GENESIS AND LATERAL VARIABILITY OF SAND- AND SILT-MANTLED SOILS IN NORTH CENTRAL OKLAHOMA

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INTRODUCTION

Parts I and II of this dissertation have been prepared according to the format of the Soil Science Society of America Journal and will be submitted as separate manuscripts to that journal for publication.

PART I

GENESIS AND SAND MINERALOGY OF SAND- AND SILT-MANTLED SOILS IN NORTH CENTRAL OKLAHOMA

ABSTRACT

The genesis of two silt-mantled and three sand-mantled soils developed in Quaternary age sediments of the Cimarron, Arkansas, and Salt Fork of the Arkansas Rivers was investigated to assist in an on-going soil survey of Woods County, Oklahoma. Soil morphology, chemical analyses, and depth trends of selected particle sizes and sand mineralogy were used to evaluate lithologic and stratigraphic discontinuities. Significant particle size and sand mineral differences between adjacent horizons were determined by taking subsamples from the horizons of each soil site and calculating the least square means and standard errors associated with those means. The 't' statistic was used to test for significant differences between the means of adjacent horizons.

The dominant sand minerals observed were quartz, microcline feldspars, plagioclase feldspars, altered feldspars, and rock fragments (polycrystalline quartz). Heavy minerals were present in trace amounts but did not show consistent trends. Very fine sand, coarse, and medium silt were the dominant particle sizes in the silt-mantled soils. Medium and fine sand were dominant in the sand-mantled soils.

Three to five depositional events were recognized in the soil sites studied. The soil sites are silt- or sand-mantled. The silt-mantled soil sites have had additions of sediments from varied sources. The sediment sources for the sand-mantled soil sites have remained relatively constant. Two of the sand-mantled soils have buried soils with similar sand mineralogy at an approximate depth of 2 m which may be Pleistocene age.

The parent-material of the silt-mantled soil sites are from different sources. Only one of the sand-mantled soils could be separated from the other two by comparing sand mineralogy of the most recent soil parent material.

Additional index words: Lithologic discontinuity, stratigraphic discontinuity, Depth trends, Subsampling, Provenance, Quaternary, Geomorphic surfaces.

INTRODUCTION

Mineralogical studies of sand separates have been used to evaluate differences in geologic deposits (Ruhe et al., 1976) and to document lithologic discontinuities (Khangarot et al., 1971). Other methods besides sand mineralogy used to indicate lithologic discontinuities include particle size distribution and soil morphology. Price et al. (1975) suggested that best results for detecting lithologic breaks are obtained when particle size distribution, soil morphology and quartz to feldspar ratios are used concurrently. Barshad (1964) indicated the suitability of quartz to microcline ratios as well as the ratios of other resistant minerals for studying parent material uniformity.

Drees and Wilding (1973) suggested that lateral variability of elements in a given deposit should be determined before significant depth trends are indicated. It follows that the determination of lateral variability of other measurable laboratory parameters should precede statements concerning parent material homogeneity or the location of lithologic discontinuities.

The objectives of this study are to i) determine the genesis of sand- and silt-mantled soils in north central Oklahoma, by examining the soil morphology, particle size distribution and sand mineralogy; and ii) relate the soils studied to the three Quaternary deposits associated with the Cimarron, Salt Fork, and Arkansas River systems which were recognized by Fay (1965).

MATERIALS AND METHODS

The soils in five mapping delineations were sampled. The site locations and associated terrace deposits are shown in Fig. 1. Quaternary geology is as described by Fay (1965). Soil sites 1 and 4 are silt-mantled soils. Soil sites 2, 9, and 5 are sand-mantled. The soils were classified according to Soil Taxonomy (Soil Survey Staff, 1975). Soil classification, site description and vegetation are given in Table 1. The mean annual air temperature is 15°C with extremes in January and July of 2 and 28°C, respectively. The mean annual precipitation is 65 cm with very little falling during the winter. The prevailing wind direction is south and southwest. Northerly winds are as frequent as southerly winds between November and March (Oklahoma Water Resource Board, 1972).

Field

The five soil sites were located along a southwest to northeast transect. The area of each site was approximately ten hectares. Two kg, bulk samples were collected from each horizon of five pedons within each site. The five pedons were located by randomly selecting a compass heading and pacing distance. Limitations placed on pedon selection were that they must be contained within a mapping delineation and that only side slopes of sand dunes would be sampled. Six subsamples were taken from a 2 m^2 area of one of the five pedons. Subsampling procedure was similar to that described by Drees and Wilding (1973). Transition horizons were discarded from three of the six subsamples as it was felt that depth trends could be determined without them. A power soil probe was used to extract all samples. The sampling design resulted in a two-fold nested design with horizons considered as a fixed variable. Recent river sediments were collected from the Cimarron, Salt Fork and Arkansas River floodplains to determine current sand mineralogy. The Cimarron River sample was collected southwest of site 9. The Salt Fork River was sampled in two locations. The west sample was located near the border of Woods County, Oklahoma and Kansas. The east sample was collected south of site 2 near the eastern border of Woods County and the adjoining county. It was thought that the eastern sample may be mixed with ancient Arkansas River sediments. The Arkansas River floodplain was sampled near Dodge City, Kansas.

Laboratory

Physical and chemical measurements were made on three randomly selected pedons from each area. Soils were prepared for laboratory analysis as described in method 1B1 and IB1a (Soil Conservation Service, 1972). Particle size analysis was done by method 3A1 except a hydrometer was used to determine medium silt, fine silt, and clay fractions. Organic carbon was determined by method 6A1a and base saturation by method 5C2. All chemical tests were arranged in a slipped-block design (W. E. Timon, 1962, The slipped-block design, Ph.D. Dissertation, Oklahoma State University) to reduce variability due to day-to-day changes in reagents and analytical instruments. Dominant sand fractions, fine (fs) and very fine (vfs) sands for soil sites 1 and 4, and medium (ms) and fine (fs) sands for soil sites 2, 9, and 5, were saved from particle size analysis for sand mineralogy. Sand mineralogy was determined by method 7B1. Heavy liquid separation of heavy and light minerals was not done due to the very small amount of heavy minerals observed. The percentage of sand minerals present in each sample was determined by observing two hundred grains per slide. The sand fractions of calcareous soils horizons for sand mineralogy determination were separated by method 3A1 except the carbonates were not removed by 1 N sodium acetate, pH 5. The sand mineralogy was determined for all pedons sampled.

RESULTS AND DISCUSSION

Selected morphological, physical and chemical properties of the soil sites are given in Table 2.

Lithologic discontinuities were observed in three of the soil sites studied. Soil site 1 had a lithologic break at 199 cm. The underlying material is Permian age siltstone. The median particle size of soil sites 1 and 4 is between 22 and 28 μ and all horizons are extremely well sorted except horizon IIC in site 1, which is well sorted as defined by Trask (1932). The median particle size and sorting coefficients are within the range of eolian material. The thickness of the sand deposit in soil site 2 is estimated to be from six to nine meters by water well depths in the same vicinity. Soil sites 9 and 5 had buried soils at 172 and 186 cm, respectively. It is not known if they are related. The buried soils are similar to the buried Pleistocene age soils found in the Sand Hills of Texas as described by Gile (1979). Since the lower horizons below the depth of 209 and 226 cm in soil sites 9 and 5, respectively, have weak to moderate structure, roots, and root pores, it was thought that the horizons are associated with buried soils and not with stratified sediments except where stratification within the horizon was observed as in the case of horizon IIICb in soil site 9. In both areas the organic carbon does not decrease steadily with depth and increases of organic carbon deep in the soils correspond to buried B2 horizons.

The sand minerals and percentages present in each soil site are shown in Table 3. The dominant sand minerals recognized were quartz (qtz), microcline feldspars (mcln), plagioclase feldspars (plag), altered feldspars (alt. feld.) and rock fragments (rock frag.). Feldspars deformed by weathering were classified as altered feldspars. Rock fragments may also be known as polycrystalline quartz. The percentage reported for each mineral is the mean of the observations made for each horizon and laboratory duplicates. Heavy minerals were recorded when observed in the total sand fraction and also appear in Table 3. The calcareous clay aggregates were observed only when samples were not subjected to 1 N NaAc, pH 5. The aggregates effervesced and partially disintegrated when weak hydrochloric acid was applied. The aggregates were predominantly in the fine sand fraction and were stable in water.

An analysis of variance was computed for each soil site and each mineral to detect difference between sand sizes and horizons. Significant differences were observed at the 0.05 level of probability between all sand sizes for each soil site and each mineral. Hence the data for the two sand fractions, fine sand and very fine sand for soil sites 1 and 4, and medium sand and fine sand for soil sites 2, 9, and 5, are presented separately. In general, the amount of quartz and altered feldspars increased and microcline feldspars, plagioclase feldspars and rock fragments decreased as sand size decreased. Mineral differences among horizons were also detected at the 0.05 level of probability but the differences were not consistent for the minerals in each soil site. To determine where mineral differences occurred, least square means and estimates of the standard errors of the least square means were calculated for the minerals in each soil site. The 't'-test (Steel and Torrie, 1960) was used to measure mineral differences between horizons. Only adjacent horizons were compared because of the principles of superimposition and original horizontality. The horizontal, dashed lines on Table 3 show where mineral differences occur between adjacent horizons and the level of significance associated with that line.

Mineral differences between adjacent horizons in all soil sites showed the presence of lithologic or stratigraphic unconformities which were not detected by soil morphology. Soil sites 1 and 4 seem to have many stratigraphic breaks among the horizons indicating a multiple depositional history. Buried soils observed in soil sites 9 and 5 appeared to have mineral compositions similar to that of the overlying soil.

Soil homogeneity was further investigated by plotting depth trends of coarse silt for soil site 1 and 4 and the dominant sand fractions and the quartz to microcline ratio (qtz/mcln) for each soil site (Figs. 2-6). Horizontal lines indicate the presence of particle size or qtz/mcln differences between adjacent horizons and the associated significance level is given for each line. The particle size values plotted are the means of three pedons and duplicates for each area. The qtz/mcln was used as an indicator of soil uniformity as suggested by Barshad (1964). The values plotted are the means of the ratios of quartz to microcline.

The depth trends for soil site 1 (Fig. 2) show the presence of several breaks indicating soil unconformity. The discontinuities between horizons B1 and B21t and between horizons B21t and B22t are observed in both particle sizes and in the qtz/mcln. The mineral difference between the Ap and A12 horizons may be due to weathering at the surface which reduced the microcline content or a different source of material which was deposited by a similar mode as the A12 horizon. Differences in particle sizes between the B3 and IIC horizons substantiate the presence of a lithologic discontinuity but similar evidence is unavailable for the qtz/mcln.

Fig. 3 shows the depth trends for soil site 4. The coarse silt fraction of the Ap horizon is significantly different from the same fraction in the A12 horizon. The qtz/mcln does not show the same relationship. Qtz/mcln differences are also noted between the B21t and B22t horizons and between the B22t and B3 horizons, but only the latter difference is also detected in the very fine sand fraction. Other differences between horizons are shown for the fine sand fraction.

Depth trends for soil site 2 (Fig. 4) indicate that significant differences exist between horizons. The difference between the A1 and B2 horizons may be due to successional deposition or the shifting of sand by wind. The C12 horizon may have been deposited by running water as suggested by the stratification present in the C12 horizon and later covered by eolian sand.

Fig. 5 shows the depth trends for soil site 9. The particle sizes are uniform to the top of the first buried soil and are irregular below that. Only the discontinuity between the VB2b and VIC horizons is shown by both particle size depth and qtz/mcln depth trends. The uniformity of the qtz/mcln depth trends above 275 cm suggests that the source of the parent materials had not significantly changed although time and mode of deposition were different.

The depth trends for soil site 5 (Fig. 6) are similar to those of soil site 9. The qtz/mcln is uniform with depth and does not reflect the presence of buried soils indicated by soil morphology or particle size depth trends.

The sand mineralogy of recent river sediments from the Arkansas, Salt Fork of the Arkansas, and Cimarron Rivers was determined to evaluate the rivers as possible sources for the sediments associated with the soil sites studied. The means and 95% confidence intervals for selected sand minerals and qtz/mcln in the medium and fine sand fractions are given in Table 4. Significant mineral differences between river sediments were observed when the confidence interval associated with that mineral mean failed to include the mineral mean of sediments from a different river. By this method, the mineral data of the medium sand fraction allowed separation of the Arkansas, Salt Fork, and Cimarron River sediments but did not allow separation of the west and east Salt Fork samples. The mineral data of the fine sand fraction was interpreted as follows: the Arkansas sediments were different from the other river sediments, the west and east Salt Fork River samples were similar, and the east Salt Fork sample and Cimarron River sediments were similar, but the west Salt Fork and Cimarron sediments were not similar.

Because the sand mineralogy of the sediments from different parts of the Salt Fork River were similar, the current sediments of the Salt Fork River apparently have not been mixed with ancient Arkansas River sediments. The data from the medium and fine sand fractions indicate that the mineralogy from the medium sand fraction is a more reliable differentia of river sediments.

Since recent river sediments could be separated on the basis of sand mineralogy and the qtz/mcln, comparisons of similar soils were made by estimating the 95% confidence intervals of the qtz/mcln associated with the means of each horizon and sand fraction for each soil site. If the confidence interval did not include the adjacent mean, the horizons were said to be significantly different. Only similar horizons were compared in soil sites 1 and 4 and the first four horizons for soil sites 2, 9, and 5. In addition, the buried soil at approximately 2 m depth in soil sites 9 and 5 were compared.

The comparison of similar horizons in soil sites 1 and 4 is shown in Fig. 7. Apparent differences in geologic history and superimposed weathering phenomena make comparisons difficult. A geologic event common to both areas seems to have occurred between the B22t and B3 horizons of the fine sand fraction. It is unknown if this stratigraphic break is due to separate events or similar events expressed in different size fractions. The least weathered horizons, the B3 horizons, suggest that the parent material source for the two soil sites were different and supports the terrace deposit delineations proposed by Fay (1965).

Fig. 8 shows the comparison of the qtz/mcln for similar horizons in soil sites 2, 9, and 5. Interpretation of the data for the medium and fine sand fractions shows conflicting conclusions. Since the medium sand fraction of the river sediments was the more reliable differentia among sediments and is the dominant sand fraction in soil sites 2, 9, and 5, inferences will be based on the medium sand fraction. No significant qtz/mcln differences were found between soil sites 9 and 5, but soil site 2 was significantly different from sites 9 and 5. This was true for every horizon examined at soil sites 2, 9, and 5. Inference is drawn from the mineral data that the soil at site 2 developed in different parent materials than the soils at sites 9 and 5. It is possible that the soils at sites 9 and 5 developed in similar parent materials. The soils at site 5 are classified as Udic Paleustalfs and show much more development than the Typic Ustipsamments at soil site 9. Perhaps the parent materials at soil site 5 are related to Cimarron terrace deposits rather than the Salt Fork terrace deposits as suggested by Fay (1965).

SUMMARY AND CONCLUSIONS

All of the soils studied in eastern Woods County showed evidence of mantling. The evidence was obtained by studying soil morphology, particle size distribution and sand mineralogy. When all three were used concurrently, the most information concerning lithologic discontinuities was obtained. Both soil sites 1 and 4 were mantled with silty sediments but further study is necessary to determine whether the mantle is of alluvium or eolian origin. Soil site 1 is most likely to be of eolian origin with the source being from the ancient Salt Fork floodplain or the Cimarron floodplain. Studies determining thickness and distribution of the silt-mantled may indicate the precise source. Soil sites 1 and 4 may have had as many as three or four depositional events.

The mineralogical data for soil sites 2, 9, and 5 did not show the presence of all lithologic discontinuities. It is assumed that the uniformity of the minerals indicates a similar source of sediments from which the soils developed. Three depositional events were detected in the soils of soil site 2 by differences in soil morphology and particle size distribution. The soils at sites 9 and 5 have had at least five depositional events. The buried soils at approximately 2 m at soil sites 9 and 5 may be related, and may be remnant terrace deposits of Pleistocene age as suggested by Gile (1979). Subsequent geologic events indicate the deposition of well sorted, eolian sand which covered the Pleistocene age soils. Recent Holocene soils have developed in the soils at site 9 and older soils at site 5.

Mineralogical data was effectively used to detect significant statistical differences among sediments. The medium sand fraction seemed to be a reliable differentia of sediments. Comparisons of qtz/mcln in the least weathered horizons of soil sites 1 and 4 suggested that the soils developed from parent materials with different sources. Soil site 4 is probably associated with ancient Arkansas River sediments and soil site 1 with either the ancient Salt Fork or Cimarron River sediments. Comparisons of qtz/mcln for similar horizons in soil sites 2, 9, and 5 were effective in differentiating parent materials from varied sources. Soil sites 2 and 9 seem to be associated with ancient Arkansas and Cimarron River sediments, respectively. Soil site 5 was mapped in ancient Salt Fork sediments by Fay (1965) but the sand mineralogy is similar to that of soil site 9 which suggests that site 5 may be related to the Cimarron river sediments.

The recent additions of sediments to the soils studied contain large quantities of weatherable minerals which are an important nutrient source for crop and range production. Future soil surveys will need to give more attention to describing and mapping mantled and buried soils since they are extensive in north central Oklahoma and adjoining areas.

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LIST OF TABLES AND FIGURES

Table 1. Physiographic position, soil classification, and vegetation of the soil sites.

Terrace deposit	Soil site	Soil classification	Location	Slope elevation	Vegetation†
Salt Fork	1	Fine silty, mixed, thermic Pachic Argiustolls	SW¼ of SW¼ Sec 4 T26N, R12W	0-1% 440 m	Tall dropseed, annual weeds, and *Bromus* spp.
Arkansas	4	Coarse silty, mixed, thermic Udic Argiustolls (no known series)	W½ of SW¼ Sec 30 T29N, R12W	0-1% 388 m	Cultivated wheat field
Arkansas	2	Mixed, thermic Typic Ustipsamments (Tivoli series taxadjunct)	SE¼ of SE¼ Sec 1 T27N, R13W	2-8% 385 m	Sand bluestem, sideoats grama, prickly pear, blue grama, hairy grama, sand burr, and ragweed
Cimarron	9	Mixed, thermic Typic Ustipsamments	SW¼ of SW¼ Sec 25 T24N, R15W	3-8% 468 m	Sand sagebrush, annual forbs, and *Bromus* spp.
Salt Fork	5	Coarse loamy, mixed, thermic Udic Paleustalfs (no known series)	SE¼ of SE¼ Sec 16 T25N, R14W	3-8% 445 m	Cultivated wheat field

†Scientific names are wheat (*Triticum aestivum* L.), sand bluestem (*Andropogon hallii* Hack.), sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.), blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.), hairy grama (*Bouteloua hirsuta* Lag.), tall dropseed (*Sporobulus asper* (Michx.) Kunth), ragweed (*Ambrosia psilotachya* DC.), sand sagebrush (*Artemisia filifolia* Torr.), sand burr (*Cenchrus pauciflorus* Benth.), and prickly pear (*Opuntia* sp.).

Table 2. Selected morphological, physical, and chemical properties of the soil sites.

Horizon	Depth	Munsell color (moist)	Structure†	Consistency† (moist)	Boundary†	Features†	Sand	Silt	Clay	Texture†	Org. carb.	Base sat.
	cm						%				%	
				Soil site 1								
Ap	0-24	7.5YR 3/2	1mgr	vfr	cs		17.5	66.3	16.2	sil	1.55	81.0
A12	24-39	7.5YR 3/2	2msbk	fr	gs		20.2	61.3	18.5	sil	0.80	92.7
B1	39-68	5YR 3/2	2msbk	fr	cs		21.0	60.1	18.9	sil	0.64	88.8
B21t	68-92	5YR 4/6	3cpr	fi	gs	cf‡	30.1	50.7	19.2	sil	0.37	83.5
B22t	92-138	5YR 4/6	2cpr	fi	gs	cf	20.2	61.2	18.6	sil	0.19	>100
B3	138-199	5YR 4/6	1cpr	fr	as	CaCO$_3$films	19.6	62.6	17.7	sil	0.13	>100
IIC	199-232	2.5YR 3/6	m			cl-2 conca	20.9	56.6	22.5	sil	0.09	>100
				Soil site 4								
Ap	0-23	7.5YR 3/2	1fgr	fr	as		14.5	73.0	12.5	sil	0.56	67.7
A12	23-50	7.5YR 3/2	2fsbk	fr	cs		18.2	65.5	16.3	sil	0.59	84.1
B21t	50-82	7.5YR 3/4	2mpr	fi	gs	cf	13.1	69.8	17.1	sil	0.42	82.4
B22t	82-107	7.5YR 3/4	2mpr	fi	gs	cf	13.6	71.2	15.2	sil	0.33	>100
B3	107-151	5YR 4/6	1cpr	fr	gs	es	21.3	70.4	8.3	sil	0.20	>100
C1	151-206	5YR 4/6	m	fr	ds	es	17.0	76.4	6.6	sil	0.11	>100
C2	206-267	5YR 4/6	m	fr		es, strat§	19.4	74.4	6.2	sil	0.09	>100

Table 2. (Continued).

Horizon	Depth	Munsell color (moist)	Structure[†]	Consistency[†] (moist)	Boundary[†]	Features[†]	Sand	Silt	Clay	Texture[†]	Org. carb.	Base sat.
	cm						----------	%	----------		------- %	-------
				Soil site 2								
A1	0-30	7.5YR 3/4	1f-mgr	vfr	cw		88.0	9.1	2.9	s	0.23	98.0
AC1	30-65	7.5YR 4/6	1fsbk	vfr	dw		93.8	4.1	2.1	s	0.06	>100
AC2	65-98	7.5YR 5/6	1fsbk	1	dw	e	94.1	3.8	2.1	s	0.03	>100
C11	98-123	7.5YR 5/6	sg	1	gw	e	94.2	3.3	2.5	s	0.02	>100
C12	123-214	7.5YR 5/6	sg	1		e, strat	87.4	9.5	3.1	s	0.03	>100
				Soil site 9								
A1	0-27	7.5YR 3/2	1msbk	vfr	cs		79.7	15.7	4.6	ls	0.56	81.5
AC1	27-79	7.5YR 3/4	1msbk	vfr	gs		86.7	9.1	4.2	ls	0.18	93.6
AC2	79-140	7.5YR 4/4	1msgk	vfr	gw		89.0	7.4	3.6	s	0.10	79.8
C	140-186	7.5YR 4/6	sg	1	as	strat, mot[¶]	85.1	10.5	4.4	ls	0.07	70.4
IIB2tb	186-209	5YR 3/4	2msbk	vfi	cs	cf	46.7	33.3	20.0	1	0.17	>100
IIICb	209-237	7.5YR 4/4	sg	1	cw	strat,mot[#]	79.8	12.7	7.5	ls	0.09	82.4
IVB2tb	237-263	7.5YR 4/5	1msbk	fr	cw	cf;f2,conca	68.9	22.0	9.1	sl	0.08	87.0
VB2b	263-290	5YR 5/6	1msbk	fr	cs	cl,conca	43.3	42.2	14.5	1	0.13	>100
VIC	290-308	5YR 4/6	m	fr		fl,conca	78.3	10.4	11.3	sl	0.06	>100
				Soil site 5								
Ap	0-23	7.5YR 4/4	1msbk	vfr	as		85.9	6.8	7.3	ls	0.19	95.5
B2t	23-52	5YR 4/4	1msbk	vfr	gw	cf	78.5	11.1	10.4	sl	0.17	75.3
B3	52-86	5YR 4/4	1mpr	vfr	gw	cf	80.2	11.3	8.5	ls	0.11	70.4
IIB2	86-138	5YR 4/5	1mpr	vfr	gw		64.0	26.5	9.5	sl	0.08	>100
IIIB2	138-172	5YR 4/5	1mpr	fr	as		78.4	11.0	10.6	sl	0.08	>100
IVB2b	172-226	7.5YR 3/2	3mabk	vfi	cs	es;m3,conca	40.5	36.4	23.1	1	0.15	>100
VB21b	226-238	5YR 4/4	2mpr	fi	gs	e;c3,conca	25.4	52.3	22.3	sil	0.07	>100
VB22b	238-293	5YR 4/4	2mpr	fr	gw	ev;fl,conca	21.3	56.4	22.3	sil	0.07	>100
VB23b	293-356	5YR 4/4	1msbk	fr	gw		26.6	54.9	18.5	sil	0.06	>100
VIC	356-460	2.5YR 4/6	m	fr			16.3	54.7	28.9	sil	0.08	>100

[†] Symbols are the same as given in the Soil Survey Manual, Agric. Handb. no. 18, USDA, p. 139-140.

[‡] Clay films

[§] Stratified

[¶] Mottles 10 YR 5/4, f1f; 10YR 3/1, f2f.

[#] Mottles 10YR 4/6, 10YR 5/6, 10YR 6/1, f2f.

Table 3. Sand mineralogy of the soil sites.

Horizon	Qtz		Mcln		Plag		Alt. feld.		Rock frag.		Qtz/Mcln		Minerals present in trace amounts[§]
	fs	vfs	fs	vfs	fs	vfs	fs	vfs	fs	vfs	fs	vfs	
	%												
								Soil site 1					
Ap	74.2	76.2	4.8	3.5	5.6	4.0	13.7	16.0	1.7	0.3	17.0	39.1	rut
		†---*	--**	--*	--**	--*		---*		---‡	---**	---**	
A12	73.0	73.8	8.4	4.6	2.8	2.5	14.4	19.0	1.4	0.1	9.4	18.1	rut
B1	73.7	75.1	7.8	4.1	2.9	2.0	14.5	18.7	1.1	0.1	10.8	20.6	rut
			---‡	---*	---*	---*				---‡	----‡	---**	
B21t	73.7	75.6	6.2	2.7	4.4	3.8	14.9	17.7	0.8	0.2	14.2	39.7	
				---‡								----*	
B22t	74.2	75.6	7.0	3.8	4.1	2.9	13.5	17.7	1.2	tr	12.3	26.5	
			--**		--‡				---‡		----*		
B3	75.2	76.3	9.6	4.6	2.6	2.0	12.0	17.0	0.6	0.1	8.3	18.3	calc clay agg
IIC	77.8	78.0	8.8	3.9	2.0	1.6	11.1	16.5	0.3	tr	9.5	25.7	calc clay agg
								Soil site 4					
Ap	72.1	77.8	11.1	3.7	2.8	2.2	13.3	16.2	0.7	0.1	7.1	30.5	horn, zirc, calc clay agg
		----‡						----‡		---‡			
A12	71.5	75.2	12.2	4.0	2.8	2.2	12.6	18.6	0.9	0	6.4	22.4	horn, zirc, tour, calc clay agg
B21t	72.8	76.5	11.3	4.5	2.5	2.0	12.6	16.9	0.8	0.1	7.2	21.2	horn, zirc, gar, oliv, tour, biot
	----‡		---**	--**								----*	
B22t	75.1	78.3	8.4	3.2	3.4	2.4	12.2	16.1	0.9	tr	10.7	34.0	horn, chert, tour
	----*		----‡			---‡					----*		
B3	78.6	76.5	6.5	3.5	3.1	1.7	11.2	18.2	0.6	0.1	15.6	26.6	horn, tour, calc clay agg
C11	79.7	75.8	6.8	3.2	2.1	1.7	11.0	19.3	0.4	0	13.5	30.8	tour, calc clay agg, dol crys
C12	80.3	76.8	7.0	3.8	2.8	1.8	9.5	17.5	0.4	0.1	12.5	23.8	zirc, tour, calc clay agg, dol crys

Table 3. (Continued).

Horizon	Qtz		Mcln		Plag		Alt. feld.		Rock frag.		Qtz/Mcln		Minerals present in trace amounts§
	ms	fs	ms	fs	ms	fs	ms	fs	ms	fs	ms	fs	
	------------------------	----------	----------	----------	----------	%	----------	----------	----------	----------	----------		
									Soil site 2				
A1	67.2	70.2	16.3	11.1	2.8	4.2	10.6	13.4	3.1	1.1	4.2	6.5	horn, zirc, gar
			----*	----‡							----‡		
AC1	65.6	69.2	18.5	12.5	2.6	4.2	10.4	12.9	2.9	1.2	3.6	6.1	horn, zirc, gar, chert, tour
AC2	66.9	68.1	17.2	13.0	2.0	3.6	10.8	13.9	3.1	1.4	4.0	5.7	horn, zirc, gar, tour, oliv
C1	67.8	68.9	16.3	12.7	2.4	3.4	10.2	13.6	3.3	1.4	4.4	5.7	horn, zirc, gar, oliv
									---‡				
C2	66.6	68.8	17.9	12.0	2.8	3.1	10.5	15.1	2.2	1.0	3.8	6.9	
									Soil site 9				
A1	74.5	76.3	13.0	11.6	1.9	2.4	7.2	8.7	3.4	1.1	6.0	6.8	tour, horn, zirc
						---‡	---‡						
AC1	74.6	75.2	13.9	10.7	2.8	4.0	5.9	8.6	2.8	1.5	5.8	7.5	chal
										---*			
AC2	74.9	76.7	12.7	10.8	2.7	3.2	6.7	8.6	3.0	0.7	6.4	7.9	zirc, tour
					---‡					---*			
C	75.3	74.6	13.1	12.1	1.4	3.6	6.5	7.9	3.7	1.8	6.2	7.8	tour
IIB2tb	75.3	75.2	13.3	12.2	1.7	3.4	6.1	8.1	3.6	1.1	5.8	6.5	horn, gar, tour
					---*								
IIICb	74.5	74.7	13.5	12.0	3.0	4.2	5.2	7.5	3.8	1.6	6.1	6.8	
	----‡				---‡				--**				
IVB2tb	77.8	75.4	11.4	11.2	2.1	3.4	6.5	7.7	2.2	2.3	7.2	7.6	horn
			----*				---‡				--*		
VB2b	76.9	74.9	13.7	11.6	2.0	4.6	4.5	7.4	2.9	1.5	5.8	7.0	chal, tour
	----*				--**				---‡		---‡		
VIC	69.5	74.2	7.3	7.8	10.5	5.0	7.2	10.8	5.5	2.2	9.6	9.7	

Table 3. (Continued).

Horizon	Qtz		Mcln		Plag		Alt. feld.		Rock frag.		Qtz/Mcln		Minerals present in trace amounts§
	ms	fs	ms	fs	ms	fs	ms	fs	ms	fs	ms	fs	
	%												
								Soil site 5					
Ap	73.0	75.7	14.8	11.8	3.4	3.9	5.8	7.2	3.0	1.4	5.6	7.0	gar, chal
B2t	74.2	74.7	14.4	13.1	3.1	3.3	5.8	7.5	2.5	1.4	5.4	5.8	oliv, chal
B3	73.4	74.7	14.7	12.9	2.6	3.6	6.9	7.5	2.4	1.3	6.1	6.2	horn, tour, chal
IIB2	73.2	75.2	14.1	11.7	3.1	3.9	7.1	7.8	2.5	1.4	5.6	6.8	gar, chal
IIIB2	73.3	74.5	15.8	12.5	2.8	3.8	6.0	8.0	2.1	1.2	4.8	6.1	horn, zirc
IVB2b	74.6	75.0	14.1	12.0	1.9	3.9	6.6	8.1 ---*	2.8	1.0	5.4	6.8	chal, zirc, tour, calc clay agg
VB21b	73.7	73.2	15.3	12.4	2.6	3.5	6.2	9.9	2.2	1.0	5.0	6.9	zirc, calc clay agg
VB22b	73.2	73.5	15.8	11.4	2.2	3.8 ---*	6.9	10.1 ----*	1.9	1.2	4.9	7.2	tour, calc clay agg, dol crys
VB23b	75.2	72.9 ----*	14.4	9.5	1.8	7.8 ---†	5.6	8.6	3.0	1.2	5.3	10.2	calc clay agg, dol crys
VIC	77.2	78.6	14.5	7.8	1.0	4.4	4.9	8.1	2.4	1.1	5.8	11.4	calc clay agg, dol crys

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†Line denotes significant mineral differences between adjacent horizons.

‡, *, **Significance at the 0.10, 0.05, and 0.01 levels of probability, respectively.

§Abbreviations for minerals and sand fractions are rut (rutile), calc clay agg (calcareous clay aggregates), tour (tourmaline), horn (hornblende), zirc (zircon), gar (garnet), oliv (olivine), biot (biotite), chert (chert), dol crys (colomite crystals), chal (chalcedony), ms (medium sand), fs (fine sand), and vfs (very fine sand).

Table 4. Selected sand mineral means ($\bar{x}$) and 95% confidence intervals (CI) for the dominant sand fractions of the Arkansas, Salt Fork of the Arkansas and Cimarron River sediments.

River	Qtz	Mcln	Qtz/Mcln
	$\bar{x}$[†] CI[‡]	$\bar{x}$ CI	$\bar{x}$ CI
	Medium sand		
Arkansas	65.6 ± 2.2 a[§]	19.0 ± 1.4 a	3.5 ± 0.3 a
W. Salt Fork	72.5 ± 1.3 b	14.4 ± 0.9 b	5.1 ± 0.3 b
E. Salt Fork	71.3 ± 1.5 b	16.0 ± 1.4 c	4.6 ± 0.6 b
Cimarron	75.7 ± 0.9 c	11.9 ± 0.7 d	6.5 ± 0.5 c
	Fine sand		
Arkansas	64.8 ± 1.9 a	12.5 ± 1.2 a	5.4 ± 0.6 a
W. Salt Fork	75.1 ± 1.4 b	10.4 ± 0.7 b	7.4 ± 0.8 b
E. Salt Fork	77.9 ± 1.2 c	10.2 ± 1.4 bc	8.3 ± 1.6 bc
Cimarron	77.6 ± 1.2 c	8.8 ± 0.9 c	9.1 ± 1.0 c

[†] n=12 for all samples; no significant differences among replications within river sediments at the 0.05 level of probability; significant differences between sizes for each river sediment at the 0.05 level of probability.

[‡] $t_{\alpha=0.025,df=11} = 1.796$.

[§] Same letter within a column and sand fraction indicates no significant differences among river sediments at the 0.05 level of probability.

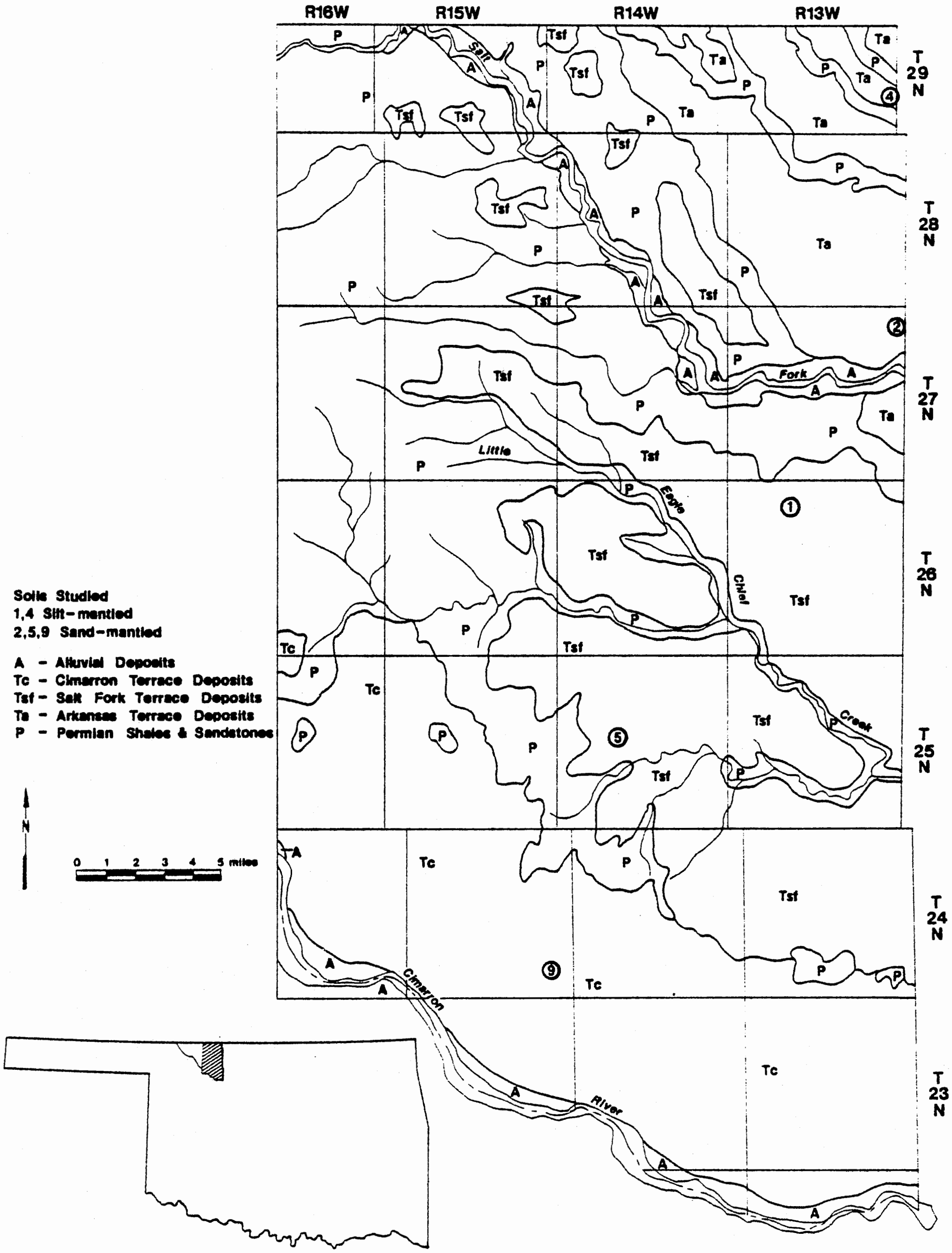
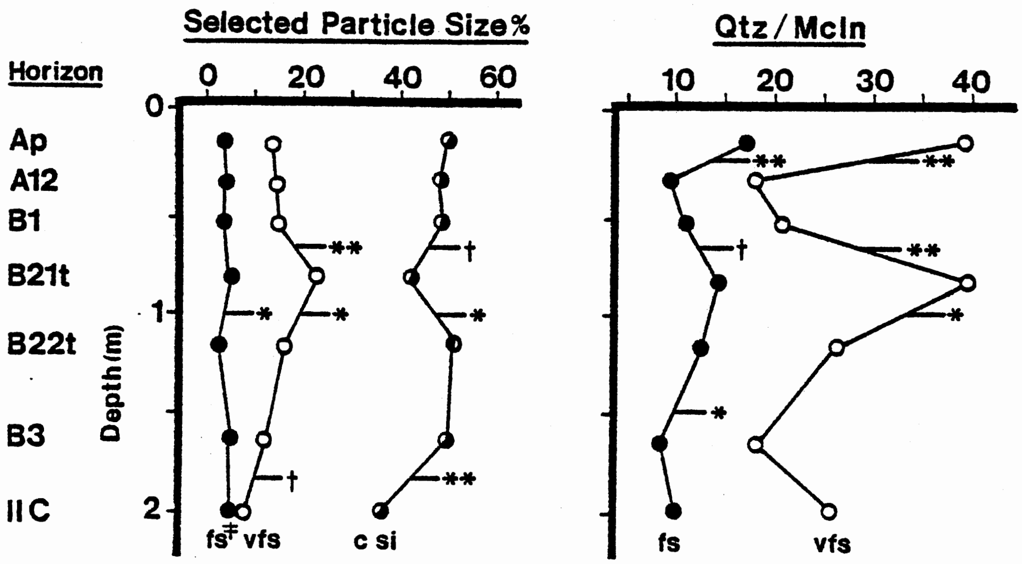


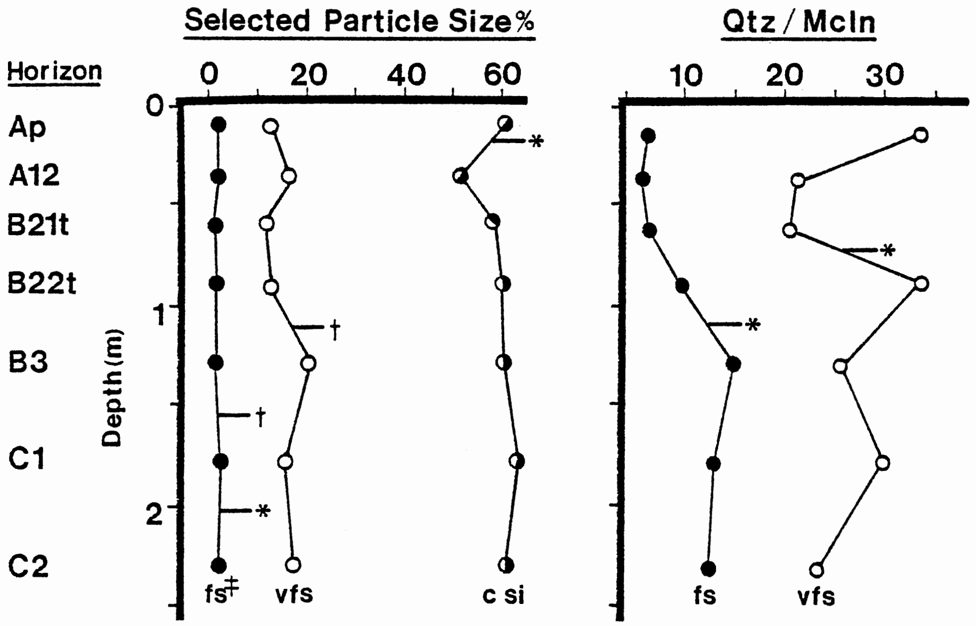
Fig. 1. Location of soil sites in Oklahoma.



†, *, **Denote significant differences between adjacent horizons at the 0.10, 0.05, and 0.01 levels of probability, respectively.

‡Code: fs (fine sand), vfs (very fine sand), and c si (coarse silt).

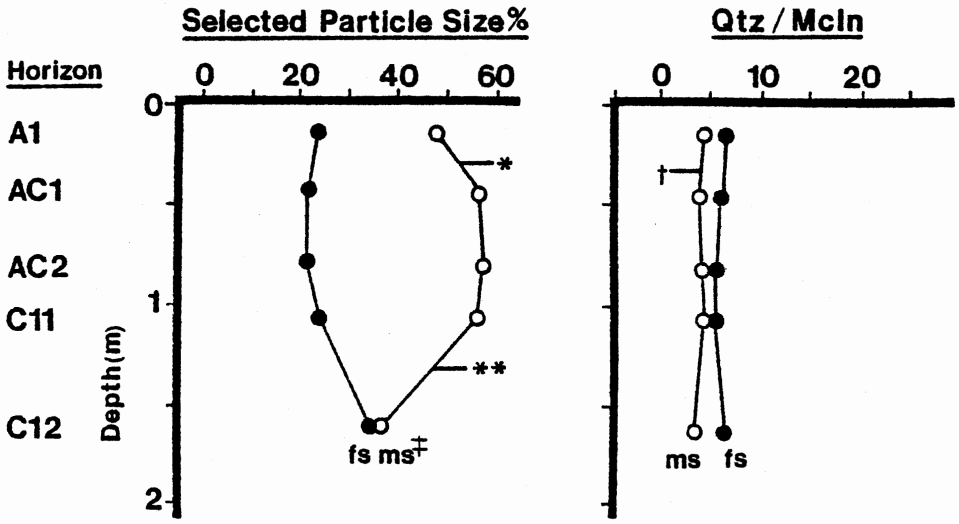
Fig. 2. Depth trends for selected particle sizes and the quartz to microcline ratio in soil site 1.



†, *, **Denote significant differences between adjacent horizons at the 0.10, 0.05, and 0.01 levels of probability, respectively.

‡Code: fs (fine sand), vfs (very fine sand), and c si (coarse silt).

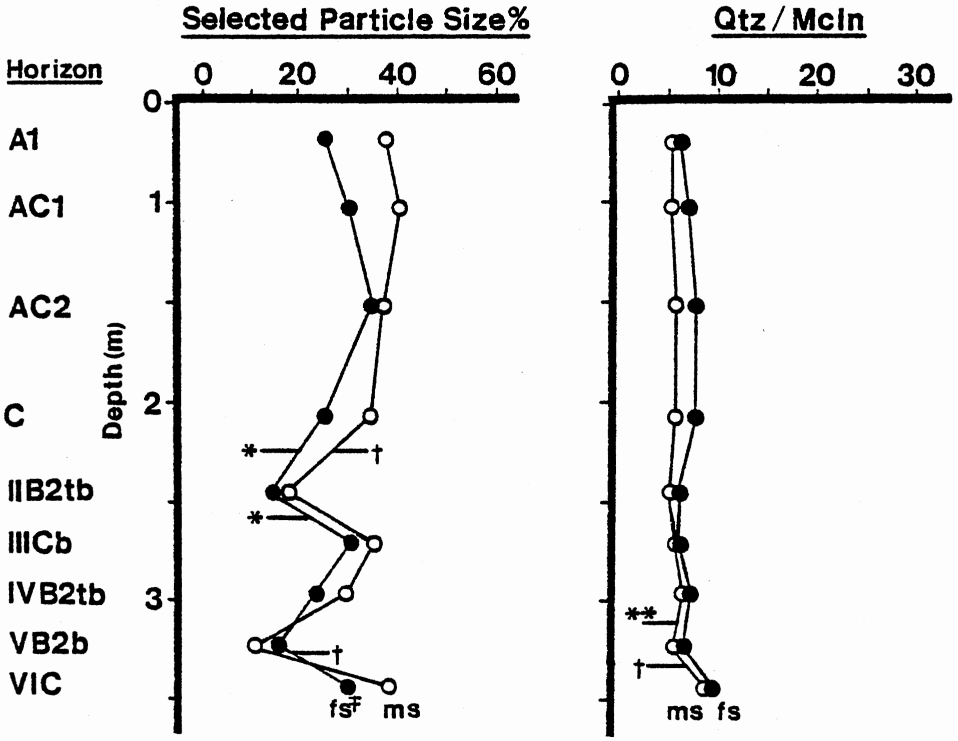
Fig. 3. Depth trends for selected particle sizes and the quartz to microcline ratio in soil site 4.



†, *, **Denote significant differences between adjacent horizons at the 0.10, 0.05, and 0.01 levels of probability, respectively.

‡Code: ms (medium sand) and fs (fine sand).

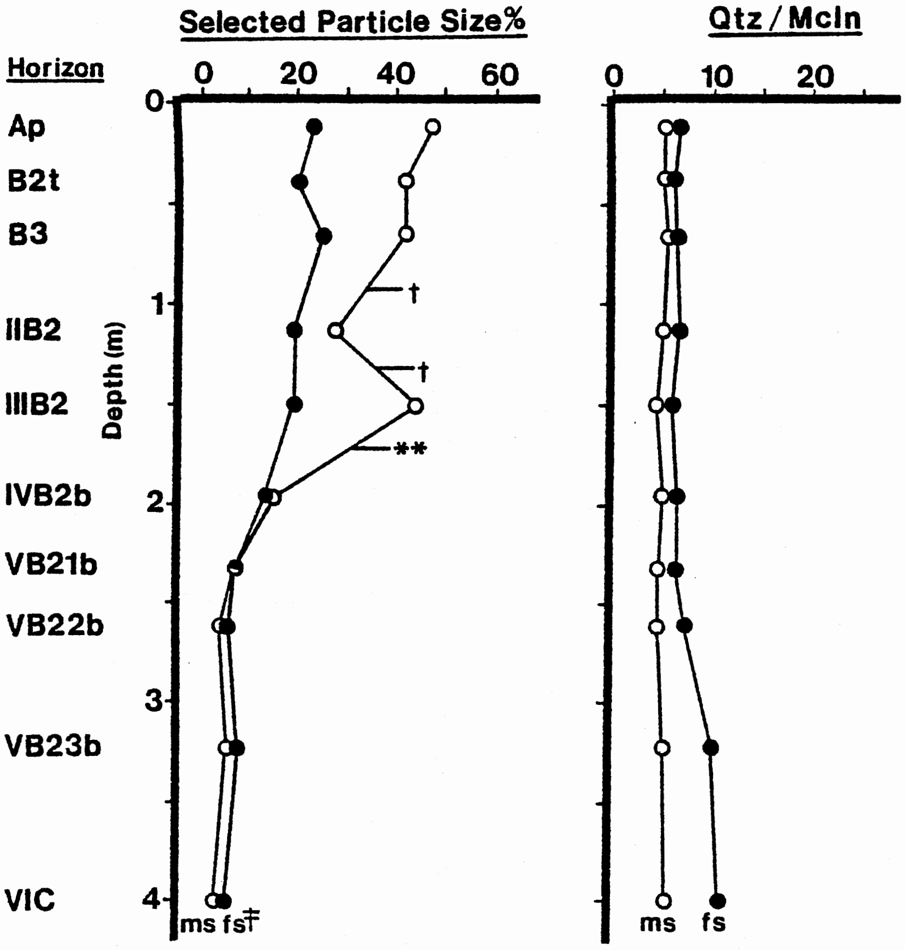
Fig. 4. Depth trends for selected particle sizes and the quartz to microcline ratio in soil site 2.



†, *, **Denote significant differences between adjacent horizons at the 0.10, 0.05, and 0.01 levels of probability, respectively.

‡Code: ms (medium sand) and fs (fine sand).

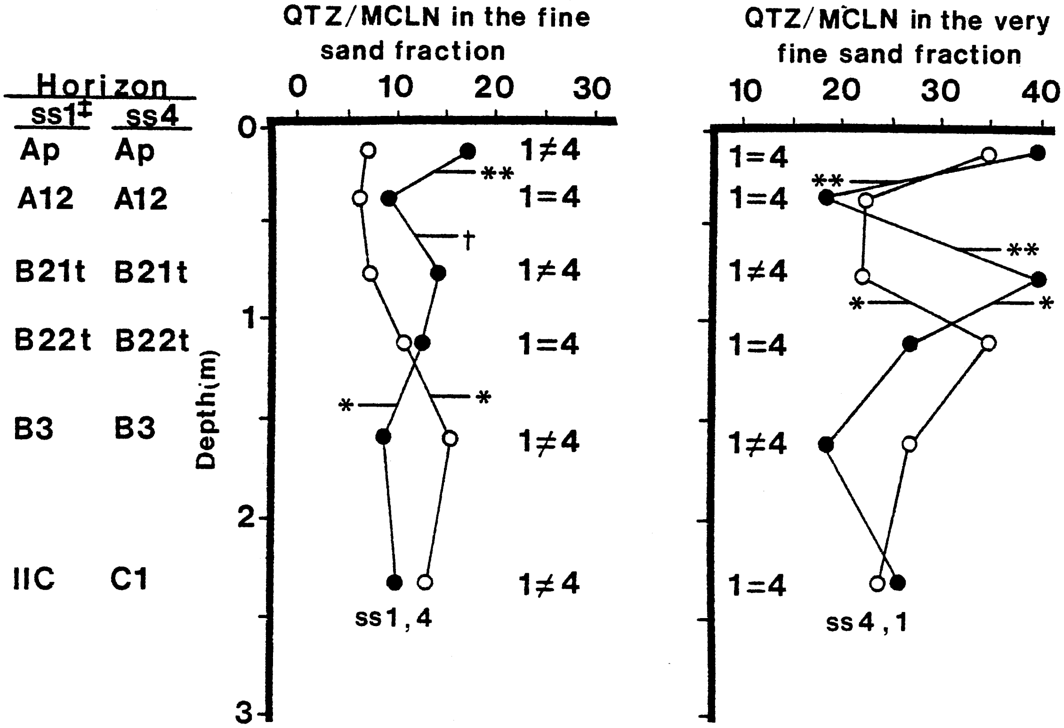
Fig. 5. Depth trends for selected particle sizes and the quartz to microcline ratio in soil site 9.



†, *, **Denote significant differences between adjacent horizons at the 0.10, 0.05, and 0.01 levels of probability, respectively.

‡Code: ms (medium sand) and fs (fine sand).

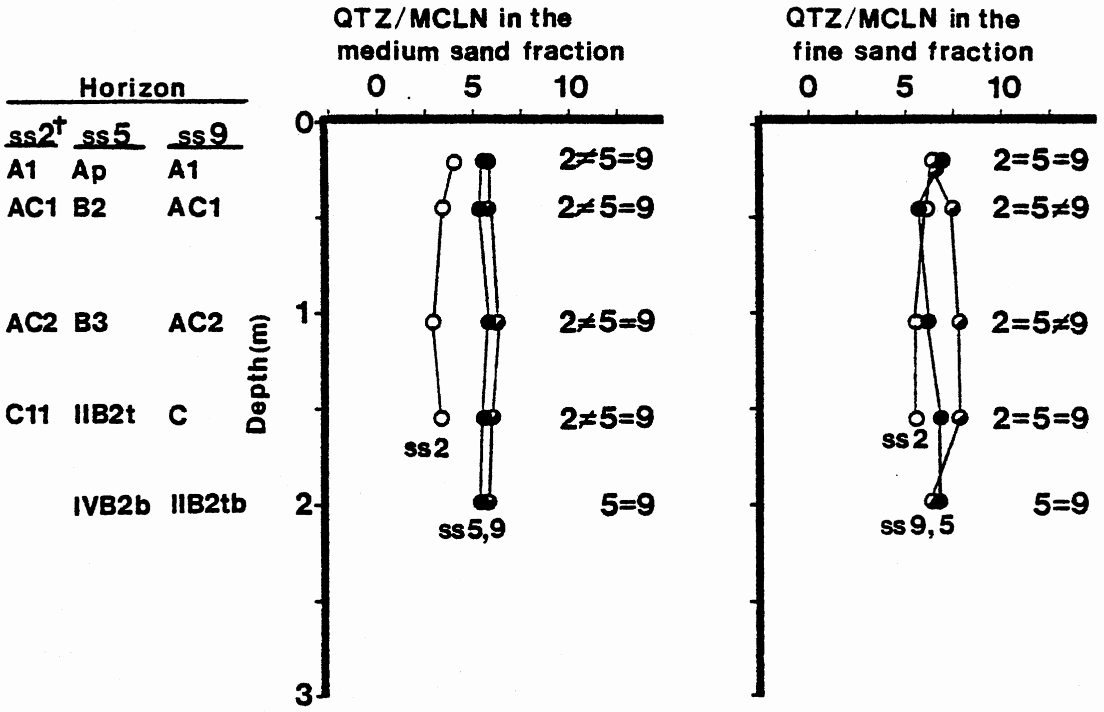
Fig. 6. Depth trends for selected particle sizes and the quartz to microcline ratio in soil site 5.



†, *, **Denote significant differences between adjacent horizons at the 0.10, 0.05, and 0.01 levels of probability, respectively.

‡Code: ss1 (soil site 1) and ss4 (soil site 4).

Fig. 7. Comparison of the quartz to microcline ratio depth trends between soil sites 1 and 4.



†, *, **Denote significant differences between adjacent horizons at the 0.10, 0.05, and 0.01 levels of probability, respectively.

‡Code: ss2 (soil site 2), ss5 (soil site 5), and ss9 (soil site 9).

Fig. 8. Comparison of the quartz to microcline ratio depth trends among soil sites 2, 9, and 5.

PART II

LATERAL VARIABILITY OF SAND MINERALOGY IN THE SOIL PEDON AND POLYPEDON

ABSTRACT

The lateral variability of quartz, microcline feldspars, plagioclase feldspars, altered feldspars, and rock fragments in a soil pedon and polypedon was examined to estimate the size of the parent material variability and locate lithologic and stratigraphic discontinuities. Horizons were sampled from five pedons within a polypedon. Six profiles were subsampled from a 2 m^2 area from one of the five pedons. The sampling method resulted in a two-fold nested design. The soils studied are classified as Pachic Argiustolls and Typic Ustipsamments. The percentage of light minerals in the fine and very fine sand and medium and fine sand separates for the Argiustolls and Ustipsamments, respectively, were determined by optical mineralogy on duplicate, random samples. Significant mineral differences were observed between a few horizons and all sand sizes.

Pedons within a polypedon, profiles within a pedon, horizon X pedon interaction, horizon X profile interaction, and error variance components were estimated for each sand size fraction, mineral, and soil site. The most consistently significant estimated variance component was the profiles within a pedon component, which suggests that most of the lateral variability was contained in a 2 m^2 area with little additional variability contributed by other pedons in the polypedons.

Sub-sampling the soil horizons allowed significant mineral depth trends to be recognized. Lithologic or stratigraphic discontinuities were found in both soils. Studies of soil genesis by the use of sand mineralogy should be accompanied by field observations and other reliable laboratory measurements.

Additional index words: Pachic Argiustolls, Typic Ustipsamments, Sub-sampling, Variance components, Lithologic discontinuity, Parent material homogeneity.

INTRODUCTION

Mantled soils have frequently been studied to determine their genesis. Price et al. (1975) determined diagnostic criteria which distinguished loess mantles from underlying residuum. They concluded that particle size distribution, soil morphology, and quartz/feldspar ratios were all reliable parameters for recognizing lithological discontinuities. They also reported that elemental percentages of TiO_2 and ZrO_2 were not consistent indicators of parent material homogeneity.

Barshad (1964) suggested using the ratio of quartz to microcline or other resistant minerals to indicate parent material uniformity. Others (Sudom and St. Arnaud, 1971) proposed using more than just one or two minerals as indices.

Studies using elemental analysis to determine parent material homogeneity have been reviewed by Drees and Wilding (1973). They stated that "before one could establish significant depth trends in elemental properties, it is necessary to evaluate the magnitude of lateral variability within the sampling unit." In order to achieve accurate estimates of vertical differences, their data indicate the need to analyze horizons subsamples in lateral directions to increase the accuracy of mean estimates. Mausbach et al. (1980) also indicated that variability can be efficiently estimated by sampling one complete pedon plus subsamples of important horizons from other pedons. They also recommended that studies of lateral variability be made on the pedon and polypedon.

Although many studies have used mineralogical data of the sand separates to compare differences between landscapes and determine parent material homogeneity, there seems to be a paucity of studies indicating the amount of lateral variability in a sand mineralogy. It appears that lateral homogeneity of a sampling unit and mapping delineation should be determined prior to any other spatial comparisons (Drees and Wilding, 1973). This study will provide an estimate of sand mineralogy variability within a sampling unit (pedon) and mapping delineation (polypedon) by examining the estimated variance components of pedons within a polypedon (ped), profiles with a pedon (prof), horizon X pedon interaction (hp) and horizon X profile interaction (hp'). This information will be used to establish significant mineralogical differences between horizons in the soils studied.

SOIL SITES

The soil sites were randomly selected from five predetermined locations in the eastern half of Woods County, Oklahoma. Soil site 1 is a mapping delineation located on a summit position and appears to be loess overlaying Permian siltstone. The soils in the mapping unit are classified as fine-silty, mixed, thermic Pachic Argiustolls (Pond Creek series). The soils are borderline in having an argillic horizon. Soil site 9 is located in a mapping complex of hummocky dunes. Only the side slopes of the sand dunes where sampled to reduce variability of contrasting soils. The soils on the side slopes were classified as mixed, thermic Typic Ustipsamments (Tivoli series). The sand dunes are underlaid by a buried soil at a depth of about 2 m. Horizons and depths are given in Table I.

METHODS

Field

One sand-mantled and one silt-mantled polypedon were randomly selected from five identified soil sites. Soil morphology was recorded but is not reported here. Two kg, bulk samples were collected from each horizon of five pedons within each soil site. The area of each soil site was approximately ten hectares. The five pedons were located by randomly selecting a compass heading and pacing distance. Six profiles were subsampled from a 2 m^2 area of one of the five pedons. Subsampling procedure was similar to that described by Drees and Wilding (1973). Transition horizons were discarded from three of the six subsamples as it was felt that depth trends could be determined without them. A power soil probe was used to extract all samples. The sampling method resulted in a two-fold nested design with horizons as a fixed variable.

Laboratory

Samples were air-dried and randomized in the laboratory to reduce operator bias. Duplicate, 40 g samples of each horizon were dispersed with sodium hexametaphosphate after removing the organic matter with 30-35% hydrogen peroxide (Kilmer and Alexander, 1949). The dispersed samples were separated into sand fractions by wet sieving through nested sieves. The two dominant sand fractions, fine (0.25-0.1 mm) (fs) and very fine (0.1-0.05 mm) (vfs) sand for soil site 1 and medium (0.5-0.25 mm) (ms) and fine sand for soil site 9, were retained for petrographic analysis as suggested by Chapman and Horn (1968). A small sample of each sand fraction was placed on a glass slide, immersed with a refractive oil ($\eta=1.5400$), and examined with a petrographic microscope. Types and percentages of light minerals present in each sample were determined by traversing the slide. Two hundred sand grains were examined and tabulated per slide. Heavy minerals present were also recorded but are not reported here. The heavy minerals found in the samples accounted for less than one percent of the fine and very fine sand fractions, hence heavy liquid separations were omitted.

The data were scaled to a percentage basis and means were calculated for the minerals in each horizon, sand size fraction, and soil site. Variance components were estimated for the minerals in each horizon, sand size fraction, and soil site by using the statistical analysis system (SAS).

RESULTS AND DISCUSSION

The light sand minerals present in both areas were quartz (qtz), microcline feldspars (mcln), plagioclase feldspars (plag), altered feldspars (alt feld.), and rock fragments (rock frag.). The altered feldspars are highly weathered. The alteration of the feldspars prevented the identification of feldspar type. The quartz to microcline ratio (qtz/mcln) was calculated as suggested by Barshad (1964).

The analyses of variance computed indicated that all minerals in the fine and very fine sand fractions were significantly different at the $P = 0.05$ level in soil site 1. The minerals in the medium and fine sand fractions in soil site 9 were also significantly different at the same probability level with the exception of quartz. Since significant differences also existed among horizons in each soil site, it was decided to examine the minerals separately for each horizon and sand size.

Variance components were estimated for the minerals in each horizon, sand size component, and soil site. An example is shown in Table 2.

Estimated variance components for soil sites 1 and 9 are shown in Tables 3 and 4, respectively. Negative values, for which zero is the most logical value, are thought to be associated with sampling errors. The large estimated variance components associated with the quartz to microcline ratio particularly in the very fine sand fraction of soil site 1 are the results of very small amounts of microcline in some of the observations. In both soil sites, the majority of the significant mineral differences are found in the profile component. Very few significant mineral differences are indicated in the pedon component. The variability associated with the pedon and profile components seemed to be evenly distributed between the fine and very fine sand fractions. When the error variance components is large in comparison to the profile and pedon variance components, a large portion of the variability is most likely associated with laboratory technique.

Trends for each separate horizon in soil site 1 will now be considered. The majority of the significant mineral differences in horizons Ap and A12 were confined to the very fine sand fraction. The B22t horizon appeared to have the most variability as determined by the number of significant profile components for the minerals of both fine and very fine sand fractions while the IIC horizon had the least.

Trends of the variability among minerals seem to indicate that plagioclase and altered feldspars are the most variable for both size fractions since more than half of the horizons have significant profile components.

Examination of the variability trends among horizons in soil site 9 indicate that more than half of significant profile components are confined to the more recent parent material, mainly the first four horizons. The majority of the significant variance components in the first four horizons seems to be associated with the AC1 horizon. More than half of the profile components associated with horizon IVB2tb are significant. The only two significant pedon components are found in horizon IIB2tb.

The variability trends among the minerals seem to indicate that significant profile components are frequently associated with microcline and plagioclase feldspars in both the medium and fine sand fractions. Quartz in the medium sand fraction has similar variability.

In order to determine if the variance components of each horizon for each mineral and sand size fraction were homogeneous, an F-test was made by using the ratio of the maximum and minimum σ^2_e for each horizon and each mineral with degrees of freedom corresponding to the average number of observations in each $\sigma^2{}_e$ and the number of horizons (Steel and Torrie, 1960). Since very few of the F-tests were significant, the data for all horizons were pooled for testing.

Table 5 shows the source of variation, degrees of freedom and expected mean squares associated with each soil site. The levels of the variable 'horizon' were considered fixed in the analyses. The irregularity of the expected mean square coefficients is due to the unbalanced nature of the data.

The estimates of the various variance components resulted from the combined analysis of variance are shown in Table 6. In soil site 9 more than half of the profile components for all minerals and both sizes are significant while none of the pedon components are significant. This suggests that most of the variability in soil site 9 is within a 2 m^2 area as suggested by Beckett and Webster (1971) and very little additional variation is contributed by the pedons in the polypedon. In other words, the profiles close together (within the same pedon) are just as variable as profiles in different pedons. The lack of significant pedon or profile components in soil site 1, with the exception of the pedon component for qtz/mcln in the fine sand fraction, indicates that soil site 1 is much more homogeneous than site 9. This result agrees with Carey et al. (1976). They concluded that deposits of eolian origin (loess) should be more uniform (less variable) than other types of deposits.

A significant hp or hp' interaction component suggests that mineral differences among horizons are not the same for each pedon or profile within pedons, respectively. An examination of the hp and hp' components indicates that the hp' component is significant more often than the hp component and most of the significant hp' components are found in soil site 9.

Mineral means for each horizon, sand fraction, and soil site are presented in Table 7. Multiple sampling allowed statistical comparisons to be made between horizons. The sum of squares for profiles within pedons and pedons were pooled in this analysis since they were not significantly different in most cases. The principle of superimposition suggests that only adjacent horizons be compared. Least square means were calculated for each horizon and statistical comparisons were made using the standard error of the means and the 't' statistic (Steel and Torrie, 1960). The mineral means reported in Table 7 are the means of the raw data. Horizontal dashed lines denote significant differences between horizons at the indicated level of probability.

Mineral differences between horizons were not the same for both sand fractions in all cases and did not correspond with lithological discontinuities observed in the field. Mineral weathering is also superimposed and is confounded with observed mineral differences. These limitations do not prevent the use of light mineral components, particularly the quartz to microcline ratio, as indicators of lithological discontinuities.

SUMMARY AND CONCLUSIONS

The mineral differences between horizons can be used as indicators of parent material homogeneity as indicated by other workers (Barshad, 1964; Sudom and St. Arnaud, 1971; and Price et al., 1975) but should also be substantiated with other laboratory methods and field observations as suggested by Drees and Wilding (1973). Subsampling the horizons in a pedon improves the mean estimates and allows for differences between horizons to be detected. The statistical analysis suggests that subsampling could be limited to a 2 m^2 area and fewer subsamples are needed for more homogeneous materials such as eolian deposits.

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LIST OF TABLES AND FIGURE

Table 1. Brief description of soil sites 1 and 9.

Soil site 1 (Pachic Argiustolls)			Soil site 9 (Typic Ustifluvents)		
Horizon	Depth	Deposit Type	Horizon	Depth	Deposit Type
	cm			cm	
Ap	0-24	Alluvium or eolian deposit	A1	0-27	Sand dune
A12	24-39		AC1	27-79	
B1	39-68		AC2	79-140	
B21t	68-92		C	140-186	
B22t	92-138		IIB2tb	186-209	Pleistocene soil?
B3	138-199		IIICb	209-237	Unidentified buried soils
IIC	199-232+	Permian silt stone	IVB2tb	237-263	
			VB2b	263-290	
			VIC	290-308+	

Table 2. Analysis of variance and expected mean squares.

Source	df[†]	Expected Mean Square
Pedons (ped)	4	$\sigma^2_e + 2\sigma^2_{prof} + 3\sigma^2_{ped}$
Profiles within pedons (prof)	5	$\sigma^2_e + 2\sigma^2_{prof}$
Duplicates within profiles within pedons (e)	10	σ^2_e

[†] df will not be the same for every analysis of variance.

Table 3. Estimated variance components of the light minerals in the sand fractions for soil site 1.

Horizon	Variance component	df	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln
			Fine sand						Very fine sand					
Ap	ped[†]	4	0.340	-0.341	2.702	4.893	0.298	-3.015	-3.860	0.902	2.239	4.826	0.040	87.894
	prof	5	6.738	0.548	1.479	1.373	-0.096	4.514	7.612*	-1.508	3.235*	10.198*	-0.021	-257.872
	e	10	8.963	1.788	3.362	6.675	0.962	25.609	3.712	5.188	1.612	5.975	0.112	1980.021
A12	ped	4	-6.674	2.135	-3.587	1.031	-0.420	4.067	-0.927	0.274	0.497	-0.656	0.045	17.299
	prof	2	5.964	-1.613	5.062*	-4.595	-0.054	-2.415	5.554‡	1.670‡	0.048	3.521‡	-0.004	9.628
	e	7	6.946	5.393	1.500	10.982	1.607	6.212	4.393	1.286	0.696	3.000	0.018	16.872
B1	ped	4	-0.670	-1.132	-1.486	2.246	-0.733	-7.108	-0.587	1.747‡	-0.851	1.906	0.017	29.837‡
	prof	2	-2.366	1.527	0.830	0.780	0.887*	13.393‡	-3.238	-0.845	0.717	-0.568	-0.018	-14.619
	e	7	13.857	6.821	2.839	5.982	0.268	11.521	11.768	1.982	1.857	5.429	0.036	36.259
B21t	ped	4	3.939	-0.182	-1.524	4.965‡	0.201	21.550	-6.492	0.084	-7.352	-12.421	0.126	498.534*
	prof	5	-1.640	1.935	2.173‡	-0.333	-0.227	-10.991	5.204	-0.156	11.254*	13.117‡	-0.002	-355.632
	e	10	15.000	3.762	2.775	5.888	0.775	50.341	10.825	2.212	1.862	14.350	0.225	1002.423
B22t	ped	4	-13.301	-4.876	-3.882	-1.732	-0.047	-10.579	-0.017	0.488	-1.723	-4.404	0.010	122.334
	prof	3	22.904*	6.724‡	4.333‡	19.201**	0.635‡	19.570‡	-2.531	-0.938	2.958‡	8.034‡	-0.008	-150.632
	e	8	8.109	6.000	3.031	3.266	0.438	13.979	12.938	2.750	3.031	5.797	0.016	425.320
B3	ped	4	-9.292	-1.316	-3.503	-0.743	0.090	0.547	3.851‡	-0.441	-0.899	3.962	-0.007	6.535
	prof	2	9.940*	0.646	5.280**	3.057‡	-0.086	-1.269	-3.854	-0.515	1.412*	-1.720	0.003	-29.788
	e	7	4.661	7.000	0.607	2.554	0.464	6.757	8.500	2.571	0.679	8.107	0.036	78.657
IIC	ped	4	0.705	2.618	0.375	1.309	-0.014	3.695	-1.181	0.604	0.094	-1.944	-0.014	-3.975
	prof	2	4.554‡	-0.702	0.128	-0.167	0.048	0.289	3.140	-1.533	-0.312	5.679	0.012	-5.510
	e	7	3.768	3.946	0.911	4.625	0.071	5.420	8.018	5.607	1.000	12.643	0.018	175.393

[†] ped, prof, and e are the variance components estimating mineral differences among pedons, profiles, and lab error, respectively.

‡, *, **Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively.

Table 4. Estimated variance components of the light minerals in the sand fractions for soil site 9.

Horizon	Variance component	df	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln
			Medium sand						Fine sand					
A1	ped	4	-5.036	-5.070	-1.379	-1.440	-0.688	-1.325	-1.578	-1.069	-0.925	1.234	-0.040	-1.541
	prof	5	3.931	6.456*	2.117**	2.179	0.692	1.678*	4.923*	3.442**	0.379	1.848	0.212	3.006**
	e	10	10.338	3.925	0.750	3.462	1.650	1.111	2.187	0.738	3.425	4.688	0.462	0.427
AC1	ped	4	-6.107	-9.920	-0.428	-0.060	-1.195	-2.600	-8.475	-1.074	-8.217	-0.804	-1.382	0.776
	prof	5	6.548†	14.473**	0.519	0.838	1.544*	3.828**	17.954*	6.631**	12.462**	3.375†	2.548**	3.469**
	e	10	6.525	6.088	1.950	2.962	1.200	1.649	9.925	1.088	2.725	4.300	0.388	1.309
AC2	ped	4	2.168	-3.152	0.205	-0.157	-0.807	-1.281	3.060	-2.021	-4.608	1.014	-0.078	-0.442
	prof	5	0.073	1.042	1.110	2.198	-0.002	1.169	-0.408	4.604†	6.654*	-0.731	0.023	1.804
	e	10	7.875	12.038	3.462	2.975	2.825	3.180	6.888	5.375	3.275	4.950	0.588	7.945
C	ped	4	5.292	-13.323	-3.021	-1.642	-2.996	-4.373	16.983	-33.278	-23.510	0.688	-0.104	-40.907
	prof	2	0.914	18.958*	4.396**	1.500	4.839*	6.397**	-0.554	49.378**	34.878**	2.057	0.565	56.003**
	e	7	3.339	4.625	0.250	4.625	1.696	1.386	2.607	3.411	0.786	4.679	0.661	3.998
IIB2tb	ped	4	6.399**	-1.055	0.173	4.283*	-0.541	-0.131	-4.714	-0.934	-0.232	-2.385	-0.226	-0.919
	prof	3	-5.005	0.414	0.440*	-1.354	-0.213	-0.046	2.268	-2.221	2.229	2.914	0.039	-0.333
	e	8	10.375	3.453	0.328	3.906	4.125	1.042	13.047	9.391	2.406	4.953	0.703	4.552
IIICb	ped	4	0.188	1.688	2.350	0.272	-1.194	0.128	-7.476	0.608	-1.934	-12.896	-0.174	-3.013
	prof	1	5.083†	1.688	-1.614	-0.333	1.302	1.035	14.771*	7.628†	6.116*	13.128	0.012	4.943†
	e	6	2.083	12.625	3.792	3.729	1.396	3.705	5.500	4.286	1.643	11.911	1.518	3.405
IVB2tb	ped	2	-5.920	-6.396	-3.628	-0.670	0.345	-4.442	-0.509	-7.619	1.982	1.685	-1.875	-0.458
	prof	2	8.562†	7.983†	4.408*	1.762*	1.246	5.863*	10.475	10.283	1.325	4.533†	3.850*	0.450
	e	5	4.250	4.075	1.475	0.350	1.300	1.798	8.675	15.225	2.225	3.100	1.425	7.655
VB2b	ped	0	-----	-----	-----	-----	-----	-----	-----	------	-----	-----	------	-----
	prof	1	16.000*	2.938	4.375*	-0.625	0.750*	1.128	14.250	-11.000	-4.875	5.375	-0.500	-3.590
	e	2	1.062	3.125	0.250	2.250	0.062	0.962	4.562	22.062	12.812	3.312	1.000	7.180
VIC	ped	0	-----	-----	-----	-----	-----	-----	-----	------	------	-----	-----	-----
	prof	0	-----	-----	-----	-----	-----	-----	-----	------	------	-----	-----	-----
	e	1	2.000	0.125	4.500	1.125	4.500	0.440	3.125	1.125	2.000	0.125	1.125	2.414

[†] ped, prof, and e are the variance components estimating mineral differences among pedons, profiles, and lab error, respectively.

†, *, **Significance at the 0.10, 0.05, and 0.01 levels of probability, respectively.

Table 5. Analyses of variance for soil sites 1 and 9.

Source of Variation	df	Expected mean square
	Soil site 1	
horizon (h)	6	$\sigma^2_e+2\sigma^2_{hp'}+5.071\sigma^2_{hp}+0.190\sigma^2_{prof}+0.142\sigma^2_{ped}+\theta K^2_h$
pedons (ped)	4	$\sigma^2_e+2\sigma^2_{hp'}+2.748\sigma^2_{hp}+13.728\sigma^2_{prof}+19.03\sigma^2_{ped}$
profiles within pedons (prof)	5	$\sigma^2_e+2\sigma^2_{hp'}+0.201\sigma^2_{hp}+8.618\sigma^2_{prof}$
horizon X pedon (hp)	24	$\sigma^2_e+2\sigma^2_{hp'}+2.673\sigma^2_{hp}$
horizon X profiles within pedon (hp')	16	$\sigma^2_e+2\sigma^2_{hp'}$
error (e)	56	σ^2_e
	Soil site 9	
horizon (h)	8	$\sigma^2_e+2\sigma^2_{hp'}+5.095\sigma^2_{hp}+0.633\sigma^2_{prof}+0.329\sigma^2_{ped}+\theta K^2_h$
pedons (ped)	4	$\sigma^2_e+2\sigma^2_{hp'}+2.825\sigma^2_{hp}+12.674\sigma^2_{prof}+18.293\sigma^2_{ped}$
profiles within pedons (prof)	5	$\sigma^2_e+2\sigma^2_{hp'}+0.147\sigma^2_{hp}+10.261\sigma^2_{prof}$
horizon X pedon (hp)	22	$\sigma^2_e+2\sigma^2_{hp'}+2.779\sigma^2_{hp}$
horizon X profiles within pedon (hp')	20	$\sigma^2_e+2\sigma^2_{hp'}$
error (e)	60	σ^2_e

Table 6. Estimated variance components for each dominant sand fraction in soil sites 1 and 9.

Soil Site	Variance component	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln
			Medium sand fraction				
9	ped[†]	0.947	-2.549	-0.516	-0.176	-0.752	-1.174
	prof	-0.402	4.996**	0.858*	0.054	0.971**	2.185**
	hp	-2.057	-1.773	-0.096	-0.016	-0.263	-0.283
	hp'	4.002**	1.500‡	0.645*	1.231*	0.174	0.116
	e	6.638	6.492	1.714	3.176	2.053	1.882
			Fine sand fraction				
9	ped	-0.219	-1.475	-1.366	-1.568	-0.049	-0.498
	prof	2.252‡	3.017*	2.653‡	2.290*	0.081	1.672
	hp	-1.500	-1.781	-2.582	0.408‡	-0.463	-2.926
	hp'	5.817**	4.438**	4.596**	0.673	0.801**	4.612**
	e	6.456	5.391	2.798	5.304	0.758	4.002
1	ped	1.409	0.229	-0.558	1.048	-0.045	1.234‡
	prof	-0.929	0.218	0.615	-0.534	0.024	-0.854
	hp	-5.097	-0.634	-0.994	0.365	0.003	-1.448
	hp'	7.617**	1.112	2.120**	3.674**	0.082	5.215
	e	9.089	4.737	2.261	5.731	0.674	19.173
			Very fine sand fraction				
1	ped	0.426	0.191	-0.121	-0.965	-0.006	-37.414
	prof	-0.721	-0.301	-0.124	0.079	0.004	24.966
	hp	-3.216	0.250	-2.571	-3.400	0.031*	72.384
	hp'	3.924	-0.280	4.589**	8.522**	-0.003	-93.301
	e	8.529	3.145	1.583	8.105	0.076	631.737

[†] ped, prof, hp, hp', and e are the components of variance estimating mineral differences among pedons in a polypedon, profiles within pedons, horizon X pedon interaction, horizon X profiles within pedons interaction, and error, respectively.

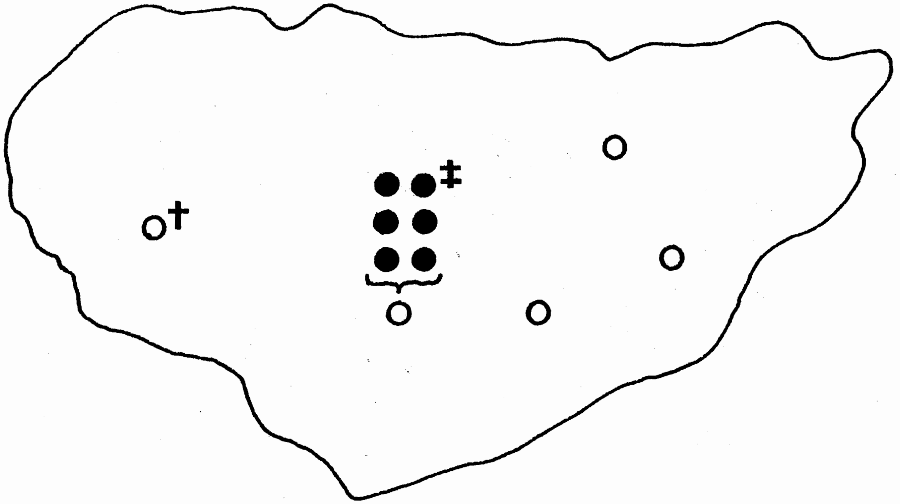
‡, *, **Significance at the 0.10, 0.05, and 0.01 levels of probability, respectively.

Table 7. Mineral means for each horizon and sand fraction in soil sites 1 and 9.

Horizon	Qtz		Mcln		Plag		Alt. feld.		Rock frag.		Qtz/Mcln	
	fs	vfs	fs	vfs	fs	vfs	fs	vfs	fs	vfs	fs	vfs
	--------%	--------	--------	--------	--------	--------	--------	--------	--------	--------		
					Soil site 1							
Ap	74.2	76.2	4.8	3.5	5.6	4.0	13.7	16.0	1.7	0.3	17.0	39.1
		†---*	--**	--*	--**	--*		---*		---‡	---**	---**
A12	73.0	73.8	8.4	4.6	2.8	2.5	14.4	19.0	1.4	0.1	9.4	18.1
B1	73.7	75.1	7.8	4.1	2.9	2.0	14.5	18.7	1.1	0.1	10.8	20.6
			---‡	---*	---*	---*				---‡	----‡	---**
B21t	73.7	75.6	6.2	2.7	4.4	3.8	14.9	17.7	0.8	0.2	14.2	39.7
				---‡								----*
B22t	74.2	75.6	7.0	3.8	4.1	2.9	13.5	17.7	1.2	tr	12.3	26.5
			--**		--‡				---‡		----*	
B3	75.2	76.3	9.6	4.6	2.6	2.0	12.0	17.0	0.6	0.1	8.3	18.3
IIC	77.8	78.0	8.8	3.9	2.0	1.6	11.1	16.5	0.3	tr	9.5	25.7
	ms	fs	ms	fs	ms	fs	ms	fs	ms	fs	ms	fs
					Soil site 9							
A1	74.5	76.3	13.0	11.6	1.9	2.4	7.2	8.7	3.4	1.1	6.0	6.8
						---‡	---‡					
AC1	74.6	75.2	13.9	10.7	2.8	4.0	5.9	8.6	2.8	1.5	5.8	7.5
										---*		
AC2	74.9	76.7	12.7	10.8	2.7	3.2	6.7	8.6	3.0	0.7	6.4	7.9
					---‡					---*		
C	75.3	74.6	13.1	12.1	1.4	3.6	6.5	7.9	3.7	1.8	6.2	7.8
IIB2tb	75.3	75.2	13.3	12.2	1.7	3.4	6.1	8.1	3.6	1.1	5.8	6.5
					---*							
IIICb	74.5	74.7	13.5	12.0	3.0	4.2	5.2	7.5	3.8	1.6	6.1	6.8
	----‡				---‡				--**			
IVB2tb	77.8	75.4	11.4	11.2	2.1	3.4	6.5	7.7	2.2	2.3	7.2	7.6
			----*				---‡				--*	
VB2b	76.9	74.9	13.7	11.6	2.0	4.6	4.5	7.4	2.9	1.5	5.8	7.0
	----*				--**				---‡		---‡	
VIC	69.5	74.2	7.3	7.8	10.5	5.0	7.2	10.8	5.5	2.2	9.6	9.7

†Denotes significant mineral differences between adjacent horizons.

‡, *, **Significant at the 0.10, 0.05, and 0.01 levels of probability, respectively.



†pedons (area≈10 ha), ‡profiles (area≈2 m^2)

Fig. 1. Example of sampling design and profiles sampled.

PART III

APPENDIX

Table 1. Estimated variance components of the light minerals in the sand fractions for soil site 4.

Horizon	Variance component	df	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln
			Fine Sand						Very Fine Sand					
Ap	ped[†]	4	8.498*	5.498	0.981	-0.652	0.133‡	3.178*	-0.182	-0.483	0.026	-1.541	0.030*	-333.71
	prof	5	-1.471	-4.250	0.654	-0.450	-0.046	-1.723	0.373	-0.788	0.031	2.185	-0.002	66.60
	e	10	7.312	10.588	3.662	6.188	0.225	4.772	15.638	3.825	0.888	16.800	0.025	1090.12
Al	ped	4	3.151	4.568	4.709**	2.214‡	-0.300	5.548*	4.959	1.451	-0.602	0.092	0.000	85.604*
	prof	5	-0.315	3.085‡	-0.040	-4.440	0.275	0.605‡	2.231	0.506	0.325	2.725	0.000	-15.479
	e	10	9.150	3.650	1.412	11.262	0.550	0.739	6.288	1.025	1.638	7.350	0.000	74.418
B21t	ped	4	-4.674	-6.627	-0.494	4.780‡	-0.125	-3.419	-0.786	-0.857	-0.016	-4.794	-0.003	-3.561
	prof	5	11.310‡	6.967	0.117	-0.102	-0.100	3.768	-0.940	0.060	-0.690	5.800	-0.002	-20.065
	e	10	11.112	9.488	2.688	3.838	0.950	5.831	23.650	4.850	2.450	13.488	0.038	146.33
B22t	ped	4	-6.560	0.568	1.590	-6.291	-0.060	9.610‡	11.273*	-1.400	-0.846	6.221*	-0.006	-149.16
	prof	5	9.129	-5.144	-0.075	-1.340	-0.046	-18.692	0.854	1.154	1.450‡	-0.300	0.004	124.44
	e	10	27.412	13.175	2.538	26.912	0.562	45.436	5.662	2.925	1.500	6.450	0.012	435.76
B3	ped	4	-0.511	4.072‡	-0.182	1.421	-0.228	191.382**	-2.117	0.148	-0.602	-1.592	-0.008	1.263
	prof	5	11.535**	-0.427	1.419	-0.971	0.294	-2.706	0.650	0.129	0.417	6.079	0.004	20.678
	e	10	3.612	4.188	2.400	7.325	0.750	19.194	16.800	2.112	1.288	11.575	0.025	118.581
C1	ped	4	0.096	0.223	-1.061	-4.620	0.065	-12.896	-7.233	-0.058	-0.332	-7.582	0.000	-25.311
	prof	5	5.362*	-0.833	1.081*	15.735**	0.012	0.427	9.267*	-0.038	0.398	12.044‡	0.000	-50.857
	e	10	3.475	5.288	1.275	2.300	0.112	58.100	6.950	2.075	0.788	10.412	0.000	368.354
C2	ped	4	6.071	0.058	-0.245	2.801‡	0.017	-2.120	-2.916	0.231	-0.257	-6.850	-0.023	39.985*
	prof	5	2.479	-0.058	-0.140	0.119	0.054	4.026	6.194	-0.862	-0.202	9.779	0.012	-53.260
	e	10	3.275	4.200	2.662	2.762	0.375	11.368	16.800	2.762	1.575	12.875	0.062	133.874

[†] ped, prof, and e are the variance components estimating mineral differences among pedons, profiles, and lab error, respectively.

‡, *, **Significance at the 0.10, 0.05, and 0.01 levels of probability, respectively.

Table 2. Estimated variance components of the light minerals in the sand fractions for soil site 2.

Horizon	Variance component	df	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln	Qtz	Mcln	Plag	Alt feld.	Rock frag.	Qtz/Mcln
			Medium sand						Fine sand					
A1	ped[†]	4	-4.253	3.135*	-0.933	-0.769	1.201*	0.219	-0.270	1.160*	-0.541	0.143	0.129	0.296
	prof	5	-1.052	-1.908	1.750	1.138	-0.052	-0.216	5.360	-1.040	0.585	1.144	0.217*	-0.309
	e	10	22.975	5.788	4.100	4.862	0.675	0.704	13.000	2.750	5.662	3.912	0.150	1.176
AC1	ped	4	1.922	-0.382	-1.569	-1.300	-1.977	-0.013	-1.738	-2.003	-1.077	1.488	-0.070	-0.992
	prof	5	-1.090	-4.556	2.429‡	2.054	2.492*	-0.234	-0.333	-4.377	1.754‡	0.829	0.148	-1.849
	e	10	13.150	13.400	3.012	6.425	1.438	0.780	20.400	17.175	1.662	8.225	0.438	7.842
AC2	ped	4	2.109	-0.628	-0.002	-1.295	-0.307	-0.188	5.358	-7.219	1.805	0.500	-0.260	-1.801
	prof	5	-2.577	5.073*	-0.708	0.110	0.206	0.515*	7.438	7.380	1.885	-3.119	-0.075	1.791
	e	10	10.875	4.288	2.238	6.062	2.138	0.398	13.725	11.712	3.050	14.025	1.338	2.741
C11	ped	4	-2.566	-2.007	0.130	2.834	0.838**	-1.284	-7.999	-1.379	-2.941	-4.810	0.023	-0.200
	prof	5	1.669	8.156‡	1.473	-1.365	-0.483	2.021*	9.585‡	3.654‡	4.485**	6.200	-0.258	0.856
	e	10	11.200	7.025	1.625	8.400	1.100	1.021	9.162	3.525	1.762	8.688	0.938	1.078
C12	ped	1	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	prof	0	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	e	2	3.062	6.312	1.625	2.250	0.2500	0.355	27.625	30.500	3.312	31.562	0.250	19.006

[†] ped, prof, and e are the variance components estimating mineral differences among pedons, profiles, and lab error, respectively.
‡, *, **Significance at the 0.10, 0.05, and 0.01 levels of probability, respectively.

Table 3. Estimated variance components of the light minerals in the sand fraction for soil site 5.

Horizon	Variance component	df	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln	Qtz	Mcln	Plag	Alt. feld.	Rock frag.	Qtz/Mcln
			Medium sand						Fine sand					
Ap	ped†	4	-1.429	-0.102	-5.686	3.475‡	-1.028	1.153	-8.824	-3.445	3.008*	-0.042	0.106	-2.662
	prof	5	4.325	-11.058	8.160*	-4.562	-0.081	-2.741	9.173	5.331	-1.525	-0.238	-0.471	4.001*
	e	10	9.700	35.238	4.100	13.025	4.212	7.013	18.238	10.575	4.100	6.025	1.112	2.947
B2t	ped	4	-6.670	-3.895	-4.790	-0.608	-0.988	-0.611	-2.486	0.648	-0.844	-0.254	-0.086	0.071
	prof	5	8.606†	7.106*	7.300**	1.542	0.754	1.089*	2.973	-0.971	1.742*	0.467	-0.402	-0.140
	e	10	9.888	4.725	2.038	3.200	2.225	0.722	4.788	3.612	0.838	3.350	1.538	0.791
B3	ped	4	-4.460	-18.357	-3.238	-29.661	-0.988	-16.315	5.879	-4.766	1.183	0.630	-0.094	-0.505
	prof	5	9.354*	29.556**	4.229*	43.498**	1.400*	25.748**	2.179	-0.152	-1.375	0.610	1.167**	-0.212
	e	10	4.662	5.238	2.325	6.075	1.050	2.009	11.025	17.388	5.650	2.550	0.388	2.753
IIB2	ped	4	-1.718	-2.433	2.212	-2.806	-2.124	-3.111	-2.620	2.206	1.707	-1.354	-0.203	-0.686
	prof	3	3.682	4.242	2.958**	5.089*	2.773**	3.072	4.674‡	-0.682	-0.763	-1.258	-0.133	1.085
	e	8	5.219	6.516	0.500	2.438	0.484	5.029	4.516	6.281	3.234	7.890	1.047	2.697
IIIB2	ped	3	9.404*	2.032	-1.312	0.982	-0.179	0.191	-1.204	2.282	1.244	0.333	-0.125	0.783†
	prof	3	-0.182	-1.056	4.390**	0.864	-0.205	0.007	-0.631	-1.121	0.528	-0.449	0.182	-0.399
	e	7	2.071	5.893	0.804	2.803	1.286	0.479	7.679	4.107	2.643	3.982	0.554	1.156
IVB2b	ped	3	1.155	2.015	-0.442	1.627*	0.240	0.238	6.128‡	7.378‡	3.424*	0.375	-0.038	1.097
	prof	5	-1.596	-0.176	0.539	-3.360	0.242	-0.121	-1.340	2.660	0.133	-3.413	0.041	2.154
	e	9	9.875	3.222	2.556	7.542	2.000	0.895	7.764	3.417	1.306	8.014	0.306	2.922
VB21b	ped	3	0.012	-0.730	0.174	3.703*	-0.534	-0.289	-16.275	4.342	-4.766	-10.504	0.224	-2.738
	prof	3	-1.574	-0.243	0.528	-1.684	0.361	-0.086	25.122**	11.804**	10.013**	14.577*	0.114	10.724*
	e	7	6.857	7.768	1.393	3.982	2.393	2.020	4.339	2.643	1.839	7.554	0.804	4.023
VB22b	ped	2	2.528	-1.384	-0.666	-1.554	-0.056	-0.108	-7.415	5.151	-0.655	-1.497	-1.226	0.164
	prof	3	0.229	-6.104	0.818	-0.368	0.018	-0.754	8.261‡	3.205	4.197**	0.872	1.517*	2.160
	e	8	6.984	20.180	3.703	7.516	1.352	2.255	8.570	7.891	1.039	5.875	0.860	5.641
VB23b	ped	0	-----	------	-----	------	-----	-----	-----	-----	-----	-----	-----	-----
	prof	1	-2.000	1.250	-0.875	0.375	0.000	0.149	-6.125	21.250	9.875*	10.375‡	0.625	20.805
	e	2	6.250	2.562	2.000	0.812	0.500	0.630	12.812	6.500	0.500	1.812	1.000	41.114
VIC	ped	0	-----	-----	-----	-----	-----	-----	------	-----	-----	-----	-----	------
	prof	1	23.875	22.875†	-0.188	0.000	0.000	5.045†	-1.125	12.438**	4.500	-3.375	0.750*	28.593**
	e	2	8.500	3.250	0.625	0.625	0.625	0.893	5.312	0.125	5.062	7.312	0.0625	0.395

† ped, prof, and e are the variance components estimating mineral differences among pedons, profiles, and lab error, respectively.
†, *, **Significance at the 0.10, 0.05, and 0.01 levels of probability, respectively.

Table 4. Mean ($\bar{x}$) and standard error of the mean ($s_{\bar{x}}$) for chemical analyses of the soil sites.

Horizon	Depth	Statistic	pH1:1 H_2O	Organic carbon	Extractable Cations				Extractable acidity	CEC	Base saturation
					Ca	Mg	K	Na			
	cm			%	---------------meq/100g---------------						%
					Soil site 1						
Ap	0-24	n=3									
		$\bar{x}$	7.77	1.55	9.41	3.55	1.10	0.03	3.58	17.62	81.02
		$s_{\bar{x}}$	0.28	0.23	0.17	0.04	0.23	0.01	0.86	1.45	6.71
A12	24-39	n=2									
		$\bar{x}$	7.50	0.80	10.02	3.94	0.74	0.03	2.44	15.89	92.69
		$s_{\bar{x}}$	0.10	0.06	0.22	0.08	0.06	0.00	0.48	0.28	0.57
B1	39-68	n=3									
		$\bar{x}$	7.48	0.64	10.31	4.20	0.61	0.03	2.38	17.07	88.75
		$s_{\bar{x}}$	0.08	0.06	0.20	0.34	0.03	0.01	0.21	0.15	2.46
B21t	68-92	n=3									
		$\bar{x}$	7.85	0.37	10.58	4.91	0.42	0.05	1.72	19.70	83.52
		$s_{\bar{x}}$	0.13	0.05	0.68	0.29	0.03	0.01	0.00	2.87	8.81
B22t	92-138	n=3									
		$\bar{x}$	7.70	0.19	17.62	5.79	0.33	0.07	2.60	16.40	>100
		$s_{\bar{x}}$	0.25	0.02	7.68	0.43	0.02	0.00	1.30	0.62	56.92
B3	138-199	n=3									
		$\bar{x}$	7.73	0.13	31.56	8.68	0.34	0.27	0.21	17.92	>100
		$s_{\bar{x}}$	0.13	0.03	0.71	0.76	0.02	0.05	0.00	0.69	5.64
IIC	199-232	n=1									
		$\bar{x}$	8.20	0.09	31.27	9.07	0.34	0.64	nd	22.84	>100
		$s_{\bar{x}}$	----	----	----	----	----	----	----	----	----
					Soil site 4						
Ap	0-23	n=3									
		$\bar{x}$	6.97	0.55	6.69	2.82	0.68	0.04	4.61	15.13	67.67
		$s_{\bar{x}}$	0.12	0.01	0.07	0.06	0.03	0.01	0.18	0.43	1.63
A12	23-50	n=3									
		$\bar{x}$	7.70	0.59	7.82	4.91	0.47	0.07	2.44	15.94	84.09
		$s_{\bar{x}}$	0.23	0.04	0.86	0.66	0.03	0.02	0.24	1.17	5.51
B21t	50-83	n=3									
		$\bar{x}$	7.60	0.42	8.28	4.68	0.38	0.09	1.06	16.53	82.40
		$s_{\bar{x}}$	0.38	0.04	1.01	0.85	0.02	0.03	0.11	1.43	6.92
B22t	83-107	n=3									
		$\bar{x}$	8.08	0.33	8.25	4.98	0.42	0.07	1.12	13.16	>100
		$s_{\bar{x}}$	0.04	0.02	0.81	0.71	0.05	0.01	0.29	1.63	8.13
B3	107-151	n=3									
		$\bar{x}$	7.90	0.20	13.73	6.43	0.35	0.08	1.50	11.39	>100
		$s_{\bar{x}}$	0.21	0.02	6.89	0.43	0.07	0.01	0.15	0.75	49.5
C1	151-206	n=3									
		$\bar{x}$	8.43	0.11	17.76	7.60	0.23	0.18	1.20	8.88	>100
		$s_{\bar{x}}$	0.03	0.04	2.44	0.40	0.06	0.02	0.12	1.33	31.71
C2	206-267	n=3									
		$\bar{x}$	8.40	0.09	11.20	6.93	0.28	0.19	1.16	10.96	>100
		$s_{\bar{x}}$	0.15	0.03	4.90	0.28	0.08	0.02	0.80	0.72	33.47

Table 4. (Continued).

Horizon	Depth	Statistic	pH1:1 H_2O	Organic carbon	Extractable Cations Ca	Mg	K	Na	Extractable acidity	CEC	Base saturation
	cm			%	-----------------	----	meq/100g	----	----------	----------	%
					Soil site 2						
A1	0-30	n=3									
		$\bar{x}$	8.40	0.23	4.72	0.57	0.13	0.08	0.45	5.63	97.96
		$s_{\bar{x}}$	0.21	0.07	0.03	0.05	0.02	0.07	0.07	0.23	3.55
AC1	30-65	n=3									
		$\bar{x}$	8.30	0.57	7.71	0.59	0.06	0.02	0.31	4.42	>100
		$s_{\bar{x}}$	0.06	0.01	0.20	0.02	0.00	0.01	0.13	0.15	4.19
AC2	65-98	n=3									
		$\bar{x}$	8.58	0.03	8.50	0.55	0.30	0.03	0.31	4.27	>100
		$s_{\bar{x}}$	0.16	0.00	0.11	0.01	0.24	0.00	0.13	0.09	8.63
C11	98-123	n=3									
		$\bar{x}$	8.60	0.02	9.36	0.63	0.06	0.02	0.24	4.13	>100
		$s_{\bar{x}}$	0.30	0.00	0.27	0.06	0.01	0.00	0.07	0.09	11.47
C12	123-214	n=1									
		$\bar{x}$	8.10	0.03	12.17	0.89	0.07	0.02	0.29	4.78	>100
		$s_{\bar{x}}$	----	----	-----	----	----	----	----	-----	-----
					Soil site 9						
A1	0-27	n=3									
		$\bar{x}$	6.57	0.56	3.92	1.21	0.29	0.02	2.32	7.14	81.54
		$s_{\bar{x}}$	0.09	0.02	0.44	0.10	0.02	0.01	0.16	1.08	17.86
AC1	27-79	n=3									
		$\bar{x}$	7.80	0.18	3.65	1.27	0.22	0.04	1.84	5.50	93.63
		s_x	0.90	0.03	0.46	0.28	0.06	0.03	0.22	0.47	5.47
AC2	79-140	n=3									
		$\bar{x}$	7.12	0.10	3.18	1.43	0.14	0.01	1.98	5.96	79.82
		$s_{\bar{x}}$	0.25	0.02	0.64	0.18	0.05	0.01	0.07	0.51	9.81
C	140-186	n=2									
		$\bar{x}$	7.12	0.07	3.10	1.40	0.08	0.02	1.84	6.86	70.36
		$s_{\bar{x}}$	0.32	0.01	1.19	0.06	0.04	0.01	----	0.87	26.63
IIB2tb	186-209	n=3									
		$\bar{x}$	6.92	0.17	9.77	3.09	0.36	0.14	1.46	11.80	>100
		$s_{\bar{x}}$	0.36	0.03	4.11	1.18	0.13	0.11	0.06	2.93	18.08
IIICb	209-237	n=3									
		$\bar{x}$	7.33	0.09	5.43	2.31	0.16	0.05	3.03	10.16	82.42
		$s_{\bar{x}}$	0.20	0.00	0.90	0.54	0.03	0.02	0.54	2.59	8.68
IVB2tb	237-263	n=3									
		$\bar{x}$	7.22	0.08	6.03	2.51	0.16	0.08	2.00	10.50	86.99
		$s_{\bar{x}}$	0.11	0.02	0.99	0.40	0.04	0.04	0.60	2.57	6.97
VB2b	263-293	n=1									
		$\bar{x}$	7.55	0.13	27.56	3.76	0.26	0.15	nd	13.94	>100
		$s_{\bar{x}}$	----	----	-----	----	----	----	----	-----	------
VIC	290-308	n=1									
		$\bar{x}$	7.60	0.06	7.80	2.63	0.23	0.09	nd	9.85	>100
		$s_{\bar{x}}$	----	-----	-----	----	-----	----	-----	-----	-----

Table 4. (Continued).

Horizon	Depth	Statistic	pH1:1 H_2O	Organic carbon	Extractable Cations				Extractable acidity	CEC	Base saturation
					Ca	Mg	K	Na			
	cm			%	------------------			meq/100g	------------------		%
					Soil site 5						
Ap	0-23	n=3									
		$\bar{x}$	6.72	0.19	2.52	1.04	0.25	tr	0.26	4.15	95.54
		$s_{\bar{x}}$	0.13	0.02	0.71	0.35	0.02	0.00	0.06	1.28	6.49
B2t	23-52	n=3									
		$\bar{x}$	6.73	0.17	5.44	2.38	0.44	0.01	1.13	11.23	75.29
		$s_{\bar{x}}$	0.17	0.03	0.34	0.06	0.12	0.01	0.49	1.35	7.33
B3	52-86	n=3									
		$\bar{x}$	7.85	0.11	5.25	2.11	0.28	0.01	0.54	11.70	70.45
		$s_{\bar{x}}$	0.33	0.01	0.48	0.25	0.08	0.01	0.22	2.48	12.14
IIB2	86-138	n=3									
		$\bar{x}$	7.45	0.08	9.47	2.89	0.20	0.05	1.90	12.08	>100
		$s_{\bar{x}}$	0.19	0.02	4.51	1.27	0.05	0.04	1.14	2.95	29.17
IIIB2	138-172	n=2									
		$\bar{x}$	7.90	0.08	8.47	2.36	0.30	0.01	0.38	11.38	>100
		$s_{\bar{x}}$	0.60	0.02	3.47	1.00	0.15	0.00	----	3.22	52.19
IVB2b	172-226	n=3									
		$\bar{x}$	7.90	0.15	25.80	5.02	0.37	0.03	2.22	21.43	>100
		$s_{\bar{x}}$	0.00	0.01	7.88	1.47	0.08	0.01	0.92	3.76	29.56
VB21b	226-238	n=2									
		$\bar{x}$	7.92	0.07	34.64	7.99	0.38	0.26	1.08	21.38	>100
		$s_{\bar{x}}$	0.08	0.01	0.18	1.03	0.07	0.17	----	5.14	56.42
VB22b	238-295	n=2									
		$\bar{x}$	7.98	0.14	33.72	6.52	0.36	0.20	1.08	15.84	>100
		$s_{\bar{x}}$	0.18	0.10	0.40	0.14	0.08	0.16	----	1.44	22.51
VB23b	293-356	n=2									
		$\bar{x}$	8.08	0.06	21.99	7.52	0.34	0.10	1.29	19.06	>100
		$s_{\bar{x}}$	0.22	0.00	9.66	2.80	0.15	0.08	----	7.52	14.65
VIC	356-460	n=1									
		$\bar{x}$	8.00	0.08	33.29	5.93	0.35	0.21	nd	23.13	>100
		$s_{\bar{x}}$	----	----	-----	----	----	----	----	-----	-----

Table 5. Mean ($\bar{x}$) and standard error of the mean ($s_{\bar{x}}$) for particle-size distribution of the soil sites.

			Coarse	Sand (mm)					Silt (μ)			Clay (μ)
Horizon	Depth	Statistic	fragments, >2mm	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	50-20	20-5	5-2	<2
	cm		%									
					Soil site 1							
Ap	0-24	n=6										
		$\bar{x}$	0.0	0.1	0.5	0.7	2.8	13.4	49.8	13.3	3.1	16.3
		$s_{\bar{x}}$	0.0	0.0	0.1	0.1	0.2	0.9	1.4	0.5	0.7	1.2
A12	24-39	n=6										
		$\bar{x}$	0.1	0.2	0.7	1.1	3.3	14.8	47.3	11.5	2.5	18.6
		$s_{\bar{x}}$	0.0	0.0	0.1	0.1	0.2	1.0	1.2	1.5	0.4	0.6
B1	39-68	n=6										
		$\bar{x}$	1.0	0.1	0.7	1.4	3.9	14.9	48.3	9.1	2.7	18.9
		$s_{\bar{x}}$	1.0	0.0	0.1	0.2	0.4	0.8	2.2	0.6	0.5	0.7
B21t	68-92	n=6										
		$\bar{x}$	0.1	0.2	0.9	1.3	5.1	22.6	41.5	7.8	1.4	19.2
		$s_{\bar{x}}$	0.0	0.0	0.1	0.2	0.8	1.0	1.8	0.8	0.6	0.8
B22t	92-138	n=6										
		$\bar{x}$	0.1	0.3	0.7	0.8	2.5	15.9	50.7	8.2	2.3	18.6
		$s_{\bar{x}}$	0.1	0.1	0.1	0.1	0.4	1.6	1.3	1.0	0.8	0.7
B3	138-199	n=6										
		$\bar{x}$	0.3	0.5	1.2	1.4	4.2	12.2	49.6	10.7	2.3	17.9
		$s_{\bar{x}}$	0.1	0.4	0.6	0.6	0.9	1.0	2.1	0.9	0.1	0.2
IIC	199-232	n=6										
		$\bar{x}$	2.1	2.6	3.6	3.7	3.0	7.9	36.3	11.2	9.2	22.5
		$s_{\bar{x}}$	1.4	0.8	0.9	0.9	0.6	0.5	2.8	1.5	1.5	0.9
					Soil site 4							
Ap	0-23	n=6										
		$\bar{x}$	tr	0.2	0.8	1.0	0.7	11.8	59.0	12.1	1.9	12.5
		$s_{\bar{x}}$	0.0	0.0	0.1	0.1	0.0	0.3	0.7	0.3	0.3	0.9
A12	23-50	n=6										
		$\bar{x}$	tr	0.1	0.6	0.9	0.7	15.8	50.4	13.1	2.0	16.4
		$s_{\bar{x}}$	0.0	0.0	0.1	0.2	0.1	2.7	2.9	0.4	0.4	0.5
B21t	50-82	n=6										
		$\bar{x}$	tr	0.1	0.6	0.8	0.6	10.9	56.8	9.8	3.3	17.1
		$s_{\bar{x}}$	0.0	0.0	0.0	0.1	0.0	0.7	0.5	0.4	0.3	0.3
B22t	82-107	n=6										
		$\bar{x}$	tr	0.1	0.4	0.5	0.5	12.1	58.9	10.3	2.0	15.2
		$s_{\bar{x}}$	0.0	0.0	0.1	0.1	0.1	1.2	0.9	0.5	0.4	1.4
B3	107-151	n=6										
		$\bar{x}$	0.2	0.1	0.3	0.4	0.8	19.7	57.2	10.3	2.8	8.4
		$s_{\bar{x}}$	0.2	0.0	0.1	0.0	0.1	2.4	2.8	0.6	0.8	0.9
C1	151-206	n=6										
		$\bar{x}$	0.1	0.2	0.4	0.7	1.1	14.6	61.3	13.5	1.6	6.6
		$s_{\bar{x}}$	0.0	0.0	0.1	0.1	0.1	1.6	2.0	1.3	0.6	0.7
C2	206-267	n=6										
		$\bar{x}$	0.1	0.3	1.0	1.3	0.7	16.1	58.1	12.8	3.4	6.3
		$s_{\bar{x}}$	0.0	0.1	0.4	0.5	0.1	2.8	2.8	1.4	0.5	0.6

Table 5. (Continued).

			Coarse Fragments,	Sand (mm)					Silt (μ)			Clay (μ)
Horizon	Depth	Statistic	>2mm	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	50-20	20-5	5-2	<2
	cm		%									
					Soil site 2							
A1	0-30	n=6										
		$\bar{x}$	tr	0.1	8.5	47.6	24.0	7.8	8.6	0.1	0.4	2.9
		$s_{\bar{x}}$	0.0	0.0	1.9	0.8	0.9	0.3	1.4	0.1	0.3	0.7
AC1	30-65	n=6										
		$\bar{x}$	0.0	0.2	9.7	56.2	21.1	6.7	3.3	0.6	0.1	2.1
		$s_{\bar{x}}$	0.0	0.0	1.7	1.5	1.3	0.3	0.5	0.2	0.1	0.3
AC2	65-98	n=6										
		$\bar{x}$	0.0	0.1	9.4	57.2	21.2	6.2	2.1	0.7	1.0	2.1
		$s_{\bar{x}}$	0.0	0.0	1.6	1.2	1.7	0.3	0.5	0.2	0.3	0.5
C11	98-123	n=6										
		$\bar{x}$	0.0	0.2	8.8	56.6	23.1	5.5	1.7	1.0	0.6	2.5
		$s_{\bar{x}}$	0.0	0.1	2.3	1.3	1.3	0.2	0.5	0.2	0.4	0.6
C12	123-214	n=2										
		$\bar{x}$	0.0	tr	1.9	35.6	33.2	16.7	8.6	0.3	0.6	3.1
		$s_{\bar{x}}$	0.0	0.0	0.1	0.1	0.6	0.6	0.4	0.3	0.6	0.6
					Soil site 9							
A1	0-27	n=6										
		$\bar{x}$	0.0	tr	3.9	37.8	25.6	12.5	14.0	0.5	1.1	4.6
		$s_{\bar{x}}$	0.0	0.0	0.3	3.9	1.1	1.7	1.1	0.3	0.6	0.8
AC1	27-79	n=6										
		$\bar{x}$	0.0	0.1	4.0	40.2	30.3	12.2	7.4	0.9	0.7	4.2
		$s_{\bar{x}}$	0.0	0.0	0.3	3.0	0.8	1.6	1.2	0.5	0.4	0.8
AC2	79-140	n=6										
		$\bar{x}$	0.0	0.1	2.8	37.0	35.8	13.8	5.9	0.5	0.9	3.6
		$s_{\bar{x}}$	0.0	0.0	0.7	4.8	2.4	3.3	1.5	0.3	0.3	0.7
C	140-186	n=4										
		$\bar{x}$	tr	0.3	9.9	34.9	25.0	15.0	8.2	1.2	1.1	4.4
		$s_{\bar{x}}$	0.0	0.1	2.4	3.8	2.0	2.5	2.2	0.5	0.5	0.6
IIB2tb	186-209	n=6										
		$\bar{x}$	0.0	0.1	2.9	17.1	14.6	12.0	20.2	9.6	3.5	20.0
		$s_{\bar{x}}$	0.0	0.1	1.4	5.4	3.9	4.2	2.5	3.9	1.7	7.6
IIICb	209-237	n=4										
		$\bar{x}$	0.0	0.1	4.9	35.1	30.2	9.6	10.6	1.1	0.9	7.5
		$s_{\bar{x}}$	0.0	0.1	1.4	0.5	2.3	1.3	1.5	0.2	0.3	2.9
IVB2tb	237-263	n=6										
		$\bar{x}$	0.0	0.1	3.8	29.4	23.6	12.0	18.3	2.9	0.8	9.1
		$s_{\bar{x}}$	0.0	0.0	1.2	6.0	4.9	2.2	6.5	1.1	0.6	1.6
VB2b	263-290	n=2										
		$\bar{x}$	0.9	0.3	2.0	9.8	14.2	17.0	35.9	5.0	1.3	14.5
		$s_{\bar{x}}$	0.9	0.1	1.3	3.7	6.3	2.5	0.2	0.0	1.2	0.5
VIC	290-308	n=2										
		$\bar{x}$	0.1	tr	3.9	38.6	30.4	5.4	5.4	3.5	1.5	11.3
		$s_{\bar{x}}$	0.1	0.0	0.5	0.9	0.8	0.3	1.8	0.3	1.0	3.8

Table 5. (Continued).

Horizon	Depth	Statistic	Coarse fragments, >2mm	Sand (mm)					Silt (μ)			Clay (μ)
				2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	50-20	20-5	5-2	<2
	cm		%									
				Soil site 5								
Ap	0-23	n=6										
		$\bar{x}$	0.0	0.6	8.5	48.1	23.7	5.0	4.5	1.3	1.0	7.3
		$s_{\bar{x}}$	0.0	0.4	1.3	2.0	0.6	0.5	2.0	0.5	0.7	1.9
B2t	23-52	n=6										
		$\bar{x}$	0.0	tr	9.4	43.1	20.7	5.3	7.8	2.7	0.6	10.4
		$s_{\bar{x}}$	0.0	0.0	2.0	0.8	1.1	0.5	2.3	1.2	0.3	0.5
B3	52-86	n=6										
		$\bar{x}$	0.0	tr	6.3	42.4	25.7	5.7	8.6	1.7	1.0	8.6
		$s_{\bar{x}}$	0.0	0.0	1.5	3.6	3.0	0.8	0.5	0.3	0.4	0.9
IIB2	86-138	n=6										
		$\bar{x}$	0.1	0.1	9.3	27.6	19.9	7.1	21.6	2.6	2.3	9.5
		$s_{\bar{x}}$	0.0	0.0	1.6	6.3	0.9	1.2	5.4	0.9	1.1	1.4
IIIB2	138-172	n=4										
		$\bar{x}$	tr	0.1	8.7	44.3	19.4	6.0	7.2	2.0	1.7	10.6
		$s_{\bar{x}}$	0.0	0.1	0.8	3.9	2.6	0.9	1.1	0.9	0.3	1.2
IVB2b	172-226	n=6										
		$\bar{x}$	0.4	0.2	2.0	15.0	14.8	8.5	25.7	6.7	4.0	23.1
		$s_{\bar{x}}$	0.2	0.1	0.4	2.1	2.6	1.4	3.1	0.4	1.2	2.2
VB21b	226-238	n=4										
		$\bar{x}$	0.3	0.3	1.4	7.0	7.1	9.6	36.2	10.5	5.6	22.3
		$s_{\bar{x}}$	0.1	0.0	0.7	3.0	2.8	1.0	4.4	1.8	1.8	0.8
VB22b	238-293	n=4										
		$\bar{x}$	2.9	0.2	0.7	4.4	5.6	10.4	40.5	11.6	4.3	22.3
		$s_{\bar{x}}$	2.9	0.0	0.2	0.8	1.2	1.8	4.6	2.7	1.0	0.4
VB23b	293-356	n=4										
		$\bar{x}$	0.2	0.3	1.0	6.4	7.7	11.2	40.3	9.6	5.0	18.5
		$s_{\bar{x}}$	0.2	0.1	0.3	3.0	2.1	0.3	2.0	1.0	1.2	3.2
VIC	356-460	n=2										
		$\bar{x}$	0.6	0.5	0.6	2.9	3.3	9.0	37.9	10.0	6.9	28.9
		$s_{\bar{x}}$	0.6	0.2	0.1	1.2	1.4	2.2	0.9	2.5	0.6	1.1

VITA

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