

**CHARACTERISTICS, GENESIS AND CLASSIFICATION OF REDDISH SOILS
FROM SIDAMO REGION OF ETHIOPIA**

By

ABAYNEH ESAYAS ATENGO

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in
Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

January 2005

DEDICATION

THIS THESIS IS DEDICATED TO MY DEAREST BROTHER

Late YISMACHEW ESAYAS

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**CHARACTERISTICS, GENESIS AND CLASSIFICATION OF REDDISH SOILS
FROM SIDAMO REGION OF ETHIOPIA**

By

ABAYNEH ESAYAS ATENGO

January 2005

Chairman: Associate Professor Siti Zauyah Darus, Ph D

Faculty: Agriculture

Sesquioxidic reddish soils are one of the major agricultural soils in Ethiopia. They are intensively cultivated for coffee. Accurate and detailed information on the nature and properties of these soils is necessary to improve and sustain their agricultural productivity. To achieve this objective, ten representative pedons developed from different parent materials of volcanic and metamorphic origin in Sidamo highlands, Ethiopia, were investigated.

Feldspar and ferromagnesians are the dominant minerals in the basalt, whereas quartz, feldspar and minor amounts of hornblende phenocrysts embedded in a groundmass of volcanic ash and glass are dominant in the ignimbrites and rhyolite. Zeolites (clinoptilolite and mordenite) were discovered in substantial amounts in the ignimbrites.

The soil texture, profile depth and morphology of the soils vary according to parent material groups. The soil pH values range from 4.2 to 6.8 and due to leaching of bases; soils developed under udic moisture regime have the lowest pH. The pH_{NaF} values are

generally less than 9.4, indicating that the soils are not allophanic. The cation exchange capacity (CEC) varies according to parent material groups in the order of ignimbrite > rhyolite > basalt > gneiss with the value of 4.0 to 39.6 cmol_c/kg soil. Exchangeable cations and available micronutrients content of the surface soils are higher than the subsurface soils. This is attributed to the cycling of nutrients by the plants. Available phosphorus (P) is low (< 6 mg P/kg soil) and it is the most limiting nutrient for crop production in the area, although copper and potassium are marginal. The P sorption studies indicated that the soils are high P sorbing soils, with the subsurface soils have higher P sorption capacity than the surface soils. The P sorption characteristics of the soils have significant positive correlation with clay content and different forms of Fe and Al, and negative correlation with soil pH. The P requirement of the surface soils varies from 41 to 142 mg P kg⁻¹ soil.

The sand and silt fractions are dominated by quartz and varied amounts of feldspar. The clay fractions are dominated by kaolinite and minor amounts of illite. The relative abundance of illite and feldspar is higher in the soils from younger geological units (ignimbrites). Iron (Fe) is dominantly in crystalline form, whereas aluminium (Al) is in amorphous form in the soils. Hematite, maghemite and goethite are the common Fe-oxide minerals in the clay fractions. The relative abundance of goethite is higher in soils from higher altitudes (cooler and wetter environments). The Al substitution for Fe in hematite and goethite varied from 7 to 24 and from 14 to 39 mole % Al, respectively.

The relative proportion and distribution of coarse to fine materials (c/f-ratio) varied according to parent material groups from open porphyric in basaltic soils to single spaced porphyric in gneissic soils. Microlaminated clay coatings are abundant in soils derived from the younger geological units (ignimbrites) compared to basaltic and gneissic soils. The pedogenetic processes in the soils were mainly related to the weathering of primary minerals, clay illuviation, bioturbation and translocation of Fe-oxides to saprolitic layers. Halloysite is mainly restricted in the saprolitic layers, whereas kaolinite is dominant in the soil solum.

The Chuko and Morocho pedons, derived from Quaternary ignimbrites and characterized by appreciable clay illuviation in the B horizons are classified as Kandic Paleustalfs (Soil Survey Staff, 1999) or Profondic Lixisols (WRB, 1998), whereas the Dengora pedon derived from similar material is classified as Typic Rhodustult or Hyperdystric Acrisol due to low base saturation. The rest of the soils, due to uniform clay distribution with depth and presence of horizons of very low CEC (oxic horizon) are classified as Oxisols (Eustrtox, Eutradox, Haplustox, Hapludox and Kandiudox) or Ferralsols (Humic Ferralsol, Rhodic Ferralsol and Hypereutric Ferralsol).

The surface charge of the soils is dominated by permanent negative charge with minor amounts of variable charge. There is an increase in AEC and a decrease in CEC with soil depth, indicating higher potential leaching losses of cations. Comparison of the fingerprint (FP) and the compulsive exchange methods indicated that the FP method can satisfactorily predict the basic nutrient retention capacity of the soils.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor falsafah

**CIRI-CIRI, GENESIS DAN PENGELASAN TANAH MERAHAN DARIPADA
KAWASAN SIDAMO DI ETHIOPIA**

Oleh

ABAYNEH ESAYAS ATENGO

Januari 2005

Pengerusi: Profesor Madya Siti Zaayah Darus, PhD

Fakulti: Pertanian

Tanah merah seskuioksida adalah tanah pertanian yang utama di Ethiopia. Tanah tersebut ditanam secara intensif dengan kopi. Maklumat yang tepat dan terperinci mengenai tanah tersebut adalah sangat penting untuk memperbaiki dan mengekalkan hasil pertanian. Untuk mencapai tujuan tersebut, sepuluh pedon di kawasan tanah tinggi Sidamo, Ethiopia yang terbentuk daripada bahan induk berbeza iaitu daripada vulkanik dan metaforfik, telah dikaji.

Mineral utama dalam basalt ialah feldspar dan ferromagnesium. Sebaliknya kuarza, feldspar dan sedikit hornbelend finokris terdapat dalam abu vulkanik dan kaca adalah dominan dalam ignimbrit and riolit. Zeolit (clinoptilolit dan mordenit) banyak terdapat dalam ignimbrit.

Tekstur tanah, kedalaman profil dan morfologi tanah adalah berbeza mengikut kumpulan bahan induk. Nilai pH tanah adalah dari 4.2 hingga 6.8 dan disebabkan larutlesap bes; tanah yang terbentuk di bawah rejim lembapan udik mempunyai pH terendah. Nilai pH_{NaF} secara keseluruhannya kurang daripada 9.4. Ini menunjukkan bahawa tanah tersebut tidak

mengandung alofan. Nilai kadar tukarganti kation berbeza mengikut kumpulan bahan induk mengikut turutan ignimbrit > riolit > basalt > gneis dengan 4.0 hingga 39.6 cmol/kg tanah. Kation tukarganti dan kandungan mikronutrien tersedia adalah tinggi pada permukaan tanah berbanding pada lapisan bawah permukaan. Ini disebabkan oleh kitaran nutrient oleh tumbuhan. Fosforus tersedia (P) dalam tanah adalah rendah (< 6 mg P/kg tanah) dan merupakan nutrient penghad bagi hasil tanaman di kawasan tersebut walaupun kuprum dan potassium adalah marginal. Kajian terhadap jerapan P menunjukkan bahawa tanah tersebut adalah tanah penyerap P yang tinggi dan tanah lapisan bawah permukaan mempunyai kapasiti serapan P yang lebih tinggi berbanding tanah permukaan. Ciri-ciri jerapan P tanah mempunyai hubungan positif dengan kandungan lempung dan Fe dan Al dalam bentuk yang berbeza, dan mempunyai hubungan negatif dengan pH tanah. Keperluan P bagi tanah permukaan adalah dari 41 kepada 142 mg P kg⁻¹ tanah.

Bahagian pasir dan kelodak didominasi oleh kuarza dan pelbagai kandungan feldspar. Bahagian lempung didominasi oleh kaolinit dan sedikit ilit. Taburan relative ilit dan feldspar lebih tinggi pada tanah dari unit geologi yang muda (ignimbrit). Ferum adalah dalam bentuk kristal, manakala aluminium (Al) dalam bentuk amorfus dalam tanah. Hematit, magnetit dan goetit adalah mineral Fe-oksida yang sering ditemui dalam bahagian lempung. Taburan goetit adalah lebih tinggi dalam tanah di kawasan altitud yang tinggi (keadaan sejuk dan lembap). Tukarganti Al untuk Fe di dalam hematit dan goetit berbeza dari 7 hingga 24 dan dari 14 kepada 39 mol % Al.

Pembahagian dan taburan relatif bahan kasar kepada halus (c/f-ratio) berbeza mengikut kumpulan bahan induk dari porphyric ruang tunggal dalam tanah gneissic. Selaput lempung berlaminamikro ditemui dengan banyak dalam tanah unit geologi muda (ignimbrit) berbanding dengan tanah basalt dan gneis. Proses pedogenik dalam tanah secara amnya berhubungkait dengan proses luluhawa mineral primer, iluviasi lempung, bioturbasi dan translokasi Fe-oksida ke lapisan saprolit. Haloisit terhad dalam lapisan saprolit. Sebaliknya kaolinit adalah dominan dalam solum tanah.

Pedon Chuko dan Morocho berasal daripada ignimbrit Kuartenari mengandungi lempung iluviasi lempung pada horizon B diklasifikasikan sebagai *Kandic Paleustalfs* (Soil Survey Staff, 1999) ataupun *Profondic Lixisol* (WRB, 1998), sebaliknya pedon Dengora diambil dari bahan yang hampir sama diklasifikasi sebagai *Typic Rhodustult* atau *Hyperdystric Acrisol* disebabkan kandungan ketepuan bes yang rendah. Tanah-tanah yang lain, mengalami pengagihan lempung yang sekata dengan kedalaman dan kehadiran horizon yang rendah KPK (horizon oxic) diklasifikasikan sebagai Oksisol (*Eustrustox*, *Eutrudox*, *Haplustox* dan *Kandiudox*) atau *Ferralsols* (*Humic Ferralsol*, *Rhodic Ferralsol* dan *Hypereutric Ferralsol*).

Cas permukaan tanah didominasi oleh cas cas negatif kekal dengan sedikit cas pelbagai. Terdapat peningkatan dalam AEC dan penurunan dalam CEC selaras dengan kedalaman tanah, menunjukkan potensi kehilangan kation yang lebih banyak melalui proses larutlesap. Perbandingan fingerprint (FP) dan kaedah tukarganti kompulsif menunjukkan bahawa kaedah FP dapat meramal kapasiti penahanan nutrient asas tanah.

ACKNOWLEDGEMENTS

First and foremost, my sincere gratitude and appreciation are due to my Supervisory Committee chairperson, Assoc. Prof. Dr. Siti Zauyah Darus, Head, Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia (UPM), for accepting me as a PhD student and for the professional guidance, concerned advice and constructive comments from the beginning of the research till the final submission of the thesis. I am also grateful to her for the determination to travel great distances to visit my sampling sites and for the discussions held.

I am also very much thankful to my Supervisory Committee members, Assoc. Prof. Dr. Mohd Hanafi Musa and Assoc. Prof. Dr. Rosenani Abu Bakar, Department of Land Management, Faculty of Agriculture, UPM, for their concerned follow up of the research progress, helpful suggestions, valuable comments and critical review of the manuscript. Their constant suggestions and comments have made the completion of this work possible.

I wish to thank Assoc. Prof. Dr. Che Fauziah Ishak, for allowing me to use the facilities of the Analytical Soil Laboratory. My thanks also go to Prof. Dr. Shamshuddin Jusop for providing valuable highlights on surface charge characteristics.

I wish to express my gratitude to Prof. Dr. Zaharah Abd Rahman for scheduling the seminars at convenient times and for the encouragement during my study in UPM.

Special thanks to Assoc. Prof. Dr. Anuar Abd Rahim for the lectures on GIS and for allowing me to use the facilities of GIS Laboratory. I thank En. Asri Ruslan for his help on the GIS practical lessons and preparation of maps.

I am very much thankful to the staffs of the laboratories in the Department of Land Management, Faculty of Agriculture, UPM, for their technical assistance and introduction to various instrumental techniques. Their whole-hearted help during my laboratory work has contributed a lot to the completion of my study. I wish also to express my gratitude to the administrative staff who contributed to the completion of this work in handling administrative and procurement processes. My thanks are due to the staff of Spectroscopy Laboratory, Department of Chemistry, Faculty of Science, UPM, for the technical assistance on IR analysis. My acknowledgement also goes to the staff of Microscopy and Microanalysis Unit, Laboratory of Enzyme and Microbial Technology, Institute of Bioscience, UPM, for their technical assistance during SEM and TEM examination of the samples.

I gratefully acknowledge the Ethiopian Agricultural Research Organization (EARO) for awarding me the scholarship and a study leave during my stay in Malaysia. I wish to express my gratitude to Dr. Sahlemedhin Sertu, for his valuable comments on the research proposal and continued encouragement to do the best.

My heartfelt thanks are due to the staffs of the National Soil Research Center, EARO, for their assistance during my field work and the routine soil analyses. Special thanks to Mr.

Gebeyehu Belay for his assistance during soil sampling, preparation and shipment to Malaysia. Thanks to Mr. Engida Mersha for kindly providing the meteorological data of the study area. I am also thankful to Dr. Kurkura Kabeto for the discussions on the geology of Ethiopia.

I am indebted to Mr. Roslan Ismail and Mr. Arif Sugndi for their hospitality and to be there to comfort me in times of difficulties. I am very much thankful to Mr. Ahmad Bakar (Papa) for his fatherly care to make my stay comfortable and enjoyable in Malaysia. I also wish to express my gratitude to all Ethiopian students in UPM for their assistance in times of hardships. Finally, my sincere gratitude goes to my family for their forbearance during my stay abroad.

I certify that an Examination Committee met on 05 January 2005. to conduct the final examination of Abayneh Esayas Atengo on his Doctor of Philosophy thesis entitled "Characteristics, Genesis and Classification of Sesquioxidic Soils From Sidamo Region of Ethiopia" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Hamdan Jol, PhD

Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Zaharah A. Rahman, PhD

Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Shamshuddin Jusop, PhD

Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Eric Van Ranst, PhD

Professor
Faculty of Sciences
Ghent University, Belgium
(Independent Examiner)

GULAM RUSUL RAHMAT ALI, PhD

Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The Members of Supervisory Committee are as follows:

Siti Zauyah Darus, PhD

Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Mohd. Hanafi Musa, PhD

Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Rosenani Abu Bakar, PhD

Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

AINI IDERIS, PhD

Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

I hereby declare that the thesis is based on my original work except for the quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted to any other degree at UPM or other institutions.

ABAYNEH ESAYAS ATENGO

Date:

TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	vi
ACKNOWLEDGMENTS	ix
APPROVAL	xii
DECLARATION	xiv
LIST OF TABLES	xix
LIST OF FIGURES	xxi
CHAPTER	
1 INTRODUCTION	1.1
1.1 Background	1.1
1.2 Objectives	1.4
2 LITERATURE REVIEW	2.1
2.1 Soil Formation	2.1
2.1.1 Physical Processes	2.2
2.1.2 Chemical Processes	2.3
2.1.3 Biological Processes	2.5
2.2 Geological Settings of Ethiopia	2.6
2.3 Rocks and Alteration Products	2.9
2.4 Iron Oxides in Soils	2.13
2.4.1 Sources of Iron Oxides	2.13
2.4.2 Forms of Iron Oxides	2.14
2.4.3 Methods of Identification	2.15
2.5 Pedogenic Significance of Iron Oxides	2.17
2.6 Properties of Sesquioxidic Soils	2.19
2.6.1 Color	2.19
2.6.2 Structure	2.20
2.6.3 Water Retention	2.20
2.6.4 Charge Characteristics	2.21
2.6.5 Phosphorus Adsorption	2.23
2.7 Soil Classification in Ethiopia	2.26
3 DESCRIPTION OF THE STUDY AREA	3.1
3.1 Location	3.1
3.2 Geology	3.2
3.3 Physiography and Soils	3.4
3.4 Climate	3.5
3.4.1 Rainfall	3.6
3.4.2 Temperature	3.7
3.4.3 Relative Humidity and Sunshine	3.8

3.4.4	Potential Evapotranspiration	3.8
3.5	Vegetation and Land Use	3.10
4	MATERIALS AND METHODS	
4.1	The Soils used for the Study	4.1
4.2	Soil Description and Sampling	4.1
4.3	Physical Analysis	4.5
4.3.1	Particle Size Distribution	4.6
4.3.2	Water-Dispersible Clay	4.6
4.3.3	Bulk Density	4.6
4.3.4	Particle Density	4.7
4.3.5	Water Retention and Plant Available Water	4.7
4.3.6	Soil Porosity	4.8
4.4	Chemical Analysis	4.8
4.4.1	Soil pH	4.9
4.4.2	Organic Carbon	4.9
4.4.3	Total Nitrogen	4.9
4.4.4	Available Phosphorous	4.10
4.4.5	Phosphate Retention	4.10
4.4.6	Exchangeable Cations and Cation Exchange Capacity	4.10
4.4.7	Exchangeable Acidity and Aluminum	4.11
4.4.8	Available Micronutrients	4.12
4.5	Soil Mineralogical Analysis	4.12
4.5.1	Particle Size Fractionation	4.13
4.5.2	Removal of Free Oxides in the Clay	4.13
4.5.3	X-Ray Diffraction Analysis of Soil and Rock Samples	4.14
4.6	Determination of Forms of Sesquioxides	4.14
4.6.1	Dithionite Citrate Bicarbonate Extraction	4.15
4.6.2	Acid Oxalate Extraction	4.15
4.6.3	Sodium Pyrophosphate Extraction	4.16
4.7	Determination of Fe-Oxide Mineralogy of the Clay	4.16
4.7.1	Concentration of Iron Oxides	4.17
4.7.2	XRD Analysis of the Iron Oxide Concentrate	4.17
4.7.3	Estimation of Al-Substitution in Goethite and Hematite	4.18
4.8	Total Elemental Analysis	4.18
4.9	Micromorphological Analysis	4.19
4.10	Phosphate Adsorption Analysis	4.20
4.10.1	Phosphorus Adsorption Measurement	4.21
4.10.2	Evaluation of Phosphorus Sorption Data	4.21
4.11	Surface Charge Analysis	4.22
4.11.1	Determination of pH_0	4.23
4.11.2	Determination of Point of Zero Net Charge	4.23
4.11.3	Determination of Exchange Capacity by Compulsive Exchange Method	4.23
4.12	Infrared Spectroscopic Analysis	4.25

4.13	Scanning Electron Microscopy and Energy Dispersive X-Ray Analyses	4.26
4.14	Transmission Electron Microscopic Analysis	4.27
4.15	Statistical Analysis	4.27
5	PROPERTIES, GENESIS AND CLASSIFICATION OF THE SOILS	
5.1	Composition of the Parent Rocks	5.1
	5.1.1 Basalt	5.1
	5.1.2 Rhyolite	5.1
	5.1.3 Pyroclastic Rocks	5.2
5.2	Morphological Properties of the Soils	5.3
	5.2.1 Soil Horizons	5.12
	5.2.2 Soil Color	5.12
	5.2.3 Soil Structure and Consistence	5.14
5.3	Physical Properties	5.15
	5.3.1 Particle Size Distribution	5.16
	5.3.2 Bulk Density and Total Porosity	5.16
	5.3.3 Water Retention and Plant Available Water	5.20
5.4	Chemical Properties	5.20
	5.4.1 Soil pH	5.23
	5.4.2 Organic Carbon and Total Nitrogen	5.23
	5.4.3 Cation Exchange Capacity and Exchangeable Cations	5.26
	5.4.4 Phosphorus Content and Phosphate Retention	5.28
	5.4.5 Available Micronutrients Content	5.31
5.5	Mineralogical Properties of the Soils	5.33
	5.5.1 Mineralogical Composition of the Fine Earth Fraction	5.35
	5.5.2 Forms of Sesquioxides and Iron Oxide Mineralogy	5.35
5.6	Micromorphological Properties	5.53
	5.6.1 Microstructure	5.69
	5.6.2 Coarse to Fine Fraction Ratios and Related Distribution	5.69
	5.6.3 Coarse Fractions	5.71
	5.6.4 Fine Fractions	5.73
	5.6.5 Pedofeatures	5.74
5.7	Soil Genesis	5.75
	5.7.1 Parent Materials of the Soils	5.83
	5.7.2 The Processes of Soil Formation	5.83
5.8	Soil Classification	5.87
	5.8.1 Soil Classification According to Soil Taxonomy	5.96
	5.8.2 Soil Classification According to WRB	5.96
		5.100
6	PHOSPHORUS ADSORPTION AND SURFACE CHARGE CHARACTERISTICS OF THE SOILS	
6.1	Phosphorus Adsorption Characteristics of the Soils	6.1

6.1.1	Phosphorus Sorption Behavior	6.1
6.1.2	Phosphorus Sorption Parameters	6.1
6.1.3	Relationship between P Sorption Parameters and Soil Properties	6.4
6.2	Surface Charge Properties of the Soils	6.9
6.2.1	Comparison of pH values	6.14
6.2.2	The pH_0 characteristics	6.14
6.2.3	The PZNC and Permanent Charge	6.14
6.2.4	Charge Variation with pH	6.17
		6.21
6.2.5	Comparison of Compulsive Exchange and Ammonium Acetate Methods	
6.2.6	Comparison of Compulsive Exchange and Fingerprint Methods	6.23
		6.27
7	CONCLUSIONS	
		7.1
	REFERENCES	
	APPENDICES	R.1
	BIODATA OF THE AUTHOR	A.1
		B.1

LIST OF TABLES

Table		Page
3.1	Meteorological data of Yirga Chefe area.	3.7
3.2	Meteorological data of Agere Mariyam area.	3.7
4.1	Location, annual rainfall, rock type, geological age and slope of the studied pedons.	4.2
5.1	A summary of the mineralogical and chemical properties of the rocks.	5.11
5.2	Major morphological properties of soils from Sidamo region.	5.13
5.3	Particle size distribution, bulk density and total porosity of the soils from Sidamo region.	5.17
5.4	Moisture content and available water capacity of the soils from Sidamo region.	5.22
5.5	Soil acidity, pH_{NaF} and exchangeable aluminum content of soils from Sidamo region.	5.24
5.6	Organic carbon and total nitrogen content of soils from Sidamo region.	5.27
5.7	Exchangeable cations and cation exchange capacity of the soils from Sidamo region.	5.29
5.8	Available phosphorus and phosphate retention of soils from Sidamo region.	5.32
5.9	Available micronutrients content of soils from Sidamo region.	5.34
5.10	Relative abundance of minerals in the sand fraction of the soils from Sidamo region as identified by XRD.	5.38
5.11	Relative abundance of minerals in the silt fraction of the soils from Sidamo region as identified by XRD.	5.43
5.12	Relative abundance of minerals in the clay fraction of the soils from Sidamo region as identified by XRD.	5.46
5.13	Different forms of Fe, Al and Si extracted from the fine earth fractions of the soils.	5.55
5.14	Relative proportions of different forms of Fe and Al, and ferrihydrite content of the fine earth fractions of the soils.	5.57

5.15	The Fe-oxide mineralogy of the clay fraction.	5.60
5.16	Aluminium substitution for Fe in goethite and hematite.	5.65
5.17	Some micromorphological properties of the soils derived from basalt in Sidamo region.	5.78
5.18	Some micromorphological properties of the soils derived from ignimbrite in Sidamo region.	5.79
5.19	Some micromorphological properties of the soils derived from gneiss in Sidamo region.	5.82
5.20	Some micromorphological properties of the soils derived from rhyolite in Sidamo region.	5.82
5.21	Different soil parameter ratios from B horizons of selected soils.	5.88
5.22	Some molar ratios of the total elements of the soil profiles from Sidamo region.	5.91
5.23	Diagnostic horizons, properties, and family names of the soils from Sidamo region according to Soil Taxonomy (1999).	5.97
5.24	Definitions of mollic, umbric and ochric horizons.	5.98
5.25	Definitions of argillic and oxic horizons.	5.99
5.26	Diagnostic horizons and properties, and soil units of the soils from Sidamo region according to WRB (1998).	5.101
5.27	Definition of nitic horizon according to WRB (1998).	5.103
6.1	The Freundlich and Langmuir isotherm constants and coefficient of determination (R^2) of the equations for the soils from Sidamo region.	6.3
6.2	Phosphate sorption parameters for the surface and subsurface soils from Sidamo region.	6.5
6.3	Correlations between P sorption parameters and selected soil properties of Sidamo region.	6.10
6.4	Correlations between selected soil properties of Sidamo region.	6.10
6.5	Stepwise regression analysis of the effect of selected soil properties on P sorption parameters of the soils from Sidamo region.	6.12
6.6	The pH_o , and soil pH values measured using different solutions.	6.15
6.7	The relationship between pH_o and other soil variables.	6.17

6.8	Permanent charge, AEC, CEC_B and CEC_T of the soils at pH_0 .	6.20
6.9	Charges estimated from FP data at different pH values.	6.22
6.10	Sum of basic cations ($\sum BC$) and ion exchange capacity of the soils determined by the NH_4OAc and CE methods.	6.25

LIST OF FIGURES

Figure		Page
3.1	Map of Ethiopia (A) showing location of the study area (Sidamo) and (B) topographic map of the study area showing locations of sampling sites.	3.2
3.2	Geological map of the study area and soil sampling sites.	3.4
3.3	Water balance conditions of Agere Mariyam area.	3.9
3.4	Water balance conditions of Yirga Chefe area.	3.10
4.1	Topographic cross-sections along (a) Finchawa to Morocho, and (b) Bule to Dila.	4.3
5.1	Thin section micrographs of basalt samples form Bule (A, B) and Dila (C, D) under PPL (A and C) and XPL (B and D).	5.2
5.2	Thin section micrograph of a rhyolitic rock (PPL) and XRD patterns of its pulverized sample from Sidamo region.	5.3
5.3	Thin section micrographs (PPL) of pyroclastic rocks from four localities in Sidamo region.	5.4
5.4	X-ray diffractograms of pulverized pyroclastic rock from Morocho.	5.6
5.5	Scanning electron micrographs of zeolites: (a) clinoptilolite plates and (b) mordenite fibers in a pyroclastic rock from Sidamo region.	5.7
5.6	Electron micrograph and EDX spectrum of clinoptilolite and mordenite	5.8
5.7	Scanning electron micrograph of tubular halloysite in pyroclastic rock from Dengora in Sidamo region.	5.9
5.8	Particle size distribution in the surface (a) and subsurface horizons (b) of soils derived from different parent material groups in Sidamo region.	5.18
5.9	Clay distribution with soil depth in selected pedons developed on the different parent material groups.	5.19
5.10	X-ray diffractograms of the sand fraction from Finchawa pedon.	5.36
5.11	X-ray diffractograms of the sand fraction of the Agere Mariyam	

	pedon.	5.36
5.12	X-ray diffractograms of the sand fraction of Morocho pedon.	5.37
5.13	X-ray diffractograms of the sand fraction of Tumticha pedon.	5.37
5.14	X-ray diffractograms of the silt fraction of Finchawa pedon.	5.40
5.15	X-ray diffractograms of the silt fraction of Yirga Chefe pedon.	5.40
5.16	X-ray diffractograms of the silt fraction of the Agere Mariyam pedon.	5.41
5.17	X-ray diffractograms of the silt fraction of Tumticha pedon.	5.41
5.18	X-ray diffractograms of the silt fraction of Dengora pedon.	5.42
5.19	X-ray diffractograms of the silt fraction of Morocho pedon.	5.42
5.20	Transmission electron micrographs of kaolinite (B) and clusters of hematite (A) from gneissic soil from Sidamo region.	5.45
5.21	X-ray diffractograms of the untreated clay fraction of Finchawa pedon.	5.46
5.22	X-ray diffractograms of the untreated clay fraction of Agere Mariyam pedon.	5.47
5.23	X-ray diffractograms of the untreated clay fractions of Yirga Chefe pedon.	5.47
5.24	X-ray diffractograms of the untreated clay fraction of Chuko pedon.	5.48
5.25	X-ray diffractograms of the untreated clay fraction of Tumticha pedon.	5.48
5.26	X-ray diffractograms of the untreated clay fraction of Morocho pedon.	5.49
5.27	X-ray diffractograms of the DCB-treated clay fraction of Finchawa pedon.	5.49
5.28	X-ray diffractograms of DCB-treated clay fraction of Agere Mariyam pedon.	5.50
5.29	X-ray diffractograms of the DCB-treated clay fraction of Yirga Chefe pedon.	5.50

5.30	Scanning electron micrograph of tubular halloysite from saprolite of pyroclastic rock from Yirga Chefe in Sidamo region.	5.52
5.31	X-ray diffractogram of the Fe concentrates from B horizons of selected pedons from Sidamo region of Ethiopia.	5.61
5.32	Infrared spectrum of the Fe concentrate of the clay fraction from B horizons of selected pedons.	5.63
5.33	Relationship between levels of Al substitution in co-existing goethite and hematite for soils from Sidamo region.	5.67
5.34	The relationship between unit cell dimension and Al substitution in goethite.	5.68
5.35	The relationship between unit cell dimension and Al substitution in hematite.	5.68
5.36	Thin section micrographs showing different types of microstructure of the soils.	5.70
5.37	Thin section micrographs showing open (A) and single spaced (B) porphyric random c/f related distribution of soils developed from basalt (A) and gneiss (B) from Sidamo region.	5.72
5.38	This section micrographs showing double spaced porphyric random c/f related distribution of soils developed from rhyolite (A) and ignimbrite (B) from Sidamo region.	5.72
5.39	Thin section micrograph showing microlaminated clay hypo-coatings and infillings from subsurface horizon of the Chuko pedon. (A) PPL, (B) and (C) XPL.	5.76
5.40	Thin section micrograph showing relative distribution of goethite (G) and hematite (H) with respect to pore space in the soils. (A) PPL, and (B) XPL.	5.77
5.41	Thin section micrograph showing ferruginous coatings and red impregnation of the adjacent micromass of C horizon from Tumticha pedon.	5.77
5.42	Scanning electron micrographs showing pumice (A) and obsidian (B) particles in the sand fraction of Bt1 horizon of the Chuko pedon.	5.85
	Scanning electron micrograph and EDX showing the composition	

5.43	of a sand grain in the pyroclastic rock from Dengora.	5.86
5.44	Thin section micrograph showing subhedral phenocryst of feldspar (F) in B horizon of the Bule pedon.	5.87
5.45	Thin section micrographs, (a) PPL and (b) XPL, showing iddingsitization of olivine in basaltic rock from Bule.	5.92
5.46	Thin section micrograph showing neformed birefringent kaolinite (K) and iron oxide (Fe) in the micromass of the C horizon of the Morocho pedon.	5.95
5.47	This section micrograph showing parallel alteration of feldspar phenocryst to clay mineral, (A) PPL and (B) XPL.	5.95
6.1	Phosphorus sorption isotherms for the surface soils from Sidamo region.	6.2
6.2	Phosphorus sorption isotherms for the subsurface soils from Sidamo region.	6.2
6.3	Comparison of the maximum amount of P sorbed (P_{max}) at highest level of P added and PSM for the surface and subsurface soils from Sidamo region.	6.6
6.4	Phosphate requirements estimated by the Langmuir equation for the surface and subsurface soils of Sidamo region.	6.8
6.5	The variations of AEC, CECB and CECT with pH in the surface soils of selected pedons from Sidamo region.	6.23
6.6	The variations of AEC, CECB and CECT with pH in the subsurface soils of selected pedons from Sidamo region.	6.23
6.7	The relationship between sum of basic cations determined by NH_4OAc and CE methods.	6.26
6.8	Relationship between CEC values measured by the CE and FP methods.	6.28
6.9	Relationship between AEC values measured by CE and FP methods.	6.28