TRACE ELEMENT DISTRIBUTION IN SIX OKLAHOMA BENCHMARK SOILS

By

BRAD D. LEE

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Thesis approved:

Brian J. Carter

Thesis Adviser

Zuhair al-Shaieb

Thomas C. Collins

Dean of the Graduate College

PREFACE

This study was conducted to provide information about metal distribution in Oklahoma soils. Metal concentrations within soils have been studied extensively in other states but studies involving metal concentrations in Oklahoma soils are limited. In uncontaminated soils, metal concentrations vary depending on metal concentrations in parent rocks. As soil begins to form, pedogenic processes such as additions, losses, transformations, and translocations redistribute the metals within the soil profile. Specific objectives of this research were i) to characterize six key uncontaminated benchmark soils based on their Co, Cu, Ni, Pb, and Zn content by horizon to parent material, and ii) determine what processes establish metal distribution within the soil profile using soil characterization and morphology.

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INTRODUCTION

This thesis is presented in two chapters following the manuscript format of the Soil Science Society of America Journal.

CHAPTER I

PEDOGENIC DISTRIBUTION OF HEAVY METALS IN SIX OKLAHOMA BENCHMARK SOILS

ABSTRACT

Soils are a receptacle for sludge and other sources of trace elements and heavy metals. Determination of background concentrations of heavy metals in uncontaminated soils can be used as an index to determine the severity of soil contamination. The objective of this study was to determine how soil formation affects the natural heavy metal distribution within soil profiles. Six key benchmark Oklahoma agricultural soils were selected and sampled to the depth of the parent material by diagnostic horizon. Cobalt, Cu, Ni, Pb, Zn, Ti, Zr, and Y concentrations by horizon in total soil and clay fraction were determined by x-ray fluorescence. Parent material uniformity was determined by optical mineralogy of the fine and very fine sand fraction, Ti/Zr and Zr/Y ratios in clay free soil fraction, clay free sand percentages, and soil morphology. There is five fold more Cu, two fold more Zn and Ni, and one and one-half fold more Co and Pb in the clay and oxide fraction compared to the total soil. Within the clay fraction, the surface horizons contain a greater concentration of Cu, Zn, and Co, possibly due to biocycling of these micronutrients from roots in the subsoil. Using Zr as an index mineral, gains and losses of metal within each soil profile were calculated by reconstruction analysis in the total soil and clay fraction. All soils showed a net loss of all metals in the total soil fraction except Co and Pb in the Dalhart: Pb -0.019 to 0.001%; Zn -0.110 to -0.005%; Cu, -0.0334 to -0.001%; Co, -0.0381 to 0.003%; and Ni, -0.042 to -0.002%. The mean loss of metals for all soils in the clay fraction was 3 fold less for Zn, 4 fold less for Pb, Co, and Ni, and 5 fold less for Cu than the metal loss in the soil fraction. Biocycling reduces the amount of metal loss in the clay fraction of surface horizons compared to subsoil horizons.

INTRODUCTION

Heavy metal content and distribution within soils are influenced by several factors: parent material, organic matter content, mineralogy, particle size distribution, soil horizonation, soil age, drainage, vegetation, and aerosol input (Esser et al., 1991). Naturally occurring background levels of heavy metals in soils are usually low compared to contaminated sites and are related to the geochemistry of the parent materials (Karathanasis and Seta, 1993). Parent materials containing the majority of heavy metals are mafic and ultramafic rocks and shales compared to siliceous rocks and sandstone (Alloway, 1993).

Tiller (1958) and Fleming and Ryan (1964) found an enrichment of trace elements in the clay and silt fractions. Tiller (1958) concluded that feldspars, micas, iron oxides and hydroxides, clay minerals, and humus are the principal carriers of trace elements and that each of these groups carries certain associations of trace elements. Secondary Fe and Al-hydroxides are important in sorption of trace elements that have been released by weathering (Tiller et al., 1963; Jenne, 1968; Koons et al., 1980).

Natural levels of heavy metals can be used as a baseline level for comparison to contaminated sites. Potential sources of heavy metal pollutants in soils are: atmospheric pollution from motor vehicles, agricultural fertilizers and pesticides, organic manures, incineration of urban and industrial wastes, and emissions from metal smelters (Alloway, 1993). The heavy metals that receive the most attention for accumulation in soils and uptake in plants include Cu, Ni, Pb, and Zn because there is a large amount of these metals introduced into the ecosystem by mining activities.

The objectives of this study were: i) to characterize six key Oklahoma soils and their Co, Cu, Ni, Pb, and Zn content by horizon and ii), determine what processes establish trace element distribution within the soil profile using soil characterization and morphology.

MATERIALS AND METHODS

Twenty-eight uncontaminated benchmark soils (Gray and Roozitalab, 1976) were chosen for this study from the different major land resource areas across Oklahoma. Soil samples were collected by horizon to a depth of parent material. The soils were sampled from excavated pits or with a Giddings probe using a 7.62 cm diameter tube. Soil profile descriptions followed national cooperative soil survey guidelines (Soil Survey Staff, 1993).

From the 28 soils (Appendix A) used in the study, six were selected based on the large agricultural land use and their range in classification and parent material (Fig. 1): Carnasaw, fine mixed thermic Typic Hapludult (Pennsylvanian shale, Atoka formation); Dalhart, fine-loamy mixed mesic Aridic Haplustalf (eolian Pleistocene dunes of reworked Ogallala formation); Dennis, fine mixed thermic Aquic Paleudoll (Pennsylvanian shale, Senora formation); Durant, fine smectitic Vertic Argiustoll (Cretaceous shale, Woodbine formation); Kirkland fine mixed thermic Udertic Paleustoll (Permian Hennessey shale); and Tillman, fine mixed thermic Typic Paleustoll (Permian Hennessey shale).

Particle size distribution for the six soils was determined by pipet method (Gee and Bauder, 1986). Clays were separated by sedimentation and clay mineralogy was determined (Jackson, 1979). Heavy minerals in the fine sand fraction in the Carnasaw, Dalhart, Dennis, and Durant soil and the very fine sand fraction of the Kirkland and Tillman soils were separated by a 2.72 Mg m^{-3} specific gravity separation (Cady et. al., 1986). Grain counts on the fine sand and very fine sand fractions greater than 2.72 Mg m^{-3} were completed by an area count outlined by an ocular grid (Brewer 1976).

Air-dry moisture content, base saturation, exchangeable acids, and exchangeable bases were determined (Soil Survey Investigations Staff, 1991). Electrical conductivity and pH were determined on a saturated paste extract (Soil Survey Investigations Staff, 1991). Cation exchange capacity was determined in the Dalhart, Kirkland, Durant, and Tillman soils by using 0.4N NaOAc - 0.1N NaCl (Rhodes, 1982) and in the Dennis and Carnasaw soils by sum of cations (Soil Survey Investigations Staff, 1991). Organic carbon was determined by dry combustion (Nelson and Sommers, 1982) and a modified Mebius method (Yeomans and Bremner, 1988). Iron oxides were extracted by citrate-bicarbonate-dithionite (Jackson, 1979).

All soil samples were air dried, ground and screened to pass a 2 mm sieve. The screened soil samples were stored in sealed polyethylene containers before analysis for Ti, Y, Zr, Cu, Ni, Co, Pb, and Zn by x-ray fluorescence spectroscopy. The screened soil and clay samples were powdered in a corundum-ball mill and pressed into briquettes with a H_3BO_3 backing. The pressed powders were analyzed at the University of Oklahoma using a Rigaku SMAX wavelength dispersive x-ray fluorescence spectrometer (Rigaku Corp., Tokyo), with an Rh anode end-window x-ray tube operated at 60 kV and 45 mA. For the elements Zn and Zr, background corrected intensities of the Kα lines were measured, whereas for Pb the Lβ lines were measured. Mass absorption corrections were applied using the intensity of the Rh Kα Compton scatter peak. Calibration curves were constructed using a wide range of international rock powders. Lower limits of detection (2σ) for the elements analyzed are in the range from 1 to 3 mg kg^{-1}.

Lithologic discontinuities were determined by field morphology, clay-free sand percentages (Rutledge et al., 1975), optical mineralogy, Ti/Zr ratios, and Zr/Y ratios (Murad, 1978) in silt and sand fractions.

RESULTS AND DISCUSSION

METAL DISTRIBUTION

Introduction

Trace element concentrations for all soils are within the range presented by Holmgren et al. (1993) and Shacklette and Boerngen (1984) for clay and clay loam soils. Zinc is the most abundant metal in all soils, exceeding Ni and Pb by 3 fold, and Cu and Co by 5 fold.

The distribution of trace elements with particle size, is a function of mineral composition and amount of adsorption sites in each size fraction (Esser et al., 1991).

All metals were concentrated in the < 0.002 mm fraction when compared to the < 2 mm fraction (Appendix B). Metal concentration in the clay fraction is higher than the metal concentration in the total soil (Fig. 2).

Lead

Pettry and Switzer (1993) concluded that lead is concentrated in the surface horizons of soil profiles reflecting its association with organic matter. However, of the soils studied, Pb was correlated with organic carbon in only 1 of the 6 soils ($P= 0.05$). Lead in the Dennis soil is correlated to organic carbon ($r= -0.72$, $P= 0.05$). No correlation in 5 of 6 soils and negative correlations of Pb to organic carbon in 1 of 6 soils indicates that in clayey soils, with organic matter concentrations ranging from 22 to 1 g kg^{-1} (Table 1), organic carbon does not influence Pb distribution. The content of Pb in the clay fraction, is much larger that the accumulation of Pb in the organic fraction of clayey soils.

Lead content in all soils, other than the Carnasaw profile, increased with increasing depth, suggesting Pb has an association with pedogenesis (translocations, additions, and losses), clay content (clay sized particles contain more Pb than silt or sand sized particles (Appendix B)), and parent material (soil metal contents are dependent on the metal content of the rocks from which soils form). The larger concentration of Pb (29 mg kg^{-1}) in the all soils increased with increasing depth (Appendix B). Negative correlations with organic carbon and increasing Zn content with increasing depth suggest Zn is associated with clay content and/or parent material.

Zinc concentration was significantly correlated to clay in all soils except the Carnasaw (P= 0.05) (Fig. 3). A students t-test determined that the slopes of the linear order regression lines for the Dalhart, Dennis, Durant, Kirkland, and Tillman soils were not significantly different (mean b=1.23; P=0.05) (Fig. 3). The y intercept value is dependent on the Zn content in the parent material.

Kaolinite was the dominant clay mineral, followed by illite and vermiculite in the Dalhart, Dennis, Kirkland, and Tillman soils. The Durant soil was dominated by kaolinite and montmorillonite (Appendix D). Although clay minerals are selective for divalent metals (Bittell and Miller, 1974; Pulls and Bohn, 1988), there was no evidence of a relationship between clay type and Zn content between horizons. Absolute amount of Zn within a soil profile is dependent on parent material. Distribution of Zn within the profile is dependent on clay distribution.

Zn content in the Carnasaw soil does not correlate to clay content due to mineralogical similarities between particle size fractions. The 250-106μm mineral fraction > 2.72 Mg g^{-1} in each horizon contains 92.2 - 99.6% argillaceous shale fragments (range 92.2% in Bt1, 99.6% in C1 and Cr2; CI =

95%, P=0.05; mean n=570 grains) (Appendix E). Although the clay content in the C1 and Cr2 horizons of the Carnasaw profile decreases, the mineralogy remains the same as in the subsurface horizons.

Mean concentration Zn in the clay fraction of the surface horizon of all soils was 25% larger than the mean metal content in the clay fraction of the subsurface horizons (Bt1 and Bt2 horizons) (Appendix B). Zinc content in the surface horizon of the clay fraction when compared to the Zn content in the subsurface suggests biological mining of Zn from the subsurface. Plants remove micronutrients from the subsurface and concentrate them in the surface horizon. As organic matter decomposes, Zn is released into the soil and subsequently sorbed onto sequioxides and clay minerals. This biological process offsets the effects of downward translocation.

Copper

Copper is associated with soil organic matter, Fe oxides, and soil silicate clays (Baker, 1993). Copper was correlated to organic carbon (r= -0.72, P= 0.05) in the Durant soil (Table 1), and was not significantly correlated to organic carbon in any other soil. However, Cu was significantly correlated to citrate-bicarbonate-dithionite extractable Fe in the Durant r= 0.74 and the Dalhart r= 0.98 (P= 0.05), and significantly correlated to clay content in the soil, contains a mean $CaCO_3$ content of 27g kg^{-1} (Appendix C). Cobalt correlated with the Tillman $CaCO_3$ content ($r= 0.87$, $P= 0.05$) (Table 1). Cobalt correlations to organic carbon and $CaCO_3$ were not significant in any other soil. Cobalt was not significantly correlated ($P= 0.05$) to clay content in any soil. Possibly Co content in the 6 parent materials is too variable to predict by clay, $CaCO_3$, and organic carbon contents.

Mean concentration Co in the clay fraction of the surface horizons was 88% larger than the mean metal content in the clay fraction of the subsurface horizons (Bt1 and Bt2 horizons). Cobalt content in the surface horizon of the clay fraction when compared to the Co content in the subsurface suggests biological mining Co from the subsurface.

Nickel

Nickel distribution in soil profiles is related either to organic matter or to amorphous oxides and clay (Kabata-Pendias and Pendias, 1984). In surface horizons, Ni occurs mainly as organically bound forms, and in subsurface horizons, Ni is mobilized during weathering and is coprecipitated with Fe oxides (Kabata-Pendias and Pendias, 1984). Nickel content was negatively correlated to organic carbon in the Durant, Kirkland, and Tillman soil profiles and was not significantly correlated to the remaining soils ($P=0.05$) (Table 1). Nickel concentrations for all soils increased with increasing depth (Appendix

not Sig [illegible]

B), reflecting an association with Fe oxides, clay content, and/or parent material. The organic carbon contents in the surface horizon of the six soils range from 22 to 3 g kg^{-1} (Appendix C). Possibly organic matter contents in clayey soils are too low to concentrate Ni in surface horizons when soils have contrasting clay contents between horizons.

Nickel concentration was significantly correlated to clay in all soils except the Carnasaw and Tillman ($P = 0.05$) (Table 1). A students t-test determined that the slopes of the linear regression lines for the four soils were not significantly different (mean $b = 0.79$; $P = 0.05$) (Fig. 4). The y intercept value is soil specific and dependent on the absolute Ni content in the soil parent material. There was no evidence of a relationship between clay type and Ni content between horizons.

Ni content in the Carnasaw soil does not correlate to clay content due to mineralogical similarities between particle size fractions. Nickel content in the Tillman soil does not correlate to clay content due to a parent material change at the bottom of the profile. The Ni concentration increases with increasing depth through the Tilman profile. Clay concentration increases with increasing depth from 22.2% in the surface horizon to 51.0% in the BC horizon. However, in the 2Cr horizon, below the BC horizon, the clay content is 29.5% (Appendix F). the change in Ni concentration at the parent material change, reinforces the idea that Ni content in a soil profile is dependent on the soil parent material.

Reconstruction Analysis

Reconstruction analysis is a technique used to estimate the gain and losses of substances from soil profiles. Three assumptions are made to determine gains and losses: 1) the soil is formed from a uniform parent material, 2) the stable base constituent is resistant to weathering and does not move in profile upon pedogenic transformations (Zr in the clay free soil fraction, zircon), and 3) reconstruction based upon a base line level of mobile constituents and the stable base constituent in an unweathered horizon, assumed parent material. Pedogenic processes redistribute soil materials in a soil profile, concentrating stable components in the surface horizons and removing the least stable minerals from the profile or leaching them to the bottom of the soil profile. All estimates of metal gain and loss are made relative to the concentration of these elements in the assumed base horizon.

Compared to the base horizons in each soil, all soil profiles have a loss of all metals in the soil surface with the exception of Co and Pb in the Dalhart soil (Table 2). The Dalhart soil profile is the least developed soil in the study. Possibly pedogenic processes have not had time to redistribute metal concentrations in the soil profile, or our assumption of a base horizon was incorrect. Possibly the base horizon was not in an unweathered horizon, rendering it unsuitable for reconstruction analysis.

Parent material uniformity in the Dalhart soil was determined by Ti, Zr, and Y used as index elements representing the resistant minerals of titanium oxides, zircon, and xenotime (Murad, 1978) (Fig. 5). The distribution curves of these elements when compared as a ratio (Ti/Zr and Zr/Y in the clay free soil fraction) represent a uniform soil (Fig. 6), but the distribution of these elements are not representative of a well developed soil profile. The Ti, Zr, and Y distribution curves appear to be dependent on particle size, not pedogenic processes.

The percent loss of metals in all soils except Pb and Co in the Dalhart soil, indicates a larger loss of metal in the surface horizons, with a decrease in metal loss with increasing soil depth (Table 2). The translocation of clay from the surface horizon to the subsurface argillic horizon is responsible for the large loss of metals in the surface horizon (Appendix F). The net loss of metal with all the soil profiles, except the Dalhart, results from leaching and time. Metal concentration increases with increasing depth as pedogenic processes, specifically illuviation and leaching, influence metal distribution. Over time, some of these metals can be removed from the soil profile by translocation to groundwater. Removal of metals from the soil profile is evident by the more developed, highly leached, Carnasaw soil having the most loss and the least leached soil, Dalhart, having the least loss.

The gain or loss of metals in the surface (kilogram per hectare furrow slice) based on the assumptions listed above is in Table 3. As expected the soils well developed soils (soils containing well defined argillic horizons, thick eluviated layers near the surface, and high organic matter concentration in the surface horizon) have larger losses. The micronutrients Cu, Zn, and Co could also be lost to plant uptake and subsequent removal by animal consumers, but this loss is probably relatively small compared leaching loss of these metals from the upper 15 cm of soil.

The percent loss of metal in the clay fraction is much lower than the percent metal loss in the total soil (Table 2). All soils have the most metal concentration in the surface horizon clay fraction than in the clay fraction of the subsurface argillic horizons, possibly due to biocycling of these metals from the root zone to the surface and near-surface horizons, and the ability of clays to absorb metals.

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Table 1. Correlation and regression curve data.

			clay	OC	CBD Fe_2O_3	$CaCO_3$
Carnasaw	Pb	r	-0.54	0.46	-0.12	
		r squared	0.29	0.21	0.02	
		slope	-0.05	1.65	-22.22	
		Y intercept	28.76	25.11	33.00	
	Zn	r	0.33	-0.43	0.45	
		r squared	0.11	0.18	0.20	
		slope	0.26	-12.63	656.67	
		Y intercept	66.52	87.37	-123.20	
	Cu	r	0.36	-0.48	0.56	
		r squared	0.13	0.23	0.32	
		slope	0.11	-5.35	310.00	
		Y intercept	9.47	18.22	-80.80	
	Co	r	-0.98 *	0.87 *	-0.55	
		r squared	0.95	0.76	0.30	
		slope	-0.19	6.19	-191.11	
		Y intercept	19.72	6.54	69.40	
	Ni	r	0.54	-0.58	0.58	
		r squared	0.29	0.33	0.33	
		slope	0.17	-6.70	330.00	
		Y intercept	25.01	37.64	-68.40	
Dalhart	Pb	r	0.94 *	-0.16	0.93 *	0.74
		r squared	0.88	0.02	0.86	0.55
		slope	0.38	-3.06	77.62	1.60
		Y intercept	7.12	16.63	4.82	10.94
	Zn	r	1.00 *	-0.33	0.99 *	0.70
		r squared	0.99	0.11	0.97	0.49
		slope	1.75	-28.35	360.92	6.61
		Y intercept	24.02	73.04	13.27	44.11
	Cu	r	0.96 *	-0.31	0.98 *	0.75
		r squared	0.92	0.10	0.96	0.57
		slope	0.63	-10.09	135.15	2.68
		Y intercept	-3.35	14.33	-7.87	3.09
	Co	r	-0.72	0.71	-0.75	-0.42
		r squared	0.51	0.50	0.56	0.17
		slope	-0.15	7.38	-33.19	-0.48
		Y intercept	13.99	8.03	15.17	11.95

Table 1. Continued.

			clay	OC	CBD Fe_2O_3	$CaCO_3$
	Ni	r	0.95 *	-0.40	0.96 *	0.82 *
		r squared	0.90	0.16	0.92	0.68
		slope	0.63	-12.93	133.19	2.94
		Y intercept	-4.89	13.74	-9.17	0.77
Dennis	Pb	r	0.57	-0.72 *	-0.14	
		r squared	0.32	0.52	0.02	
		slope	0.28	-11.76	-79.03	
		Y intercept	16.51	32.25	52.11	
	Zn	r	0.93 *	-0.47	0.28	
		r squared	0.86	0.22	0.08	
		slope	0.76	-12.59	266.13	
		Y intercept	41.62	74.90	-16.95	
	Cu	r	0.43	-0.49	0.39	
		r squared	0.18	0.24	0.15	
		slope	0.07	-2.74	77.42	
		Y intercept	9.43	13.31	-12.97	
	Co	r	0.41	-0.48	-0.43	
		r squared	0.17	0.23	0.18	
		slope	0.39	-15.20	-482.26	
		Y intercept	9.71	31.15	179.40	
	Ni	r	0.92 *	-0.63	0.27	
		r squared	0.85	0.40	0.07	
		slope	1.02	-23.09	351.61	
		Y intercept	-1.04	46.80	-77.65	
Durant	Pb	r	0.41	-0.14	0.36	0.09
		r squared	0.17	0.02	0.13	0.01
		slope	0.07	-0.38	9.49	0.23
		Y intercept	16.26	19.26	16.21	18.78
	Zn	r	0.93 *	-0.98 *	0.93 *	0.56
		r squared	0.86	0.96	0.86	0.31
		slope	0.99	-17.45	158.01	9.88
		Y intercept	26.10	78.09	19.46	56.49
	Cu	r	0.63	-0.72 *	0.74 *	0.66
		r squared	0.40	0.53	0.55	0.44
		slope	0.17	-3.30	32.35	2.99
		Y intercept	5.09	14.31	2.50	9.16

Table 1. Continued.

			clay	OC	CBD Fe_2O_3	$CaCO_3$
	Co	r	0.57	-0.50	0.50	0.58
		r squared	0.32	0.25	0.25	0.33
		slope	0.17	-2.50	23.50	2.85
		Y intercept	6.78	15.25	6.60	10.79
	Ni	r	0.86 *	-0.97 *	0.86 *	0.58
		r squared	0.73	0.93	0.74	0.33
		slope	0.71	-13.40	113.75	7.94
		Y intercept	-8.72	29.13	-13.66	12.20
Kirkland	Pb	r	-0.07	-0.01	-0.21	-0.56
		r squared	0.01	0.00	0.04	0.32
		slope	-0.02	-0.05	-5.62	-0.18
		Y intercept	18.63	18.03	19.01	19.02
	Zn	r	0.76 *	-0.88 *	0.70 *	0.34
		r squared	0.58	0.77	0.49	0.12
		slope	0.89	-21.79	107.05	0.62
		Y intercept	32.49	80.29	50.29	65.91
	Cu	r	0.83 *	-0.65	0.22	0.77 *
		r squared	0.69	0.42	0.05	0.60
		slope	0.43	-7.01	14.42	0.62
		Y intercept	-1.76	19.38	13.31	12.40
	Co	r	-0.58	0.32	0.02	-0.09
		r squared	0.34	0.10	0.00	0.01
		slope	-0.27	3.20	1.29	-0.06
		Y intercept	24.51	11.63	12.99	13.58
	Ni	r	0.80 *	-0.95 *	0.84 *	0.76 *
		r squared	0.64	0.90	0.71	0.58
		slope	0.81	-20.33	110.98	1.20
		Y intercept	-11.30	32.34	2.37	15.44
Tillman	Pb	r	0.77 *	-0.58	0.27	0.49
		r squared	0.59	0.33	0.08	0.24
		slope	1.03	-33.02	49.52	8.52
		Y intercept	-7.23	48.23	23.37	9.14
	Zn	r	0.77 *	-0.71	-0.02	0.70
		r squared	0.59	0.50	0.00	0.49
		slope	1.76	-70.07	-5.33	20.93
		Y intercept	25.16	126.71	93.52	36.07

Table 1. Continued.

		clay	OC	CBD Fe_2O_3	$CaCO_3$
Cu	r	0.76 *	-0.38	0.30	0.30
	r squared	0.58	0.15	0.09	0.09
	slope	0.48	-10.33	25.46	2.44
	Y intercept	3.56	26.89	17.35	15.27
Co	r	0.01	-0.88 *	-0.11	0.85 *
	r squared	0.00	0.77	0.01	0.73
	slope	0.00	-12.53	-5.04	3.67
	Y intercept	12.81	19.10	13.89	3.08
Ni	r	0.39	-0.85 *	-0.01	0.94 *
	r squared	0.15	0.72	0.00	0.88
	slope	0.33	-30.94	-1.10	10.31
	Y intercept	11.17	38.93	24.05	-3.98

* = significant at the 0.05 probability level.

Table 2. Gain and loss of metals using reconstruction analysis (Zr = stable index element)

Horizon	Depth (cm)	Total Soil (<2.000 mm)					Clay Fraction (<0.002 mm)				
		Pb	Zn	Cu	Co	Ni	Pb	Zn	Cu	Co	Ni
						%					
						Carnasaw					
A	0-6	-0.00582	-0.03136	-0.00903	-0.00091	-0.01244	-0.00019	-0.00287	-0.00119	0.00025	-0.00108
E	6-18	-0.00873	-0.04463	-0.01278	-0.00184	-0.01777	-0.00068	-0.00467	-0.00248	0.00031	-0.00174
Bt1	18-41	-0.00204	-0.00902	-0.00315	-0.00070	-0.00339	-0.00113	-0.00540	-0.00394	-0.00035	-0.00125
Bt2	41-61	-0.00112	-0.00943	-0.00326	-0.00086	-0.00321	-0.00072	-0.00672	-0.00398	-0.00074	-0.00142
Btss3	61-112	-0.00123	-0.00793	-0.00266	-0.00055	-0.00260	-0.00058	-0.00573	-0.00437	-0.00052	-0.00073
C1	112-174	-0.00026	-0.00716	-0.00256	-0.00034	-0.00216	-0.00047	-0.00546	-0.00270	-0.00033	-0.00071
Cr2*	174-220	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
						Dalhart					
A	0-28	0.00019	-0.00130	-0.00124	0.00098	-0.00105	0.00019	0.00114	0.00125	0.00011	0.00000
BA	28-36	0.00040	0.00070	-0.00083	0.00140	-0.00069	0.00027	0.00161	0.00090	0.00013	0.00016
Bt1	36-75	0.00008	0.00028	-0.00074	0.00028	-0.00073	0.00016	0.00016	0.00014	0.00006	-0.00026
Bt2	75-101	-0.00002	-0.00183	-0.00046	-0.00055	-0.00011	-0.00022	-0.00215	-0.00130	-0.00002	-0.00082
Bk3	101-128	0.00002	-0.00213	-0.00006	-0.00040	0.00018	-0.00082	-0.00412	-0.00274	-0.00055	-0.00116
Btk4	128-163	0.00000	-0.00061	-0.00027	-0.00056	0.00065	-0.00053	-0.00241	-0.00073	-0.00036	-0.00078
BCk*	163-187+	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table 2. Continued.

		Total Soil (<2.000 mm)					Clay Fraction (<0.002 mm)				
Horizon	Depth (cm)	Pb	Zn	Cu	Co	Ni	Pb	Zn	Cu	Co	Ni
						%					
						Dennis					
A	0-33	-0.00711	-0.01138	-0.00225	-0.01099	-0.01161	-0.00091	-0.00079	0.00104	-0.00190	-0.00198
AB	33-49	-0.00580	-0.01072	-0.00085	-0.00938	-0.00970	-0.00079	-0.00133	0.00130	-0.00175	-0.00167
BA	49-71	-0.00596	-0.01268	-0.00217	-0.00956	-0.01061	-0.00059	-0.00206	0.00031	-0.00127	-0.00178
Bt1	71-94	-0.00363	-0.00840	-0.00140	-0.00793	-0.00735	-0.00137	-0.00304	0.00025	-0.00271	-0.00253
Bt2	94-129	-0.00249	-0.00573	-0.00048	-0.00652	-0.00700	-0.00121	-0.00209	0.00027	-0.00253	-0.00301
2C1*	129-174	-0.00166	-0.00301	-0.00020	-0.00297	-0.00293	-0.00027	-0.00089	0.00015	-0.00074	-0.00100
2C2*	174-190	0.00169	0.00305	0.00021	0.00300	0.00297	0.00043	0.00140	-0.00023	0.00117	0.00158
2C3	190-200	-0.00146	0.00286	0.00020	-0.00476	0.00262	-0.00090	0.00058	0.00069	-0.00338	0.00136
						Durant					
A	0-18	-0.00021	-0.00564	-0.00073	-0.00024	-0.00358	0.00030	-0.00077	-0.00002	0.00059	-0.00081
BA	18-32	-0.00018	-0.00420	-0.00102	-0.00022	-0.00297	0.00024	-0.00098	0.00349	0.00026	-0.00105
Bt1	32-59	0.00031	-0.00171	-0.00011	0.00021	-0.00145	0.00046	-0.00158	0.00249	0.00043	-0.00103
Bt2ss	59-82	0.00052	-0.00163	-0.00007	0.00025	-0.00153	0.00043	-0.00153	0.00117	0.00053	-0.00111
Btss3	82-103	0.00057	-0.00114	-0.00050	0.00090	-0.00085	0.00025	-0.00114	-0.00140	0.00075	-0.00048
Bt4	103-132	0.00031	0.00014	0.00000	0.00110	-0.00016	0.00007	-0.00060	0.00187	0.00058	-0.00030
Bt5*	132-162	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2Btkbss	162-195	0.00012	-0.00019	0.00045	0.00045	0.00009	0.00000	-0.00059	-0.00194	0.00020	0.00009

Table 2. Continued.

Horizon	Depth (cm)	Total Soil (<2.000 mm)					Clay Fraction (<0.002 mm)				
		Pb	Zn	Cu	Co	Ni	Pb	Zn	Cu	Co	Ni
						%					
						Kirkland					
Ap	0-20	-0.00193	-0.01537	-0.00437	-0.00056	-0.00869	-0.00042	-0.00325	0.00000	-0.00025	-0.00200
Bt1	20-47	-0.00157	-0.01078	-0.00313	-0.00174	-0.00645	-0.00109	-0.00428	0.00017	-0.00043	-0.00224
Bt2	47-71	-0.00110	-0.00900	-0.00252	-0.00147	-0.00589	-0.00112	-0.00409	-0.00079	-0.00052	-0.00240
Bt3	71-104	-0.00106	-0.00810	-0.00216	-0.00146	-0.00493	-0.00104	-0.00372	-0.00153	-0.00056	-0.00226
Bt4	104-127	-0.00067	-0.00664	-0.00196	-0.00097	-0.00392	-0.00092	-0.00291	-0.00209	-0.00041	-0.00194
Bt5	127-152	-0.00079	-0.00696	-0.00183	-0.00080	-0.00431	-0.00111	-0.00351	-0.00198	-0.00061	-0.00211
Bt6	152-188	-0.00037	-0.00415	-0.00040	-0.00024	-0.00222	-0.00064	-0.00284	-0.00153	-0.00018	-0.00120
Bt7*	188-216	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2Cr	216-246	0.00090	0.00175	-0.00101	0.00056	-0.00028	0.00000	0.00126	-0.00097	0.00045	0.00053
						Tillman					
Ap	0-22	-0.01101	-0.02725	-0.00566	-0.00275	-0.00717	-0.00213	-0.00552	-0.00045	-0.00062	-0.00154
BA	22-33	-0.00923	-0.02147	-0.00467	-0.00220	-0.00512	-0.00285	-0.00716	0.00065	-0.00094	-0.00193
Bt1	33-46	-0.00806	-0.01829	-0.00401	-0.00240	-0.00473	-0.00278	-0.00673	0.00212	-0.00085	-0.00175
Bt2	46-85	-0.00592	-0.01561	-0.00317	-0.00181	-0.00414	-0.00149	-0.00519	0.00277	-0.00082	-0.00114
Btk3	85-129	-0.00200	-0.00946	-0.00090	-0.00079	-0.00208	0.00021	-0.00191	0.00000	-0.00048	-0.00046
BC*	129-152	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2Cr	152-200+	-0.00305	-0.00240	-0.00156	0.00075	0.00120	-0.00121	-0.00050	-0.00028	0.00044	0.00107

* = base horizon (Dennis profile base horizon values are an average of the 2C1 and 2C2 horizons)

Table 3. Quantity of metal gained or lost in surface soils.

	Total soil					Clay fraction				
	kg hectare-furrow-slice-1									
	Pb	Zn	Cu	Co	Ni	Pb	Zn	Cu	Co	Ni
CARNASAW	-17292	-89888	-25785	-3357	-35749	-202	-1654	-821	120	-617
DALHART	436	-2982	-2844	2229	-2400	32	193	211	18	0
DENNIS	-16247	-26012	-5151	-25117	-26552	-399	-346	455	-830	-864
DURANT	-490	-12885	-1666	-539	-8181	139	-364	-8	279	-383
KIRKLAND	-4421	-35137	-9989	-1274	-19877	-233	-1810	0	-141	-1115
TILLMAN	-25177	-62284	-12946	-6286	-16385	-1186	-3081	-254	-347	-861

Fig. 1. Sample location.

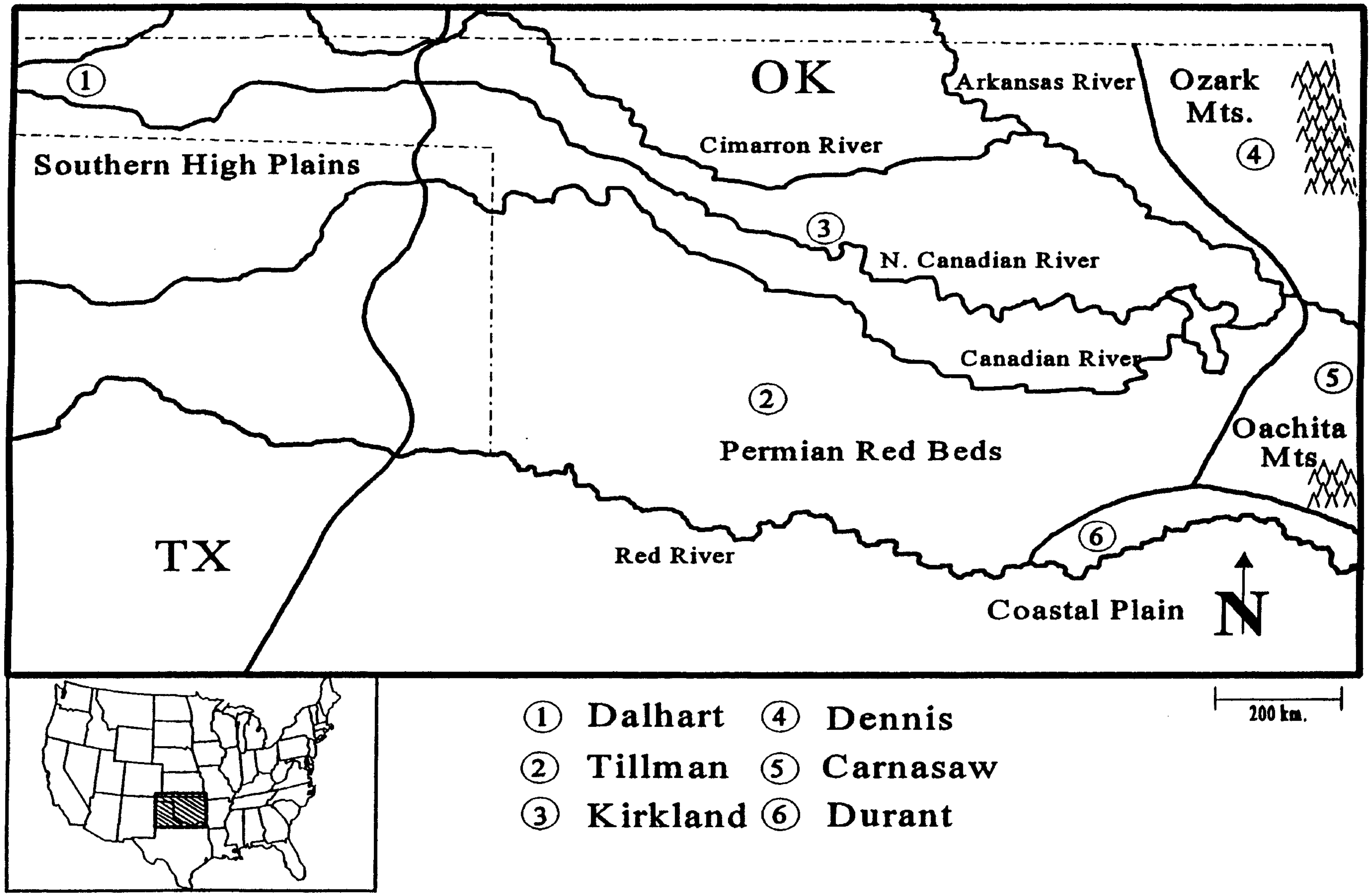


Fig. 2. Metal concentrations in soil and clay.

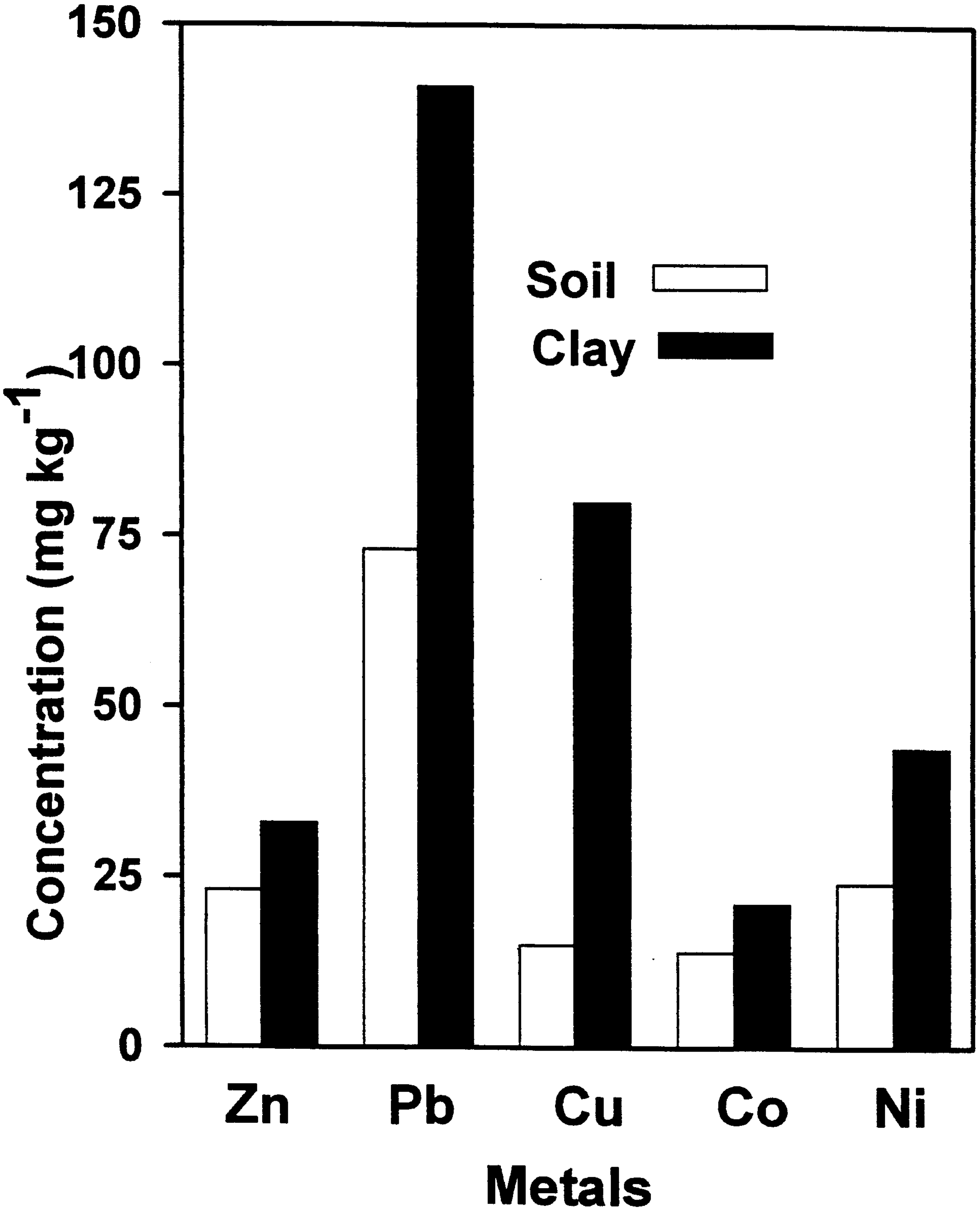


Fig. 3. Zinc concentration vs. clay % in soils studied (P=0.05).

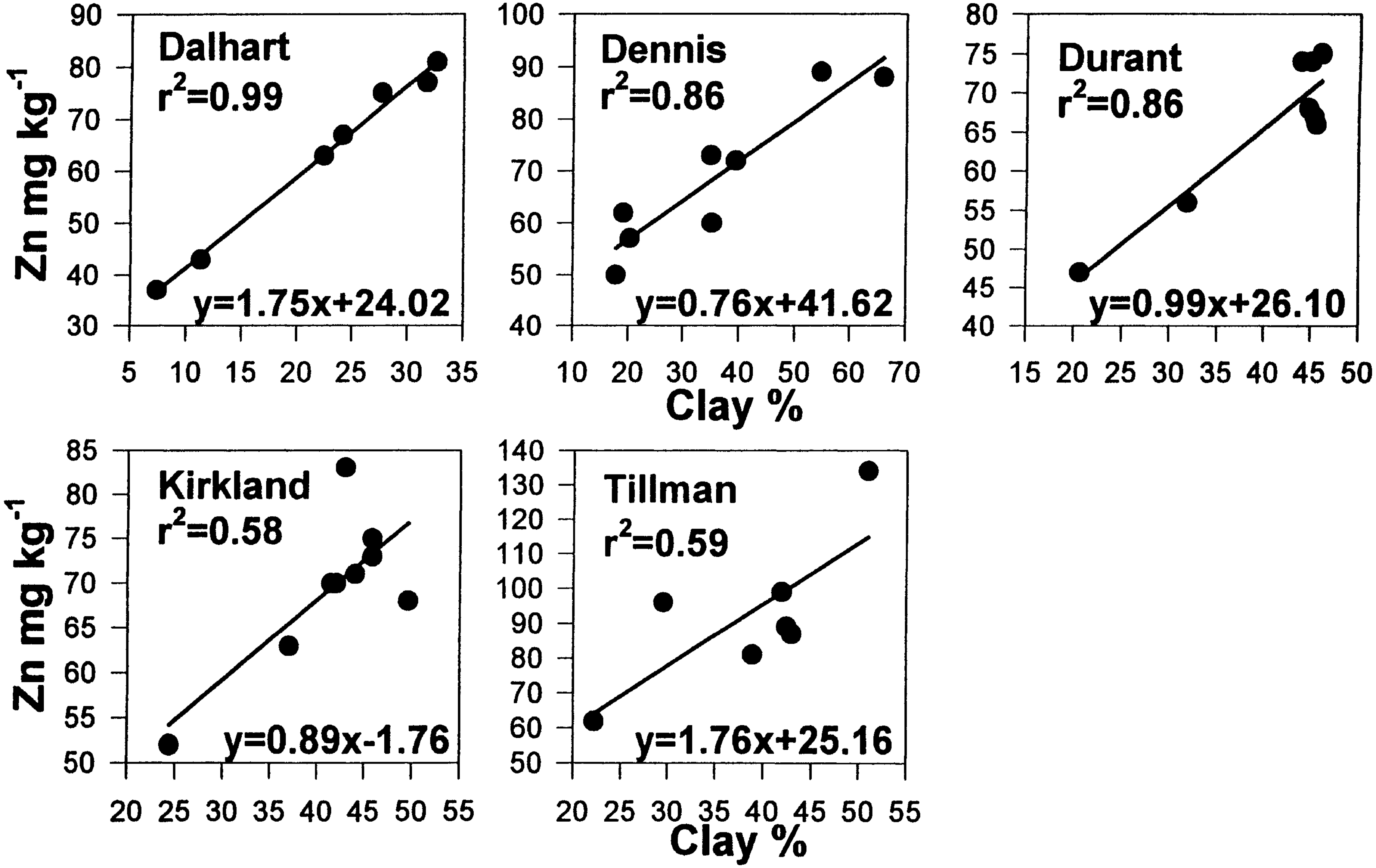


Fig. 4. Nickel concentration vs. clay % in soils studied (P=0.05).

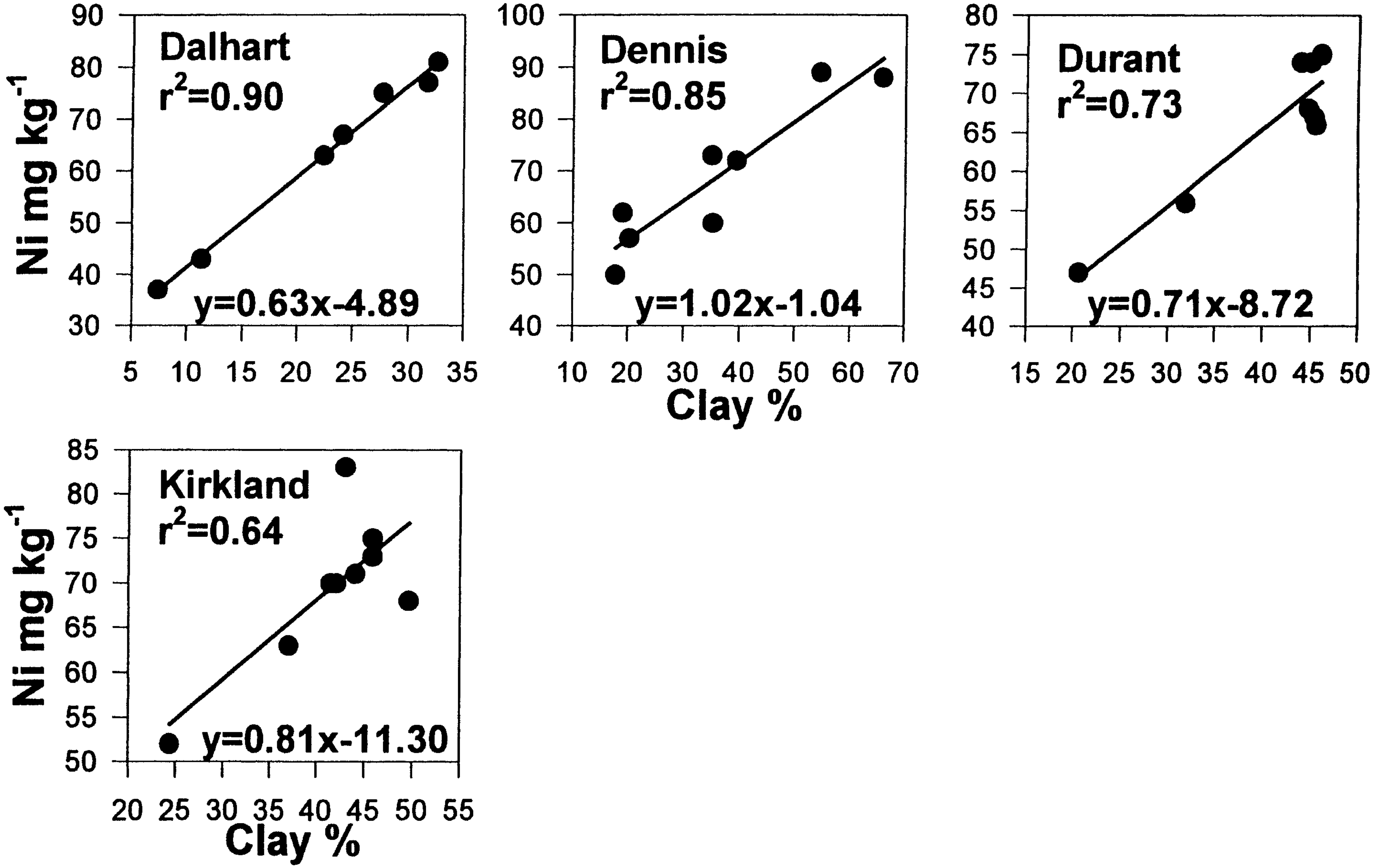
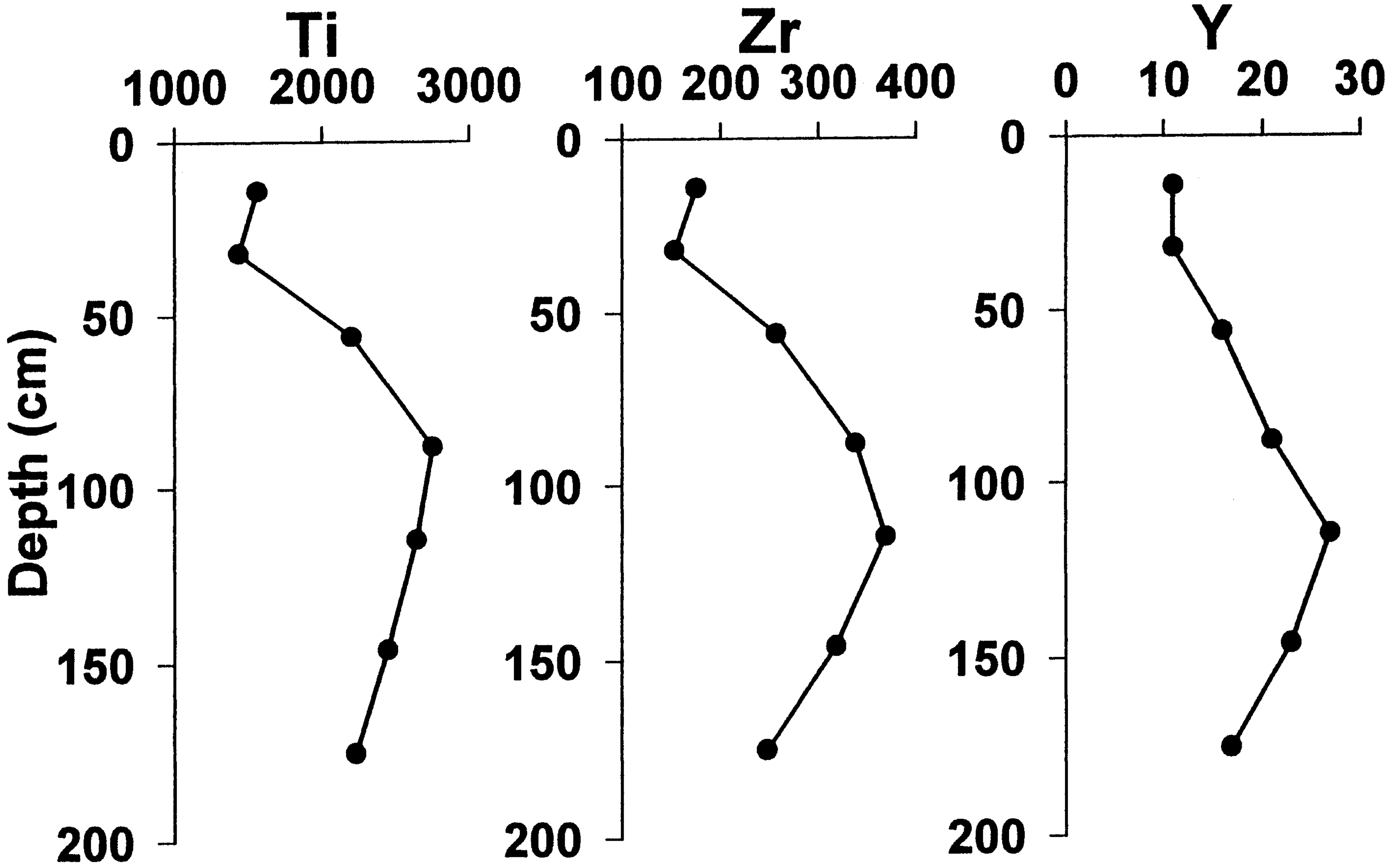


Fig. 5. Dalhart Ti, Zr, and Y distributions (mg kg^{-1})



CHAPTER II

Zr/Y RATIO AS A PARENT MATERIAL UNIFORMITY INDICATOR IN SIX OKLAHOMA BENCHMARK SOILS

ABSTRACT

Determination of parent material uniformity is an important component of soil morphologic research. Zirconium/yttrium ratios as mineral specific elements of xenotime (YPO_4) and zircon ($ZrSiO_4$), in the 50µm - 2µm fraction, were compared to previously determined soil parent material uniformity or discontinuity in six Oklahoma soils formed on various parent materials. Yttrium and Zr concentrations were determined by x-ray fluorescence in the total soil and clay fraction. Parent material uniformity and discontinuities were identified by one or more of the following criteria; soil morphology, particle size distribution, clay free sand percentages, and optical mineralogy of the > 2.72 Mg m^{-3} fraction. Zr/Y did

not adequately identify parent material uniformity in five of six soils. Zr/Y ratios adequately identified parent material uniformity in the Dalhart, a Fine loamy mixed mesic Aridic Haplustalf, mean Zr/Y ratio 14.9 ($r = 0.98$, $n = 7$).

INTRODUCTION

Soil profile discontinuities can be identified in the field due to sudden changes in soil properties such as texture, color, and structure. Where changes in these soil properties are not well defined, mineralogical analysis must be used to determine soil uniformity and discontinuity. Estimates of soil uniformity should be based on as many lines of evidence as possible. Methods used to determine soil uniformity and parent material discontinuitites include particle size analysis, clay free particle size analysis, light/heavy mineral ratio comparison, and optical analysis of heavy minerals.

One method of assessing the uniformity of soil parent material is to compare the ratio of the amounts of two resistant minerals in one or more size fraction (Smeck and Runge, 1971; Evans and Adams, 1975). Depth distributions of resistant minerals which exhibit smooth curves without inflections imply soil uniformity, but this must be supported by additional evidence to be conclusive. (Brewer, 1976).

Sufficient grain counts of resistant minerals to be statistically sound are laborious and time consuming (Brewer, 1976). The quantity of resistant minerals can be determined by elemental analysis if the resistant mineral contains an element that is specific to the resistant mineral, i.e. B in tourmaline and Zr in zircon (Marshall 1940). Elemental determination of mineral specific elements can quickly and adequately estimate the quantity of desired resistant minerals (Chapman and Horn, 1968; Murad, 1978; Smeck and Wilding, 1980).

Many researchers use Ti/Zr ratios to determine soil parent material uniformity, but Ti is not exclusively in the resistant mineral fraction (Brewer, 1955; Sudom and St. Arnaud, 1971; Chittleborough and Oades, 1980a, b; El Shazly et al., 1981). Considerable amounts of Ti are found in weatherable minerals (Chapman and Horn, 1968; Smeck and Wilding, 1980; Kaup and Carter, 1987). Murad (1978) suggests the use of Y in xenotime and Zr in zircon as mineral specific elements to establish associations between soil parent materials. Because optical properties of xenotime and zircon are very similar, counting grains these minerals at sufficient quantity to be statistically sound are quite laborious (Murad, 1978). Murad (1978) concluded that constant Zr/Y ratios in soils and stream sediments indicate that soils in the Schwarzach valley of central Europe were formed from one parent material. Only the absolute amounts of Zr and Y changed, whereas their ratio remained relatively constant.

The objectives of this study were to determine Y and Zr concentrations in six Oklahoma soils and compare Zr/Y ratios with previously determined parent material uniformity and discontinuities identified by standard methods.

MATERIALS AND METHODS

Six soils were selected based on their range in parent material and classification: Carnasaw, fine mixed thermic Typic Hapludult (Pennsylvanian shale, Atoka formation); Dalhart, fine-loamy mixed mesic Aridic Haplustalf (eolian Pleistocene dunes of reworked Ogallala formation); Dennis, fine mixed thermic Aquic Paleudoll (Pennsylvanian shale, Senora formation); Durant, fine smectitic Vertic Argiustoll (Cretaceous shale, Woodbine formation); Kirkland fine mixed thermic Udertic Paleustoll (Permian Hennessey shale); and Tillman, fine mixed thermic Typic Paleustoll (Permian Hennessey shale).

Soil samples were collected by soil horizon to a depth of parent material from excavated pits or with a Giddings probe (Model HD-GSRP-S; Fort Collins, Colorado), using a 7.62 cm diameter tube. Soil profile descriptions followed national cooperative soil survey guidelines (Soil Survey Staff, 1993).

Particle size was determined for the six soils by pipet method (Gee and Bauder, 1986) and clays separated by sedimentation (Jackson, 1979). Heavy metals were separated in the fine sand fraction in the Carnasaw, Dalhart, Dennis, and Durant soil and the very fine sand fraction of the Kirkland and Tillman soils by a 2.72 Mg m^{-3} separation (Cady et. al., 1986). Grain counts were completed by an area count outlined by an ocular grid (Brewer, 1976). Parent material discontinuities were determined by soil morphology, particle size distribution, clay-free sand percentages (Rutledge et al., 1975), and optical mineralogy of minerals > 2.72 Mg g^{-1}. Zr/Y ratios are plotted on a clay free basis to remove inflections due to carbonate leaching and clay movement (Smeck and Wilding, 1980).

All soil samples were air dried, ground and screened to pass a 2 mm sieve. The screened soils were stored in sealed polyethylene containers before analysis for total TiO_2, Zr, and Y by X-ray fluorescence spectroscopy. Screened soil and clay samples were powdered in a corundum-ball mill and pressed into briquettes with a H_3BO_3 backing. The pressed powdered samples were analyzed at the University of Oklahoma using a Rigaku SMAX wavelength dispersive x-ray fluorescence spectrometer (Rigaku Corp., Tokyo), with an Rh anode end-window x-ray tube operated at 60 kV and 45 mA. For the element Zr, background corrected intensities of the Kα lines were measured. Mass absorption corrections were applied using the intensity of the Rh Kα Compton scatter peak. Calibration curves were constructed using a wide range of international rock powders. Lower limits of detection (2σ) for the elements analyzed are in the range from 1 to 3 mg kg^{-1}.

RESULTS AND DISCUSSION

Zr/Y Ratios

Carnasaw soil was formed from a Pennsylvanian, argillaceous shale from the Atoka formation. There was no evidence of a parent material discontinuity. Optical analysis of the fine sand fraction > 2.72 Mg m^{-3} in each horizon indicates that 92.2 - 99.6% of the grains > 2.72 Mg m^{-3} are argillaceous shale fragments (range: 92.2% in Bt1, 99.6% in C1 and Cr2; CI = 95%, P_i = 5%). Mean grain count for the Carnasaw soil was 570 grains (Appendix E). Morphology data indicates the Carnasaw is a well developed forested soil, identified by an eluviated horizon (Appendix G), high organic carbon content in the surface horizon (Appendix C), and low base saturation (Appendix C). Shale fragments in the C1 horizon and highly fractured thin beds of shale, tilted 20-30 degrees, indicate a well developed uniform soil (Appendix G).

Zr/Y ratio within Carnasaw has a mean of 11.3 (s=4.3, CV=38.5%). Because Zr/Y ratios vary between horizons, they inadequately identified parent material uniformity in the Carnasaw profile. Possibly Y is concentrated in the shale fragments. Feromagnesian minerals in argillaceous shale fragments can contain quantities the order of 100 to 1000 mg kg^{-1} Y in their lattices (Murad, 1978). Weathering of shale fragments limits the suitability of Y as an index element in soils formed from argillaceous shales, like the Carnasaw.

Dalhart soil is formed from an eolian deposit from North Canadian River alluvial sediment. The North Canadian River contains sediments from the Ogallala formation (outwash from the Sangre de Cristo Mountains of New Mexico and Colorado). The Dalhart is a uniform soil, indicated by the similar mineralogy in the >2.72 Mg g^{-1} fraction between horizons (Appendix E), gradual changes in particle size throughout the profile, and uniform clay free sand percentages between horizons (Appendix F).

Yttrium and Zr concentrations in the sand and silt fractions of Dalhart horizons increase with increasing depth and from 11 and 175 mg kg^{-1} in the A horizon to 27 and 370 mg kg^{-1} in the Btk3 horizon in the sand and silt fractions (Table 1). The Zr/Y ratio of 14.9 (s=1.2, CV=8.0%, $r = 0.98$, $n = 7$) in the silt and sand fractions (Figure 2) indicates a uniform soil.

The Dennis soil was sampled in northeastern Oklahoma near the Ozark Plateau and formed from colluvium and residuum. The residuum parent material is Pennsylvanian shale (Des Moines age) of the Senora formation in the Cabiness group. The discontinuity between the colluvium and residuum is identified by soil morphology and clay-free sand percentages (Table 1) at 129 cm between the Bt2 and the 2C1 horizons. There was no difference in mineralogy of the >2.72 Mg g^{-1} between horizons (Appendix E). Although the texture (clay loam) remained the same between the Bt2 and 2C1 horizons, clay free sand percentages increased from 28.1% to 55.4% respectively (Appendix F). Morphological differences were observed by an abrupt boundary between the Bt2 and 2C1 horizon and a rock content of 40% sandstone cobbles and 30% sandstone gravel in the 2C1 horizon whereas the Bt2 horizon contained no cobbles or gravel (Appendix G).

The Zr/Y ratio in the colluvium (A to Bt2 horizons) is 16.2 (s=2.9, CV=18.2%) and in the residuum (2C1 to 2C3 horizons) 11.3 (s=2.3, CV=16.7%) (Figure 1). A t test comparing the Zr/Y means between the alluvium (0-129 cm) and residuum (129-200 cm) indicates a discontinuity between the Bt2 and 2C1 horizons at 192 cm (P=0.05). Although statistically there is a difference between the Zr/Y ratio at the morphologically determined discontinuity, the variability of the Zr/Y ratio through the entire Dennis profile (mean 14.4, s=3.6, CV=24.9%) is less than the variability of the Zr/Y ratio of the uniform Carnasaw soil, therefore Zr/Y ratios did not adequately identify differing parent materials within the Dennis soil.

The Durant soil formed from alluvium and residuum on the southern coastal plain region in Southeast Oklahoma. Durant is an alluvial Red River sediment deposit on top of a Cretaceous shale of the Woodbine formation. The discontinuity between the alluvium and residuum was identified by differences in soil morphology and optical mineralogy between the Bt5 and 2Btkbss horizons at 162 cm. The 2Btkbss horizon contains 28% apatite, in the 105-53 μm mineral fraction > 2.72 Mg m^{-3} (n = 437, CI = 80%, P_i = 10%), but apatite was not a significant component of the 250-105μm fraction in any other horizon (Appendix

E). Morphological differences are indicated by an abrupt boundary and a color change of 2.5YR5/3 to 2.5YR5/6, between the Bt5 and 2Btkbss horizon (Appendix G).

The Zr/Y ratio mean in the Red River alluvium (A to Bt5 horizon) is 25.7 (s=3.8, CV = 10.2%). The 2Btkbss horizon, formed from residual shale, has a Zr/Y ratio of 21 (Figure 1). Although the Zr/Y ratio of 21 in the 2Btkbss horizon is outside the standard deviation of the mean (21.9 to 29.5), the Zr/Y ratio difference between the alluvium and residuum is not large enough to be confident that Zr/Y ratios adequately identified the parent material discontinuity between the Bt5 and 2Btkbss horizons.

The Kirkland and Tillman soils are formed from alluvial sediment from the Cimarron and Washita Rivers respectively, deposited over residuum formed from Permian Hennessey shale. The Cimarron and Washita Rivers contain sediments predominantly from the Ogallala formation (outwash from the Sangre de Cristo Mountains of New Mexico and Colorado).

The discontinuity identified by optical mineralogy in the Kirkland soil between the Bt5 and Bt6 horizon differs from the discontinuity identified by soil morphology at 216 cm between the Bt7 and 2Cr horizons. Optical mineralogy of the > 2.72 Mg m^{-3} very fine sand fraction (mean grain count = 581) indicates a mineralogy change at 152 cm. Calcite was evident in the Bt6 (74.4%), Bt7 (86.0%), and 2Cr (95.8%) horizons (152 to 256 cm), but calcite was not a significant constituent in any other horizon (0 to 152 cm) (CI = 80%, P_i = 5%) (Appendix E). The soil morphology data identifies a discontinuity between the alluvium and residual siltstone at 216 cm between the Bt7 and 2Cr horizons, indicated by an abrupt boundary, color change of 2.5YR3/2 to 2.5YR4/8, and rock structure in the 2Cr horizon (Appendix G). The Zr/Y ratio mean of 15.8 (s=3.8, CV=23.9%) in the alluvium, 0-216 cm, is too variable too adequately identify a discontinuity at 152 cm or 216 cm (Figure 1).

Particle size distribution, clay free sand percentages, and optical mineralogy indicate an abrupt boundary between the BC and 2Cr horizons of the Tillman soil. Silt content at the abrupt boundary of the discontinuity doubled from 33.7% in the BC horizon to 67.1% in the 2Cr horizon (Appendix F). The clay free sand percentage decreased from 31.8% in the BC horizon to 4.4% in the 2Cr horizon (Appendix F). Horizons Ap to BC contained 23 to 31% opaque FeTi oxides in the mineral fraction > 2.72 Mg m^{-3}(CI = 80%, P_i = 10%), but only trace amounts of opaque FeTi oxides were found in the 2Cr horizon. Mean grain count for the Tillman was 519 grains (Appendix E).

Zr/Y ratios suggest a discontinuity at 85 cm, between the Bt2 and Btk3 horizons identified by a decrease in the Zr/Y ratio (Figure 1). Zr/Y ratios did not adequately indicate a parent material discontinuity in the Tillman soil. The Zr/Y ratio of 19.3 (s=4.8, CV=24.8%) in the alluvium is too variable between horizons to identify the parent material discontinuity at 152 cm.

Alternative methods

Xenotime was not identified in any sample. Similar optical properties of zircon and xenotime make determination between the two minerals difficult (Murad, 1978).

Because all the soils within the study contain tourmaline, an elemental determination of boron, a mineral specific element of tourmaline (Marshall, 1940) could be a better index element for comparison with Zr. The very fine sand fraction of the Tillman soil and fine sand fraction of the Dalhart soil have sufficient quantities of zircon and tourmaline, identified by optical mineralogy, to compare their ratios between horizons. The other soils did not contain sufficient quantities of zircon and/or tourmaline in one or more horizons to calculate zircon/tourmaline ratios.

Mean zircon/tourmaline ratio in the fine sand fraction of the Dalhart profile is 2.57 (s=0.61, CV=23.7%, range 3.46-1.88; mean grain count=508). Because the Dalhart is a uniform profile (indicated by morphology, optical mineralogy, and clay free sand percentages) therefore a CV of 23.7% is tolerable. Possibly the variability of zircon and tourmaline in the parent material or the variability of mineral concentrations in the 250 to 106 μm particle size fraction is responsible for the large CV. Grain counts of zircon and tourmaline in other sized fractions (very fine sand and coarse silt) would be beneficial as other lines of evidence to determine uniformity of mineral ratios between horizons.

Tillman mean zircon/tourmaline ratio in the very fine sand fraction in the alluvium (0-152 cm) is 1.03 (s=0.45, CV=43.7%, range 0.54-1.71; mean grain count=520). Zircon in the 2Cr horizon, 152-200 cm, was present in trace quantities (<1.0%) while tourmaline made up 9.0% of the very fine sand fraction in the 2Cr horizon. Therefore the zircon/tourmaline ratio in the 2Cr horizon of <0.11% indicates the 2Cr horizon is different from the alluvial parent material (P=0.05).

CONCLUSIONS

Within soils similar to Dalhart, formed from arkosic sediments, Zr/Y are good estimates of parent material uniformity. Zr/Y ratios in the sand and silt fractions within clayey soils formed from sedimentary rocks are too variable to adequately indicate parent material uniformity or discontinuities.

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Figure 1. Zr/Y ratios in clay free soil fraction.

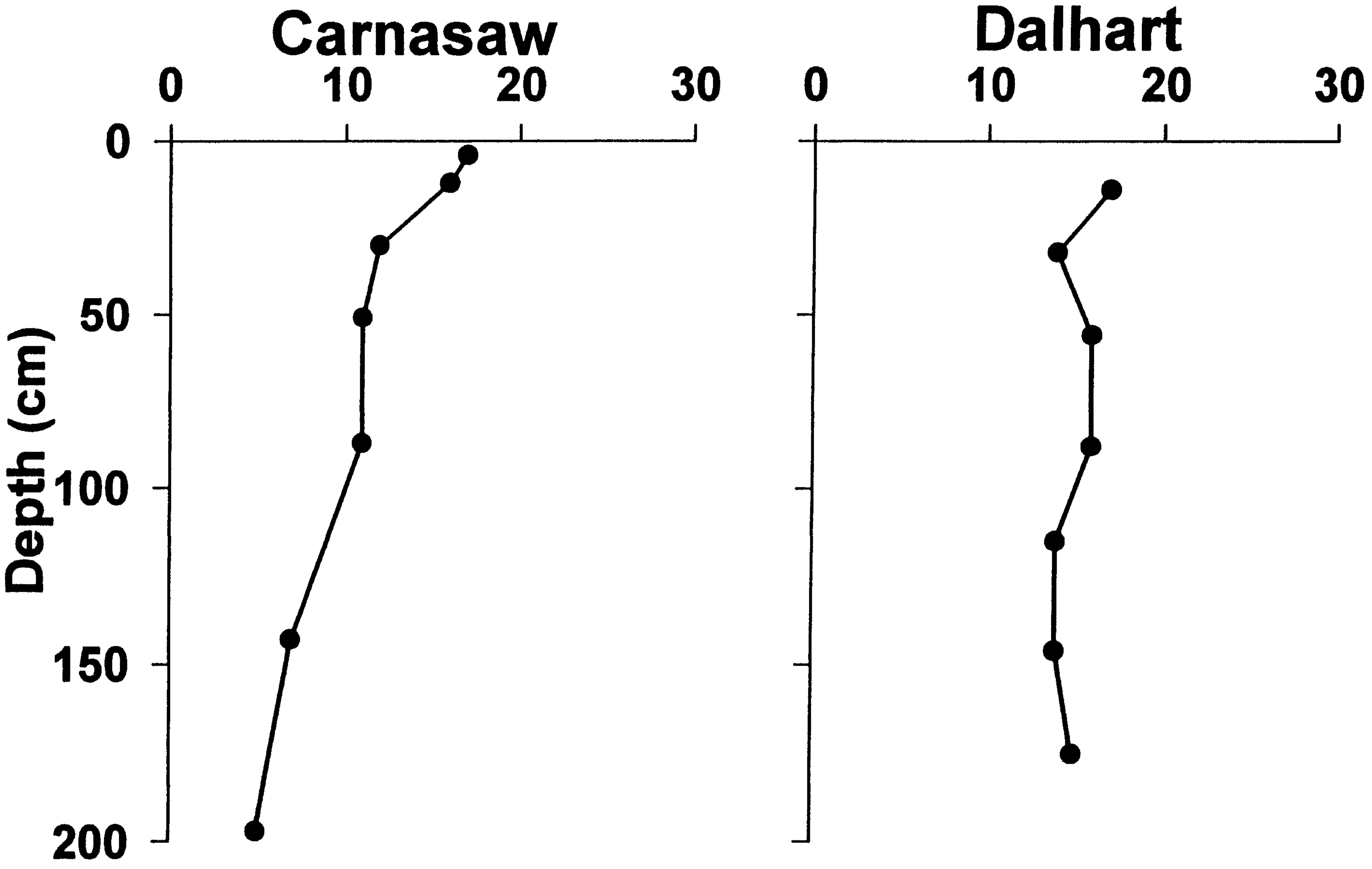


Figure 1. Continued.

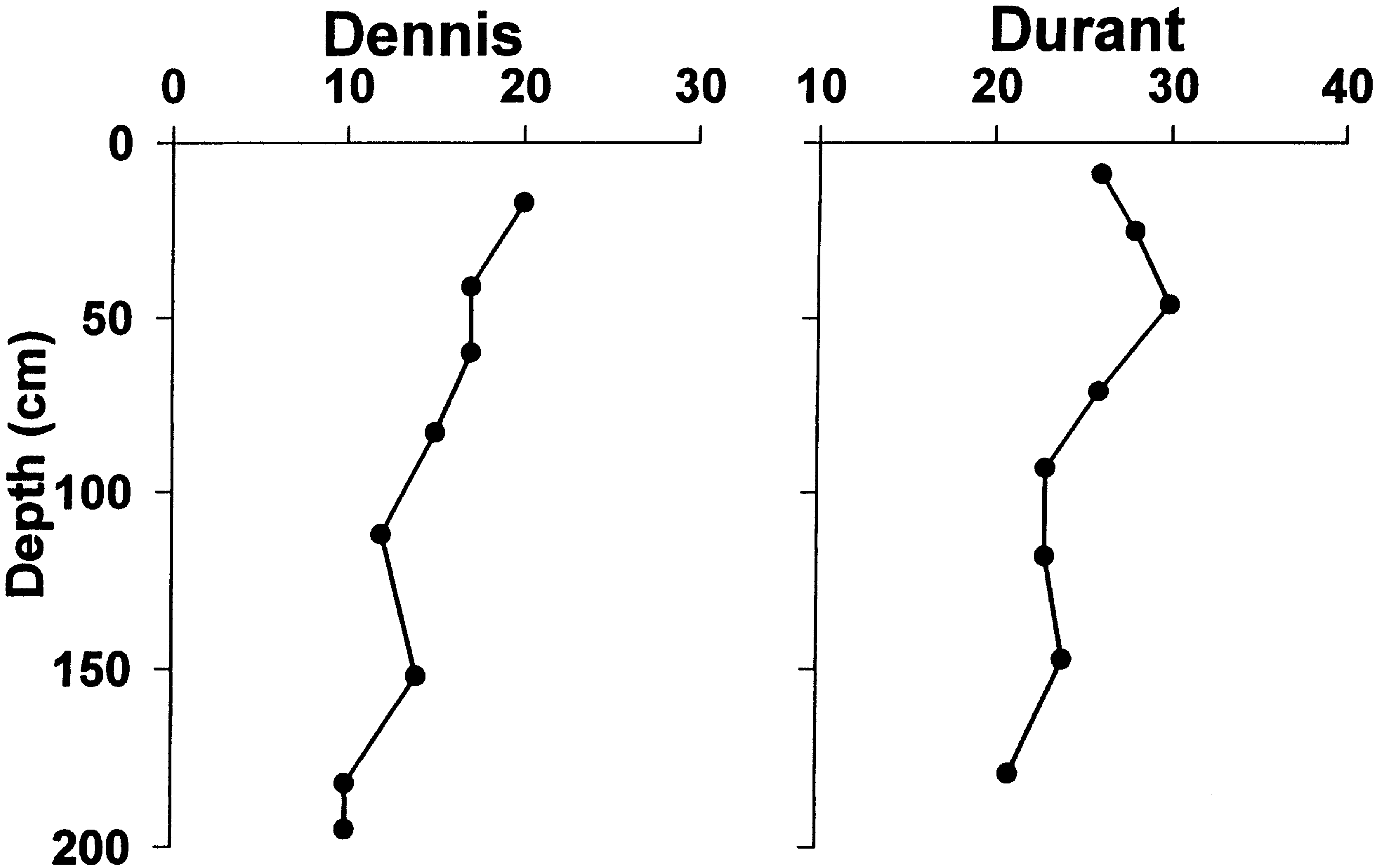
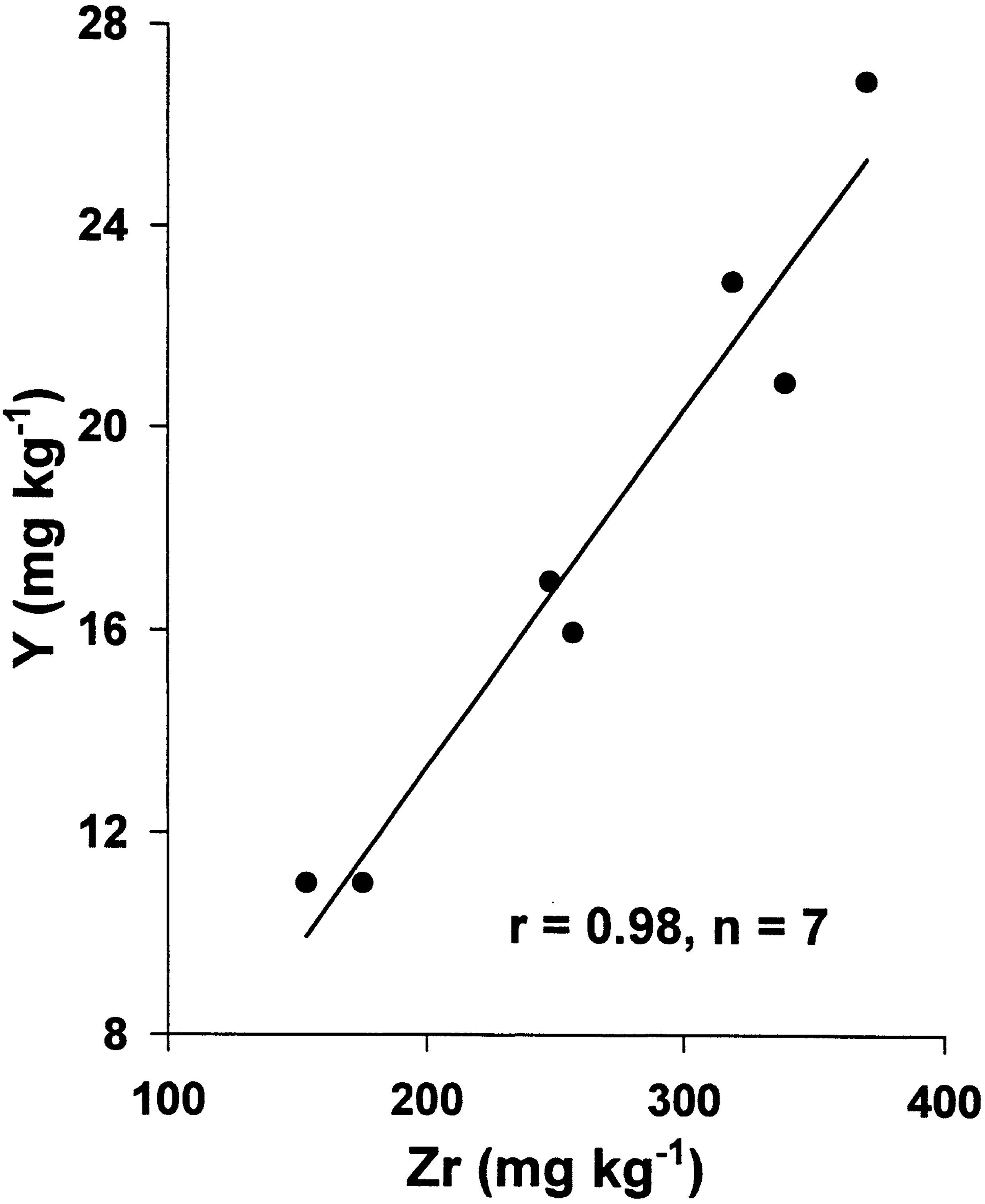


Figure 2. Y and Zr correlation in Dalhart soil.



APPENDIX

Appendix A. Benchmark soil metal concentrations.

	Diagnostic	%	mg kg-1					
SOIL	Horizon	TiO2	Zr	Pb	Zn	Cu	Co	Ni
Pratt	A	0.25	166	11	29	4	26	1
	B	0.21	156	10	30	3	19	1
	C	0.2	126	10	27	4	20	1
Woodward	A	0.68	548	15	55	10	7	13
	B	0.67	368	16	60	14	10	18
	C	0.66	394	13	54	10	12	15
Dougherty	A	1	263	13	44	1	1	1
	E	1	243	7	26	1	1	1
	B	0.39	359	10	35	4	8	2
	C	0.33	190	11	39	4	8	2
Darnell	A	0.35	376	6	32	3	29	1
	B	0.29	290	2	28	4	44	1
	C	0.34	273	4	28	1	23	1
Dalhart	A	0.29	138	10	37	2	5	1
	B	0.59	242	19	78	16	13	14
	C	0.63	289	20	78	18	11	14
Saint Paul	A	0.67	583	16	57	16	5	10
	B1	0.66	501	18	65	14	9	15
	B2	0.65	378	18	68	32	7	17
	C	0.71	187	12	83	127	15	35
Renfrow	A	0.73	671	18	54	13	9	9
	Bt1	0.75	417	22	67	17	12	25
	Bt2	0.75	294	22	73	21	14	27
Zaneis	A	0.58	517	12	46	7	16	3
	Bt1	0.58	410	12	52	8	13	9
	BC	0.48	304	10	46	4	13	12
Yahola-Lebron	Ap	0.72	211	25	106	22	16	31
	A	0.71	212	21	96	20	17	29
	C3	0.54	480	10	36	7	5	5
Richfield	A	0.64	446	22	82	19	10	16
	B	0.66	383	21	82	17	10	20
	C	0.63	379	19	75	18	10	18

Appendix A. Continued.

SOIL	Diagnostic Horizon	% TiO2	mg kg-1					
			Zr	Pb	Zn	Cu	Co	Ni
Mansic	A	0.55	348	18	69	12	6	15
	B	0.54	273	15	58	13	6	16
	C	0.5	394	14	49	10	8	8
Durant	A	0.92	731	15	48	9	9	6
	B	1.09	578	21	67	12	11	18
	C	1.11	574	19	74	15	16	27
Cobb	A	0.34	4.22	12	37	6	3	1
	B	0.35	306	12	86	6	5	1
	R	0.36	305	13	41	8	2	2
Tillman	A	0.74	522	18	62	15	9	17
	B	0.72	321	23	85	18	14	29
	C	0.74	271	21	84	18	14	29
Dennis	A	0.84	351	27	92	14	11	29
	B	0.85	185	27	115	18	12	61
	C	0.94	153	29	133	19	21	78
Kirkland	A	0.75	549	20	55	17	8	13
	Bt1	0.72	408	19	70	16	10	20
	Bt2	0.79	340	20	75	25	13	26
Carnasaw	A	0.97	450	32	69	9	22	23
	B	0.86	193	25	75	14	7	35
	C	0.92	170	28	120	28	12	48
Bernow	A	0.5	477	11	31	1	12	1
	B	0.65	374	14	41	9	11	11
	C	0.54	444	11	33	6	11	5
Grant	A	0.72	556	16	57	10	8	11
	B	0.69	433	20	71	14	9	19
	C	0.71	375	18	71	12	7	17
Pond Creek	A	0.72	556	18	56	10	8	9
	B	0.71	391	22	75	16	9	17
	C	0.7	381	20	76	16	9	16
Ashport	A	0.67	495	21	58	7	12	10
	B	0.7	497?	16	47	11	9	13
	C	0.44	396	10	34	5	12	3

Appendix A. Continued.

SOIL	Diagnostic Horizon	% TiO2	mg kg-1 Zr	Pb	Zn	Cu	Co	Ni
Parsons	A	0.92	542	34	52	13	16	21
	B	0.88	324	37	58	20	22	41
	C	0.88	293	87	69	26	20	57
Osage	A	0.9	225	32	140	23	16	34
	B	0.9	239	25	113	22	14	32
	C	0.86	227	25	122	21	14	36
Summit	A	0.82	279	33	75	8	35	50
	B	0.81	260	29	73	8	37	57
	C	0.82	255	21	73	9	22	45
Stigler	A	0.84	693	16	47	23	6	2
	B	0.88	537	21	55	12	6	12
	C	0.88	659	39	40	8	30	12
Sallisaw	A	0.87	636	19	58	14	12	8
	B	0.88	527	20	53	9	31	11
Burleson	A	0.79	375	22	91	15	13	29
	AB	0.78	317	22	110	17	13	44
	AC1	0.78	312	19	107	16	8	39
Clarksville	A	0.7	380	21	64	11	13	12
	B	0.55	252	12	69	4	5	6
	C	0.61	225	40	169	10	2	24
average		0.68	365	19	66	14	13	19
stdev		0.20	148	11	28	14	8	16
max		1.11	731	87	169	127	44	78
min		0.20	4	2	26	1	1	1

Appendix B. Metal concentration measured by XRF analysis in total soil and clay fraction.

FeT (total Fe as FeO+Fe2O3) and TiO2 in %; other metals in mg kg-1

		Depth	Total soil (< 2000 um)									Clay fraction (< 2 um)								
	Horizon	(cm)	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni
Carnasaw	A	0-6	4.61	1.01	455	29	29	63	8	19	25	6.53	1.26	187	28	16	168	129	49	47
	E	6-18	5.09	1.04	466	31	26	59	7	16	23	6.53	1.39	196	31	18	160	102	47	44
	Bt1	18-41	7.55	0.93	231	27	23	92	17	8	38	8.69	0.89	152	24	19	123	61	12	47
	Bt2	41-61	7.77	0.85	199	26	25	68	11	5	31	7.50	0.80	140	24	17	89	50	6	38
	Btss3	61-112	7.99	0.81	188	26	23	76	15	7	34	7.86	0.86	143	25	18	95	44	8	43
	C1	112-174	7.40	0.88	176	31	28	77	15	8	35	6.84	0.82	138	28	17	88	55	9	40
	Cr2	174-220	7.74	0.93	172	36	29	121	31	10	48	7.28	0.76	134	32	19	139	80	12	46
Dalhart	A	0-28	1.15	0.28	173	12	11	37	2	12	1	4.87	0.51	143	30	34	203	164	19	27
	BA	28-36	1.59	0.30	151	13	11	43	3	14	2	5.72	0.53	138	29	31	185	106	16	32
	Bt1	36-75	3.15	0.49	230	20	15	67	9	11	6	6.08	0.51	144	32	32	171	101	17	33
	Bt2	75-101	3.54	0.62	287	25	19	75	15	9	13	6.32	0.58	152	35	32	173	100	20	34
	Bk3	101-128	3.89	0.65	297	29	21	81	19	11	16	6.41	0.64	146	34	25	163	89	12	35

Appendix B. Continued.

FeT (total Fe as FeO+Fe2O3) and TiO2 in %; other metals in mg kg-1

		Depth	Total soil (< 2000 um)									Clay fraction (< 2 um)								
	Horizon	(cm)	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni
	Btk4	128-163	3.78	0.58	263	24	18	77	15	8	17	6.16	0.54	143	27	24	158	106	12	33
	BCk	163-187	2.88	0.50	225	20	14	63	13	9	10	5.10	0.57	145	31	27	161	94	15	38
Dennis	A	0-33	3.37	0.86	469	30	15	62	8	9	15	7.43	1.04	177	42	31	169	87	20	51
	AB	33-49	5.54	0.95	414	30	20	57	15	16	23	9.23	0.96	180	39	32	134	83	24	56
	BA	49-71	5.08	0.97	452	31	21	50	8	17	20	8.55	1.10	203	37	38	113	59	36	50
	Bt1	71-94	5.75	0.86	349	31	28	60	10	17	29	7.66	0.83	172	34	27	108	47	22	53
	Bt2	94-129	6.90	0.88	326	35	33	72	15	23	28	7.79	0.85	172	33	30	122	45	27	46
	2C1	129-174	7.72	0.93	294	27	31	73	14	36	43	8.04	0.99	170	28	37	116	37	44	62
	2C2	174-190	10.08	0.79	204	28	42	89	13	60	65	9.51	0.75	142	27	37	117	24	57	79
	2C3	190-200	7.48	0.81	186	31	23	88	13	13	63	7.97	0.80	138	32	24	107	33	13	74
Durant	A	0-18	2.35	0.92	717	31	18	47	10	11	7	6.83	1.21	301	30	37	135	76	34	32
	BA	18-32	3.29	1.01	655	31	18	56	8	11	11	6.83	1.28	310	34	32	138	148	20	36

Appendix B. Continued.

FeT (total Fe as FeO+Fe2O3) and TiO2 in %; other metals in mg kg-1

		Depth	Total soil (< 2000 um)									Clay fraction (< 2 um)								
	Horizon	(cm)	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni
	Bt1	32-59	4.38	1.03	561	30	20	67	13	13	19	7.46	1.20	317	35	32	125	107	20	39
	Bt2ss	59-82	4.37	1.07	560	35	21	66	13	13	18	7.20	1.27	336	43	31	123	86	21	37
	Bt3ss	82-103	4.26	1.08	552	38	21	68	10	17	22	7.00	1.26	326	45	28	126	48	24	45
	Bt4	103-132	4.27	1.13	545	38	19	75	13	18	26	6.81	1.30	336	45	25	132	93	21	47
	Bt5	132-162	4.15	1.13	559	35	17	74	13	11	27	6.75	1.32	351	41	24	140	67	13	51
	2Btkbss	162-195	4.33	1.10	562	38	18	74	16	14	28	6.89	1.30	352	42	23	134	41	16	53
Kirkland	Ap	0-20	2.39	0.71	560	34	18	52	10	21	10	6.69	0.78	165	39	38	142	103	24	36
	Bt1	20-47	3.35	0.70	453	34	17	63	13	10	15	6.75	0.69	137	33	24	128	99	20	39
	Bt2	47-71	3.89	0.72	410	34	19	70	16	11	17	6.88	0.69	151	34	24	131	76	18	38
	Bt3	71-104	3.85	0.72	393	32	18	70	17	10	21	6.74	0.70	141	30	23	127	59	16	36
	Bt4	104-127	4.09	0.73	358	33	19	71	16	12	24	6.90	0.70	139	29	23	130	45	17	38
	Bt5	127-152	4.19	0.72	360	33	19	73	18	14	23	7.06	0.71	134	30	22	129	51	15	39

Appendix B. Continued.

FeT (total Fe as FeO+Fe2O3) and TiO2 in %; other metals in mg kg-1

		Depth	Total soil (< 2000 um)									Clay fraction (< 2 um)								
	Horizon	(cm)	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni	FeT	TiO2	Zr	Y	Pb	Zn	Cu	Co	Ni
	Bt6	152-188	4.31	0.71	280	31	17	68	22	14	27	6.46	0.64	119	26	22	105	43	17	40
	Bt7	188-216	4.44	0.79	240	34	15	75	19	12	33	6.46	0.71	129	30	24	112	50	15	44
	2Cr	216-246	4.77	0.84	249	36	20	83	12	15	30	7.41	0.81	153	32	27	126	34	21	50
Tillman	Ap	0-22	2.62	0.70	559	32	19	62	17	11	12	7.09	0.81	161	42	45	183	115	22	41
	BA	22-33	4.10	0.68	411	31	24	81	19	12	21	7.38	0.69	153	38	42	170	121	18	40
	Bt1	33-46	4.39	0.67	372	30	26	87	20	9	20	7.58	0.71	152	37	43	172	135	19	42
	Bt2	46-85	4.51	0.66	350	27	34	89	22	11	20	7.71	0.72	150	33	56	174	138	17	46
	Btk3	85-129	5.08	0.68	304	28	48	99	30	14	26	8.01	0.73	144	30	70	187	80	18	47
	BC	129-152	6.21	0.72	244	32	51	134	30	16	33	7.83	0.77	141	31	56	180	67	21	45
	2Cr	152-200	5.41	0.82	247	31	23	96	15	18	35	7.32	0.78	141	29	31	143	52	23	51

Appendix C. Soil chemical properties.

	Horizon	Depth cm	air dry moist %	OC %	pH	EC dSm-1	Fe2O3 %	Exch Bases cmol kg-1				Ex acids cmol/ kg-1	Base saturation	CEC cmol/ kg-1	CaCO3 %
								Ca	Mg	K	Na				
Carnasaw	A	0-6	1.4	2.2	7.4	0.68	0.29	15.4	0.9	0.3	1.8	9.5	66.0	27.8	--
	E	6-18	1.2	0.8	5.8	0.28	0.30	4.0	1.1	0.4	0.8	6.9	48.0	13.2	--
	Bt1	18-41	3.8	0.4	5.8	0.07	0.30	1.6	4.5	0.5	1.3	28.5	21.5	36.2	--
	Bt2	41-61	4.9	0.3	6.0	0.06	0.30	2.4	4.8	0.4	1.0	39.0	18.1	47.6	--
	Btss3	61-112	4.7	0.2	6.5	0.06	0.33	1.4	4.5	0.4	1.4	37.1	17.2	44.8	--
	C1	112-174	4.6	0.2	6.8	0.11	0.32	0.3	5.9	0.5	1.9	33.0	20.8	41.6	--
	Cr2	174-220	3.4	0.3	6.5	0.11	0.32	1.5	6.4	1.0	2.3	26.9	29.5	38.2	--
Dalhart	A	0-28	0.9	0.3	7.56	0.25	0.07	--	--	--	--	--	--	9.4	1.5
	BA	28-36	1.7	0.6	7.72	0.39	0.08	--	--	--	--	--	--	12.4	1.6
	Bt1	36-75	4.2	0.3	7.23	0.41	0.14	--	--	--	--	--	--	12.7	1.8
	Bt2	75-101	4.5	0.5	7.41	0.20	0.16	--	--	--	--	--	--	17.8	1.9
	Bk3	101-128	4.4	0.4	7.91	0.30	0.19	--	--	--	--	--	--	17.1	5.8
	Btk4	128-163	5.1	0.1	8.01	0.31	0.18	--	--	--	--	--	--	19.6	5.2
	BCk	163-187	3.5	0.2	7.96	0.32	0.15	--	--	--	--	--	--	14.7	2.5

Appendix C. Continued.

	Horizon	Depth cm	air dry moist %	OC %	pH	EC dSm-1	Fe2O3 %	Exch Bases cmol kg-1				Ex acids cmol/ kg-1	Base saturation	CEC cmol/ kg-1	CaCO3 %
								Ca	Mg	K	Na				
Dennis	A	0-33	2.3	1.7	5.7	0.26	0.31	6.3	3.5	0.2	1.4	13.8	45.3	25.3	--
	AB	33-49	2.2	0.8	5.9	0.36	0.33	2.9	2.9	0.2	1.6	13.4	35.9	20.9	--
	BA	49-71	1.9	0.4	6.3	0.29	0.31	3.1	3.0	0.8	1.8	10.4	45.9	19.1	--
	Bt1	71-94	4.2	0.3	6.9	0.47	0.33	6.6	8.3	0.3	2.8	10.5	63.2	28.5	--
	Bt2	94-129	5.1	0.2	6.9	0.60	0.33	10.0	9.6	0.4	2.4	7.8	74.3	30.2	--
	2C1	129-174	3.4	0.2	7.2	0.69	0.31	7.9	7.4	0.2	2.2	8.0	68.8	25.6	--
	2C2	174-190	5.8	0.2	7.1	0.71	0.31	12.6	11.6	0.6	4.2	9.9	74.6	38.9	--
	2C3	190-200	7.4	0.1	7.1	0.80	0.35	18.9	15.0	0.9	5.1	10.9	78.5	50.8	--
Durant	A	0-18	2.4	1.8	7.5	0.3	0.2	--	--	--	--	--	--	11.3	0.5
	BA	18-32	3.4	1.2	7.3	0.3	0.2	--	--	--	--	--	--	21.4	0.6
	Bt1	32-59	5.0	0.7	7.4	0.1	0.3	--	--	--	--	--	--	28.8	0.5
	Bt2ss	59-82	5.0	0.6	7.7	0.1	0.3	--	--	--	--	--	--	14.8	1.2
	Bt3ss	82-103	5.3	0.5	7.4	0.3	0.3	--	--	--	--	--	--	13.6	0.8
	Bt4	103-132	5.4	0.4	8.0	0.6	0.3	--	--	--	--	--	--	15.7	1.6
	Bt5	132-162	5.2	0.3	8.1	0.7	0.3	--	--	--	--	--	--	25.6	0.5

Appendix C. Continued.

	Horizon	Depth cm	air dry moist %	OC %	pH	EC dSm-1	Fe2O3 %	Exch Bases cmol kg-1				Ex acids cmol/ kg-1	Base saturation	CEC cmol/ kg-1	CaCO3 %
								Ca	Mg	K	Na				
	2Btkbss	162-195	5.3	0.1	8.4	0.8	0.3	--	--	--	--	--	--	19.9	1.9
Kirkland	Ap	0-20	3.6	1.2	7.2	0.3	0.13	--	--	--	--	--	--	18.3	1.3
	Bt1	20-47	6.3	0.9	7.5	0.2	0.14	--	--	--	--	--	--	19.5	2.1
	Bt2	47-71	7.4	0.7	8.1	0.3	0.16	--	--	--	--	--	--	24.2	2.4
	Bt3	71-104	7.0	0.5	8.3	0.6	0.13	--	--	--	--	--	--	20.9	3.5
	Bt4	104-127	7.5	0.4	8.2	0.9	0.15	--	--	--	--	--	--	22.0	5.4
	Bt5	127-152	7.2	0.3	8.0	1.8	0.16	--	--	--	--	--	--	15.1	4.2
	Bt6	152-188	6.6	0.2	7.7	2.4	0.20	--	--	--	--	--	--	16.0	14.6
	Bt7	188-216	6.0	0.2	9.2	2.5	0.27	--	--	--	--	--	--	9.2	12.4
	2Cr	216-246	5.6	0.2	8.0	2.3	0.27	--	--	--	--	--	--	12.5	5.2
Tillman	Ap	0-22	1.6	0.7	6.5	0.82	0.09	--	--	--	--	--	--	16.2	1.7
	BA	22-33	3.2	0.7	7.0	0.82	0.25	--	--	--	--	--	--	21.5	2.1
	Bt1	33-46	3.7	0.7	6.9	0.59	0.14	--	--	--	--	--	--	21.3	2.3
	Bt2	46-85	3.4	0.5	7.0	0.40	0.24	--	--	--	--	--	--	21.6	2.6

Appendix C. Continued.

Horizon	Depth cm	air dry moist %	OC %	pH	EC dSm-1	Fe2O3 %	Exch Bases cmol kg-1				Ex acids cmol/ kg-1	Base saturation	CEC cmol/ kg-1	CaCO3 %
							Ca	Mg	K	Na				
Btk3	85-129	3.1	0.4	7.4	0.52	0.26	--	--	--	--	--	--	19.3	3.2
BC	129-152	3.8	0.3	8.3	0.64	0.12	--	--	--	--	--	--	18.2	3.2
2Cr	152-200	3.1	0.2	7.8	0.80	0.14	--	--	--	--	--	--	19.6	3.8

Appendix D. Clay mineralogy data.

	Horizon	Depth	clay mineral relative peak height						
		(cm)	mont.	int m-v	verm.	illite	kaolin.	chlorite	quartz
Carnasaw	A	0-6			3	2	3		1
	E	6-18			3	2	3		2
	Bt1	18-41			3	1	4		t†
	Bt2	41-61			3	1	4		t
	Btss3	61-112		1	2	1	4	t	t
	C1	112-174			3	1	4	t	t
	Cr2	174-220		1		3	4		t
Dalhart	A	0-28	2			2	3	t	1
	BA	28-36	1			4	3		1
	Bt1	36-75	2			4	3		1
	Bt2	75-101	2			3	3		1
	Bk3	101-128	1			3	3	t	1
	Btk4	128-163		2		3	3	t	t
	BCk	163-187	2	1		2	3		t
Dennis	A	0-33			3	1	5		1
	AB	33-49	1		3	1	5		1
	BA	49-71	1			1	5		1
	Bt1	71-94	1		1	1	5		1
	Bt2	94-129	2	1	2	1	4		t
	2C1	129-174	t		1	1	5	t	t
	2C2	174-190	1	1	2	t	5	t	t
	2C3	190-200			4	t	4	1	t

Appendix D. Continued.

	Horizon	Depth	clay mineral relative peak height						
		(cm)	mont.	int m-v	verm.	illite	kaolin.	chlorite	quartz
Durant	A	0-18	3				4		1
	BA	18-32	4				3		1
	Bt1	32-59	4				3		t
	Bt2ss	59-82	3				3	t	t
	Bt3ss	82-103	3				3	t	t
	Bt4	103-132	3				3	t	t
	Bt5	132-162	4				1	1	t
	2Btkbss	162-195	5				2		t
Kirkland	Ap	0-20	3			3	2		2
	Bt1	20-47	5			2	2		1
	Bt2	47-71	3			3	2		1
	Bt3	71-104	5			2	2		1
	Bt4	104-127	4			2	3		1
	Bt5	127-152	4			2	2	t	1
	Bt6	152-188		2	2	2	3	t	1
	Bt7	188-216			2	2	3	t	t
	2Cr	216-246			2	3	3	t	t
Tillman	Ap	0-22			1	5	2		1
	BA	22-33			1	4	2		1
	Bt1	33-46	1		1	5	2		t
	Bt2	46-85	t		1	5	2		t
	Btk3	85-129	t		1	4	1	t	t
	BC	129-152	t		1	4	1	t	t
	2Cr	152-200	t		2	3	1	t	t

† = trace amount

Appendix E. % Minerals > 2.72 Mg m-3 in the 250 - 106um fraction and 106 - 53um fraction.

Ocular grid method at 40x and 100x

	Horizon	Depth (cm)	RA†	ZR	TM	QZ	FP	A FP	RU	OP	FE	FS	BT	CA	AP	HN	SP	n‡
Carnasaw	A	0-6	92.7	§t	2.1	-	4.3	-	-	-	-	-	-	-	-	t	-	667.0
	E	6-18	95.5	t	t	-	3.3	-	-	-	-	-	-	-	-	t	-	671.0
	Bt1	18-41	92.2	t	3.7	-	3.3	-	t	-	-	-	t	-	-	-	-	269.0
	Bt2	41-61	98.0	2.4	1.0	-	t	-	-	-	-	-	-	-	-	-	-	757.0
	Btss3	61-112	95.8	t	1.8	-	-	-	-	-	-	-	-	-	-	-	-	166.0
	C1	112-174	99.6	t	t	-	-	-	t	-	-	-	-	-	-	-	-	880.0
	Cr2	174-220	99.6	-	t	-	-	-	-	-	-	-	-	-	-	-	-	578.0
Dalhart	A	0-28	-	65.0	18.8	4.4	2.0	t	-	4.0	3.2	-	-	-	-	-	1.7	632.0
	BA	28-36	-	63.3	19.0	2.7	7.3	1.1	-	1.7	4.2	-	-	-	-	-	t	449.0
	Bt1	36-75	-	56.2	25.5	1.2	1.7	2.9	t	t	11.4	-	-	-	-	-	t	518.0
	Bt2	75-101	-	60.2	22.9	1.8	2.2	1.0	-	2.2	8.4	-	-	-	-	-	1.2	490.0
	Bk3	101-128	-	59.5	24.4	2.4	3.4	1.1	t	t	7.9	-	-	-	-	-	t	378.0

Appendix E. Continued.

	Horizon	Depth (cm)	RA†	ZR	TM	QZ	FP	A FP	RU	OP	FE	FS	BT	CA	AP	HN	SP	n‡
	Btk4	128-163	-	58.7	28.4	3.8	2.6	3.8	-	-	2.4	-	-	-	-	-	t	501.0
	BCk	163-187	-	53.9	28.7	5.1	3.2	4.1	-	1.5	1.9	-	-	-	-	-	t	590.0
Dennis	A	0-33	45.3	2.8	7.0	7.1	6.4	31.4	t	-	-	-	-	-	-	t	-	636.0
	AB	33-49	48.7	3.2	8.0	6.2	8.2	23.6	t	-	-	-	t	-	-	t	-	501.0
	BA	49-71	44.7	2.5	7.4	4.4	12.5	27.8	1.0	-	-	-	t	-	-	t	-	479.0
	Bt1	71-94	53.8	7.9	5.5	6.0	3.6	20.0	2.1	-	-	-	-	-	-	1.1	-	470.0
	Bt2	94-129	56.5	4.9	5.4	6.8	3.2	23.1	t	-	-	-	t	-	-	-	-	472.0
	2C1	129-174	40.1	3.5	2.4	6.1	5.6	40.0	t	-	-	-	t	-	-	1.3	-	998.0
	2C2*	174-190	55.1	2.3	5.9	6.9	6.2	17.7	t	-	-	-	2.8	-	-	1.9	-	741.0
	2C3*	190-200	68.9	2.5	6.9	6.9	1.7	-	t	-	-	-	t	-	-	1.3	-	476.0
Durant	A	0-18	-	4.3	36.7	5.2	t	-	3.9	34.9	14.2	-	-	-	-	-	-	232.0

* biological organisms = 1.3% in 2C2 horizon and 10.1% in 2C3 horizon (snails and spongelike creatures)

Appendix E. Continued.

	Horizon	Depth (cm)	RA†	ZR	TM	QZ	FP	A FP	RU	OP	FE	FS	BT	CA	AP	HN	SP	n‡
	BA	18-32	-	3.7	37.8	12.0	7.1	-	1.9	28.5	9.0	-	-	-	-	-	-	267.0
	Bt1	32-59	-	2.8	24.8	6.4	3.7	-	-	31.2	31.2	-	-	-	-	-	-	109.0
	Bt2ss	59-82	-	t	34.0	5.6	7.6	-	1.4	34.0	16.7	-	-	-	-	-	-	144.0
	Bt3ss	82-103	-	3.6	24.1	15.0	4.5	t	t	22.9	28.6	-	-	-	-	-	-	419.0
	Bt4	103-132	-	4.6	32.7	6.5	3.3	-	-	45.8	7.2	-	-	-	-	-	-	153.0
	Bt5	132-162	-	3.8	26.6	4.6	8.6	-	t	37.1	10.4	-	-	-	7.5	-	-	603.0
	2Btkbss	162-195	-	1.4	20.1	-	t	11.4	t	18.3	18.3	-	-	-	28.1	-	-	437.0
Kirkland	Ap	0-20	-	20.9	33.5	t	12.8	5.7	1.5	24.2	t	-	-	-	-	-	-	594.0
	Bt1	20-47	-	18.7	36.4	1.8	8.6	4.7	1.4	32.3	t	-	-	-	-	-	-	514.0
	Bt2	47-71	-	16.4	38.3	1.1	6.6	4.9	t	30.2	t	-	-	t	-	-	-	530.0
	Bt3	71-104	-	21.1	31.2	4.1	5.6	5.6	1.3	29.0	t	-	-	1.3	-	-	-	535.0
	Bt4	104-127	-	11.1	32.1	2.6	1.1	11.6	1.5	32.1	t	-	-	1.1	-	-	-	620.0
	Bt5	127-152	-	12.2	18.0	11.5	28.8	1.4	1.9	22.4	t	-	-	3.6	-	-	-	722.0

Appendix E. Continued.

	Horizon	Depth (cm)	RA†	ZR	TM	QZ	FP	A FP	RU	OP	FE	FS	BT	CA	AP	HN	SP	n‡
	Bt6	152-188	-	3.7	6.0	3.7	1.6	-	t	9.4	t	-	-	74.4	-	-	-	434.0
	Bt7	188-216	-	t	3.6	4.3	t	-	t	t	-	-	-	86.0	-	-	-	564.0
	2Cr	216-246	-	t	t	1.8	-	t	-	t	-	-	-	95.8	-	-	-	720.0
Tillman	Ap	0-22	-	21.4	34.1	1.2	t	8.1	1.2	22.8	3.2	6.6	-	-	-	-	1.0	602.0
	BA	22-33	-	19.6	36.0	t	2.0	6.4	t	30.7	t	3.0	-	-	-	-	t	592.0
	Bt1	33-46	-	27.0	32.2	t	1.3	3.5	1.1	27.2	4.7	2.0	-	-	-	-	t	448.0
	Bt2	46-85	-	30.0	26.2	1.1	3.8	1.1	3.1	30.3	2.2	1.8	-	-	-	-	t	557.0
	Btk3	85-129	-	33.3	19.5	t	6.3	4.7	1.1	27.0	4.5	3.4	-	-	-	-	t	445.0
	BC	129-152	-	32.7	24.9	t	3.3	3.9	1.4	26.1	3.5	3.5	-	-	-	-	t	486.0
	2Cr	152-200	-	t	9.0	-	-	24.7	-	7.3	6.5	48.1	4.3	t	-	-	-	507.0

† RA = shale fragments, ZR = zircon, TM = tourmaline, QZ = quartz, FP = plagioclase feldspar, A PF = altered plagioclase feldspar, RU = rutile, OP = opaque FeTi oxides, FE = iron oxides, FS = sanadine, BT = biotite, CA = calcite, AP = apatite, HN = hornblende,

Appendix E. Continued.

Horizon	Depth (cm)	RA†	ZR	TM	QZ	FP	A FP	RU	OP	FE	FS	BT	CA	AP	HN	SP	n‡

SP = sphene

‡ n = number of grains counted in each sample

§ t = < 1.0 %

Appendix F. Particle size analysis.

	Horizon	Depth	PARTICLE SIZE ANALYSIS (%) um									clayfree	Texture
		cm	1000	500	250	106	53	20	5	2	< 2	sand %	
Carnasaw	A	0-6	7.4	5.7	3.6	9.2	13.9	19.8	21.2	7.3	11.8	45.2	L
	E	6-18	6.8	5.3	2.9	8.1	7.9	25.8	21.7	8.5	13.0	35.6	SiL
	Bt1	18-41	1.0	0.8	0.4	1.6	3.1	6.2	13.1	7.5	66.3	18.0	C
	Bt2	41-61	0.5	0.6	0.4	1.2	2.4	4.6	11.7	7.2	71.4	17.8	C
	Btss3	61-112	0.6	0.4	0.3	1.2	2.6	4.9	10.4	8.1	71.4	17.9	C
	C1	112-174	1.4	0.5	0.5	0.8	0.9	3.6	14.8	12.6	65.8	11.7	C
	Cr2	174-220	2.9	2.8	1.4	0.9	0.5	3.8	21.7	18.6	47.1	16.2	SiC
Dalhart	A	0-28	0.0	2.8	31.7	42.6	8.8	5.2	1.0	0.2	7.4	93.1	LS
	BA	28-36	0.0	2.2	30.1	41.4	7.3	5.1	1.5	0.8	11.3	91.6	LS
	Bt1	36-75	0.0	2.4	26.5	23.8	6.1	11.0	4.9	1.0	24.1	77.7	SCL
	Bt2	75-101	0.0	1.2	16.9	19.4	6.2	16.5	9.1	2.7	27.7	60.7	CL
	Bk3	101-128	0.1	1.3	8.5	11.6	6.3	21.4	13.3	5.0	32.6	41.2	CL
	Btk4	128-163	0.9	2.3	10.9	15.3	7.7	18.8	8.1	4.2	31.7	54.4	CL
	BCk	163-187	0.1	2.8	19.3	26.8	8.7	12.5	6.1	1.3	22.4	74.4	SCL
Dennis	A	0-33	1.7	1.4	2.3	16.9	12.9	33.6	8.6	2.3	19.1	44.2	L
	AB	33-49	8.1	5.4	1.8	14.9	11.2	19.6	14.3	4.6	20.3	51.8	L
	BA	49-71	4.9	3.3	1.7	13.9	10.2	44.4	3.6	0.4	17.8	41.3	L
	Bt1	71-94	2.4	1.8	1.0	7.3	5.1	39.1	6.4	1.6	35.2	27.2	SiCL
	Bt2	94-129	2.9	2.7	1.5	8.3	5.5	33.7	4.6	15.1	39.4	28.1	CL
	2C1	129-174	7.7	4.0	2.5	14.0	7.9	22.0	4.4	2.7	35.0	55.4	CL
	2C2	174-190	5.8	3.6	2.3	11.2	6.1	11.3	2.4	3.2	54.5	63.2	C
	2C3	190-200	0.7	0.7	0.7	6.1	3.6	14.2	3.1	5.1	65.9	34.5	C

Appendix F. Continued.

	Horizon	Depth	PARTICLE SIZE ANALYSIS (%) um									clayfree	Texture
		cm	1000	500	250	106	53	20	5	2	< 2	sand %	
Durant	A	0-18	0.2	0.5	1.6	10.9	11.2	42.7	10.1	2.1	20.6	30.8	SiL
	BA	18-32	0.2	0.3	1.2	9.2	9.5	31.8	13.0	2.9	31.8	30.0	CL
	Bt1	32-59	0.3	0.3	0.8	6.5	6.7	24.4	12.1	3.6	45.3	26.7	C
	Bt2ss	59-82	0.3	0.3	0.8	5.5	6.5	24.7	12.8	3.4	45.5	24.7	SiC
	Bt3ss	82-103	0.0	0.3	0.9	5.9	6.4	24.1	12.8	4.9	44.7	24.4	SiC
	Bt4	103-132	0.2	0.4	0.9	5.9	6.9	24.1	11.6	4.0	46.0	26.5	C
	Bt5	132-162	0.5	0.3	3.2	7.0	5.3	25.4	10.6	3.7	43.9	29.1	SiC
	2Btkbss	162-195	0.3	0.3	0.9	6.1	7.1	24.8	11.5	3.9	44.9	26.8	C
Kirkland	Ap	0-20	0.1	0.2	0.5	2.4	19.9	45.8	16.8	3.1	24.4	26.0	SiL
	Bt1	20-47	0.1	0.2	0.4	1.7	14.7	33.7	17.0	4.7	37.0	23.6	SiCL
	Bt2	47-71	0.1	0.1	0.2	0.8	6.1	28.6	16.6	5.6	42.0	12.4	SiC
	Bt3	71-104	1.0	0.6	0.4	0.9	6.0	26.7	17.3	6.4	41.4	15.0	SiCL
	Bt4	104-127	0.6	0.7	0.9	1.4	6.0	23.6	16.8	6.2	44.0	17.1	SiCL
	Bt5	127-152	0.4	0.4	0.4	1.1	6.6	24.6	15.8	5.2	45.8	16.3	SiCL
	Bt6	152-188	0.3	0.5	0.5	0.9	5.1	19.4	15.9	8.0	49.6	14.4	SiCL
	Bt7	188-216	0.7	0.8	0.7	0.8	2.6	14.5	23.2	11.2	45.8	10.3	SiCL
	2Cr	216-246	0.2	0.3	0.2	0.4	2.8	14.6	27.2	11.6	42.9	6.8	SiCL
Tillman	Ap	0-22	0.1	0.2	0.2	2.4	17.6	44.9	10.3	2.2	22.2	26.3	L
	BA	22-33	0.1	0.1	0.2	2.0	13.0	31.3	10.9	3.5	38.9	25.2	SiCL
	Bt1	33-46	0.1	0.1	0.2	2.1	12.8	26.8	10.8	4.2	42.9	26.7	SiC
	Bt2	46-85	0.0	0.1	0.2	2.7	16.8	25.9	7.9	3.9	42.4	34.4	C
	Btk3	85-129	1.8	1.0	0.8	4.3	18.4	21.1	5.9	5.3	41.9	44.9	C
	BC	129-152	0.7	0.7	0.9	3.9	9.5	15.0	9.4	9.3	51.0	31.8	C
	2Cr	152-200	0.1	0.2	0.3	0.5	2.0	30.5	24.8	11.9	29.5	4.4	SiCL

Appendix G. Field morphology of selected soils.

Horizon	Depth cm	Color Moist	Structure†	Texture‡	Consistence§	Boundary!	Reaction#	Special Features††
			Carnasaw: clayey, mixed, thermic Typic Hapludult					
A	0-6	10YR4/5	1fgr	sil	vfr	as		gravels 8% (<1.5cm); myf+vf&cnm roots; fwc&cnm tubular pores
E	6-18	7.5YR5/4	1fgr	gsil	vfr	as		gravels 20%; myf+vf&cnm roots; fyc&cnvf tubular pores
Bt1	18-41	5YR5/6	2mpr-2msbk	c	fi	cw		gravels 1%; fwffl 7.5YR6/6 mottles; fwf&cnm roots; fwc&myf continuous clay films
Bt2	41-61	5YR5/6	2mpr-2msbk	c	fi	cw		gravels 10% (3cm); cnmdt 5YR6/4 mottles; fwvf+m roots; fwdt pressure faces; fwf tubular pores; continuous clay films on verticle faces
Btss3	61-112	5YR4/6	2cpr-2msbk	c	vfi	gw		gravels 5%; fwf+m roots; mympt 5YR6/2 + 5YR6/6 mottles; fwf pores; fwdt pressure faces; clay films same as Bt2
C1	112-114	5YR7/1	m	c	vfi	cw		shale gravels 10%; fwvf roots; cnfpt&fwmpt 5YR4/6 mottles
Cr2	114-220	7.5YR7/1	m	egc	efi			thin bedded (1-2cm); shale-tilted 20-30 degrees; highly fractured, (1-2cm) fractures 50cm apart, 2-3cm wide, filled w/clay
			Dalhart: fine-loamy, mixed, mesic Aridic Haplustalf					
A	0-28	10YR5/3	1fsbk	fsl	vfr	cs	--	myf roots
BA	28-36	10YR4/3	1fpr	fsl	vfr	cs	sl	myf roots

Appendix G. Continued.

Horizon	Depth	Color	Structure†	Texture‡	Consistence§	Boundary!	Reaction#	Special Features††
	cm	Moist						
Bt1	36-75	7.5YR3/4	2mpr	scl	fr	cs	sl	cndt clay films; cnf roots; fwf truncated pores; fwf worm casts
Bt2	75-101	7.5YR4/4	3mpr	cl	vfi	cs	sl	mydt clay films; cnf roots; fwf truncated pores
Bk3	101-128	7.5YR6/6 7.5YR4/6	3mpr	l	vfi	gs	vi	fwdt clay films; cnf roots; cnm rounded CaCO3 soft bodies; fwf+m rounded nodules of CO3; fwm&cnf truncated pores
Btk4	128-163	10YR5/6 10YR4/4	3mpr	cl	vfi	gs	st	cndt clay films; fwf roots; thick vertical streaks of CaCO3 along ped faces, 40% hard 60% soft; fwm&cnf truncated pores
BCk	163-187	5YR5/6 5YR4/6	2mpr	sl	fi	aw	st	fwf roots; fwf irregular soft-bodies CaCO3; cnm&myf truncated pores; fwft clay films
Ckm	187+	5YR5/8	m	l	fi		e	fwf&cnm truncated pores
Dennis: fine, mixed, thermic Aquic Paleudoll								
A	0-33	10YR3/2	2f-mgr	sil	vfr	gs		myf+vf <1% sandstone frags (<2cm); cnf&fwm tubular pores
AB	33-49	10YR4/2	1fsbk	gsil	vfr	gs		cnfft 5YR5/6, fwfft 5YR5/4 mottles; cnf&fwm tubular pores; 20% sandstone frags (<2cm); fwf FeMn nodules <5%
BA	49-71	10YR6/4	2f-msbk	gsicl	fr	as		myf+m FeMn nodules (25%); cnf tubular pores; <5% sand stone frags (<2cm); saturated

Appendix G. Continued.

Horizon	Depth cm	Color Moist	Structure†	Texture‡	Consistence§	Boundary¶	Reaction#	Special Features††
Bt1	71-94	10YR6/3	2cpr-3msbk	c	vfi	gs		fwfdt&mymdt 10YR5/6, 7.5YR5/6 mottles; cnf&fwm FeMn nodules (15%); cndt 10YR4/2 clay films on vertical faces
Bt2	94-129	10YR6/3	2cpr-3msbk	c	vfi	aw		fwvfdt&fwcdt 10YR4/2 clay films on prism faces; same mottles as Bt1; cnf&fwm FeMn nodules (10%)
2C1	129-174	10YR5/3	m	ecbc	fi	cw		40% sandstone cobbles, 30% sandstone gravels 10YR4/6; mymdt 10YR5/3, 7.5YR5/8 mottles; mydt FeMn films on rock surfaces
2Css2	174-190	7.5YR4/6	m	c	vfi	gw		cndt discontinuous FeMn coatings on shale frags; cnmdt 10YR6/6 mottles; cnf+m FeMn nodules; fw slickensides
2C3	190-200	7.5YR5/6	m	c	vfi			fw slickensides; cnmdt 10YR6/6, 7.5YR7/2 mottles
Durant: fine, smectitic, thermic Vertic Argiustoll								
A	0-18	10YR2/1	1fsbk-2mgr	sil	vfr	cs	--	myvf&fwf pores
BA	18-32	10YR3/2	2msbk	sil	fr	cw	--	cnvf pores
Bt1	32-59	2.5Y4/2	3f-mabk	sic	vfi	gw	--	mymdt 2.5YR3/6 mottles; fwvf pores; thin continuous clay films
Btss2	59-82	2.5Y4/2	3mabk	sic	efi	gw	--	cnmdt 2.5Y5/4 & mympt 2.5YR3/6 mottles; fwvf pores; cnf slickensides & pressure faces 20-30 degrees; thick continuous clay films

Appendix G. Continued.

Horizon	Depth cm	Color Moist	Structure†	Texture‡	Consistence§	Boundary!	Reaction#	Special Features††
Btss3	82-103	2.5Y5/2	3m-cabk	sic	efi	gs	--	mymdt 2.5Y5/4 mottles; fwvf pores; mypt slickensides 20-40 degrees; thick continuous clay films
Btss4	103-132	2.5Y5/3	2mabk	sic	efi	gs	--	mymft 2.5Y5/4 mottles; cnf+m round FeMn concretions; fwvf pores; cndt slickensides 40-60 degrees; thick continuous clay films
Bt5	132-162	2.5Y5/3	2mabk	sic	efi	as	vsl	mymdt 2.5Y6/0, myfdt 2.5Y5/6; fwf&fwm FeMn concretions; fwvf pores; thick continuous clay films
2Btkbss	162-195+	2.5Y5/6	3cpr	sic	vfi		sl	cnf&cnm soft masses of CO3; cnvf&cnf CO3 nodules; few fine streaks of FeMn stains; fwf FeMn nodules; mymdt 2.5Y6/0 mottles; cnpt slickensides 50-70 degrees; thin discontinuous clay films
				Kirkland: fine, mixed, thermic Udertic Paleustoll				
Ap	0-20	10YR3/2	2msbk-2fgr	sil	vfr	aw	--	discontinuous, 1/2" to 2" plowpan
Bt1	20-47	10YR2/2	1mpr-3msbk	sic	vfi	gs	--	65% of root channels have clay films; fwf FeMn concretions
Bt2	47-70	7.5YR3/2	1c-mpr-3mabk	sic	efi	cs	--	slickensides

Appendix G. Continued.

Horizon	Depth cm	Color Moist	Structure†	Texture‡	Consistence§	Boundary!	Reaction#	Special Features††
Btk3	70-103	7.5YR3/3	1c-mpr-3mabk	sic	efi	gw	st	2% cm rounded CaCO3 concretions; fwf+m round FeMn concretions; Fe coatings on above (10YR2/2); clay films on 85% of surface; tubular continuous pores; slickensides
Bt4	103-127	7.5YR3/4	3mpr-3mabk	sic	efi	gw	st	slickensides; cnm FeMn concretions
Bt5	127-151	2.5YR3/4	2m-cpr-3mabk	sic	vfi	gw	st	inner ped faces are filled w/ 7.5YR3/3 sicl material; fwmdt 7.5YR3/6 mottles on ped faces; cnf+m&fwc FeMn concretions; fwm+c CaCO3 concretions; fw 1cm gravels
Bt6	151-187	2.5YR3/4	2cpr-3mabk	sicl	vfi	dw	st	cracks filled w/ 7.5YR3/3 sicl material from above; root channels filled w/ 10YR6/1 & 3/1 material; mottles same as Bt5; threads of CaCO3
Bt7	187-217	2.5YR3/2	2cpr-3mabk	sicl	vfi	aw	sl	cnfdt 5YR5/2 mottles along root channels; fw CaCO3 threads; open root channels 10YR3/1 & 6/1 coating on 10% of ped surface; fwmdt 7.5YR5/3 mottles; pt clay films; fwcpt 10YR3/2 mottles in old root channels
2Cr	217-245	2.5YR4/8	m	siltstone	vfi		sl	many thin strata 7.5YR7/2; highly stratified; weakly cemented; rock structure, sandy siltstone; fwvf roots in fractures; fractured 3-10cm in length; laminer

Appendix G. Continued.

Horizon	Depth cm	Color Moist	Structure†	Texture‡	Consistence§	Boundary!	Reaction#	Special Features††
Tillman: fine, mixed, thermic Typic Paleustoll								
Ap	0-22	7.5YR3/2	1mgr-2m+cpl	sil	vfr	as		myf roots
BA	22-33	5YR3/3	1msbk-1fgr	sicl	fr	cs		fwf roots
Bt1	33-46	5YR3/4	2msbk	sic	fi	gs		fwf roots
Bt2	46-85	5YR4/4	2f+mpr-2mabk	sic	fi	gs		fwf roots
Btk3	85-129	2.5YR3/6	1cpr	sic	fi	gs		fwf roots
BC	129-152	2.5YR4/6	1cpr	sic	vfi	as		
2Cr	152-200+	2.5YR4/6	m					

† 1 = weak, 2 =moderate, 3 = strong; f = fine, m = medium, c = coarse; pl = platy, gr = granular, pr = prismatic, abk = angular blocky, sbk = subangular blocky

‡ sil = silt loam, mgsil = medium gravelly silt loam, c = clay, egc = extremely gravelly clay, fsl = fine sandy loam, scl = sandy clay loam, cl = clay loam, sl = sandy laom, gsicl = gravelly silty clay loam, ecbc = extremely cobbly clay, sic = silty clay, sicl = silty clay loam, m = massive

§ vfr = very friable, fr = friable, fi = firm, vfi = very firm, efi = extremely firm

! a = abrupt, c = clear, g = gradual, d = diffuse; s = smooth, w = wavy

vsl = very silghtly effervescent, sl = slightly effervescent, e = effervescent, st = strongly effervescent, vi = violently effervescent

†† fw = few, cn = common, my = many; vf = very fine, f = fine, m = medium, c = coarse; ft = faint, dt = distinct, pt = prominent

Appendix H. Bulk density values of six soil profiles.

	Avg. 2		Avg. 4		Avg. 2		Range		Actual		Range
Carnasaw	SCS	Dalhart	SCS	Dennis	SCS	Durant	SCS	Kirkland	Analysis	Tillman	SCS
depth	Db	depth	Db	depth	Db	depth	Db	depth	Db	depth	Db
0-6	1.22	0-28	1.56	0-33	1.33	0-18	1.30-1.60	0-20	1.50	0-22	1.30-1.45
6-18	1.66	28-36	1.49	33-49	1.50	18-32	1.45-1.70	20-47	1.34	22-33	1.45-1.65
18-41	1.28	36-75	1.46	49-71	1.42	32-59	1.35-1.60	47-71	1.40	33-46	1.45-1.65
41-61	1.31	75-101	1.52	71-94	1.32	59-82	1.54	71-104	1.39	46-85	1.45-1.65
61-112	1.41	101-128	1.47	94-12	1.46	82-10	1.35-1.60	104-127	1.38	85-129	1.45-1.65
112-174	1.53	128-163	1.39	129-17	1.43	103-13	1.35-1.60	127-152	1.37	129-152	1.45-1.70
174-220		163-187	1.49	174-19	1.45	132-16	1.60	152-188	1.36	152-200	1.45-1.70
				190-200		162-195		188-216	1.40		
								216-246	1.61		

Analysis of Bt horizons for ODOT

41-112	1.39	36-101	1.66	71-129	1.59	59-82	1.54
						162-19	1.60

VITA

Brad Lee

Candidate for the Degree of

Master of Science

Thesis: TRACE ELEMENT DISTRIBUTION IN SIX OKLAHOMA BENCHMARK SOILS

Major Field: Agronomy/Soil Science

Biographical:

Personal Data: Born in Parsons, Kansas, on February 18, 1970, the son of Lloyd and Dana Lee.

Education: Graduated from McPherson High School, McPherson, Kansas in May 1988; received Bachelor of Science degree in Agronomy (minor Geology) from Oklahoma State University, Stillwater, Oklahoma in July 1992. Completed the requirements for the Master of Science degree with a major in Agronomy and a minor in Geology at Oklahoma State University in December 1994.

Professional Experience: Graduate Research Assistant, Department of Agronomy, Oklahoma State University, August 1992 to December 1992 and June 1993 to December 1994. Teaching Assistant, Department of Agronomy, Oklahoma State University, January 1993 to May 1993. Field Assistant and Laboratory Assistant, Department of Agronomy, Oklahoma State University, January 1991 to August 1992.

Professional Associations:

- American Society of Agronomy
- Soil Science Society of America
- American Association of Petroleum Geologists
  - Division of Environmental Quality