabanga granites in the southern part of the Bushubi batholith and the Nyamakombe pluton (Fig. 1-3). Granite nomenclature has also been modified to fit field and petrographical observations. In subsequent sections, the term "older" or syn-orogenic granites refers to foliated or lineated muscovite-biotite granites or gneissic biotite granites, while the term "younger" or post-orogenic granites refers to non-foliated muscovite-biotite granites, biotite-muscovite granites or tourmaline-muscovite granites. Foliations are commonly defined by alignment of micas, usually NNE to NE, while lineations consist of subparallel arrangements of feldspar phenocrysts in the same

strike direction as the foliations.

3.1.0 Syn-orogenic granites in the Bushubi batholith

The Bushubi granite batholith extends from Rulenge in the northeast to Kabanga in the southwest (Fig. 1-3), and is the largest polyphase intrusive complex in the southern part of the Karagwe-Ankolean belt. The batholith is elongated parallel to the regional structural trend of Karagwe-Ankolean metasedimentary rocks and seems to plunge gently to the NE. It has a strike length of approximately 32 km and an average width of about 8 km. The occurrence of moderately to weakly foliated granites in the Bushubi batholith suggests that the batholith was probably emplaced synkinematically during the late stages of metamorphic and structural evolution of the Karagwe-Ankolean belt. The development of gneissic granites close to the contact with the metasedimentary rocks and the fracturing of country rocks adjacent to the granites, suggest diapric emplacement of the granitic magmas. Locally, mechanical stoping of the metasedimentary rocks by the granitic magmas is indicated by the presence of xenoliths and roof pendants in the granites.

The Bushubi batholith can be divided into the following granite types:

- a) medium-grained, equigranular, biotite granite containing very minor muscovite;
- b) coarse-grained muscovite-biotite granite with K-feldspar megacrysts;
- c) coarse-grained, equigranular to feldspar porphyritic muscovite-biotite granite;
- d) medium to coarse-grained, weakly foliated, muscovite-biotite granite with seriate texture, that grades into equigranular non-foliated granite.

The field relationships of the various granites are not well understood because few exposures are found. Generally, the equigranular granites tend to occur in the centre of the complex, usually surrounded by foliated porphyritic or megacrystic granites.

3.1.1 Rulenge granite

The Rulenge pluton outcrops in a few areas along Mumibindi River and its tributaries east of Rulenge township (Fig. 1-3), and consists of a grayish-white, medium to coarse-grained, equigranular muscovite-biotite granite. It is locally kaolinized and the kaolin is used for local pottery. Biotite is locally altered to chlorite. Weak mica foliation and subhorizontal feldspar lineations, trending N40E, are common. Two sets of fracture systems are associated with the granite. One set trends 300° and dips 70° SW and is occupied by tourmaline-quartz veins. The other set trends 020° and dips 65° SE and is marked by tourmaline-free quartz veins. The latter have off-set the tourmaline-quartz veins with dextral displacement.

The marginal phase of the Rulenge pluton, a medium-grained biotite granite, contains locally derived angular mica schist xenoliths. This granite outcrops at the trunk road maintenance (TRM) camp south of Rulenge Mission. Tourmaline-quartz veinlets, trending at 300° to 335° and dipping 35 - 65° SW, are also observed in the granite.

3.1.2 Muyenzi granites

Along the Muyenzi Ford, where the ford crosses the road to Mururama village, two varieties of granite occur. A medium-grained equigranular gneissic biotite granite, containing minor muscovite, outcrops near a

coarse-grained feldspar porphyritic muscovite-biotite granite. The former locally contains centimetre-size gneissic enclaves that are texturely distinct from the granite host. The porphyritic granite is cut by 045⁰-trending tourmaline-quartz-feldspar pegmatites, and 322⁰-trending muscovite-quartz-feldspar pegmatites free of tourmaline. The pegmatites range in width from 2 to 30 cm or more. Quartz veins (<5 cm wide), trending at 295⁰ to 300⁰, have cut both the gneissic and the porphyritic granites and the NE-trending pegmatites.

3.1.3 Bukiriro-Rwinyana granites

Several, texturally distinct granite units occur in the central part of main Bushubi batholith in the Bukiriro-Rwinyana area (Map 1, Appendix 9). All granite types documented earlier are represented. The oldest, a fine- to medium-grained gneissic biotite granite containing minor muscovite, is locally intruded by coarse-grained, feldspar porphyritic muscovite-biotite granites. White mica schist inclusions are common in the biotite-rich gneissic granite, but are absent or rare in later granite units. The oval or lensoid inclusions are aligned with long axis parallel to the strike of the mica foliation. Banded granite gneiss is developed locally along the contacts of the granites with the metasediments.

Feldspar megacrystic granites have been deformed, and the granites closely resemble augen gneisses. Deformation is less pronounced in the coarse-grained, equigranular and porphyritic varieties. The field relationship of the megacrystic granites to the equigranular and porphyritic granites is not clearly defined. However, the high abundance of tourmaline and the occurrence of hydrothermal alteration in the weakly porphyritic and

equigranular granites suggest that the granites may be late-stage products of the megacrystic granites. A hydrothermally altered, muscovite granite cupola was observed in one locality southeast of Bukiriro (Map 1, Appendix 9). Non-foliated, medium- to coarse-grained muscovite-biotite granites occur in small stocks in the Kihinga-Rwinyana area, and are locally kaolinized.

3.1.4 Kabanga granites

These occur at the southern end of the Bushubi batholith (Map 2, Appendix 9). Three main textural varieties of muscovite-biotite granite are documented in the Kabanga area. The eastern and western parts of the Kabanga area are underlain by coarse-grained, foliated, weakly feldspar porphyritic to equigranular tourmaline-muscovite-biotite granites. The central part of Kabanga area is occupied by a medium-grained, foliated, biotite-muscovite granite cut by numerous quartz-tourmaline veins (Map 2, Appendix 9). A feldspar porphyritic granite that outcrops on the northwestern corner of Map sheet 2 (Appendix 9), seems to grade into a medium-grained, muscovite-biotite granite towards the east. Coarse-grained, non-foliated, pink muscovite-biotite granite was observed at one locality close to the NW corner of the Kabanga map sheet.

The Kabanga granites generally appear to be more differentiated than the granites of the central and northern parts of the Bushubi batholith. This is indicated by the occurrence of zones of widespread pneumatolytic and hydrothermal alteration and the presence of aplite, pegmatite (Plate 3-1C), and numerous quartz-tourmaline veins. The veins and pegmatite fall in the following five categories:

a) monomineralic quartz veins,

- b) ilmenite-fluorite-tourmaline-quartz veinlets with leucocratic selvages of quartz and cross-hatch microcline,
- c) quartz-tourmaline veins,
- d) tourmaline-quartz-feldspar pegmatite, and
- e) quartz-feldspar $\pm$ muscovite pegmatite.

The relative ages of the pegmatites and veins are not clear. Field observations, however, suggest that the pegmatites and tourmaline-bearing veins are older than the monomineralic quartz veins. Folded, feldspathic pegmatites that cut the medium-grained muscovite-biotite granite were not observed in other Kabanga granites. Most of the tourmaline-bearing veins strike NW to NNW, whereas the quartz veins strike NE. At one locality, N50E-trending microfaults with sinistral displacement (Plate 3-1E) cut NW-trending tourmaline-quartz-feldspar pegmatites.

Tourmaline and microcline associated with late-magmatic and post-magmatic alteration in the Kabanga granites suggest boron and potassic metasomatism. Tourmalinization is locally pervasive in the coarse-grained tourmaline-muscovite-biotite granite, particularly where tourmaline-bearing aplites and veins cut the granite (Map 2, Appendix 9). The veins are normally bordered by leucocratic alteration selvages. Biotite and in some cases muscovite of the host granite have been completely altered to microcline and quartz. Hydrothermal alteration is essentially confined to the apical parts of the granites where feldspars have been kaolinized and biotite replaced by white mica.

Distinctive patches, consisting of quartz-tourmaline intergrowths (Plate 3-1A), occur in the medium-grained muscovite-biotite granite near the centre

of the pluton. Thin, mica-free, haloes of quartz and microcline commonly surround the intergrowths. Similar textural features have been documented in tourmaline-bearing granites elsewhere (e.g., Nemec, 1975; Taylor, 1979; Sinclair and Richardson, 1986). A detailed discussion of the intergrowths is given in Chapter 4.

3.2.0 Post-orogenic granites

As mentioned earlier, the term "post-orogenic granites" is used to define non-foliated, muscovite-biotite granites and muscovite granites represented by the Nyamakombe, Mumakera and Mwibanda-Maleba plutons. The Mwibanda-Maleba pluton (Map 4, Appendix 9) has been referred to as the Ruvuvu valley granites (Gray, 1963). These plutons form three distinct intrusions west of the Bushubi batholith (Fig. 1-3). The plutons are separated from each other and from the main Bushubi batholith by Karagwe-Ankolean metasedimentary rocks. Gray considered the post-orogenic granites in Bushubi to be similar to the tin-granites of the Karagwe Tinfield. The granites of the southwestern portion of the Bushubi batholith in Kabanga (Map 2, Appendix 9) were also considered by Gray (1963) to be post-orogenic and hence similar to the Ruvuvu valley granites. The present study indicates, however, that the Kabanga granites are similar to the foliated syn-orogenic granites of the northern and central parts of the Bushubi batholith. Gray also classified the northern part of Nyamakombe pluton, north of Nyamakombe river (Map 3, Appendix 9), as syn-orogenic. The present study shows that both parts of the Nyamakombe pluton, north and south of Nyamakombe River, are similar and belong to the non-foliated, post-orogenic granites. The Nyamakombe, Mumakera and Maleba pluton are geologically similar, although they are petrologically distinct. The main features of each pluton are described below.

3.2.1 Nyamakombe pluton

Coarse-grained muscovite-biotite granite forms most of the Nyamakombe pluton. The pluton is geographically divided into two parts by the westerly-flowing Nyamakombe river (Map 3, Appendix 9). The northern part of the pluton consists of muscovite-biotite granite partly hydrothermally altered to biotite-muscovite granite. The unaltered granite contains large feldspar megacrysts with Carlsbad twinning. Most megacrysts are randomly oriented, but may show local, sub-parallel alignment. Accessory tourmaline is found locally. Lenticular metasedimentary xenoliths are rare in the granite; some have been tourmalinized unlike the host granite. Hydrothermal alteration has produced weak kaolinization of the feldspars, and biotite is replaced by brownish white mica or muscovite.

The southern part of the pluton is similar to the northern part. A coarse-grained megacrystic muscovite-biotite granite forms an east-west continuous exposure about 100 m long, and seems to grade into muscovite granite at the western margin of the pluton (Map 3, Appendix 9). A few metasedimentary xenoliths occur in the muscovite granite. The Karagwe-Ankolean metasedimentary rocks adjacent to the muscovite granite form sericite-quartz hornfels, and have been tourmalinized.

3.2.2 Mumakera pluton

This pluton consists of an equigranular, non-foliated, medium-grained, muscovite-biotite granite that grades northeastward into a biotite-muscovite granite and finally into a muscovite granite (Map 4, Appendix 9). Each granite is fairly homogeneous in texture and mineral composition.

Tourmaline, a common accessory mineral in all granites, is less abundant

in the muscovite-biotite granite. Rounded and angular metasedimentary xenoliths are rare in the biotite-muscovite granite. Some xenoliths are normally preferentially tourmalinized along foliation planes. Ovoid, massive tourmaline clots occur locally in the biotite-muscovite and muscovite granites, and could represent completely tourmalinized iron-rich metasedimentary xenoliths. The granites are generally fresh except in some parts affected by weak kaolinization. Kaolinization is localized near the central part of the pluton where it seems to be associated with two prominent orthogonal fractures.

Karagwe-Ankolean phyllites at western contact of the pluton are cut by quartz-muscovite and tourmaline-quartz veins, as well as monomineralic quartz veins. Cassiterite was not found in any of the veins and the phyllites hosting the veins were not tourmalinized.

3.2.3 Mwibanda-Maleba pluton

The largest pluton of the post-orogenic granites in Bushubi, the Mwibanda-Maleba pluton (herein referred to as the Maleba pluton), has a strike length of about 14 km and an average width of 2 km (Fig. 1-3). The pluton is elongated parallel to the regional structural trend of the Karagwe-Ankolean metasediments. The northeastern end of the pluton in the Kigarama valley occupies a core of a NE-plunging anticline, marked by a prominent quartzite horizon (Map 4, Appendix 9) that has been fractured and invaded by numerous quartz veins. The northern part of the Ruvuvu river valley along Tanzania-Burundi border (Map 4, Appendix 9) is largely occupied by the pluton. A narrow contact metamorphic aureole is marked by the development of andalusite porphyroblasts in gray ferruginous phyllites, by

sericite-quartz hornfels in arenaceous sediments, and by coarse-grained, partially annealed quartzite in quartzitic sandstones.

Forceful emplacement of the pluton resulted in intense fracturing of quartzite in the Maleba part of the pluton, and later invasion by siliceous fluids and B-rich emanations which produced a network of quartz veins and tourmaline stringers. Some of the quartz veins contain cassiterite.

Four texturely distinct granite varieties occur in the Maleba pluton. These are:

- a) coarse-grained, equigranular to weakly porphyritic, biotite-muscovite or muscovite-biotite granite,
- b) coarse-grained, equigranular to weakly porphyritic, muscovite granite,
- c) medium-grained, equigranular, tourmaline-biotite-muscovite or muscovite-biotite granite, and
- d) tourmaline leucomonzogranite.

The coarse-grained biotite-muscovite granite forms a large part of the pluton, from Mwibanda in the southwest to Kigarama/Maleba valley in the northeast (Map 4, Appendix 9). The coarse-grained muscovite granite occurs mainly in the upper parts of the Ruvuvu valley, while the biotite-muscovite granites occur mainly in the lower (Map 4, Appendix 9). Potassium feldspar is light pink in the fresh two-mica granite and white in the altered two-mica granite and muscovite granite. Muscovite, in the fresh granites, forms subhedral crystals of up to 5 mm; the crystals are similar in size to co-existing quartz, feldspars and biotite. The size, shape, and textural relationships suggest a magmatic origin for the muscovite in the fresh granites. Black tourmaline, the most common accessory mineral in the two-

mica and muscovite granites, forms euhedral crystals, or veinlets in the granites or is intergrown with quartz. Quartz-tourmaline intergrowths and veinlets are mainly localized in granite cupolas.

Closely associated with the coarse-grained biotite-muscovite and muscovite granites are pegmatite pods (Plate 3-1D) and dykes, aplites, quartz-filled miarolitic cavities, quartz-tourmaline and quartz veins, and zones of hydrothermal alteration. These granite-related features are indicative of aqueous-fluid saturation in parent magmas (Jahns and Burnham, 1969; Taylor, 1979). The granites exhibit weak widespread hydrothermal alteration, indicated by turbid and kaolinized feldspar. Kaolin alteration is particularly more pervasive in the muscovite granite cupolas.

The third type of granite is a medium-grained, tourmaline-biotite muscovite granite that outcrops along the western margin of the northern portion of the Maleba pluton (Map 4, Appendix 9). The granite is capped by a strongly altered muscovite granite cupola. The texture and intensity of feldspar and biotite alteration suggest that the granite either represents a separate intrusive unit of the Maleba pluton or a different facies of the coarse-grained biotite-muscovite granite. Locally, biotite is partially or completely altered to white mica and/or chlorite, and rusty brown cavities in the apical parts of the granite possibly represent cavities originally filled with iron sulfide. Quartz-feldspar dykelets (0.5-3 cm wide), trending at 120°, in the granite contain minor muscovite and accessory, pink garnet.

Tourmaline leucomonzogranite outcrops in one locality at the northeast end of the Maleba pluton (Map 4, Appendix 9), where it is associated with a two-mica monzogranite. The contact between the two granites is not exposed,

although the two-mica monzogranite appears to be variably tourmalinized and cut by numerous tourmaline stringers (Plate 3-1B) close to the tourmaline leucomonzogranite. Garnet-bearing aplite dykes, massive quartz veins and a few muscovite-quartz veins occur in the monzogranites. Biotite in the two-mica monzogranite is partially altered to white mica and minor chlorite, and arsenopyrite is associated with fractures. The Maleba tin deposit is located in the exocontact zone of the monzogranites (Map 4, Appendix 9).

Pegmatite occurrences in the Maleba granites are limited both in number and size. Most are normally a few centimetres wide and extend for short distances laterally. They exhibit a very simple mineralogy of quartz and feldspar $\pm$ muscovite $\pm$ garnet. Pegmatites of more complex mineralogy, such as those found in similar granites in Rwanda and SW Uganda (Varlamoff, 1972), have yet to be found.

Aplites are generally more abundant than pegmatites in the Maleba granites. Three types of aplites may be distinguished. Type I is biotite-muscovite-garnet-tourmaline-bearing, Type II is muscovite-garnet-tourmaline-bearing, and Type III is muscovite-garnet-bearing. Types I and III aplites are closely associated with the monzogranites exposed at the northeastern end of the Maleba pluton in the Kigarama valley. Type II aplite is associated with the coarse-grained two-mica granite that forms the largest part of the pluton. Garnet in Types I and II is rich both in almandine and spessartine, while in Type III the garnet is rich in spessartine and poor in almandine. Type I aplite is rich in tourmaline and contains accessory biotite and muscovite and skeletal garnet (Plate 3-2H). Type II aplite is mineralogically zoned, with a fine-grained, tourmaline-rich selvage,

PLATE CAPTIONS

- Plate 3-1A. Rounded quartz-tourmaline intergrowths (arrow) in a medium-grained Kabanga biotite-muscovite granite. Photo locality close to sample KA-24 (Map 2, Appendix 9).
- Plate 3-1B. Tourmaline stringers bordered by leucocratic haloes in the Maleba monzogranite. Photo locality close to sample MA-18 (Map 4, Appendix 9).
- Plate 3-1C. Tourmaline-bearing quartz-feldspar pegmatite dyke in a medium-grained Kabanga biotite-muscovite granite. Photo locality same as sample KA-30 (Map 2, Appendix 9).
- Plate 3-1D. Pegmatite pod in a coarse-grained Maleba biotite-muscovite granite. Photo locality same as sample MB-2 (Map 4, Appendix 9).
- Plate 3-1E. Tourmaline-quartz-feldspar dykes (trending at 315°) cut by a N50E-trending mesoscopic fault with sinistral displacement. Photo locality close to sample KA-30 (Map 2, Appendix 9).
- Plate 3-1F. Cassiterite-bearing quartz vein in a muscovite schist at the Maleba tin mine (Map 4, Appendix 9).
- Plate 3-1G. Plan view of a cylindrical aggregate of biotite in a medium-grained biotite granite close to the Maleba tin mine. Photo locality same as sample MB-30 (Map 4, Appendix 9).
- Plate 3-1H. Cross-section of a cylindrical biotite aggregate shown in Plate 3-1G.

PLATE 3-1

garnet-rich inner zone, and medium to coarse-grained quartz-feldspar $\pm$ muscovite central core. Garnets in Type II and III aplites are euhedral (Plate 3-2G). Type III aplite has a saccharoidal texture and is very sodic (8.9 % Na_2O , $\text{K}_2\text{O}/\text{Na}_2\text{O} = 0.1$). Locally, the Type III aplite contains pegmatitic pods or crystals of almost pure K-feldspar. Muscovite occurs in very tiny, almost microscopic, flakes in quartz-albite groundmass. Irregular, coarse-grained, massive quartz core or vein is seen in the aplite. Compositions of garnets from the three types of aplite are discussed in more detail in section 6.4.0 of Chapter 6.

3.3.0 Mineralogy and petrography

The syn-orogenic and post-orogenic granites are either hypidiomorphic equigranular or porphyritic. The majority of the granites exhibit a simple mineralogy of potassium feldspar, sodic plagioclase ($\text{An} \leq 13$) and quartz, and accessory biotite, muscovite and tourmaline, and minor apatite, ilmenite, monazite, xenotime and zircon. The phenocrysts in the porphyritic granites are mainly potassium feldspar and rarely plagioclase or quartz.

Petrographic textures exhibited by the minerals in the granites are discussed below.

K-feldspar

K-feldspar in the granites is mainly microcline that exhibits indistinct twinning or well-developed cross-hatch twinning. Microcline with indistinct twinning is commonly resorbed or replaced by microcline showing cross-hatch twinning. Poorly twinned microcline occurs mainly as phenocrysts in a groundmass of quartz and fine-grained feldspar. Cross-hatched microcline occurs in intergranular crystals. Perthitic K-feldspar can be found as

phenocrysts, but is generally lacking or rare in the groundmass. Highly turbid K-feldspars, observed in the apical parts of most of the stanniferous granites, is lacking or rarely found in the barren granites. The majority of the feldspars showing turbidity occur as phenocrysts or coarse-grained crystals, and are locally altered to sericite.

Myrmekite is more abundant in the syn-orogenic granites than the post-orogenic granites. It occurs at contacts between potassium feldspar and plagioclase or as a replacement of phenocryst K-feldspar (Plate 3-2A). Textural relationships suggest that myrmekite formed very late during magmatic crystallization or formed by subsolidus recrystallization. The high abundance of myrmekite in the deformed, syn-orogenic granites seems to favour a subsolidus origin.

Plagioclase

Plagioclase composition is mainly oligoclase. The anorthite content of the plagioclase, estimated petrographically and confirmed by microprobe analysis, is in the range of 11 to 13 %. Plagioclase is generally lower in abundance than K-feldspar in most of the granites, with the exception of some of the post-orogenic granites, particularly the tourmaline leucomonzogranites. Strongly zoned plagioclase is generally lacking in all the granites. Oligoclase shows little or no evidence of alteration in the syn-orogenic, tin-barren granites, and it is invariably altered to sericite or albite in the post-orogenic, stanniferous granites. Albite, found locally in the stanniferous granites, is either of primary or secondary origin. Secondary albite, related to post-magmatic sodic metasomatism, replaces oligoclase or K-feldspar phenocrysts in the granites. Albite in

sodic aplite dykes that cut the stanniferous granites of the Malcoba pluton appears to be partly magmatic and partly secondary in origin.

Quartz

Quartz occurs as subhedral to anhedral grains. Strained and fractured quartz is common in the syn-orogenic granites, but is rarely found in the post-orogenic granites. At least two generations of quartz are recognized in the post-orogenic granites. Subhedral, coarse-grained, quartz forms polygonal contacts with K-feldspar and mica, and some contain zircon or apatite inclusions. Intergranular quartz, forming fine-grained anhedral crystals, is free of inclusions, and in some cases replaces mica and feldspar in the groundmass. Bluish quartz phenocrysts were observed in the granites of Lake Rushwa arena, in the Karagwe-Tinfield.

Biotite

Biotite is the main ferromagnesian mineral in the granites, and forms 5 to 10 % by volume of the syn-orogenic granites, and about 0 to 5 % of the post-orogenic granites. Rarely biotite occurs as massive lenses or aggregates (Plates 3-IG, 3-IH) in the granites. In thin section, the biotite occurs in reddish-brown subhedral crystals that range from 1 mm to 5 mm in size. Some biotite flakes occur as inclusions in K-feldspar. Apatite, zircon or xenotime inclusions, surrounded by pleochroic haloes, are ubiquitous in most of the biotites. Biotite in altered granites is replaced by chlorite, muscovite or brownish-white mica, and opaque Fe-Ti oxides.

Muscovite

Muscovite is less abundant (≤ 3 %) in the syn-orogenic two-mica granites than in the post-orogenic granites. It forms subhedral grains, 0.2 mm to 5

mm in size, and some muscovite grains appear to cut across or to replace biotite. In the post-orogenic granites, muscovite forms about 5 % to 8 % by volume of the muscovite granites, and about 3 % to 5 % by volume of the two-mica granites. The muscovite appears to be both magmatic and hydrothermal. Magmatic muscovite is coarse-grained, and normally free of zircon inclusions. In contrast, muscovite formed by metasomatism of biotite is medium- to fine-grained, and has a very weak light-brown pleochroism, and can contain zircon inclusions. This type of hydrothermal muscovite has been observed in the altered granites of the Nyamakombe and Maleba plutons and in the Karagwe Tinfield granites. Microprobe analysis (see Chapter 6) has shown that hydrothermal muscovite, formed by alteration of biotite, is phengitic and higher in F than magmatic muscovite. Fine-grained, anhedral, muscovite (sericite) formed by alteration of feldspars is colourless and free of zircon inclusions.

Tourmaline

In the syn-orogenic granites tourmaline commonly occurs as fine- to medium-grained, subhedral, black prisms set in a quartz-feldspar groundmass. Its modal abundance varies in different granites but is generally less than 1 %. Some tourmaline in the Kabanga granites occurs in rounded patches or clots (Plate 3-1A) in the apical parts of granite cupolas. Tourmaline is also common in pegmatites, aplites and pneumatolytic or hydrothermal veins in the Kabanga granites.

The modal abundance of tourmaline in the post-orogenic biotite-muscovite granites is about 1.5 %. In muscovite and tourmaline leucogranites tourmaline can be as high as 15 %. This is particularly true for tourmaline-

muscovite granite of the Mumakera pluton and tourmaline leucomonzogranite of the Maleba pluton. Tourmaline in the post-orogenic granites is similar to that found in syn-orogenic granites, but is coarser grained. Quartz-tourmaline clots, similar to those in the syn-orogenic Kabanga granites (Plate 3-1A), are also found locally in the post-orogenic granites of the Maleba and Mumakera plutons.

In thin section, tourmaline from both the syn-orogenic and post-orogenic granites has a yellowish orange-brown colour and may be optically zoned (Plate 3-2D), and some contain apatite or zircon inclusions. The zonation can be attributed to compositional variations in the tourmaline, from Fe-poor core to Fe-rich outer zone. Microprobe analyses (see Chapter 6) have indicated the tourmaline to be Fe-rich schorl of schorl-dravite solid solution series.

Although tourmaline is common in the granites and many aplites, it is not found associated with highly sodic (8.9 % Na_2O , $\text{K}_2\text{O}/\text{Na}_2\text{O} = 0.1$), mica-poor, aplites found locally in the Maleba pluton. Variations in chemical composition of tourmaline from granites, aplites, hydrothermal veins and country rocks are discussed in Chapter 6.

Other accessory minerals

Other accessory minerals in the granites and/or aplite dykes include zircon, apatite, xenotime, monazite, ilmenite, fluorite, garnet, arsenopyrite and pyrrhotite. Zircon either occurs in isolated subhedral and anhedral grains in the granite groundmass or as inclusions in biotite, tourmaline and rarely muscovite or quartz. Zircon inclusions in biotite and

tourmaline are commonly surrounded by pleochroic haloes. Euhedral apatite crystals are common and occur as inclusions in biotite or as single grains in the granite groundmass. Some apatite grains consist of cloudy, rounded, cores with euhedral apatite overgrowths (Plate 3-2C). These cloudy apatite cores probably represent restite grains inherited from the source region. Euhedral apatite also occurs in pegmatite and aplite dykes in the Karagwe Tinfeld granites. Xenotime and monazite occur as inclusions in biotite or as isolated subhedral crystals (Plate 3-2B). Ilmenite is not very abundant in most of the granites, and is more common in the syn-orogenic, than in the post-orogenic granites. Euhedral, medium- to coarse-grained, garnet (Plate 3-2G) occurs in many aplite dykes and pegmatite associated with the Maleba pluton and Karagwe Tinfeld granites. Arsenopyrite, fluorite and pyrrhotite grains were observed in samples from a metasomatised granite at the NE end of the Maleba pluton. Fluorite along with tourmaline and ilmenite occur in quartz-tourmaline veins associated with the syn-orogenic Kabanga granites in the southern part of the Bushubi batholith (Fig. 1-3).

PLATE CAPTIONS

- Plate 3-2A.** Myrmekite replacing microcline in a two-mica granite.
- Plate 3-2B.** Subhedral xenotime (Xm) and monazite (Mz) crystals in the Bukiro two-mica granite.
- Plate 3-2C.** Euhedral apatite (Ap) and subhedral zircon (Zr) crystals in a two-mica granite from Bukiro. Apatite crystals have cloudy, rounded, cores that are surrounded by euhedral apatite overgrowths.
- Plate 3-2D.** Optically and chemically zoned (Figs. 6-2A, 6-2B) tourmaline from Maleba tourmaline-leucomonzogranite (sample MA-19, Map 4, Appendix 9).
- Plate 3-2E.** Selective replacement of albite by tourmaline in a perthitic K-feldspar in the Nyamakombe granite.
- Plate 3-2F.** Pervasively tourmalinized phyllite cut by a tourmaline vein containing coarse-grained tourmaline in the exocontact zone of the Nyamakombe pluton.
- Plate 3-2G.** Euhedral garnet (57.5 % almandine, 41.2 % spessartine, 0.8 % grossular, 0.5 % pyrope) in a muscovite-tourmaline-bearing aplite dyke in the Maleba pluton (sample MB-12, Map 4, Appendix 9).
- Plate 3-2H.** Skeletal garnet (54.8 % almandine, 43.4 % spessartine, 1 % grossular, 0.8 % pyrope) in a biotite-muscovite-tourmaline-bearing aplite dyke in the Maleba pluton (sample MB-33, Map 4, Appendix 9).

PLATE 3-2

CHAPTER 4

POST-MAGMATIC ALTERATION AND TIN MINERALIZATION

4.0.0 Introduction

Hydrothermal alteration is more common in the post-orogenic-stanniferous, than the syn-orogenic-barren granites. Alteration observed in the granites includes tourmalinization, muscovitization, sericitization, albitization, chloritization and kaolinization.

4.1.0 Tourmalinization

Boron metasomatism, i.e. tourmalinization, of the granites takes the form of:

- a) quartz-tourmaline veins or tourmaline stringers (Plate 3-1B) bordered by leucocratic alteration selvages,
- b) quartz-tourmaline clots or patches (Plate 3-1A) surrounded by leucocratic haloes, and
- c) massive or anhedral tourmaline, that has replaced feldspar (Plate 3-2E) or mica.

Quartz-tourmaline veins, bordered by leucocratic alteration selvages, are well developed in the Kabanga granites at the southern end of the Bushubi batholith. The selvages consist mainly of quartz and microcline and rarely disseminated tourmaline, and appear to have formed by alteration of biotite and muscovite in the wall-rocks bordering fractures along which B-rich fluids migrated. Field and petrographic evidence from the alteration selvages suggest the following sequence of events during interaction of the B-rich fluids with granite wall-rock:

1. Complete alteration of biotite in wall-rock during early stages of alteration,
2. initial breakdown of muscovite during intermediate stages of alteration, and
3. complete alteration of muscovite in wall-rock during advanced stages of alteration.

The alteration was accompanied by the formation of alkali feldspar, especially microcline, and quartz in the alteration selvages, and quartz-tourmaline in the veins.

Chemical changes in the alteration selvages were evaluated using the computational and graphical procedure, the "isocon method", devised by Grant (1986). This method involves the comparison of chemical changes in the altered rocks relative to their unaltered equivalents, by plotting element concentrations (g/g) in the altered rock against those in the original (e.g., Figure 4-1), and determining elements which best define a line (the isocon) through the origin. The slope of the isocon defines the mass change in the alteration, and the deviation of a data point from the isocon defines the concentration change for the corresponding component (Grant, 1986). Data plotting on the isocon reflect immobile elements, and those away from the isocon are considered mobile during alteration. The isocon is defined by the equation: $C^A = (M^O/M^A)C^O$, where C^A and C^O are the concentrations (g/g) of a given component in the altered and unaltered rocks, respectively, and M^A and M^O are the weights of the altered and original rocks. If $M^O = 100$ g, then C is in weight per cent. The isocon is essentially a graphical simultaneous solution to Gresen's (1967) equation for zero concentration change of chemical components.

Gains and losses of chemical components in an alteration selvage relative to least altered granite can be deduced from the isocon plot shown in Figure 4-1. A best-fit isocon through the chemical data in Figure 4-1 is defined by K_2O , Na_2O , Y and Ba. Because the isocon has the slope of about 1, i.e. constant mass isocon ($M^O/M^A = 1$), this indicates that there was no significant change in the mass of the altered rock. Taking the constant mass alteration model as representative of the alteration, important chemical changes, shown in Table 4-1, were loss of Fe, Ti, Mn, Al, Li, Rb, Sr and Zn from, and gain of Si, Ca, P, Nb, and Zr by the granite. Some of the elements lost from the altered granite were possibly involved in tourmaline formation in hydrothermal veins. Large losses of Fe, F, Li and Zn can be attributed to the alteration of biotite from the granite. The K derived from biotite breakdown was possibly incorporated locally in feldspar to form secondary microcline that occurs in the alteration selvage. The immobility of K and Na during alteration suggests that the hydrothermal fluids migrating through fractures were already in equilibrium with these elements in the wall-rocks.

Quartz-tourmaline clots occur mainly in the apical parts of some granite cupolas. Rounded, elliptical or irregular in shape (Plate 3-1A), the clots range in size from 10 mm to 30 mm. The clots may be surrounded by leucocratic haloes of quartz and feldspar, similar to those described earlier for alteration vein selvages. Similar tourmaline clots, described as knots, patches, nodules or orbicules, have been documented in other tourmaline granites (Hutchison and Leow, 1963; Nemec, 1975; Taylor, 1979; Sinclair and Richardson, 1986). Their origin is, however, not well understood. Some authors (e.g., Nemec, 1975) consider the clots metasomatic

ALTERATION IN KABANGA GRANITES

Fig. 4-1. Isocon plot of chemical analyses of least altered and strongly altered granite samples from a quartz-tourmaline vein seldedge in Kabanga granite.

TABLE 4-1. Major and trace element changes due to alteration of granite in quartz-tourmaline vein selvage, based on constant mass isocon model (Fig. 4-1).

Component	Change in concentration ($\Delta C_i/C_i^0$)
Li	-0.96
Zn	-0.89
F	-0.77
Fe ₂ O ₃ (T)	-0.76
MnO	-0.60
TiO ₂	-0.54
Rb	-0.20
Al ₂ O ₃	-0.14
Sr	-0.07
B	-0.04
Ba	0.00
Y	0.00
Na ₂ O	0.00
K ₂ O	+0.04
SiO ₂	+0.04
CaO	+0.07
P ₂ O ₅	+0.14
Zr	+0.16
Nb	+0.83

features produced by replacement of granite by B-rich fluids. Others (e.g., Taylor, 1979) consider the clots to be magmatic features produced by crystallization of an immiscible B-rich liquid from a granitic magma. Petrographic features of the quartz-tourmaline clots in the Karagwe-Ankolean granites can not be completely explained by any of these hypotheses. The clots exhibit textures, such as rounded quartz-tourmaline intergrowths, leucocratic haloes free of biotite, straight to irregular grain boundaries, sharp contacts with host rock, and restricted distribution, which can be either late-magmatic or post-magmatic. The localization of the clots in the apical parts of granite cupolas is consistent with zones of volatile enrichment and accumulation. The clots possibly represent B-rich siliceous fluids trapped in a semi-consolidated, granite crystal-mush. Owing to their low solidification temperatures, B-rich fluids could persist to low temperatures where they are out of equilibrium with the surrounding crystal-mush and react to form tourmaline clots, surrounded by alteration haloes. Breakdown of biotite in the alteration haloes may have provided an additional source for Fe, Mg, Ti and other elements needed for tourmaline growth.

Tourmalinization of intergranular mica and feldspar (Plate 3-2E) appears to be a post-magmatic feature related to the permeation of B-rich fluids through already consolidated granites.

Exogranitic B metasomatism is reflected in zones of intense tourmaline alteration in metasedimentary rocks adjacent to the chemically specialized granites. In some cases the alteration was so pervasive that the metasedimentary rocks were converted to massive tourmaline rocks or

"tourmalinites" (Plate 3-2F). These contain interstitial quartz, and bedding is still preserved. The tourmalinites (<1 cm to tens of centimetres thick), occur as conformable units within tourmaline-bearing phyllites, schists, quartzitic phyllites and untourmalinized quartzites. Boron-rich fluids responsible for tourmalinization probably migrated along bedding and foliation planes in the metasedimentary rocks. Tourmalinization seems to be concentrated in the ferruginous phyllites and schists. Similarity in the compositions of tourmaline from the metasedimentary rocks and granites (see Chapter 6) suggests that the B-rich fluids were probably derived from the granitic magmas.

4.2.0 Albitization

Albitization is associated with some of the Maleba granites, particularly those near the Maleba tin deposit, where two-micron granite is converted into monzogranite (adamellite) containing phengitic muscovite and minor biotite. In strongly albitized zones, the original granitic texture has been obliterated, and replaced by a fine-grained granular mosaic of albite, quartz, and relict K-feldspar. Aplite dykes that cut the monzogranite have high Na_2O (8.9 %) and low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (< 0.1). These albitites could have been formed either by sodic metasomatism of granitic dykes or crystallization from a residual sodic silicate melt. Experimental studies of H_2O -saturated haplogranitic systems show that addition of F and/or B displaces the minimum melt composition towards the albite corner of the Ab-Qz-Or plane (Manning and Pichavant, 1985), implying that the residual melts derived from F and/or B-rich granitic magmas will tend to be relatively sodic. Thus the sodic aplite dykes in the Maleba granites could be of magmatic origin.

The isocon plot (Grant, 1986) of albitized granite versus unaltered granite from the Maleba pluton is given in Figure 4-2. Three isocon models involving constant mass, Al_2O_3 and TiO_2 , and Zr and Zn, respectively, are shown in the diagram (Fig. 4-2). The constant mass isocon coincides with the constant SiO_2 and TiO_2 isocon. All three isocons consistently indicate the loss of K, Ca, Ba, Sr and B, and gain of Na, P, Mn, F, Li, Sn, Rb and Y in the altered granite. Barium and Sr show depletion trends similar to those of K and Ca, consistent with the tendency for Ba and Sr to substitute for K and Ca, respectively, in minerals (Wedepohl, 1978). Rubidium and K show opposite trends in the altered granite, although Rb tends to substitute for K in K-bearing minerals. Table 4-2 shows the changes in the concentrations of oxides relative to original concentrations. Increase in the amounts of Li, Sn, F, Nb, Mn, and P in the altered granite suggests that the altering fluids may have been enriched in ore-forming elements. The depletion of K and Ca along with Ba and Sr, and enrichment of Na in the altered granite can be attributed to conversion of K-feldspar and calcic plagioclase to albite or sodic oligoclase. The loss of B from the altered granite suggests that tourmaline, the main sink for B, was probably unstable during albitization, and this would be consistent with experimental data (e.g., Smith, 1949) which indicate that tourmaline is unstable in the presence of strongly alkaline hydrothermal fluids.

Assuming that Al is immobile, the albitization of potassic and plagioclase feldspars in the granites can be represented by the following reactions:

ALTERATION IN MALEBA GRANITES

ALBITIZED GRANITE vs. UNALTERED GRANITE

Fig. 4-2. Isocon plot of chemical analyses of unaltered (Mb13) and albitized (Ma18) granites from Maleba pluton.

TABLE 4-2. Major and trace element changes in albitized granite, based on three isoccn models (Fig. 4-2).

Component	Change in concentration ($\Delta C_i/C_i^0$)		
	Model: <u>Constant Mass</u>	<u>Constant Al, Ti</u>	<u>Constant Zr, Zn</u>
Sr	-0.98	-0.98	-0.99
B	-0.65	-0.66	-0.70
Ba	-0.43	-0.45	-0.50
CaO	-0.30	-0.32	-0.38
K ₂ O	-0.24	-0.26	-0.34
SiO ₂	0.00	-0.04	-0.13
TiO ₂	0.00	0.00	-0.12
Al ₂ O ₃	+0.04	0.00	-0.09
Zr	+0.13	+0.10	0.00
Zn	+0.13	+0.10	0.00
Y	+0.21	+0.17	+0.06
Na ₂ O	+0.22	+0.19	+0.07
Fe ₂ O ₃ (T)	+0.29	+0.26	+0.13
Rb	+0.55	+0.50	+0.36
P ₂ O ₅	+0.88	+0.83	+0.65
Sn	+1.00	+0.94	+0.75
MnO	+1.33	+1.27	+1.05
F	+1.35	+1.28	+1.06
Nb	+2.00	+1.91	+1.63
Li	+2.83	+2.72	+2.36

* s: denotes a solid phase; l: denotes components carried in solution by hydrothermal fluids.

4.3.0 Muscovitization and sericitization

Formation of secondary muscovite appears to be late-magmatic or post-magmatic. Feldspar was partially altered to muscovite or sericite while biotite was replaced by brownish white-mica of phengitic composition. There are distinct textural differences between magmatic muscovite and muscovite formed by deuteric alteration, described in section 3.3.0. Chemical differences for the two muscovites are discussed in Chapter 6. Sericitization in the syn-orogenic and post-orogenic granites is restricted to grain boundaries and cleavage traces in feldspar.

Alteration of K-feldspar and biotite to form muscovite can be attributed to the following or similar reactions:

*: F can substitute for OH in the hydroxyl site.

4.4.0 Chloritization

Minor chlorite alteration is documented in the two-mica granites from Rulenge, Mumakera and Maleba areas. Biotite was partly or wholly altered to chlorite and opaque Fe-Ti oxide minerals. During alteration, Fe^{3+} and Ti^{4+}

from the biotite probably helped form oxide minerals, while Fe^{2+} and Mg^{2+} were taken up by chlorite. Potassium released from biotite alteration was used in the formation of white mica. Unlike other reactions (see 4.1 to 4.4) that can be modelled in terms of ideal mineral composition end-members, chlorite alteration is difficult to model because no ideal structural end-members of chlorite compositions have been reported (Deer et al., 1966). Natural chlorites have compositions represented by the general formula $(\text{Mg,Al,Fe})_{12}[(\text{Si,Al})_8\text{O}_{20}](\text{OH})_{16}$. Table 4-3 shows the results of microprobe analysis of chlorite, biotite and muscovite from an altered Maleba granite. Chlorite is Fe-rich (mean $\text{Fe}/(\text{Fe} + \text{Mg}) = 0.93$) and muscovite is phengitic. Chlorite in the granite represents an early stage of alteration of biotite to phengitic white mica or muscovite. If it is assumed that Al was immobile, the microprobe data suggest that the alteration of biotite to chlorite involved the loss of Si, Ti, Mg, K and Na, and the gain of Fe, Mn and Ca in the biotite. The mass transfer during the alteration may be represented by the following equation, based on the average compositions of biotite and chlorite (Table 4-3):

4.5.0 Kaolinization

Hydrothermal alteration of feldspar to kaolin, common in the post-orogenic granites of the Maleba and Nyamakombe plutons, is generally rare or lacking in the Mumakera pluton. In the Maleba pluton, pervasive alteration of granite formed a kaolin deposit in the central part of the pluton (Map 4, Appendix 9). Kaolinization is the last alteration event that affected the granites.

TABLE 4-3. Microprobe analyses of biotite, muscovite, and chlorite from an altered Maleba granite

	BIOTITE			MUSCOVITE		
	BIO1	BIO2	AVER.	MUSC1	MUSC2	AVER.
SiO ₂ %	36.62	36.14	36.38	45.33	44.86	45.10
Al ₂ O ₃	20.37	20.06	20.22	31.16	32.31	31.74
TiO ₂	2.53	2.56	2.55	0.47	0.46	0.47
FeO	23.47	23.44	23.46	4.52	4.49	4.51
MgO	1.64	1.50	1.57	0.65	0.59	0.62
MnO	0.63	0.57	0.60	0.18	0.07	0.13
K ₂ O	8.84	8.76	8.80	10.65	10.78	10.72
Na ₂ O	0.50	0.69	0.60	0.24	0.25	0.25
CaO	0.00	0.00	0.00	0.00	0.00	0.00
Total	94.60	93.72	94.16	93.20	93.81	93.51

Formula (basis 22 oxygens)

Si	5.682	5.671	5.677	6.297	6.193	6.245
Al	3.725	3.710	3.718	5.102	5.258	5.180
Ti	0.296	0.303	0.300	0.049	0.047	0.048
Fe	3.045	3.076	3.061	0.525	0.518	0.522
Mg	0.380	0.352	0.366	0.135	0.122	0.129
Mn	0.083	0.076	0.080	0.021	0.008	0.015
Ca	0.000	0.000	0.000	0.000	0.000	0.000
K	1.750	1.754	1.752	1.888	1.898	1.893
Na	0.150	0.211	0.181	0.064	0.067	0.066

CHLORITE

	CH1	CH2	CH3	CH4	AVERAGE
SiO ₂ %	23.46	23.75	23.62	23.85	23.67
Al ₂ O ₃	22.44	23.04	22.94	23.14	22.89
TiO ₂	0.13	0.07	0.05	0.10	0.09
FeO	38.42	38.51	38.27	39.04	38.56
MgO	1.71	1.75	1.67	1.73	1.72
MnO	1.33	1.27	1.31	1.37	1.32
CaO	0.07	0.08	0.01	0.03	0.05
Total	87.56	88.47	87.87	89.26	88.30

Formula (basis 28 oxygens)

Si	5.355	5.350	5.356	5.335	5.349
Al	6.037	6.116	6.130	6.100	6.096
Ti	0.022	0.012	0.009	0.018	0.015
Fe	7.335	7.255	7.257	7.303	7.287
Mg	0.582	0.588	0.563	0.577	0.578
Mn	0.257	0.242	0.252	0.259	0.252
Ca	0.016	0.019	0.001	0.007	0.011

Because kaolinization involves alteration of K-feldspar in the granites, the predominant chemical reaction may be represented by:

parallel to the c-axis, indicating that the inclusions are probably primary. On the basis of field relationships, tourmalinization preceded formation of cassiterite-bearing veins. The paragenetic sequence of mineral deposition in hydrothermal veins is summarized in Table 4-4.

In addition to cassiterite mineralization in the exocontact zone of geochemically specialized granites, cassiterite-bearing pegmatites occur in the granites. These pegmatites are too small to be economically significant. In contrast to these pegmatites, the pegmatites found in other parts of the Kibaran-Karagwe-Ankolean belt in Rwanda, SW Uganda and Zaire are associated with economic deposits of cassiterite, wolframite, columbite-tantalite and beryl (Sainsbury, 1969; Varlamoff, 1972; Pohl, 1987).

TABLE 4-4. Hydrothermal mineralization and mineral paragenetic sequence in the Kyerwa and Maleba tin deposits.

<u>Mineral</u>	<u>Mineralization</u>		
	Early stage	Intermediate stage	Final stage
Tourmaline	-----		
Cassiterite	-----		
Muscovite	-----		
Quartz		-----	
Fluorite (?)		-----	
Pyrite			-----
Arsenopyrite			-----
Scorodite (FeAsSO ₄)			-----

CHAPTER 5

CHEMISTRY OF KARAGWE-ANKOLEAN GRANITES AND RELATED ROCKS

5.0.0 Introduction

Chemical studies of the Karagwe-Ankolean granites were undertaken in order to:

- a) characterise the granites in terms of their major and trace element compositions,
- b) classify the granites using known chemical classification schemes,
- c) examine the inter-element variations within the granites and determine the parameters governing the variations,
- d) distinguish the stanniferous granites from the barren granites,
- e) compare and contrast the stanniferous granites with those from other tin provinces, and
- f) place constraints on the petrogenesis of the stanniferous granites.

5.1.0 Major element chemistry

The chemical analyses of Karagwe-Ankolean granites are summarized in Appendix 4 and plotted in Figures 5-1 to 5-31. All Fe is reported as Fe_2O_3 . Average major and trace element compositions of granites from different plutons are given in Table 5-1. It is evident from the analyses that there is little variation in the major element compositions. The granites are essentially characterised by high SiO_2 contents (71-76 %), by low contents of Fe_2O_3 , MgO, TiO_2 and CaO, and by $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios > 1 . High and restricted SiO_2 compositions and very low contents of Ca, Fe, Mg, and Ti indicate that the granites are highly differentiated. Low CaO contents place these granites into the low-calcium granites (Turckian and Wedepohl, 1961).

Chemical comparison of the granites with average calc-alkaline granite (Nockolds, 1954) indicates an enrichment in the Karagwe-Ankolean granites of SiO_2 , and depletion of Fe_2O_3 , MgO , and TiO_2 . The high $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ molar ratios (>1.1) and corundum in the norms (Appendix 4) indicate that the granites are peraluminous.

The post-orogenic stanniferous granites (the Maleba, Mumakera, Nyamakombe and Karagwe Tinfield granites) are on average lower in Fe_2O_3 , MgO , CaO , TiO_2 and K_2O , and higher in Na_2O (Table 5-1) than the syn-orogenic tin-barren granites of the Bushubi batholith; the former also show lower K/Rb and $\text{K}_2\text{O/Na}_2\text{O}$ ratios than the latter. These data suggest that the stanniferous granites are more evolved and more sodic than the barren granites. The tendency of the granites to become more sodic with decrease in age and increasing degree of chemical evolution is particularly indicated by the decrease of $\text{K}_2\text{O/Na}_2\text{O}$ ratio from an average of 2 in the syn-orogenic Bukiriro granites to an average of 1.25 in the post-orogenic Maleba granites. The sodic aplite dykes that cut the Maleba granites have the lowest $\text{K}_2\text{O/Na}_2\text{O}$ ratio (0.1).

Comparison of the stanniferous Maleba granites and those from the Mumakera and Nyamakombe plutons indicates that the former are on average lower in TiO_2 , $\text{K}_2\text{O/Na}_2\text{O}$, K/Rb , and higher in P_2O_5 than the latter. Thus the Maleba granites appear to be more chemically evolved than the granites of the Mumakera and Nyamakombe plutons. This is also supported by trace element data. The Maleba granites are very similar in composition to the Karagwe Tinfield granites.

In the Bushubi batholith, the Muyenzi gneissic biotite granite (Table 5-1, suite no. 8) appear to be the least differentiated. This gneissic granite contains lowest SiO_2 and highest CaO , MgO , Fe_2O_3 and TiO_2 contents analysed from the Bushubi batholith, and the Karagwe-Ankolean granites as whole (Table 5-1). It is possible that low H_2O and high viscosities in the original magma did not favour high degrees of chemical differentiation.

Granitoid rocks in the Lachlan Fold Belt of Australia show that restite-rich, S-type granitoids have a more mafic composition than restite-free or restite-poor granitoids (White and Chappell, 1983). Although no extensive xenolithic material has been found in the Muyenzi gneissic biotite granite, centimetre-size, texturally distinct lenticular inclusions are locally observed in the granite, that may represent relics of restite after resorption and assimilation by the magma during ascent and emplacement. This granite probably provides the least differentiated material, and its composition may be closer to source rock composition. The relatively high Al_2O_3 content of the granite suggests that the source rocks were probably very aluminous.

A coarse-grained, porphyritic, muscovite-biotite granite cut by pegmatites and quartz veins occurs adjacent to the Muyenzi gneissic biotite granite near the Muyenzi Ford. The average chemical composition of this granite is shown in Table 5-1 (suite no. 9). The granite is higher in SiO_2 , K_2O , and lower in Al_2O_3 , Fe_2O_3 , MgO , MnO , TiO_2 , CaO and Na_2O than the gneissic biotite granite (Table 5-1, suite no. 8). Although the geologic contact between the two granites is not exposed the chemical data suggest that the gneissic biotite granite is possibly a precursor for the

porphyritic granite. The Rulenge granite (samples RU-1 and RU-2, Appendix 4) at the northern end of the Bushubi batholith (Fig. 1-3), is texturally similar to the Muyenzi porphyritic two-mica granite, although it appears to be more geochemically evolved.

The Kabanga granites (Map 2, Appendix 9) at the southern end of the Bushubi batholith are chemically more variable (Appendix 4) than the Bukiriro granites in the central part of the batholith. The variation possibly reflects a more complex history of evolution of the granites as revealed by their textural and field relationships. The least evolved granite (Ka-40, Appendix 4) is lower in SiO_2 , and higher in Al_2O_3 , Fe_2O_3 , MgO and CaO than the more evolved granites.

5.1.1 Whole-rock $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio analyses

The average $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio of a few representative samples of the syn-orogenic two-mica granites from Bukiriro (Table 5-2) is 0.52. In the post-orogenic, two-mica granites from the Mumakera and Maleba plutons the average ratio is 0.53 while in the muscovite and tourmaline leucogranites the ratio is 3.71. These data suggest that the oxidizing conditions were higher for the muscovite and tourmaline leucogranites than for the two-mica granites. Assuming that the granites in the individual plutons are co-magmatic, the evolution from two-mica granites to muscovite and tourmaline leucogranites seems to have been accompanied by an increase in the oxygen fugacity of the original magmas. Fluid saturation and formation of a separate aqueous phase from the leucogranitic magmas, followed by the dissociation of H_2O into the vapour phase and hydrogen loss by diffusion (Candela, 1986) could account for high oxygen fugacities in the magmas.

TABLE 5-2. $\text{Fe}^{3+}/\text{Fe}^{2+}$ analyses of some Karagwe-Ankolean granites.

Sample	Fe_2O_3 % (T)	FeO %	Fe^{3+} %	Fe^{2+} %	$\text{Fe}^{3+}/\text{Fe}^{2+}$
BU-33	1.08	0.6	0.29	0.47	0.62
BU-48	1.94	1.3	0.35	1.01	0.35
BU-49	1.25	0.7	0.33	0.55	0.60
MU-2	1.33	0.8	0.31	0.62	0.50
MU-24	0.70	0.1	0.41	0.08	5.13
MW-5	1.03	0.6	0.25	0.47	0.53
MA-15	0.72	0.2	0.35	0.16	2.19
MA-19	1.05	0.2	0.58	0.16	3.63

Sample grouping

BU-33, BU-48, BU-49:two-mica granites from Bukiriro

MU-2:two-mica granite of the Mumakera pluton

MU-24:tourmaline-muscovite granite of the Mumakera pluton

MW-5:two-mica granite of the Maleba pluton

MA-15:muscovite granite of the Maleba pluton

MA-19:tourmaline leucadamellite of the Maleba pluton

5.1.2 Normative compositions

Partial CIPW norms of the Karagwe-Ankolean granites are presented in Appendix 4. The peraluminous composition of the granites is reflected in corundum in the norms. Most granites contain between 2.19 % and 3.88 % normative corundum. Nine partly altered samples contain 4 to 5.25 % normative corundum. Clemens and Wall (1981) reported normative corundum contents of 0.3 to 2.8 % in the "normal" peraluminous S-type granites, 2.5 to 4.1 % in the strongly peraluminous or two-mica granites, and 3.85 to 6 % in the restite-rich granites from southeastern Australia. Comparison of their data with those from the unaltered Karagwe-Ankolean granites indicates that the latter span the range of normal to strongly peraluminous granites, the majority of the data falling in the strongly peraluminous granite range.

All Karagwe-Ankolean granites analysed in this study (Appendix 4) have very high differentiation indices (i.e. D.I. = sum of normative quartz, albite and orthoclase in quartz-saturated rocks; Thornton and Tuttle, 1960) indicating their highly evolved nature. The differentiation index averages 92.9 in the Maleba granites, 93.2 in the Mumakera granites, 93.0 in the Nyamakombe pluton granites, 91.3 in the Kabanga granites, 91.1 in the Bukiriro granites, and 85.2 in the Muyenzi granites. The syn-orogenic gneissic biotite granite from Muyenzi in the Bushubi batholith exhibits the lowest DI, suggesting it is probably the least evolved, a feature consistent with the relatively high Fe, Mg, Ca and Ti contents in the granite.

Figure 5-1 shows the proportions of normative quartz (Qz), albite (Ab) and orthoclase (Or) in Karagwe-Ankolean granites, projected on the Ab-Qz-Or plane of the H₂O-saturated NaAlSi₃O₈-SiO₂-KAlSi₃O₈ haplogranitic system of

KARAGWE-ANKOLEAN GRANITES

Normative Ab-Qz-Or Projection

Δ Ternary minima

Fig. 5-1. Triangular plot of Ab-Qz-Or normative compositions of Karagwe-Ankolean granites. Projections of haplogranitic minimum melt compositions and feldspar-quartz cotectics determined by Tuttle and Bowen (1958) are also shown.

Tuttle and Bowen (1958). The projected positions of isobaric minima and cotectic lines at various $p\text{H}_2\text{O}$ determined by Tuttle and Bowen (1958) are also indicated. It is evident from the diagram in Figure 5-1 that the data from Karagwe-Ankolean granites form a cluster near the centre of the diagram. The centre for the cluster of the granite data lies to the right of the ternary minimum along the 0.5 kb cotect. The clustering of the data within or close to the "granite thermal valley" or "petrogeny's residua system" (Tuttle and Bowen, 1958) suggests that the granites are highly evolved.

The average normative anorthite contents are 2.8 % in the Bukiriro granites, 2.3 % in the Kabanga granites, 1.1 % in the Nyamakombe granites, 1.6 % in the Mumakera granites and 1.3 % in the Maleba granites. These anorthite contents may be high enough to alter the phase equilibria observed in anorthite-free Ab-Qz-Or granitic system. Experimental data on phase equilibria in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-CaAl}_2\text{Si}_2\text{O}_8\text{-SiO}_2$ at 1 kb H_2O pressure have been obtained by James and Hamilton (1969) for compositions containing 3, 5, 7.5 and 10 weight percent normative anorthite. Isobaric phase diagrams for compositions containing 0, 3 and 5 % anorthite (An_0) are shown in Figure 5-2. The major difference between the phase diagrams for anorthite-free (An_0) and anorthite-bearing compositions is the appearance of a two-feldspar cotectic at low H_2O pressures (1 kb) for the anorthite-bearing compositions. In addition, the minimum melt composition for anorthite-bearing compositions is displaced toward Qz-Or join relative to anorthite-free compositions in the Ab-Or-Qz projection (Fig. 5-2).

The normative Ab-Or-Qz compositions of the analysed granites (mean $\text{An} =$

Fig. 5-2. Ab-Qz-Or projection of minimum melt compositions in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 with or without anorthite (An) added at 1 kb H_2O vapour pressure. Data are from Tuttle and Bowen (1958) and James and Hamilton (1969).

1-3 %) are plotted on (Ab-Or-Qz)₉₇An₃ phase diagram in Figure 5-3. The centre for the cluster of the granite data on the diagram lies close to the projection of the minimum melt composition along the 1 kb cotectic. Experimental data on phase equilibria in the Ab-Or-Qz-An system at H₂O vapour pressure of greater than 1 kb are still lacking. If the addition of An to the system Ab-Or-Qz-H₂O affects the phase relationships at 2 or 3 kb in the similar manner as at 1 kb, then the minimum melt compositions at 2 or 3 kb for An-bearing compositions should also be expected to be displaced toward the Qz-Or join relative to An-free compositions in the Ab-Or-Qz projection. By analogy with Figure 5-1, the projection of the 2 kb cotectic in Figure 5-3 would possibly lie close but below the 1 kb cotectic, and would pass through the granite data.

Inasmuch as the phase equilibria depicted in the Ab-Or-Qz projections (Figs. 5-1, 5-3, and Appendix 1) apply to H₂O-saturated granitic melts, the interpretation of the granite data can only be valid for granites in which there is evidence for H₂O-saturation. For the post-orogenic stanniferous granites there is sufficient evidence suggesting that H₂O saturation was reached in the original magmas (see Chapter 3 and 4). In the syn-orogenic tin-barren granites there is not sufficient evidence for H₂O saturation in the magmas. However, the clustering together of the normative compositions of the syn-orogenic and the post-orogenic granites on the Ab-Or-Qz diagram suggest that the two types of granites formed under similar conditions. If H₂O saturation was reached in the final stages of crystallization of the syn-orogenic granites, then it is possible that not much H₂O-fluid was exsolved to allow the formation of pegmatites/aplites and zones of pervasive

KARAGWE-ANKOLEAN GRANITES

Normative Ab-Qz-Or Projection

Fig. 5-3. Normative mineralogical data for Karagwe-Ankolean granites plotted on the (Ab-Or-Qz)₉₇An₃ plane in the system Ab-Or-An-Qz-H₂O (James and Hamilton, 1969).

hydrothermal alteration seen in the post-orogenic granites.

Assuming that H₂O saturation was reached in the granitic magmas, the data in Figures 5-1 and 5-3 and Appendix 1 suggest that final crystallization occurred under pressure conditions of 1 to 2 kb, and that most of the granites crystallized at 1 kb. Applications of phase equilibria in the system (Ab-Or-Qz)₉₇An₃ at 1 kb H₂O pressure (James and Hamilton, 1969) to the granite data in Figures 5-1 and 5-3 and Appendix 1, indicates that K-feldspar and quartz were among the first minerals to crystallize from the original magmas. Sodic plagioclase crystallized later after K-feldspar and quartz had begun to crystallize. The occurrence of K-feldspar phenocrysts and quartz with seriate texture in the granites is consistent with early crystallization of these minerals.

5.1.3 Chemical classification of the granitic rocks

Data from the granitic rocks using various chemical schemes and normative mineralogy are shown in Figures 5-4 to 5-8. Data from 111 samples plotted on Na₂O-CaO-K₂O (Fig. 5-4) and Ab-An-Or (Fig. 5-5) classification diagrams, indicate that 97 samples form a tight elongated cluster in the granite field; the remaining 4 samples plot either in the adamellite (monzogranite) field or along the adamellite and granite boundary. Data that plot in the adamellite field or on the boundary separating the adamellite and granite fields are from the least differentiated Muyenzi biotite granite. Data close to the Na₂O or albite (Ab)-rich end of the cluster in the granite field are mainly from the Maleba granites. Figure 5-7 shows data on a Na₂O vs. K₂O plot for the granitic rocks analysed in this study together with data of five aplite samples from the Maleba pluton. It can be seen from the plot

Fig. 5-4. Plot of data from Karagwe-Ankolean granites on a $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}$ classification diagram. Field boundaries for various granitoids are from Bell and Dodson (1981).

Fig. 5-5. Classification of the Karagwe-Ankolean granites using the Ab-Or-An diagram of O'Connor (1965).

GRANITES OF MALEBA PLUTON

Ab-An-Or Diagram

Tml: ton taline; gnt: garnet; lgr: leucogranite; Bmgr: biotite-muscovite granite; Mgr: muscovite granite.

Fig. 5-6. Classification of granites and aplites from Maleba pluton using the Ab-Or-An diagram of O'Connor (1965).

Fig. 5-7. Classification of the Karagwe-Ankolean granites using the K₂O-Na₂O diagram. Field boundaries for various granitoids taken from Bell and Dodson (1981).

that most granitic rocks form a tight cluster in the granite field. Data from 15 samples plot in the adamellite field and 3 fall in the granodiorite field. Of the 15 points that fall in the adamellite field, 12 are from the Maleba pluton, the remainder are from the Karagwe Tinfield. The three granitic points that plot in the granodiorite field are from a tourmaline-rich leucoadamellite/monzogranite, found close to the Maleba tin mine. Data from three aplite dykes from the Maleba pluton plot in the granodiorite field, while data from two other samples plot in the tonalite field. Points in the tonalite field are from a tourmaline-free sodic aplite dyke containing spessartine-rich garnet and K-feldspar pegmatite pods. In contrast, two of the three aplite points that plot in the granodiorite field are from tourmaline-bearing aplite dykes containing almandine-rich garnet. The trend exhibited by the Maleba granites and related aplite dykes (Fig. 5-6) partly suggests that the parent magmas became enriched in Na with increase in differentiation. The presence of high B concentrations in addition to F in the original magmas could partly account for the observed sodic trend considering the experimental data of Manning and Pichavant (1985, 1988). The texture and highly sodic composition of the aplite dykes associated with the granites can be explained by pressure quenching and rapid crystallization from Na-rich residual magma. Loss of K-rich aqueous phase from the aplitic magma could also account for the composition of the aplites.

On the Rb vs. (Nb + Y) diagram (Pearce et al., 1984), the data from the Karagwe-Ankolean granites straddle the boundary between the syn-collision and within-plate granite fields (Fig. 5-8). The data from the post-orogenic granites plot mainly in the syn-collision granite field, while data from the

Fig. 5-8. Rb vs. (Y + Nb) plot (Pearce et al., 1984) of data from Karagwe-Ankolean granites. (Black circles: syn-orogenic Bukiriro granites; squares, triangles, open circles: post-orogenic granites from Mumakera, Karagwe Tinfield and Maleba, respectively).

syn-orogenic granites plot mainly in the within-plate field.

Table 5-3 compares the Karagwe-Ankolean granites with I- and S-type granites of Chappell and White (1974). The Karagwe-Ankolean granites exhibit mainly S-type granite characteristics which, according to Chappell and White, formed from magmas derived by partial melting of a sedimentary or metasedimentary protolith. Similarity with S-type granites suggests that the Karagwe-Ankolean granitic magmas formed by partial melting of crustal rocks.

5.2.0 Trace element chemistry

Rubidium, Ba, Sr, Zr, Nb, Y, Zn, B, F, Sn and W contents in the Karagwe-Ankolean granites are given in Appendix 4. A comparison of average trace element compositions in granites is given in Table 5-1. Pronounced trace element content variations occur among granites from different plutons, and subtle variations are observed in each pluton. Both unaltered barren and stanniferous granites are generally enriched in Rb, Li, B and Sn, and depleted in Ba, Sr, Zr and Y relative to the average low-calcium granite (Turekian and Wedepohl, 1961). The distribution of F in the granites is very irregular; F contents are commonly above the average of 850 ppm given by Turekian and Wedepohl for low-calcium granites, although some of the F values can be lower than the granite average.

Fluorine concentrations in the stanniferous granites vary from 310 to 2490 ppm in the Maleba pluton, from 550 to 1550 ppm in the Mumakera pluton, and from 1400 to 4000 ppm in the Nyamakombe pluton. In the Nyamakombe pluton higher F contents are found in the muscovite granite than in the two-mica granite. In contrast, unaltered two-mica granites in the Mumakera and Maleba

TABLE 5-3. Chemical comparison of I- and S-type granites (Chappell and White, 1974) with Karagwe-Ankolean granites from Bushubi area

I-Types -----	S-Types -----	Bushubi Granites -----
Relatively high Na, Na ₂ O normally > 3.2 % in felsic varieties, decreasing to > 2.2 % in more mafic varieties	Relatively low Na, Na ₂ O normally < 3.2 % in rocks with 5 % K ₂ O, decreasing to < 2.2 % in rocks with approx. 2 % K ₂ O	Contain 2.15 % to 3.52 % Na ₂ O in rocks with 5 % K ₂ O
Molar Al ₂ O ₃ /(Na ₂ O+K ₂ O+CaO) < 1.1	Molar Al ₂ O ₃ /(Na ₂ O+K ₂ O+CaO) > 1.1	Molar Al ₂ O ₃ /(Na ₂ O+K ₂ O+CaO) > 1.1
Normative diopside or < 1 % normative corundum	> 1 % normative corundum	2.20 % to 4.83 % normative corundum
Broad spectrum of compositions from felsic to mafic	Relatively restricted composition to high SiO ₂ types	Composition restricted to high SiO ₂ (71-76 %) types
Regular inter-element variations within plutons; linear or near-linear variation diagrams	Variation diagrams more irregular	Linear to irregular variation diagrams

plutons are generally more enriched in F than the tourmaline-muscovite leucogranites. Low F concentrations in the leucogranites can be attributed either to lack of biotite (the main carrier of F in the two-mica granites) or to fractionation of F into an aqueous fluid phase in the final stages of crystallization of fluid-saturated residual leucogranitic magmas. In contrast to the leucogranites, the low F values (as low as 310 ppm) in the Maleba two-mica granites are due to the removal of F by hydrothermal solutions. Granites containing very low F concentrations clearly show evidence of complete or partial alteration of biotite to chlorite and/or white mica.

The distribution of B, like F, in the stanniferous granites is highly variable. This probably reflects the mobility of B both in magmatic and hydrothermal environments. Boron variations also reflect the heterogeneous distribution of tourmaline which is the main repository of B in these rocks. Boron concentrations in the granites vary from 30 to 2000 ppm, although most values are > 150 ppm. Very high B concentrations are generally associated with muscovite-tourmaline leucogranites. If the average B content in low-calcium granites is 10 ppm (Turekian and Wedepohl, 1961), B contents in the stanniferous granites are 3 to 200 times higher than the low-calcium granite average. This indicates that the parent magmas for the stanniferous granites were highly enriched in B, and that the magmas were probably derived from a B-rich source. Petrogenetic implications of high B concentrations in the Karagwe-Ankolean granites are discussed in Chapter 9.

Tin contents in the stanniferous granites of the Maleba, Mumakera and Nyamakombe plutons are commonly in the range of 10 to 20 ppm. Tin contents <

2

MicroD

10 ppm or > 20 ppm are found only locally. The tin contents do not seem to show any clear relationship to F or B contents. Granites with high Sn and F or B contents are common as well as those with high Sn but relatively low F or B contents. Tin does, however, show a positive correlation with Li (Table 5-4). The stanniferous granites that show strong Rb enrichment and strong depletion of Ba, Sr, and commonly Zr, relative to the normal or average low-calcium granite, are generally more enriched in Sn. These observations are consistent with other observations made in the literature from other tin granites (Taylor, 1979; Imeokparia, 1984; Olade 1980; Lehmann, 1982).

Tungsten analyses were obtained only for a few granite samples (see Appendix 4). The W contents in the samples are commonly < 5 ppm W, although samples with high W contents (up to 15 ppm) are locally encountered. No clear relationship was observed between Sn enrichment and W contents in the granites.

Although the trace element contents of the stanniferous granites and the barren granites overlap, extremely high values of incompatible trace elements and extremely low values of compatible trace elements are associated with the stanniferous granites. High Rb/Ba (> 1.55), Rb/Zr (> 10) and Li/Sr (> 2), and low K/Rb (< 110) and Sr/Rb (< 0.15) ratios are diagnostic of the stanniferous granites. These features together indicate that a much higher degree of geochemical specialization was attained in the stanniferous granites than the barren granites.

5.3.0 Inter-element correlations

The inter-relationships among the major and trace elements in the

barren and stanniferous granites were investigated using bivariate variation diagrams and ternary plots. Little variation was observed in the SiO_2 contents of the granites and therefore SiO_2 could not be used as a variation index. Zirconium, found to be more suitable as a measure of the variation, decreases systematically from less specialized, syn-orogenic, tin barren granites to the more specialized, post-orogenic, stanniferous granites. A correlation matrix for the major and trace element data can be seen in Table 5-4.

TiO_2 , Fe_2O_3 , MgO , CaO , Ba and Sr show a general decrease with decreasing Zr content (Figs. 5-9 to 5-18) from the older, tin barren, granites of Muyenzi and Bukiriro in the Bushubi batholith to the younger, stanniferous, granites of the Nyamakombe, Mumakera, and Maleba plutons. Silica increases from 71 % to 76 % (Fig. 5-14) while Al_2O_3 and Na_2O remain almost constant or show subtle increase with decrease in Zr content in the granites (Figs. 5-14, 5-16). With the exception of three samples from Muyenzi, K_2O remains nearly constant or decreases slightly with decreasing Zr from the older Bukiriro granites to the younger Maleba granites. Niobium, Mn, P, W and Y are much scattered and poorly correlated with Zr. On average Rb and Sn show an inverse relationship with Zr while Li, B and F show a very poor correlation with Zr, especially in the Maleba granites. The high and anomalous Li and B contents in the Maleba granites (Figs. 5-21, 5-24) could have been partly caused by deuteric or hydrothermal alteration.

The trends shown by Fe, Mg, Ti, and Ca oxides, and by the trace elements Ba and Sr when plotted against Zr could have been produced by one or more of the following processes: a) partial melting, b) fractional crystallization,

TABLE 5-4. CORRELATION MATRIX FOR MAJOR AND TRACE ELEMENT DATA FROM KARAGWE-ANKOLEAN GRANITES

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	H ₂ O	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Rb	Ba	Sr	Zr	Nb	Y	Zn	Sn	Li	F	B
SiO ₂	1.00																				
TiO ₂	-0.60	1.00																			
Al ₂ O ₃	-0.64	0.50	1.00																		
Fe ₂ O ₃	-0.77	0.62	0.21	1.00																	
MnO	-0.44	0.07	0.51	0.45	1.00																
MgO	-0.61	0.57	0.08	0.64	0.29	1.00															
CaO	-0.66	0.54	0.17	0.70	0.25	0.72	1.00														
Na ₂ O	0.00	-0.44	0.41	-0.14	0.36	-0.26	-0.10	1.00													
K ₂ O	-0.02	0.18	-0.26	-0.17	-0.51	-0.13	-0.30	-0.73	1.00												
P ₂ O ₅	0.06	-0.34	0.27	-0.08	0.46	-0.34	-0.26	0.61	-0.43	1.00											
Rb	0.16	-0.29	0.12	-0.14	0.14	-0.53	-0.54	0.28	0.04	0.40	1.00										
Ba	-0.59	0.64	0.02	0.57	0.01	0.67	0.70	-0.50	0.24	-0.49	-0.46	1.00									
Sr	-0.52	0.57	0.02	0.48	-0.05	0.63	0.72	-0.38	0.12	-0.45	-0.50	0.88	1.00								
Zr	-0.65	0.72	0.04	0.73	0.15	0.63	0.52	-0.45	0.25	-0.31	-0.24	0.69	0.58	1.00							
Nb	-0.26	0.11	0.40	0.13	0.33	0.06	-0.07	0.21	-0.12	0.24	0.39	-0.08	-0.19	0.03	1.00						
Y	0.01	0.17	-0.16	0.05	-0.19	-0.04	-0.36	-0.39	0.52	-0.23	0.18	0.02	-0.04	0.35	0.04	1.00					
Zn	-0.12	0.21	-0.02	0.36	0.13	0.01	-0.01	-0.14	0.02	0.06	0.23	-0.06	-0.16	0.23	-0.05	0.15	1.00				
Sn	0.20	-0.30	0.22	-0.26	0.26	-0.34	-0.49	0.36	-0.16	0.37	0.56	-0.39	-0.34	-0.29	0.17	0.12	0.02	1.00			
Li	0.04	-0.20	0.29	0.04	0.26	-0.34	-0.28	0.17	-0.14	0.22	0.65	-0.32	-0.31	-0.19	0.22	0.20	0.19	0.51	1.00		
F	-0.05	0.02	-0.04	0.12	-0.01	-0.08	-0.10	0.08	0.05	0.09	0.52	-0.15	-0.18	0.06	0.32	0.25	0.21	0.09	0.20	1.00	
B	0.27	-0.35	-0.06	-0.16	0.07	-0.28	-0.18	0.55	-0.44	0.36	0.02	-0.34	-0.34	-0.35	0.01	-0.26	-0.11	0.06	-0.07	-0.11	1.00

(N = 110)

LATE AND POST-OROGENIC GRANITES

Mumakera, Maleba, Muyenzi, Bukiriro

Fig. 5-9. TiO_2 vs. Zr plot of data from Mumakera (Mum.), Maleba (Mal.), Muyenzi (Muy.) and Bukiriro (Buk.) granites.

Fig. 5-10. Fe₂O₃ vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-11. MgO vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-12. CaO vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-13. SiO_2 vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-14. Al₂O₃ vs. Zr plot (see Fig. 5-9 for symbols)

Fig. 5-15. K₂O vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-16. Na₂O vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-17. Ba vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-18. Sr vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-19. Y vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-20. Rb vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-22. Sn vs. Zr plot (see Fig. 5-9 for symbols).

Fig. 5-23. F vs. Zr plot (see Fig. 5-9 for symbols).

c) magma mixing, or d) restite unmixing (Chappell et al., 1987). Incremental or batch melting (Cox et al., 1979) can produce magmas in which the femic (Fe, Mg, Ti) oxide content increases with the degree of partial melting, which means that early-formed magmas at low temperature will be lower in Fe, Mg and Ti, than those formed at high temperature and by higher degrees of partial melting. Early granites formed from such magmas will be felsic and intruded by more mafic granitoids. The petrological and chemical data from the Karagwe-Ankolean granites do not seem to support the batch melting hypothesis.

Because of the variations in the bulk distribution coefficients (K_D) of trace elements with SiO_2 content and decreasing pressure and temperature in the magmas (McCarthy, 1976; Hanson, 1978; Cox et al., 1979), rocks related by fractional crystallization generally exhibit curved geochemical trends on variation diagrams (Whalen, 1983). In high silica granitic magmas with low SiO_2 variations, the bulk distribution coefficients are, however, likely to be little affected by SiO_2 composition. In such magmas, fractional crystallization could possibly produce linear geochemical trends. Linear trends could also be produced by other processes such as restite unmixing (White and Chappell, 1983; Chappell et al., 1987) or mixing of magmas of contrasting compositions (Price, 1983; Wall et al., 1987). High and restricted SiO_2 compositions of the Karagwe-Akolean granites, however, make magma mixing an unlikely mechanism for the formation of chemical trends documented in the granites. The lack of restite xenoliths in most Karagwe-Ankolean granites studied suggests that restite unmixing is unlikely as the main mechanism for producing chemical variations. Magmatic differentiation

by fractional crystallization is therefore favoured as the mechanism for producing the geochemical trends in the Karagwe-Ankolean granites. Similar CaO, Ba, and Sr patterns (Figs. 5-12, 5-17, 5-18) could best be explained by feldspar fractionation from the original magmas. Decrease of Fe_2O_3 , MgO, TiO_2 , Y and Zr in the granites with increasing degree of chemical evolution suggests that Fe-Ti oxides, xenotime, zircon and possibly biotite were among the minerals that fractionated from the Karagwe-Ankolean magmas. Zircon and xenotime inclusions in micas and quartz suggest that these minerals were probably early phases to crystallize from the magmas.

El Bouseily and El Sokkary (1975) used the Rb-Ba-Sr triangular diagram to monitor differentiation trends in felsic and intermediate rocks and also to discriminate magmatic from metasomatic granites. Figure 5-25 shows the plot of Rb, Ba, and Sr data (ppm) from the Karagwe-Ankolean granites on a triangular diagram. The data project onto the strongly differentiated granite field. The fact that the data points plot mainly in the strongly differentiated granite field indicates that the variations in Rb, Ba and Sr in the granites are largely due to magmatic differentiation. Evidence for the differentiation sequence from diorites through quartz diorites and granodiorites to normal granites seems to be lacking. This is inconsistent with formation of the Karagwe-Ankolean granites by magmatic differentiation of mantle-derived magmas. Partial melting of crustal rocks followed by fractional crystallization seems to be more compatible with much of the chemical data.

5.4.0 REE chemistry

REE analyses of 10 samples of Karagwe-Ankolean granites from three

Fig. 5-25. Rb-Ba-Sr triangular plot of data from Karagwe-Ankolean granites. Field boundaries for various granitoids are from El Bouseily and El Sokkary (1975).

plutons are given in Table 5-5 and plotted in Figures 5-26 and 5-27. Figure 5-26 shows that chondrite-normalized REE (Boynnton, 1984) patterns for the two-mica granites from the Bukiriro area in the central part of the Bushubi batholith, and the Mumakera and Maleba plutons are similar, suggesting similar modes of origin. The patterns exhibit negative Eu anomalies and show enrichment in light REE (LREE) relative to chondrites. The Bukiriro and Mumakera granites are distinct from the Maleba granites in having relatively high total REE abundances and more fractionated REE patterns $[(La/Lu)_{cn} = 4.84 \text{ to } 7.34 \text{ for the former and } 3.22 \text{ to } 6.46 \text{ for the latter}]$.

REE data from granites of the Maleba pluton are plotted in Figure 5-27. It can be seen that there are no large differences in the REE patterns for the different granite types. The two-mica granite, muscovite granite and tourmaline leucogranite all show significant enrichment of LREE relative to chondrites and a negative Eu anomaly. The same can be said of the REE data from the two-mica granite and tourmaline-muscovite granite of the Mumakera pluton.

It has been pointed out that the degree of chemical differentiation in the granites tends to increase from east to west across the southern part of the Karagwe-Ankolean belt. This is also shown by the REE data (Table 5-5) which show a decrease in total REE abundance from the older, less evolved, Bukiriro granites to the younger, more evolved, Maleba granites.

Feldspar fractionation, especially plagioclase, is considered responsible for negative Eu anomalies in magmatic rocks (Emmermann et al., 1975). Magmas produced by the partial melting of rocks in which plagioclase remains as a major component of restite will also exhibit negative Eu anomalies. The

TABLE 5-5. REE analyses of some Karagwe-Ankolean granites

	MW-5	MA-15	MA-19	MA-32	MU-2	MU-23	MU-24
La (ppm)	16.74	23.01	17.49	17.72	38.86	35.44	33.93
Ce	39.15	49.76	38.76	42.67	89.92	80.07	81.83
Pr							
Nd	15.95	17.88	15.39	15.69	37.86	31.14	35.10
Pm							
Sm	4.64	4.49	4.61	4.03	8.95	7.81	8.73
Eu	0.71	0.81	0.29	0.59	1.02	0.78	1.42
Gd	3.81	3.48	3.93	4.03	7.37	6.16	7.26
Tb							
Dy	6.00	4.12	5.55	5.36	8.37	7.39	8.54
Ho							
Er	3.72	2.42	3.28	3.14	4.79	4.44	4.70
Tm							
Yb	4.42	2.91	3.92	3.74	5.32	5.05	5.27
Lu	0.54	0.37	0.49	0.44	0.55	0.60	0.63
TOTAL	95.68	109.25	93.71	97.41	203.01	178.88	187.41

	MU-25	BU-48	BU-49
La (ppm)	29.07	41.11	29.33
Ce	68.28	97.15	64.43
Pr			
Nd	27.96	42.04	27.07
Pm			
Sm	6.70	10.45	6.87
Eu	0.47	1.05	1.29
Gd	5.29	9.05	6.18
Tb			
Dy	6.31	11.15	7.68
Ho			
Er	3.59	6.49	4.54
Tm			
Yb	4.09	7.21	5.25
Lu	0.52	0.85	0.63
TOTAL	152.28	226.55	153.27

SAMPLE GROUPING:

MALEBA PLUTON

MW-5: Two-mica granite
MA-15: Muscovite granite
MA-19, MA-32: Tourmaline-leucadamellite

MUMAKERA PLUTON

MU-2, MU-23: two-mica granite
MU-24, MU-25: tourmaline-muscovite granite

BUKIRIRO GRANITES

BU-48, BU-49: two-mica-granite

Fig. 5-26. Chondrite-normalized REE patterns for the two-mica granites from Bukiriro, Maleba and Mumakera plutons.

Fig. 5-27. Chondrite-normalized REE patterns for the Maleba granites.

chemical trends exhibited by Ca, Ba and Sr in the variation diagrams (Figs. 5-12, 5-17, 5-18), however, are also consistent with trends expected in magmas undergoing plagioclase fractionation. It seems reasonable therefore to suggest that negative Eu anomalies in the Karagwe-Ankolean granites are, at least, in part due to fractional crystallization of plagioclase from the original magmas.

Biotite, muscovite and monazite concentrate LREE relative to HREE (Emmermann et al., 1975; Manson Berry, 1968; Alderton et al., 1980) while xenotime and zircon concentrate HREE (Manson, 1968; Nagasawa, 1970). Tourmaline has a "U-shaped" REE pattern (Alderton et al., 1980). Apatite tends to concentrate the middle REE (Henderson, 1984). As a general rule, minerals with large co-ordination polyhedra for cations favour the large LREE ions, while those with small polyhedra favour the smaller HREE (Henderson, *op cit*). Petrographic studies suggest that apatite and zircon were among the early phases to precipitate from Karagwe-Ankolean granitic magmas and were probably followed by xenotime. Removal of these phases could produce depletion of the HREE in the magmas. Monazite probably precipitated relatively late and resulted in the concentration of LREE in the resulting granites. Further concentration of the LREE was perhaps accomplished by biotite and muscovite accumulation in the granitic magmas. Timing of tourmaline precipitation in the Karagwe-Ankolean granites is not very clear. As pointed out in chapter 3, textural relationships suggest that tourmaline saturation in Karagwe-Ankolean granitic magmas occurred at least during the intermediate stages of magmatic crystallization and reached maximum development in the final stages of crystallization. It seems likely that

tourmaline did not play any significant role in the fractionation of REE in the early and intermediate stages of magmatic evolution. This is further supported by the lack of any obvious depletion of middle REE in the granites that would have been caused by tourmaline precipitation. Tourmaline precipitation in the final stages of magmatic evolution possibly did not have any significant effect on the REE distribution of the magmas and resulting granitic rocks as it was possibly retained as part of the final rock mineral assemblage.

In summary, it can be said that the REE patterns of the Karagwe-Ankolean granites are best explained by the early separation of plagioclase, zircon and apatite, and possibly xenotime, and the accumulation or late precipitation of monazite and perhaps biotite and muscovite in the original magmas.

Total REE abundances (95 - 226 ppm, mean = 150 ppm) in the various Karagwe-Ankolean granites (Table 5-5) are generally lower than the average abundance of 250 ppm quoted by Emmermann et al. (1975) for granitic rocks. Comparison of the REE data from the Karagwe-Ankolean granites with granites from SW England and the Nigerian Tin Province reveals some significant similarities and differences. Total REE and Y concentrations in the biotite granites from northern Nigeria are in the range of 222 to 2464 ppm (mean = 1068 ppm), while higher concentrations, up to 3468 ppm, are reported from alkaline riebeckite granite (Aleksiyev, 1970). Apart from being alkaline, the Nigerian granites are distinct from granites from NW Tanzania and SW England by having much higher REE contents. Total REE contents in five unaltered granite samples from SW England range from 99 to 203 ppm, with a

Fig. 5-28. Chondrite-normalized REE patterns for fresh granites (a) and their constituent minerals (b) from SW England (After Alderton et al., 1984).

mean value of 149 ppm (Alderton et al. 1980), similar to the mean value of 150 ppm obtained from the Karagwe-Ankolean granites. Figure 5-28 shows chondrite-normalized REE patterns for fresh granites from SW England. The patterns, characterized by enrichment of LREE relative to HREE, show similar magnitudes of LREE enrichment relative to chondrites as those found in the Karagwe-Ankolean granites. In contrast, to the Karagwe-Ankolean granites which exhibit nearly flat HREE patterns, granites from SW England have REE patterns showing progressive depletion of HREE from Sm to Yb.

5.5.0 Comparison of granite, xenolith and country rock compositions

Chemical data from phyllites from country rocks surrounding the Maleba (Ma/Mb), Mumakera (Mu) and Nyamakombe (Ny) plutons are presented in Table 5-6. The phyllites vary from brownish-grey varieties (e.g., Ma-4, Mb-26) containing partially altered andalusite porphyroblasts, through to non-porphyroblastic reddish-brown ferruginous varieties (e.g., Mu-34) to whitish varieties (e.g., Nk-5). The porphyroblastic phyllite samples were taken from the contact aureole of the chemically specialized Maleba pluton. The white phyllite sample (NK-5) was taken from a locality unaffected by contact metasomatism activity, about 10 km northeast of Rulenge township (Fig. 1-3). The ferruginous sample (MU-34) was collected about 250 m southeast of the Mumakera pluton, and sample Ny-40 is a muscovite schist from about 350 km east of the Nyamakombe pluton.

The major element data for all of the phyllites show little variation in SiO_2 , Al_2O_3 , TiO_2 , MnO , MgO , CaO and K_2O , other than sample Mu-34. Sample Mu-34 is distinct in having low SiO_2 and Al_2O_3 , and high Fe_2O_3 contents relative to the other samples. Its chemical composition is consistent with

TABLE 5-6. Chemical analyses of country rocks and xenoliths from Karagwe-Ankolean granites

	Phyllites*					Xenoliths#	
	Ma-4	Mb-26	Mu-34	Ny-40	Nk-5	Bu-15	Bu-38
SiO ₂ wt %	62.60	65.31	49.52	65.29	68.25	53.65	46.93
TiO ₂	0.87	0.80	0.68	0.86	1.16	1.16	0.70
Al ₂ O ₃	23.30	22.31	17.21	21.37	19.80	27.90	34.83
Fe ₂ O ₃	2.51	2.20	24.26	5.48	2.16	4.08	2.01
MnO	0.01	0.00	0.00	0.01	0.00	0.06	0.03
MgO	0.10	0.00	0.00	0.33	0.00	1.01	0.93
CaO	0.09	0.11	0.14	0.01	0.06	1.05	0.03
Na ₂ O	1.43	1.37	1.13	0.38	0.59	2.76	0.25
K ₂ O	3.24	3.25	2.94	3.19	3.97	7.25	11.03
P ₂ O ₅	0.07	0.08	0.22	0.00	0.04	0.01	0.00
Total	94.22	95.43	96.10	96.92	96.03	98.93	96.74
Rb (ppm)	180	169	158	103	165	410	653
Ba	830	671	640	662	849	243	252
Sr	210	139	204	55	95	73	8
Zr	190	201	197	271	349	267	112
Nb	10	10	7	15	14	25	29
Y	60	42	28	28	28	20	12
Zn	-	9	53	12	14	60	24
Sn	2	5	<1	3	<1	3	-
Li	43	46	23	36	5	-	-
F	630	590	280	390	220	-	-
B	140	110	70	90	50	-	-

* Samples Ma-4 and Mb-26 are from the contact aureole of the Maleba pluton; Mu-34 and Ny-40 were taken about 250 m and 350 m from the contacts of the Mumakera and Nyamakombe plutons, respectively; NK-5 came from a locality 10 km NE of Rulenge (Fig. 1-3).

Xenoliths from Bukiriro two-mica granites: Bu-15: gneiss; Bu-38: muscovite schist.

the mineralogy which is dominated by hematite (partially altered to goethite or limonite) together with quartz and sericite. Extremely low values of MnO, MgO and CaO, and to a lesser extent P_2O_5 and Na_2O are characteristic of all the phyllites. Because regional metamorphism is considered to be largely isochemical (apart from the loss of volatile chemical components such as H_2O and CO_2 ; Mehnert, 1969), the phyllite compositions probably reflect the protolith compositions.

A comparison of trace element data for phyllites close to stanniferous granite plutons and those located distally can be seen in Table 5-6. The data indicate that there are no systematic variations in the amounts of Rb, Ba, Sr, Zr, Nb, Y and Zn between the phyllites in the two categories mentioned above. In contrast, F, Li and B are consistently more enriched in the phyllites surrounding the plutons (e.g, Ma-4, Mb-26, Mu-34, Ny-40) than in the phyllite located further away from the plutons (i.e. Nk-5). Fluorine, Li and B are most abundant in the andalusite-bearing porphyroblastic phyllite (Ma-4, Mb-26) from the contact metamorphic aureole of the more evolved Maleba pluton. Tin was detected in 3 of the four samples collected close to the plutons and was below the detection limit of 1 ppm in sample Nk-5 collected further from the plutons. Although the trace element data are very limited, the enrichment of F, Li and B in the phyllites surrounding the stanniferous granites suggest that these elements were possibly introduced in the country rocks by hydrothermal fluids derived from the granitic plutons. Sn may have also been one of the elements enriched in the country rocks by the hydrothermal fluids, especially in Sn-mineralized areas. Boron from the hydrothermal fluids was probably involved in the formation of tourmaline-bearing schists or tourmalinites in the

country rocks, while F and Li were incorporated in muscovite in mica schists and hydrothermal veins. No F minerals or Li-micas have yet been found in the country rocks.

The enrichment of F and/or B in the country rocks surrounding chemically specialized granites has been reported in other areas. For example, Simonova and Nikitina (1985) concluded from the study of B and F distribution in the Kumyshtag massif (Soviet Union) and country rocks that significant B influx had occurred in the exocontact zone of the massif. Maximum B influx was recorded in the country rocks at distances of 100-500 m above the top of the massif. The influx of F into the country rocks was found to be less than that of B, and F was considered to have been retained in the granitic magma. This is consistent with the experimental data of Pichavant and Manning (1984) which indicate that F is more soluble in granitic magmas than B. In the Karagwe-Ankolean belt, influx of B into the country rocks from the granitic magmas is indicated by the pervasive tourmaline alteration of the rocks above the chemically evolved granites.

Chemical analyses of two xenoliths, Bu-15 and Bu-38, from Bukiriro muscovite-biotite granites are shown in Table 5-6. Sample Bu-15 is a medium-grained muscovite schist while sample Bu-38 is a medium-grained biotite-muscovite gneiss. The texture and mineral composition of the schist xenolith suggest that the xenolith was probably derived locally. This contrasts with the gneiss xenolith for which no similar rock types are exposed. Chemically the gneiss is higher in Al, K, Rb, Ba and Nb, and lower in Si, Ti, Fe, Mn, Mg, Ca, Na, P, Sr, Zr, Y and Zn than the schist xenolith. Both types of xenolith are depleted in Si, P, Ba and Y, and enriched in Al, Mg, Fe, K, Ti, Rb, Zr,

and Nb relative to the granite host. Comparison of the chemical data for the schist xenolith with those of the phyllites (samples Ma-4, Mb-26, Ny-40, Nk-5) from the country rocks (Table 5-6) indicates that the schist is higher in Al, Mn, Mg, Ca, Na, K, Rb, Nb and Zn, and lower in Si, Ba and Y.

Chemical contrasts between the compositions of the granitic rocks, the xenoliths, and the phyllites have some important implications regarding the chemical evolution of the granitic magmas in the Karagwe-Ankolean belt. Extensive assimilation of the phyllites by the magmas would have substantially modified the compositions of the magmas by increasing their Al, Fe, Ti, Ba, Sr and Zr contents and decreasing their Si and Rb contents. Chemical variations in the granites would therefore reflect various degrees of assimilation of the phyllites by the granitic magmas. The scarcity of country rock xenoliths in many granites suggests that the country rocks engulfed by the magmas were completely assimilated, or extensive incorporation of the country rocks into the magmas did not occur. With viscosity of magma being high its more than likely any xenoliths would be entrained and trapped. The geometry of the granitic plutons argues against the "extensive assimilation" hypothesis. The plutons commonly form dome-shaped, circular or elongated outcrop patterns surrounded by phyllites and strongly fractured quartzite bands as at Maleba. The shape of the plutons and the fracturing of the country rocks around the plutons suggest that the predominant mode of magma emplacement was probably by "diapirism" instead of "mechanical stoping" or assimilation of the country rocks. The "assimilation hypothesis" is further constrained by the chemical data from the granites and the country rocks. Considering the chemical data in Table 5-6, the

increase in the amount of assimilated metasediments would produce chemical trends in which the amounts of Al, Fe, Ti, Ba, Sr and Zr increase and Si and Rb decrease in the granites. The chemical variations observed in the granites (Figs. 5-10 to 5-18) do not seem to support the "assimilation hypothesis". For example, Si and Al in the granites show little variation while variations in other elements such as Ti, Zr, Ba and Sr are relatively large. It is therefore reasonable to conclude that the chemical variations in the granites are largely due to other factors, such as source-rock composition and fractional crystallization, rather than the assimilation. Partial assimilation of the country rocks by the granitic magmas can not however be completely ruled out given the fact that country rock xenoliths are observed locally in a few granites. The assimilation was possibly restricted at the contact of the magmas and the country rocks.

5.6.0 Statistical analysis of chemical data from the granitic rocks

Statistical methods commonly used in the analysis of multivariate geological data are discussed in Koch and Link (1971). Some statistical methods have been successfully used in the analysis and interpretation of chemical data (e.g., Tripathi, 1979; Chatterjee et al., 1982; van Gaans et al., 1987). The advantage of statistical methods is that they allow representation of a large number of variables by a smaller number of new variables which can be easily interpreted in terms of geological processes. Two methods, factor analysis and discriminant analysis, have been chosen here to evaluate the chemical data. Factor analysis is commonly used to examine correlations within a set of data. Its main aim is to explain the covariances in the original data by a few variables called "factors". The factors provide information on variables that account for the variance

within a data set. Factor analysis can be performed in R-mode or in Q-mode. R-mode analysis deals with correlations between the variables while Q-mode analysis deals with correlations between the objects or samples (Vogt and Kollenberg, 1987).

Discriminant analysis is commonly used to classify multivariate observations into groups by performing one or more linear combinations of the variables that comprise the observations (Koch and Link, 1971). In stepwise discriminant analysis variables used in computing a discriminant function are chosen in a stepwise manner. At each step the variable that adds the most to the separation of the groups is entered and/or the variable that adds the least is removed from the discriminant function (Jennrich and Sampson, 1985).

In this study BMDP statistical software (Dixon, 1985) was used to process the chemical data using a mainframe computer. The BMDP software program P4M was used in factor analysis while program P7M was used in stepwise discriminant analysis.

5.6.1 Factor analysis

The results of factor analysis, more correctly principal component analysis, are presented in Tables 5-7A and 5-7B. Both tables show the principal factors calculated from the chemical data and the factor loadings for the variables. Factor loadings with the absolute value of less than 0.25 have been excluded from the tables since they contribute very little to the calculated factors. The variance in the major element data is accounted by three principal factors (Table 5-7A). Factor 1A is heavily loaded with CaO,

TABLE 5-7A. Principal factors and factor scores for major element variables in the stanniferous and barren granites.¹

	FACTOR 1A	FACTOR 2A	FACTOR 3A
CaO	0.895		
MgO	0.895		
Fe ₂ O ₃	0.833		0.285
TiO ₂	0.745	-0.387	
K ₂ O		-0.940	
Na ₂ O		0.841	
P ₂ O ₅	-0.350	0.639	0.357
MnO	0.305	0.559	0.522
Al ₂ O ₃			0.882
SiO ₂	-0.683		-0.689
VP*	3.642	2.539	1.813

* VP is variance explained by each factor.

1: Factor scores with absolute value < 0.25 have been omitted from the table for clarity.

TABLE 5-7B. Shows principal factors and factor scores for trace element variables in the stanniferous and barren granites.

	FACTOR 1B	FACTOR 2B	FACTOR 3B	FACTOR 4B
Ba	0.850	-0.347		
Sr	0.823	-0.292		
Zr	0.781	-0.254		0.299
B	-0.656			
Sn		0.827		
Li		0.810		
Rb	-0.268	0.656	0.506	
Nb			0.841	
F			0.732	0.400
Zn				0.844
Y	0.332	0.302		0.504
VP	2.663	2.212	1.574	1.467

MgO, Fe₂O₃ and TiO₂ and to a lesser extent with MnO. These components show a strong antipathetic relationship with respect to SiO₂ and P₂O₅. This factor is interpreted as a "mafic mineral" factor which indicates the fractionation of mafic minerals, mainly biotite and Fe-Ti oxides, and calcic plagioclase from the original magmas, and the concentration of SiO₂ and P₂O₅ in residual magmas. Factor 2A is heavily loaded with Na₂O, P₂O₅ and MnO which show an antipathetic relationship with respect to K₂O and TiO₂. This factor is interpreted as an "albitization" factor which indicates sodic metasomatism in the granites. Factor 3A is strongly loaded with Al₂O₃ and MnO, and to a lesser extent with P₂O₅ and Fe₂O₃, which are negatively correlated with SiO₂. This is interpreted as a "muscovitization" or "sericitization" factor which indicates alteration of feldspar, biotite and quartz by hydrothermal fluids to form muscovite ± apatite and chlorite.

The variance in the trace element data can be explained by 4 main factors (Table 5-7B). Factor 1B is heavily loaded with Ba, Sr, and Zr, and to a lesser extent with Y. These elements show an antipathetic relationship with respect to B and Rb. This factor, correlated with Factor 1A in Table 5-7A, is also interpreted to indicate magmatic fractionation. The loading of this factor with respect to Zr and Y suggests that zircon and xenotime were among the phases fractionated from the parent magmas. Ba and Sr, correlated with Ca in 1A, indicate plagioclase fractionation. The negative correlation of B and Rb with respect to Ba, Sr, Zr and Y suggests that these elements were enriched in residual magmas along with P₂O₅ and SiO₂ (see Factor 1A). Factor 2B is heavily loaded with Sn, Li, and Rb, which are negatively correlated with Ba, Sr, and Zr. This is interpreted as "Sn specialization" factor which indicates Sn enrichment in the granites with increasing degree

of geochemical differentiation. Factor 3B is heavily loaded with Nb, F and Rb while Factor 4B is heavily loaded with Zn and Y and to lesser extent with F and Zr. The geologic significance of these two factors is not known. It is, however, possible that the variance attributed to those factors is due to hydrothermal alteration.

5.6.2 Discriminant analysis

The results of stepwise discriminant analysis are shown in the histograms in Figures 5-29 and 5-30. The discriminant function (D_{F1}) calculated from the statistical analysis of the major element data using the BMDP software program P7M is given by:

$$D_{F1} = 0.70650\text{Na}_2\text{O} - 0.50776\text{CaO} - 0.38007\text{MgO} - 3.79034.$$

It can be seen from the above equation that only 3 (i.e. Na_2O , CaO , MgO) of the major element variables (SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , K_2O , Na_2O , P_2O_5) are required for the discrimination of the stanniferous from the barren granites. Although the calculated discriminant function yields a good separation of the two groups of samples (Fig. 5-29), it does not yield 100 % separation. There is short interval of overlap of the two groups of samples around the 0.0 mark of the histogram shown in Figure 5-29. Apart from this overlap there are a few outliers of barren granite samples in the cluster defined by the stanniferous granites in the histogram. These outliers could be due to analytical errors or misclassification of the original samples.

The discriminant function (D_{F2}) calculated from trace element data (Rb, Ba, Sr, Zr, Nb, Y, Zn, Sn, Li, F, B, Rb/Sr, K/Rb, K/Ba, Rb/Zr, Li/Sr, Rb/Ba) is given by the following equation:

$$D_{F2} = 0.01972\text{Y} - 0.02239\text{Zr} - 0.01326\text{Zn} - 0.04670\text{K/Rb} + 6.19790.$$

Fig. 5-29. Histogram showing results of stepwise discriminant analysis for distinguishing the stanniferous granites from the barren granites using major element data.

Fig. 5-30. Histogram showing results of stepwise discriminant analysis for distinguishing the stanniferous (S) granites from the barren (B) granites using trace element data.

Only 4 of the trace element variables listed above appear in the discriminant function. This suggests that other linear combinations of the trace element variables do not effectively discriminate between the stanniferous (S) and barren (B) granite samples. With the exception of a few outliers, samples with discriminant scores of ≥ 0 appear to fall in the stanniferous category while those with scores of < 0 fall in the barren category (Fig. 5-30).

In summary, the statistical analysis of the chemical data has shown that the stanniferous granites can be distinguished from the barren granites using the discriminant functions:

$$D_{F1} = 0.70650\text{Na}_2\text{O} - 0.50776\text{CaO} - 0.38007\text{MgO} - 3.79034$$

or

$$D_{F2} = 0.01972\text{Y} - 0.02239\text{Zr} - 0.01326\text{Zn} - 0.04670\text{K/Rb} + 6.19790.$$

Because few variables, Na_2O , CaO and MgO or Y , Zn , Zr and K/Rb , are used in the discriminant functions, analyses of other elements are not necessary to discriminate the stanniferous granites from the barren granites. The above discriminant functions can be used in regional exploration surveys to delineate granite areas suitable for more detailed tin exploration in the Karagwe-Ankolean belt.

5.7.0 Geochemistry of gabbroic intrusions

XRF analyses of four samples of gabbroic intrusion from Nyakisasa-Mpanyula valley about 9 km northeast of Rulenge (Fig. 1-2) are presented in Table 5-8 and Figure 5-31. The gabbro appears to be part of exposed and unexposed basic and ultrabasic intrusions forming a linear chain close to the northeastern margin of the Kibaran-Karagwe-Ankolean belt in northwestern Tanzania and eastern Burundi (van Straaten, 1984). It is not known whether or not the intrusions mark a paleosuture. In the absence of oceanic volcanic rocks associated with the intrusions all that can be said is that the intrusions reflect a deep-seated crustal structure or lineament along which mantle derived magma migrated. A comparison of mean Ti, Zr, Y, Nb and Sr contents of Nyakisasa gabbro with those of basic volcanic rocks representing different magma types and tectonic settings (Pearce and Cann, 1973) can be seen in Table 5-9. It is evident from the data in Table 5-9 that the Ti, Zr, Y, Nb and Sr contents of the Nyakisasa gabbro are lower than the mean values in basic volcanic rocks from modern ocean ridge, volcanic arc, ocean island and continental geologic settings. This suggests that the Nyakisasa gabbro is either rich in cumulate minerals, in which case the rock composition does not necessarily represent magma composition, or formed from a magma with trace element composition distinct from modern magma types. The high Y/Nb ratio of the Nyakisasa gabbro is possibly indicative of the tholeiitic nature of the parent magma. On the tectonic setting discrimination diagrams shown in Figure 5-31, the data from the Nyakisasa gabbro plot in the field occupied by ocean floor basalts and/or island arc low-potassium tholeiitic basalts.

The spatial separation (> 10 km) of the Nyakisasa gabbro and other

TABLE 5-8. Chemical analyses of Nyakisasa gabbro

Sample no:	NK-1	NK-2	NK-3	NK-4
SiO ₂ %	51.63	52.00	52.10	52.13
Al ₂ O ₃	11.07	11.44	11.01	11.33
Fe ₂ O ₃ (T)	10.86	10.96	11.03	10.68
MgO	13.99	13.30	14.18	14.10
CaO	7.56	7.86	7.57	7.41
Na ₂ O	1.51	1.66	1.64	1.81
K ₂ O	0.08	0.10	0.07	0.08
TiO ₂	0.45	0.49	0.47	0.45
P ₂ O ₅	0.00	0.00	0.00	0.00
MnO	0.18	0.18	0.18	0.18
S	0.03	0.02	0.05	0.03
Total	97.36	98.01	98.03	98.19
Ba ppm	85	80	99	104
Cr	1296	1145	1302	1295
Zr	43	42	43	42
Sr	62	73	58	66
Rb	0	0	1	0
Y	16	15	15	19
Nb	0	0	0	1
Zn	86	63	65	85
Ni	0	0	0	0
V	260	263	254	269

TABLE 5-9. Comparison of mean Ti, Zr, Y, Nb and Sr contents (ppm) of Nyakisasa gabbro with those of basic volcanics (Pearce and Cann, 1973) representing different magma types and tectonic settings.

Rock type/tectonic setting	Ti	Zr	Y	Nb	Sr
Nyakisasa gabbro	2833	43	16	0.25	65
Ocean floor basalts (OFB) (Ocean ridge)	8350	92	30	5.0	131
Low-K tholeiites (LKT) (Volcanic arc)	5150	52	19	1.5	207
Calc-alkali basalts (CAB) (Volcanic arc)	5400	106	23	2.5	375
Ocean island basalt (OIB) (Ocean island)	16250	215	29	32	438
Continental basalt (Continental)	15150	215	29	20	460

CAB: calc-alkali basalts; LKT: low-K tholeiites

OIB: ocean island basalt; OFB: ocean floor basalts

Fig. 5-31. Data from Nyakisasa gabbro plotted on Zr-Ti, Zr-Ti-Y, and Zr-Ti-Sr diagrams (Pearce and Cann, 1973) for discrimination of tectonic settings and magma types.

basic intrusions from granites in the Karagwe-Ankolean belt and a large compositional gap between the gabbro and the granites suggest that the two rock types are unlikely to be genetically related.

CHAPTER 6

MINERAL CHEMISTRY

6.0.0 Tourmaline composition

Tourmaline is a complex borosilicate mineral with the general formula $XY_3Z_6(BO_3)_3Si_6O_{18}(OH)_4$, where Y (Fe, Mg, Al, Li) and Z (Al) represent octahedrally coordinated ions, and X the large cations Na and Ca and rarely K (Werding and Schreyer, 1984; Henry and Guidotti, 1985; Plimer, 1986). The principal tourmaline end-member compositions are schorl (X = Na, Y = Fe^{2+} , Fe^{3+} , Z = Al), dravite (X = Na, Y = Mg, Z = Al), uvite (X = Ca, Y = Mg, Z = Al, Mg) and elbaite (X = Na, Y = Al, Li, Z = Al) (Plimer, 1986). These and other common end-members are listed in Table 6-1. Solid solution in tourmaline involves substitution of cations mainly in the Y site, although substitution also occurs in the X and Z sites to maintain charge balance. Fluorine and Cl can substitute for OH^- in the hydroxyl site. Other minor elements that can be accommodated in tourmaline include Ti, Mn, V, and Cr. The important substitutions in tourmaline are summarized in Table 6-2.

Variations in composition and texture of tourmaline are a function of P-T-X conditions, and this makes tourmaline useful in petrogenetic studies (Manning, 1982; Henry and Guidotti 1985; Plimer, 1986). Chemical data from tourmaline from several of the Karagwe-Ankolean granites, aplites, and tourmalinized country rocks in the contact metamorphic/metasomatic aureoles were obtained by electron microprobe analysis. The data are used together with petrographical studies to place constraints on the genesis of tourmaline and the host rocks.

TABLE 6-1. Chemical formulae of common tourmaline end-members
(After Henry and Guidotti, 1985)

End-member	Formula
Schorl	$\text{NaFe}^{2+}_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
Dravite	$\text{NaMg}_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
Tsiliasite	$\text{NaMn}_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
Elbaite	$\text{Na}(\text{Li}, \text{Al})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
Uvite	$\text{CaMg}_3(\text{MgAl}_5)(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
Liddicoatite	$\text{Ca}(\text{Li}, \text{Al})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
Alkali-defect tourmaline	$\square(\text{Y}^{2+}_2, \text{Y}^{3+})\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4^*$
Proton-deficient tourmaline	$\text{NaY}^{3+}_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})$
Buergerite	$\text{NaFe}^{3+}\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{22}\text{F}$
Ferridravite	$\text{NaMg}_3\text{Fe}^{3+}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$

* Y^{2+} and Y^{3+} represent divalent and trivalent cations

TABLE 6-2. Important chemical substitutions in tourmaline

1. $\text{Fe}^{2+} \rightarrow \text{Mg}_Y$
2. $\text{Na}_X + \text{Al}_Z \rightarrow \text{Ca}_X + \text{Mg}_{Z2+}$ (Uvite substitution)
3. $\text{Na}_X + \text{Al}_Y \rightarrow \text{Ca}_X + \text{Fe}^{2+}_Y$
4. $\text{Na}_X + \text{Al}_Y \rightarrow \text{Mg}_X + \text{Fe}^{2+}_Y$
5. $\text{Na}_X + \text{Al}_Y \rightarrow \text{Ca}_X + \text{Li}_Y$ (Liddicoatite substitution)
6. $\text{Mg}_Y \text{ T Si}_T \rightarrow \text{Al}_Y + \text{Al}_T$ (Tschermarks substitution)
7. $\text{Na}_X + \text{Mg}_Y \rightarrow \text{Al}_Y + \#_X$ (Alkali-defect substitution)
8. $\text{Mg}_Y + \text{OH}^- \rightarrow \text{Al}_Y + \text{O}^{2-}$ (Aluminobuergerite substitution)
9. $\text{Fe}^{2+}_Y + \text{OH}^- \rightarrow \text{Fe}^{3+}_Y + \text{O}^{2-}$ (Buergerite substitution)
10. $\text{Al}_Z \rightarrow (\text{Fe}^{3+}, \text{Cr}^{3+}, \text{V}^{3+})_Z$
11. $\text{Mg}_Y + 2\text{Si}_T \rightarrow \text{Ti}_Y + 2\text{Al}_T$
12. $2\text{Fe}^{2+}_Y \rightarrow \text{Li}_Y + \text{Al}_Y$
13. $\text{OH}^- \rightarrow \text{F}^-$

The subscripts represent the alkali site (X), the octahedral sites (Y and Z), and the tetrahedral site (T) in the general structural formula. The symbol # in (7) represent a vacancy in the X site.
(Data from Henry and Guidotti, 1985).

6.0.1 Results of microprobe analysis

Microprobe analyses of tourmalines, presented in Tables 6-3 and 6-4 and Appendix 5, indicate that the tourmalines belongs to the schorl-dravite solid solution series (Deer et al., 1966). Most tourmalines have compositions that lie toward the schorlitic end-member. The $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios in the tourmalines (Table 6-5) vary from 0.57-0.62 in the two-mica granites, 0.67-0.81 in the tourmaline leucogranites, and 0.67-0.89 in the aplite dykes. Tourmaline from contact metamorphic aureoles and hydrothermal veins in metasediments exhibit the highest $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios (mean = 0.87 ± 0.02).

On the Fe-Al-Mg tourmaline classification diagram (Henry and Guidotti, 1985), the data for tourmaline from the Karagwe-Ankolean granites, aplites, and quartz-tourmaline veins plot within the field occupied by tourmaline from Li-poor granitoids (Fig. 6-1). The data for tourmaline from the contact boron metasomatic aureoles around the granites also plot in the field occupied by tourmaline from Li-poor granitoids. The data for magmatic tourmaline from granites and aplites are distinct from those of pneumatolytic or hydrothermal vein tourmaline on the Al-Fe-Mg diagram (Fig. 6-1). The former are distinguished from the latter on the basis of their Al content.

Figure 6-2 shows chemical profiles across optically zoned magmatic tourmaline (Plate 3-2D) from a tourmaline leucomonzogranite in the Maleba pluton. The profiles show trends characterised by an increase of Ti, Fe and commonly F, and a decrease of Mg and commonly Ca from tourmaline core to the rim; Na remains almost constant. The chemical trends exhibited by Mg, Fe, Ca

TABLE 6-3. Microprobe analyses of optically zoned tourmaline from tourmaline-leucomonzogranite in the Maleba pluton

Tourmaline: 1					2					3					4					5				
	cr	iz	rm		cr	iz	rm			cr	iz	rm			cr	iz	rm			cr	iz	rm		
SiO ₂	34.57	35.08	34.71		34.90	34.91	34.61			34.85	34.78	34.63			35.55	34.93	34.53			35.19	34.57	34.35		
Al ₂ O ₃	35.62	35.31	34.57		34.95	35.83	34.56			35.23	34.11	34.37			36.10	35.21	33.73			36.03	33.98	33.91		
FeO *	10.73	10.92	12.40		11.29	11.56	12.53			11.34	11.97	12.93			10.28	11.22	12.56			11.16	11.98	12.93		
B ₂ O ₃	10.03	10.18	10.07		10.12	10.11	10.03			10.10	10.09	10.34			10.31	10.13	10.02			10.21	10.03	9.96		
MgO	2.92	2.71	1.81		2.66	2.22	1.66			2.67	2.38	1.37			2.54	2.68	1.65			1.91	2.19	1.70		
Na ₂ O	1.83	1.78	1.88		1.80	1.85	1.91			1.93	1.89	1.93			1.45	1.83	1.88			1.39	1.86	1.94		
K ₂ O	0.03	0.03	0.03		0.04	0.04	0.03			0.03	0.04	0.04			0.04	0.04	0.05			0.01	0.04	0.04		
CaO	0.20	0.19	0.09		0.16	0.09	0.06			0.20	0.10	0.05			0.07	0.07	0.06			0.03	0.10	0.04		
MnO	0.90	0.16	0.25		0.08	0.23	0.20			0.12	0.16	0.24			0.09	0.08	0.23			0.12	0.17	0.33		
TiO ₂	0.37	0.54	0.67		0.51	0.58	0.88			0.47	0.60	0.78			0.16	0.44	0.89			0.16	0.66	0.85		
F	0.33	0.33	0.47		0.41	0.47	0.50			0.59	0.40	0.38			0.14	0.45	0.48			0.14	0.45	0.45		
Cl	0.00	0.02	0.00		0.00	0.00	0.00			0.00	0.41	0.00			0.00	0.00	0.00			0.01	0.00	0.00		
O=F	- 0.14	0.14	0.20		0.17	0.20	0.21			0.25	0.17	0.16			0.06	0.19	0.20			0.06	0.19	0.19		
Total	96.59	97.10	96.75		96.75	97.71	96.75			97.29	96.36	96.97			96.68	96.89	95.89			96.28	95.84	96.33		

Atomic proportions on the basis of 29 (O, F, Cl)

Si	5.760	5.814	5.824		5.816	5.775	5.814			5.792	5.845	5.813			5.863	5.810	5.854			5.851	5.844	5.815		
Al	6.996	6.896	6.836		6.866	6.986	6.842			6.901	6.757	6.800			6.018	6.905	6.740			6.061	6.771	6.766		
Fe*	1.495	1.513	1.740		1.574	1.599	1.760			1.576	1.682	1.815			1.418	1.561	1.781			1.552	1.694	1.831		
B	2.884	2.911	2.916		2.913	2.887	2.907			2.896	2.927	2.911			2.936	2.910	2.931			2.930	2.926	2.912		
Mg	0.726	0.670	0.452		0.662	0.548	0.415			0.660	0.597	0.434			0.625	0.663	0.416			0.473	0.552	0.430		
Na	0.590	0.571	0.612		0.582	0.593	0.621			0.622	0.617	0.628			0.464	0.589	0.619			0.447	0.611	0.636		
K	0.006	0.007	0.007		0.008	0.009	0.007			0.007	0.008	0.008			0.008	0.008	0.011			0.001	0.009	0.008		
Ca	0.036	0.033	0.017		0.029	0.016	0.011			0.036	0.019	0.010			0.013	0.013	0.011			0.004	0.018	0.008		
Mn	0.013	0.023	0.036		0.012	0.032	0.029			0.017	0.023	0.035			0.012	0.011	0.034			0.017	0.024	0.048		
Ti	0.046	0.067	0.084		0.064	0.072	0.111			0.059	0.076	0.098			0.029	0.055	0.114			0.020	0.084	0.108		
F	0.174	0.173	0.251		0.214	0.248	0.266			0.312	0.215	0.204			0.073	0.236	0.259			0.072	0.243	0.240		
Cl	0.000	0.006	0.000		0.000	0.000	0.000			0.000	0.002	0.000			0.000	0.000	0.000			0.004	0.000	0.000		

Symbols: cr = tourmaline core; iz = inner zone; rm = rim

* Calculated assuming Si:B = 2:1

TABLE 6-4. Microprobe analyses of tourmaline from a quartz-tourmaline vein from Kabanga two-mica granite

Tourmaline	1		2		3		4		5	
	CR	RM	CR	RM	CR	RM	CR	RM	CR	RM
SiO ₂	33.97	34.20	33.53	34.34	33.92	34.18	34.36	34.38	34.64	34.12
Al ₂ O ₃	33.31	32.91	33.58	31.62	33.57	32.99	33.52	33.46	34.25	34.02
FeO *	11.50	11.73	13.19	12.63	12.10	11.98	12.77	11.96	12.10	12.40
B ₂ O ₃	9.85	9.92	9.71	9.95	9.84	9.90	9.97	9.96	10.03	10.03
MgO	3.27	3.33	2.42	3.84	3.24	3.21	2.87	3.16	3.02	3.04
Na ₂ O	2.09	2.09	2.03	2.22	2.10	2.05	1.93	2.09	2.09	2.03
K ₂ O	0.07	0.06	0.06	0.07	0.14	0.07	0.04	0.04	0.03	0.05
CaO	0.49	0.40	0.38	0.50	0.42	0.43	0.31	0.37	0.37	0.52
MnO	0.10	0.11	0.12	0.23	0.06	0.12	0.09	0.06	0.08	0.09
TiO ₂	0.75	0.70	0.90	0.95	0.76	0.72	0.45	0.62	0.73	0.73
F	0.66	0.67	0.69	0.77	0.60	0.69	0.55	0.68	0.62	0.71
Cl	0.04	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
O=F	0.28	0.28	0.29	0.32	0.25	0.29	0.23	0.29	0.26	0.30
Total	95.82	95.85	96.35	96.79	96.52	96.06	96.62	96.49	97.71	97.29

Atomic proportions on the basis of 29 (O, F, Cl)

Si	5.773	5.811	5.716	5.824	5.739	5.803	5.803	5.815	5.772	5.732
Al	6.672	6.591	6.749	6.322	6.696	6.603	6.673	6.766	6.725	6.738
Fe*	1.635	1.666	1.881	1.791	1.713	1.702	1.803	1.831	1.686	1.742
B	2.890	2.909	2.858	2.912	2.874	2.901	2.901	2.912	2.886	2.866
Mg	0.829	0.843	0.616	0.791	0.818	0.811	0.733	0.430	0.750	0.761
Na	0.690	0.689	0.672	0.729	0.689	0.676	0.631	0.636	0.675	0.660
K	0.016	0.013	0.013	0.015	0.031	0.016	0.009	0.008	0.007	0.010
Ca	0.088	0.073	0.070	0.091	0.076	0.078	0.056	0.008	0.067	0.093
Mn	0.014	0.016	0.017	0.033	0.008	0.017	0.012	0.048	0.012	0.013
Ti	0.096	0.089	0.115	0.121	0.096	0.092	0.057	0.108	0.091	0.093
F	0.354	0.360	0.373	0.411	0.323	0.373	0.295	0.240	0.325	0.379
Cl	0.010	0.002	0.004	0.003	0.002	0.000	0.000	0.001	0.000	0.000

(See Table 6-3 for definition of symbols)

Compositional range of tourmalines from different rock types (Henry and Guidotti, 1985): Field 1: Li-rich granitoid pegmatites and aplites; 2: Li-poor granitoids, pegmatites and aplites; 3: Fe^{3+} -rich quartz-tourmaline rocks or hydrothermally altered granites; 4: metapelites containing Al-rich phase (e.g., staurolite); 5: metapelites and metapsammities not containing Al-rich phase; 6: Fe^{3+} -rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites; 7: low-ca metaultramafics and Cr, V-rich metasediments; 8: metacarbonates and meta-pyroxenites.

Fig. 6-1. Al-Fe-Mg plot (in molecular proportions) for tourmaline from granites and tourmalinized country rocks in the southern part of the Karagwe-Ankolean belt. All tourmaline data plot in the field occupied by tourmaline from Li-poor granitoids. Clusters of data from tourmaline in different rock types are indicated as follows: I-hydrothermal veins in metasediments, II-tourmalinized phyllites, III-tourmaline leucogranite, IV-quartz-tourmaline veins in two-mica granites, and V-two-mica granites.

Fig. 6-2A. FeO and MgO profiles across optically zone tourmaline from a tourmaline-leucogranite in the Maleba pluton.

Fig. 6-2B. CaO, Na₂O and F profiles across optically zoned tourmaline from a tourmaline-leucogranite in the Maleba pluton.

and F in the tourmaline are compatible with differentiation trends in a magma undergoing crystal fractionation. Enrichment in Ti from core to rim in tourmaline, is however, difficult to reconcile with normal fractional crystallization. Table 6-4 shows analyses of hydrothermal tourmaline from a quartz-tourmaline vein from Kabanga two-mica granite. This, hydrothermal, tourmaline is unzoned, unlike the magmatic tourmaline from Maleba (Table 6-3). Similarity in core and rim compositions of the hydrothermal tourmaline suggests that the tourmaline probably formed under stable physico-chemical conditions.

In the study of chemical variation in tourmalines from different environments in southwest England, Power (1968) noted a systematic decrease of Ca, Mg, and Ti in tourmalines from granites through to aplites, pegmatites, and certain quartz-tourmaline rocks. Neiva (1974) found similar variations in the Mg and Ti contents of tourmalines from comagmatic granite, aplite and pegmatite in Northern Portugal. In both cases, Ca, Mg and Ti variations in tourmaline were attributed to fractionation, observed from the rocks hosting the tourmaline. Chemical variations shown by Ca and Mg in zoned tourmaline in the Maleba leucomonzogranite are consistent with fractionation trends in tourmalines from SW England or Northern Portugal.

A comparison of $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios of tourmaline from the Karagwe-Ankolean belt, the Oliver Creek tin occurrence, Canada (Emond, 1985), and the Hub Kapong batholith, Thailand (Manning, 1982), can be seen in Table 6-5. $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios associated with tourmaline in the two-mica granites from the Karagwe-Ankolean belt are lower than those found in tourmaline from the granites of the Oliver Creek tin deposit. In contrast with tourmaline

TABLE 6-5. Comparison of Fe/(Fe + Mg) ratios for tourmaline from Karagwe-Ankolean granites, NW Tanzania, Oliver Creek tin occurrence, Canada (Emond, 1985), and Hub Kapong batholith, Thailand (Manning, 1982).

Locality	Tourmaline host rock	Fe/(Fe+Mg) Range	Fe/(Fe+Mg) Average
Karagwe-Ankolean	biotite-muscovite granites	0.57-0.62	0.59
	tourmaline-leucogranite	0.67-0.81	0.75
	apfites in two-mica granites	0.67-0.89	0.81
	hydrothermal veins in two-mica granites	0.65-0.75	0.69
	tourmalinized pelitic metasediments	0.80-0.88	0.86
	hydrothermal veins in pelitic metasediments	0.85-0.91	0.89
Oliver Creek Yukon, Canada	biotite-muscovite granite	0.60-0.86	0.76
	hydrothermal vein or breccia matrix		0.53
Hub Kapong batholith, Thailand	apfite dykes	0.68-0.95	0.82
	pegmatites	0.85-0.96	0.90

from the granites, tourmaline from hydrothermal veins in the Oliver Creek deposit has low $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios (0.53). Tourmalines associated with aplite dykes in the Karagwe-Ankolean granites and the Hub Kapong batholith (Manning, 1982) have similar $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios (Table 6-5).

In summary, $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios > 0.5 are generally associated with tourmaline (schorl) in granitic rocks and tin deposits. In contrast, tourmaline from massive sulfide deposits is Mg-rich dravite, with very low $\text{Fe}/(\text{Fe} + \text{Mg})$ ($<< 0.5$) ratios (Taylor and Slack, 1984).

Data from tourmaline from the contact metasomatic aureole and quartz-tourmaline veins in metasediments in the exocontact zone of the Nyamakombe pluton plot in the granite field on the Fe-Al-Mg diagram (Fig. 6-1). Tourmaline in the aureole probably formed by alteration of metasediments by B-rich fluids derived from the pluton. It is possible that tourmalinization of the country rocks took place under conditions of low fluid/rock ratio. Under such conditions the compositions of hydrothermal fluids and tourmaline crystallizing from the fluids were likely to be buffered by the composition of the country rocks. The Fe-rich composition of the tourmaline indicates equilibration with Fe-rich country rocks.

6.1.0 Biotite composition

Experimental and petrological studies of biotite (Eugster and Wones, 1962; Wones and Eugster, 1965; Munoz and Swenson, 1981) have shown that biotite composition depends on the physico-chemical conditions prevailing during crystallization. In addition, some workers (e.g., Levashev et al., 1971, Volkov and Gorbacheva, 1980) have used biotite compositions to deduce qualitatively or quantitatively the P-T-X conditions of magmatic

crystallization. Analytical data for biotite from the Karagwe-Ankolean granites were obtained using an electron microprobe at Carleton University.

6.1.1 Results of microprobe analysis

Representative analyses of biotite from post-orogenic and syn-orogenic two-mica granites are presented in Tables 6-6 and 6-7. The analyses indicate that biotite from the syn-orogenic Bukiriro granite is richer in MgO and lower in FeO than biotite from the post-orogenic granites of the Maleba pluton. The average MgO content in the former is 5.56 wt %; in the latter the average is 2.47 wt %. Consequently, biotite associated with the Bukiriro granite has a lower iron index (average $f_i = 71\%$, where $f_i = \text{molar Fe.100/(Fe+Mg)}$, Levashev et al., 1971) than biotite associated with the Maleba granite (average $f_i = 83\%$). In addition, biotite from the Bukiriro granite contains more Ti, F, K and Na, and less Al and Mn than biotite from the Maleba granite.

Several major element ratios have been used to characterize biotite composition, relating composition to P-T-X conditions. Some ratios are defined and given in Table 6-6 for the biotite analysed in this study. They include the aluminium index (I_i), potassium activity index (K_i), alkalinity index (A_i) and iron index (f_i). The aluminium index (I_i) and K activity index (K_i) of biotite in granitoids depend mainly on the chemical potential of K, and hence can be used as indicators of alkalinity or acidity conditions (Volkov and Gorbacheva, 1980). The aluminium index for biotite decreases with increasing alkalinity whereas the K activity index increases with alkalinity. Also the Si/Al ratio (A_i) of biotite is considered a good indicator of alkalinity conditions (Levashev et al., 1971). This ratio is

Table 6-6 : Microprobe analyses of biotite from Maleba two-mica granite

	Mean				Mean			
	MW-5-1/1	MW-5-1/2	MW-5-1/3	MW-5-1	MW-5-2/1	MW-5-2/2	MW-5-2	
SiO ₂	35.19	35.29	35.28	35.25	34.81	34.86	34.84	
Al ₂ O ₃	18.42	18.46	18.49	18.46	18.53	18.49	18.51	
TiO ₂	2.60	2.47	2.48	2.52	2.42	2.42	2.42	
FeO	26.46	26.36	26.10	26.31	26.20	26.47	26.34	
MgO	3.04	3.04	3.03	3.04	2.83	2.88	2.86	
MnO	0.62	0.64	0.58	0.61	0.55	0.58	0.57	
K ₂ O	9.16	9.12	8.81	9.03	8.89	8.91	8.90	
Na ₂ O	0.01	0.02	0.00	0.01	0.02	0.00	0.01	
F	0.97	0.99	0.99	0.98	0.93	0.94	0.94	
Cl	0.00	0.01	0.00	0.00	0.00	0.00	0.00	
F=O	-0.41	-0.42	-0.42	-0.41	-0.39	-0.40	-0.39	
Cl=O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Total	96.07	95.97	95.34	95.80	94.78	95.17	94.98	

Structural formulae on the basis of 22 (O, F, Cl)

Si	5.534	5.550	5.566	5.550	5.537	5.530	5.534
Al(IV)	2.466	2.450	2.434	2.450	2.463	2.470	2.467
Al(VI)	0.949	0.971	1.005	0.975	1.012	0.987	1.000
Ti	0.308	0.293	0.295	0.299	0.289	0.289	0.289
Fe	3.480	3.467	3.444	3.464	3.486	3.512	3.499
Mg	0.712	0.712	0.712	0.712	0.670	0.682	0.676
Mn	0.083	0.086	0.078	0.082	0.074	0.078	0.076
K	1.838	1.829	1.773	1.813	1.805	1.804	1.805
Na	0.002	0.006	0.000	0.003	0.006	0.001	0.004
F	0.483	0.492	0.492	0.489	0.468	0.473	0.471
Cl	0.000	0.002	0.000	0.001	0.000	0.000	0.000

Compositional indices

f(i)	83.02	82.96	82.87	82.95	83.88	83.74	83.81
l(i)	25.99	26.02	26.13	26.04	26.39	26.23	26.31
A(i)	1.62	1.62	1.62	1.62	1.59	1.60	1.60
K(i)	1.23	1.22	1.21	1.22	1.20	1.21	1.20
Al(IV/VI)	2.60	2.52	2.42	2.51	2.43	2.50	2.47

Definition of compositional indices (After Levashev et al., 1971)

Iron index: $f(i) = \text{Fe}/(\text{Fe} + \text{Mg})$ Aluminium index: $l(i) = \text{Al}/(\text{Al} + \text{Fe} + \text{Mg} + \text{Si})$ Alkalinity index: $K(i) = \text{Si}/\text{Al}$ K activity index: $K(i) = (\text{Fe} + \text{Mg})/\text{Al}$

Al(IV) = Al in tetrahedral coordination

Al(VI) = Al in octahedral coordination

Table 6-7. Microprobe analyses of biotite from Bukiriro two-mica granite

	BU-48/1	BU-48/2	BU-48/3	Mean BU-48
SiO ₂	36.24	35.68	35.52	35.81
Al ₂ O ₃	17.12	17.48	17.24	17.28
TiO ₂	2.68	2.68	2.56	2.64
FeO	24.23	24.03	23.26	23.84
MgO	5.63	5.58	5.47	5.56
MnO	0.30	0.30	0.34	0.31
K ₂ O	9.18	9.24	9.07	9.16
Na ₂ O	0.03	0.03	0.03	0.03
F	1.31	1.54	1.28	1.38
F=O	-0.55	-0.65	-0.54	-0.58
Total	97.27	97.20	95.29	97.24

Structural formulae on the basis of 22 (O, F)

Si	5.631	5.573	5.620	5.608
Al (IV)	2.369	2.427	2.380	2.392
Al (VI)	0.767	0.790	0.835	0.797
Ti	0.313	0.314	0.305	0.311
Fe	3.150	3.138	3.077	3.122
Mg	1.304	1.299	1.289	1.297
Mn	0.039	0.039	0.045	0.041
K	1.820	1.841	1.830	1.830
Na	0.010	0.008	0.008	0.009
F	0.645	0.763	0.638	0.682

Compositional indices *

f(i)	70.72	70.72	70.48	70.64
l(i)	23.72	24.32	24.35	24.13
A(i)	1.80	1.73	1.75	1.76
K(i)	1.42	1.38	1.36	1.39
Al(IV/VI)	3.09	3.07	2.85	3.00

* See Table 6-6 for definition of symbols.

known to increase with increasing pH. The iron index (f_j) (Table 6-6) reflects, to a first approximation, the temperature of biotite crystallization. It increases as the temperature of crystallization decreases and as the degree of geochemical differentiation of the parent magma increases at nearly constant oxygen fugacity. (Volkov and Gorbacheva, 1980; Levashev et al., 1971). Elevated TiO_2 contents in micas are also considered to reflect higher temperatures of crystallization (Volkov and Gorbacheva, 1980; Speer, 1984).

The iron index (f_j) for biotite from the Maleba granite is higher than that of biotite from the Bukiriro granite, suggesting that the Maleba biotite probably formed at low temperatures from a more evolved magma. This is consistent with field and chemical evidence which indicate that the Maleba granite crystallized at shallower depths from a magma with higher $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{MgO})$ ratio (0.89) than the Bukiriro granite [$\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{MgO}) = 0.81$]. Low TiO_2 biotites associated with the Maleba granites also points to low crystallization temperatures. The alkalinity indices, A_j and K_j , are slightly higher and the aluminium index (l_j) slightly lower for biotite associated with the Bukiriro granite than those for biotite associated with the Maleba granite. Following the work of Levashev et al. (1971) and Volkov and Gorbacheva (1980), the indices suggest that biotite in the syn-orogenic Bukiriro granite crystallized under more alkaline conditions than biotite associated with the post-orogenic Maleba granite. It has been suggested in the literature that the chemical potential of alkalis in a magma governs the isomorphous substitution of Si and $\text{Mg} + \text{Fe}$ for Al in biotite (Yermolov and Tyan, 1975). Increase in potential reduces the amount

of excess Al_2O_3 and produces biotite low in alumina and vice-versa (Yermolov and Tyan, *op cit*). Differences in the chemical potential of alkalis in the parent magmas may have been responsible for the formation of biotite of contrasting alumina content in the studied granites.

Differences in F content of biotite from the Bukiro and the Maleba granites can be related either to "Fe-F avoidance" or differences in the F contents of the original magmas. Hydroxyl-bearing ferromagnesian minerals with high Mg/Fe ratios concentrate more F than comparable minerals with lower Mg/Fe ratios. This is commonly referred to as "Fe-F avoidance" (Rosenberg and Foit, 1977; Munoz, 1984). High F contents in biotite from the Bukiro granite, relative to biotite from the Maleba granite, correlates with high MgO content in the biotite and high F content in the whole-rocks from the granite.

Figure 6-3 shows the plot of biotite compositions on the $\text{KFe}_3^{2+}\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ - $\text{KFe}_3^{3+}\text{AlSi}_3\text{O}_{12}(\text{H}_2\text{O})$ - $\text{KMg}_3^{2+}\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ triangular diagram (Wones and Eugster 1965). Biotite solid solutions under various oxygen fugacity buffers from Wones and Eugster are also shown. It can be seen that the data for biotite from the Karagwe-Ankolean granites plot close to the trend of biotite solid solutions buffered by the nickel-bunsenite (Ni-NiO) buffer. Data from the Maleba biotites (Mb-13) plot on the Ni-NiO buffer line while data for the Bukiro biotites (Mk-2) plot slightly above the line. These data suggest that biotite in the Maleba and Bukiro two-mica granites crystallized or equilibrated under oxygen fugacity conditions approximating those of Ni-NiO buffer. The moderate oxygen fugacity conditions indicated by the biotite compositions for the crystallization of

□ Maleba granites

△ Bukiriro granites

Fig. 6-3. Fe^{2+} - Fe^{3+} -Mg triangular plot for biotite from the Bukiriro and Maleba two-mica granites. Biotite compositions under various oxygen fugacity buffers from Wones and Eugster (1965) are also shown.

the two-mica granites are consistent with ilmenite being the main oxide phase in the granites.

XRF analyses of co-existing biotite-K-feldspar pairs from the Maleba and the Bukiriro granites are presented in Table 6-8. It can be seen from the analyses that Rb, Zn Nb, Y, Zr, Sr, Cr, Ni, and V are more enriched in biotite than in K-feldspar, a feature that can be partly attributed to the ability of biotite to accommodate a large number of trace elements, and to include minerals such as zircon, apatite, xenotime and monazite. In contrast to biotite, few trace elements are accommodated in K-feldspar and these are mainly Rb, Ba and Sr. Mineral inclusions are also rare or lacking in K-feldspar.

It is interesting to note that K-feldspar from the Maleba granite (MB-13, Table 6-8) is lower in Ba and Sr and higher in Rb than K-feldspar from the Bukiriro granite (MK-2). Barium is also lower and Rb and Zn higher in the Maleba biotite than in the Bukiriro biotite. These data are consistent with whole-rock major and trace element data which indicate that the Maleba granites are more differentiated than the Bukiriro granites. The occurrence of Sn-bearing pegmatites in the former is yet another indication of geochemical specialization.

The distribution of Rb between co-existing biotite and K-feldspar in the granites could be used to constrain temperatures of crystallization or final "equilibration" (Beswick, 1973). Beswick has shown from experimental data that phlogopite-sanidine distribution coefficients ($K_D^{p/s}$) for Rb/K are temperature dependent in the dilute Rb concentration range found in natural mica and feldspar. The temperature dependence of the distribution

Table 6-8. XRF analyses of biotite-K-feldspar pairs from Maleba (MB-13) and Bukiriro (MK-2) two-mica granites

	MB-13	MB-13	MK-2	MK-2
	BIOTITE	K-FELDS.	BIOTITE	K-FELDS.
SiO ₂	35.42	64.44	35.32	65.17
Al ₂ O ₃	19.92	18.81	18.9	18.49
TiO ₂	2.46	0.01	2.74	0.02
Fe ₂ O ₃ (T)	27.1	0.08	27.78	0.11
MgO	3.44	0	3.82	0
MnO	0.64	0	0.42	0.01
CaO	0.12	0.36	0.1	0.44
K ₂ O	8.64	13.04	9.04	12.98
Na ₂ O	0	1.92	0.06	1.84
P ₂ O ₅	0.16	0.21	0.14	0.17
Rb	1802	690	1736	652
Ba	94	425	186	653
Sr	46	94	44	117
Zn	1010	7	890	10
Cr	110	9	120	7
Ni	142	0	12	4
V	28	0	30	0
Nb	146	0	118	0
Zr	136	17	198	26
Y	76	21	104	26
K/Rb	39.82	156.88	43.23	165.46
Rb/Sr	39.16	7.34	41.35	5.62
Ba/Sr	2.06	4.52	4.44	5.63

coefficients is given by the equation: $\text{Log}(K_D^{p/s}) = 0.406 \times 10^3/T^\circ \text{K} + 0.091$. Applications of this equation to the co-existing alkali feldspar and biotite in igneous or metamorphic rocks have, in many cases, yielded reasonable temperatures for magmatic crystallization or metamorphic recrystallization (Beswick, 1973; Speer, 1984). A temperature correction of the order of $\pm 50^\circ \text{C}$ may be needed to account for errors in Rb and K determinations (Beswick, 1973). The distribution coefficients ($K_D^{b/f}$) of Rb/K in biotite-K-feldspar pairs from the Karagwe-Ankolean granites and corresponding temperatures of "equilibration" are given in Table 6-9 together with some of Beswick's data from other granites. Biotite and K-feldspar pairs from the Maleba granite (MB-13) and Bukiriro granite (MK-2) give "equilibration" temperatures of 570°C and 590°C , respectively. These temperatures appear to be relatively low for magmatic crystallization of rocks with chemical composition similar to the Maleba and Bukiriro granites. If, however, biotite and K-feldspar underwent re-equilibration it is possible that the calculated temperatures are indicative of this event. Re-equilibration of biotite and K-feldspar in the granites may have occurred during the Bukoban-Katangan tectonothermal events which affected the Kibaran/Karagwe-Ankolean rocks at ca 900-700 Ma.

6.2.0 White mica composition

Electron microprobe analyses and structural formulae of white micas or "muscovite" from Maleba granites are given in Tables 6-10 and 6-11. The micas include mica from: a) biotite-muscovite granite, b) muscovite granite and, c) hydrothermally-altered two-mica granite. Muscovite from the first two groups is considered magmatic because of texture and other criteria

Table 6-9. Biotite-alkali feldspar distribution coefficients (K_D) for Rb/K from Maleba and Bukiriro granites and their corresponding temperatures of "equilibration". Beswick's (1973) data for granites in other localities are also shown for comparison.

K_D	$^{\circ}\text{C}$	Rock type/Locality
3.83	590	Bukiriro two-mica granite
3.94	570	Maleba two-mica granite
2.7	970	Granodiorites
3.8	590	from Corsica (Beswick, 1973)
2.61	1020	Granitic rocks,
4.03	570	New England (Beswick, 1973)
4	550	Granites,
4.05	550	S. Australia (Beswick, 1973)

Table 6-10. Representative microprobe analyses of magmatic muscovite from Maleba granites

	MW-5/1	MW-5/2	MW-5/3	Mean MW-5	MA-15/1	MA-15/2	Mean MA-15
SiO ₂ %	45.70	45.12	45.62	45.48	45.35	45.87	45.61
Al ₂ O ₃	34.19	34.26	34.26	34.24	34.83	34.38	34.61
TiO ₂	0.36	0.40	0.40	0.39	0.17	0.22	0.20
FeO	2.51	2.38	2.58	2.49	1.36	1.52	1.44
MgO	0.67	0.66	0.65	0.66	0.74	0.82	0.78
MnO	0.07	0.06	0.08	0.07	0.12	0.20	0.16
K ₂ O	10.83	10.42	10.71	10.65	10.32	10.66	10.49
Na ₂ O	0.30	0.36	0.34	0.33	0.46	0.40	0.43
F	0.42	0.40	0.39	0.40	0.51	0.43	0.47
Cl	0.00	0.00	0.04	0.01	0.00	0.00	0.00
F=O	-0.18	-0.17	-0.16	-0.17	-0.21	-0.18	-0.20
Cl=O	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
Total	94.87	93.89	94.90	94.55	93.65	94.32	93.98

Structural formulae on the basis of 22 (O, F, Cl)

Si	6.178	6.149	6.166	6.164	6.163	6.203	6.183
Al(IV)	1.822	1.851	1.834	1.836	1.837	1.797	1.817
Al(VI)	3.626	3.653	3.624	3.634	3.741	3.682	3.712
Ti	0.037	0.041	0.040	0.039	0.017	0.022	0.020
Fe	0.284	0.271	0.291	0.282	0.156	0.172	0.164
Mg	0.135	0.133	0.131	0.133	0.149	0.165	0.157
Mn	0.008	0.007	0.009	0.008	0.014	0.023	0.019
K	1.867	1.811	1.847	1.842	1.788	1.839	1.814
Na	0.078	0.096	0.089	0.088	0.122	0.106	0.114
F	0.178	0.172	0.166	0.172	0.219	0.183	0.201
Cl	0.000	0.000	0.009	0.003	0.000	0.000	0.000

Cation site occupancies

X	1.945	1.907	1.936	1.929	1.910	1.945	1.928
Y	4.090	4.105	4.095	4.097	4.077	4.064	4.071
Z	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Y'	3.960	3.982	3.965	3.969	3.976	3.951	3.964

Y': Y site cations expressed in terms of Al cation equivalents

MW-5: muscovite from biotite-muscovite granite, Maleba pluton

MA-15: muscovite from muscovite leucogranite, Maleba pluton

Table 6-11. Microprobe analyses of white mica from hydrothermally altered two-mica granite in the Maleba pluton.

	Mean			Mean		
	MA-33-1A	MA-33-1B	MA-33-1	MA-33-2A	MA-33-2B	MA-33-2
SiO ₂ %	45.39	44.52	44.96	45.39	45.28	45.34
Al ₂ O ₃	32.46	34.60	33.53	31.71	31.84	31.78
TiO ₂	0.41	0.14	0.28	0.47	0.43	0.45
FeO	0.29	2.65	1.47	3.51	3.38	3.45
MgO	0.15	0.40	0.28	0.64	0.58	0.61
MnO	0.21	0.14	0.18	0.26	0.20	0.23
K ₂ O	10.57	10.65	10.61	10.59	10.46	10.53
Na ₂ O	0.26	0.32	0.29	0.24	0.23	0.24
F	0.58	0.42	0.50	0.75	0.57	0.66
Cl	0.02	0.00	0.01	0.01	0.01	0.01
F=O	-0.24	-0.18	-0.21	-0.32	-0.24	-0.28
Cl=O	0.00	0.00	0.00	0.00	0.00	0.00
Total	90.09	93.66	91.88	93.25	92.74	92.99

Structural formulae on the basis of 22 (O, F, Cl)

Si	6.384	6.104	6.244	6.294	6.295	6.295
Al(IV)	1.616	1.896	1.756	1.706	1.705	1.706
Al(VI)	3.765	3.695	3.730	3.476	3.511	3.494
Ti	0.044	0.015	0.030	0.049	0.045	0.047
Fe	0.034	0.304	0.169	0.407	0.393	0.400
Mg	0.031	0.082	0.057	0.132	0.062	0.097
Mn	0.025	0.016	0.021	0.031	0.024	0.028
K	1.896	1.862	1.879	1.874	1.855	1.865
Na	0.070	0.086	0.078	0.066	0.062	0.064
F	0.256	0.184	0.220	0.328	0.251	0.290
Cl	0.004	0.000	0.002	0.001	0.002	0.002

Cation site occupancies

X	1.966	1.948	1.957	1.940	1.917	1.929
Y	3.899	4.112	4.006	4.095	4.035	4.065
Z	8.000	8.000	8.000	8.000	8.000	8.000
Y'	3.884	3.983	3.933	3.921	3.890	3.906

Y': Y site cations expressed in terms of Al cation equivalents

given by Speer (1984). Analytical data indicate that significant differences in FeO, MgO, MnO and TiO₂ contents occur in the two types of magmatic muscovite but none in F content. Magmatic muscovite from the two-mica granite is higher in FeO ($\bar{x}$ = 2.49 %) and TiO₂ ($\bar{x}$ = 0.39 %), and lower in MgO ($\bar{x}$ = 0.66 %), MnO ($\bar{x}$ = 0.07) and Na₂O ($\bar{x}$ = 0.33) than muscovite from the muscovite granite. Distribution of Fe and Ti between muscovite from the two granite types are consistent with chemical trends expected in minerals crystallizing from magma undergoing crystal fractionation. The enrichment of MgO and MnO in muscovite from the muscovite granite is, however, not compatible with fractional crystallization. It is possible that the lack of ferromagnesian minerals to scavenge Mg and Mn from the leucogranitic magma resulted in the enrichment of these elements in muscovite.

White mica from hydrothermally-altered two-mica granite could represent either magmatic muscovite that has re-equilibrated with hydrothermal fluids or secondary muscovite produced by metasomatic alteration of feldspar and/or biotite. Unlike the magmatic muscovite, the hydrothermal muscovite commonly contains detectable amounts of Cl of up to 0.02 wt % (Table 6-11). The FeO, MnO and SiO₂ contents of the hydrothermal muscovite are slightly higher, and MgO and TiO₂ contents slightly lower than those of magmatic muscovite from unaltered two-mica granite. Mean Na/(Na + K) atomic ratio is higher in the magmatic muscovite ($\bar{x}$ = 0.057) than in hydrothermal muscovite in the two-mica granite. In the muscovite from the unaltered two-mica granite the mean Na/(Na + K) ratio is 0.045 while in the altered granite the ratio is 0.037. The Na/(Na + K) ratios observed in the muscovites from the Maleba granites fall within the range of ratios given by Speer (1984) for magmatic and hydrothermal muscovites. Magmatic muscovites are considered the most sodic,

with Na/(Na + K) values of 0.06 to 0.12, late to post-magmatic muscovites have Na/(Na + K) values in the range of 0.01 to 0.07 while hydrothermal muscovites have values < 0.04 (Speer, 1984).

Like other igneous and hydrothermal muscovites reported in the literature, muscovite from the Maleba granites shows marked deviations from the ideal composition $K_2Al_4(Si_6Al_2)O_{20}(OH, F)_4$. The deviations are attributed to coupled atomic substitutions involving atoms mainly in the octahedral (Y) and tetrahedral (Z) sites but also in the interlayer (X) site, in response to variations in bulk composition, pressure and temperature conditions of muscovite crystallization. The "Tschermak" exchange $(Mg, Fe^{2+})^{vi}, Si^{iv} = Al^{vi}, Al^{iv}$ and the substitution of Fe^{3+} for Al^{vi} account for the large part of the deviation of muscovite from the ideal composition (Guidotti, 1984). In addition, other medium-sized cations such as Ti, V, Cr, Mn, Co, Ni, Cu and Zn may be incorporated in the octahedral (Y) site, and Na may substitute for K in the X site (Bailey, 1984). Vacancies or uncharged components, e.g., Ar or H_2O , are partly permissible in the X site if charge balance is accomplished (Bailey, op cit.). As can be seen from Tables 6-10 and 6-11, the muscovite from the Maleba granites has slight deficiency in X site cations and excess cations in the Y site. The number of cations in the Y site, from 4.071 to 4.105, exceeds the required number of 4 by an amount of 0.071 to 0.105 cations per formula unit. Excesses of cations in the Y site appear, however, to be counterbalanced by cation deficiencies of the same orders of magnitude in the X site. It is, however, not well-known whether some of the cations accommodated in the Y site (e.g., Fe^{2+} , Mg) can be also partly accommodated in the X site to

maintain charge balance. Nevertheless, the amounts of excess Y site cations in the calculated formulae for muscovite from the Maleba granites are several orders of magnitude lower than those observed in other muscovite analyses reported in the literature (e.g., Neiva, 1982). Other variations in the muscovite composition may be partly explained by the Tschermak substitution mentioned earlier. The increase in the amount of Si in the tetrahedral site appears to be accompanied by the general decrease of Al^{IV} and Al^{VI} , and the increase of Fe and Mg in the octahedral site, in accordance with the Tschermak exchange scheme. The observed values of Al^{VI} are, however, 3 % to 6 % lower than the expected values if Al^{VI} variations in the muscovite (Table 6-10) were controlled by the Tschermak exchange toward phengite ($K_2[Al_3(Mg,Fe^{2+})](Si_7Al)O_{20}(OH,F)_4$) composition. Also Fe and Mg contents in the muscovite are 43 % to 60 % higher than those expected from Tschermak exchange. An additional cation exchange of the type: $(Mg,Fe^{2+}),Ti^{4+} = 2Al^{VI}$ appears necessary to fully account for the compositional variations in the muscovite from the Maleba granites.

Comparison of chemical analyses of muscovites from stanniferous granites of Portugal (Neiva, 1982) with those of muscovites from the Maleba granites reveals some significant differences. Muscovites from Portugal granites have higher contents of $FeO + Fe_2O_3$ (3.25-3.94 %), MgO (2.17-1.49 %), TiO_2 (0.60-0.89 %) and Cl (0.02-0.04 %), and lower F (0.03-0.02 %) than muscovites from the stanniferous granites of the Maleba pluton. The fact that muscovites from Portugal granites have higher contents of Fe, Mg and Ti and lower F than muscovites from the Maleba granites suggest higher temperatures of crystallization. Elevated F and B contents in the parent magmas for the Maleba granites may have lowered solidus temperatures and allowed

crystallization of muscovite with low Fe, Mg and Ti contents and relatively high F content. Contrasts in F content of the muscovites from Portugal and Tanzania may reflect F differences in the original magmas. Because muscovites from the Portugal granites have lower Fe/(Fe + Mg) ratios (0.45-0.58) than muscovites from the Maleba granites ($\text{Fe}/(\text{Fe} + \text{Mg}) = 0.58\text{-}0.85$), the low F content in the former cannot be accounted for by "Fe-F avoidance" (e.g., Munoz, 1984).

6.3.0 Composition and structural state of alkali feldspars

X-ray and optical studies of alkali feldspars (Wright and Stewart, 1968; Stewart and Wright, 1974) complemented by chemical or microprobe analyses have provided useful information which relates variations in composition and structural state of the feldspars to their unit cell parameters. These and other studies have shown that various polymorphic modifications or structural states of an alkali feldspar differ mainly in their aluminium-silicon (Al-Si) distributions. Highest degree of Al-Si disordering is found in high sanidine (HS)-high albite (AA) feldspar series while maximum ordering is found in maximum or low microcline (LM)-low albite (LA) series. Thus high temperature monoclinic $c2/m$ alkali feldspars have essentially random Al-Si distributions while their low temperature triclinic counterparts are almost completely ordered. Feldspars with Al-Si ordering between that of HS-AA and LM-LA limiting series are said to be of intermediate structural states. Unit cell parameters of an alkali feldspar depend mainly on composition and Al-Si configuration; in some cases the parameters also reflect strain resulting from sanidine-microcline inversion or from exsolution of coherent phases (Kroll and Ribbe, 1983). The degree

of Al-Si ordering in alkali feldspar, expressed in terms of tetrahedral site (T_i) occupancy, can be estimated from the average Al content ($t_{10} + t_{1m}$ for triclinic symmetry, $2t_1$ for monoclinic symmetry) of tetrahedral sites calculated from b and c unit cell parameters (Kroll and Ribbe, op cit). Values of $t_{10} + t_{1m}$ and $2t_1$ can either be calculated from the equations given by Kroll and Ribbe (1983):

$$t_{10} + t_{1m} = (b - 0.7138 - (1.7505)c)/(-7.7245 + (1.0150)c) \quad (1)$$

$$2t_1 = -7.590 - (2.3258)b + (5.3581)c \quad (2)$$

or estimated from b - c plots contoured for $t_{10} + t_{1m}$ (e.g., Fig. 6-4) or $2t_1$. Relative comparison of structural states of alkali feldspars from various geologic settings is easily accomplished on a b - c plot.

Composition of alkali feldspar, expressed as molar proportion of KAlSi_3O_8 (n_{Or}), can be estimated from unit cell volume. Compositional and structural studies of alkali feldspar indicate that unit cell volume V depends mainly on K, Na content and is almost, but not entirely, independent of Al, Si distribution. Polynomial functions proposed by Kroll and Ribbe (1983) for estimating feldspar composition from cell volume are given below.

For AA-HS series, (3)

$$n_{Or} = -584.6683 + (2.58732)V - (3.83499 \times 10^{-3})V^2 + (1.90428 \times 10^{-6})V^3$$

For LA-LM series, (4)

$$n_{Or} = -1227.8023 + (5.35958)V - (7.81518 \times 10^{-3})V^2 + (3.80771 \times 10^{-6})V^3$$

For feldspar of intermediate or unknown structural state, (5)

$$n_{Or} = -929.1523 + (4.07032)V - (5.96146 \times 10^{-3})V^2 + (2.91994 \times 10^{-6})V^3$$

A simpler equation for estimating orthoclase content of alkali feldspar from unit cell volume, given by Stewart and Wright (1974), is as follows:

$$\text{Or (mole \%)} = \frac{0.2962 - (0.953131 - (0.0013 \times V))^{1/2}}{0.00018062}$$

In the present study, alkali feldspars from various Karagwe-Ankolean granites and aplites were analysed by X-ray diffraction and microprobe to determine composition and structural state. Analytical procedures and data reduction techniques are given in Appendices 3 and 7. The results are discussed in the following section.

6.3.1 Results of X-ray diffraction and microprobe analysis

Refined unit cell parameters from X-ray diffraction data of alkali feldspars are given in Table 6-12 and Figures 6-4 and 6-5. Potassic feldspars from unaltered or least altered post-orogenic two-mica granite (Mb-13) and tourmaline leucogranite (Ma-19) of the Maleba pluton plot along $0.89 t_{10} + t_{1m}$ contour on the b-c plot (Fig. 6-4) while potassic and sodic feldspars from hydrothermally altered, Sn-enriched, two-mica granite (Ma-18) and pegmatitic aplite dyke (Mb-37) plot close to the 1.0 contour. These data suggest that alkali feldspar from the unaltered two-mica granite and tourmaline leucogranite are of equivalent structural state. Furthermore, the data indicate that alkali feldspars from altered, Sn-enriched, granite and aplite dyke are more ordered in terms of Al-Si distribution than alkali feldspars from the unaltered granites.

Data from potassic feldspar from the syn-orogenic Bukiro granite (Mk-2) in the central part of the Bushubi batholith plot on the 0.9 contour on the b-c plot (Fig. 6-4). This alkali feldspar is of similar structural state to the alkali feldspars from the unaltered Maleba granites. Alkali feldspars from tourmaline-muscovite granite (Mu-27, Mumakera pluton), and

TABLE 6-12. Unit cell parameters of alkali feldspars from Karagwe-Ankolean granites and aplite-pegmatite.

	a (Å)	b (Å)	c (Å)	γ (°)	α	β	γ
MB-13 Microcline	8.5495 (0.0022)	12.9428 (0.0090)	7.1982 (0.0019)	714.9 (0.8)	90.60 (0.03)	116.02 (0.02)	87.80 (0.03)
MB-37 Microcline	8.6001 (0.0014)	12.9552 (0.0050)	7.2198 (0.0012)	724.4 (0.4)	90.87 (0.03)	115.82 (0.02)	87.65 (0.03)
MB-37 Albite	8.1473 (0.0016)	12.7961 (0.0070)	7.1641 (0.0015)	666.3 (0.4)	94.28 (0.02)	116.56 (0.02)	87.74 (0.03)
MA-18 Albite	8.1452 (0.0018)	12.8123 (0.0135)	7.1670 (0.0024)	666.5 (1.2)	94.32 (0.01)	116.62 (0.02)	87.96 (0.02)
MA-19 Microcline	8.5617 (0.0037)	12.9333 (0.0081)	7.1948 (0.0020)	716.5 (0.7)	90.54 (0.06)	115.91 (0.02)	87.90 (0.05)
MU-27 Microcline	8.5665 (0.0028)	12.9349 (0.0087)	7.2075 (0.0020)	717.6 (0.8)	90.69 (0.03)	115.93 (0.02)	87.65 (0.03)
MK-2 Microcline	8.5523 (0.0017)	12.9400 (0.0062)	7.1986 (0.0011)	715.5 (0.6)	90.58 (0.02)	115.98 (0.02)	87.79 (0.02)
KT-10 Microcline	8.5627 (0.0023)	12.9357 (0.0092)	7.2041 (0.0024)	717.4 (0.8)	90.75 (0.03)	115.91 (0.03)	87.60 (0.03)
KY-4 Microcline	8.5954 (0.0018)	12.9715 (0.0082)	7.2174 (0.0014)	722.9 (0.8)	90.88 (0.04)	115.96 (0.02)	87.62 (0.03)
KY-4 Albite	8.1471 (0.0015)	12.8101 (0.0059)	7.1572 (0.0011)	664.8 (0.5)	94.27 (0.01)	116.71 (0.02)	87.69 (0.02)

MB-13: two-mica granite, MB-37: sodic pegmatitic aplite, MA-18: altered two-mica granite, MA-19: tourmaline leucadamellite, from Maleba pluton;
 MU-2: two-mica granite, Mumakera pluton; MK-2: Bukiro two-mica granite;
 KT-10: two-mica granite, KY-4: pegmatitic aplite, from Karagwe Tinfield.

Sample numbers: 1 = MK-2, 2 = MB-13, 3 = MA-19, 4 = MA-18, 5 = MB-37 (LM), 6 = MB-37 (LA), 7 = NU-27, 8 = KT-10, 9 = KY-4 (LM), 10 = KY-4 (LA). (Sample descriptions are given in Table 6-12).

Fig. 6-4. "b" versus "c" plot of unit cell parameters for alkali feldspars from Karagwe-Ankolean granites and aplite dykes. The $t_{10} + t_{1m}$ contours are those given by Kroll and Ribbe (1983).

hydrothermally altered two-mica granite (Kt-10) and pegmatitic aplite dyke (Ky-4) of the Kaitambuzi/Kasanza cupola, Ibanda arena, in the Karagwe Tinfield plot close to the 0.95 contour. They are therefore slightly more ordered than alkali feldspars from the unaltered Maleba granites.

Higher degree of Al-Si ordering in the alkali feldspars from the hydrothermally altered, Sn-enriched, granites and pegmatitic aplites relative to those from unaltered granites may be attributed to hydrothermal fluid-rock interaction and Al-Si re-distribution in the feldspars. The interaction of hydrothermal fluids with the feldspars may have facilitated migration of Al from the T_{20} and T_{2m} sites to the T_{10} and T_{1m} sites. Although re-equilibration of the granites with hydrothermal fluids at low temperatures was probably responsible for promoting the Al-Si ordering of their alkali feldspars, this may not be necessarily true for feldspars in the pegmatitic aplites. High Al-Si ordering in the latter may be primary and possibly related to low temperature crystallization from H_2O -saturated residual silicate magmas. Pegmatite pods in the aplites indicate H_2O -fluid saturation in the residual magmas (Jahns and Burnham, 1969).

The information derived from the study of alkali feldspars shows that altered granites and aplites in the Karagwe-Ankolean belt of northwestern Tanzania contain structurally more ordered feldspars than the unaltered granites. This could be particularly useful in identifying weakly altered granites, which otherwise lack obvious alteration features, that may be closely associated with tin or other rare-metal mineralization.

Figure 6-5 shows the plot of "a" parameter against "bxc". According

Fig. 6-5. "b x c" versus "a" plot of unit cell parameters for alkali feldspars from Karagwe-Ankolean granites and aplites. Unstrained alkali feldspar normally plot in a narrow band shown in the diagram, while strained feldspars plot outside this band (Kroll and Ribbe, 1983). (Sample numbers same as in Figure 6-4).

to Kroll and Ribbe (1983), unstrained or normal alkali feldspars plot in a narrow curved band while strained/ coherent alkali feldspars plot outside the band. The strain referred to here is that resulting from exsolution of coherent K-rich and Na-rich phases from originally homogeneous alkali feldspar upon cooling from high to low temperatures. The effects of strain are manifested in the formation of alkali feldspars with anomalous unit cell dimensions, in which $|\Delta a| = |a_{\text{observed}} - a_{\text{estimated from b and c}}|$ is at least greater than $0.05 \text{ \AA}$ (Stewart and Wright, 1974). Table 6-13 gives $|\Delta a|$ values calculated from unit cell parameters of alkali feldspars from Karagwe-Ankolean granites and aplites. Alkali feldspars from more hydrothermally altered, Sn-enriched, granite (Ma-18) and aplites (Mb-37, Ky-4) have $|\Delta a|$ values lower than $0.05 \text{ \AA}$ while feldspars from unaltered or weakly altered granites have values greater than $0.05 \text{ \AA}$. The former plot either within or close to the field of normal alkali feldspars on the "a" vs. "bxc" plot (Fig. 6-5) while the latter are more displaced from the normal feldspar field. These data suggest that potassic and sodic alkali feldspars from unaltered or moderately altered Karagwe-Ankolean granites are more coherent and hence more strained than those from more altered granites or aplites.

Table 6-14 shows orthoclase (Or) contents of alkali feldspars determined from unit cell volume and/or microprobe analysis. Although good agreement between measured and calculated alkali feldspar composition has been reported by some authors (e.g., Crosby, 1971) this does not seem to be true for the data presented in Table 6-14. The calculated compositions are 9 to 16 mole percent orthoclase lower than those obtained from microprobe analysis. The only exceptions are the highly ordered potassic feldspars from aplite,

Table 6-13. $|\Delta a|$ values calculated from *b* and *c* unit cell parameters of alkali feldspar from Karagwe-Ankolean granites and aplites.

	$a_{\text{obs.}}$	$a_{\text{est.}}$	$ \Delta a = a_{\text{obs.}} - a_{\text{est.}} $
MB-13 Microcline	8.5495	8.4179	0.1316
MB-37 Microcline	8.6001	8.5950	0.0058
MB-37 Albite	8.1473	8.1554	0.0081
MA-18 Albite	8.1452	8.1787	0.0335
MA-19 Microcline	8.5617	8.3883	0.1734
MU-27 Microcline	8.5665	8.4367	0.1298
MK-2 Microcline	8.5523	8.4134	0.1388
KT-10 Microcline	8.5627	8.4251	0.1375
KY-4 Microcline	8.5954	8.6341	0.0386
KY-4 Albite	8.1471	8.1569	0.0098

$$a_{\text{est.}} = 8.634 - (11.437 - 0.12226 \times b \times c^{1/2}) \quad (\text{Kroll and Ribbe, 1983}).$$

Table 6-14. Orthoclase contents (mole %) of alkali feldspars estimated from unit cell volumes and/or microprobe analysis.

	Or (estimated) %	Or (micro. analysis) %
MB-13 Microcline	79.5	95.6
MB-37 Microcline	105.6	--
MB-37 Albite	4.2	--
MB-18 Albite	4.5	--
MA-19 Microcline	83.4	--
MU-27 Microcline	86.3	95.8
MK-2 Microcline	81.0	94.7
KT-10 Microcline	85.6	94.7
KY-4 Microcline	100.8	--
KY-4 Albite	1.6	--

with calculated orthoclase content* close to 100 %. Kroll and Ribbe (1983) noted that differences of up to 10-15 mole % Or may be encountered in the composition estimated from cell volume and that estimated by microprobe analysis. The calculated compositions are expected to be more accurate if the structural state and composition of feldspars being studied are similar to those of feldspars from which the empirical equations for estimating Or content were originally derived.

It is clear from the microprobe analyses given in Table 6-14 that potassic feldspars from the Karagwe-Ankolean granites are very low in the albite component. The analysed feldspars generally contain less than 5 mole percent albite. Alkali feldspars with very low albite content (<15 mole %) are considered to be products of low-temperature crystallization or re-equilibration (Tuttle and Bowen, 1958). Experimental data indicate that the position of the alkali feldspar solvus is dependent on the structural state of the phases. The maximum-microcline low-albite solvus is considered stable below about 500° to 600° C (Yund and Tullis, 1983). Such temperatures are in good agreement with K-feldspar-biotite equilibration temperatures of 570° to 590° C estimated from Beswick's (1975) geothermometer. It appears likely that maximum-microcline of very low albite content in the Karagwe-Ankolean granites owes its origin to low temperature crystallization or re-equilibration.

6.4.0 Garnet composition

Garnets have the general formula $X_3Y_2Z_3O_{12}$ (Černý and Hawthorne, 1982), where $X = \text{Ca, Mn, Fe}^{2+}, \text{Mg} \pm \text{Zn}$, Y^{3+}, Na ; $Y = \text{Al, Fe}^{3+}, \text{Cr}^{3+} \pm \text{Ti, V}^{3+}, \text{Fe}^{2+}, \text{Sn}^{4+}, \text{Zr}$; $Z = \text{Si} \pm \text{Al, Ti, Fe}^{3+}, \text{P}$. There are at least 17 documented

garnet group end-members. Complete isomorphism occurs within the individual groups but may be limited or less common between them. Garnets found in granitic rocks belong mainly to the almandine ($\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$)-spessartine ($\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$) solid solution series, although minor amounts of Mg, Ca and other elements may be also present in the garnets (Cerny and Hawthorne, *op cit*).

6.4.1 Results of microprobe analysis

Compositions of garnet from aplites in the Karagwe-Ankolean granites have been determined by microprobe analysis and are presented in Table 6-15 and Appendix 6. The compositions are closely similar to those of garnet from similar rock types (e.g., Leake, 1967; Manning, 1983). The garnets vary in chemical composition from Fe- and Mn-rich to Mn-rich Fe-poor varieties of the almandine-spessartine series. Two types of spessartine-rich garnets are distinguished from the aplites. Type 1 is very high in spessartine (78-82 %) and grossular (3.03-3.36 %) contents and low in almandine (14.57-18.40 %) content. Type 2 is low in spessartine (55.5-68 %) and grossular (0.35-0.7 %) contents but high in almandine (31.53-43.86 %). The two types of garnets occur in chemically and texturally distinct aplite dykes (see section 3.2.3). Aplites (Type III) that host Type 1 garnet have a fine-grained, albite-rich ($\text{K}_2\text{O}/\text{Na}_2\text{O} = 0.1$) groundmass locally containing K-feldspar pegmatite pods. Fine-grained (≤ 0.25 mm), poorly developed, white mica flakes are scattered throughout the groundmass while garnet forms euhedral crystals (2-4 mm). Aplite (Type IV) hosting Type 2 garnet contains fine-grained albite and has a K-feldspar groundmass ($\text{K}_2\text{O}/\text{Na}_2\text{O} = 0.39$). Garnet occurs in pink euhedral crystals up to 2 mm in size. Muscovite occurs in well-developed medium-

TABLE 6-15. Microprobe analyses of garnets from aplites expressed in terms of molar proportions of almandine, pyrope, spessartine and grossular (raw data are given in Appendix 6)

	ALM. %	PYRO. %	SPES. %	GROS. %
MA-28-1	18.40	0.00	78.19	3.33
	14.64	0.00	82.24	3.04
	14.86	0.00	81.92	3.15
Average	15.97	0.00	80.78	3.17
MA-28-2	14.89	0.00	82.00	3.03
	14.62	0.00	81.93	3.36
	14.57	0.04	82.29	3.10
Average	14.69	0.07	82.07	3.16
KY-4-1	38.27	0.04	61.34	0.36
	31.53	0.04	67.82	0.61
	43.86	0.04	55.52	0.59
Average	37.89	0.04	61.56	0.52
KY-4-2	33.45	0.00	65.96	0.58
	38.21	0.04	61.06	0.70
	43.05	0.04	56.56	0.35
Average	38.24	0.03	61.19	0.54
KY-4-3	42.95	0.00	56.61	0.44
	31.55	0.04	67.94	0.47
	39.54	0.00	60.11	0.35
Average	38.01	0.01	61.55	0.42
MB-12-1	58.02	0.70	40.49	0.79
	57.55	0.62	41.03	0.80
	57.70	0.57	40.58	1.15
Average	57.76	0.63	40.70	0.91
MB-12-2	57.48	0.53	41.27	0.73
	54.20	0.20	44.87	0.73
	57.96	0.53	40.76	0.76
Average	56.55	0.42	42.30	0.74
MB-12-3	58.00	0.65	40.54	0.73
	57.55	0.61	40.93	0.91
Average	57.82	0.63	40.74	0.82
MB-12-4	57.50	0.20	40.83	1.31
	56.52	0.24	42.43	0.81
	57.59	0.20	41.22	0.90
Average	57.23	0.27	41.49	1.01
MB-12-5	58.51	0.37	40.41	0.71
	57.73	0.32	41.16	0.78
Average	58.12	0.35	40.79	0.75
MB-33-1	62.38	1.22	35.34	1.05
	55.65	0.85	42.01	0.70
	60.38	0.89	37.74	0.99
	59.86	1.20	37.90	1.04
	60.56	1.04	37.36	1.04
Average	59.77	1.04	38.23	0.96
MB-33-2	54.74	0.81	43.60	0.76
	56.21	0.65	42.18	0.96
	53.46	0.89	44.40	1.25
Average	54.80	0.78	43.42	0.99

Sample descriptions:

MA-28: garnet from sodic aplite dyke in the Maleba pluton (MLP)

MB-12: garnet from muscovite-tourmaline aplite in the MLP

MB-33: garnet from biotite-muscovite-tourmaline aplite, MLP

KY-4: garnet from muscovite-bearing Kaitambuzi aplite, Karagwe Tinfield.

grained crystals (5-10 mm), locally associated with apatite crystals.

Almandine-rich garnet occurs either in zoned, tourmaline-muscovite aplite (Type II) or in unzoned biotite-muscovite-tourmaline aplite (Type I). Zoned aplites normally show a fine-grained, tourmaline-rich outer zone, a fine- to medium-grained garnet-rich inner zone and a narrow coarse-grained central core of muscovite, quartz, sodic plagioclase and K-feldspar. Garnet (Type 3) associated with the zoned aplite contains between 54 % to 58.5 % almandine and spessartine content of 45 % to 40 % (Table 6-15). The unzoned aplite contains garnet (Type 4) with an almandine content of 51 % to 62 % and a spessartine content of 39 % to 35 %. In addition, Type 4 garnet is higher in grossular ($\bar{x} = 0.97$ %) and pyrope ($\bar{x} = 0.94$ %) components than Type 3 garnet. Type 3 garnet occurs as pink, euhedral crystals (Plate 3-2G) associated with feldspar, muscovite and tourmaline. In contrast, Type 4 garnet occurs predominantly as pink skeletal crystals containing quartz inclusions (Plate 3-2H). Subhedral garnet occurs rarely, and is usually higher in almandine and pyrope components than the skeletal garnet. Aplites hosting garnet Types 1, 3 and 4 occur in the Maleba pluton while those hosting Type 2 garnet occur in the Kaitambuzi granite in the Karagwe Tinfield.

That the aplites in the Maleba pluton show chemical and mineralogical variations suggests that they possibly represent different magma fractions from a fractionated magma chamber. This is supported by the chemical data from the aplites. The aplite hosting Type 4 garnet is the least differentiated, while the aplite hosting Type 1 garnet is the most differentiated.

The chemical variations among the garnets could reflect variations in magma composition and mineral paragenesis with increasing degree of magmatic differentiation. Changes in the mineralogy of the aplites from biotite and tourmaline-bearing through tourmaline-bearing to tourmaline-free felsic mineral assemblages possibly suggest a differentiation sequence reflecting a magma that was being progressively depleted in the major mafic components (e.g., FeO), and enriched in alkalis. In response to these chemical changes garnet crystallized over a wide range of chemical compositions. Enrichment of Mn in the magma with increasing degree of geochemical evolution possibly led to the formation of Mn-rich garnet in the final stages of magmatic crystallization.

Mn-rich garnets have been reported from highly fractionated granites, aplites and pegmatites (Leake, 1967; Miller and Stoddard, 1981; Černý and Hawthorne, 1982; Manning, 1983). Like the garnets from the Karagwe-Ankolean aplites, the concentration of Mn in late-magmatic differentiates is considered to have been the main factor controlling garnet composition and paragenesis in the fractionated rocks of other localities.

Available experimental data on the stability fields of garnet (Green, 1977) indicate that garnet with about 20-25 % spessartine may crystallize in equilibrium with a granitic liquid at pressures as low as 3 kb or at much lower pressures with higher spessartine component. Green's experimental data have also shown that garnets with lower spessartine component (< 10 %) may crystallize from granitic liquids only at higher pressures of at least > 5 kb. Therefore, the cause of increased spessartine content of garnet in granitic magmas is the expansion of its stability field to lower pressures

and lower temperatures. The molar proportion of spessartine in the garnets from the Karagwe-Ankolean aplites varies from 35 % to 82 %. This means that the amount of spessartine in the garnets is almost 2 to 4 times higher than the minimum amount required for the crystallization of garnet from a granitic magma at a pressure of 3 kb. Garnets with such high amounts of spessartine may have been stable and crystallized at pressures as low as 2 kb based on the normative Ab-Qz-Or composition of the granites hosting the garnet-bearing aplites, and the increased stability of spessartine-rich garnets at low pressures.

6.5.0 Tin contents of various mineral phases

Tin analyses (DCP method, Bondar-Clegg Lab.) of 4 biotites, 8 muscovites, 4 tourmalines and 2 K-feldspars from Karagwe-Ankolean granites are presented in Table 6-16. Muscovite contains the highest Sn concentrations, followed by tourmaline and biotite. The Sn content of the K-feldspar was below the analytical detection limit of about 5 ppm. The average Sn content of two muscovite samples from the Karagwe Tinfield granites (Fig. 1-3) is 102 ppm, in the post-orogenic granites represented by the Maleba and Mumakera plutons (Figs. 1-2, 1-3) the average for three muscovite samples is 43 ppm, while in the syn-orogenic Bukiriro granites the average for two muscovite samples is 26 ppm. These data indicate that muscovite from the post-orogenic granites is richer in Sn than muscovite from the syn-orogenic granites. The data also indicate that muscovite from the Karagwe Tinfield granites contains more Sn than muscovite from the stanniferous granites of the southern part of the Karagwe-Ankolean belt in Bushubi. High Sn-enrichment in the Karagwe Tinfield muscovites could be due partly to primary crystallization from more Sn-

TABLE 6-16. Tin contents (ppm) of whole-rocks and minerals from the Karagwe-Ankolean granites

Sample No.	Rock Type	Whole-rock	Biotite	Muscovite	Tourmaline	K-feldspar
Mb-13	Bmgr.	12	8	43	8	<5
Ma-15	Msgr.	21		45		
Mb-31	Mbgr.	26	12			
Mu-27	Tmsgr.	17		42	26	
Bu-53	Mbgr.	9	5	12		
Mk-2	Mbgr.	11	15	39	14	<5
Kt-11	(B)mgr.	25		148		
Kt-10	(B)mgr.	10		56	12	
Kt-5	Pegmatite	105		350		

Abbreviations

Bmgr: Biotite-muscovite granite; Msgr: Muscovite granite;

Mbgr: Muscovite-biotite granite; Tmsgr: Tourmaline-muscovite granite

(B)mgr: Altered biotite-muscovite granite; almost all biotite altered to brownish white mica

Sample grouping

Mb-13, Ma-15, Mb-31 : Maleba pluton granites

Mu-27: Mumakera pluton granite

Mk-2, Bu-53: Bukiriro granites from the Bushubi batholith

Kt-11, Kt-10, Kt-5: Karagwe Tinfield granite and pegmatite

enriched magmas, and partly to hydrothermal alteration. Evidence for primary Sn-enrichment in mica with increasing degree of magmatic differentiation is given by muscovite from a pegmatite (Kt-5) which contains 2 to 6 times more Sn than muscovite from the granites (Kt-10 and Kt-11). Support for Sn-enrichment by hydrothermal processes is shown by the higher Sn content of muscovite from the more altered granite sample (Kt-11) than muscovite from the least altered granite sample (Kt-10). Hydrothermal alteration in the Karagwe Tinfield granites has altered the biotite to brownish white mica or phengitic muscovite.

In the two-mica granites represented by samples Bu-53, Mb-13 and Mk-2 (Table 6-16), Sn is also preferentially concentrated in muscovite. Muscovite in these granites may have crystallized late in the sequence after the magmas became more enriched in Sn. Tin analyses of three muscovite-tourmaline pairs and two biotite-tourmaline pairs shown in Table 6-16 indicate that the Sn contents of tourmaline are 1.5 to 5 times lower (sample Kt-10 excepted) than that of co-existing muscovite, but equal to or higher than that of co-existing biotite.

Table 6-17 compares Sn contents of micas from stanniferous/tin-bearing and barren granites from Portugal (Neiva, 1982), Blue Tier batholith, Australia (Groves, 1972) and Nigeria (Imcokparia, 1982), with those from the Karagwe-Ankolean granites. It can be seen that the Sn contents of micas from the Karagwe-Ankolean granites are substantially lower than those of micas from granites in the other localities. The data in Table 6-17 can suggest that the Sn content of the Karagwe-Ankolean magmas was low in comparison to the other magmas.

TABLE 6-17. Comparison of average tin contents (ppm) of micas from stanniferous granites from various localities

Locality	(Stanniferous granites)		(Tin-barren granites)	
	Biotite	Muscovite	Biotite	Muscovite
Portugal (Neiva, 1982)		144 (2)*		
Blue Tier (Groves, 1972)	556 (6)	235 (2)	64 (5)	
Nigeria (Imeokparia, 1982)	500 (23)		158 (13)	
Karagwe-Ankolean Belt	10 (2)	67 (5)	10(2)	26 (2)

* Numbers in brackets indicate the number of analyses.

CHAPTER 7

Rb-Sr AND $^{40}\text{Ar}/^{39}\text{Ar}$ GEOCHRONOLOGY

7.0.0 Introduction

The Karagwe-Ankolean belt (Figs. 1-2) is the least understood geochronologically of the areas affected by the mid-Proterozoic Kibaran orogeny in central Africa (Fig. 1-1). During the last 22 years numerous radiometric age data have been reported from granites in other parts of the Kibaran orogenic belt in Zaire, Burundi, Rwanda and SW Uganda (Cahen and Snelling, 1966; Cahen et al., 1984; Brinckmann et al., 1987; Lehmann and Lavreau, 1987) while there have been virtually none from NW Tanzania. The only date published comes from Karagwe-Ankolean metasedimentary rocks at Ndeke hill in Nagara district, NW Tanzania. A muscovite, produced by contact metamorphism, by a post-orogenic granite, yielded a K-Ar of 900 ± 20 Ma (Cahen and Snelling, 1966). The lack of geochronological data has hindered the interpretation of the geologic evolution and the timing of granite magmatism and related W-Sn mineralization in NW Tanzania.

Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ results were obtained from four separate plutons, namely Bukiriro (Bu), Mumakera (Mu), Maleba (Ma) and Kaitambuzi (Kt). The first three are located in the southern part of the Karagwe-Ankolean belt in Bushubi (Fig. 1-3), the fourth is located in the northern part in the Karagwe Tinfield (Fig. 1-2). The dating methods and analytical data are discussed below.

7.1.0 Rb-Sr dating method

Rubidium-strontium isotope systematics have been discussed in detail by

Faure and Powell (1972) and Faure (1986). A brief overview is given here. Rubidium is an alkali element with two naturally occurring isotopes, ^{85}Rb and ^{87}Rb . The isotopic abundances of these isotopes are 72.1654 % and 27.8346 %, respectively. ^{87}Rb is unstable and decays by beta emission to form ^{87}Sr . Strontium belongs to the alkali earth elements that include Ca, Sr and Ba among others. It has four naturally occurring isotopes whose approximate atomic abundances are 82.53 % (^{88}Sr), 7.04 % (^{87}Sr), 9.87 % (^{86}Sr) and 0.56 % (^{84}Sr) (Faure, 1986). As a result of the radioactive decay of ^{87}Rb to form ^{87}Sr , the atomic abundances of Sr isotopes vary depending on the Rb/Sr ratio and the age of the rocks. The decay of ^{87}Rb isotope occurs according to the reaction :

where β^- is the beta particle, ν is an antineutrino and Q is the decay energy (Faure, 1986). The accepted decay constant (λ) for ^{87}Rb is $1.42 \times 10^{-11} \text{ y}^{-1}$, which corresponds to the half life of 4.88×10^{10} years. The relationship between the number of ^{87}Rb and ^{87}Sr isotopes and the age of a rock or mineral is given by the following equation:

$$^{87}\text{Sr} = ^{87}\text{Sr}_i + ^{87}\text{Rb}(e^{\lambda t} - 1) \quad (7.2)$$

or

$$^{87}\text{Sr}/^{86}\text{Sr} = (^{87}\text{Sr}/^{86}\text{Sr})_i + ((^{87}\text{Rb}/^{86}\text{Sr})(e^{\lambda t} - 1)), \quad (7.3)$$

where ^{87}Sr and ^{87}Rb represent atomic abundances of these isotopes at the present time; $^{86}\text{Sr}_i$ and $^{87}\text{Sr}_i$ represent the abundances of these isotopes at the time of formation of a rock or mineral; λ is the decay constant of ^{87}Rb ; and t is the age of a system (rock or mineral) in years. Plotting of $^{87}\text{Rb}/^{86}\text{Sr}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for comagmatic rocks that have remained closed with respect to Rb and Sr since the time of formation yields a series of points

defining a straight line called an "isochron", with a slope (m) given by: $m = (e^{\lambda t} - 1)$. The intercept of the isochron with the $^{87}\text{Sr}/^{86}\text{Sr}$ axis (when $^{87}\text{Rb}/^{86}\text{Sr}$ is 0) gives the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio at the time of formation of the rocks. The age of the rocks can be obtained from the slope (m) of the isochron by solving the equation: $m = e^{\lambda t} - 1$, and obtaining:

$$t = \{\ln(1 + m)\}/\lambda \quad (7.4)$$

7.1.1 Analytical procedure

Rb and Sr isotopic ratio analyses of whole-rocks and mineral separates were obtained using a multi-collector Finnigan-MAT 261 solid-source mass spectrometer in the Geoscience Department at Carleton University. Details of the analytical procedure are given in Bell and Blenkinsop (1984, 1987), Kian (1987) and Richardson (1988). Rb-Sr dating of the granites proved to be rather difficult because of lack of suitable, fresh samples. Most of the granites have been variably altered by late-magmatic or post-magmatic alteration processes, that include muscovitization or sericitization, chloritization, kaolinization and in some cases albitization. Tropical weathering also makes preservation of fresh outcrops difficult.

7.1.2 Results of Rb-Sr isotopic analysis

The analytical data are presented in Tables 7-1 and 7-2 and Figures 7.1 to 7.3. Six whole-rock samples of syn-tectonic muscovite-biotite granite from the Bukiriro pluton (Fig. 1-2) yielded an isochron (Fig. 7-1) corresponding to a date of 1324 ± 23 Ma (MSWD = 0.45). This age compares well with a date of 1324 ± 71 Ma for the Kibaran adamellites of Mwanza and Mount Bia in Zaire, and the date of 1329 ± 55 Ma for syn-tectonic granitoid gneisses from Shaba (Cahen et al. 1984).

TABLE 7.1. Summary of Rb-Sr isotopic data from Karagwe-Ankolean granites

SAMPLE NO.	Rb (ppm)	Sr (ppm)	Rb/Sr (weight)	$^{87}\text{Sr}/^{86}\text{Sr}^*$ (atomic)	$^{87}\text{Rb}/^{86}\text{Sr}$ (atomic)
MK-2	363	72.4	5.00	1.0150	15.06
MK-3	362	73.0	4.96	1.0149	14.95
MK-4	360	73.4	4.90	1.0102	14.59
MK-5	370	119.5	3.10	0.9045	9.10
BU-48 (W)	398	93.1	4.28	0.9589	12.64
BU-49	378	126.3	2.99	0.8987	8.81
BU-33	349	80.2	4.35	0.9780	12.87
BU-48 (B)	1685	8.6	196.31	22.978	1805.6
MU-2 (W)	396	73.5	5.39	1.0368	16.05
MU-23	389	71.0	5.48	1.0515	16.70
MU-25	389	63.3	6.15	1.0932	19.54
MU-29	382	69.7	5.48	1.0406	16.38
MU-30	391	74.5	5.24	1.0365	15.65
MU-31	380	74.2	5.12	1.0275	15.28
MU-2 (B)	1416	11.7	120.52	8.0630	599.6
MB-13 (W)	355	71.5	4.96	1.0225	14.72
MB-13 (F)	616	94.8	6.49	1.0865	19.56
MB-13 (B)	1564	10.3	151.33	14.344	1023.5
MB-11	356	67.8	5.26	1.0307	15.66
MA-21	377	86.6	4.35	0.9928	12.94
MA-24	385	66.1	5.82	1.0629	17.79
MW-5	397	65.2	6.09	1.0869	18.28

Abbreviations: W: whole-rock, B: biotite, F: K-feldspar; the rest of the samples are whole-rocks; * present day.

Sample localities: Bukiriro pluton: BU- and MK-samples
 Mumakera pluton: MU-samples
 Maleba pluton: MW-, MB- and MA-samples

TABLE 7-2. Summary of Rb-Sr ages of granites and minerals from the Karagwe-Ankolean belt.

Pluton	No. of samples	Type of samples	Age (Ma)	$^{87}\text{Sr}/^{86}\text{Sr}$ (Ri)	Apparent age (Ma)	$^{87}\text{Sr}/^{86}\text{Sr}$ (Ri)
Bukiro	6	whole-rocks	1324 ± 23 (0.45)*	$0.7319 \pm .0038$		
		whole-rock, biotite			860	0.805
Mumakera	6	whole-rocks	1088 ± 59 (1.46)	$0.7892 \pm .0138$		
		whole-rock, biotite			843	0.844
Maleba	4	whole-rocks	1006 ± 44 (1.71)	$0.8075 \pm .0095$		
		whole-rock, biotite, K-feldspar			921 ± 9 (1.62)	0.831
		whole-rock, biotite,			924	0.832
		whole-rock, K-feldspar			868	0.844

*MSWD's are indicated by numbers in brackets

Fig. 7-1

Samples from post-tectonic non-foliated, equigranular, two-mica granite and tourmaline-muscovite leucogranite of the Mumakera pluton (Fig. 1-2) yielded a six point isochron (Fig. 7-2) corresponding to a date of 1088 ± 59 Ma (MSWD = 1.46). This date is similar to that from the biotite alkaline granites from Rwanda which, according to Gerards and Ledent (1976), are 1094 ± 50 Ma old (Cahen et al. 1984). Samples from post-tectonic two-mica granite and muscovite leucogranite in the Maleba pluton (Fig. 7-3) yielded a four point isochron corresponding to a date of $1006 \text{ Ma} \pm 44 \text{ Ma}$ (MSWD = 1.71). Although this is considered only a tentative date because few samples were available for analysis, it suggests that the Maleba granites are probably younger than the Mumakera pluton. These younger granites are associated with tin and tungsten mineralization.

All granites analysed in this study have very high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios (R_i). The syn-orogenic Bukiriro granites in the Bushubi batholith have initial ratios of 0.7318 ± 0.0038 ; the initial ratios for the post-orogenic granites of the Mumakera and Maleba plutons are 0.7892 ± 0.0138 and 0.8075 ± 0.0095 , respectively. These ratios, if considered initial, show an increasing trend from east to west across the southern part of the Karagwe-Ankolean belt. The increase in the ratios is possibly an indication for more crustal involvement in the evolution of the granitic magmas. It is interesting to note that the increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios coincides with Sn-enrichment in the granites. This suggests that the stanniferous granitic magmas were probably derived by partial melting of a more radiogenic source.

Rb-Sr dates obtained from whole-rock-mineral pairs are much younger than

Fig. 7-2

3

Fig. 7-3

those obtained from whole-rock isochrons, indicating partial or complete resetting of minerals by later tectonothermal events. Two whole-rock-biotite pairs from the Bukiro and Mumakera plutons yielded ages of 860 Ma, $R_i = 0.8047$, and 843 Ma, $R_i = 0.8436$, respectively. Discordant ages were obtained from biotite and K-feldspar from a two-mica granite in the Maleba pluton. The biotite-whole-rock pair yielded a date of 924 Ma, $R_i = 0.832$, while K-feldspar-whole-rock pair yielded a date of 868 Ma, $R_i = 0.844$. The whole-rock sample (MB-13) together with biotite and K-feldspar yielded a three point isochron corresponding to a date of 921 ± 9 Ma (MSWD = 1.62, $R_i = 0.831$). The discordance of the mineral ages may be explained by the differences in biotite and K-feldspar closure temperatures.

7.2.0 $^{40}\text{Ar}/^{39}\text{Ar}$ dating method

The $^{40}\text{Ar}/^{39}\text{Ar}$ dating method is based on the measurement of $^{40}\text{Ar}/^{39}\text{Ar}$ isotope ratios in potassium-bearing minerals that have been irradiated with neutrons. The basic principles of this dating method can be found in Faure (1986). This method essentially involves measurement of ^{40}Ar produced by the radioactive decay of ^{40}K isotope (see Figure 7-4), and ^{39}Ar produced artificially from ^{39}K by neutron irradiation of the minerals. The nuclear reaction involved can be written as:

The number of ^{39}Ar atoms produced in a sample by neutron irradiation is given by:

$$^{39}\text{Ar} = ^{39}\text{K} \Delta T \int \phi(E) r(E) dE, \quad (7.6)$$

where ^{39}K is the number of the isotope in the sample, T is the amount of time the sample is irradiated; $\phi(E)$ is the neutron flux density of energy E ;

FIGURE 7-4

Decay scheme of K^{40} . The four branches are: (1) electron capture accompanied by the emission of a γ ray, (2) electron capture without γ ray emission, (3) positron emission, and (4) beta, or electron, emission. Also indicated are the energy, E , released in each mode of decay and the percentage of K^{40} that decays by each mode. (After Dalrymple and Lanphere, 1969).

and $r(E)$ is the neutron capture cross section of ^{39}K (Faure, 1986). The amount of ^{40}Ar produced by natural radioactivity in the sample is given by:

$$^{40}\text{Ar}_{\text{rad}} = \frac{\lambda_e}{\lambda} (^{40}\text{K} (e^{\lambda t} - 1)), \quad (7.7)$$

where λ_e is the electron capture decay constant of ^{40}K , and λ is the natural total decay constant of ^{40}K . The $^{40}\text{Ar}_{\text{rad}}/^{39}\text{Ar}$ ratio of the irradiated sample is given by:

$$^{40}\text{Ar}_{\text{rad}}/^{39}\text{Ar} = \frac{\lambda_e}{\lambda} \frac{^{40}\text{K} (e^{\lambda t} - 1)}{^{39}\text{K} (\Delta T) \int_0^{\Delta T} \phi(E) r(E) dE} \quad (7.8)$$

$$= \frac{e^{\lambda t} - 1}{J}, \quad (7.9)$$

$$\text{where } J = \frac{\lambda_e}{\lambda} \frac{^{39}\text{K} (\Delta T) \int_0^{\Delta T} \phi(E) r(E) dE}{^{40}\text{K}}. \quad (7.10)$$

Equation 7.9 can be rearranged and solved for t :

$$t = \frac{1}{\lambda} \ln((^{40}\text{Ar}_{\text{rad}}/^{39}\text{Ar} \times J) + 1). \quad (7.11)$$

In any given batch of irradiated samples, the J values are normally obtained empirically by analysing the $^{40}\text{Ar}_{\text{rad}}/^{39}\text{Ar}$ ratio in standard samples of known ages and calculating J values from equation 7.9. The J values of the standards are plotted graphically and the J values of other samples irradiated at the same time as the standards obtained from the graph by extrapolation.

All $^{40}\text{Ar}/^{39}\text{Ar}$ ratio measurements are usually corrected for atmospheric argon, either present in impurities or adsorbed onto the surface of the samples during preparation. Other corrections have to be made because of interfering nuclear reactions involving Ca, K and Cl during irradiation.

The $^{40}\text{Ar}/^{39}\text{Ar}$ dating method has several advantages over the conventional K-Ar method. Firstly, not much sample material is required for analysis;

only a few tens of milligrams are needed, especially for K-rich and very old samples such as those analysed in this study. Secondly, only argon isotopic ratios are measured on the samples, thereby eliminating the problems of obtaining absolute measurements of Ar and K (Dalrymple and Lanphere, 1969). Thirdly, a spectrum of ages may be obtained from a single sample by degassing the sample in small temperature increments. The ages may provide some useful information regarding the thermal history of the mineral being dated. Moreover, plateau ages obtained from high temperature gas fractions may approximate the age of the mineral or the time of initial cooling. The main disadvantage of $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique is that it requires several isotopic corrections to be made if the analysed sample contained significant amounts of Ca, and/or Cl, because these two elements produce Ar isotopes during neutron irradiation. Also the J parameter in the $^{40}\text{Ar}/^{39}\text{Ar}$ age equation (see 7.10) is difficult to determine, and uncertainties in the J parameter introduce errors in the calculated $^{40}\text{Ar}/^{39}\text{Ar}$ ages. Despite these limitations, the $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique is commonly used in geochronology because of refinements of the technique and high precision measurements.

7.2.1 Analytical procedure

Incremental, gas-release, heating experiments were performed on 9 irradiated mica samples. Six were muscovites and 3 biotites. Neutron irradiations of the samples were made at the McMaster University nuclear reactor. The heating experiments were carried out in the $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological laboratory at Dalhousie University. The experiments were carried out over a total temperature interval from 25^o C to 1100^o C.

In each experiment, the first gas step was collected in the interval from 25⁰ C to 500⁰ or 600⁰ C. In the subsequent gas steps the temperature was incremented at either 30⁰ or 50⁰ C intervals. Isotopic ratios were measured on a modified MS 10 mass spectrometer operating in the static mode. Ar isotopes in each gas fraction were measured 15 times (see Appendix 8). Isotopic ratios were extrapolated back to zero time, the time at which the gas was first admitted into the spectrometer. The ratios were finally corrected for atmospheric Ar; the correction was typically < 10 %. No corrections were made for interfering isotopes produced by Ca or Cl during the irradiation because of the lack of these elements in the samples in any detectable amounts. The accuracy of ⁴⁰Ar/³⁹Ar ages is within ± 2 % of the reported values.

7.2.2 Results of ⁴⁰Ar/³⁹Ar analysis

⁴⁰Ar/³⁹Ar age spectra are shown in Figures 7-5 and 7-6. An "age plateau" is defined when at least two successive heating steps representing more than 50 % of total gas yield apparent ages that are identical within experimental uncertainty (Reynolds et al., 1988). A total gas age is a weighted average of ages obtained from individual temperature gas steps.

A biotite and muscovite pair from the Bukiriro two-mica granite (MK-2) yielded plateau ages of 897 Ma and 910 Ma, respectively. Total gas ages for biotite and muscovite are 892 Ma and 904 Ma, respectively. The average total gas age of 898 Ma for the biotite-muscovite pair is similar, within analytical uncertainty, to the average plateau age of 904 Ma. These data suggest that biotite and muscovite in the Bukiriro pluton have not undergone any thermal disturbances, sufficient to affect their K-Ar systematics, since ca 900 Ma.

Fig. 7-5. Argon age spectrum plots for muscovite (Mu) and biotite (Bi) from the Bukiriro, Mumakera and Maleba plutons. Half-height of bars represent 1 σ (74 uncertainties). Total gas ages are given in parentheses. Whole-rock (W) Rb-Sr dates of the plutons are also shown.

The incremental gas release age spectra for muscovite (MU-2, MU-27) from the Mumakera pluton is shown in Figure 7-5. Sample MU-2 is from a biotite-muscovite granite while sample MU-27 is from a tourmaline-muscovite leucogranite. Ignoring the last gas step in sample MU-2, provides a remarkable similarity in the shapes of the age spectra for the two muscovite samples. Both show a smooth curve with a steep slope for low temperature gas fractions and a flat or nearly flat age plateau for high temperature gas fractions (Fig. 7-5). The shape of the curve is a good example of an ideal $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum (see Faure, 1986) expected from a sample that has undergone partial argon loss after initial cooling through the Ar blocking temperature. It can be seen from Figure 7-5 that muscovite from the two-mica granite (MU-2) yields a plateau age of ca 950 Ma for 52 % of the gas released while muscovite from the leucogranite (MU-27) yields a plateau age of ca 965 Ma based on 54 % of gas released. There is a difference of about 2 % in the two gas ages but this is insignificant and falls almost within the limits of analytical uncertainty. The average plateau age for the two samples of muscovite is ca 960 Ma. Total gas ages for the two samples are almost identical; sample MU-2 yields a date of 921 Ma and sample MU-27 a date of 922 Ma.

The age spectrum for muscovite (MB-13) from the Maleba pluton (Fig. 7-5) resembles very closely the age spectra obtained from muscovite and biotite from the Bukiriro pluton. The plateau age corresponds to ca 907 Ma and the total gas to a date of ca 902 Ma. These ages do not differ significantly from the average plateau age of ca 904 Ma and average total gas age of 898 Ma for a biotite-muscovite pair from the Bukiriro pluton. Two biotite

samples (MB-13) MB-31) from the Maleba pluton yield ages which are significantly lower than those obtained from muscovite. A total gas age of 837 Ma was obtained from biotite (MB-13) that coexists with muscovite (MB-13). Biotite sample, MB-31, yielded a total gas age of 853 Ma. Figure 7-5 shows that the age spectrum for biotite sample MB-13 has a positive age anomaly for a small gas step released in the intermediate temperature interval of 750⁰-800⁰ C. If this anomaly is ignored, a plateau age of 851 Ma is obtained for 56 % of the released gas. This plateau age is similar, within limits of analytical uncertainty, to the total gas age of 853 Ma. In contrast with sample MB-13, the age spectrum for biotite sample MB-31 (Fig. 7-5) has a negative age anomaly represented by a "saddle" close to the middle of the spectrum. The presence of "saddle"-shaped, low gas age, patterns in ⁴⁰Ar/³⁹Ar age spectra of biotites is attributed to recoil effects following neutron irradiation and the occurrence of low-K mineral phases, e.g. chlorite, in biotite (Hess and Lippolt, 1986; Reynolds P., personal communication).

⁴⁰Ar/³⁹Ar age spectra for muscovite from Kaitambuzi granite (KT-10) and pegmatite (KT-5) of the Karagwe Tinfield (Fig. 7-6) are distinctively lower than those of muscovite and biotite from the Bukiriro, Mumakera and Maleba plutons in the southern part of the Karagwe-Ankolean belt (Fig. 7-5). The spectra also exhibit high age anomalies for gas released in the intermediate temperature intervals of 750⁰-780⁰ C for sample KT-10 and 780⁰-840⁰ C for sample KT-5. The causes for the anomalies in these samples are not known but could be partly due to recoil effects (Hess and Lippolt, 1986). The apparent plateau age of 758 Ma for muscovite from the pegmatite (KT-5) is higher than the apparent plateau age 684 Ma obtained from the muscovite from the granite

Fig. 7-6. Argon age spectrum plots for muscovite (Mu) from Kaitambuzi granite (KT-10) and pegmatite (KT-5) in the Karagwe Tinfeld (see Fig. 7-5 for descriptions).

(KT-10) thought to be magmatically associated with the pegmatite. The total gas age (740 Ma) for muscovite from the pegmatite is also higher than the total gas age (683 Ma) for muscovite from the granite. These ages appear to be anomalous because the pegmatite is thought to be geologically younger than the granite. The reversed age relationship of muscovite from the granite and associated pegmatite may be attributed to: a) the presence of excess or extraneous Ar in the pegmatite muscovite, or b) the loss of Ar from muscovite in the granite. Excess Ar in micas and other minerals can produce anomalous K-Ar ages that are not compatible with the observed geological relationships. Hypotheses advanced to explain excess Ar are: a) incorporation of Ar in minerals at the time of formation, b) diffusion of Ar into the minerals after their formation, and c) creation of Ar in the minerals by some unknown mechanisms of nuclear reactions. Minerals in pegmatites have greater chance of incorporating extraneous Ar because pegmatites are formed from gas-, or fluid-rich residual magmas. Although excess Ar may account for the high $^{40}\text{Ar}/^{39}\text{Ar}$ apparent age of muscovite from the Kaitambuzi pegmatite, partial resetting of the muscovites by tectonothermal events could also be the cause for the anomalous ages. It is possible that because of differences in the grain-size and texture, muscovite in the pegmatite was partially reset while muscovite in the granite was more or less completely reset by the thermal event(s). The differences in age may therefore be due to different degrees of loss of Ar from the systems.

7.3.0 Significance of Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ ages

Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ age data presented in the preceding sections

constrain episodes of granite magmatism and thermal events in the Karagwe-Ankolean (NE Kibaran) belt. Early granite magmatism is constrained by the date of syn-tectonic two-mica granites of the Bukiriro pluton (Fig. 7-5).

These granites are dated at 1324 ± 23 Ma by the Rb-Sr method. The formation of these granites may pre-date or coincide with the episode of metamorphism and deformation in the NE Kibaran belt, which imparted a NE-trending penetrative fabric to the granites and country rocks. Another igneous event is indicated that took place at 1088 ± 59 Ma ago, represented by the isochron date from the Mumakera pluton. This episode of granite magmatism produced equigranular two-mica granites and tourmaline-muscovite leucogranites which have more evolved major and trace element chemistry than the syn-tectonic granites. These granites, although not Sn-mineralized, have high Sn contents (9-21 ppm). The formation of Sn-mineralized granites and pegmatites in the Maleba pluton (Fig. 7-5) and in the Karagwe Tinfield (Fig. 7-6) is not well constrained. The provisional date of 1006 ± 44 Ma, obtained from a four point Rb-Sr isochron of the Maleba granites is the only date, yet available, from Sn-mineralized granites in the Karagwe-Ankolean belt.

Two post-granite magmatism thermal events, one at ca 900 Ma and another at ca 685 Ma, are recorded by Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ ages from biotite and muscovite. Effects of the younger thermal event are recorded in micas from granites of the northern part of the Karagwe Ankolean belt close to the Tanzania-Rwanda-Uganda border (Fig. 7-6). Both thermal events resulted in complete or partial resetting of micas in the granites. Complete resetting of micas by the 900 Ma thermal event appears to have taken place in the Bukiriro and Maleba plutons (Fig. 7-5) while partial resetting took place in the Mumakera pluton. The shallower depth of intrusion for the Mumakera

pluton may account for the differences observed in the mica dates. Limited $^{40}\text{Ar}/^{39}\text{Ar}$ data from muscovite in the Karagwe Tinfield granite and pegmatite (Fig. 7-6) suggest that complete resetting of muscovite by the 685 Ma thermal event occurred in medium-grained muscovite associated with the granites.

7.4.0 Petrological and geochronological correlations

Petrological and geochronological studies of granitoids in the various parts of the Kibaran Belt in Zaire, Rwanda, Burundi and SW Uganda (Cahen and Snelling, 1966; Cahen et al., 1984, Lehman and Lavreau, 1987; Brinckmann et al., 1987) have led to the recognition of at least four categories of granitoids, each corresponding to a distinct episode of granite magmatism. The first two categories comprise the syn-tectonic granites designated as Types A and B in Zaire or G1 and G2 in Rwanda while the latter two categories comprise the post-tectonic granitoids designated as Types G3 and G4 in Rwanda. The oldest, Type A/G1 granitoids, consist of cataclastic porphyritic biotite adamellites, thought to be pre- or early-tectonic. Type B/G2 granitoids, considered to be syn-tectonic with respect to the main phase of deformation (F2) and metamorphism in the Kibaran orogen, are composed mainly of porphyritic two-mica adamellite gneisses (Cahen et al., 1984). G3 granitoids, forming a distinct group of biotite alkaline granites, have been documented in Rwanda and Zaire. The fourth category (G4) encompasses the tin granites associated with several types of cassiterite $\pm$ wolframite $\pm$ columbite $\pm$ beryl-bearing pegmatites.

Geochronological data (Table 7-3) from Cahen et al. (1984), Klerkx et al. (1987) and Brinckmann et al. (1987) for the Kibaran Belt (Kibarides; Fig. 7-

TABLE 7-3. Comparison of geochronological data from various parts of the Kibaran Belt.

Locality	Rock type	Dating method	Age (Ma)	$^{87}\text{Sr}/^{86}\text{Sr}$	MSWD	Sources of data*
NW TANZANIA						
Bukiriro	Syn-tectonic two-mica granite	Rb-Sr	1324 ± 23	0.732	0.45	1
Mumakera	Post-tectonic two-mica granite and tourmaline-muscovite leucogranite	Rb-Sr	1088 ± 59	0.789	1.46	1
Maleba	Post-tectonic two-mica granite and muscovite leucogranite	Rb-Sr	1006 ± 44	0.807	1.71	1
BURUNDI						
Nyamurungu	Granite (G1)	U:Pb	1370			2
Cankuzo	Rhyodacites	Rb-Sr	1353 ± 46	0.707	3.5	3, 4
Kayanza	Biotite-muscovite granite (G1)	Rb-Sr	1330 ± 30	0.721	2.1	3, 4
Rumeza	Biotite granite (G1)	Rb-Sr	1268 ± 44	0.719	2.4	4
Muramba	Biotite-muscovite granite (G2)	Rb-Sr	1279 ± 65	0.716	2.9	3, 4
Mugere-Mutumba	Granite (G2)	Rb-Sr	1261 ± 25	0.719	2.18	3, 4
Akanyaru	Granite (G2)	Rb-Sr	1272 ± 41	0.719	9.2	4
RWANDA						
Gatsibo-Gitarama	Granite (G1)	Rb-Sr	1366 ± 32	0.705	0.34	2
Gitarama	Granite (G1)	U:Pb	1348			2
Gatsibo	Granite (G1)	U:Pb	1317 ± 67			2
Kimonyi	Biotite alkaline-granites (G3)	Rb-Sr	1094 ± 50	0.714	0.02	2, 3
Kirengo	Leucocratic alkaline tin-granites (G4)	Rb-Sr	972 ± 15	0.778	1.15	2
ZAIRE						
Shaba	Adamellites	Rb-Sr	1324 ± 71	0.709	0.27	2
Mwanza-Bukena	Granites (G2)	Rb-Sr	1329 ± 55	0.702	0.06	2
Bukena	Granites (G2)	U:Pb	1291			2
Mwanza	Alkaline tin-granites (G4)	Rb-Sr	977 ± 18	0.731	0.94	2

* Sources of data: 1: This study; 2: Cahen et al. (1984); 3: Brinckmann et al. (1987); 4: Klerkx et al. (1987).

7) indicate the age relationships of the various granitoids. The G1/Type A granitoids are dated at 1370 ± 25 Ma, the G2/Type B at 1310 ± 25 Ma, the G3 at 1094 ± 50 Ma, and the G4 at 976 ± 10 Ma (Cahen et al., 1984). Klerkx et al. (1987) considered the G1 and G2 granitoids in Burundi to have formed at 1330 ± 30 Ma and 1260-1280 Ma, respectively. Although the tin granites (G4) are post-tectonic with respect to the Kibaran orogenic cycle, they are considered to fall within the time range of the Lomamian phase (976 ± 10 Ma to 938 ± 30 Ma) of the "Katangan" orogenic cycle in western and central equatorial Africa (976 ± 10 Ma to 503 Ma, Cahen et al., 1984). Rb-Sr and K-Ar model ages of biotite from Kibaran granites in Shaba, Zaire, are reported of about 850 Ma, although in Kivu they are much younger, and can be as low as 550 Ma (Cahen and Snelling, 1966; Cahen et al., 1984). These younger ages are thought to indicate biotite rejuvenation during the Katangan orogeny (see Table 7-4).

The episodes of granite magmatism in the Karagwe-Ankolean (NE Kibaran) belt in NW Tanzania, inferred from Rb-Sr age data, seem to correlate with igneous activities responsible for the formation of G1/G2, G3, G4 granitoids in Burundi, Rwanda and Zaire. On the basis of age data in Table 7-3, the Bukiriro granites correlate either with the G2/Type B granitoids of Cahen et al. (1984) or the G1 granitoids of Brinckmann et al. (1987) and Klerkx et al. (1987). Ages allocated to G1 and G2 granitoids by the various authors (Table 7-3) appear, however, indistinguishable at 2 sigma levels. True alkaline granites (G3) documented in Rwanda and other parts of Kibaran belt are lacking in NW Tanzania. Their age equivalents, i.e. the 1088 ± 59 Ma Mumakera pluton, are two-mica granites and tourmaline-muscovite granites of peraluminous composition. Sn-mineralized granites in the Maleba pluton (Fig.

TABLE 7-4. Main deformation phases of the Kibaran and Katangan orogenies in central and eastern Africa (Fig. 7-7); data obtained from Cahen et al. (1984) and Klerkx et al. (1987).

Ma	Phase of deformation	Orogenic cycle
602 656	Lufilian	KATANGAN
850	Lusakan	
938 $\pm$ 30 976 $\pm$ 10	Lomamian	
1100	D2' shearing	
1200	D2 deformation (open, upright folding)	KIBARAN
1250 1330	D1 deformation (horizontal schistosity)

1. Bukoban (B)-Katangan (K) and correlated formations, mainly tabular sediments; 2. Folded Katangan; 3. Pre-Katangan formations affected by intra- and post-Katangan folding; 4. Plateau series; 5. Kibarides and Irumides, reworked by later activity; 6. Areas cratonic from at least ca 1800 Ma. (After Cahen et al., 1984).

Fig. 7-7. Map showing areas affected by the Kibaran, Bukoban-Katangan and other tectonic events in central and eastern Africa.

7-5) and the Karagwe Tinfield (Fig. 7-6) can be correlated with the G4 tin granitoids in Rwanda, Burundi and Zaire. The age of Sn-mineralized granites in NW Tanzania is not yet well-constrained, although a provisional date of 1006 ± 44 Ma has been obtained from the Maleba pluton.

Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ dates of biotite and muscovite, in the range 965 to 685 Ma, in the Karagwe-Ankolean (NE Kibaran) granites fall within the time span of the Katangan orogenic cycle (976 ± 10 Ma to 503 Ma, Cahen et al., 1984) of Pan-African tectonism in western and eastern-central Africa. This is in agreement with Rb-Sr and K-Ar mineral ages compiled by Cahen and Snelling (1966) and Cahen et al. (1984) from other parts of the Kibaran Belt. Re-setting of biotite and muscovite by thermal events in the Karagwe-Ankolean (NE Kibaran) Belt occurred at ca 900 Ma and at ca 685 Ma. The thermal event at ca 900 Ma correlates with early igneous activities responsible for the formation of basic lavas and intrusives in the Katangan sediments and their age equivalent the Bukoban (Fig. 7-7). These igneous activities marked the initial phase, the "Lomamian tectonic phase" (976 ± 10 Ma to 938 ± 30 Ma, Cahen et al., 1984), of the Katangan orogenic cycle. The thermal event at ca 685 Ma can be attributed to the "Lufilian tectonic phase" (≥ 656 to 503 Ma, Cahen et al., 1984) of the Katangan. This thermal event can be also correlated with events that produced Rb-Sr rehomogenization in Kibaran granites of western Burundi at 697 ± 18 Ma, and in pre-Kibaran gneisses of Rwanda at 676 ± 70 Ma (Tack et al., 1984).

7.5.0 Summary

Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data record at least three episodes of granite magmatism and two post-tectonic thermal events in the NE Kibaran

belt of NW Tanzania. The first episode, dated at 1324 ± 23 Ma, corresponds to the emplacement of the syn-tectonic two-mica granites in the Bushubi batholith. This episode appears to be coeval with deformation and metamorphism in the NE Kibaran belt. The second episode, dated at 1088 ± 59 Ma, is marked by the age of emplacement of the post-tectonic two-mica granite and tourmaline-muscovite leucogranite of the Mumakera pluton. Granites associated with this episode are more chemically evolved than the syn-tectonic granites. Their high Sn contents (average = 14 ppm) suggests that they are possible precursors of the Sn-mineralized granites. The third episode is not well constrained, but appears to be responsible for the formation of the Sn-mineralized granites and pegmatites in the Maleba pluton and in the Karagwe Tinfield. Preliminary Rb-Sr isotopic data from the Maleba pluton indicate a date for the Sn-mineralized granites of about 1006 ± 44 Ma. These three episodes of granite magmatism are correlated with the formation of G2/Type B, G3, and G4 granitoids, respectively, in Zaire, Rwanda and Burundi.

Biotite and muscovite dates record two main thermal events, one at ca 900 Ma, and another at ca 685 Ma. These thermal events correlate with the termination of the Lomamian and the beginning of Lufilian phases of the Katangan-Bukoban orogeny.

CHAPTER 8

COMPARISON OF GRANITES FROM KARAGWE-ANKOLEAN BELT AND OTHER TIN PROVINCES

8.0.0 Introduction

In this chapter the petrological and geochemical aspects of granitoids in well-studied Tin Provinces including Southeast Asia, Nigeria, Australia, Cornwall and Bolivia are discussed and compared with those of Karagwe-Ankolean granites. Published data are summarized in Tables 8-1 and 8-2, and Figures 8-1 and 8-2. Key reference papers used in data compilation include those by Ishihara et al. (1980), Cobbing et al. (1986) and Manning (1986) for Southeast Asian tin belt; Bowden (1970), Olade (1980) and Imeokparia (1984, 1985) for Nigerian tin granites; Flinter et al. (1972), and Juniper and Kleeman (1978) for New England complex, Australia; Jackson et al. (1982) and Stone (1982) for Cornwall granites, and Dulski et al. (1982), McBride et al. (1983) and Lehmann (1985) for the Bolivian tin province. In addition to these references, extensive reviews of tin deposits of the world are given by Sainsbury (1969) and Taylor (1979). In the following discussion, a summary of petrological and mineralization features of granites in each province is given, followed by a synthesis of data from all provinces.

8.1.0 Petrological comparison

A literature review indicates that tin deposits are associated with granitoid rocks that range in composition from true granites, as defined by Streckeisen (1976), to granodiorites. Most deposits are associated with granites of monzogranite/adamellite composition. Granitoids with S-type characteristics (Chappell and White, 1974) appear to be the most abundant

type in most tin provinces, although I-type granitoids are also found. Major rock types spatially associated with tin deposits in various provinces include one or more of the following lithologies: biotite granite, muscovite granite, two-mica granite and associated pegmatite and aplite, topaz-Li-mica granite, and in some cases hornblende-bearing granite or granodiorite. Accessory minerals found in these granites vary, possibly because of differences in trace element composition or differences in P-T-fO₂ conditions of crystallization. Common accessory minerals in tin-bearing granitic rocks include zircon, apatite, fluorite, topaz and tourmaline. Accessory garnet and Fe-Ti oxides may also be found. Accessory minerals such as fluorite, topaz and tourmaline may be of magmatic, autometasomatic or hydrothermal origin.

In the Southeast Asian tin belt, batholiths and plutonic complexes composed of cassiterite- and/or wolframite-bearing S- and/or I-type granitic suites have been described by Cobbing (1986) and others who recognized three main granite provinces. From east to west they are the Eastern Province (Eastern Thailand and Peninsular Malaysia) consisting of I-type granitic rocks, the Main Range Province consisting of S-type granites, and the Western Province (Peninsular Thailand-Burma) consisting of S and I-type granitic rocks. Plutons in the Eastern Province consist of biotite granite cores, surrounded by biotite-hornblende granites. Plutons constituting the Main Range batholith consist mainly of biotite and muscovite granites, associated with narrow thermal aureoles. Coarse- to medium-grained K-feldspar megacrystic granites constitute the majority of the S-type granite batholiths of the Western Province while medium-grained equigranular hornblende and biotite granites predominate in the I-type plutons (Cobbing

et al., 1986).

The Jurassic Younger Granites of northern Nigeria constitute a tin province (Olade, 1980; Imeokparia, 1985), and are essentially multiphase high level anorogenic ring complexes emplaced into Precambrian basement gneisses and granites. The principal types are biotite granite, hornblende granite, and riebeckite- and fayalite-bearing granites emplaced as isolated or overlapping complexes (Olade, 1980). In some of the more well-studied complexes, such as Jawara and Kwandonkaya (Imeokparia, 1984, 1985), early hornblende-fayalite and/or hornblende-biotite granites are intruded by biotite granite and microgranites. Important cassiterite and columbite deposits are associated with the biotite granites. Although peralkaline amphibole-bearing granites contain very high Sn concentrations (up to 150 ppm) most of the Sn is contained in amphiboles and does not form economic deposits (Olade, op cit). Several accessory minerals occur in the different granite types. They include fluorite, topaz, zircon, allanite, ilmenite, thorite, monazite, ilmenite, cassiterite and columbite. White mica or muscovite appears to be lacking or present in very minor amounts in the documented Nigerian Younger Granites. Tourmaline is also absent in the granites, although it is found as an accessory mineral in the "basement" pegmatites belonging to an older generation of tin granites (Bowden, 1970).

The New England complex of southeastern Australia was a locus of polymetallic Sn-W $\pm$ Mo and Cu mineralization. The chemical, mineralogical and petrological features of granitoids of the New England complex have been discussed by Flinter et al. (1972) and Juniper and Kleeman (1978). The complex consists of several intrusions ranging in composition from gabbro

through tonalite, granodiorite, adamellite to granite. The polymetallic mineralization occurs either in biotite-bearing leucogranitoids or in hornblende-biotite or hornblende-bearing mesogranitoids. Feldspar porphyritic and equigranular granitoid phases both occur in the complex. Common accessory minerals are sphene, apatite and magnetite. Rare accessory phases include ilmenite, monazite, tourmaline zircon, fluorite, topaz and muscovite.

The Cornish granites, belonging to the Cornubian metallogenic province of SW England, have been extensively studied to provide better understanding of magmatic and hydrothermal processes involved in the formation of Sn and other rare-metal deposits. More recent studies of the Cornish granites and related mineralization include those by Hall (1971), Floyd (1972), Edwards (1976), Halls et al. (1977), Jackson et al. (1982), and Stone (1982). The granites occur in six major plutons, emplaced into a deformed upper Paleozoic volcano-sedimentary sequence (Jackson et al., 1982). The plutons are mainly two-mica granite-adamellite and granite porphyry stocks and dykes. Granites from the Land's End pluton and the Tregonning-Godolphin cupola highlight the main petrological features of the Cornish granites. The Land's End pluton consists of medium- to coarse-grained, usually porphyritic, two-mica granite and adamellite with local marginal facies of fine-grained granite, leucogranite and aplite-pegmatite sheets (Jackson et al., *op cit*). The main granite of the Tregonning-Godolphin cupola (Stone, 1982) is a biotite-adamellite similar to the Land's End pluton. In addition, the Tregonning-Godolphin cupola contains more evolved lithium-rich, albite-topaz granites. Stone (1982) documents differentiation sequence starting

from biotite granite through lithium mica-albite-topaz granite to lithium mica-albite-topaz leucogranite and aplite in the Tregonning-Godolphin granite cupola. Regions of Sn-W mineralization are commonly associated with lithium-rich granites (Stone, 1982).

Magmatic activities associated with Sn mineralization in Bolivia range from Late-Precambrian to Tertiary (Lehmann, 1985). Precambrian pegmatite deposits, that form part of the Rondonia tin province of the Brazilian Shield are geologically and mineralogically distinct from the stratabound and Mesozoic and Tertiary porphyry and vein deposits of the Andean-Bolivian tin belt (Dulski et al., 1982). The magmatic and metallogenic episodes of the northern Bolivian tin belt in the Cordillera Real have been discussed by McBride et al. (1983). Intrusion of biotite monzogranites and granodiorites during the Triassic and Tertiary, was accompanied by tin and tungsten vein deposits. Some of the monzogranites are peraluminous and contain primary muscovite and locally cordierite (McBride et al., *op cit*). Sub-volcanic porphyries associated with polymetallic Sn-W-Ag and base metal mineralization are more characteristic of the southern part of the Bolivian tin belt (Dulski et al., 1982).

In the case of the Karagwe-Ankolean granites tourmaline-bearing two-mica granites predominate among the stanniferous granites, while muscovite and tourmaline leucogranites or adamellites occur only locally in the apical parts of some plutons. Granodiorite and more basic rocks in close association with the stanniferous granites are lacking. Common accessory minerals in the stanniferous granites are tourmaline, apatite and zircon and ilmenite. Xenotime and monazite were detected in a few granite samples by

EDS microprobe analysis. Garnet occurs commonly in aplite and pegmatite. The granites exhibit predominantly S-type (Chappell and white, 1974) features; granites with I-type affinities are generally lacking.

Although the Karagwe-Ankolean granites resemble granites in other tin provinces some important differences do exist. In contrast with granitoid rocks from Southeast Asia, New England, and Bolivia, granodiorites and more mafic rocks associated with granites are lacking in the Karagwe-Ankolean belt of northwestern Tanzania. Hornblende-bearing granite-adamellites do not occur in the Karagwe-Ankolean belt. Lithium mica-topaz-albite, presumably of magmatic origin, found in Cornwall (Stone, 1982), have not been found in the Karagwe-Ankolean belt nor documented in other regions. Peralkaline granites, found in the Nigerian tin province, do not occur in the Karagwe-Ankolean belt. These contrasts suggest that tin granites can form in a variety of geologic settings from magmas of possibly differing compositions, and that the evolution of the parent magmas may have followed different fractionation trends. It seems that in some provinces, different magma sources were tapped nearly simultaneously or at different times to produce S-type and I-type granitic magmas. In the case of the Karagwe-Ankolean granites there was only one magma source, that produced mainly S-type granitic magmas.

8.2.0 Chemical comparison

Chemical data from well documented tin granites in selected provinces are compared with data from Karagwe-Ankolean granites. Such a comparison is based mainly on average compositions of well-studied granitic suites from each province. Although calculated average compositions may not be as representative as the original analyses, they highlight the main chemical

features of granites in different provinces.

8.2.1 Major element composition

Major element data of tin-bearing granitic rocks from several provinces, including the Karagwe-Ankolean belt, are given in Table 8-1. Average compositions for tin granites and normal granites quoted by Taylor (1979), after Stempok and Skvor (1974), are also shown for comparison. There are no obvious major differences in chemical compositions of the granitoid rocks from the different tin provinces, except those from Bolivia. The Bolivian granitoids are lower in SiO_2 and higher in CaO , Al_2O_3 , MgO and FeO than the granitoids from other provinces. The Cornwall lithium mica-topaz-albite granites and leucogranites are higher in Al_2O_3 , while the Nigerian alkaline granites are slightly higher in total alkalis and lower in Al_2O_3 than the other granitoids. Tin granitoids, other than the Bolivia granitoids, are slightly higher in SiO_2 and K_2O , and lower in CaO and $\text{FeO} + \text{MgO} + \text{MnO} + \text{TiO}_2$ than in average granites (Table 8-1). With the exception of the Nigerian and/or Malaysian granites, the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios and peraluminosity indices (molar $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) are higher in tin granitoids than in average granites.

The Karagwe-Ankolean granites are distinguished from most other tin granites, because they are low in Ca and total $\text{Fe} + \text{Mg} + \text{Mn} + \text{Ti}$. The relatively high peraluminosity index of the Karagwe-Ankolean granites can be attributed to low $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$ in the granites compared to other tin granites with similar alumina contents.

The similarity of the major element compositions of most tin granites and very low abundances of Fe, Mg, Ti and Ca, suggests that these granites

TABLE 8-1. Comparison of average chemical compositions of tin-granites in selected tin provinces, including the Karagwe-Ankolean belt.

No. analyses	K-A BELT 11	K-A BELT 4	THAI. 11	MALY. 10	CORN. 3	CORN. 4	NIGERIA (N) [#]	BOLIVIA 14	AV. GRAN. 546
SiO ₂ %	73.89	74.32	72.42	73.05	72.07	71.93	73.49	66.50	70.18
TiO ₂	0.11	0.12	0.24	0.08	0.27	0.04	0.12	0.30	0.39
Al ₂ O ₃	14.60	14.06	14.36	13.48	14.77	16.15	12.62	15.61	14.47
Fe ₂ O ₃ *	1.26	1.35	0.56	0.86	0.88	0.14	0.62	1.55	1.57
FeO			1.28	1.39	1.23	0.50	1.02	2.71	1.78
MnO	0.04	0.03	0.05	0.06	0.03	0.09	0.02	0.01	0.12
MgO	0.20	0.23	0.45	0.47	0.37	0.05	0.16	1.82	0.88
CaO	0.51	0.44	1.03	1.32	0.56	0.33	0.54	2.35	1.99
Na ₂ O	3.36	2.93	3.14	3.20	2.45	4.52	4.18	2.61	3.48
K ₂ O	4.59	4.93	5.10	5.41	5.80	3.99	4.63	5.07	4.11
P ₂ O ₅	0.20	0.12	0.18	0.09	0.27	0.58	0.03	0.11	0.19
Total	98.76	98.53	98.81	99.41	98.7	98.32	99.43	98.64	99.16

NORMALIZED DATA

SiO ₂ %	74.92	75.54	73.34	73.55	73.09	73.17	75.97	67.53	70.89
TiO ₂	0.11	0.12	0.24	0.08	0.27	0.04	0.12	0.30	0.39
Al ₂ O ₃	14.80	14.29	14.54	13.57	14.98	16.43	12.70	15.85	14.62
FeO (T)	1.15	1.23	1.81	2.18	2.05	0.64	1.59	4.17	3.22
MnO	0.04	0.03	0.05	0.06	0.03	0.09	0.02	0.01	0.12
MgO	0.20	0.23	0.46	0.47	0.38	0.05	0.16	1.85	0.89
CaO	0.52	0.45	1.04	1.33	0.57	0.34	0.54	2.39	2.01
Na ₂ O	3.41	2.98	3.18	3.22	2.48	4.60	4.21	2.65	3.52
K ₂ O	4.65	5.01	5.16	5.45	5.88	4.06	4.66	5.15	4.15
P ₂ O ₅	0.20	0.12	0.18	0.09	0.27	0.59	0.03	0.11	0.19
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
K ₂ O/Na ₂ O	1.37	1.68	1.62	1.69	2.37	0.88	1.11	1.94	1.18
A/CNK	1.28	1.28	1.14	1.00	1.30	1.31	0.98	1.11	1.05

Abbreviations and symbols: *: Total Fe expressed as Fe₂O₃;

K-A: Karagwe-Ankolean; THAI.: Peninsular Thailand; MALY.: Malaysia; CORN.: Cornwall;

AV. GRAN.: Average granite; A/CNK: Molar Al₂O₃/(CaO+Na₂O+K₂O); # "N" not given;

Sources of data:

Taylor (1979): Malaysia; Bolivia; Average granite;

Ishihara et al. (1980): Thailand;

Stone (1982): Cornwall;

Olade (1980): Nigeria.

Data for Karagwe-Ankolean granites have been derived from the present study.

represent highly evolved or fractionated magmatic compositions. The excess SiO_2 and K_2O abundances found in tin granites relative to an average granite reflect either the tendency of tin deposits to be largely associated with leucogranites and alaskites or may be due to post-magmatic alteration processes involving silicification or greisenization and potassic magmatism (Taylor, 1979).

8.2.2 Trace element composition

Selected trace element data of tin granites and barren granites from various provinces, including the Karagwe-Ankolean belt, are shown diagrammatically in Figures 8-1 and 8-2. It is evident from the diagrams that the tin granites are enriched in Sn, Li, F or B, and depleted in Sr, Ba, or Zr relative to the barren granites. The enrichment of incompatible lithophile trace elements and the depletion of compatible trace elements in specialized granites have been attributed to one or more of the following factors: (i) geochemical heredity (i.e. derivation of magmas from crustal sources enriched in certain trace elements), (ii) magmatic differentiation or (iii) deuteric or post-magmatic alteration. Although the relative importance of each of these factors may vary in different areas, magmatic differentiation by fractional crystallization is considered to play a vital role in the formation of tin-specialized granites (Lehmann, 1987). Earlier chapters have shown that major and trace element data for the Karagwe-Ankolean granites support fractional crystallization as a mechanism for producing the chemically-specialized tin granites. Regional variations in the trace element composition of granites and associated tin and rare-metal deposits across the Kibaran-Karagwe-Ankolean belt can, however, be

Fig. 8-1. Diagrams showing average trace element contents in the stanniferous and barren granites from NW Tanzania and Nigerian Tin Province. Data for the Nigerian granites are from Imeokparia (1985).

* The stanniferous granites in the Maleba and Nyamakombe plutons are compared with the barren granites from the Bukiro pluton.

Fig. 8-2. Trace element patterns for stanniferous granites from NW Tanzania, Nigeria, and Thailand. The stanniferous/barren ratio was obtained by dividing the mean value of each element in Sn-mineralized granite with the corresponding value in the barren granites in each province.

attributed to source rock heterogeneities.

8.3.0 Style of tin mineralization

A comparison of styles of tin mineralization and associated alteration in the various provinces can be seen in Table 8-2. In the Southeast Asian tin belt, primary tin-tungsten mineralization takes the form of endogranitic greisen-bordered vein swarms of cassiterite and wolframite, endogranitic pegmatites of cassiterite and wolframite or magnetite-cassiterite skarns $\pm$ base metal sulfides (Cobbing et al., 1986). Exogranitic breccia pipe and pegmatite deposits also occur in Southeast Asia, particularly in Peninsular Thailand (Ishihara et al., 1980; Manning, 1986). In the Nigerian Younger Granites, cassiterite occurs as greisen veins and as disseminations in the margins and roof zones of biotite granites (Olade, 1980; Imeokparia, 1985). Wolframite, columbite, sphalerite and galena are commonly associated with cassiterite in lodes and fracture-controlled greisen veins. Envelopes of reddened granite consisting of K-feldspar $\pm$ hematite $\pm$ sericite commonly surround greisenized granite and greisen bordered quartz veins, while intense albitization occurs in zones of disseminated cassiterite mineralization (Olade, 1980). Cassiterite-bearing, greisen-bordered, lodes and vein swarms also characterise most of the deposits in the New England complex, Australia, and the Cornish granites of SW England (Table 8-2). Although mineralized pegmatites occur in SW England, they are economically less important because of their limited occurrence (Manning, 1986).

In contrast to the tin deposits from the other provinces, the Bolivian deposits are geologically and mineralogically more complex. Polymetallic vein deposits of cassiterite, tin sulfides, wolframite and base metal

sulfides are associated with Mesozoic granitoids in the Bolivian Cordillera. In addition, Tertiary sub-volcanic stocks, in the Cordillera, are associated with deposits that consist of cassiterite-wolframite Ag-rich paragenetic sequence in vein swarms and breccia pipes (Dulski et al., 1982). Disseminated cassiterite mineralization associated with porphyry stocks also occur in the Bolivian Cordillera (Sillitoe et al., 1975).

Tin-bearing, polymetallic, vein deposits described in the other provinces appear to be absent in the Karagwe-Ankolean belt, NW Tanzania. Tin deposits in the Karagwe-Ankolean belt are mainly of cassiterite-muscovite-quartz vein-type in the exocontact zone of chemically specialized granites. Endogranitic vein deposits are rare or absent. In addition to cassiterite, minor wolframite in quartz-hematite-mica veins in metasediments occur in a few localities (Harris, 1961). Cassiterite-bearing pegmatites, occurring locally in biotite-muscovite granites, are usually too small to have any direct economic significance.

Cassiterite-bearing breccia pipes found in B-rich tin areas, e.g., Bolivia (Grant et al., 1980) and SW England (Allmann-Ward et al., 1982) are lacking in NW Tanzania. Instead of brecciation and sudden deposition of cassiterite from ore-fluids, the metasediments were perhaps permeable enough and allowed B-rich fluids to diffuse out easily. The net result was the formation of conformable or semi-conformable tourmalinites and tourmaline-bearing schists containing disseminated cassiterite $\pm$ wolframite or cassiterite-bearing muscovite-quartz veins.

It follows from the preceding review that the types of economic deposits may vary from province to province, and may be related to differences in

physico-chemical environments.

Abbreviations for Table 8-2.

adamel.	adamellite
amph.	amphibole
biot.	biotite
cass.	cassiterite
exogran.	exogranitic
gran.	granite
granodir.	granodiorite
hornb.	hornblende
hydro.	hydrothermal
magn.	manganese
musc.	muscovite
qtz.	quartz
tour.	tourmaline
wolf.	wolframite

TABLE 8-2. PETROLOGICAL COMPARISON OF TIN GRANITOIDS FROM KARACHE-ANKOLEAN BELT AND OTHER TIN PROVINCES

Province	Karache-Akaleen NW Tanzania	Thailand/Malaysia Southeast Asia	Cornwall SW England	New England Australia	Nigeria West Africa	Bolivia South America
A. Geologic setting	Intracontinental orogenic belt	Subduction followed by collision of microplates	Orogenic belt	Orogenic belt	Anorogenic	Cordillera, subduction related
B. Rock types	musc.-biot. [*] biot.-musc., tour.-musc., musc.-tour. granites	biot. or hornb. bearing monzogran. and granodiorites, locally musc. bearing granite cupolas	biot. gran., Li-mica-topaz -albite gran. and leucogran.	biot. and/or hornb. bearing gran., adamel., and granodit.	alkali biot. gran. and asph. bearing granite	monzogranites and granodiorites
C. Age	Late-Proterozoic	Triassic to Tertiary	Permian	Upper Permian	Jurassic	Triassic and Tertiary
D. Style of tin mineralization	exogranitic hydro. cass.- musc. and/or qtz. veins, minor endo and exogran. pegmatites	endogran. greisen- bordered vein swarms and pegmatite of cass. + wolframite ,magn.-cass. skarns + base metal sulfides	cass.-bearing greisen-bordered red vein swarms + pegmatite	cass. bearing lodes and veins, musc.-qtz. greisen and disseminated cassiterite	disseminated cass.-columbite in gran. cupola, lodes and veins of cass. + wolf. + galena + sphal.	cass.-wolf. vein deposits + silver + base metal sulfides, dissemina- ted cass. in "tin porphyries"
E. Alteration	tourmalinisation, muscovitisation, kaolinisation, + albification, + chloritization	greisenisation tourmalinisation, albification, kaolinisation, + chloritization, + silicification	greisenisation, albification, tourmalinisation, kaolinisation	greisenisation	greisenisation, albification	greisenisation, tourmalinisation
F. Source of data	Present study, Gray (1963), Harris (1961), Stockley and Williams (1938)	Cobbing et. al. (1986), Manning (1986), Ishihara et. al. (1980), Sainsbury (1969)	Manning (1986), Jackson et. al. (1982), Stone (1982), Sainsbury (1969)	Juniper and Kleeman (1979), Taylor (1979) Flinter et. al. (1972)	Imokparia (1985, 1984), Olade (1980) Bowden (1970), Sainsbury (1969)	Lehmann (1985), McBride (1983), Duiski et. al. (1982), Sainsbury (1969)

^{*} Abbreviations: see page 210

CHAPTER 9

PETROGENESIS OF KARAGWE-ANKOLEAN GRANITES

9.0.0 Mineralogical constraints

The main minerals of the Karagwe-Ankolean granites are quartz, microcline and sodic plagioclase (An_{11-13}). Accessory minerals include biotite, muscovite, tourmaline and minor apatite, ilmenite, zircon, monazite and xenotime. The granites are classified as S-type (Chappell and White, 1974; White et al., 1986) on the basis of mineralogy and chemical composition. Apart from the bulk chemical composition, the mineralogy of S-type granites is controlled by the temperature and pressure of crystallization as well as the fugacities of volatile species such as H_2O , HF , H_3BO_3 and O_2 (Clemens and Wall, 1988). Pressure and temperature conditions for crystallization of the Karagwe-Ankolean granites are constrained by the occurrence of primary muscovite in the granites. Magmatic, fluorine-poor muscovite in granitic rocks indicates crystallization at relatively low temperature, high f_{H_2O} and moderate to high pressure (Clemens and Wall, 1981; 1988). The lower stability limit of muscovite in granitic magmas is considered to be > 3 kb based on the intersection of muscovite P-T stability curve and the H_2O -saturated granite solidus (Fig. 9-1). Primary muscovite in the Karagwe-Ankolean granites therefore suggests that the granitic magmas crystallized at p_{H_2O} conditions of > 3 kb, assuming that the magmas were saturated with respect to H_2O at the time of muscovite crystallization. The presence of sodic feldspar (oligoclase-albite) in addition to K-feldspar in the granites requires that the p_{H_2O} during crystallization be at least 3.5 kb, based on the experimental data of Tuttle and Bowen (1958) for the $NaAlSi_3O_8$ - $KAlSi_3O_8$ -

$\text{SiO}_2\text{-H}_2\text{O}$ haplogranite system. These pressure estimates are, however, not supported by the normative albite, quartz and orthoclase data which suggest crystallization pressures of < 3 kb, when the data are plotted on Ab-Qz-Or ternary diagram (Figs. 5-1, 5-3, and Appendix 1).

The pressure estimates based on the muscovite stability field, feldspar crystallization, and normative Ab-Qz-Or projections of the Karagwe-Ankolean granites can be reconciled if the effects of volatiles B and F on the solidus and liquidus temperatures and the presence of Ca in the granites are taken into account. James and Hamilton (1969) have shown that the addition of anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) to the $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$ system will cause the intersection of the liquidus with the solvus to occur at lower H_2O vapour pressures than in the anorthite-free system. Their experimental data indicate that both sodic and potassic feldspars can crystallize at pressures as low as 1 kb in granitic systems containing anorthite in the norm, and that the minimum melt composition in the Ab-Qz-Or projection is shifted toward the Qz-Or join relative to anorthite-free compositions (Fig. 5-2).

The liquidus and solidus temperatures of H_2O -saturated granitic magmas are affected by the presence of elements such F and B. Experimental data for B-, or F-rich granitic systems are discussed in detail in section 9.4.0. Simply stated, the presence of these elements reduces solidus temperatures at 1 kb from 715°C , with water alone, to less than 600°C with 4.66 % B in the system or less than 550°C with 4 % F (Manning and Pichavant, 1983). These low crystallization temperatures permit phases such as muscovite, topaz, and two alkali feldspars to crystallize from F and B enriched

granitic melts at low pressures (Pichavant and Manning, 1984). Because the P-T stability curve for muscovite has a positive slope and the H₂O-saturated granite solidus a negative slope (Fig. 9-1), lowering of solidus temperature by the presence of F and/ or B will expand the stability field of muscovite in the magma to lower pressures.

The combined effects of F, B and Ca in the Karagwe-Ankolean granitic magmas probably enabled crystallization of muscovite and two feldspars to take place at relatively low pressure and temperature conditions. Pressure conditions of up to 1 or 2 kb for crystallization of the granites, inferred from the normative Ab-Qz-Or projections (Figs. 5-1, 5-3), appear to be realistic in terms of the experimental data discussed above. These pressure estimates are not at variance with estimates for the crystallization of other granites of similar mineralogy and chemistry or degrees of geochemical evolution as the Karagwe-Ankolean granites. Desborough et al. (1980) gave pressure estimates of 1 kb for the crystallization of an highly evolved, two-mica, two-feldspar, F-rich (0.35-0.46 %), tin-bearing Redskin granite of the Pikes Peak batholithic complex, Colorado, USA, based on (a) the normative mineral composition of the granite when projected onto the Ab-Qz-Or ternary system (Tuttle and Bowen, 1958), and (b) the low temperature of crystallization indicated by the composition of albite (An₁₋₅) and K-feldspar (Or₉₆₋₁₀₀), and (c) the presence of Fe-rich dioctahedral mica and biotite of low Ti content. Pressure estimates of 2 to 2.5 kb are given by de Albuquerque (1971) for the crystallization of the two-mica granites in northern Portugal, based on the Ab-Qz-Or normative composition of the granites. Dilles (1987) concluded that biotite-bearing quartz monzonite and granite associated with Cu-Mo porphyry deposits, Yerington, Nevada,

Fig. 9-1:

Simplified P-T stability fields for some of the phases found in peraluminous granites and their relationship to the field of silicate melts. Overlap of the two fields (shaded) indicates that a primary magmatic origin for that phase is possible; however, the positions of all stability curves, including that of the granite solidus, are sensitive to many chemical parameters. The result may be to expand, contract or even eliminate the areas of overlap in the natural system. (After Clarke, 1981).

crystallized at pressure conditions of 2 to 1 kb on the basis of phase petrology and mineral composition studies. From these examples it can be seen that the pressure estimates for the crystallization of the Karagwe-Ankolean granites are within the range of other estimates from granites of similar phase relationships.

The temperature and pressure of crystallization of the Karagwe-Ankolean granitic magmas are further constrained by the occurrence of andalusite (Al_2SiO_5) in the contact metamorphic thermal aureoles around the granites. Two conflicting experimental data sets are available regarding the P-T stability fields for andalusite and its polymorphs (Fig. 9-2). The data of Holdaway (1971) put the invariant point for andalusite-sillimanite-kyanite stability fields at a pressure slightly below 4 kb and a temperature of about 500°C . Richardson et al. (1969) put the invariant point at a pressure of about 5.5 kb and a temperature of about 625°C . Using the presently accepted andalusite-sillimanite univariant curve of Holdaway (White and Chappell, 1977), the maximum pressure for andalusite stability would be ≤ 4 kb. If this pressure estimate is accepted then the presence of andalusite in the contact aureoles of the Karagwe-Ankolean granites would suggest a maximum lithostatic pressure of ≤ 4 kb for the crystallization of the parent magmas. The location of the H_2O -saturated granite solidus at ≤ 4 kb on a P-T plot (Fig. 9-2) constrain the temperature for the Karagwe-Ankolean granitic magmas to at least 660°C in the final stages of crystallization.

9.2.1 Geochemical constraints

Chemical data for Karagwe-Ankolean granites, presented and discussed in Chapters 5 and 6, are used together with experimental data and petrological

Fig. 9-2. Stability relationships of the Al_2SiO_5 polymorphs after Richardson et al. (1969; dotted lines) and Holdaway (1971; solid lines). P-T curve for H_2O -saturated granite solidus is also shown. (Diagram modified after White and Chappell, 1977).

information from the literature to characterise the source rocks and modes of magma generation and evolution for the Karagwe-Ankolean granitic magmas. Chemical parameters that help constrain the origin of the magmas are the peraluminosity indices, K_2O/Na_2O ratios, as well as the SiO_2 , B, CaO, Zr and P contents. High peraluminosity indices (up to 1.3), i.e. molar $Al_2O_3/(CaO + K_2O + Na_2O)$ ratios, indicate that the granites are peraluminous. Mechanisms for generation of peraluminous magmas (Miller, 1985) include: a) congruent melting of aluminous minerals in metapelitic rocks; b) anatexis of an ultramafic source through reactions such as: anorthite + olivine + orthopyroxene $\rightarrow$ clinopyroxene + liquid; c) anatexis of a mafic source involving reactions such as: hornblende $\rightarrow$ clinopyroxene + olivine + liquid, or garnet $\rightarrow$ clinopyroxene + liquid; d) anatexis of a quartzofeldspathic source involving reactions such as: high-Al biotite $\rightarrow$ low-Al biotite + liquid, or biotite + plagioclase $\rightarrow$ hornblende + liquid; and e) fractional crystallization of non-aluminous phases (e.g., pyroxene) from calc-alkaline magmas or (f) vapour phase removal of alkalis from weakly metaluminous or weakly peraluminous magmas. Partial melting of ultramafic or mafic source by mechanisms (a) and (b) to produce strongly peraluminous magmas of composition akin to the Karagwe-Ankolean granites seems unlikely considering the high SiO_2 and K_2O contents and very low FeO, MgO and CaO contents of the granites. The lack of mafic and intermediate rocks associated with the Karagwe-Ankolean granites rules out the derivation of the granites by fractional crystallization of less aluminous phases from calc-alkaline magmas. Removal of alkalis in a fluid phase from magmas as in model (e) is unlikely to produce large volumes of magmas of batholithic dimensions. Mechanisms (a) and (d) are the most likely for the origin of the

Karagwe-Ankolean granitic magmas. Anatexis of a quartzofeldspathic source has limitations because it is difficult to yield large magma volumes if melting takes place under vapour-absent conditions. Partial melting of metapelitic rocks involving biotite dehydration reactions such as those suggested by Le Breton and Thompson (1988) and Vielzeuf and Holloway (1988) is favoured for generating the Karagwe-Ankolean, peraluminous, granitic magmas. Low CaO and $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios coupled with high B contents in the Karagwe-Ankolean granites suggest a source, probably of pelitic composition (e.g., Chappell and White, 1974; Miller, 1985).

Abnormally high B concentrations, 3 to 200 times the average abundance in low calcium-granites (Turekian and Wedepohl, 1961), indicate that the parent magmas of the Karagwe-Ankolean granites were strongly enriched in B. Such B-rich magmas can be produced either by the melting of a B-rich source or by the introduction of a B-rich fluid during magma ascent and emplacement into low-grade metasedimentary rocks. High B concentrations occur mainly in clay-rich pelitic rock and evaporitic sedimentary sequences (Ethier and Campbell, 1977) or their metamorphosed equivalents. Boron, in sedimentary sequences, is either concentrated in detrital tourmaline or in clay minerals where it substitutes for Al at levels up to 2000 ppm (Manning and Pichavant, 1983). During diagenesis and metamorphism, B in clay minerals is released to form tourmaline, stable over a wide range of P-T conditions. Less commonly, B may be hosted in other borosilicate minerals such as dumortierite, grandidierite, kornerupine and sinhalite (Manning and Pichavant, *op cit*). Because of the refractory nature of tourmaline, B-rich granitic magmas are produced at high temperatures. Experimental data indicate that tourmaline

remains stable up to about 750⁰ C (Benard et al., 1985). Above this temperature, tourmaline becomes unstable and breaks down, releasing B to the silicate melt. If B in the Karagwe-Ankolean magmas was derived from the breakdown of tourmaline in the metasediments it is then possible that temperatures of > 750⁰ C were probably attained during melting. Because of their low viscosity and solidus temperature, B-rich magmas are likely to rise quickly to shallow crustal levels before complete solidification of the magmas can take place.

The origin of Karagwe-Ankolean granites is further constrained by their Zr and P contents. It has already been shown that Zr shows decreasing trends from the less evolved to the more evolved granites, that were attributed to the removal of zircon by fractional crystallization from the original magmas. This is supported by zircon inclusions in micas, quartz, and tourmaline grains, indicating early crystallization from the magmas. Zircon was probably a liquidus or a near-liquidus phase in the Karagwe-Ankolean magmas. The solubility of Zr in felsic magmas has been experimentally investigated by Watson (1979) and Watson and Harrison (1983). For peraluminous melts and melts lying in the quartz-albite-orthoclase composition plane, zircon crystallization occurs with <100 ppm Zr at low temperatures (< 750⁰ C). The solubility of Zr strongly depends on the molar (Na₂O + K₂O)/Al₂O₃ ratio of the melts and increases as the ratio increases (Watson, 1979). The solubility of Zr also increases with increasing temperature. Low Zr contents (25-111 ppm) in the Karagwe-Ankolean granites suggest that the parent magmas crystallized at relatively low temperatures (≤ 750⁰ C). Such low Zr contents are typical of crustally derived anatectic magmas (Watson, 1979).

Phosphorus in the Karagwe-Ankolean granites is contained mainly in apatite, although some of the P may be contained in accessory xenotime and monazite. It has been shown in Chapter 5 that P remained relatively constant in all of the Karagwe-Ankolean granitic magmas, suggesting that the P content was possibly buffered by apatite precipitation. Apatite saturation in the magmas probably occurred relatively early in the crystallization histories, as indicated by apatite phenocrysts and apatite inclusions in micas and tourmaline in the granites. Experimental data indicate that apatite saturation in felsic magmas (70-80 % SiO_2) occurs when the P_2O_5 content in the magmas reaches an average of 0.14 wt % (Watson and Capobianco, 1981). This implies that the P_2O_5 content of felsic magmas produced by the partial melting of crustal rocks will be buffered at about 0.14 wt % for magmas derived in source regions containing > 0.14 wt %, and that apatite will remain in the restite. For sources containing < 0.14 wt % P_2O_5 , the P_2O_5 content of the magmas will be buffered at 0.14 wt % as long as apatite remains in the restite (Watson and Capobianco, 1981). The distribution of P_2O_5 contents in the Karagwe-Ankolean granites is more or less consistent with the experimental data of P_2O_5 -saturated felsic magmas. This suggests that apatite was probably a restite phase in the source region for the Karagwe-Ankolean granitic magmas. Rounded and cloudy apatite, forming cores of euhedral apatite crystals (Plate 3-2C), perhaps represent apatite inherited from the source region.

9.2.0 Isotopic constraints

Additional constraints on the origin of granitic magmas in the Karagwe-Ankolean belt are provided by Rb-Sr isotopic data obtained from the

granites. $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios for the granites are unusually high (0.732-0.807) compared to those observed in I-type granites (Chappell and White, 1974), which typically have ratios in the range 0.704-0.706. Granites with high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios, higher than those of Sr evolution in the mantle (0.704 ± 0.002 ; Faure, 1986), are thought to have crystallized from magmas produced by: a) partial melting of crustal sialic rocks enriched in radiogenic ^{87}Sr or b) fractional crystallization of mantle-derived mafic magmas that have been contaminated by crustal material rich in radiogenic ^{87}Sr . The lack of rocks of mafic or intermediate compositions closely associated with the Karagwe-Ankolean granites precludes the derivation of the granites by fractional crystallization of mafic magmas. This is also supported by Rb-Sr-Ba data presented in Figure 5-25 and Appendix 2, which show that the association of rocks of gabbroic, dioritic and granitic composition, that would be expected of fractionation, is lacking. The Sr isotopic composition of Karagwe-Ankolean granitic magmas can not be explained by the assimilation of crustal material by mafic magmas. An origin by partial melting of crustal sialic material enriched in radiogenic ^{87}Sr appears to be more consistent with the petrological and chemical data of the Karagwe-Ankolean granites. Older, Precambrian basement gneisses may have been potential source rocks for the granitic magmas. The increase of $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios from the value of ca 0.732 in the syn-orogenic granites of the Bushubi batholith (Fig. 7-5) to values of ca 0.789 and ca 0.807 in the post-orogenic granites of the Mumakera and Maleba plutons, respectively, can be explained by a) the derivation of the granitic magmas from an heterogeneous source, b) the contamination of the magmas by low-grade metasediments rich in radiogenic ^{87}Sr , at different crustal levels, or c) a

combination of both of these processes. The available petrological, chemical and isotopic data can not be used to discriminate between the above processes. Muscovite schist enclaves within some of the granites indicate that the granitic magmas were possibly contaminated by assimilation of country rocks.

A comparison of $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios of the Karagwe-Ankolean granites with those of granites from other parts of the Kibaran Belt in Zaire, Burundi and Rwanda can be seen in Table 7-3. With the exception of the alkaline tin-granites (G4), the remainder of the granites have initial ratios substantially lower than those of the Karagwe-Ankolean granites. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for G1, G2 and G3 granites shown in Table 7-3 fall in the range 0.702-0.721; the tin-granites (G4) have ratios in the range 0.731-0.778. These data suggest that the source rocks for the G1, G2 and G3 granites in other parts of the Kibaran Belt had Sr isotopic compositions quite different from the sources for the Karagwe-Ankolean granites. The presence of a lower crust or sub-crustal Sr component in the G1, G2 and G3 granitoids appears likely in view of low $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios. The relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios for the alkaline tin-granites (G4), however, suggest that these granites probably crystallized from magmas rich in radiogenic Sr from continental crust.

$^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios for S-type granites (Chappell and White, 1974) are typically > 0.708 . For I-type granites the ratios are in the range 0.704-0.706. Beckinsale (1979) and others have reported initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the range 0.710-0.733 for stanniferous S-type Triassic granites in Thailand, and such granites were considered to contain a major component of

crustal Sr because of their high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios. The similarity of the stanniferous granites in the Karagwe-Ankolean belt and the southeast Asian tin belt, including Thailand (see Chapter 8), suggest similar modes of origin of granite in both areas.

In summary, the peraluminous composition, high $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios, and high B contents of the Karagwe-Ankolean granitic magmas suggest a pelitic source.

9.3.0 Concentration of tin during magmatic differentiation

Important parameters which influence the crystal-chemical behaviour of Sn are summarized in Table 9-1. These chemical parameters determine whether tin accumulates in residual magma or is incorporated into the structure of crystallizing mineral phases.

TABLE 9-1. Properties of Sn, Ti and Fe important for their crystal-chemical behaviour (Bergerkoff et. al., 1978)

	Sn ²⁺ *	Sn ⁴⁺	Ti ⁴⁺	Fe ³⁺
Ionic radius (Å)	1.30	0.71	0.68	0.64
Coordination number	6 (8)	6	6	6
Ionization potential (eV)		40.57	44.66	55.42
Electronegativity (Kcal/g atom)		235	260	245

* (Sn²⁺ parameters are from Krauskopf, 1979)

Tin exists in silicate magmas either in the divalent (Sn²⁺) state or in tetravalent (Sn⁴⁺) state depending on the oxygen fugacity ($f\text{O}_2$) of the magma. At relatively high oxygen fugacities, above those of nickel-bunsenite (Ni-NiO) buffer (Fig. 9-3A), tin exists in the magma predominantly in the

tetravalent state (Durasova et al., 1984; 1985; 1986). Under those conditions, Sn^{4+} can substitute for Ti^{4+} and/or Fe^{3+} in the crystallizing ferromagnesian silicates or oxides such as hornblende, biotite, titanite or magnetite (Fig. 9-3B). Therefore, crystallization of these ferromagnesian minerals has a profound effect on the Sn-productivity of the magma. Early crystallization of these mineral phases will tend to deplete Sn in the magmas, and reduce the chance for the magmas to form Sn ore deposits. Late crystallization of the above minerals enables Sn to be concentrated in residual magmas, and increases the potential of producing Sn-mineralized granites.

At low oxygen fugacities, corresponding to wüstite-magnetite buffer (Fig. 9-3A), Sn exists in silicate magmas largely in the bivalent state (Sn^{2+}) and does not easily substitute for Fe^{3+} or Ti^{4+} in the ferromagnesian minerals. Instead it is concentrated in residual magma, increasing the Sn-ore potential of the magma (Durasova et. al., 1985; 1986). High pH and alkali (K, Na) contents in silicate magma also prevent entry of Sn into the ferromagnesian minerals and favours its accumulation in residual magma (Levashev et. al., 1971) by forming alkali-stannate complexes. The P-T-X-f O_2 conditions of a magma influences the stability and sequence of crystallization of minerals. Some minerals (e.g., biotite) may concentrate Sn during early stages of crystallization and release Sn to hydrothermal fluids during late-magmatic or post-magmatic, metasomatic alteration.

Hornblende and titanite are absent, while biotite, tourmaline and ilmenite are present in the Karagwe-Ankolean granites. The absence of titanite and hornblende, the main concentrators of Sn among the silicate

Fig. 9-3B. Solubility of Sn in magnetite as affected by temperature and oxygen potential (Durasova et al., 1986).

Fig. 9-3A. Valence states of Sn in hawaiiite at various oxygen fugacities (Durasova et al., 1986).

minerals, suggest that Sn fractionation into residual magmas was possible during the formation of Karagwe-Ankolean granites.

Comparison of Sn contents of various minerals (Table 6-16) indicates that Sn in the Karagwe-Ankolean granites is mainly concentrated in muscovite and that little Sn is carried in biotite or tourmaline. Early crystallization of biotite and late-crystallization of tourmaline did not deplete Sn from residual magmas. Biotite compositions (Fig. 6-3) suggest that low oxygen fugacities prevailed in the early stages of crystallization of the two-mica granites in the Maleba pluton. Preferential entry of Sn into biotite was not possible because Sn probably existed in the magmas predominantly in the divalent state. High alkali contents in the magmas may have also prevented large entry of Sn into biotite, by the formation of alkali-stannate complexes.

Muscovite apparently crystallized late from the magmas, after the magmas were enriched in H_2O , Sn and other incompatible trace elements. The timing of muscovite precipitation from the magmas and H_2O saturation may have been critical in determining Sn-ore potential of the various plutons. Water saturation before or during muscovite crystallization would have favoured concentration of Sn in exsolved aqueous fluids, especially if the fluids contained ligands such F^- and/or Cl^- .

Available petrologic evidence suggests that H_2O saturation and formation of Sn-bearing fluids was largely attained in the post-orogenic granites but not in the syn-orogenic granites. Support to this is given by the occurrence of Sn-bearing hydrothermal veins and minor pegmatites in the post-orogenic granites of the Maleba pluton and Karagwe-Tinfield, and the lack of any Sn

deposits in the syn-orogenic granites. Low Sn levels in the syn-orogenic granites possibly indicate original low Sn concentrations in the magmas. It is also possible that the P-T-X conditions for crystallization of the syn-orogenic magmas did not favour the enrichment of Sn in residual magmas. The original magmas may have been relatively anhydrous as suggested by the lack or paucity of pegmatites, miarolitic cavities, and hydrothermal alteration in the syn-orogenic granites.

9.4.0 Role of boron and other volatiles

Experimental studies of haplogranitic systems (Tuttle and Bowen, 1958; Pichavant, 1981; Manning, 1982) enriched in H_2O , F and B, have contributed to the understanding of the role of volatiles in the generation and crystallization of granitic melts. Volatiles act as fluxes, and facilitate partial melting of crustal rocks. The amount of melt produced is more or less proportional to the volatile content of the rocks undergoing partial melting. The physicochemical properties of granitic melts produced by partial melting are greatly modified by the solubility of volatiles in the melts. The interaction of volatiles with silicate melt structural components results in depolymerization and hence reduction in viscosity (Manning and Pichavant, 1985). Volatiles in granitic melts also lower the liquidus and solidus temperatures. Volatile-rich granitic magmas may rise to higher crustal levels, and cooling and crystallization may result in the separation of a volatile phase from the magmas. Partitioning of valuable elements (e.g., Sn, W, Nb, Ta) between the volatile fluids and the magmas may result in the concentration of the elements into the hydrothermal fluids, especially if the fluids are enriched in Cl, F and B, in the form of metal

complexes. Changes in temperature, pH and Eh of hydrothermal fluids may cause precipitation of metals from solution to form ore deposits.

It has been shown in Chapter 5 that stanniferous granites in the Karagwe-Ankolean belt crystallized from magmas rich in B. Useful information regarding the effect of B on the crystallization of granitic melts in the system Qz-Ab-Or-B₂O₃-H₂O is derived from experimental studies (Chorlton and Martin, 1978; Pichavant, 1981; Pichavant and Manning, 1984), and experimental data show that B increases the solubility of water in granitic melts and lowers solidus and liquidus temperatures. At 1 kb p_{H₂O}, the solubility of H₂O in granitic melts of minimum melt composition is 4.0 wt % for melts containing 1 wt % B₂O₃ (3105 ppm B), and 6.5 wt % for melts containing 4.5 wt % B₂O₃ (Manning and Pichavant, 1985). The solidus for water saturated granitic melt without B is about 710-725° C at 1 kb p_{H₂O} (Tuttle and Bowen, 1958; Pichavant, 1981). Addition of 2 % to 5 % B₂O₃ to H₂O in equilibrium with the melt, lowers the solidus temperature to 680° C and 655° C respectively (Chorlton and Martin, 1978; Pichavant, 1981). Figure 9-4 shows the effect of B, F and Li on liquidus temperatures and composition of granitic melts. With the addition of B or F, the minimum melt composition in the system Qz-Ab-Or-H₂O is displaced toward the albite corner when projected onto the Qz-Ab-Or plane. This means that fractional crystallization of B and/or F-rich granitic magmas will tend to yield residual melts relatively rich in Na₂O. In H₂O saturated granitic systems, B partitions in favour of the aqueous phase (K_D melt/vapour = 0.33, Pichavant, 1981). This contrasts with F which partitions in favour of silicate melt. The overall solubility of Al, K, Na, and Si in the aqueous fluids is increased by B enrichment, suggesting that B behaves as a complexing agent

for various elements in high temperature solutions (Pichavant, op cit).

The presence of high B and moderate to high F concentrations in the Karagwe-Ankolean granitic magmas may have had profound effects on the chemical evolution of the magmas. Reduced magma viscosity and liquidus and solidus temperatures due to the presence of B and F in the magmas allowed higher degrees of differentiation and Sn-enrichment, by promoting fractionational crystallization. Increased H₂O solubility in the presence of B may have allowed Sn-enrichment and high level emplacement (≤ 3 kb) of the magmas before reaching H₂O-saturation. Water saturation during final stages of crystallization possibly permitted the separation of aqueous fluids from residual magmas.

Water saturation and separation of volatile-rich fluid phases from the post-orogenic granitic magmas is indicated by hydrothermal quartz-tourmaline veins and zones of hydrothermal alteration in the stanniferous granites. The predominance of tourmalinization in the granites and surrounding country rocks suggests that the hydrothermal fluids were strongly enriched in B. The lack of evidence for fluorine metasomatism and greisenization in the Karagwe-Ankolean granites indicates relatively low F activities in the hydrothermal fluids.

Boron metasomatism and tourmalinization of the granites and surrounding country rocks preceded the emplacement of cassiterite-bearing, hydrothermal quartz veins. Loss of B from the magmas reduced H₂O solubility in the magmas and forced the magmas toward H₂O saturation as crystallization proceeded. Water saturation and exsolution of aqueous fluids from the magmas was

presumably accompanied by the partitioning of various elements, including elements such as Sn and W, between residual magmas and co-existing aqueous fluids. Preferential partitioning of these elements into the aqueous fluids may have resulted in the formation of Sn-rich fluids. Pressure build up as result of exsolved fluids, and fracturing of granite carapace, resulted in the escape of fluids from the magmas. Cooling and interaction of the fluids with the country rocks resulted in the precipitation of cassiterite in mica-quartz veins. The precipitation of cassiterite was probably brought about by the drop in temperature and increase of Eh and pH of hydrothermal fluids as the fluids reacted with the country rocks.

9.5.0 Source rock composition and the origin of the stanniferous and barren granitic magmas

Factors which may have favoured the concentration or depletion of Sn in the magmas during fractional crystallization have been discussed in section 9.3.0. As shown in section 9.0.0, the chemical composition of the Karagwe-Ankolean granites suggests derivation of their parent magmas by partial melting of metasedimentary rocks. The causes for partial melting are not known but could be due to (a) injection of mafic and ultramafic magmas from the mantle into the lower crust, (b) crustal thickening and increase in the amount of radioactive heat flow (e.g., Kroner, 1984) or (c) both of these processes. Given the heterogeneity of sedimentary rocks, it is possible that variations in chemical composition of the source rocks may have influenced the Sn content of the magmas produced by the partial melting. Because of contrasting trace element contents of sandstone and shale (Table 9-2), magmas formed by partial melting of these rocks or their metamorphosed equivalents will have different amounts of valuable metals and volatiles. On

the basis of chemical data in Table 9-2, magmas derived by partial melting of a pelitic source are likely to be enriched in Sn, Be, Nb, W, Li, B, F and possibly H₂O, over those derived from a psammitic source. The former could be termed as "fertile" (e.g., Černý and Meintzer, 1988) and the latter "barren". Partial melting of a sequence containing psammitic and pelitic metasediments would yield magmas with chemical compositions between those of the "barren" and "fertile" end-member magma compositions. Fractional crystallization of the magmas derived from such pelitic-psammitic source

TABLE 9-2. Comparison of trace element averages of sandstone and shale (Data from Turekian and Wedepohl, 1961)

	sandstone (psammitic sediments)	shale (pelitic sediments)
Sn (ppm)	0.0X	3.00
Be	0.0X	3.00
Nb	0.0X	2.60
W	1.60	1.80
Li	15.00	66.00
B	35.00	100.00
F	270.00	740.00
H ₂ O	less hydrous	more hydrous

would yield residual magmas with compositions along the mixing line between the "fertile" and "barren" end-member compositions. Magmas with compositions close to the "fertile", meta-pelitic end-member composition (Fig. 9-5) are likely to produce granites associated with pegmatites of rare-metals.

Extreme fractionation of such magmas will under favourable conditions result in the exsolution of metal-rich "ore-fluids" which may form hydrothermal ore-deposits upon cooling. Relatively anhydrous, Sn-, W-, Nb-, Be-poor, magmas with compositions toward the "barren", psammitic end-member (Fig. 9-

Fig. 9-5. Schematic flow flow diagram showing possible ways by which ore-bearing and barren granites may originate based on source rock compositions.

5) are likely to produce granites lacking in ore-pegmatites or hydrothermal ore-deposits.

The spatial distribution of the barren and stanniferous granites in the southern part of the Karagwe-Ankolean belt can be best explained by the model presented above. The barren granites are generally restricted to the Bushubi batholith (Fig. 7-5) whereas the stanniferous granites occur in three plutons namely Mumakera, Nyamakombe and Maleba, west of the Bushubi batholith. The spatial separation of the two types of granites can be easily explained if the granites originated from the partial melting of an heterogeneous source. Low contents of Sn, F, B and Li, and the paucity or lack of aplite or pegmatite in the granites of the Bushubi batholith, suggest that the source rocks for these granites were poor in those elements, and perhaps less hydrous. In contrast, granites of the Mumakera, Nyamakombe and Maleba plutons are generally rich in Sn, F, B, and Li, and locally contain aplite, pegmatite and zones of pervasive hydrothermal alteration. Their parent magmas were possibly more hydrous and fertile than the magmas associated with the Bushubi batholith. It is possible that the stanniferous granites in the Mumakera, Maleba and Nyamakombe plutons formed from magmas generated by the partial melting of a metapelitic source while the barren granites in the Bushubi batholith formed from magmas derived mainly from a source rich in metapsammitic rocks. In conclusion, the spatial separation of stanniferous and barren granites in the Karagwe-Ankolean belt can be explained if the parent magmas were derived from rocks with contrasting compositions.

9.6.0 Tectonic model

The tectonic model for the evolution of the Karagwe-Ankolean orogenic belt in northwestern Tanzania is shown in cartoon diagrams in Figure 9-6. The model consists of five stages, commencing at $ca \geq 1370$ Ma and terminating at $ca 700$ Ma. The initial stage (Stage I) was characterized by lithospheric extension, crustal attenuation, rifting and formation of a sedimentary basin (Fig. 9-6). The causes for the lithospheric extension are not known but could have been in response to asthenospheric upwelling. In the Karagwe-Ankolean belt rifting did not permit formation of large amounts of volcanic rocks in the sedimentary basin. The compressional stage (Stage II), at 1324 ± 46 Ma, resulted in the deformation and metamorphism of Karagwe-Ankolean sedimentary rocks. Pre- or syn-orogenic (G1/G2) granites were formed during this stage. Early post-orogenic granite magmatism (Stage III) resulted in the formation of G3 granites at 1088 ± 118 Ma. Sn-mineralized granites (G4) were formed at 1006 ± 88 Ma (Stage IV, Fig. 9-6). Uplift and erosion of the Karagwe-Ankolean orogenic belt (Stage V) was accompanied by the formation of Bukoban molasse along the eastern margin of the belt. Resetting of minerals in Karagwe-Ankolean granites occurred between 700-900 Ma as a result of tectono-thermal events related to the Bukoban-Katagan tectonic cycle in western and eastern-central Africa.

Cartoon diagrams showing the evolution of the Karagwe-Ankolean belt

Fig. 9-6

CHAPTER 10

SUMMARY AND CONCLUSIONS

Field studies, mineralogical, chemical and isotopic data have been used to constrain the petrogenesis of stanniferous and barren granites in the Karagwe-Ankolean belt, NW Tanzania. Geological mapping (scale 1:10,000) has shown that the granites consist mainly of two-mica granites that are locally surrounded by contact aureoles. Tourmaline-muscovite-, and tourmaline-leucogranites, found locally in the apical parts of the two-mica granites, are considered to be late-magmatic differentiation products. K-feldspar in the two-mica granites and leucogranites is low-microcline, and plagioclase has the composition $An_{\leq 13}$. Common accessory minerals are biotite, muscovite, tourmaline, apatite, zircon, ilmenite, xenotime and monazite. Garnet-bearing aplite dykes and pegmatites in the stanniferous granites are not associated with the barren granites. The stanniferous granites are distinguished from the barren granites by their predominantly non-foliated texture and spatial association with tin deposits.

On the basis of field relationships and texture, the formation of the stanniferous granites post-dated the main metamorphic and deformational episodes that produced the NE-trending structural fabric of the Karagwe-Ankolean-Kibaran orogen. The formation of the barren granites pre-dated or was synchronous with the deformation and metamorphism.

The barren (syn-orogenic) and stanniferous (post-orogenic) granites, characterized by evolved major and trace element compositions, are peraluminous, low-calcium granites, with low Fe_2O_3 , MgO and TiO_2 contents

and restricted SiO_2 (71-76 %) contents. Most are enriched in Sn, Li, Rb, B and commonly F, and depleted in Sr, Ba, and Zr relative to the average low-calcium granites (Turekian and Wedepohl, 1961). Highest degrees of enrichment of incompatible elements and depletion of compatible elements are attained in the stanniferous granites. High Rb/Ba (>1.55), Rb/Zr (>10) and Li/Sr (>2), and low K/Rb (<110) and Sr/Rb (<0.15) ratios in the stanniferous granites indicate highly evolved granites.

Major and trace element variation diagrams for the stanniferous and barren granites are consistent with fractional crystallization of plagioclase, K-feldspar, biotite, and Fe-Ti oxides. The chemical trends shown by Fe, Mg, Ca, Na and F in optically zoned tourmaline in the leucogranites are also consistent with crystal fractionation. Formation of the stanniferous granites is thought to have been favoured by high B and/or F contents which allowed high degrees of fractional crystallization and Sn-enrichment by increasing H_2O solubility, lowering the viscosity in the original magmas, and depressing the granite solidus. The depression of the granite solidus by the presence of high B and F contents in the granitic magmas enabled the magmas to rise to higher crustal levels and crystallize at H_2O pressures as low as 1 or 2 kb. H_2O saturation during the final stages of magmatic crystallization resulted in the separation of fluids enriched in Sn from the magmas. Brittle deformation and fracturing of the country rocks, above the chemically specialized granites, enabled the fluids to escape from the granites and form exogranitic hydrothermal tin deposits. Early fluids released from the granites were strongly enriched in B and caused pervasive tourmalinization of the country rocks. These fluids were less enriched in Sn and no tin deposits were formed from the fluids. Late fluids released from

the granites were poor in B but more enriched in Sn than the early fluids, and are responsible for the majority of the hydrothermal cassiterite-muscovite-quartz veins in the country rocks. Economic tin deposits were produced by these late fluids.

Subsequent to igneous crystallization, subsolidus re-equilibration occurred in both the syn-orogenic/barren and post-orogenic/stanniferous granites. This re-equilibration was accompanied by the development of myrmekite and structurally more ordered microcline. Temperatures of K-feldspar-biotite re-equilibration in the granites are estimated to be between 570⁰ and 590⁰ C, based on Rb/K partitioning.

High B (30-2000 ppm) and low Zr (30-126) contents in the barren and stanniferous granites, together with high initial ⁸⁷Sr/⁸⁶Sr ratios (0.732-0.807) and P₂O₅ contents (0.1-0.2 %) that are close to P saturation values in felsic magmas suggest that the granites crystallized from magmas produced by crustal anatexis. The strongly peraluminous composition and very high B contents in the granites indicate that the parent magmas were possibly derived by partial melting of B-rich metapelitic source. The lack of basic or intermediate rocks associated with the granites and the Rb-Ba-Sr data precludes the formation of the granites by fractional crystallization of mafic magmas.

Whole-rock Rb-Sr isotopic data record at least two events of granite magmatism in the Karagwe-Ankolean belt. The first event is dated at 1324 ± 23 Ma by the date of the syn-orogenic Bukiriro granites in the Bushubi batholith. The second is dated at 1088 ± 59 Ma by the date of the post-

orogenic granites in the Mumakera pluton. A third less constrained event is indicated at 1006 ± 44 Ma by the date of post-orogenic granites in the Maleba pluton. The latter two dates are, however, indistinguishable at the 2 sigma level and may indicate the same granitic event. The above events may be correlated with igneous activities responsible for the formation of G1/G2, G3 and G4 granites, respectively, in other parts of the Karagwe-Ankolean/Kibaran orogen in Zaire, Burundi, Rwanda and SW Uganda. Tin mineralization in the Karagwe-Ankolean belt appears to be related to the latest granitic events. Rb-Sr and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of biotite and muscovite are in the range 965 Ma to 685 Ma and represent the resetting of micas by tectono-thermal events post-dating the Karagwe-Ankolean/Kibaran orogeny but contemporaneous with the Bukoban-Katangan cycle of Pan-African tectonism in western and eastern-central Africa.

REFERENCES

- ABBEY S., 1977. Studies in "Standard Samples" for use in the general analysis of silicate rocks and minerals; Part 5: Edition of "Usable Values"; GSC Pap. 77-34, 31 p.
- ALDERTON D.H.M., PEARCE J.A. AND POTTS P.J., 1980. Rare-earth element mobility during granite alteration: evidence from Southwest England. *Earth Plan. Sci. Lett.*, v. 49, pp. 149-165.
- ALEKSIYEV E.I., 1970. Genetic significance of the rare-earth elements in the younger granites of northern Nigeria and the Cameroons. *Geochem. Inter.*, v. 7, pp. 127-132.
- ALLMANN-WARD P., HALLS C., RANKIN A. AND BRISTOW C.M., 1982. An intrusive breccia body at Wheal Remfry in the western part of the St. Austell granite pluton, Cornwall, England; in Evans A.M. (Ed.): *Metallization associated with acid magmatism*. John Wiley & Sons Ltd., New York, pp. 1-28.
- BAILEY S.W., 1984. Classifications and structures of the micas; in Bailey S.W. (Ed.): *Reviews in Mineralogy Vol. 13: Micas*. Miner. Soc. Amer., pp. 1-12.
- BECKINSALE R.D., SUENSILPONG S., NAKAPADUNGRAT S. AND WALSH J.N., 1979. Geochronology and geochemistry of granite magmatism in Thailand in relation to a plate tectonic model. *Jour. Geol. Soc. London*, v. 136, pp. 529-540.
- BELL K. AND BLENKINSOP J., 1987. Nd and Sr isotopic compositions of East African carbonatites: Implications for mantle heterogeneity. *Geology*, v. 15, pp. 99-102.
- BELL K. AND BLENKINSOP J., 1984. Multiple collection in solid-source mass spectrometry. *Geoscience Canada*, v. 11, pp. 50-52.
- BELL K. AND DODSON M.H., 1981. The geochronology of the Tanzania Shield. *Jour. Geol.*, v. 89, pp. 109-128.
- BENARD F., MOUTOU P. AND PICHAVANT M., 1985. Phase relations of tourmaline leucogranites and the significance of tourmaline in silicic magmas. *Jour. Geol.*, v. 93, pp. 271-291.
- BERGERKOFF G., HAMAGUCHI H.K., KURODA R. AND WEDEPOHL K.H., 1978. Tin; in Wedepohl K.H. (Ed.): *Handbook of Geochemistry*, Vol. II-2. Springer-Verlag, New York; pp. 50-A-1 - 50-M-1.
- BERRYMAN H.O., 1941. Mineral Report on Maleba Mine, Bushubi, Ngara District, Tanganyika (Tanzania). *Tanzania Geol. Surv.*, Dodoma, 3 p.
- BESWICK A.E., 1973. An experimental study of alkali metal distributions in feldspars and micas. *Geochem. Cosmoch. Acta*, v. 37, pp. 183-208.

- BOWDEN P., 1970. Origin of the Younger granites of Northern Nigeria. *Contr. Mineral. Petrol.* 25, pp. 153-162.
- BOYNTON W.V., 1984. Cosmochemistry of the rare-earth elements: Meteorite studies; in Henderson P. (Ed.): *Rare Earth-Element Geochemistry*. Elsevier, Amsterdam; pp. 63-114.
- BRINCKMANN J., HOEHNDORF A., KREUZER H., LEHMANN B., LENZ H. AND MUELLER P., 1987. Radiometric time scale for granitoids of the Kibaran and Post-Kibaran period. Poster session: 14th Colloquium on African Geology, Berlin (west), 18-22 August, 1987.
- BROWNLOW A.H., 1979. *Geochemistry*. Prentice-Hall, USA, 490 p.
- CAHEN L. AND SNELLING N.J., 1966. *The Geochronology of Equatorial Africa*. North-Holland, Amsterdam; 195 p.
- CAHEN L., SNELLING N.J., DELHAL J., VAIL J.R., BONHOMME M. AND LEDENT L. 1984. *The Geochronology and Evolution of Africa*. Clarendon Press, Oxford; 512 p.
- CANDELA P.A., 1986. The evolution of aqueous vapour from silicates melts: effect on oxygen fugacity. *Geochem. Cosmoch. Acta*, v. 50, pp. 1205-1211.
- ČERNÝ P. AND HAWTHORNE F.C., 1982. Selected peraluminous minerals; in Černý P. (Ed.): *Short course in granitic pegmatites in science and industry*; Mineral. Assoc. Canada, v. 8; pp. 163-186.
- CERNY P. AND MEINTZER R.E., 1988. Fertile granites in the Archean and Proterozoic fields of rare-element pegmatites: Crustal environment, geochemistry and petrogenetic relationships; in Taylor R.P. and Strong D.F. (Eds.): *Recent Advances in the geology of granite-Related Mineral Deposits*. CIMM Spec. Vol. 39, pp. 170-207.
- CHAPPELL B.W. AND WHITE A.J.R., 1974. Two contrasting granite types. *Pacific Geology* 8, 173-174.
- CHAPPELL B.W., WHITE A.J.R. AND WYBORN D., 1987. The importance of residual source material (restite) in granite petrogenesis. *Jour. Petrol.*, v. 28, pp. 1111-1138.
- CHAROY B., 1982. Tourmalization in Cornwall, England; in Evans A.M. (Ed.): *Metallization Associated with Acid Magmatism*. John Wiley and Sons, New York; pp. 63-70.
- CHATTERJEE A.K., STRONG D.F. AND MUECKE G.K., 1983. A multivariate approach to geochemical distinction between tin-specialized and uranium-specialized granites of southern Nova Scotia. *Can. Jour. Earth Sci.*, v. 20, pp. 420-430.

- CHORLTON L.B. AND MARTIN R.F., 1978. The effect of boron on the granite solidus. *Canadian Mineralogist*, v. 16, pp. 239-244.
- CLARKE D.B., 1981. The mineralogy of peraluminous granites: A Review. *Can. Mineralogist*, v. 19, pp. 3-17.
- CLEMENS J.D. AND WALL V.J., 1988. Controls on the mineralogy of S-type volcanic and plutonic rocks. *Lithos*, v. 21, pp. 53-66.
- CLEMENS J.D. AND WALL V.J., 1981. Origin and crystallization of some peraluminous S-type granitic magmas. *Can. Mineral.*, v. 19, pp. 111-131.
- COBBING E.J., MALLICK D.I.J., PITFIELD P.E. AND TEOH L.H., 1986. The granites of southeast Asian tin belt. *Jour. Geol. Soc., London*, v. 143; pp. 537-550.
- COMBE A.D., 1926. Summary of field work carried out in 1925. *Uganda Geol. Surv. Ann. Rep. (1925)*, pp. 15-24.
- COX K.G., BELL J.D. AND PANKHURST J.R. 1979. The interpretation of igneous rocks. *George Allen & Unwin, London*, 450 p.
- CROSBY P., 1971. Composition and structural state of alkali feldspars from charnockitic rocks on Whiteface mountain, New York. *Amer. Miner.*, v. 56, pp. 1788-1811.
- DALRYMPLE G.B. AND LANPHERE M.A., 1969. Potassium-Argon dating: Principles, Techniques and Applications to Geochronology. *W.H. Freeman and Company, San Francisco*; 258 p.
- DE ALBUQUERQUE C.A.R., 1971. Petrochemistry of series of granitic rocks from northern Portugal. *Geol. Soc. Amer. Bull.*, v. 82, pp. 2783-2798.
- DEER W.A., HOWIE R.A. AND ZUSSMAN J., 1966. An introduction to the rock-forming minerals. *Longman, London*; 528 p.
- DESBOROUGH G.A., LUDINGTON S.D. AND SHARP W.N., 1980. Redskin granite: A rare-metal-rich Precambrian pluton, Colorado, USA. *Miner. Magaz.*, v. 43, No. 332, pp. 959-966.
- DILLES J.H., 1987. Petrology of the Yerington batholith, Nevada: Evidence for Evolution of porphyry copper ore fluids. *Econ. Geol.*, v. 82, pp. 1750-1789.
- DIXON W.J., 1985. *BMDP Statistical Software Manual (2nd ed.)*. University of California Press; pp. 734.
- DULSKI P., MOLLER P., VILLALPANDO A. AND SCHNEIDER H.J., 1982. Correlation of trace element fractionation in cassiterites with the genesis of the Bolivian metallotect; in Evans A.M. (Ed.):

- Metallization associated with acid magmatism.** John Wiley and Sons, New York; pp. 71-83.
- DURASOVA N.A., BARSUKOV V.L., RYABCHIKOV I.O., KHRAMOV D.A. AND KRAVTSOVA R.P., 1984.** The valency states of tin in basalts at various oxygen fugacities. *Geoch. Intern.*, v. 21, No. 4, pp. 7-8.
- DURASOVA N.A., BARSUKOV V.L., RYABCHIKOV I.D., KRAVTSOVA R.P. AND YEFIMOV A.S., 1985.** The behaviour of tin in the crystallization of aluminosilicate melts. *Geoch. Intern.* 22, No. 7, pp. 58-62.
- DURASOVA N.A. RYABCHIKOV I.D. AND BARSUKOV V.L., 1986.** The redox potential and the behaviour of tin in magmatic systems. *Intern. Geol. Review*, v. 28, No. 3, pp. 305-311.
- EDWARDS R.P., 1976.** Aspects of trace metal and ore distribution in Cornwall. *Trans. Inst. Min. Metal., Sect. B*, v. 85; pp. B83-90.
- EL BOUSEILLY A.M. AND EL SOKKARY A.A., 1975.** The relation between Rb, Ba, and Sr in granitic rocks. *Chem. Geol.*, v. 16, pp. 207-219.
- EMMERMANN R., DAIEVA L. AND SCHNEIDER J., 1975.** Petrologic significance of rare-earths distribution in granites. *Contr. Miner. Petrol.*, v. 52, pp. 267-283.
- EMOND D.S., 1985.** Geology, Mineralogy and Pterogenesis of Tin-bearing breccia/veins at Oliver Creek, Mcquesten River area, Yukon. Msc. Thesis, Carleton University, 196 p.
- ETHIER V.G. AND CAMPBELL F.A., 1977.** Tourmaline concentrations in Proterozoic sediments of the southern Cordillera of Canada and their economic significance. *Can. Jour. Earth Sci.*, v. 14, pp. 2348-2363.
- EUGSTER H.P. AND WONES D.R., 1962.** Stability relations of the ferruginous biotite, annite. *J. Petrol.* v. 3, pp. 82-125.
- FAURE G., 1986.** Principles of Isotope Geology (2nd. edition). John Wiley and Sons, New York; 589 p.
- FAURE G. AND POWELL J.L., 1972.** Strontium Isotope Geology. Springer-Verlag, New York, 188 p.
- FLINTER B.H., 1971.** Tin in acid granitoids: The search for a geochemical scheme of mineral exploration, in Boyle R.W. (Ed.): *Geochemical Exploration*. CIMM Spec. Vol. 11, pp. 323-330.
- FLINTER B.H., HESP W.R. AND RIGBY D., 1972.** Selected geochemical, mineralogical and petrological features of granitoids of the New England complex, Australia, and their relation to Sn, W, Mo and Cu mineralization. *Econ. Geol.*, v. 67, pp. 1241-1262.
- FLOYD P.A., 1972.** Geochemistry origin and tectonic environment of the basic

- and acidic rocks of Cornubia, England. *Proc. Geol. Assoc. London*, v. 83, pp. 385-404.
- GRANT J.A., 1986. The Isocon Diagram: A simple solution to Gresens' equation for metasomatic alteration. *Econ. Geol.*, v. 81, pp. 1976-1982.
- GRANT J.N., HALLS C., SHEPPARD S.M.F. AND AVILA W., 1980. Evolution of the porphyry tin deposits of Bolivia. *Soc. Min. Geol. Japan, Spec. Iss. No. 8*, pp. 151-173.
- GRAY I.M., 1963. Brief explanation of the geology of QDS 29 and 29 W: Ngara. *Tanzania Geol. Surv.*, Dodoma, (Published in 1967).
- GREEN T.H., 1977. Garnet in silic liquids and its possible use as a P-T indicator. *Contr. Miner. Petrol.*, v. 65, pp. 59-67.
- GRESENS R.L., 1967. Composition-volume relationships of metasomatism. *Chem. Geol.*, v. 2, pp. 47-65.
- GROOVES D.I., 1972. The geochemical evolution of tin-bearing granites in the Blue Tier Batholith, Tasmania. *Econ. Geol.*, v. 67, pp. 445-457.
- GUIDOTTI C.V., 1984. Micas in Metamorphic Rocks; in Bailey S.W. (Ed.): *Reviews in Mineralogy Vol. 13*; *Miner. Soc. Amer.*, pp. 357-467.
- HALL A., 1971. Greisenization in the granite of Cligga head, Cornwall. *Proc. Geol. Assoc. London*, v. 82, pp. 209-230.
- HALLS C., RANKIN A., FERRIDAY I.L., BLAIN C.F., BRISTOW C.M., 1977. A tourmalinized hydrothermal intrusion breccia at Wheal Remfry in the western part of the St. Austell pluton, Cornwall. *Trans. Inst. Min. Metal., Sect. B*, v. 86; p. B163.
- HANSON G. N., 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth Planet. Sci. Lett.*, v.38, pp. 26-43.
- HARPUM J.R., 1969. Summary of the Geology of Tanzania, Part V: Structure and Geotectonics of the Precambrian. *Tanzania Geol. Surv., Miner. Res. Div.*, Dodoma; 58 p.
- HARRIS J.F., 1961. Summary of the Geology of Tanganyika, Part IV: Economic Geology; *Memoir No. 1*. Govnt. Printer, Dodoma, Tanzania; 143 p.
- HENDERSON P., 1984. Geochemical properties and abundances of the rare earth elements; in Henderson P. (Ed.): *Developments in Geochemistry 2: Rare Earth Element Geochemistry*. Elsevier, Amsterdam; pp. 1-32.
- HENRY D.J. AND GUIDOTTI C.V., 1985. Tourmaline as petrogenetic indicator mineral: an example from the staurolite-grade metapelites of NW Maine. *Amer. Mineral.*, v. 70, pp. 1-15.

- HESS J.C. AND LIPPOLT H.J., 1986. Kinetics of Ar isotopes during neutron irradiation: ^{39}Ar loss from minerals as a source of error in $^{40}\text{Ar}/^{39}\text{Ar}$ dating. *Chem. Geol. (Isot. Geosc. Sect.)*, v. 59, pp. 223-236.
- HOLDAWAY M.J., 1971. Stability of andalusite and the aluminum silicate phase diagram. *Amer. Jour. Sci.*, v. 271, pp. 91-131.
- HUANG W.L. AND WYLLIE P.J., 1975. Melting reactions in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 to 35 kb, dry and with excess water. *Jour. Geol.*, v. 83, pp. 737-748.
- HUTCHISON C.S. AND CHAKRABORTY K.R., 1979. A mantle or crustal source; in Yeap C.H. (Ed.): *Geology of Tin deposits*; Geol. Soc. Malaysia, Bulletin 11; pp. 71-79.
- HUTCHISON C.S. AND LEOW J.H., 1963. Tourmaline greisenization at Langkawi, N.W. Malaya. *Econ. Geol.*, v. 58, pp. 587-592.
- IMEOKPARIA E.G., 1985. Geochemical evolution of the Jawara Younger Granite Complex and its related mineralization, northern Nigeria. *Geol. Magaz.*, v. 122, pp. 163-173.
- IMEOKPARIA E.G., 1984. Geochemistry of the granitic rocks from the Kwandonkaya complex, Nigeria. *Lithos*, v. 17, pp. 103-115.
- IMEOKPARIA E.G., 1982. Tin content of biotites from the Afu Younger Granite Complex, Central Nigeria. *Econ. Geol.*, v. 77, pp. 1710-1724.
- ISHIHARA S., SAWATA H., SHIBATA K., TERASHIMA, ARRYKUL S. AND SATO, 1980. Granites and Sn-W deposits of Peninsular Thailand. *Min. Geol. Spec. Iss. No. 8*, Japan; pp. 223-241.
- ISHIHARA S., 1977. The magnetite-series and ilmenite-series granitic rocks. *Min. Geol. Japan*, v. 27., pp. 293-305.
- JACKSON N.J., HALLIDAY A.N., SHEPPARD S.M.F. AND MITCHELL J.G. 1982. Hydrothermal activity in the St. Just Mining District, Cornwall, England; in EVANS, A.M. (Ed.): *Metallization associated with acid magmatism*. John Wiley and Sons, New York; pp. 137-179.
- JAHNS R.H. AND BURNHAM C.W., 1969. Experimental studies of pegmatite genesis: I. A model for the derivation and crystallization of granitic pegmatites. *Econ. Geol.*, v. 64, pp. 843-864.
- JAMES R.S. AND HAMILTON D.L., 1969. Phase relations in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - $\text{CaAl}_2\text{Si}_2\text{O}_8$ - SiO_2 at 1 kb water vapour pressure. *Contr. Miner. Petrol.*, v.21, pp. 111-141.
- JENNRICH R. AND SAMPSON P., 1985. Stepwise Discriminant Analysis; in

- Dixon W.J. (Ed.): BMDP Statistical Software Manual (2nd ed.); University of California Press; pp. 519-535.
- JUNIPER D.N. AND KLEEMAN J.D., 1979. Geochemical characterization of some tin-mineralizing granites of New South Wales. *Jour. Geoch. Expl.*, v. 11, pp. 321-333.
- KIAN F., 1987. Geophysical and Isotopic Constraints on the Lithosphere of the East African Rift System. Unpub. Ph.D. Thesis, Carleton University, 308 p.
- KAMPUNZU A.B., KABENGELE M., KAPENDA D., RUMVEGERI B.T. AND TSHIMANGA K., 1985. Geological evolution of the Ubendian and Kibaran belts in central Africa with special references to the magmatism. 13 Colloquium of African Geology, St. Andrews-Scotland, 10-13th September, 1985; Abstracts vol., p.45.
- KLERKX J., LIEGEOIS J-P., LAVREAU J., AND CLAESSENS W., 1987. Crustal evolution of the northern Kibaran Belt, eastern and central Africa. *Amer. Geoph. Un.*, pp. 217-233.
- KOCH G.S. Jr. AND LINK R.F., 1971. Statistical Analysis of Geological Data: Volume II. John-Wiley & Sons Inc., New York. 438 p.
- KRAUSKOPF K.B., 1979. Introduction to Geochemistry (2nd edition). McGraw-Hill Book Company, New York; 617 p.
- KROLL H. AND RIBBE P.H., 1983. Lattice parameters, composition and Al, Si order in alkali feldspars; in Ribbe P.H. (Ed.): Reviews in Mineralogy Volume 2: Feldspar Mineralogy. *Miner. Soc. Amer.*, pp. 57-99.
- KRÖNER A., 1984. Late Precambrian plate tectonics and orogeny: A need to redefine the term "Pan-African"; in Klerkx J and Michot J. (eds.) : African Geology (A volume in honour of L. Cahen). Royal Museum of Central Africa, Tervuren; pp. 23-28.
- LEAK B.E., 1967. Zoned garnets from the Galway granite and its aplites. *Earth Planet. Sci. Lett.*, v. 3, pp. 311-316.
- LE BRETON N. AND THOMPSON A.B., 1988. Fluid-absent (dehydration) melting of biotite in metapelites in the early stages of crustal anatexis. *Contr. Miner. Petrol.*, v. 99, pp. 226-237.
- LEHMANN B., 1987. Tin granites, geochemical heritage, magmatic differentiation. *Geol. Rundsch.*, v. 76, pp. 177-185.
- LEHMANN B., 1985. Formation of the strata-boud Kellhuani tin deposits, Bolivia. *Mineral. Deposita*, v. 20, pp. 169-176.
- LEHMANN B., 1982. Metallogeny of tin: Magmatic differentiation versus geochemical heritage. *Econ. Geol.* 77, pp. 50-59.

- LEHMANN B. AND LAVREAU J., 1987. Tin granites of the northern Kibaran belt, Central Africa (Kivu/Zaire, Rwanda, Burundi); In Matheis G. and Schandelmeyer H. (Eds.): Current Research in African Earth Sciences; Extended Abstracts, 14th Colloquium on African Geology, Berlin (West), 18-22 August, 1987; pp. 33-36.
- LEVASHEV G.B., STRIZHKOVA A.A. AND GOLUBEVA E.D., 1971. Geochemistry of tin in the granitoids of different tectonic zones of the Maritime province. *Geoch. Intern.*, v.8, no.15, pp. 643-659.
- LUTH W.C., JAHNS R.H. AND TUTTLE O.F., 1964. The granite system at 4 to 10 kb. *Jour. Geophys. Research*, v. 64, pp. 759-773.
- MANNING D.A.C., 1986. Contrasting styles of Sn-W mineralization in Peninsular Thailand and SW England. *Mineral. Deposita*, v. 21, pp. 44-52.
- MANNING D.A.C., 1983. Chemical variation in garnets from aplites and pegmatites, Peninsular Thailand. *Mineral. Magaz.*, v. 47, pp. 353-358.
- MANNING D.A.C., 1982. Chemical and morphological variation in tourmalines from the Hub Kapong batholith of peninsular Thailand. *Mineral. Magaz.*, v. 45, pp. 139-147.
- MANNING D.A.C. AND PICHAVANT M., 1988. Volatiles and their bearing on the behaviour of metals in granitic systems; In Taylor R.P. and Strong, D.F. (Eds.): Recent Advances in the Geology of Granite-Related Mineral Deposits. *CIMM Spec. Vol.* 39, pp. 13-14.
- MANNING D.A.C. AND PICHAVANT M., 1985. Volatiles and their bearing on the behaviour of metals in granitic systems; In Taylor R.P. and Strong D.F. (Eds.): Granite-Related Mineral Deposits; geology, petrogenesis and tectonic setting. Extended abstracts, CIMM confer., Sept. 15-17th, 1985, Halifax, Canada; pp. 184-187.
- MANNING D.A.C. AND PICHAVANT, M., 1983. The role of fluorine and boron in the generation of granitic melts; In Atherton M. P. and Gribble C.D. (Eds.): Migmatites, melting and metamorphism. *Shiva*, pp. 94-109.
- MANSON B. AND BERRY L.G., 1968. *Elements of Mineralogy*. W.H. Freeman & Comp., San Francisco, 550 p.
- McBRIDE S.L., ROBERTSON R.C.R., CLARK, A.H. AND FARRAR, E., 1983. Magmatic and Metallogenetic episodes in the northern tin belt, Cordillera Real, Bolivia. *Geol. Rundsch.*, v. 72, pp. 685-713.
- MCCARTHY T.S. AND HASTY R.A., 1976. Trace element distribution patterns and their relationship to the crystallization of granitic melts. *Geochim. Cosmoch. Acta*, v. 40, pp. 1351-1358.
- McCONNELL R.B. (1942). Reconnaissance to western Biharamulo district:

Regional geology. Tanzania Geol. Surv., Dodoma.

- MEHNERT K.R., 1969. Composition and abundance of common metamorphic rock types; in Wedepohl K.H. (Ed.): Handbook of Geochemistry Vol. I. Springer-Verlag, Berlin; pp. 272-296.
- MILLER C.F., 1985. Are strongly peraluminous magmas derived from pelitic sedimentary sources ?. Jour. Geol., v. 93., pp. 673-689.
- MILLER C.F. AND STODDARD E.F., 1981. The role of manganese in the paragenesis of magmatic garnet: An example from the Old Woman-Piute range, California. Jour. Geol., v. 89, pp. 233-246.
- MSANYA B.A., 1976. Mineral Exploration in NW Tanzania: Technical progress report on detailed geological and geomorphological mapping of Maleba tin occurrences in Rulenge (Map Sheet 29/1). Tanzania Geol. Surv., Dodoma; 7 p.
- MUNOZ J.L., 1984. F-OH and Cl-OH Exchange in Micas with Applications to Hydrothermal Ore Deposits; in Reviews in Mineralogy, v. 13. Min. Soc. Amer., pp. 469-493.
- MUNOZ J.L. AND SWENSON A., 1981. Chloride-hydroxyl exchange in biotite and estimation of relative Hcl/Hf activities in hydrothermal fluids. Econ. Geol., v. 76, pp. 2212-2221.
- NAGASAWA H., 1970. Rare-earth concentrations in zircons and apatites and their host dacites and granites. Earth Planet. Sci. Lett., v. 9, pp. 359-364.
- NEIVA A.M.R., 1982. Geochemistry of Muscovite and some Physico-chemical Conditions of the Formation of some Tin-tungsten Deposits; in Evans A.M. (Ed.): Metallization Associated with Acid Magmatism; John Wiley & Sons Ltd., pp. 243-259.
- NEIVA A.M.R., 1974. Geochemistry of tourmaline (schorliite) from granites, aplites and pegmatites from Northern Portugal. Geochim. Cosmoch. Acta, v. 38, pp. 1307-1317.
- NEMEC D., 1975. Genesis of tourmaline spots in leucocratic granites. Neues. Jahrb. Mineral. Monatsh; 308-317.
- NOCKOLDS S.R., 1954. Average chemical composition of some igneous rocks. Geol. Soc. Amer. Bull., v. 65, pp. 1007-1032.
- O'CONNOR J.T., 1965. A classification for quartz-rich igneous rocks based on feldspar ratios. US Geol. Surv. Prof. Paper 525-B, pp. 79-84.
- OLADE M.A., 1980. Geochemical characteristics of tin-bearing and tin-barren granite, Northern Nigeria. Econ. Geol., v. 75, pp. 71-82.
- PEARCE J.A., HARRIS N.B.W. AND TINDLE A.G., 1984. Trace element

- discrimination diagrams for the tectonic interpretation of granitic rocks. *Jour. Petrol.* 25, pp.956-983.
- PEARCE J.A. AND CANN J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet. Sci. Lett.*, v. 18, pp. 290-300.
- PICHAVANT M. AND MANNING, D.A.C., 1984. Petrogenesis of tourmaline granites and topaz granites; the contribution of experimental data: *Phys. Earth Planet. Int.*, v. 35, pp. 31-50.
- PICHAVANT M., 1981. An experimental study of the effect of boron on a water-saturated haplogranite at 1 kb pressure: Geological applications. *Contr. Miner. Petrol.*, v. 76, pp. 430-439.
- PLIMER I.R., 1986. Tourmalinites from the Golden Dyke Dome, Northern Australia. *Mineral. Deposita*, v. 21, pp. 263-270.
- POHL W., 1987. Metallogeny of the northeastern Kibaran belt, Central Africa. *Geol. Jour.*, v. 22, Thematic Issue, pp. 103-119.
- POWER G.M., 1968. Chemical variation in tourmalines from south-west England. *Mineral. Magaz.*, v. 36, pp. 1078-1089.
- PRICE R.C., 1983. Geochemistry of a peraluminous suite from northeastern Victoria, southeastern Australia. *Geochim. Cosmoch. Acta*, v. 47, pp. 31-42.
- QUENNEL A.M. AND BOOTH J.K.B., 1953. The Geology of part of Ngara District. Records of the Geol. Surv. of Tanganyika (Tanzania), Vol. III; pp. 1-3.
- REYNOLDS P.H., JAMIESON R.A., BARR S.M. AND RAESIDE R.P., 1988. A $^{40}\text{Ar}/^{39}\text{Ar}$ dating study in the Cape Breton Highlands, Nova Scotia: thermal histories and tectonic implications. (Submitted to *Can. Jour. Earth Sci.*, July 1988).
- RICHARDSON J.M., 1988. Genesis of the East Kemptville greisen-hosted tin deposit, Davis Lake complex, southwestern Nova Scotia, Canada. Ph.D. Thesis, Carleton University; 293 p.
- RICHARDSON S.W., GILBERT, M.C. AND BELL, P.M., 1969. Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria; the alumino-silicate triple point. *Amer. Jour. Sci.*, v. 267, pp. 259-272.
- ROSENBERG P.E. AND FOIT F.F., Jr., 1977. Fe^{2+} -F avoidance in silicates. *Geochim. Cosmoch. Acta*, v. 41, pp. 345-346.
- SAINSBURY C.L., 1969. Tin Resources of the World. *Bull. US. Geol. Surv.*, 1301, 55 p.

- SALTIKOFF B., 1977. Final Report on Kyerwa Tin Project: Geology and Ore Reserves of Kyerwa Tin Deposits. Ministry of Minerals, Tanzania, Conf. Rep. C 2139.
- SAWKINS F.J., 1984. Metal Deposits in Relation to Plate Tectonics. Springer-Verlag, New York; 325 p.
- SHAW D.M., 1969. Evaluation of Data; in Wedepohl K.H. (Ed.): Handbook of Geochemistry, Vol. I. Springer-Verlag, Berlin, pp. 324-375.
- SILLITOE R.H., 1976. Andean Mineralization a Model for the Metallogeny of convergent Plate Margins; in Strong D.F. (Ed.): Metallogeny and Plate Tectonics. GAC Spec. Pap. 14, pp. 59-100.
- SILLITOE R.H., GRANT J.N. AND HALLS C., 1975. Porphyry tin deposits in Bolivia. Econ. Geol., v. 70, pp. 913-927.
- SIMONOVA L.I. AND NIKITINA I.B., 1985. Boron and fluorine in granites and country rocks in the Kumyshtag Massif, North Tien Shan. Geoch. Intern., v. 2, No. 3, pp. 48-51.
- SINCLAIR W.D. AND RICHARDSON J.M., 1986. Quartz-tourmaline orbicules in the seagull batholith, Yukon Territory: Mineralogy, geochemistry, and relationship to tin mineralization; (submitted to Canadian Mineralogist); 36 p.
- SMITH F.G., 1949. Transport and deposition of the non-sulfide vein minerals: IV. Tourmaline. Econ. Geol., v. 44., pp. 186-192.
- SMITH F.G., 1947. Transport and deposition of the non-sulfide vein materials: II. Cassiterite. Econ. Geol., v. 42, pp. 251-263.
- SPEER J.A., 1984. Micas in Igneous Rocks, in Bailey, S.W. (Ed.): Reviews in Mineralogy Vol. 13: Micas. Mineral. Soc. Am., pp.299-356.
- STEMPROK M., 1979. Mineralized granites and their origin. Episodes, v. 1979, NO. 3, pp. 20-24.
- STEWART D.B. AND WRIGHT T.L., 1974. Al/Si order and symmetry of natural alkali feldspars, and the relationship of strained cell parameters to bulk composition. Bull. Soc. fr. Mineral. Cristallogr., v. 97, pp. 356-377.
- STHEEMAN H.A., 1932. The Geology of Southwestern Uganda with Special Reference to the Stanniferous Deposits. Martinus Nijhoff, 144 p.
- STOCKLEY M.G. AND WILLIAMS J.G., 1938. Explanation of the Geology, Degree Sheet No. 1.: Karagwe Tinfields; Bull. No. 10. Tanzania Geol. Surv., Dodoma; 95 p.
- STONE M., 1982. The behaviour of tin and some other trace elements during granite differentiation, West Cornwall, England; in Evans A.M.

- (Ed.): Metallization Associated with acid magmatism. John Wiley and Sons, New York; pp. 339-355.
- STRECKEISEN A., 1976. To each plutonic rock its proper name. *Earth Sci. Reviews*, No. 12, pp. 1-33.
- TACK L., DE PAEPE P., DEUTSCH S. AND LIEGEOIS J.P., 1984. The Alkaline plutonic complex of the Upper Ruvubu (Burundi): Geology, age, isotopic geochemistry and implications for the regional geology of the Western Rift; in Klerkx J. and Michot J. (eds.): *African Geology* (A volume in honour of L. Cahen); Royal Museum of Central Africa, Turvuren; pp. 91-114.
- TAYLOR B.E. AND SLACK J.F., 1984. Tourmalines from Applachian-Caledonian massive sulfide deposits: Textural, chemical, and isotopic relationships. *Econ. Geol.*, v. 79, pp. 1703-1726.
- TAYLOR R.G., 1979. *Geology of Tin Deposits*. Elsevier Sci. Publ. Comp., Amsterdam; 543 p.
- THORNTON C.P. AND TUTTLE O.F., 1960. Chemistry of Igneous Rocks: I. Differentiation Index. *Amer. Jour. Sci.*, v. 258, pp. 664-684.
- TRIPATHI V.S., 1979. Factor analysis in geochemical exploration. *Jour. Geoch. Expl.*, v. 11, pp. 263-275.
- TUREKIAN K.K. AND WEDEPOHL K.H., 1961. Distribution of the elements in some major units of the earth's crust. *Geol. Soc. Amer. Bull.*, v. 72, pp. 175-192.
- TUTTLE O.F. AND BOWEN N.L., 1958. Origin of granite in the light of experimental studies in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 - H_2O . *Geol. Soc. Amer.*, Memoir 74.
- UNDP Report, 1977. Mineral Exploration in NW Tanzania: Bushubi Tin Prospection. *Tanzania Geol. Surv., Miner. Res. Div.*, pp. 20-23.
- VAN GAANS P.F.M., SCHREURS J.M.C.M., VRIEND S.P. AND MAIJER C., 1978. The petrogenesis of charnockitic and granitic migmatites of the high-grade metamorphic Precambrian of Rogaland/Vest-Agder, S.W. Norway: A statistical interpretation of major element rock chemistry. *Geologie en Mijnbouw*, v. 66, pp. 177-190.
- VAN STRAATEN H.P., 1984. Contributions to the geology of the Kibaran Belt in Northwest Tanzania; in UNESCO: *Geology for Development Newsletters*, No. 3, pp. 59-68.
- VARLAMOFF N., 1972. Central and West Africa Rare-Metal Granitic Pegmatites, Related Aplites, Quartz Veins and Mineral Deposits. *Mineral. Deposita*, v. 7, pp. 202-216.
- VIELZEUF D. AND HOLLOWAY J.R., 1988. Experimental determination of the

- fluid-absent melting relations in the pelitic system: consequences for crustal differentiation. *Contr. Miner. Petrol.*, v. 98, pp. 257-276.
- VOGT J.H. AND KOLLENBERG W., 1987. Genetic implications of geochemical factor analysis in a sediment-hosted Cu-Pb-Ba mineralization. *Miner. Deposita*, v. 22, pp. 151-160.
- VOLKOV V.N. AND GORBACHEVA S.A., 1980. Composition of rock forming biotite and the variation in crystallization conditions in vertically exposed intrusion. *Geoch. Intern.*, v. 17, No. 1, pp. 75-79.
- WALL V.J., CLEMENS J.D. AND CLARKE D.B., 1987. Models for granitoid evolution and source compositions. *Jour. Geol.*, v. 95, pp. 731-749.
- WATSON E.B. AND HARRISON T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth Plan. Sci. Letters*, v. 64, pp. 295-304.
- WATSON E.B. AND CAPOBIANCO C.J., 1981. Phosphorus and the rare-earth elements in felsic magmas: an assessment of the role of apatite. *Geochem. Cosmoch. Acta*, v. 45, pp. 2349-2358.
- WATSON E.B., 1979. Zircon saturation in felsic liquids: experimental results and applications to trace element geochemistry. *Contr. Miner. Petrol.*, v. 70, pp. 407-419.
- WEDEPOHL K.H., 1978. *Handbook of Geochemistry Vol. II/4: Rb, Sr*. Springer-Verlag, Berlin; pp. 37-A-1 - 38-N-2.
- WERDING G. AND SCHREYER W., 1984. Alkali-free tourmaline in the system $\text{MgO-Al}_2\text{O}_3\text{-B}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$. *Geochim. Cosmoch. Acta*, v. 48, pp. 1331-1344.
- WHALEN J.B., 1983. The Ackley City Batholith, southeastern Newfoundland: Evidence for crystal versus liquid-state fractionation. *Geochim. Cosmoch. Acta*, v. 47, pp. 1443-1457.
- WHITE A.J.R., CLEMENS J.D., HOLLOWAY J.R., SILVER L.T., CHAPPELL B.W. AND WALL V.J., 1986. S-type granites and their probable absence in southwestern North America. *Geology*, v. 4, pp. 115-118.
- WHITE A.J.R. AND CHAPPELL B.W., 1983. Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia. *Geol. Soc. Amer., Memoir* 159, 21-34.
- WHITE A.J.R. AND CHAPPELL B.W., 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics*, v. 43, pp. 7-22.
- WINDELSCHMIDT C.J., 1958. Report on a regional survey for tin and wolfram in Bushubi Chiefdom, Ngara District; Report No. CJW/15M, File C1302;

Tanzania Geol. Surv.; 9 p.

WINKLER H.G.F., 1979. Petrogenesis of metamorphic rocks. Springer-Verlag, New York, 348 p.

WONES D.R. AND EUGSTER H.P., 1965. Stability of biotite: experiment, theory and applications. Amer. Mineral., v. 50, pp. 1228-1272.

WRIGHT T.L. AND STEWART D.B., 1968. X-ray and optical study of alkali feldspar: I. Determination of composition and structural state from refined unit-cell parameters and 2V. Amer. Miner., v. 53, pp. 38-87.

YERMOLOV P.V. AND TYAN V.D., 1975. Fluorine Geochemistry in Granite Formation. Geoch. Intern., v. 12, no. 3, pp. 158-164.

YUND R.A. AND TULLIS J., 1983. Subsolidus phase relations in the alkali feldspars with emphasis on coherent phases; In Ribbe P.H. (Ed.): Reviews in Mineralogy Volume 2: Feldspar Mineralogy. Miner. Soc. Amer.; pp. 141-176.

APPENDIX 1

Normative Ab-Or-Qz plots for Karagwe-Ankolean granites from different plutons. Minimum melt compositions at 0.5, 1, 2 and 5 kb H_2O pressure, determined by Tuttle and Bowen (1958) and Luth et al. (1964) are shown on the plots. The quartz-feldspar and two-feldspar cotectics in the diagrams are valid for granitic compositions containing 3 % anorthite at 1 kb H_2O vapour pressure (James and Hamilton, 1969)

Normative Ab-Qz-Or Projection

KARAGWE TINFIELD GRANITES

KARAGWE-ANKOLEAN GRANITES

MUMAKERA PLUTON GRANITES

1. 0.5, 1, 2, 3 ab

1. 0.5, 1, 2, 3 ab

NYAMAKOMBE PLUTON GRANITES

Normative AB-Qz-Or Projection

BUKIRO GRANITES

Normative AB-Qz-Or Projection

KABANGA GRANITES

Normative AB-Qz-Or Projection

MUYENZI-RULENGE GRANITES

Normative AB-Qz-Or Projection

1 0.5, 1, 2, 3 kb

1 0.5, 1, 2, 3 kb

APPENDIX 2

Triangular plots of Rb-Ba-Sr data for Karagwe-Ankolean granites from different plutons. Field boundaries for various granitoids are taken from El Bouseily and El Sokkary (1975).

□ Mumukere ○ Muyenzi

○ Muyenzi △ Buhiriro

♦ Molebo ○ Muyenzi

♦ Nyamulombe ○ Muyenzi

APPENDIX 3

SAMPLE PREPARATION, ANALYTICAL METHODS, ACCURACY AND PRECISION OF GEOCHEMICAL DATA

SAMPLE PREPARATION FOR CHEMICAL AND ISOTOPIC ANALYSES

After removing weathered surfaces using an hydraulic rock splitter whole-rock samples were crushed to ≤ 1.25 cm fragments in a steel, jaw-crusher. Crushed samples were ground to about -200 mesh in a chrome-steel pulverizer. Each pulverized sample was thoroughly mixed by rolling and folding the sample on a clean white paper. Each sample was then split in four quarters; one quarter was kept in air tight bag, the remaining three quarters were placed in labelled plastic bottles for geochemical analysis.

For mineral separation, whole-rock samples were trimmed to remove weathered surfaces and then crushed to ≤ 1.25 cm fragments in a steel, jaw-crusher. The fragments were then reduced to various grain sizes, suitable for the separation of individual minerals, by grinding in chert-lined crusher, sieving, and re-grinding the coarse-fractions.

Muscovite and biotite for Rb-Sr isotopic analysis were handpicked under the binocular microscope from a +50-40 mesh grain fraction. Muscovite and biotite mineral separates were subsequently ground to -80+100 mesh in a vibrating steel capsule and washed in analytical grade acetone/methanol using a sonic cleaner. Washed samples were left to dry in an oven at low temperature ($<50^{\circ}$ C). Dried samples were stored in dry glass bottles cleaned with methanol.

Muscovite and biotite for $^{40}\text{Ar}/^{39}\text{Ar}$ analysis were separated from crushed rock samples using methylene iodide heavy liquid (S.G. 3.29), diluted with acetone to obtained specific gravities suitable for various mineral separations. Muscovite and biotite mineral concentrates obtained through the heavy liquid were washed in acetone, dried under ultra-violet lamp, and

purified by handpicking under the binocular microscope. Purified samples were kept in cleaned glass bottles before sent to Dalhousie University in Halifax for $^{40}\text{Ar}/^{39}\text{Ar}$ analysis.

Alkali-feldspars, tourmaline, muscovite and biotite for Sn analysis were separated from crushed whole-rock samples using the heavy liquid mineral separation procedure described earlier. The mineral separates were washed in acetone, dried, and purified by handpicking under the binocular microscope using the same procedure described for muscovite and biotite in the preceding paragraph.

ANALYTICAL METHODS

Analytical methods employed in the analysis of rock and mineral samples are summarized in Table A3-1. Whole-rocks were analysed for Si, Al, Ti, Fe, Mn, Mg, Ca, Na, K, P, Rb, Ba, Sr, Zr, Y, Nb and Zn by X-ray fluorescence at the University of Ottawa. Analyses were performed on glass pellets by using a 1410 Phillips X-Ray Spectrometer. Pellets were prepared by fusing a mixture consisting of 1.3 g of powdered sample, 0.433 g of lithium carbonate (Li_2CO_3) and 3.9 g of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) in a platinum crucible and cooling the molten material in air in a platinum mold.

The majority of whole-rock samples were analysed for F, Li, B and W at the X-Ray Assay Laboratories (XRAL). A few samples were analysed for these elements in the Geology Department at the University of Ottawa (UO). At XRAL Li was analysed by atomic absorption and F by wet chemical method. Boron was analysed by the DCP method and W by the neutron activation method. Similar procedures for Li and F analysis at XRAL were followed at the UO. Both B and

W were analysed by the DCP method at the UO. Samples were fused with Na_2CO_3 - NaNO_3 (5:1) flux. After the fusion, B and W were leached in distilled water for analysis.

Pressed powder pellets of whole-rock samples were analysed for Sn by X-ray fluorescence at Bondar Clegg & Company laboratory in Ottawa. Mineral samples were analysed for Sn at the same laboratory using borate-fusion extraction and DCP method analytical technique.

Rb-Sr isotopic analyses of whole-rocks and mineral separates were performed in the isotope laboratory in the Department of Earth Sciences at Carleton University. Details of analytical procedure can be found in Bell and Blenkinsop (1984, 1987) and Richardson (1988). $^{40}\text{Ar}/^{39}\text{Ar}$ analyses were done in the isotope geochemistry laboratory at Dalhousie University. The analytical procedure is given in Chapter 7.

ELECTRON MICROPROBE ANALYSES OF MINERALS

Quantitative analyses of biotite, muscovite, alkali-feldspar, tourmaline and garnet in polished thin sections or mineral mounts were obtained by the wavelength-dispersive technique (WDS) using a Cambridge Microscan 5 electron microprobe in the Department of Earth Sciences, Carleton University. Calibrated mineral standards were used to determine the contents of elements in the minerals. An operating voltage of 20 kV and a sample current of about 40 nA was used in the analysis. Counting times were in the order of 20 to 30 seconds depending on the element being analysed. Some tourmaline analyses were performed at CRPG in France using an electron microprobe utilizing an acceleration voltage of 15 kV.

X-RAY DIFFRACTION (XRD) ANALYSIS OF ALKALI-FELDSPARS

X-ray diffraction data on alkali-feldspars were obtained using both the Gandolfi (114.6 mm) camera and the diffractometer (Phillips PW 1050/81) in the Department of Earth Sciences, Carleton University. Alkali-feldspar mineral separates were finely ground in an agate mortar and mounted with alcohol on a glass slide to form a thin film of about 2 x 2 cm. Dried mounts were loaded, one at a time, in the diffractometer. The interplanar atomic spacings (d-values) from the diffractometer scan were indexed using XRD data for alkali feldspars given in the mineral powder diffraction file data book (JCDPS International Centre for Diffraction Data, USA, 1986). In the camera method, individual grains from single alkali-feldspar crystals were mounted with petroleum gel on a glass fibre before being loaded into the camera. The camera was loaded with the film and then attached to the X-ray machine. Copper K-alpha X-ray radiation was used in the analysis. After the irradiation, the film was developed and two-theta (2θ) values were measured from the XRD pattern. Miller indices corresponding to 2θ values were determined using the data of Wright and Stewart (1968). Unit cell parameters were obtained from the XRD data using the least squares unit cell refinement program of Appleman and Evans (1973), implemented by Garvey, R.G. (1986; Dept. Chemistry, N. Dakota State University). The procedure suggested by Wright and Stewart (1968) for the refinement of alkali-feldspar unit cell parameters was followed throughout the refinement process. An example of a computer out-put of the refinement is shown in Appendix 7. The results for all 9 alkali feldspar samples are summarised in Table 6-12, Chapter 6.

ACCURACY AND PRECISION OF THE ANALYTICAL DATA

Accuracy and precision of the geochemical data is evaluated using the data obtained from replicate analyses of reference standards and other samples from the Karagwe-Ankolean granites. The standards used include a diorite (DR-N), a syenite (SY-2), a rhyolite (RGM-1), and a "granite" (GS-N), all of which have been thoroughly documented by Abbey (1977). Analyses of the first three standards together with the analyses of the Karagwe-Ankolean granites were provided by the XRF laboratory at the University of Ottawa, and include results obtained during the period of 3 years (1985-1987). Analytical data for the fifth standard (GS-N) were acquired in late 1987. A sample of the standard (GS-N) was obtained from Dr. R.P. Taylor, and supplied blind to the XRF laboratory for analysis. In addition to those five standards, a standard sample (SGS-1 rhyolite) from the Geological Survey of Saskatchewan was obtained from Dr. K. Bell and analysed along with other samples from the Karagwe-Ankolean granites. Replicate analyses of the standards and the Karagwe-Ankolean granites are presented in Tables A3-2 and A3-3, and in Figures A3-1 to A3-3.

The accuracy may be estimated from the difference between XRF analyses and the certified values reported by Abbey (1977) for the reference standards. The difference, expressed as "DIFF. %" (Table A3-3), may be calculated from the equation:

$$\text{DIFF. \%} = 100[\text{MEAN XRF VALUE} - \text{CERTIFIED VALUE}]/\text{CERTIFIED VALUE}$$

"DIFF. %" values of 0 indicate 100 % agreement between the XRF analyses and the certified values. The "DIFF. %" values are negative when XRF analyses are lower than the certified values, and positive when the analyses are higher than the certified values.

On average the accuracy of Si, Al, Fe, Na, and K is better than ± 1 %, based on the results of the DR-N standard (Table A3-3) for which enough data was obtained. The accuracies of Ca, Mn, Ti, Mg and P are within -1.88 %, 3.4 %, -4.22 %, -7.05 % and -30 % of the certified values, respectively. Mg and P analyses are, therefore, the least accurate. A comparison of the mean values of XRF analyses of the DR-N standard with the certified values (Abbey, 1977) can be seen in Figure A3-1. The analyses of the other standards give more or less similar degrees of accuracy as those obtained from the DR-N standard. Improved accuracy in Mg and P analyses is obtained using SY-2 syenite standard (Table A3-3). Using this standard the accuracies of Mg and P are within -2.11 % and -6.06 % of the certified values, respectively.

The accuracy of Rb, Ba, Sr, Zr, Y and Zn is within ± 0.4 -5.4 % of the certified values, based on the results of the DR-N, SY-2 and GS-N standards (Table A3-3). The accuracy of Nb is very poor. Values are uncertain to ± 24 % of the recommended value for the SY-2 standard.

Analyses of Li, F and B were obtained for the GS-N standard (Table A3-3) but no certified values are known for these elements (based on the data compiled by Abbey, 1977) to allow accuracy estimates. Sn and W were not analysed in the standard because it was not possible to get enough material for analysis. In spite of these snags, many replicate analyses of Li, F, B, Sn and W were obtained on granite samples (Table A3-2) from the Karagwe-Ankolean belt. The analyses show good reproducibility for Li and Sn, and to a lesser extent B and W. Reproducibility for F is moderate to poor.

The precision may be estimated from the standard deviations (STD)

calculated from replicate analyses of the reference standards (Table A3-3) and the Karagwe-Ankolean granites (Table A3-2). The standard deviation (STD) is given by the formula:

$$\text{STD} = \text{SQRT}[(X-X)^2/N-1],$$

where SQRT is the square root; $\bar{X}$ is the value of the variable; $\bar{X}$ is the mean value; and N is the number of analyses. Another statistical parameter used in the estimate of precision is the coefficient of variation (CV), defined as:

$$\text{CV} = 100(\text{STD}/\text{MEAN}) \%$$

Acceptable levels of precision for geochemical research depend on the analytical method and the nature of the problem being studied. Acceptable CV values are usually in the range of 0.5 to 5 % for the major elements, and 5 to 15 % for most trace elements (Shaw, 1969).

It can be seen from the replicate analyses, STD, and CV in Tables A3-2 and A3-3, that the major and trace elements analysed by X-ray fluorescence show good precision. The coefficient of variation is less than 5 % for all major elements and some of the trace elements, based on the analyses of the DR-N standard (Table A3-3). The only exceptions are P, Nb and Zn, whose precisions vary from acceptable (CV = 5-15 %) to poor (CV >15 %). Low precision in Nb analyses is attributed to the very low abundances of this element in the analysed samples. The detection limit for Nb is 10 ppm. Low P abundances in some of the analysed samples may be also the cause of low precision in the P analyses. The XRF data compiled by Ron Hartree (XRF Laboratory, University of Ottawa) and shown in Table A3-4 clearly indicate that the precision of the major and trace elements is low at lower concentrations and high at higher concentrations.

TABLE A3-1: SUMMARY OF THE ANALYTICAL METHODS

ELEMENT	ANALYTICAL METHOD	DETECTION LIMIT	LABORATORY USED
Si, Al	XRF	1, .1 %	XRF,UO
Ti, Fe	XRF	.01,.01 %	XRF,UO
Mn, Mg	XRF	.01, .5 %	XRF,UO
Ca, Na	XRF	.1, .5 %	XRF,UO
K, P	XRF	.02,.05 %	XRF,UO
Rb, Ba	XRF	10 ppm	XRF,UO
Sr, Zr	XRF	10 ppm	XRF,UO
Y, Nb, Zn	XRF	10 ppm	XRF,UO
Sn	XRF	1 ppm	BCL
Sn	DCP	5 ppm	BCL
Li	ABS	1 ppm	XRAL
Li	ABS	1 ppm	ABS,UO
F	WET	20 ppm	XRAL
F	WET	25 ppm	GSC/UO
B	DCP	10 ppm	XRAL
B	DCP	2 ppm	DCP,UO
W	NA	1 ppm	XRAL
W	DCP	2 ppm	DCP,UO

ABBREVIATIONS:

XRF: X-Ray Fluorescence

DCP: Direct Current Plasma Emission Spectrometry

ABS: Atomic Absorption

NA : Neutron Activation

WET: Wet chemical method (Liquid chromatography)

XRF,UO: XRF Laboratory, University of Ottawa

XRAL: X-Ray Assay Laboratories Limited

BCL: Bondar Clegg & Company Laboratory

GSC: Geological Survey of Canada

DCP,UO: DCP Laboratory, University of Ottawa

ABS,UO: Atomic Absorption Laboratory, University Ottawa

Table A3-2: Replicate analyses of some Karagwe-Ankolean granites

Sample	MU-2 1	MR-10 2	RU-3 3	MU-2 MEAN	STD	CV %
SiO ₂ %	74.29	73.93	74.12	74.11	0.18	0.24
Al ₂ O ₃	14.44	14.32	14.55	14.44	0.12	0.80
TiO ₂	0.19	0.18	0.18	0.18	0.01	3.15
Fe ₂ O ₃	1.47	1.51	1.46	1.48	0.03	1.79
MnO	0.03	0.03	0.03	0.03	0.00	0.00
MgO	0.32	0.34	0.39	0.35	0.04	10.30
CaO	0.70	0.71	0.72	0.71	0.01	1.41
Na ₂ O	2.88	2.79	2.82	2.83	0.05	1.62
K ₂ O	5.56	5.54	5.62	5.57	0.04	0.75
P ₂ O ₅	0.14	0.14	0.16	0.15	0.01	7.87
TOTAL	100.02	99.49	100.05	99.85	0.32	0.32
Rb ppm	383	381	380	381	1.53	0.40
Ba	272	294	238	268	28.21	10.53
Sr	71	65	68	68	3.00	4.41
Zr	74	75	71	73	2.08	2.84
Nb	11	5	10	9	3.21	37.09
Y	63	62	47	57	8.96	15.63
Zn	55	55	181	97	72.75	75.00
Sn	12	13	11	12	1.00	8.33
Li	120	130	160	137	20.82	15.23
F	1100	1200	1600	1300	264.58	20.35
B	350	300	300	317	28.87	9.12
W	3	4	4	4	0.58	15.75

Table A3-2 (cont.): Replicate analyses of some Karagwe-Ankolean granites

Sample	MU-23 1	MU-23D 2	MU-27 1	MU-33 2	MU-27D 3	MU-27 MEAN	STD	CV %
SiO ₂ %	73.20	74.07	74.36	74.10	74.30	74.25	0.14	0.18
Al ₂ O ₃	14.33	14.52	14.40	14.44	14.42	14.42	0.02	0.14
TiO ₂	0.16	0.17	0.16	0.16	0.16	0.16	0.00	0.00
Fe ₂ O ₃	1.41	1.46	0.47	0.46	0.47	0.47	0.01	1.24
MnO	0.03	0.03	0.02	0.02	0.02	0.02	0.00	0.00
MgO	0.23	0.24	0.00	0.00	0.00	0.00	0.00	
CaO	0.66	0.67	0.33	0.33	0.33	0.33	0.00	0.00
Na ₂ O	2.99	2.88	2.86	2.69	2.94	2.83	0.13	4.51
K ₂ O	5.50	5.57	5.50	5.50	5.49	5.50	0.01	0.11
P ₂ O ₅	0.15	0.13	0.17	0.15	0.17	0.16	0.01	7.07
TOTAL	98.66	99.74	98.27	97.85	98.30	98.14		
Rb ppm	370	377	405	409	398	404	5.57	1.38
Ba	141	231	250	243	247	247	3.51	1.42
Sr	59	63	59	52	58	60	2.08	3.49
Zr	65	63	66	65	64	65	1.00	1.54
Nb	4	5	7	8	5	7	1.53	22.91
Y	54	54	45	46	46	46	0.58	1.26
Zn	50	40	11	15	7	11	4.00	36.36
Sn	12	12	17	13		15		
Li	137	135	130	130		130		
F	1600	1660	670	680		675		
B	205	208	140	130		135		
W	2	2						

Table A3-2 (cont.): Replicate analyses of some Karagwe-Ankolean granites

Sample	MA-18 1	MA-18 2	MA-32 1	MA-36 2	MB-12* 1	MB-12D 2	KT-9* 1	KT-9D 2
SiO ₂ %	73.33	73.47	73.83	74.74	73.68	73.61	69.82	69.28
Al ₂ O ₃	15.31	15.41	13.94	14.08	14.88	14.75	16.84	16.78
TiO ₂	0.12	0.13	0.05	0.06	0.02	0.02	0.00	0.00
Fe ₂ O ₃	1.59	1.47	1.41	1.47	1.00	1.06	0.21	0.20
MnO	0.07	0.06	0.03	0.03	0.11	0.11	0.07	0.07
MgO	0.27	0.26	0.18	0.18	0.00	0.00	0.00	0.00
CaO	0.50	0.50	0.47	0.47	0.48	0.48	0.21	0.21
Na ₂ O	3.63	3.65	4.22	4.30	5.21	5.33	5.53	5.31
K ₂ O	4.07	4.05	3.43	3.48	3.49	3.48	6.40	6.35
P ₂ O ₅	0.32	0.26	0.25	0.25	0.19	0.18	0.22	0.22
TOTAL	99.21	99.26	97.81	99.06	99.06	99.02	99.30	98.42
Rb ppm	547	549	314	310	244	246	1145	1142
Ba	125	59	56	77	69	83	103	107
Sr	1	6	17	16	23	20	96	92
Zr	51	54	42	45	31	34	11	9
Nb	18	24	0	0	4	9	61	54
Y	52	52	45	44	13	13	17	15
Zn	43	46	20	14	80	59	12	0
Sn	24		10	7	3		397	
Li	460		40	43	25		22	
F	1600		730	800	640		800	
B	90		2008	1828	1400		20	
W	6							

4

Microl

Table A3-2 (cont.): Replicate analyses of some Karagwe-Ankolean granites

Sample	NY-28 1	NY-33 2	NY-30 1	NY-34 2	BU-15* 1	BU-15 2	BU-42 1	BU-47 2
SiO ₂ %	74.22	74.49	74.21	73.32	53.53	53.77	72.79	72.50
Al ₂ O ₃	14.32	14.36	14.61	14.49	27.88	27.92	14.71	14.72
TiO ₂	0.18	0.18	0.20	0.22	1.15	1.16	0.20	0.20
Fe ₂ O ₃	1.50	1.52	1.18	1.11	4.20	3.96	1.63	1.64
MnO	0.03	0.03	0.02	0.02	0.06	0.06	0.02	0.02
MgO	0.29	0.29	0.31	0.33	0.99	1.02	0.28	0.32
CaO	0.65	0.66	0.10	0.11	1.05	1.05	0.78	0.78
Na ₂ O	2.88	2.99	2.87	2.58	2.76	2.76	2.66	2.62
K ₂ O	5.61	5.63	5.82	5.80	7.23	7.26	6.27	6.27
P ₂ O ₅	0.13	0.12	0.17	0.14	0.00	0.02	0.17	0.12
TOTAL	99.81	100.27	99.49	98.12	98.85	98.98	99.51	99.19
Rb ppm	438	443	469	469	410	411	390	397
Ba	213	187	248	224	238	248	369	376
Sr	44	41	93	92	70	75	85	81
Zr	74	72	91	87	267	267	98	100
Nb	13	12	12	11	25	26	6	5
Y	69	64	114	112	20	20	54	54
Zn	61	53	37	39	55	66	52	66
Sn	10	9	29	30	3		7	7
Li	150	150	250	230			79	79
F	3400	3800	4000	3600			1200	1800
B	80	70	30	40			122	133
W	5	4	14	14				4

* Gneissic xenolith from Bukiriro granite

Table A3-2 (cont.): Replicate analyses of some Karagwe-Ankolean granites

Sample	KA-2 1	KA-2 2
SiO ₂ %	74.30	74.16
Al ₂ O ₃	14.35	14.38
TiO ₂	0.22	0.18
Fe ₂ O ₃	1.24	1.21
MnO	0.02	0.03
MgO	0.41	0.40
CaO	0.58	0.49
Na ₂ O	2.62	2.41
K ₂ O	5.59	5.57
P ₂ O ₅	0.13	0.13
TOTAL	99.46	98.96
Rb ppm	409	405
Ba	241	220
Sr	76	70
Zr	68	67
Nb	11	10
Y	63	65
Zn	69	55
Sn	12	
Li	160	
F	1200	
B	140	
W	4	

Table A3-3: Chemical Analyses of Reference Standards

Sample	DR-N 1	DR-N 2	DR-N 3	DR-N 4	DR-N 5	DR-N 6	DR-N 7	DR-N 8	DR-N 9
SiO ₂ %	52.73	52.86	52.74	52.90	53.46	52.63	52.93	52.56	52.80
Al ₂ O ₃	17.61	17.61	17.52	17.57	17.73	17.54	17.73	17.59	17.67
TiO ₂	1.06	1.06	1.06	1.06	1.06	1.04	1.05	1.04	1.05
Fe ₂ O ₃	9.69	9.68	9.44	9.47	9.84	9.54	9.62	9.64	9.71
MnO	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
MgO	4.37	4.25	4.25	4.30	4.32	4.10	4.15	4.09	4.02
CaO	6.97	6.96	6.98	6.99	7.10	6.92	6.94	6.92	6.92
Na ₂ O	3.20	3.08	2.87	2.83	2.92	2.85	3.00	2.98	3.13
K ₂ O	1.68	1.69	1.71	1.71	1.73	1.72	1.71	1.71	1.72
P ₂ O ₅	0.20	0.17	0.17	0.19	0.18	0.14	0.17	0.13	0.15
TOTAL	97.73	97.58	96.96	97.24	98.56	96.70	97.52	96.88	97.39
Rb ppm	68	69	70	79	74	71	70	69	71
Ba	364	375	342	346	362	385	428	410	407
Sr	398	393	391	397	399	388	388	388	386
Zr	128	133	134	132	129	130	130	131	132
Nb	0	4	5	0	7	5	3	3	2
Y	28	30	29	30	25	30	27	30	28
Zn	143	137	165	227	166	119	139	137	154

Sample	DR-N 10	DR-N 11	DR-N 12	DR-N 13	DR-N 14	DR-N MEAN	STD	CV %
SiO ₂ %	52.91	52.88	52.71	52.75	52.76	52.83	0.21	0.40
Al ₂ O ₃	17.68	17.66	17.65	17.55	17.71	17.63	0.07	0.40
TiO ₂	1.05	1.06	1.05	1.06	1.05	1.05	0.01	0.71
Fe ₂ O ₃	9.71	9.66	9.64	9.72	9.58	9.64	0.11	1.09
MnO	0.22	0.22	0.22	0.22	0.22	0.22	0.00	0.00
MgO	4.02	4.07	4.04	4.04	4.15	4.16	0.12	2.91
CaO	6.94	6.96	6.93	6.91	6.95	6.96	0.05	0.69
Na ₂ O	3.01	3.08	3.06	3.04	2.91	3.00	0.11	3.68
K ₂ O	1.72	1.72	1.72	1.72	1.72	1.71	0.01	0.77
P ₂ O ₅	0.18	0.19	0.18	0.20	0.19	0.17	0.02	12.27
TOTAL	97.44	97.50	97.20	97.21	97.24	97.37		
Rb ppm	71	72	67	69	73	71	3.00	4.23
Ba	416	433	412	411	403	392	29.90	7.62
Sr	390	385	389	390	389	391	4.39	1.12
Zr	131	130	131	132	130	131	1.59	1.22
Nb	4	2	3	5	0	3	2.13	69.32
Y	28	27	28	29	26	28	1.58	5.59
Zn	154	136	147	163	144	152	25.20	16.55

Table A3-3 (cont.): Chemical Analyses of Reference Standards

Sample	DR-N MEAN	STD	CV %	DR-N CERT.VAL. [ABBEY, 1977]	DIFF. %
SiO ₂ %	52.83	0.21	0.40	52.88	-0.09
Al ₂ O ₃	17.63	0.07	0.40	17.56	0.40
TiO ₂	1.05	0.01	0.71	1.10	-4.22
Fe ₂ O ₃	9.64	0.11	1.09	9.69	-0.53
MnO	0.22	0.00	0.00	0.21	3.40
MgO	4.16	0.12	2.91	4.47	-7.05
CaO	6.96	0.05	0.69	7.09	-1.88
Na ₂ O	3.00	0.11	3.68	3.00	-0.10
K ₂ O	1.71	0.01	0.77	1.73	-0.99
P ₂ O ₅	0.17	0.02	12.27	0.25	-30.29
TOTAL	97.37			97.98	
Rb ppm	71	3.00	4.23	75	-5.43
Ba	392	29.90	7.62	380	3.27
Sr	391	4.39	1.12	400	-2.30
Zr	131	1.59	1.22	125	4.74
Nb	3	2.13	69.32		
Y	28	1.58	5.59	32	-11.83
Zn	152	25.20	16.55	150	1.48

Sample Type: Diorite

Abbreviations:

DR-N CERT. VAL.: Certified values for DR-N standard (Abbey, 1977)

DIFF. %: $100[\text{DR-N MEAN XRF VALUE} - \text{DR-N CERT. VALUE}]/\text{CERT. VALUE}$

CV %: Coefficient of variation = $100[\text{STD}/\text{MEAN}]$

Table A3-3 (cont.): Chemical Analyses of Reference Standards

Sample	RGM-1 1	RGM-1 2	RGM-1 3	RGM-1 4	RGM-1 5	RGM-1 6	RGM-1 7	RGM-1 8	RGM-1 9
SiO ₂ %	72.72	72.90	72.72	73.15	73.02	72.94	72.70	72.66	72.66
Al ₂ O ₃	13.74	13.73	13.71	13.78	13.84	13.70	13.85	13.81	13.87
TiO ₂	0.27	0.30	0.27	0.26	0.29	0.25	0.26	0.26	0.26
Fe ₂ O ₃	1.87	1.88	1.87	1.88	1.88	1.88	1.92	1.92	1.92
MnO	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
MgO	0.39	0.42	0.41	0.38	0.39	0.42	0.07	0.00	0.07
CaO	1.20	1.20	1.20	1.21	1.20	1.20	1.20	1.20	1.20
Na ₂ O	3.94	4.02	3.89	4.05	4.14	4.10	4.09	4.21	4.33
K ₂ O	4.35	4.37	4.37	4.38	4.37	4.35	4.34	4.33	4.33
P ₂ O ₅	0.03	0.03	0.03	0.03	0.04	0.01	0.02	0.04	0.00
TOTAL	98.55	98.89	98.51	99.16	99.21	98.89	98.49	98.47	98.68
Rb ppm	53	144	141	150	145	142	162	162	162
Ba	795	794	823	821	794	826	877	873	859
Sr	107	104	102	105	106	105	107	106	106
Zr	202	205	205	204	206	200	215	216	216
Nb	5	6	7	5	5	6	5	4	5
Y	42	27	25	25	26	25	26	25	23
Zn	17	41	40	28	32	0	19	30	33

Sample	RGM-1 10	RGM-1 MEAN	STD	CV %	RGM-1 CERT. VAL. [ABBAY, 1977]	DIFF. %
SiO ₂ %	72.48	72.80	0.20	0.28	73.4	-0.82
Al ₂ O ₃	13.84	13.79	0.06	0.46	13.8	-0.09
TiO ₂	0.26	0.27	0.02	5.78	0.27	-0.74
Fe ₂ O ₃	1.92	1.89	0.02	1.20	1.87	1.28
MnO	0.04	0.04	0.00	0.00	0.04	0.00
MgO	0.06	0.26	0.18	70.15	0.28	-6.79
CaO	1.21	1.20	0.00	0.35	1.12	7.32
Na ₂ O	4.06	4.08	0.13	3.10	4.08	0.07
K ₂ O	4.35	4.35	0.02	0.41	4.36	-0.14
P ₂ O ₅	0.03	0.03	0.01	48.65	0.05	-48.00
TOTAL	98.25	98.71	0.32	0.32	99.27	
Rb ppm	164	143	32.80	23.02	170	-16.18
Ba	895	836	37.66	4.51	750	11.43
Sr	105	105	1.49	1.42	110	-4.27
Zr	215	208	6.35	3.04	210	-0.76
Nb	4	5	0.92	17.67		
Y	24	27	5.45	20.35		
Zn	35	28	12.43	45.20	32	-14.06

Sample Type: Rhyolite

RGM-1 CERT. VAL.: Certified values for RGM-1 standard (Abbey, 1977)

DIFF. %: 100[RGM-1 MEAN XRF VALUE - RGM-1 CERT. VALUE]/CERT. VALUE

Table A3-3 (cont.): Chemical Analyses of Reference Standards

Sample	SY-2 1	SY-2 2	SY-2 3	SY-2 MEAN	STD	CV %	SY-2 CERT.VAL [ABBAY, 1977]	DIFF. %
SiO ₂ %	59.48	60.19	59.91	59.86	0.36	0.60	60.09	-0.38
Al ₂ O ₃	12.01	12.05	12.18	12.08	0.09	0.74	12.15	-0.58
TiO ₂	0.14	0.13	0.13	0.13	0.01	4.33	0.15	-11.11
Fe ₂ O ₃	6.24	6.28	6.31	6.28	0.04	0.56	6.29	-0.21
MnO	0.32	0.32	0.32	0.32	0.00	0.00	0.32	0.00
MgO	2.72	2.68	2.50	2.63	0.12	4.45	2.69	-2.11
CaO	7.88	7.96	7.87	7.90	0.05	0.62	8.00	-1.21
Na ₂ O	4.42	4.42	4.44	4.43	0.01	0.26	4.35	1.76
K ₂ O	4.44	4.51	4.52	4.49	0.04	0.97	4.51	-0.44
P ₂ O ₅	0.44	0.38	0.42	0.41	0.03	7.39	0.44	-6.06
TOTAL	98.09	98.92	98.60	98.54			98.99	
Rb ppm	229	228	238	232	5.51	2.38	220	5.30
Ba	450	460	477	462	13.65	2.95	460	0.51
Sr	271	273	269	271	2.00	0.74	270	0.37
Zr	280	278	283	280	2.52	0.90	270	3.83
Nb	17	17	23	19	3.46	18.23	25	-24.00
Y	126	121	123	123	2.52	2.04	130	-5.13
Zn	253	239	228	240	12.53	5.22	250	-4.00

Sample Type: Syenite

Abbreviations:

SY-2 CERT. VAL.: Certified values for SY-2 standard (Abbey, 1977)

DIFF. %: $100[\text{SY-2 MEAN XRF VALUE} - \text{SY-2 CERT. VALUE}]/\text{CERT. VALUE}$

Table A3-3 (cont.): Chemical Analyses of Reference Standards

Sample	MK-10 GS-N CERT. VAL.		DIFF. %
	[GS-N]	[ABBAY, 1977]	
SiO ₂ %	65.95	65.98	-0.05
Al ₂ O ₃	14.87	14.71	1.09
TiO ₂	0.64	0.68	-5.88
Fe ₂ O ₃	3.65	3.75	-2.67
MnO	0.05	0.06	-16.67
MgO	2.03	2.31	-12.12
CaO	2.47	2.51	-1.59
Na ₂ O	3.78	3.78	0.00
K ₂ O	4.67	4.64	0.65
P ₂ O ₅	0.34	0.28	21.43
TOTAL	98.45	98.70	
Rb ppm	198	190	4.21
Ba	1445	1400	3.21
Sr	590	570	3.51
Zr	239	240	-0.42
Nb	19		
Y	21		
Zn	44	48	-8.33
Sn			
Li	46	55 ?	-16.36
F	910		
B	20		

Sample Type: "Granite"

Abbreviations:

GS-N CERT. VAL.: Certified values for GS-N standard (Abbey, 1977)

DIFF. %: $100[\text{GS-N MEAN XRF VALUE} - \text{GS-N CERT. VALUE}]/\text{CERT. VALUE}$

Table A3-3 (cont.): Chemical Analyses of Reference Standards

Sample	SGS-1 1	SGS-1 2	SGS-1 3	SGS-1* MEAN	STD	CV %	SGS-1 # AVERAGE	STD
SiO ₂ %	77.36	77.06	76.74	77.05	0.31	0.40	76.83	0.31
Al ₂ O ₃	12.05	12.10	11.76	11.97	0.18	1.53	11.92	0.14
TiO ₂	0.13	0.13	0.15	0.13	0.00	0.00	0.12	0.01
Fe ₂ O ₃	2.32	2.30	2.38	2.33	0.04	1.78	2.39	0.06
MnO	0.04	0.04	0.04	0.04	0.00	0.00	0.04	0.01
MgO	0.49	0.57	0.49	0.52	0.05	8.94	0.48	0.12
CaO	1.72	1.76	1.73	1.74	0.02	1.20	1.73	0.02
Na ₂ O	4.24	3.92	3.91	4.02	0.19	4.67	3.90	0.15
K ₂ O	1.61	1.65	1.62	1.63	0.02	1.28	1.63	0.02
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00		0.00	0.00
TOTAL	99.96	99.53	98.80	99.43	0.59		99.05	0.55
Rb ppm	28	32	22	27	5.03	18.41	27	3.26
Ba	436	502	507	482	39.63	8.23	468	35.23
Sr	127	123	119	123	4.00	3.25	122	2.65
Zr	140	132	145	139	6.56	4.72	142	6.14
Nb	0	2	0	1	1.15	173.21	0	0.88
Y	41	39	43	41	2.00	4.88	45	4.75
Zn	43	53	15	37	19.70	53.24	36	10.75
Sn	2	1	1	1	0.58	43.30		
Li	6	6	6	6	0.00	0.00		
F	130	160	20					
B	126	30	50					
W		410	440					

* No certified analyses are known for the SGS-1 rhyolite sample, although many analyses have been done by the graduate students in the Department of Earth Sciences at Carleton.

SGS-1 AVERAGE: Represents average compositional data compiled from analyses (N = 9) obtained from Richardson (1988) and the present study. Only those analyses that were made in the XRF Laboratory (University of Ottawa) were averaged.

Lithium, F and B analyses for SGS-1 replicate sample 1 were made at UO; the other replicates were analysed for the same elements at XRAL.

Table A3-4: Precision of XRF analyses (Ron Hartree; XRF Lab., UO)

Concentration Range (%)	0.1-1.0	1-2	1-3	2-5	1-20	50-100
SiO ₂ (%)*						+/-1.25
Al ₂ O ₃	+/-10		+/-1.5	+/-1.5	+/-1.5	
Fe ₂ O ₃	+/-5				+/-2	
MgO	+/-25				+/-3	
CaO	+/-5				+/-2	
Na ₂ O		+/-15		+/-8		
K ₂ O	+/-5				+/-1	
TiO ₂	+/-2		+/-1			
P ₂ O ₅	+/-10		+/-1			
MnO	+/-10					

* All in relative %

Concentration Range (ppm)	<10	10-30	>30
Rb (%)*	<10	+/-50	+/-10
Ba	<10	+/-50	+/-10
Sr	<10	+/-50	+/-10
Zr	<10	+/-50	+/-10
Y	<10	+/-50	+/-10
Nb	<10	+/-50	+/-10
Zn	<10	+/-50	+/-10

FIG. A3-1

FIG. A3-2

FIG. A3-3

APPENDIX 4

CHEMICAL ANALYSES OF KARAGWE-ANKOLEAN GRANITES

ABBREVIATIONS:

BMG : Biotite-muscovite granite

MBG : Muscovite-biotite granite

MGR : Muscovite-granite

PEGA: Aplite with pegmatite pods

PEGM Pegmatite

TLGR Tourmaline leucogranite/adamellite/monzogranite

SAMPLE	MA-5	MA-15	MA-17	MA-18	MA-21	MA-24	MA-25	MA-29	MA-30
ROCK	BMG	MGR	MGR	BMG	MGR	MBG	MBG	BMG	BMG
SiO ₂ %	75.66	75.46	73.91	73.33	75.18	75.87	73.20	73.47	72.09
TiO ₂	0.08	0.13	0.06	0.12	0.11	0.09	0.13	0.07	0.15
Al ₂ O ₃	14.03	14.30	15.06	15.31	14.75	13.71	14.80	13.36	16.22
Fe ₂ O ₃	1.23	0.76	1.04	1.59	0.87	1.31	1.09	0.69	1.90
MnO	0.04	0.04	0.06	0.07	0.02	0.04	0.03	0.03	0.08
MgO	0.23	0.25	0.14	0.27	0.17	0.19	0.14	0.14	0.28
CaO	0.48	0.41	0.28	0.50	0.46	0.51	0.48	0.53	0.48
Na ₂ O	3.62	2.98	3.95	3.63	3.41	3.58	2.98	2.91	3.66
K ₂ O	3.89	4.98	3.92	4.07	5.02	3.66	5.39	5.01	4.43
P ₂ O ₅	0.21	0.15	0.31	0.32	0.12	0.23	0.12	0.11	0.25
TOTAL	99.47	99.46	98.73	99.21	100.11	99.19	98.36	96.32	99.54
Rb ppm	420	406	590	547	368	415	410	357	587
Ba	97	275	105	125	169	88	260	197	61
Sr	25	83	24	1	77	15	60	54	5
Zr	39	34	25	51	53	40	40	33	62
Nb	6	9	17	18	7	10	30	1	21
Y	34	36	28	52	51	42	70	36	70
Zn	74	9	52	43	37	72	0	25	66
Sn	17	21	29	24	20	13	15	17	23
W	0	5	9	6	4	0	4	0	0
Li	222	170	294	460	141	140	250	294	557
F	1620	670	1440	1600	750	690	650	1570	2490
B	1066	130	49	90	66	91	240	495	449
K/Rb	77	102	55	62	113	73	109	116	63
K/Ba	332.9	150.3	309.9	270.2	246.5	345.2	172.1	211.1	602.8
Rb/Sr	16.8	4.89	24.58	547	4.78	27.67	6.83	6.61	117.4
Rb/Zr	10.77	11.94	23.60	10.73	6.94	10.38	10.25	10.82	9.47
Rb/Ba	4.33	1.48	5.62	4.38	2.18	4.72	1.58	1.81	9.62
Sr/Rb	0.06	0.20	0.04	0.00	0.21	0.04	0.15	0.15	0.01
Li/Zr	5.69	5.00	11.76	9.02	2.66	3.50	6.25	8.91	8.98
Li/Sr	8.88	2.05	12.25	460.00	1.83	9.33	4.17	5.44	111.40

Partial CIPW Norms

Qz	38.81	38.29	36.15	35.92	35.00	40.29	34.66	37.54	32.74
Ab	30.82	25.36	33.87	30.99	28.84	30.56	25.65	25.57	31.15
An	1.01	1.06	0.00	0.40	1.50	1.04	1.62	1.98	0.75
Or	23.13	29.61	23.48	24.27	29.65	21.82	32.41	30.75	26.33
Cm	3.52	3.64	4.61	4.83	3.15	3.51	3.54	2.54	5.16
Ap	0.50	0.36	0.74	0.76	0.28	0.55	0.29	0.27	0.59

Differentiation Index (DI)

DI	92.76	93.26	93.50	91.18	93.49	92.67	92.72	93.86	90.22
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	MW-5	MB-5	MB-9	MB-11	MB-13	MB-17	MB-18	MB-19	MB-20
ROCK	BMG	BMG	BMG	BMG	BMG	BMG	BMG	MGR	MGR
SiO ₂ %	73.60	73.45	75.84	73.83	73.89	74.79	74.31	74.06	73.63
TiO ₂	0.12	0.14	0.12	0.13	0.12	0.10	0.10	0.10	0.12
Al ₂ O ₃	14.80	14.71	13.93	14.66	14.75	14.40	14.46	14.35	14.25
Fe ₂ O ₃	1.03	1.24	0.87	1.30	1.23	1.11	1.12	1.13	1.27
MnO	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03
MgO	0.13	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.59	0.59	0.46	0.71	0.71	0.29	0.57	0.50	0.45
Na ₂ O	3.15	2.74	3.00	2.94	2.97	3.09	3.29	3.26	3.05
K ₂ O	5.69	5.41	4.28	5.35	5.37	4.82	4.79	4.74	4.73
P ₂ O ₅	0.13	0.13	0.13	0.20	0.17	0.16	0.17	0.17	0.20
TOTAL	99.26	98.43	98.67	99.15	99.24	98.79	98.84	98.34	97.73
Rb ppm	370	388	364	359	353	434	431	433	469
Ba	240	233	152	188	219	192	204	199	192
Sr	70	69	59	62	64	48	61	55	46
Zr	30	44	37	38	45	37	39	35	41
Nb	10	5	6	6	6	8	7	8	11
Y	60	45	26	37	43	33	34	35	41
Zn	0	54	38	47	38	54	40	52	61
Sn	14	6	14	9	12	15	15	15	23
W	3	0							
Li	100	210	120	180	120	290	240	290	350
F	610	1200	710	720	680	750	590	310	1700
B	150	200	850	170	260	790	680	570	680
K/Rb	128	116	98	124	126	92	92	91	84
K/Ba	196.8	192.7	233.7	236.2	203.5	208.4	194.9	197.7	204.5
Rb/Sr	5.29	5.62	6.17	5.79	5.52	9.04	7.07	7.87	10.2
Rb/Zr	12.33	8.82	9.84	9.45	7.84	11.73	11.05	12.37	11.44
Rb/Ba	1.54	1.67	2.39	1.91	1.61	2.26	2.11	2.18	2.44
Sr/Rb	0.19	0.18	0.16	0.17	0.18	0.11	0.14	0.13	0.10
Li/Zr	3.33	4.77	3.24	4.74	2.67	7.84	6.15	8.29	8.54
Li/Sr	1.43	3.04	2.03	2.90	1.88	6.04	3.93	5.27	7.61

Partial CIPW Norms

Qz	32.42	36.45	41.90	35.57	35.25	38.63	36.49	36.95	38.22
Ab	26.87	23.54	25.71	25.08	25.31	26.45	28.15	28.04	26.39
An	2.09	2.11	1.45	2.23	2.43	0.40	1.73	1.39	0.94
Or	33.90	32.50	25.65	31.90	31.99	28.85	28.65	28.50	28.61
Cm	2.72	3.64	3.88	3.24	3.19	4.00	3.27	3.41	3.86
Ap	0.31	0.31	0.31	0.47	0.40	0.38	0.40	0.40	0.47

Differentiation Index (DI)

DI	93.19	92.49	93.26	92.55	92.55	93.93	93.29	93.49	93.22
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	MB-21	MB-30	MB-32	MB-34	MB-38	MA-19	MA-32	MB-35	MA-27
ROCK	MGR	BMG	MGR	BMG	BMG	TLGR	TLGR	TLGR	PEGA
SiO ₂ %	74.02	71.74	73.05	73.98	73.93	75.10	73.83	74.64	72.63
TiO ₂	0.10	0.20	0.09	0.09	0.12	0.09	0.05	0.06	0.02
Al ₂ O ₃	14.50	15.91	15.19	14.47	14.99	14.30	13.94	13.85	17.83
Fe ₂ O ₃	0.69	2.14	1.03	1.06	1.58	1.05	1.41	1.12	0.33
MnO	0.02	0.06	0.05	0.03	0.03	0.04	0.03	0.03	0.03
MgO	0.00	0.11	0.00	0.00	0.00	0.15	0.18	0.00	0.02
CaO	0.47	0.49	0.46	0.62	0.58	0.49	0.47	0.50	0.30
Na ₂ O	3.11	3.12	3.71	3.06	3.59	4.11	4.22	3.92	8.85
K ₂ O	5.25	4.78	4.25	5.05	3.82	3.77	3.43	3.71	0.96
P ₂ O ₅	0.16	0.20	0.28	0.20	0.25	0.21	0.25	0.25	0.14
TOTAL	98.32	98.75	98.11	98.56	98.89	99.31	97.81	98.08	101.11
Rb ppm	391	517	543	377	456	360	314	350	124
Ba	234	128	66	144	84	100	56	79	37
Sr	75	34	10	45	16	10	17	16	12
Zr	41	93	38	45	48	30	42	36	40
Nb	5	15	19	6	15	20	0	0	71
Y	51	69	31	40	41	40	45	31	15
Zn	27	94	36	36	81	0	20	56	37
Sn	17	26	22	13	10	12	10	9	15
W						3	0		8
Li	190	590	300	340	330	70	40	77	61
F	1300	210	1800	920	1300	600	730	840	800
B	170	180	120	240	850	1900	1918	1700	16
K/Rb	111	77	65	111	70	87	91	88	64
K/Ba	186.2	310.0	534.5	291.1	377.5	312.9	508.4	389.8	215.4
Rb/Sr	5.21	15.21	54.3	8.38	28.5	36	18.47	21.88	10.33
Rb/Zr	9.54	5.56	14.29	8.38	9.50	12.00	7.48	9.72	3.10
Rb/Ba	1.67	4.04	8.23	2.62	5.43	3.60	5.61	4.43	3.35
Sr/Rb	0.19	0.07	0.02	0.12	0.04	0.03	0.05	0.05	0.10
Li/Zr	4.63	6.34	7.89	7.56	6.88	2.33	0.95	2.14	1.53
Li/Sr	2.53	17.35	30.00	7.56	20.63	7.00	2.35	4.81	5.08

Partial CIPW Norms

Qz	35.85	35.07	35.66	36.59	38.29	36.06	35.97	37.98	16.91
Ab	26.75	26.73	31.98	26.26	30.70	35.04	36.54	33.80	74.07
An	1.31	1.14	0.46	1.79	1.25	1.07	0.72	0.86	0.57
Or	31.57	28.63	25.61	30.30	22.84	22.45	20.74	22.37	5.61
Cm	3.28	5.25	4.40	3.37	4.54	3.09	3.10	3.13	2.00
Ap	0.38	0.47	0.66	0.47	0.59	0.50	0.60	0.59	0.33

Differentiation Index (DI)

DI	94.17	90.43	93.25	93.15	91.83	93.55	93.25	94.15	96.59
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	MA-28	MB-23	MB-33	MB-12	MB-14	MU-2	MU-13	MU-23	MU-24
ROCK	PEGA	APLITE	APLITE	APLITE	PEGM	BMG	BMG	BMG	TMGR
SiO ₂ %	72.20	73.82	73.79	73.68	73.69	74.29	74.17	73.20	73.50
TiO ₂	0.02	0.02	0.02	0.02	0.09	0.19	0.16	0.16	0.20
Al ₂ O ₃	17.74	14.72	14.33	14.88	14.41	14.44	14.28	14.33	14.70
Fe ₂ O ₃	0.20	0.53	0.78	1.00	0.95	1.47	1.44	1.41	0.70
MnO	0.06	0.08	0.10	0.11	0.02	0.03	0.03	0.03	0.03
MgO	0.00	0.00	0.00	0.00	0.00	0.32	0.24	0.23	0.24
CaO	0.49	0.41	0.56	0.48	0.56	0.70	0.64	0.66	0.18
Na ₂ O	8.95	5.20	4.89	5.21	2.88	2.88	2.78	2.99	2.83
K ₂ O	1.00	4.05	4.16	3.49	4.90	5.56	5.45	5.50	5.74
P ₂ O ₅	0.35	0.29	0.34	0.19	0.17	0.14	0.16	0.15	0.12
TOTAL	101.01	99.12	98.97	99.06	97.67	100.02	99.35	98.66	98.24
Rb ppm	128	436	375	244	313	383	374	370	360
Ba	72	174	66	69	173	272	218	141	300
Sr	7	87	14	23	78	71	59	59	60
Zr	42	13	9	31	30	74	62	65	70
Nb	48	16	0	4	3	11	3	4	20
Y	19	16	10	13	30	63	59	54	80
Zn	29	27	41	80	38	55	43	50	0
Sn	14	12	2	3	7	12	11	12	16
W	9					3		2	6
Li	67	170	50	25	79	120	121	136	54
F	790	1400	1300	640	710	1100	1550	1600	790
B	19	160	750	1400	1500	350	135	206	1100
K/Rb	65	77	92	119	130	120	121	123	132
K/Ba	115.3	193.2	523.2	419.8	235.1	169.7	207.5	323.8	158.8
Rb/Sr	18.29	5.01	26.79	10.61	4.01	5.39	6.34	6.27	6
Rb/Zr	3.05	33.54	41.67	7.87	10.43	5.18	6.03	5.69	5.14
Rb/Ba	1.78	2.51	5.68	3.54	1.81	1.41	1.72	2.62	1.20
Sr/Rb	0.05	0.20	0.04	0.09	0.25	0.19	0.16	0.16	0.17
Li/Zr	1.60	13.08	5.56	0.81	2.63	1.62	1.95	2.09	0.77
Li/Sr	9.57	1.95	3.57	1.09	1.01	1.69	2.05	2.31	0.90

Partial CIPW Norms

Qz	15.98	28.24	29.46	29.78	38.32	34.48	35.77	33.55	35.21
Ab	74.97	44.37	41.78	44.47	24.94	24.39	23.69	25.66	24.38
An	0.15	0.14	0.56	1.15	1.70	2.55	2.14	2.33	0.11
Or	5.85	24.16	24.85	20.83	29.66	32.88	32.45	32.97	34.54
Cm	1.86	1.74	1.59	2.13	3.84	2.75	3.05	2.67	3.86
Ap	0.82	0.68	0.80	0.45	0.40	0.33	0.38	0.36	0.29

Differentiation Index (DI)

DI	96.80	96.77	96.09	95.08	92.92	91.75	91.91	92.18	94.13
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE MU-25 MU-27 MU-28 MU-29 MU-30 MU-31 BU-12 BU-17 BU-20

ROCK	TMGR	TMGR	TMGR	TMGR	BMG	BMG	MBG	MBG	MBG
SiO ₂ %	74.58	74.36	74.68	74.75	73.66	73.67	73.14	73.90	73.34
TiO ₂	0.15	0.16	0.15	0.15	0.17	0.17	0.25	0.21	0.21
Al ₂ O ₃	14.17	14.40	14.41	14.52	14.31	14.34	14.58	14.06	14.18
Fe ₂ O ₃	0.71	0.47	0.49	0.56	1.47	1.41	1.87	1.42	1.72
MnO	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.03	0.02
MgO	0.24	0.00	0.00	0.01	0.05	0.00	0.47	0.30	0.39
CaO	0.36	0.33	0.39	0.38	0.73	0.73	0.70	0.76	0.86
Na ₂ O	2.96	2.86	2.72	2.74	2.65	2.70	2.89	2.83	2.77
K ₂ O	5.45	5.50	5.57	5.50	5.55	5.49	5.50	5.39	5.15
P ₂ O ₅	0.13	0.17	0.14	0.18	0.15	0.17	0.13	0.14	0.16
TOTAL	98.77	98.27	98.57	98.81	98.77	98.71	99.57	99.04	98.80

Rb ppm	390	405	413	390	388	381	352	335	306
Ba	187	250	213	221	282	270	273	250	266
Sr	56	59	60	66	66	70	86	80	65
Zr	59	66	60	60	71	67	91	81	87
Nb	4	7	7	9	6	7	4	0	5
Y	48	45	43	45	52	48	69	81	45
Zn	19	11	11	23	44	52	52	51	58
Sn	19	17	21	11	10	9	7	11	6
W							3		2
Li	122	130	130	88	150	140	63	70	86
F	970	670	780	550	1300	1300	1000	1240	830
B	107	140	90	430	270	460	184	368	114

K/Rb	116	113	112	117	119	120	130	134	140
K/Ba	241.9	182.6	217.0	206.6	163.4	168.8	167.2	178.9	160.7
Rb/Sr	6.96	6.86	6.88	5.91	5.88	5.44	4.09	4.19	4.71
Rb/Zr	6.61	6.14	6.88	6.50	5.46	5.69	3.87	4.14	3.52
Rb/Ba	2.09	1.62	1.94	1.76	1.38	1.41	1.29	1.34	1.15
Sr/Rb	0.14	0.15	0.15	0.17	0.17	0.18	0.24	0.24	0.21
Li/Zr	2.07	1.97	2.17	1.47	2.11	2.09	0.69	0.86	0.99
Li/Sr	2.18	2.20	2.17	1.33	2.27	2.00	0.73	0.88	1.32

Partial CIPW Norms

Qz	36.07	37.05	37.60	37.86	36.20	36.30	33.19	35.18	35.61
Ab	25.37	24.61	23.34	23.45	22.69	23.13	24.58	24.19	23.74
An	0.95	0.53	1.03	0.72	2.67	2.54	2.64	2.89	3.26
Or	32.63	33.09	33.41	32.91	33.22	32.88	32.68	32.19	30.84
Cm	3.10	3.61	3.58	3.84	3.01	3.07	2.93	2.55	2.91
Ap	0.31	0.40	0.33	0.42	0.35	0.40	0.31	0.33	0.38

Differentiation Index (DI)

DI	94.07	94.75	94.35	94.22	92.11	92.31	90.45	91.56	90.19
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	BU-26	BU-30	BU-33	BU-37	BU-41	BU-42	BU-44	BU-45	BU-48
ROCK	MGR	MBG	MBG	MBG	MBG	MBG	MBG	MBG	MBG
SiO ₂ %	74.36	73.87	74.55	73.06	73.45	72.79	74.02	73.44	72.60
TiO ₂	0.12	0.19	0.14	0.24	0.21	0.20	0.21	0.25	0.30
Al ₂ O ₃	14.11	14.41	13.75	14.79	14.43	14.71	14.10	14.28	14.80
Fe ₂ O ₃	1.11	1.47	1.26	1.80	1.64	1.63	1.69	1.96	1.94
MnO	0.02	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.03
MgO	0.19	0.30	0.26	0.34	0.33	0.28	0.32	0.41	0.46
CaO	0.44	0.71	0.76	1.04	0.73	0.78	0.80	0.71	0.71
Na ₂ O	2.74	2.75	2.61	3.11	2.54	2.66	2.66	2.53	2.55
K ₂ O	5.48	5.43	5.24	5.39	5.64	6.27	5.17	5.67	5.65
P ₂ O ₅	0.13	0.12	0.14	0.10	0.15	0.17	0.15	0.15	0.13
TOTAL	98.70	99.27	98.74	99.90	99.15	99.51	99.15	99.43	99.17
Rb ppm	348	366	336	334	360	390	328	373	370
Ba	214	260	314	353	287	369	265	340	450
Sr	56	81	75	91	82	85	76	88	100
Zr	50	66	63	106	76	98	87	119	100
Nb	3	4	1	4	3	6	5	5	30
Y	52	67	76	49	73	54	79	75	80
Zn	40	40	61	54	40	52	69	73	0
Sn	11	11	7	5	13	7	11	7	12
W	3	2	4	2					4
Li	88	85	92	72	80	79	81	84	130
F	880	1010	760	1140	1040	1200	790	1400	1200
B	255	284	240	92	151	122	32	151	200
K/Rb	131	123	129	134	130	133	131	126	127
K/Ba	212.5	173.3	138.5	126.7	163.1	141.0	161.9	138.4	104.2
Rb/Sr	6.21	4.52	4.48	3.67	4.39	4.59	4.32	4.24	3.7
Rb/Zr	6.96	5.55	5.33	3.15	4.74	3.98	3.77	3.13	3.70
Rb/Ba	1.63	1.41	1.07	0.95	1.25	1.06	1.24	1.10	0.82
Sr/Rb	0.16	0.22	0.22	0.27	0.23	0.22	0.23	0.24	0.27
Li/Zr	1.76	1.29	1.46	0.68	1.05	0.81	0.93	0.71	1.30
Li/Sr	1.57	1.05	1.23	0.79	0.98	0.93	1.07	0.95	1.30

Partial CIPW Norms

Qz	36.82	35.42	37.88	31.54	35.41	31.52	36.95	35.11	34.22
Ab	23.50	23.46	22.38	26.37	21.70	22.63	22.72	21.55	21.78
An	1.36	2.76	2.90	4.52	2.67	2.77	3.02	2.56	2.70
Or	32.83	32.35	31.39	31.92	33.65	37.28	30.85	33.74	33.71
Cm	3.23	3.03	2.77	2.19	3.21	2.55	3.06	3.07	3.54
Ap	0.31	0.28	0.33	0.24	0.36	0.41	0.36	0.36	0.31

Differentiation Index (DI)

DI	93.15	91.23	91.65	89.83	90.76	91.43	90.52	90.40	89.71
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	BU-49	BU-50	BU-53	BU-58	MK-1	MK-2	MK-3	MK-4	MK-5
ROCK	MBG	MBG	MBG	MBG	MBG	MBG	MBG	MBG	MBG
SiO ₂ %	73.00	73.48	74.56	73.65	73.99	73.81	73.57	74.42	73.69
TiO ₂	0.19	0.20	0.21	0.26	0.19	0.18	0.19	0.21	0.17
Al ₂ O ₃	14.60	14.06	14.01	14.47	14.14	14.59	14.30	14.21	14.40
Fe ₂ O ₃	1.25	1.76	1.79	1.89	1.42	1.47	1.58	1.68	1.27
MnO	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.02
MgO	0.26	0.35	0.37	0.45	0.05	0.08	0.03	0.12	0.05
CaO	0.72	1.00	0.72	0.64	0.73	0.74	0.77	0.78	0.72
Na ₂ O	2.90	2.96	2.59	2.53	2.50	2.70	2.72	2.71	2.75
K ₂ O	5.82	4.48	5.28	5.54	5.44	5.48	5.29	5.10	5.61
P ₂ O ₅	0.18	0.13	0.14	0.12	0.24	0.13	0.12	0.16	0.17
TOTAL	98.95	98.45	99.70	99.59	98.73	99.21	98.60	99.42	98.85
Rb ppm	360	314	372	377	371	363	365	359	366
Ba	330	246	301	330	287	281	284	268	299
Sr	140	75	82	86	116	66	66	66	112
Zr	80	90	96	111	67	71	60	87	69
Nb	10	4	5	3	7	7	6	6	5
Y	80	49	62	73	50	55	49	65	52
Zn	0	105	113	113	58	50	66	37	53
Sn	10	11	9	14	11	11	8	11	5
W	3			3					
Li	93	112	67	96	130	130	130	150	110
F	1000	1410	1330	1520	1400	1600	1700	1900	1200
B	140	134	119	130	250	170	180	220	280
K/Rb	134	118	118	122	122	125	120	118	127
K/Ba	146.4	151.2	145.6	139.3	157.3	161.9	154.6	157.9	155.7
Rb/Sr	2.57	4.19	4.54	4.38	3.2	5.5	5.53	5.44	3.27
Rb/Zr	4.50	3.49	3.88	3.40	5.54	5.11	6.08	4.13	5.30
Rb/Ba	1.09	1.28	1.24	1.14	1.29	1.29	1.29	1.34	1.22
Sr/Rb	0.39	0.24	0.22	0.23	0.31	0.18	0.18	0.18	0.31
Li/Zr	1.16	1.24	0.70	0.86	1.94	1.83	2.17	1.72	1.59
Li/Sr	0.66	1.49	0.82	1.12	1.12	1.97	1.97	2.27	0.98

Partial CIPW Norms

Qz	32.52	37.01	37.31	35.78	38.12	36.04	36.62	37.93	35.46
Ab	24.82	25.46	22.00	21.52	21.41	23.02	23.33	23.05	23.53
An	2.42	4.18	2.67	2.41	2.08	2.84	3.08	2.84	2.49
Or	34.79	26.92	31.33	32.92	32.58	32.67	31.72	30.33	33.56
Cm	2.68	2.88	3.07	3.45	3.42	3.20	3.02	3.21	2.93
Ap	0.43	0.31	0.33	0.28	0.56	0.30	0.28	0.37	0.40

Differentiation Index (DI)

DI	92.13	89.39	90.64	90.22	92.11	91.73	91.67	91.31	92.55
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	MK-6	MY-1	MY-2	MY-3	MY-4	MY-5	RU-1	RU-2	KA-1
ROCK	MBG	MBG	MBG	MBG	MBG	MBG	BMG	BMG	BMG
SiO ₂ %	73.56	71.15	74.67	73.92	70.83	71.49	74.00	75.06	74.85
TiO ₂	0.26	0.42	0.17	0.12	0.38	0.39	0.11	0.17	0.19
Al ₂ O ₃	14.28	15.13	14.26	14.13	15.34	15.15	14.39	14.28	14.33
Fe ₂ O ₃	1.81	3.12	1.06	1.07	3.15	2.85	1.34	1.38	1.11
MnO	0.02	0.05	0.03	0.02	0.06	0.04	0.03	0.03	0.03
MgO	0.15	1.05	0.42	0.43	1.47	1.25	0.39	0.41	0.37
CaO	0.79	1.90	0.70	0.81	2.14	2.14	0.75	0.84	0.76
Na ₂ O	2.58	2.94	2.23	2.18	2.90	3.29	2.69	2.62	2.58
K ₂ O	5.47	3.93	6.06	5.91	3.56	3.60	5.22	4.96	5.26
P ₂ O ₅	0.11	0.16	0.11	0.09	0.12	0.09	0.14	0.16	0.13
TOTAL	99.03	99.85	99.71	98.68	99.95	100.29	99.06	99.91	99.61
Rb ppm	376	262	281	282	225	243	314	306	363
Ba	378	439	399	356	786	475	237	205	230
Sr	85	140	108	121	224	192	64	68	56
Zr	111	115	69	66	126	121	52	50	62
Nb	10	19	3	0	9	13	9	8	8
Y	74	20	73	42	22	17	36	37	37
Zn	75	69	0	0	35	58	26	94	66
Sn	7	4	5	4	3	4	15	14	12
W					2		5	5	4
Li	140	110	55	47	110	120	72	80	170
F	1800	1500	600	570	1400	1600	1600	1700	1700
B	170	90	80	60	50	80	180	200	210
K/Rb	121	125	179	174	131	123	138	135	120
K/Ba	120.1	74.3	126.1	137.8	37.6	62.9	182.8	200.8	189.8
Rb/Sr	4.42	1.87	2.6	2.33	1	1.27	4.91	4.5	6.48
Rb/Zr	3.39	2.28	4.07	4.27	1.79	2.01	6.04	6.12	5.85
Rb/Ba	0.99	0.60	0.70	0.79	0.29	0.51	1.32	1.49	1.58
Sr/Rb	0.23	0.53	0.38	0.43	1.00	0.79	0.20	0.22	0.15
Li/Zr	1.26	0.96	0.80	0.71	0.87	0.99	1.38	1.60	2.74
Li/Sr	1.65	0.79	0.51	0.39	0.49	0.63	1.13	1.18	3.04

Partial CIPW Norms

Qz	36.33	33.90	36.77	36.96	33.95	32.31	36.91	38.89	38.02
Ab	22.04	24.94	18.92	18.69	24.58	27.78	22.97	22.19	21.91
An	3.23	8.40	2.76	3.48	9.85	10.01	2.83	3.12	2.93
Or	32.66	23.31	35.95	35.42	21.10	21.25	31.17	29.36	31.23
Cm	2.97	2.97	3.03	2.92	3.12	2.16	3.31	3.46	3.33
Ap	0.26	0.37	0.26	0.21	0.28	0.21	0.32	0.37	0.30

Differentiation Index (DI)

DI	91.03	82.15	91.64	91.07	79.63	81.34	91.05	90.44	91.16
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	KA-2	KA-5	KA-14	KA-18	KA-19	KA-20	KA-22	KA-23	KA-24
ROCK	BMG	MGR	BMG	MBG	MBG	BMG	BMG	BMG	MGR
SiO ₂ %	74.30	76.30	74.37	73.92	74.87	73.82	74.70	74.12	75.15
TiO ₂	0.22	0.14	0.18	0.15	0.34	0.54	0.34	0.18	0.08
Al ₂ O ₃	14.35	13.65	14.15	14.68	14.33	14.10	14.56	14.40	15.11
Fe ₂ O ₃	1.24	0.65	1.43	1.41	1.21	1.38	1.08	1.35	0.67
MnO	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03
MgO	0.41	0.32	0.45	0.35	0.34	0.41	0.28	0.40	0.23
CaO	0.58	0.47	0.83	0.63	0.69	0.62	0.59	0.75	0.57
Na ₂ O	2.62	2.27	2.94	2.78	2.94	2.54	2.82	2.61	3.21
K ₂ O	5.59	5.27	4.67	5.49	5.28	5.66	5.16	5.42	4.01
P ₂ O ₅	0.13	0.16	0.10	0.16	0.16	0.12	0.18	0.14	0.12
TOTAL	99.46	99.25	99.14	99.60	100.18	99.21	99.74	99.40	99.18
Rb ppm	409	357	347	402	374	376	416	219	156
Ba	241	105	173	213	256	269	180	230	53
Sr	76	60	68	59	72	66	64	46	26
Zr	68	32	75	56	58	71	45	69	16
Nb	11	11	13	11	10	8	12	9	8
Y	63	44	41	40	47	69	38	95	58
Zn	69	0	0	0	45	59	53	42	0
Sn	12	5	10	15	9	13	7	6	7
W	4	5	2	5	3	2	4	3	5
Li	160	100	130	210	160	130	140	150	92
F	1200	1000	860	1000	1300	1100	2200	2700	1000
B	140	30	160	290	220	220	100	50	40
K/Rb	113	123	112	113	117	125	103	205	213
K/Ba	192.5	416.6	224.1	213.9	171.2	174.6	237.9	195.6	628.0
Rb/Sr	5.38	5.95	5.1	6.81	5.19	5.7	6.5	4.76	6
Rb/Zr	6.01	11.16	4.63	7.18	6.45	5.30	9.24	3.17	9.75
Rb/Ba	1.70	3.40	2.01	1.89	1.46	1.40	2.31	0.95	2.94
Sr/Rb	0.19	0.17	0.20	0.15	0.19	0.18	0.15	0.21	0.17
Li/Zr	2.35	3.13	1.73	3.75	2.76	1.83	3.11	2.17	5.75
Li/Sr	2.11	1.67	1.91	3.56	2.22	1.97	2.19	3.26	3.54

Partial CIPW Norms

Qz	36.35	42.18	37.53	35.43	35.93	36.04	37.44	36.57	40.22
Ab	22.29	19.35	25.09	23.61	24.82	21.66	23.92	22.22	27.38
An	2.04	1.29	3.49	2.09	2.37	2.31	1.75	2.82	2.06
Or	33.24	31.40	27.86	32.60	31.17	33.74	30.60	32.25	23.91
Cm	3.26	3.76	3.01	3.41	2.90	2.97	3.70	3.23	4.78
Ap	0.30	0.37	0.23	0.37	0.37	0.28	0.42	0.33	0.28

Differentiation Index (DI)

DI	91.88	92.93	90.48	91.64	91.92	91.44	91.96	91.04	91.51
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	KA-29	KA-32	KA-34	KA-39	KA-40	KA-41	KA-43	KA-49	KA-36
ROCK	BMG	MGR	MGR	MBG	MBG	MBG	MBG	MBG	APLITE
SiO ₂ %	75.05	74.74	74.44	73.83	71.76	74.03	76.82	73.97	74.30
TiO ₂	0.21	0.10	0.20	0.26	0.27	0.23	0.20	0.17	0.06
Al ₂ O ₃	14.46	14.95	14.70	14.29	15.17	14.14	12.32	14.17	14.26
Fe ₂ O ₃	1.34	0.49	1.32	2.05	2.08	1.48	1.43	1.34	1.09
MnO	0.02	0.01	0.03	0.03	0.04	0.02	0.02	0.03	0.04
MgO	0.43	0.26	0.37	0.45	1.01	0.38	0.63	0.00	0.20
CaO	0.58	0.43	0.52	0.15	1.85	0.77	0.63	0.61	0.37
Na ₂ O	2.46	3.47	2.27	1.83	2.78	2.15	1.36	2.89	3.98
K ₂ O	5.74	4.60	5.71	7.18	4.76	5.95	6.32	5.46	3.99
P ₂ O ₅	0.14	0.15	0.06	0.16	0.05	0.09	0.08	0.17	0.26
TOTAL	100.43	99.20	99.62	100.23	99.77	99.24	99.81	98.81	98.55
Rb ppm	400	286	355	463	253	323	280	476	402
Ba	214	145	246	295	605	337	363	277	167
Sr	55	32	49	36	147	71	95	70	34
Zr	71	2	64	91	120	103	78	69	21
Nb	9	10	8	13	11	9	5	7	7
Y	66	15	67	97	25	70	81	62	12
Zn	121	49	114	188	22	0	0	73	166
Sn	10	7	10	12	1	1	3	12	7
W	3	4	3	3		2			4
Li	120	33	150	180	60	82	51	130	31
F	1200	800	880	1700	880	1000	560	1800	870
B	50	330	140	100	60	100	40	50	1800
K/Rb	119	133	133	129	156	153	187	95	82
K/Ba	222.6	263.3	192.7	202.0	65.3	146.5	144.5	163.6	198.3
Rb/Sr	7.27	8.94	7.24	12.86	1.72	4.55	2.95	6.8	11.82
Rb/Zr	5.63	143.00	5.55	5.09	2.11	3.14	3.59	6.90	19.14
Rb/Ba	1.87	1.97	1.44	1.57	0.42	0.96	0.77	1.72	2.41
Sr/Rb	0.14	0.11	0.14	0.08	0.58	0.22	0.34	0.15	0.08
Li/Zr	1.69	16.50	2.34	1.98	0.50	0.80	0.65	1.88	1.48
Li/Sr	2.18	1.03	3.06	5.00	0.41	1.15	0.54	1.86	0.91

Partial CIPW Norms

Qz	37.10	36.31	38.01	34.92	32.11	37.04	42.71	35.83	36.03
Ab	20.72	29.60	19.28	15.44	23.58	18.33	11.53	24.74	34.17
An	1.95	1.23	2.20	0.00	8.87	3.26	2.61	1.94	0.14
Or	33.80	27.43	33.90	42.36	28.23	35.46	37.45	32.67	23.95
Cm	3.46	3.84	3.99	3.49	2.20	3.00	2.29	2.83	3.39
Ap	0.32	0.33	0.14	0.37	0.12	0.21	0.19	0.40	0.61

Differentiation Index (DI)

DI	91.62	93.34	91.19	92.72	83.92	90.83	91.69	93.24	94.15
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	NY-1	NY-2	NY-3	NY-19	NY-21	NY-23	NY-25	NY-28	NY-29
ROCK	BMG	BMG	BMG	BMG	BMG	BMG	BMG	BMG	BMG
SiO ₂ %	74.39	73.82	75.54	74.63	74.49	74.67	74.53	74.22	74.57
TiO ₂	0.21	0.15	0.19	0.16	0.19	0.16	0.20	0.18	0.21
Al ₂ O ₃	14.68	14.80	14.17	14.49	14.22	14.43	14.24	14.32	14.72
Fe ₂ O ₃	1.52	1.13	1.17	1.23	1.44	1.44	1.49	1.50	1.22
MnO	0.04	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.02
MgO	0.37	0.29	0.30	0.29	0.31	0.31	0.32	0.29	0.33
CaO	0.42	0.56	0.59	0.52	0.56	0.28	0.26	0.65	0.16
Na ₂ O	2.96	3.13	2.74	3.52	2.84	2.87	2.57	2.88	2.70
K ₂ O	5.71	5.91	4.89	5.50	5.31	5.68	5.91	5.61	5.88
P ₂ O ₅	0.24	0.11	0.15	0.16	0.16	0.17	0.08	0.13	0.12
TOTAL	100.54	99.93	99.77	100.53	99.55	100.03	99.63	99.81	99.93
Rb ppm	432	434	417	500	437	451	457	438	445
Ba	195	147	118	153	200	241	235	213	235
Sr	51	37	22	38	43	60	56	44	46
Zr	105	58	82	67	82	67	92	74	90
Nb	18	10	17	15	14	13	15	13	12
Y	84	53	86	62	66	47	72	69	133
Zn	70	11	133	35	33	28	62	61	58
Sn	8	7	11	9	12	13	9	10	16
W	3	5	6	4	7	6	5	5	6
Li	160	110	94	180	160	160	190	150	180
F	1400	2300	3100	3000	2400	2300	1400	3400	2200
B	170	50	200	50	70	50	50	80	80
K/Rb	110	113	97	91	101	105	107	106	110
K/Ba	243.0	333.7	344.0	298.4	220.4	195.6	208.7	218.6	207.7
Rb/Sr	8.47	11.73	18.96	13.16	10.163	7.52	8.16	9.95	9.67
Rb/Zr	4.11	7.48	5.09	7.46	5.33	6.73	4.97	5.92	4.94
Rb/Ba	2.22	2.95	3.53	3.27	2.19	1.87	1.94	2.06	1.89
Sr/Rb	0.22	0.09	0.05	0.08	0.10	0.13	0.12	0.10	0.10
Li/Zr	1.52	1.90	1.15	2.69	1.95	2.39	2.07	2.03	2.00
Li/Sr	3.14	2.97	4.27	4.74	3.72	2.67	3.39	3.41	3.91

Partial CIPW Norms

Qz	34.33	31.67	39.67	31.82	36.58	35.62	36.26	34.58	35.87
Ab	24.91	26.50	23.23	29.62	24.14	24.27	21.82	24.41	22.86
An	0.51	2.06	1.95	1.52	1.74	0.28	0.77	2.37	0.01
Or	33.59	34.98	28.99	32.36	31.55	33.58	35.08	33.25	34.80
Cm	3.42	2.50	3.66	2.17	3.18	3.45	3.34	2.64	3.91
Ap	0.55	0.26	0.35	0.37	0.37	0.39	0.19	0.30	0.28

Differentiation Index (DI)

DI	92.83	93.15	91.89	93.80	92.27	93.47	93.16	92.24	93.53
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	NY-30	KY-3	KY-5	KY-6	KY-7	KT-3	KT-7	KT-8	KT-10
ROCK	MGR	BMG	BMG	BMG	BMG	BMG	BMG	BMG	BMG
SiO ₂ %	74.21	74.41	74.99	73.74	74.13	74.55	74.55	74.20	74.35
TiO ₂	0.20	0.14	0.13	0.16	0.14	0.23	0.15	0.15	0.13
Al ₂ O ₃	14.61	13.58	13.89	14.50	14.28	13.78	13.92	14.26	14.19
Fe ₂ O ₃	1.18	1.39	1.18	1.49	1.34	1.73	1.34	1.28	1.14
MnO	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.02	0.02
MgO	0.31	0.23	0.27	0.25	0.17	0.09	0.00	0.00	0.00
CaO	0.10	0.39	0.51	0.48	0.38	0.58	0.47	0.50	0.50
Na ₂ O	2.87	2.22	2.85	3.15	3.50	2.38	2.88	2.97	2.81
K ₂ O	5.82	4.77	5.18	4.93	4.85	5.13	4.93	5.22	5.63
P ₂ O ₅	0.17	0.10	0.09	0.12	0.17	0.16	0.09	0.17	0.13
TOTAL	99.49	97.26	99.11	98.84	98.99	98.66	98.36	98.77	98.90
Rb ppm	469	478	452	439	530	465	465	461	466
Ba	248	171	185	184	206	231	209	253	210
Sr	93	32	37	93	67	53	86	104	45
Zr	91	50	38	73	50	94	45	53	50
Nb	12	6	6	5	5	12	9	10	9
Y	114	75	76	127	79	78	66	78	71
Zn	37	72	53	10	42	52	72	51	51
Sn	29	12	15	10	39	17	20	16	10
W	14		3			4	2	3	3
Li	250	473	220	394	412	560	360	350	400
F	4000	2280	1500	2330	1970	1800	1300	1700	1500
B	30	94	120	238	208	180	130	70	260
K/Rb	103	83	95	93	76	92	88	94	100
K/Ba	194.8	231.5	232.4	222.4	195.4	184.3	195.8	171.2	222.5
Rb/Sr	5.04	14.94	12.22	4.72	7.91	8.77	5.4	4.43	10.36
Rb/Zr	5.15	9.56	11.89	6.01	10.60	4.95	10.33	8.70	9.32
Rb/Ba	1.89	2.80	2.44	2.39	2.57	2.01	2.22	1.82	2.22
Sr/Rb	0.20	0.07	0.08	0.21	0.13	0.11	0.18	0.23	0.10
Li/Zr	2.75	9.46	5.79	5.40	8.24	5.96	8.00	6.60	8.00
Li/Sr	2.69	14.78	5.95	4.24	6.15	10.57	4.19	3.37	8.89

Partial CIPW Norms

Qz	34.89	43.21	37.42	35.57	34.66	40.65	38.78	36.77	36.12
Ab	24.37	19.33	24.34	26.98	29.94	20.40	24.76	25.43	24.03
An	0.00	1.32	1.96	1.62	0.79	1.85	1.77	1.38	1.65
Or	34.56	29.01	30.91	29.50	28.98	30.74	29.64	31.25	33.66
Cm	3.60	4.42	2.91	3.44	3.02	3.68	3.26	3.26	2.90
Ap	0.40	0.24	0.21	0.29	0.41	0.38	0.21	0.40	0.31

Differentiation Index (DI)

DI	93.82	91.55	92.67	92.05	93.58	91.79	93.18	93.45	93.81
----	-------	-------	-------	-------	-------	-------	-------	-------	-------

SAMPLE	KT-11	KT-12	KT-13	KT-14	KT-16	KY-4	KT-5	KT-9	RS-1
ROCK	BMG	BMG	BMG	BMG	BMG	PEGA	PEGM	PEGA	BMG
SiO ₂ %	74.16	73.67	73.71	73.84	73.96	67.25	78.81	69.82	73.53
TiO ₂	0.15	0.15	0.15	0.14	0.14	0.00	0.01	0.00	0.12
Al ₂ O ₃	14.29	14.27	14.66	14.45	14.32	13.55	12.75	16.84	14.15
Fe ₂ O ₃	1.27	1.37	1.40	1.25	1.21	0.42	1.57	0.21	1.32
MnO	0.02	0.02	0.02	0.02	0.02	0.12	0.08	0.07	0.03
MgO	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00
CaO	0.46	0.51	0.53	0.55	0.49	0.17	0.14	0.21	0.52
Na ₂ O	2.64	2.76	2.81	2.79	2.90	6.54	3.19	5.53	3.10
K ₂ O	5.22	5.60	5.54	5.56	5.28	2.55	2.29	6.40	5.09
P ₂ O ₅	0.13	0.15	0.11	0.15	0.10	0.16	0.06	0.22	0.20
TOTAL	98.34	98.50	98.93	98.75	98.42	90.79	98.90	99.30	98.06
Rb ppm	695	467	485	444	459	436	562	1145	565
Ba	190	198	228	207	182	60	165	103	181
Sr	46	52	48	45	53	9	31	96	49
Zr	61	63	37	43	56	18	0	11	53
Nb	9	12	10	7	9	34	26	61	16
Y	75	84	46	58	74	16	17	17	47
Zn	72	66	82	66	64	0	94	12	43
Sn	25	8	2	5	12	55	105	397	9
W	5	6	2	4	4		0	0	15
Li	590	440	450	380	310	36	370	27	130
F	2800	1900	2400	1500	1200	240	1400	800	3400
B	120	170	100	260	100	26	40	20	450
K/Rb	62	100	95	104	95	49	34	46	75
K/Ba	228.0	234.7	201.7	222.9	240.8	352.8	115.2	515.7	233.4
Rb/Sr	15.11	8.98	10.1	9.87	8.66	48.44	18.13	11.93	11.53
Rb/Zr	11.39	7.41	13.11	10.33	8.20	24.22	ERR	104.09	10.66
Rb/Ba	3.66	2.36	2.13	2.14	2.52	7.27	3.41	11.12	3.12
Sr/Rb	0.07	0.11	0.10	0.10	0.12	0.02	0.06	0.08	0.09
Li/Zr	9.67	6.98	12.16	8.84	5.54	2.00	ERR	2.00	2.45
Li/Sr	12.83	8.46	9.38	8.44	5.85	4.00	11.94	0.23	2.65
Partial CIPW Norms									
Qz	38.82	36.02	35.68	35.99	36.66	21.22	51.90	13.21	36.14
Ab	22.71	23.70	24.02	23.89	24.92	60.97	27.28	47.06	26.74
An	1.46	1.57	1.93	1.77	1.80	0.00	0.31	0.00	1.30
Or	31.39	33.62	33.11	33.29	31.72	16.60	13.69	38.08	30.69
Cm	3.83	3.14	3.37	3.24	3.23	0.12	4.96	0.82	3.13
Ap	0.31	0.35	0.26	0.35	0.24	0.42	0.14	0.51	0.47
Differentiation Index (DI)									
DI	92.92	93.34	92.81	93.17	93.30	98.79	92.87	98.35	93.57

SAMPLE	RS-2	RS-3	RS-5	RS-6
ROCK	BMG	BMG	MGR	MGR
SiO ₂ %	74.22	74.32	74.41	73.76
TiO ₂	0.12	0.12	0.12	0.12
Al ₂ O ₃	14.11	14.09	14.00	14.19
Fe ₂ O ₃	1.14	1.31	1.37	1.40
MnO	0.02	0.03	0.03	0.02
MgO	0.00	0.00	0.00	0.00
CaO	0.57	0.53	0.52	0.55
Na ₂ O	3.35	3.33	3.14	3.27
K ₂ O	5.06	4.95	4.99	5.07
P ₂ O ₅	0.22	0.17	0.16	0.15
TOTAL	98.81	98.85	98.74	98.53

Rb ppm	546	552	545	537
Ba	152	183	158	196
Sr	36	39	46	45
Zr	46	46	48	48
Nb	16	15	15	18
Y	48	44	46	45
Zn	45	63	43	40
Sn	10	11	8	14
W	15	15	15	15
Li	100	130	150	120
F	3900	3300	3800	3700
B	360	420	440	950

K/Rb	77	74	76	78
K/Ba	276.3	224.5	262.1	214.7
Rb/Sr	15.17	14.15	11.85	11.93
Rb/Zr	11.87	12.00	11.35	11.19
Rb/Ba	3.59	3.02	3.45	2.74
Sr/Rb	0.07	0.07	0.08	0.08
Li/Zr	2.17	2.83	3.13	2.50
Li/Sr	2.78	3.33	3.26	2.67

Partial CIPW Norms

Qz	35.15	35.72	36.82	35.06
Ab	28.67	28.49	26.90	28.07
An	1.40	1.53	1.55	1.77
Or	30.28	29.61	29.88	30.42
Cm	2.64	2.72	2.90	2.72
Ap	0.52	0.40	0.38	0.35

Differentiation Index (DI)

DI	94.10	93.82	93.60	93.55
----	-------	-------	-------	-------

APPENDIX 5

Microprobe analyses of tourmalines from Karagwe-Ankolean granites, aplites, and tourmalinized country rocks. Additional analyses are given in Tables 6-3 and 6-4 in Chapter 6.

ABBREVIATIONS

HOST: host rock for tourmaline

AN. NO.: analysis number

COLOR: color of zoned tourmaline in thin section

Color codes^{*} : CYG RYB CLB RLB RBN CBN CYB, CWY CYB CWB

In each code "C" stands for tourmaline core, "R" for rim; the next two letters represent the color as follows:

YG : yellowish-gray, YB: yellowish-brown, LB: light brown, BN: brown, WY: white-yellow, WB: white-brown.

*** Where the code is not given the color was not determined.**

TABLE A5: TOURMALINE ANALYSES

SAMPLE	KA-24										KA-36										KA-37										
	two-mica granite					aplite dyke					two-mica granite					two-mica granite															
HOST	CBN	RBN	CBN	RBN	CTB	RLB	RBN	RLB	RBN	CTB	RLB	RBN	CTB	RLB	RBN	CTB	RLB	RBN	CTB	RLB	RBN	CTB	RLB	RBN	CTB	RLB	RBN	CTB	RLB	RBN	
COLOR	1	2	1	2	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2	3	4	1	2	3	4	
AN. NO.	35.53	35.40	34.72	35.62	35.38	34.87	35.32	35.26	35.40	35.54	35.39	35.79	34.57	35.01	35.48	36.19	35.40	35.65	36.19	35.40	35.65	36.19	35.40	35.65	36.19	35.40	35.65	36.19	35.40	35.65	
SiO2 %	14.76	14.92	14.83	13.30	11.39	13.52	14.14	14.18	12.10	14.00	14.24	11.36	11.12	13.69	13.72	10.44	10.86	11.35	10.44	10.86	11.35	10.44	10.86	11.35	10.44	10.86	11.35	10.44	10.86	11.35	
FeO	2.39	2.47	2.47	2.70	2.30	2.27	2.20	2.28	1.91	2.26	2.18	1.85	2.06	2.35	2.23	2.17	2.25	2.62	2.17	2.25	2.62	2.17	2.25	2.62	2.17	2.25	2.62	2.17	2.25	2.62	
Na2O	0.09	0.05	0.10	0.43	0.32	0.08	0.12	0.16	0.49	0.20	0.12	0.10	0.56	0.12	0.21	0.16	0.65	0.51	0.16	0.65	0.51	0.16	0.65	0.51	0.16	0.65	0.51	0.16	0.65	0.51	
CaO	35.06	35.06	35.34	32.98	35.64	35.15	34.37	34.75	34.63	35.04	34.49	36.50	35.58	34.54	34.43	35.60	35.15	33.08	35.60	35.15	33.08	35.60	35.15	33.08	35.60	35.15	33.08	35.60	35.15	33.08	35.60
Al2O3	0.62	0.33	0.48	0.24	0.00	0.27	0.15	0.15	0.00	0.00	0.27	0.00	0.10	0.18	0.22	0.07	0.13	0.22	0.07	0.13	0.22	0.07	0.13	0.22	0.07	0.13	0.22	0.07	0.13	0.22	
MnO	0.74	0.52	0.66	3.50	3.13	1.17	1.22	1.03	3.39	1.15	1.11	2.41	2.98	1.43	1.01	3.62	4.35	4.36	3.62	4.35	4.36	3.62	4.35	4.36	3.62	4.35	4.36	3.62	4.35	4.36	
MgO	0.04	0.06	0.03	0.12	0.04	0.08	0.02	0.00	0.03	0.05	0.04	0.02	0.08	0.00	0.10	0.04	0.04	0.02	0.10	0.04	0.02	0.04	0.04	0.02	0.04	0.04	0.02	0.04	0.04	0.02	
K2O	0.36	0.31	0.30	0.81	0.74	0.34	0.45	0.59	0.91	0.57	0.56	0.23	1.04	0.42	0.73	0.34	0.89	1.02	0.34	0.89	1.02	0.34	0.89	1.02	0.34	0.89	1.02	0.34	0.89	1.02	
TiO2	89.59	89.11	88.95	89.69	88.94	87.75	87.98	88.40	88.86	88.80	88.40	88.26	88.08	87.74	88.14	88.63	89.72	88.85	88.63	89.72	88.85	88.63	89.72	88.85	88.63	89.72	88.85	88.63	89.72	88.85	
Total	Number of atoms based on 24.5 oxygens																														
Si	5.804	5.811	5.721	5.799	5.716	5.772	5.841	5.807	5.745	5.816	5.833	5.789	5.645	5.802	5.851	5.821	5.674	5.799	5.821	5.674	5.799	5.821	5.674	5.799	5.821	5.674	5.799	5.821	5.674	5.799	
Fe	2.016	2.048	2.043	1.811	1.539	1.872	1.955	1.953	1.642	1.916	1.962	1.536	1.517	1.896	1.894	1.404	1.455	1.544	1.404	1.455	1.544	1.404	1.455	1.544	1.404	1.455	1.544	1.404	1.455	1.544	
Na	0.757	0.786	0.789	0.853	0.720	0.728	0.706	0.730	0.600	0.718	0.696	0.581	0.652	0.757	0.713	0.679	0.698	0.826	0.679	0.698	0.826	0.679	0.698	0.826	0.679	0.698	0.826	0.679	0.698	0.826	
Ca	0.015	0.007	0.017	0.076	0.056	0.015	0.022	0.029	0.086	0.034	0.022	0.017	0.098	0.022	0.037	0.027	0.113	0.088	0.027	0.113	0.088	0.027	0.113	0.088	0.027	0.113	0.088	0.027	0.113	0.088	
Al	6.747	6.782	6.842	6.328	6.784	6.858	6.698	6.745	6.622	6.757	6.698	6.958	6.845	6.745	6.693	6.747	6.640	6.341	6.745	6.693	6.747	6.640	6.341	6.745	6.693	6.747	6.640	6.341	6.745	6.693	
Mn	0.086	0.047	0.066	0.032	0.000	0.037	0.022	0.020	0.000	0.000	0.037	0.000	0.015	0.025	0.029	0.010	0.017	0.029	0.010	0.017	0.029	0.010	0.017	0.029	0.010	0.017	0.029	0.010	0.017	0.029	
Mg	0.181	0.127	0.162	0.848	0.752	0.289	0.301	0.252	0.821	0.279	0.272	0.581	0.725	0.353	0.247	0.867	1.039	1.061	0.867	1.039	1.061	0.867	1.039	1.061	0.867	1.039	1.061	0.867	1.039	1.061	
K	0.007	0.012	0.007	0.025	0.007	0.017	0.002	0.000	0.005	0.010	0.010	0.005	0.017	0.000	0.020	0.010	0.007	0.005	0.010	0.007	0.005	0.010	0.007	0.005	0.010	0.007	0.005	0.010	0.007	0.005	
Ti	0.044	0.037	0.037	0.098	0.091	0.042	0.056	0.074	0.110	0.069	0.069	0.029	0.127	0.051	0.091	0.042	0.108	0.125	0.042	0.108	0.125	0.042	0.108	0.125	0.042	0.108	0.125	0.042	0.108	0.125	
Fluor	0.92	0.94	0.93	0.68	0.67	0.87	0.87	0.89	0.67	0.87	0.88	0.73	0.68	0.84	0.88	0.62	0.58	0.59	0.62	0.58	0.59	0.62	0.58	0.59	0.62	0.58	0.59	0.62	0.58	0.59	

Number of atoms based on 24.5 oxygens

Si	5.804	5.811	5.721	5.799	5.716	5.772	5.841	5.807	5.745	5.816	5.833	5.789	5.645	5.802	5.851	5.821	5.674	5.799
Fe	2.016	2.048	2.043	1.811	1.539	1.872	1.955	1.953	1.642	1.916	1.962	1.536	1.517	1.896	1.894	1.404	1.455	1.544
Na	0.757	0.786	0.789	0.853	0.720	0.728	0.706	0.730	0.600	0.718	0.696	0.581	0.652	0.757	0.713	0.679	0.698	0.826
Ca	0.015	0.007	0.017	0.076	0.056	0.015	0.022	0.029	0.086	0.034	0.022	0.017	0.098	0.022	0.037	0.027	0.113	0.088
Al	6.747	6.782	6.862	6.328	6.784	6.858	6.698	6.745	6.622	6.757	6.698	6.958	6.845	6.745	6.693	6.747	6.640	6.341
Mn	0.086	0.047	0.066	0.032	0.000	0.037	0.022	0.020	0.000	0.000	0.037	0.000	0.015	0.025	0.029	0.010	0.017	0.029
Mg	0.181	0.127	0.162	0.848	0.752	0.289	0.301	0.252	0.821	0.279	0.272	0.581	0.725	0.353	0.247	0.867	1.039	1.061
K	0.007	0.012	0.007	0.025	0.007	0.017	0.002	0.000	0.005	0.010	0.010	0.005	0.017	0.000	0.020	0.010	0.007	0.005
Ti	0.044	0.037	0.037	0.098	0.091	0.042	0.056	0.074	0.110	0.069	0.069	0.029	0.127	0.051	0.091	0.042	0.108	0.125
FM*	0.92	0.94	0.93	0.68	0.67	0.87	0.87	0.89	0.67	0.87	0.88	0.73	0.68	0.84	0.88	0.62	0.58	0.59

*: FM = Fe/(Fe + Mg)

TABLE A5 (continued)

SAMPLE	KA-37 (cont.)				NY-22				NY31/1				NY31/1			
	two-mica granite				tourmalinized xenolith				tourmalinized schist				tourmaline vein in schist			
HOST	CLB	RYB	RBN		CLB	RYB	RBN		CLB	RLB	CLB	RLB	CYG	RYB	CLB	RBN
AN. NO.	1	2	3		1	2	3	1	1	2	1	2	1	2	1	2
SiO ₂ %	36.08	35.25	35.82	35.94	35.23	35.46	35.97	46.32	35.20	35.76	35.92	35.43	35.60	36.12	35.61	35.97
FeO	9.71	10.22	12.96	13.44	13.81	13.01	14.59	2.70	13.60	13.98	13.62	14.88	14.24	16.36	14.46	14.18
Na ₂ O	1.68	2.18	2.47	2.41	2.54	2.50	2.66	0.29	2.71	2.56	1.70	2.33	2.04	1.78	2.48	1.88
CaO	0.09	0.49	0.60	0.17	0.16	0.20	0.18	0.00	0.22	0.12	0.08	0.09	0.01	0.07	0.24	0.01
Al ₂ O ₃	36.67	35.15	32.11	33.26	32.29	33.29	32.09	34.05	33.05	32.38	35.54	34.79	35.36	36.65	34.97	35.88
MnO	0.09	0.10	0.03	0.00	0.06	0.11	0.02	0.01	0.00	0.00	0.00	0.05	0.00	0.04	0.09	0.00
MgO	3.51	4.29	3.91	2.39	2.89	2.62	2.79	1.07	2.87	3.19	1.05	1.17	1.05	0.79	1.16	1.09
K ₂ O	0.02	0.07	0.06	0.06	0.09	0.06	0.07	10.51	0.04	0.05	0.03	0.00	0.05	0.04	0.00	0.12
TiO ₂	0.34	0.98	0.75	0.53	0.73	0.79	0.85	0.63	0.56	0.78	0.45	0.69	0.54	0.30	0.73	0.56
Total	88.18	88.73	88.71	88.20	87.80	88.03	89.23	95.58	88.24	88.82	88.39	89.13	88.72	90.14	89.73	89.54

Number of atoms based on 24.5 oxygens																
Si	5.789	5.686	5.878	5.917	5.863	5.851	5.909	6.892	5.819	5.878	5.863	5.760	5.799	5.794	5.802	5.789
Fe	1.303	1.379	1.779	1.850	1.923	1.796	2.004	0.336	1.879	1.921	1.860	2.041	1.950	2.068	1.928	1.965
Na	0.522	0.681	0.784	0.769	0.818	0.799	0.848	0.083	0.870	0.816	0.537	0.740	0.649	0.733	0.554	0.782
Ca	0.015	0.086	0.105	0.029	0.029	0.037	0.032	0.000	0.039	0.022	0.015	0.017	0.002	0.017	0.012	0.042
Al	6.936	6.686	6.211	6.451	6.331	6.473	6.213	5.973	6.439	6.274	6.840	6.723	6.821	6.637	6.938	6.701
Mn	0.012	0.015	0.005	0.000	0.007	0.015	0.002	0.000	0.000	0.000	0.000	0.007	0.000	0.000	0.005	0.012
Mg	0.838	1.034	0.958	0.588	0.718	0.644	0.684	0.238	0.706	0.782	0.255	0.287	0.257	0.314	0.189	0.279
K	0.005	0.012	0.012	0.012	0.017	0.012	0.015	1.994	0.010	0.010	0.007	0.000	0.010	0.010	0.010	0.000
Ti	0.042	0.118	0.093	0.066	0.091	0.098	0.105	0.071	0.069	0.096	0.054	0.086	0.066	0.091	0.037	0.088
FM*	0.61	0.57	0.65	0.76	0.73	0.74	0.75	0.59	0.73	0.71	0.88	0.88	0.88	0.87	0.91	0.88

*: FM = Fe/(Fe + Mg)

TABLE A5 (continued)

SAMPLE	NR31/1 (cont.)				NY-31/2				NY31/2			
	tourmaline vein in schist				tourmalinized schist				tourmaline vein in schist			
HOST	CLB	CLB	CLB	CLB	CLB	RYB	CLB	CGR	RYB	CLB	RYB	CLB
COLOR	1	2	3	4	1	2	1	1	2	1	1	1
AN. NO.	1	2	3	4	1	2	1	1	2	1	1	1
SiO ₂ %	35.33	36.19	35.09	36.00	36.38	35.61	35.81	35.63	35.93	35.34	34.94	35.55
FeO	15.21	15.24	14.67	15.36	13.35	13.76	14.39	13.82	14.32	14.63	12.75	13.63
Na ₂ O	2.26	2.36	2.35	2.22	1.73	2.34	2.54	2.26	2.45	2.48	1.93	2.37
CaO	0.08	0.12	0.07	0.18	0.00	0.03	0.10	0.10	0.13	0.03	0.16	0.21
Al ₂ O ₃	34.13	33.67	34.55	34.03	35.75	34.69	34.81	34.85	34.20	34.14	35.31	34.73
MnO	0.00	0.04	0.14	0.05	0.00	0.10	0.02	0.00	0.26	0.01	0.12	0.00
MgO	0.90	1.24	1.12	0.82	0.98	1.21	1.44	1.92	1.39	1.45	1.91	2.02
K ₂ O	0.00	0.01	0.00	0.05	0.05	0.00	0.03	0.01	0.05	0.05	0.00	0.00
TiO ₂	0.78	0.67	0.87	0.82	0.29	0.80	0.69	0.51	0.83	0.51	0.30	0.41
Total	88.69	89.52	88.86	89.53	88.54	88.54	89.81	89.08	89.56	88.65	87.41	88.92

Number of atoms based on 24.5 oxygens

Si	5.329	5.914	5.770	5.885	5.912	5.836	5.811	5.807	5.853	5.824	5.767	5.738
Fe	2.100	2.083	2.019	2.100	1.815	1.887	1.953	1.884	1.950	2.016	1.759	1.862
Na	0.720	0.747	0.750	0.703	0.546	0.745	0.799	0.713	0.774	0.791	0.617	0.701
Ca	0.015	0.020	0.012	0.032	0.000	0.005	0.017	0.017	0.022	0.007	0.027	0.059
Al	6.635	6.483	6.696	6.556	6.848	6.703	6.657	6.693	6.566	6.630	6.870	6.919
Mn	0.000	0.005	0.020	0.007	0.000	0.015	0.002	0.000	0.037	0.002	0.017	0.025
Mg	0.220	0.301	0.274	0.201	0.238	0.296	0.348	0.465	0.338	0.355	0.468	0.446
K	0.000	0.002	0.000	0.010	0.010	0.000	0.007	0.002	0.010	0.012	0.000	0.002
Ti	0.098	0.083	0.108	0.100	0.037	0.098	0.083	0.061	0.103	0.064	0.037	0.081
FM*	0.90	0.87	0.88	0.91	0.88	0.86	0.85	0.80	0.85	0.85	0.79	0.78

*: FM = Fe/(Fe + Mg)

APPENDIX 6

Microprobe analyses of garnets from aplite dykes associated with the Maleba and Karagwe Tinfield granites.

TABLE 6A: MICROPROBE ANALYSES OF GARNETS FROM APLITES ASSOCIATED WITH MALEBA AND KARAGWE TINFIELD GRANITES

SAMPLE ANALYSIS	MA-28-2			MB-12-1			MB-12-2			MB-12-3			MB-12-1		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
SiO ₂ %	36.42	36.65	36.30	35.89	36.54	36.25	36.44	36.61	36.62	36.24	36.36	36.89	37.04	36.72	36.87
Al ₂ O ₃	20.63	20.93	20.83	20.82	20.96	20.70	20.85	20.78	20.89	20.74	20.79	20.94	20.98	20.87	20.63
TiO ₂	0.01	0.02	0.01	0.06	0.04	0.04	0.07	0.05	0.05	0.04	0.03	0.04	0.06	0.09	0.02
MgO	0.02	0.02	0.02	0.02	0.02	0.01	0.17	0.15	0.14	0.13	0.05	0.13	0.16	0.15	0.07
FeO	8.20	6.47	6.59	6.56	6.46	6.44	25.25	24.92	25.07	25.36	23.77	25.48	25.38	25.19	25.38
MnO	34.41	35.89	35.88	35.66	35.74	35.92	17.40	17.54	17.41	17.98	19.43	17.69	17.49	17.69	17.77
CaO	1.16	1.05	1.09	1.04	1.16	1.07	0.27	0.27	0.39	0.25	0.25	0.26	0.25	0.31	0.45
Total	100.85	101.03	100.72	100.05	100.92	100.43	100.45	100.32	100.57	100.74	100.68	101.43	101.36	101.02	101.19

Number of atoms based on 24 oxygens

Si	5.962	5.971	5.945	5.919	5.960	5.953	5.990	6.008	5.995	5.953	5.969	5.997	6.014	5.992	6.015
Al(IV)	0.038	0.029	0.055	0.081	0.040	0.047	0.020	0.000	0.005	0.047	0.031	0.003	0.000	0.008	0.000
Al(VI)	3.942	3.990	3.965	3.966	3.988	3.960	4.012	4.018	4.026	3.967	3.990	4.009	4.014	4.005	3.966
Ti	0.001	0.002	0.001	0.007	0.005	0.005	0.009	0.006	0.006	0.005	0.004	0.005	0.007	0.011	0.002
Mg	0.005	0.005	0.005	0.005	0.005	0.002	0.042	0.037	0.034	0.032	0.012	0.032	0.039	0.036	0.017
Fe	1.123	0.882	0.903	0.905	0.881	0.885	3.465	3.420	3.433	3.484	3.263	3.464	3.446	3.437	3.463
Mn	4.771	4.953	4.977	4.982	4.937	4.997	2.419	2.438	2.414	2.502	2.702	2.436	2.405	2.465	2.456
Ca	0.203	0.183	0.191	0.184	0.203	0.188	0.047	0.047	0.068	0.044	0.044	0.045	0.043	0.054	0.079
Alm % *	18.40	14.64	14.86	14.89	14.62	14.57	58.02	57.55	57.70	57.48	54.20	57.96	58.08	57.55	57.58
Pyro	0.08	0.08	0.08	0.08	0.08	0.04	0.70	0.62	0.57	0.53	0.20	0.53	0.65	0.61	0.28
Spes	78.19	82.24	81.92	82.00	81.93	82.29	40.49	41.03	40.58	41.27	44.87	40.76	40.54	40.93	40.83
Gros	3.33	3.04	3.15	3.03	3.36	3.10	0.79	0.80	1.15	0.73	0.73	0.76	0.73	0.91	1.31

* Molecular proportions of almandine (Alm), pyrope (Pyro), spessartine (Spes) and grossular (Gros) expressed in percentages.

Sample MA-28: tourmaline-barren, sodic (K₂O/Na₂O = 0.1), aplite dyke, Maleba pluton

MB-12: muscovite-tourmaline aplite dyke, Maleba pluton

TABLE 6A (continued)

SAMPLE ANALYSIS	MB-33-1			MB-33-2					KY-4-1				KY-4-2				
	1	2	1	2	3	4	5	1	2	3	4	1	2	3	1	2	3
SiO2 %	36.92	36.70	37.17	36.98	36.83	36.85	37.18	37.80	36.06	36.75	36.46	36.12	36.07	35.64	36.18	36.29	35.98
Al2O3	20.72	20.24	20.76	20.54	20.57	20.36	20.52	20.80	20.29	20.65	20.58	20.66	20.58	20.35	20.69	20.98	20.49
TiO2	0.04	0.06	0.09	0.10	0.08	0.06	0.06	0.01	0.12	0.12	0.12	0.01	0.01	0.00	0.01	0.00	0.00
MgO	0.09	0.08	0.30	0.21	0.22	0.30	0.26	0.14	0.20	0.16	0.22	0.01	0.01	0.01	0.00	0.01	0.01
FeO	25.43	25.44	27.28	24.62	26.61	26.60	26.96	23.39	24.00	24.78	23.55	16.51	13.80	19.17	14.67	16.82	18.93
MnO	17.34	17.91	15.26	18.70	16.42	16.63	16.42	17.80	18.91	18.36	19.31	26.13	29.31	23.96	28.56	26.54	24.56
CaO	0.24	0.27	0.36	0.24	0.34	0.36	0.36	3.20	0.26	0.33	0.43	0.12	0.21	0.20	0.20	0.12	0.12
Total	100.78	100.70	101.22	101.39	101.07	101.16	101.76	103.14	99.84	101.15	100.67	99.56	99.99	99.33	100.31	100.88	100.09

Number of atoms based on 24 oxygens

Si	6.033	6.027	6.038	6.020	6.013	6.018	6.031	6.021	5.975	5.998	5.980	5.984	5.964	5.948	5.962	5.945	5.957
Al(IV)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.002	0.020	0.016	0.036	0.052	0.038	0.055	0.043
Al(VI)	3.989	3.917	3.974	3.940	3.957	3.918	3.922	3.904	3.937	3.969	3.957	4.017	3.974	3.949	3.980	3.996	3.954
Ti	0.005	0.007	0.011	0.012	0.010	0.007	0.007	0.001	0.015	0.015	0.015	0.001	0.001	0.000	0.001	0.000	0.000
Mg	0.022	0.020	0.073	0.051	0.054	0.073	0.063	0.033	0.049	0.039	0.054	0.002	0.002	0.002	0.000	0.002	0.002
Fe	3.475	3.494	3.706	3.352	3.633	3.633	3.657	3.116	3.326	3.382	3.230	2.287	1.908	2.675	2.022	2.304	2.621
Mn	2.400	2.491	2.099	2.578	2.271	2.300	2.256	2.402	2.654	2.538	2.683	3.667	4.105	3.387	3.987	3.683	3.444
Ca	0.042	0.048	0.063	0.042	0.059	0.063	0.063	0.546	0.046	0.058	0.076	0.021	0.037	0.036	0.035	0.042	0.022
ALM % *	58.51	57.73	62.38	55.65	60.38	59.86	60.56	51.11	54.74	56.21	53.46	38.27	31.53	43.86	33.45	38.21	43.05
PYRO	0.37	0.32	1.22	0.85	0.89	1.20	1.04	0.55	0.81	0.65	0.89	0.04	0.04	0.04	0.00	0.04	0.04
SPES	40.41	41.16	35.34	42.81	37.74	37.90	37.36	39.39	43.68	42.18	44.40	61.34	67.82	55.52	65.96	65.96	56.56
GROS	0.71	0.78	1.05	0.70	0.99	1.04	1.04	8.96	0.76	0.96	1.25	0.36	0.61	0.59	0.58	0.58	0.35

* Molecular proportions of almandine (ALM), pyrope (PYRO), spessartine (SPES) and grossular (GROS) expressed in percentages.

Sample MB-12: muscovite-tourmaline aplite dyke, Maleba pluton

MB-33: biotite-tourmaline aplite dyke, Maleba pluton

KY-4 : muscovite-bearing aplite dyke from Kaitambuzi granite, Karagwe Tinfield

TABLE 6A (continued)

SAMPLE ANALYSIS	KY-4-3		
	1	2	3
SiO ₂ %	35.73	35.79	35.77
Al ₂ O ₃	20.50	20.35	20.63
TiO ₂	0.00	0.00	0.01
MgO	0.00	0.01	0.00
FeO	17.29	13.87	18.72
MnO	25.95	29.49	24.36
CaO	0.12	0.16	0.15
Total	99.59	99.67	99.64

Number of atoms based on 24 oxygens

Si	5.944	5.952	5.942
Al(IV)	0.056	0.048	0.058
Al(VI)	3.962	3.939	3.980
Ti	0.000	0.000	0.001
Mg	0.000	0.002	0.000
Fe	2.405	1.929	2.601
Mn	3.656	4.154	3.427
Ca	0.021	0.029	0.027
ALM % *	39.54	31.55	42.95
PYRO	0.00	0.04	0.00
SPES	60.11	67.94	56.61
GROS	0.35	0.47	0.44

* Molecular proportions of almandine (ALM), pyrope (PYRO), spessartine (SPES) and grossular (GROS) expressed in percentages.

APPENDIX 7

Computer output of X-ray diffraction (XRD) data and unit cell refinement results for an alkali feldspar (MB-37). Unit cell parameters for all 9 alkali feldspar samples are summarized in Table 6-12.

Least Squares Unit Cell Refinement
 H B S U version Denver 06.8 after Appleman and Evans (1973).
 implementation by Roy G Garvey
 Department of CHEMISTRY
 NORTH DAKOTA STATE UNIVERSITY
 Fargo ND 58105 - 5516

Feldspar Pb-37a -- 1988/ 1/27 15:34

	A	B	C	Alpha	Beta	Gamma	Volume
Direct CELL:	8.58100	12.96100	7.22300	90.650	115.940	67.650	721.7564 Ang3
Reciprocal CELL:	0.12970	0.07722	0.15396	90.430	64.064	92.319	0.0014 Ang3

1-Theta Angles Thetax = 26.0 Mcyc = 2 Tolen = 0.0125 Tolez = 0.0625 Thetaz = 26.0 Doin = 1.758533 TRICL System
 Conditions for non-extinctions Called for Class Condition(s)

Cycle	1	Feldspar Pb-37a	2- Theta Tolerance = 0.12500	TRICL	2- Theta Calc	2- Theta Obs	2- Theta Diff	Weight		
M	H	K	L	D Calc	D Obs	Lambda				
1	-2	0	1	4.223613	4.232178	1.541780	21.03365	20.99000	0.04305	1.00000
2	1	1	1	3.985128	3.984672	1.541780	22.30741	22.31000	-0.00259	1.00000
3	1	3	0	3.833134	3.835418	1.541780	23.20401	23.19000	0.01401	1.00000
4	2	2	0	3.372955	3.378415	1.541780	26.42346	26.38000	0.04346	1.00000
5	0	0	2	3.247559	3.250850	1.541780	27.46335	27.43500	0.02835	1.00000
6	1	3	1	3.033147	3.032348	1.541780	29.44706	29.43500	-0.01194	1.00000
7	0	4	1	2.906142	2.902927	1.541780	30.76508	30.80000	-0.03492	1.00000
8	-3	1	1	2.763781	2.770625	1.541780	32.39222	32.31000	0.08222	1.00000
9	1	-4	1	2.520856	2.528633	1.541780	35.61319	35.50000	0.11319	1.00000
10	-3	2	2	2.429548	2.430763	1.541780	36.99917	36.98000	0.01917	1.00000
11	0	6	0	2.158258	2.159954	1.541780	41.85441	41.82000	0.03441	1.00000
12	2	2	2	1.992364	1.994698	1.541780	45.32143	45.47000	-0.14857	1.00000
13	1	-1	3	1.857347	1.861793	1.541780	49.04423	48.92000	0.12423	1.00000
14	-2	0	4	1.805342	1.804351	1.541780	50.55526	50.58500	-0.02974	1.00000

	A	B	C	Alpha	Beta	Gamma	Volume
Direct CELL:	8.60069	12.95692	7.22067	90.879	115.831	67.641	724.4262 Ang3
Reciprocal CELL:	0.12927	0.07717	0.15386	90.430	64.064	92.319	0.0014 Ang3
--- Direct Cell Corrections:	0.01967	-0.00406	-0.00293	0.229	-0.109	0.011	2.4478

Cycle	2	Feldspar Pb-37a	2- Theta Tolerance = 0.02699	TRICL	2- Theta Calc	2- Theta Obs	2- Theta Diff	Weight		
M	H	K	L	D Calc	D Obs	Lambda				
1	-2	0	1	4.230768	4.232178	1.541780	20.99707	20.99000	0.00707	1.00000
2	1	1	1	3.989577	3.984672	1.541780	22.28222	22.31000	-0.02778	1.00000
3	1	3	0	3.834564	3.835418	1.541780	23.19524	23.19000	0.00524	1.00000
4	2	2	0	3.378653	3.378415	1.541780	26.37809	26.38000	-0.00191	1.00000
5	0	0	2	3.249683	3.250850	1.541780	27.44505	27.43500	0.01005	1.00000
6	1	3	1	3.031705	3.032348	1.541780	29.46138	29.43500	0.02638	1.00000
7	0	4	1	2.902859	2.902927	1.541780	30.80074	30.80000	0.00074	1.00000
8	-3	1	1	2.770623	2.770625	1.541780	32.31003	32.31000	0.00003	1.00000
9	1	-4	1	2.529389	2.528633	1.541780	35.48904	35.50000	-0.01096	1.00000
10	-3	2	2	2.430549	2.430763	1.541780	36.98336	36.98000	0.00336	1.00000
11	0	6	0	2.159864	2.159954	1.541780	41.82183	41.82000	0.00183	1.00000
12	2	2	2	1.994788	1.994698	1.541780	45.46783	45.47000	-0.00217	1.00000
13	1	-1	3	1.861270	1.861793	1.541780	48.95466	48.92000	0.03466	1.00000
14	-2	0	4	1.804699	1.804351	1.541780	50.57456	50.58500	-0.01044	1.00000

	A	B	C	Alpha	Beta	Gamma	Volume
Direct CELL:	8.60075	12.95524	7.21979	90.867	115.820	67.646	724.4449 Ang3
Reciprocal CELL:	0.12925	0.07717	0.15385	90.430	64.064	92.319	0.0014 Ang3
--- Direct Cell Corrections:	0.00006	-0.00168	-0.00029	-0.013	-0.011	0.005	0.0187

Cycle				Felepar Mb-37a	2- Theta tolerance = 0.02000		Initial	2- Theta			Weight
N	M	K	L	D Calc	D Obs	Lambda	2- Theta Calc	2- Theta Obs	2- Theta Diff		
1	-2	0	1	4.230666	4.232178	1.541780	20.99759	20.99000	0.00759	1.00000	
2	1	1	1	3.990190	3.984672	1.541780	22.27875	22.31000	-0.03125	1.00000	
3	1	1	0	3.834544	3.835418	1.541780	23.19536	23.19000	0.00536	1.00000	
4	2	2	0	3.378876	3.378415	1.541780	26.37633	26.38000	-0.00367	1.00000	
5	0	0	2	3.245859	3.250650	1.541780	27.44353	27.43500	0.00853	1.00000	
6	1	3	1	3.032050	3.032348	1.541780	29.45796	29.43500	0.00296	1.00000	
7	0	4	1	2.903027	2.902927	1.541780	30.79891	30.80000	-0.00109	1.00000	
8	-3	1	1	2.770720	2.770625	1.541780	32.30887	32.31000	-0.00113	1.00000	
9	1	-4	1	2.529316	2.528633	1.541780	33.49010	33.50000	-0.00990	1.00000	
10	-3	2	2	2.430557	2.430763	1.541780	36.98324	36.98000	0.00324	1.00000	
11	0	6	0	2.159787	2.159954	1.541780	41.82339	41.82000	0.00339	1.00000	
12	2	2	2	1.995095	1.994698	1.541780	45.46045	45.47000	-0.00955	1.00000	
13	1	-1	3	1.861401	1.861793	1.541780	48.93096	48.92000	0.01096	1.00000	
13	-2	0	4	1.804638	1.804251	1.541780	50.37637	50.38500	-0.00863	1.00000	
				A	B	C	Alpha	Beta	Gamma	Volume	
Direct CELL:				8.60075	12.93524	7.21979	90.867	115.820	87.646	724.4449 Aee3	
Reciprocal CELL:				0.12925	0.07717	0.15385	90.430	64.064	92.319	0.0014 Aee3	
e- Direct Cell				Corrections:							
				-0.00000	-0.00000	-0.00000	0.000	-0.000	0.000	-0.0000	
e- Direct Cell				Standard Errors							
				0.0014087	0.0046915	0.0012474	0.03145	0.01554	0.03082	0.444865	
Felepar Mb-37a				W/L Listing -		e- Refers to Filed, R to Rejects		TRICL			
N	M	K	L	D Calc	D Obs	Lambda	2- Theta Calc	2- Theta Obs	2- Theta Diff	Weight	
1	0	1	0	12.958724		1.541780	6.82086				
2	1	0	0	7.734826		1.541780	11.43677				
3	1	1	0	6.757753		1.541780	13.10054				
4	-1	0	1	6.584575		1.541780	13.44466				
5	-1	1	0	6.533794		1.541780	13.55166				
6	0	0	1	6.499719		1.541780	13.62304				
7	0	2	0	6.479362		1.541780	13.66604				
8	-1	-1	1	5.941364		1.541780	14.91025				
9	0	1	1	5.817019		1.541780	15.23085				
10	0	-1	1	5.802747		1.541780	15.26853				
11	-1	1	1	5.801601		1.541780	15.27156				
12	1	2	0	5.063772		1.541780	17.51309				
13	-1	2	0	4.676446		1.541780	18.19145				
14	-1	-2	1	4.687926		1.541780	18.92959				
15	0	2	1	4.595829		1.541780	19.31252				
16	0	-2	1	4.581765		1.541780	19.37238				
17	-1	2	1	4.551782		1.541780	19.50122				
18	0	3	0	4.319575		1.541780	20.56085				
e-	-2	0	1	4.230666	4.232178	1.541780	20.99759	20.99000	0.00759	1.00000	
21	1	0	1	4.163451		1.541780	21.34051				
21	-2	-1	1	4.069709		1.541780	21.83695				
e-	1	1	1	3.990190	3.984672	1.541780	22.27875	22.31000	-0.03125	1.00000	
23	-2	1	1	3.975286		1.541780	22.36336				
24	1	-1	1	3.958103		1.541780	22.57727				
25	2	0	0	3.868413		1.541780	22.98950				
e-	1	3	0	3.834544	3.835418	1.541780	23.19536	23.19000	0.00536	1.00000	
27	2	1	0	3.746282		1.541780	23.74970				
28	-1	3	0	3.711587		1.541780	23.97499				
29	-2	1	0	3.668494		1.541780	24.26088				
30	-1	-3	1	3.661586		1.541780	24.30735				
31	-1	0	2	3.609277		1.541780	24.66514				
32	-2	-2	1	3.608864		1.541780	24.66800				
33	0	3	1	3.602660		1.541780	24.71115				
34	0	-3	1	3.592494		1.541780	24.78219				
35	-1	3	1	3.563918		1.541780	24.98409				
36	1	2	1	3.539159		1.541780	25.16173				
37	-1	-1	2	3.489995		1.541780	25.52212				
38	-2	2	1	3.479479		1.541780	25.60056				
39	1	-2	1	3.467270		1.541780	25.69225				
40	-1	1	2	3.464022		1.541780	25.71675				
e-	2	2	0	3.378876	3.378415	1.541780	26.37633	26.38000	-0.00367	1.00000	
42	-2	0	2	3.292288		1.541780	27.08308				
43	-2	2	0	3.268977		1.541780	27.29763				
e-	0	0	2	3.245859	3.250650	1.541780	27.44353	27.43500	0.00853	1.00000	
45	0	4	0	3.239681		1.541780	27.53145				
46	-2	-1	2	3.213596		1.541780	27.75938				
47	-1	-2	2	3.172634		1.541780	28.12511				
48	-2	1	2	3.168711		1.541780	28.16064				
49	0	1	2	3.154525		1.541780	28.28991				
50	0	-1	2	3.149966		1.541780	28.33171				
51	-1	2	2	3.133891		1.541780	28.48010				
52	-2	-3	1	3.084563		1.541780	28.94540				
e-	1	3	1	3.032050	3.032348	1.541780	29.45796	29.43500	0.00296	1.00000	
54	1	4	0	3.029873		1.541780	29.47960				
55	-2	-2	2	2.970682		1.541780	30.08071				

56	1	-5	1	2.964451	1.541780	30.14343			
57	-2	-5	1	2.963993	1.541780	30.15021			
58	-1	-4	0	2.963346	1.541780	30.31405			
59	-1	-4	1	2.961425	1.541780	30.38709			
60	0	3	0	2.958155	1.541780	30.42172			
61	0	2	2	2.908509	1.541780	30.73942			
62	0	4	1	2.903027	1.541780	30.79891	30.80000	-0.00109	1.00000
63	0	-2	2	2.901374	1.541780	30.81690			
64	-2	2	2	2.900801	1.541780	30.82314			
65	0	-4	1	2.899731	1.541780	30.87626			
66	-1	4	1	2.873541	1.541780	31.12290			
67	-3	0	1	2.861952	1.541780	31.25215			
68	-2	3	0	2.828416	1.541780	31.43212			
69	2	0	1	2.827077	1.541780	31.64773			
70	-5	-1	1	2.819128	1.541780	31.73931			
71	-1	-3	2	2.789389	1.541780	32.08442			
72	2	1	1	2.779121	1.541780	32.20854			
73	-3	1	1	2.770720	1.541780	32.30887	32.31000	-0.00113	1.00000
74	-1	3	2	2.750199	1.541780	32.35442			
75	2	-1	1	2.745409	1.541780	32.61501			
76	-5	0	2	2.661571	1.541780	33.47248			
77	-3	-2	1	2.658661	1.541780	33.71043			
78	-2	-3	2	2.654454	1.541780	33.73927			
79	-3	-1	2	2.626363	1.541780	34.13762			
80	-2	-4	1	2.623121	1.541780	34.18110			
81	2	2	1	2.619435	1.541780	34.23042			
82	1	0	2	2.617000	1.541780	34.26352			
83	0	3	2	2.600779	1.541780	34.48389			
84	0	-3	2	2.593132	1.541780	34.58879			
85	0	5	0	2.591745	1.541780	34.60788			
86	-3	1	2	2.588349	1.541780	34.65472			
87	1	4	1	2.585242	1.541780	34.69749			
88	-2	3	2	2.582828	1.541780	34.74236			
89	-3	2	1	2.579038	1.541780	34.78381			
90	3	0	0	2.578942	1.541780	34.78516			
91	1	1	2	2.572921	1.541780	34.86917			
92	2	-2	1	2.565779	1.541780	34.99751			
93	1	-1	2	2.557576	1.541780	35.08515			
94	3	1	0	2.548077	1.541780	35.22021			
95	2	4	0	2.531886	1.541780	35.45288			
96	1	-4	1	2.529316	1.541780	35.49010	35.50000	-0.00990	1.00000
97	-2	4	1	2.524049	1.541780	35.54663			
98	-3	1	0	2.511010	1.541780	35.75753			
99	-3	-2	2	2.494595	1.541780	36.00086			
100	1	3	0	2.486349	1.541780	36.12436			
101	1	2	2	2.439642	1.541780	36.84057			
102	-2	4	0	2.438223	1.541780	36.86277			
103	-1	-5	1	2.436243	1.541780	36.89381			
104	-3	-3	1	2.432304	1.541780	36.92572			
105	-3	2	2	2.430557	1.541780	36.98324	36.98000	0.00324	1.00000
106	-1	5	0	2.429675	1.541780	36.99715			
107	-3	-4	2	2.428419	1.541780	37.01698			
108	1	2	0	2.428260	1.541780	37.01950			
109	1	-2	2	2.413664	1.541780	37.25156			
110	0	5	1	2.409956	1.541780	37.31100			
111	0	-5	1	2.404879	1.541780	37.39269			
112	2	3	1	2.397904	1.541780	37.50550			
113	-1	4	2	2.393780	1.541780	37.57254			
114	-1	5	1	2.387793	1.541780	37.67028			
115	-2	0	3	2.383744	1.541780	37.73668			
116	-1	0	3	2.371523	1.541780	37.93856			
117	-3	2	0	2.365217	1.541780	38.04260			
118	-2	-1	3	2.352886	1.541780	38.25069			
119	-2	-4	2	2.343963	1.541780	38.40201			
120	-3	3	1	2.341878	1.541780	38.43753			
121	-1	-1	3	2.336249	1.541780	38.53381			
122	-2	1	3	2.334024	1.541780	38.53765			
123	2	-3	1	2.334333	1.541780	38.56630			
124	-1	1	3	2.329329	1.541780	38.65283			
125	-3	-3	2	2.304344	1.541780	39.08886			
126	0	4	2	2.297915	1.541780	39.26270			
127	0	-4	2	2.290883	1.541780	39.32798			
128	-2	4	2	2.275991	1.541780	39.59783			
129	1	3	0	2.253713	1.541780	40.00405			
130	3	3	0	2.252584	1.541780	40.02495			
131	-2	-2	3	2.251946	1.541780	40.05677			
132	-2	-3	1	2.250331	1.541780	40.06674			
133	-1	-3	3	2.233083	1.541780	40.38963			
134	-3	3	2	2.229431	1.541780	40.45869			
135	1	3	2	2.223131	1.541780	40.57858			
136	1	3	1	2.222877	1.541780	40.58323			
137	-2	4	3	2.222640	1.541780	40.58774			
138	-1	2	3	2.221041	1.541780	40.61825			
139	-3	0	3	2.194858	1.541780	41.12457			
140	2	5	0	2.192315	1.541780	41.17445			
141	-3	-4	1	2.190030	1.541780	41.21935			
142	1	-5	1	2.178329	1.541780	41.45093			
143	-3	-5	0	2.177931	1.541780	41.45864			

144	-3	-1	3	2.174614	1.541780	41.32561			
145	-2	0	3	2.171790	1.541780	41.38151			
146	-2	0	3	2.166573	1.541780	41.69629			
147	2	4	1	2.161691	1.541780	41.78482			
148	-3	0	0	2.159787	1.541780	41.82227	41.8200	0.00339	1.00000
149	-3	1	3	2.153614	1.541780	41.94892			
150	0	1	3	2.137979	1.541780	42.27026			
151	0	-1	3	2.135848	1.541780	42.31455			
152	-4	0	1	2.123727	1.541780	42.56778			
153	-1	-5	2	2.119768	1.541780	42.65115			
154	-2	0	6	2.116045	1.541780	42.72958			
155	-4	0	2	2.113333	1.541780	42.74497			
156	-4	-1	1	2.109626	1.541780	42.86652			
157	-2	-3	3	2.105120	1.541780	42.96260			
158	-3	0	1	2.103692	1.541780	42.99322			
159	-3	4	1	2.102411	1.541780	43.02072			
160	1	-4	0	2.101182	1.541780	43.04714			
161	-4	-1	2	2.101060	1.541780	43.04978			
162	-3	-4	1	2.099818	1.541780	43.07651			
163	-3	-2	3	2.097693	1.541780	43.12232			
164	-3	-4	2	2.094897	1.541780	43.18277			
165	-1	3	1	2.090940	1.541780	43.26860			
166	3	1	1	2.087169	1.541780	43.35072			
167	-1	-3	3	2.086213	1.541780	43.37160			
168	-4	1	1	2.082182	1.541780	43.45983			
169	2	0	2	2.081726	1.541780	43.46964			
170	-4	1	3	2.074594	1.541780	43.62692			
171	-1	3	3	2.071521	1.541780	43.69497			
172	-1	-4	1	2.070356	1.541780	43.72082			
173	-2	3	3	2.069427	1.541780	43.74147			
174	-2	-3	2	2.066256	1.541780	43.81207			
175	3	-1	1	2.066009	1.541780	43.81756			
176	2	-1	2	2.062674	1.541780	43.89210			
177	-3	-1	3	2.060437	1.541780	43.94177			
178	-1	-4	0	2.059936	1.541780	43.95348			
179	0	4	0	2.056642	1.541780	44.02755			
180	0	4	0	2.056412	1.541780	44.03272			
181	0	-2	3	2.052854	1.541780	44.11306			
182	0	4	1	2.051478	1.541780	44.14420			
183	1	4	2	2.051283	1.541780	44.14860			
184	2	-1	2	2.048151	1.541780	44.21967			
185	0	-6	1	2.047718	1.541780	44.22953			
186	-4	-2	1	2.043045	1.541780	44.33606			
187	-4	-2	2	2.034935	1.541780	44.52174			
188	-1	-6	1	2.034532	1.541780	44.53147			
189	0	6	2	2.029321	1.541780	44.65198			
190	0	-5	2	2.023266	1.541780	44.79284			
191	1	-4	2	2.020602	1.541780	44.85511			
192	3	4	2	2.020215	1.541780	44.86417			
193	-3	2	1	2.020076	1.541780	44.86742			
194	-2	2	2	2.007896	1.541780	45.15457	45.4700	-0.00925	1.00000
195	-2	2	2	1.995093	1.541780	45.44045			
196	-4	2	1	1.994825	1.541780	45.48622			
197	-3	-2	2	1.987643	1.541780	45.64049			
198	-3	-2	1	1.982208	1.541780	45.77272			
199	-3	4	0	1.981093	1.541780	45.79996			
200	-3	-3	3	1.980455	1.541780	45.81556			
201	-3	-3	2	1.969051	1.541780	46.09614			
202	-3	-3	1	1.961638	1.541780	46.28045			
203	-2	-4	1	1.955444	1.541780	46.43563			
204	0	0	3	1.959006	1.541780	46.85266			
205	2	0	1	1.958939	1.541780	46.85439			
206	-2	-4	3	1.958802	1.541780	46.85789			
207	-4	-4	1	1.957569	1.541780	46.88949			
208	1	-6	1	1.953106	1.541780	46.95275			
209	0	0	3	1.954249	1.541780	46.97481			
210	-4	0	0	1.954206	1.541780	46.97591			
211	-3	3	3	1.953867	1.541780	46.98444			
212	-4	-3	2	1.950403	1.541780	47.07704			
213	-1	1	6	1.923793	1.541780	47.24532			
214	-1	4	3	1.921288	1.541780	47.31099			
215	2	0	0	1.917272	1.541780	47.41611			
216	3	0	1	1.915769	1.541780	47.45560			
217	-4	0	3	1.915349	1.541780	47.46665			
218	-1	4	3	1.906008	1.541780	47.71366			
219	-4	-1	0	1.904482	1.541780	47.75427			
220	-4	1	0	1.902414	1.541780	47.80943			
221	-2	4	3	1.901746	1.541780	47.82727			
222	-1	-6	1	1.899743	1.541780	47.88084			
223	-2	-6	1	1.895301	1.541780	48.05402			
224	-3	-6	2	1.892145	1.541780	48.08521			
225	-2	-6	2	1.892078	1.541780	48.08704			
226	-4	0	3	1.885193	1.541780	48.27581			
227	-1	0	3	1.884182	1.541780	48.30137			
228	-4	0	1	1.883140	1.541780	48.32979			
229	-4	0	1	1.882944	1.541780	48.33514			
230	-4	0	1	1.875621	1.541780	48.53066			
231	-4	0	1	1.873141	1.541780	48.60446			

232	-4	3	1	1.870545	1.541780	48.81843			
233	3	-3	1	1.867787	1.541780	48.75278			
234	1	1	3	1.867766	1.541780	48.75336			
235	-1	-6	2	1.865224	1.541780	48.82413			
236	3	5	0	1.864114	1.541780	48.83506			
237	1	-1	3	1.861401	1.541780	48.93096	48.9200	0.010%	1.00000
238	2	-3	2	1.858982	1.541780	48.99864			
239	1	3	2	1.855642	1.541780	49.08664			
240	-2	6	3	1.853794	1.541780	49.08656			
241	-4	-2	1	1.854604	1.541780	49.12214			
242	0	7	3	1.851246	1.541780	49.21714			
243	-3	-4	3	1.842489	1.541780	49.46674			
244	-1	6	2	1.841622	1.541780	49.49158			
245	-4	2	0	1.834247	1.541780	49.70403			
246	-2	-6	2	1.830793	1.541780	49.80419			
247	1	-5	2	1.827675	1.541780	49.90078			
248	-3	5	2	1.823431	1.541780	50.01905			
249	-4	2	3	1.819454	1.541780	50.13593			
250	1	7	0	1.816223	1.541780	50.23130			
251	1	2	3	1.815079	1.541780	50.26516			
252	-4	-4	1	1.810497	1.541780	50.40126			
253	-2	0	4	1.804638	1.541780	50.57637	50.5850	-0.00863	1.00000
254	0	4	3	1.803511	1.541780	50.61023			
255	0	4	3	1.803450	1.541780	50.61205			
256	1	-2	3	1.801330	1.541780	50.67983			
257	0	6	2	1.798410	1.541780	50.76396			
258	0	-4	3	1.796247	1.541780	50.82941			
259	0	-6	2	1.795993	1.541780	50.83711			
260	-1	-7	1	1.794089	1.541780	50.89493			
261	-3	5	0	1.792738	1.541780	50.93601			
262	-3	4	3	1.791062	1.541780	50.98709			
263	4	3	0	1.790929	1.541780	50.99116			
264	-2	-1	4	1.790895	1.541780	50.99219			
265	3	4	1	1.785028	1.541780	51.17166			
266	-1	7	0	1.783872	1.541780	51.20744			
267	-2	1	4	1.781959	1.541780	51.26658			
268	-2	6	2	1.781877	1.541780	51.26892			
269	0	7	1	1.779002	1.541780	51.35780			
270	0	-7	1	1.774226	1.541780	51.50617			
271	-4	-3	3	1.772434	1.541780	51.56207			
272	-2	-5	3	1.769579	1.541780	51.65127			
273	2	4	2	1.768624	1.541780	51.68133			
274	-1	7	1	1.764081	1.541780	51.82430			
275	-3	0	4	1.756949	1.541780	52.05039			
276	-1	-3	3	1.750918	1.541780	52.24318			
277	-1	0	4	1.736387	1.541780	52.71392			
278	-1	-1	4	1.733919	1.541780	52.79473			
279	-1	1	4						

80J ... Feldspar Pb-37a ... 15:40
 LSURIPC v. Denver 86.8

APPENDIX 8

Laboratory results of $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating experiments for muscovite and biotite from Karagwe-Ankolean granites.
(The accuracy of $^{40}\text{Ar}/^{39}\text{Ar}$ ages is within $\pm 2\%$ of the reported values).

MU-2 (650-700) ALL IN FULL LINE

OPERATOR - J. H. INGURA

DATE OF ANALYSIS - 4 07/14/88 18:59:27 139

<u>Ar³⁶</u>	<u>Ar³⁷</u>	<u>% TAIL</u> <u>Ar³⁷</u>	<u>Ar⁴⁰</u>	<u>Ar³⁶/Ar³⁷</u>	<u>Ar³⁷/Ar³⁶</u>	<u>Ar⁴⁰/Ar³⁷</u>
5.6E-04	0	3.04634 .0148	4.06254	.03849	0	274.39328
5.5E-04	0	3.03444 .01477	4.06043	.03735	0	274.77017
5.3E-04	0	3.10926 .01477	4.05606	.0376	0	274.60108
5.4E-04	0	2.9661 .01474	4.05374	.03675	0	274.93611
5.9E-04	0	3.07466 .01471	4.04955	.04034	0	275.2817
5.7E-04	0	3.05254 .01471	4.0451	.03887	0	274.91148
5.4E-04	0	2.98353 .01471	4.04537	.0373	0	274.9019
5.4E-04	0	2.87539 .0147	4.04836	.03709	0	275.2705
5.4E-04	0	3.04079 .01474	4.04328	.03697	0	274.289
5.7E-04	0	3.23635 .01476	4.06006	.03917	0	274.93756
5.8E-04	0	3.10104 .0148	4.05216	.03972	0	273.76177
5.7E-04	0	3.13226 .01477	4.04969	.03899	0	274.1811
6E-04	0	3.11434 .01477	4.05358	.04067	0	274.31708
6.1E-04	0	3.07563 .01475	4.05215	.04148	0	274.6644
6E-04	0	3.17342 .01478	4.05629	.04068	0	274.36248
-----				-----	-----	-----
MEAN TAIL CORR. = 3.06774 %				.03876	0	274.63877
+/- .08693 %				g=1.03661 % g=0 %		g=.039 %

MU-2 MUSCOVITE SUMMARY

TEMP. (DEG.C)	mV Ar39	% Ar39	AGE (Ma)	% ATMOS.	Ar37/Ar39	% I.I.C.
---------------	---------	--------	----------	----------	-----------	----------

$J = 2.2E-03$

20-600	12.6	3.1	767 +/- 2.6	18.4	0	0
600-650	9	2.2	813.6 +/- 2.3	4.8	0	0
650-700	14.7	3.6	846.6 +/- 1.2	3.5	0	0
700-750	16.7	4.1	868.5 +/- 1.3	3.1	0	0
750-780	20.4	5	885.8 +/- 1.3	3.4	0	0
780-810	32.4	7.9	910.8 +/- 1.6	2.8	0	0
810-840	41.6	10.2	925.8 +/- 3.6	2.5	0	0
840-870	43.4	10.6	918.3 +/- 3.6	3.7	0	0
870-900	80.2	19.7	946.5 +/- 2.2	1	0	0
900-950	85.3	20.9	949.7 +/- 1.7	2.6	0	0
950-1000	32.9	8.1	949.6 +/- 4.8	6.2	0	0
1000-1050	12.8	3.1	946 +/- 3.3	18.4	0	0
1050-1100	4.2	1	917.4 +/- 12.6	48	0	0

TOTAL GAS AGE = 921.2 MY. +/- 4.3 MY. (.4 %)

% I.I.C. - INTERFERING ISOTOPES CORRECTION

ERROR ESTIMATES AT ONE SIGMA LEVEL

MU-27 MUSCOVITE SUMMARY

TEMP. (DEG. C)	mV Ar39	% Ar39	AGE (Ma)	% ATMOS.	Ar37/Ar39	% I.I.C.
----------------	---------	--------	----------	----------	-----------	----------

J = 2.2E-03

20-600	12.7	3.5	695.6 +/- 2.4	18	0	0
600-650	10.7	3	741.2 +/- 2.4	1.9	0	0
650-700	10.5	2.9	792.2 +/- 1.9	1.2	0	0
700-750	20.1	5.6	836 +/- 1.6	.7	0	0
750-780	20.3	5.7	883.7 +/- 1.8	1.1	0	0
780-810	31.2	8.7	930.1 +/- 3.6	.9	0	0
810-840	29.4	8.2	904.2 +/- 8.1	1.5	0	0
840-870	29.2	8.2	943.1 +/- 4.5	.6	0	0
870-900	71.6	20.1	956.5 +/- 2.8	.6	0	0
900-950	43.7	12.2	961.2 +/- 3.6	1.4	0	0
950-1000	36	10.1	972.7 +/- 3.8	2	0	0
1000-1050	25.4	7.1	969.2 +/- 1.8	5.3	0	0
1050-1100	15	4.2	975 +/- 2.8	12.8	0	0

TOTAL GAS AGE = 922.3 MY. +/- 5.7 MY. (.6 %)

% I.I.C. - INTERFERING ISOTOPES CORRECTION

ERROR ESTIMATES AT ONE SIGMA LEVEL

MB13 MUSCOVITE SUMMARY

TEMP. (DEG.C)	mV Ar39	% Ar39	AGE(Ma)	% ATMOS.	Ar37/Ar39	% I.I.C.
---------------	---------	--------	---------	----------	-----------	----------

 $J = 2.2E-03$

20-600	8.7	2	768.3 +/- 4	12.4	0	0
600-650	10.8	2.5	861.2 +/- 2.4	5.1	0	0
650-700	13.6	3.1	881.9 +/- 3.8	3.6	0	0
700-750	17.2	4	889.4 +/- 2.8	3.5	0	0
750-780	29	6.7	892.5 +/- 1.4	3	0	0
780-810	51.9	12	902.2 +/- 3.2	2.1	0	0
810-840	68.3	15.9	904.2 +/- 2.1	1.3	0	0
840-870	85.1	19.8	912 +/- 1.6	1.8	0	0
870-900	69.9	16.2	911.1 +/- 1.9	2.3	0	0
900-950	44.2	10.3	910.2 +/- 3.2	4.5	0	0
950-1000	10.7	2.5	906.6 +/- 3.1	8.5	0	0
1000-1050	14	3.2	904.8 +/- 2.7	17.9	0	0
1050-1100	5.2	1.2	905.3 +/- 9.3	45.1	0	0

TOTAL GAS AGE = 901.5 MY. +/- 4 MY. (.4 %)

% I.I.C. - INTERFERING ISOTOPE CORRECTION

ERROR ESTIMATES AT ONE SIGMA LEVEL

MB13 BIOTITE SUMMARY

TEMP. (DEG. C)	mV Ar39	% Ar39	AGE (Ma)	% ATMOS.	Ar37/Ar39	% I.I.C
----------------	---------	--------	----------	----------	-----------	---------

J = 2.2E-03

20-500	7.9	3.3	413.3 +/- 4.6	32.5	0	0
500-550	8.5	3.5	732.3 +/- 5.8	8.7	0	0
550-600	16.4	6.9	836.2 +/- 3.4	2.2	0	0
600-650	46.9	19.7	869.1 +/- 4.2	.8	0	0
650-700	38.4	16.2	865.2 +/- 3.2	.5	0	0
700-750	9.4	3.9	850.6 +/- 3.4	.7	0	0
750-800	9.4	3.9	837.2 +/- 2.9	1.7	0	0
800-850	8.8	3.7	812.1 +/- 3.2	3.1	0	0
850-900	36.4	15.3	841.9 +/- 3.7	.8	0	0
900-950	47.9	20.1	858.3 +/- 3	1.5	0	0
950-1000	6.9	2.9	865.2 +/- 5.7	10.3	0	0

TOTAL GAS AGE = 837.3 MY. +/- 5.9 MY. (.7 %)

% I.I.C. - INTERFERING ISOTOPES CORRECTION

ERROR ESTIMATES AT ONE SIGMA LEVEL

MB-31 BIOTITE SUMMARY

TEMP. (DEG. C) mV Ar39 % Ar39 AGE (Ma) % ATMOS. Ar37/Ar39 % I.I.C.

$J = 2.2E-03$

20-500	4.3	1.5	633.5 +/- 5.3	24.2	0	0
500-550	7.6	2.7	821.7 +/- 2.6	3.9	0	0
550-600	29	10.2	837.6 +/- 1.2	1.6	0	0
600-650	53	18.6	851.2 +/- 2	.6	0	0
650-700	30	10.5	854.6 +/- 1.5	1	0	0
700-750	10	3.5	852.6 +/- 2.6	3.3	0	0
750-800	6.8	2.3	912.3 +/- 6.7	2.6	0	0
800-850	18	6.3	840.9 +/- 7.4	4.9	0	0
850-900	48	16.9	852.2 +/- 4.9	2.5	0	0
900-950	66.5	23.4	871.2 +/- 3.3	2.5	0	0
950-1000	8.9	3.1	872.4 +/- 3.5	23	0	0
1000-1050	1.3	.4	846.7 +/- 42.6	67.1	0	0

TOTAL GAS AGE = 852.7 MY. +/- 5.5 MY. (.6 %)

% I.I.C. - INTERFERING ISOTOPES CORRECTION
ERROR ESTIMATES AT ONE SIGMA LEVEL

MK2 MUSCOVITE SUMMARY

TEMP. (DEG.C)	mV Ar39	% Ar39	AGE (Ma)	% ATMOS.	Ar37/Ar39	% I.I.C.
---------------	---------	--------	----------	----------	-----------	----------

$$J = 2.2E-03$$

20-600	5.7	2.1	806.2 +/- 4.6	11.6	0	0
600-650	2.3	.8	861.1 +/- 10	1.2	0	0
650-700	8.1	3	869.3 +/- 2.3	1.8	0	0
700-750	11.5	4.3	878.2 +/- 1.9	1.8	0	0
750-780	17.4	6.5	887.3 +/- 1.8	1.2	0	0
780-810	37.9	14.2	902.1 +/- 3	.4	0	0
810-840	29.3	11	908.7 +/- 5	.6	0	0
840-870	41.3	15.5	909.4 +/- 3	.9	0	0
870-900	33	12.4	917.1 +/- 3.8	1.2	0	0
900-950	29.9	11.2	910.6 +/- 3.6	2.8	0	0
950-1000	30.9	11.6	916 +/- 1.5	4.8	0	0
1000-1050	13.3	5	918.7 +/- 3.5	11.4	0	0
1050-1100	4.4	1.6	901.5 +/- 8.3	38.3	0	0

TOTAL GAS AGE = 903.9 MY.

% I.I.C. - INTERFERING ISOTOPES CORRECTION
 ERROR ESTIMATES AT ONE SIGMA LEVEL

MK2 BIOTITE SUMMARY

TEMP. (DEG.C)	MY Ar39	% Ar39	AGE (Ma)	% ATMOS.	Ar37	Ar39	% I.I.C.
---------------	---------	--------	----------	----------	------	------	----------

J = 2.2E-03

20 -500	6	1.3	470.8 +/- 30.8	48.1	0	0
500-550	6.8	1.5	832.4 +/- 3.7	8.3	0	0
550-600	40.8	9.2	891.1 +/- 1.2	2.9	0	
600-650	60.9	13.8	903.9 +/- 2.6	1.2	0	0
650-700	92	20.8	903.7 +/- 1.6	.7	0	0
700-750	38.3	8.6	896.2 +/- 3.7	2.5	0	0
750-800	24.5	5.5	896 +/- 1.4	5.2	0	0
800-850	19.7	4.4	899.1 +/- 2.1	9.1	0	0
850-900	38.2	8.6	887.9 +/- 4.6	5.1	0	0
900-950	83.3	18.9	896.9 +/- 3.4	3	0	0
950-1000	30	6.8	900.5 +/- 5.5	16.9	0	0

TOTAL GAS AGE = 892.1 MY. +/- 5.1 MY. (.5 %)

% I.I.C. - INTERFERING ISOTOPES CORRECTION

ERROR ESTIMATES AT ONE SIGMA LEVEL

KT-3 MUSCOVITE SUMMARY

TEMP. (DEG.C) mV Ar39 % Ar39 AGE(Ma) % ATMOS. Ar37/Ar39 % I.I.C.

$J = 2.2E-03$

20-600	18.1	4.7	605.4 +/- 4.5	20.7	0	0
600-650	6.8	1.7	599.8 +/- 3.1	5.6	0	0
650-700	12.5	3.2	595.9 +/- 1.8	4.8	0	0
700-750	31.6	8.2	609.8 +/- 1.3	5.2	0	0
750-780	10.8	2.8	689 +/- 2.7	10.7	0	0
780-810	18	4.7	822.3 +/- 2.2	9.6	0	0
810-840	33	8.6	821 +/- 1.4	6.2	0	0
840-870	52.8	13.8	770.3 +/- 2.4	4.3	0	0
870-900	76.4	20	760.7 +/- 1.7	3.8	0	0
900-950	70.5	18.4	758.8 +/- 1.8	4.4	0	0
950-1000	40.2	10.5	752.2 +/- 3.3	8.6	0	0
1000-1050	10.8	2.8	763.1 +/- 4.5	26	0	0

TOTAL GAS AGE = 740 MY. +/- 3.4 MY. (.4 %)

% I.I.C. - INTERFERING ISOTOPES CORRECTION

ERROR ESTIMATES AT ONE SIGMA LEVEL

KT-10 MUSCOVITE SUMMARY

TEMP. (DEG.C)	mV Ar39	X Ar39	AGE (Ma)	% ATMOB.	Ar37/Ar39	% I.I.C.
---------------	---------	--------	----------	----------	-----------	----------

J = 2.2E-03

20-600	8.3	2.2	585.1 +/- 3.1	17.1	0	0
600-650	6.8	1.8	640.2 +/- 3.4	5.7	0	0
650-700	5.8	1.5	650.1 +/- 3.7	5.9	0	0
700-750	10.7	2.8	678.8 +/- 2.1	5	0	0
750-780	22.7	6	722.8 +/- 1.4	0	0	0
780-810	39.4	10.4	689.3 +/- 1	1.6	0	0
810-840	45.8	12.1	688.4 +/- 2.2	1.7	0	0
840-870	40	10.6	678.7 +/- 1.1	2	0	0
870-900	87.4	23.2	678.4 +/- 1.6	1.3	0	0
900-950	85.3	22.7	685.4 +/- 1.7	2.2	0	0
950-1000	15	3.9	693 +/- 2.4	8.6	0	0
1000-1050	8	2.1	701.1 +/- 6.6	24.8	0	0

TOTAL GAS AGE = 683 MY. +/- 2.7 MY. (.3 %)

% I.I.C. - INTERFERING ISOTOPES CORRECTION
 ERROR ESTIMATES AT ONE SIGMA LEVEL

APPENDIX 9 (FOLDER)

Geological maps for the Bukiriro, Kabanga, Nyamakombe, Mumakera and Mwibanda-Maleba plutons. Sample locations are also shown on the maps.

5 of/de 5

MicroD

- Lithic soil
- Karst deposit
- Quartzite, variably foliated (Dolomite) Muscovite interbedded (?) by tourmaline-tourmaline granites (Lg)
- Muscovite granites with accessory tourmaline medium-grained (ming), coarse-grained (Lg)
- Muscovite-tourmaline granites with accessory tourmaline medium-grained (ming), coarse-grained (Lg)
- Karstic-karstic metasediments (Phyllite and Quartzite)
- Phyllite and schists

GENERAL SYMBOLS

- Quartz vein, with muscovite (mg), tourmaline (Lg)
- Tourmaline veinlets
- Aplite dyke, with tourmaline (mg) garnet (Lg)
- Pegmatite, with cassiterite (Pg:st)
- Approximate geologic contact
- Internal geologic contact
- Granite outcrop, partially landscape (Lg) with tourmaline (mg)
- Sample number and location
- Metasedimentary sandstone
- National boundary
- River or stream
- Secondary road
- Mile to line

Compiled by J.R. Kington, 1989

Compiled by J.R. King, 1989

30° 27' E

30° 28' E

30° 29' E

30° 30' E

1:60,000

Lateite unit

Zone of widespread lower metamorphism and

Coarse grained, equigranular to slightly porphyroblastic
isolated tourmaline muscovite biotite graniteMedium grained, mostly equigranular isolated biotite
with quartz tourmaline intergrowth myloniteMedium to coarse grained, foliated porphyroblastic
locally contains biotite inclusions (Lil)

Kagera Archaean Metasediments

Quartz-schists (tourmaline hornblende)

Phyllites and schists

Quartzites

Phyllites and schists

GENERAL SYMBOLS

Foliated basement or mica foliation

Qiv: Quartz veins

Qiv: Quartz (tourmaline veins)

Tol: Tourmaline quartz foliated veins

Qiv: Quartz (foliated veins)

Pg: Quartz (foliated) + muscovite pegmatite

Ap: Tourmaline bearing aplite dykes

Exploration trench

Inferred geologic contact

National boundary

River or stream

Swamp

Road

KABANGA: Location and name of the site

0 500 1000

Scale in km

1:60,000

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

Topographic position

10° 27' E

30° 28'

30° 29'

30° 30' E

LEGEND

- Lateite crust
- Zone of widespread boron metasomatism and/or hydrothermal leaching
- Coarse-grained, equigranular or slightly porphyritic, leucocratic or weakly foliated tourmaline-muscovite-biotite granite
- Medium-grained, mainly equigranular foliated biotite-muscovite granite with quartz-tourmaline intergrowth spots
- Medium- to coarse-grained foliolar porphyritic muscovite-biotite granite, locally contains biotite enclaves (lt)

Karaga-Andolep metasediments

- Quartz-schist (tourmaline hornfels)
- Phyllonite and schists
- Quartzites
- Phyllonite and schists

GENERAL SYMBOLS

- Folded lineation or mica foliation
- Quartz veins
- Quartz-tourmaline veins
- Tourmaline-quartz-feldspar veins
- Quartz-feldspar veins
- Quartz-feldspar-muscovite pegmatites
- Tourmaline-bearing aplite dykes
- Exploration trench
- Inferred geologic contact
- National boundary
- River or stream
- Swamp
- Road
- Granite outcrop
- KA 1 Sample number and location
- KABANGA Location and name of locality

0 500 1000 m

MAP 1

BURUNDI

30° 27' E

30° 28'

30° 29'

30° 30' E

MAP 3: NYAMAKOMBE MAP SHEET

LEGEND

- Muscovite granite with accessory tourmaline
- Megacrystic muscovite-biotite granites with accessory tourmaline
- Karaga-Akidean metasediments
- Tourmalinized orthite-quartz hornfels
- Phyllites and schists
- Quartzites, medium-grained (mg), coarse-grained (cg)
- Phyllites and schists

GENERAL SYMBOLS

- Laterite crust or soil
- Quartz vein
- Tourmaline-quartz-iodine vein
- Quartz-muscovite pegmatitic veins
- Apatite dyke
- Metasedimentary inclusions
- Outcrop NY-1 Sample number and location
- Inferred geological contact
- National boundary
- River or stream
- Swamp

0 500 1000 m

MAP 3

Compiled by J. F. Tongue, 1986

END

1|6·0|2·90

FIN