GEOCHEMICAL SURVEY OF MISSOURI

Geography of Soil Geochemistry and Classification by Factor Analysis of Missouri Agricultural Soils

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MARCH 3, 1849

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By RONALD R. TIDBALL

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A study of the distribution of 43 elements
in agricultural soils at 1,140 locations
in Missouri

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ABSTRACT

Samples of 1,140 agricultural soils from throughout the State of Missouri were analyzed for total concentrations of 43 elements. The results are shown on gray-level symbol maps. Soils developed on young parent materials, such as glacial till, loess, and alluvium, tend to have large concentrations of numerous elements, notably calcium, potassium, magnesium, and sodium. Soils developed on deeply weathered residuum from carbonate rocks have large amounts of silicon (exceeding 40 percent in some cases), titanium, and zirconium and have very small amounts of most other elements.

INTRODUCTION

The amounts of various elements in surficial geologic material differ from one location to another. This condition has resulted from geologic and soil-forming processes that have concentrated certain elements more in some environments than in others. More recent processes, including the activities of man, have tended to redistribute the elements in still more diverse patterns. The character of these patterns may be estimated by reconnaissance geochemical survey techniques such as those being developed by the U.S. Geological Survey (Miesch, 1976).

The geochemical survey of the agricultural soils of Missouri was undertaken (1) to determine typical natural concentrations of the elements in soils as expressed by total analyses, and (2) to describe the geographic patterns of compositional variation. Both univariate and multivariate interpretations of the data will be given, but the multivariate treatment appears separately in a companion report, Chapter I. Typical concentrations of elements are given by the grand mean and deviation, by histograms, and by the 95 percent expected range. The geographic distributions are illustrated by gray-level symbol maps.

The geochemical survey was conducted primarily to assist epidemiologists at the University of Missouri in their studies of the possible relation between health (animal and human) and trace substances in the environment. In addition, the survey is part of the continuing development of reconnaissance sampling techniques for large areas: Missouri contains about 180,000 square kilometers.

REVIEW OF LITERATURE

There are very few previous reports of total chemical analyses of soils in Missouri. Several important soil series were analyzed for both major and minor elements by Pickett and Dinius (1954). Johnson (1950) studied the cobalt and copper concentrations in 26 different soils. The arsenic, copper, and lead concentrations of both contaminated orchard soils and selected natural soils were reported by Hess and Blanchar (1977). Missouri was included in extensive geochemical maps of the conterminous U.S. that showed the distribution of over 30 elements in soils and other surficial materials (Shacklette and others, 1971a, b; 1973; 1974).

Plants and associated soils were collected from within major native-vegetation-type areas in Missouri in two different studies. In the first one, Erdman Shacklette, and Keith (1976a) collected native plants and the *B* horizon of uncultivated soils at 60 sites from throughout the State. In the second study (Erdman and others, 1976b), crop plants and the plow zone of cultivated soils were collected from 40 sites.

ACKNOWLEDGMENTS

Sample collection was guided by the Statewide staff of the Extension Division of the University of Missouri under the supervision of Dr. Walter F. Heidlage, Program Coordinator, Extension Environmental Health. Chemical analyses of all samples were made in the laboratories of the U.S. Geological Survey in Denver, Colorado and Reston, Virginia by: L. A. Bradley, semiquantitative spectrograph and J. S. Wahlberg, M. W. Solt, and Mike Brown, X-ray fluorescence. Additional analyses for selected elements were done by Johnnie Gardner and Violet Merritt, magnesium and

sodium; I. C. Frost, G. T. Burrow, and G. D. Shipley, carbon; J. P. Cahill, cadmium; J. A. Thomas, lithium and zinc; R. L. Turner, mercury; F. W. Brown, Joseph Budinsky, B. A. McCall, Leung Mei, and Roosevelt Moore, arsenic and fluorine; A. J. Bartel, iodine; A. J. Bartel, E. L. Brandt, J. P. Hemming, R. J. Knight, H. T. Millard, R. J. Vinnola, R. J. White, uranium and thorium. Computer programs for mechanical plotting were written by M. R. Mall. The special assistance of J. G. Boerngen in automatic data processing is gratefully acknowledged.

SOIL PARENT MATERIALS

The distribution of bedrock in Missouri was compiled by McCracken (1961) and the geology of Missouri was summarized by Vineyard and others (1967, p. 13–31). The distribution of soil parent materials in Missouri is shown in figure 1; the bedrock in more than half of the State is covered by an overburden of glacial materials that includes till, loess, and outwash. These glacial materials are geologically younger, and therefore less weathered than the residual type of parent materials in the southern half of the State. The southern limit of glaciation across central Missouri defines the approximate limit of glacial till. However, loess extends as far south as the 38th parallel. Loess also occurs in a narrow band along the Mississippi River valley in southeast Missouri. Much of the original loess cover has been completely eroded away, especially on the steeper slopes, but some deposits remain on the broad interstream divides. Loess deposits of maximum thickness (more than 10 meters) occur on the bluffs along both the Missouri and Mississippi Rivers. The thickest loess deposits occur in northwest Missouri along the Missouri River; they diminish in thickness and extent toward the east where recognizable deposits occur only on the broad interstream divides.

Glacial till is widely exposed in northern Missouri where the loess cover is absent. A typical exposure is on the side slopes of the rolling terrain between the loess cover of the interstream divide that tapers from above and the mixed alluvium of the valley bottom that tapers from below. Most of northern Missouri is, therefore, a mosaic of loess and glacial till with scattered exposures of bedrock in the lower portions of the valley sides.

A limited exposure of granites and felsites of Precambrian age occurs in southeast Missouri in Iron, Madison, and St. Francois Counties, with an outlier in Shannon County. These exposures are surrounded by outcrops of cherty dolomite of Cambrian age. The bulk of the Ozark Plateaus province is covered by a thick, brick-red, cherty, and highly weathered residuum from carbonate rocks—dolomite of Ordovician age and limestone of Mississippian age. Sandstones, shales, and limestones of Pennsylvanian age are exposed in west-central Missouri. The bedrock in areas near the southern limit of glaciation is covered to various degrees by loess, which ranges in thickness from a few centimeters to several meters.

The valleys of the Missouri and Mississippi Rivers are flat plains composed of fine-grained alluvial sediments of recent age. The Mississippi Alluvial Plain (Fenneman, 1946) of southeast Missouri contains sedimets from both the Mississippi and Ohio Rivers as well as local streams. A central ridge on the Plain is composed of materials of Tertiary and Cretaceous ages.

METHODS

The methods of sampling, laboratory analysis, and statistical reduction of data that are used in this study were described by Miesch (1976). The following sections under the headings of field methods, laboratory methods, and data management discuss the application to this study.

FIELD METHODS

The soil samples represent the population of soils defined as the surface soil horizon (plow zone, 0–15 cm depth) of agricultural fields throughout Missouri. The samples were collected by individual landowners from selected fields for fertilizer recommendation under the program of the University of Missouri Extension Division. Each sample is a composite of several vertical channel subsamples collected haphazardly within a field. Each local county Extension Agent selected 10 of the composite samples that were thought to be representative of some of the principal soils that occur in the county. About 10 percent of the samples had to be recollected by the author because the original samples were insufficient in amount. A total of 1140 samples (10 each from 114 counties) were collected. The sampling localities are scattered throughout most of the counties.

LABORATORY METHODS

A random selection of 60 samples were each split into two parts in order to estimate analytical reproducibility. The entire suite of samples including the 60 duplicates were arranged in a randomized sequence. Both sample preparation and analysis were performed in that sequence to avoid confounding any inherent geographic variation with a possible systematic analytical error. Randomization does not eliminate a systematic error, but the error is effectively transformed into one that

FIGURE 1.—Map showing soil-forming parent materials of Missouri. (Adapted from Scrivner and others, 1966; physical regions after Fenneman, 1946).

is random with respect to geographic location. Each sample was air dried, gently disaggregated, sieved through a 2-mm stainless steel screen, ground in a ceramic mill to –100 mesh, and then thoroughly mixed to ensure homogeneity.

The samples were analyzed for 70 elements. The total concentrations were determined chiefly by emission spectrographic analysis. The concentrations of some elements, however, were outside of the optimum range of the spectrographic method. For those elements of special interest, therefore, other analytical methods, such as atomic absorption, neutron activation, and X-ray fluorescence, were substituted for the spectrographic method. It was impractical to analyze all 1200 samples for iodine, thorium, and uranium because of the expense of the neutron activation procedure. Therefore, only one randomly selected sample from each county was analyzed for iodine, and two randomly selected samples from each county were analyzed for thorium and uranium.

The elements looked for, the methods of analysis, and the lower limits of determination are summarized in table 1. Elements that were looked for in all samples but were never found above the lower limits of determination are as follows: antimony, bismuth, germanium, gold, hafnium, indium, palladium, platinum, rhenium, tantalum, tellurium, thallium, tin, and tungsten. If cerium and lanthanum were found, then other elements were looked for as follows: europium, neodymium, praseodymium, and samarium. If yttrium was found in concentrations greater than 50 parts per million, which was rare, then the following elements were looked for: dysprosium, erbium, gadolinium, holmiun, lutetium, terbium, and thulium. If lead or platinum were found, then the following elements were looked for: iridium, osmium, rhodium, and ruthenium.

Detailed descriptions of the analytical procedures are given for semiquantitative emission spectrography (Neiman, 1976), X-ray fluorescence (Wahlberg, 1976), atomic absorption and other related chemical methods (Huffman and Dinnin, 1976), radioisotope dilution-neutron activation for iodine (Bartel and Millard, 1976), and delayed neutron counting for uranium and thorium (Millard, 1976). The method of reporting semiquantitative spectrographic analyses has been described by Miesch (1976). The concentrations of elements in soils are expressed as either parts per million or percentages of air-dry weight of the less-than-2 mm soil material.

DATA ANALYSIS

Most tests of statistical significance require normal distributions in the populations from which the data are drawn. Tests for this condition show that the distributions of most elements are much closer to being lognormal than normal. Consequently, the data for all elements except aluminum, iodine, iron, potassium, sodium, and silicon were transformed to logarithms prior to statistical analysis.

The average concentrations for those elements thought to be lognormally distributed are estimated by the geometric mean (GM), which is the antilogarithm of the mean of the logarithmic values (table 2). The deviation about the mean is estimated by the geometric

TABLE 1.—*List of elements looked for, methods of analysis, and lower limits of determination*

[*, element has been looked for but the range of concentrations in most common soils is below the lower limit of determination for the method and no data are available; or element has not been looked for because associated elements were not detected]

Element	Analytical method	Lower limit of determination (parts per million)
Ag	Spectrographic	0.5
Al	X-ray fluorescence	10,000
As	Spectrophotometric	1
Au*	Spectrographic	20
B	do	20
Ba	do	2
Be	do	1
Bi*	do	10
C (total)	Induction Furnace	500
C (inorganic)	Gasometric	100
C (organic)	Difference between total and inorganic.	1,000
Ca	X-ray fluorescence	150
Cd	Atomic absorption	1
Ce	Spectrographic	150
Co	do	3
Cr	do	1
Cu	do	1
Dy*	do	50
Er*	do	50
Eu*	do	100
F	Selective ion electrode	40
Fe	X-ray fluorescence	150
Ga	Spectrographic	5
Gd*	do	50
Ge*	do	10
Hf*	do	100
Hg	Instrumental atomic absorption	.01
Ho*	Spectrographic	20
I	Neutron activation	.05
In*	Spectrographic	10
Ir*	do	50
K	X-ray fluorescence	200
La	Spectrographic	30
Li	Atomic absorption	5
Lu*	Spectrographic	30
Mg	Atomic absorption	200
Mn	Spectrographic	1
Mo	do	3
Na	Atomic absorption	80
Nb	Spectrographic	10
Nd	do	70
Ni	do	5
Os*	do	50
P	X-ray fluorescence	500
Pb	Spectrographic	10
Pd*	Spectrographic	2
Pr*	do	100
Pt*	do	50
Re*	do	50
Rh*	do	2
Ru*	do	10
Sb*	do	200
Sc	do	5
Se	X-ray fluorescence	.1
Si	X-ray fluorescence	1,000
Sm*	Spectrographic	100
Sn	do	10
Sr	do	5
Ta*	do	500
Tb*	do	300
Te*	do	2,000
Th	Neutron activation	1.2
Ti	Spectrographic	2
Tl*	do	50
Tm*	do	20
U	Neutron activation	.1
V	Spectrographic	7
W*	do	100
Y	do	10
Yb	do	1
Zn	Atomic absorption	10
Zr	Spectrographic	10

deviation (GD), which is the antilogarithm of the standard deviation of the logarithmic values. The error variance for logarithmic values is estimated by the geometric error (GE), which is the antilogarithm of the square root of the logarithmic analytical error variance. The arithmetic mean (AM), the standard deviation (SD), and the standard error (SE) are given for the other elements.

The GD describes the dispersion about the GM so that the expected range of 68 percent of the population is within the bounds of GM÷GD to GM×GD. The expected range of 95 percent of the population is from $GM \div GD^2$ to $GM \times GD^2$. The expected range of 68 percent of the population on an arithmetic scale lies within the bounds of AM±SD; the 95 percent expected range lies within the bounds of AM±2SD. GE and SE express the reproducibility of the laboratory procedures for this sample set, but more particularly they provide an estimate of that portion of the total variation that is attributed to analytical imprecision. The remainder of the total variation is attributed to sampling and geographic variability.

The lower limits of determination by certain methods are above some of the smaller concentrations that are typical for some elements; some of the frequency distributions, therefore, are truncated on the left side or left-censored. The means and deviations for such elements were estimated by the method of Cohen (1959), described by Miesch (1976). However, some of the frequency distributions are so severely censored that it was possible to report only that the mean is less than the lower limit of determination.

The frequency distribution of data for each element was divided into 3 or 5 classes; the classes are of unequal width and were defined so that each contains about the same number of samples. Gray-level symbol maps (figs. 2–44) illustrate the distribution of samples that have concentrations within each class.

The total variation for each element is comprised of the analytical-error variance and the geographic variance. Excessive error variance can easily obscure the geographic variation, but there is no way of subtracting the effects of such error from each sample. Because all the samples were analyzed in a randomized sequence, however, it is unlikely that any resulting map patterns reflect a systematic error generated in the laboratory. In general, the smaller the proportion of analytical-error variance, the greater is the confidence that a given map symbol reflects the actual sample composition. Even under conditions of perfect analysis, however, local variation in soil compositions can obscure regional geographic patterns. Soils tend to be naturally heterogeneous in composition and a sample collected at a given point may differ markedly from another one collected only a few meters away. Although a map symbol may truly reflect the composition of the sample, it may also misrepresent the composition of the general area from which the sample was collected. Chance fluctuations due to small-scale compositional diversity, therefore, may cause small-scale patterns that are not reproducible.

If the actual geographic variance of an element is small, even small analytical errors or small local fluctuations can cause a regional geochemical map to be unstable. An unstable geochemical map is one whose pattern would be nonreproducible if the sampling and laboratory analysis were to be repeated. Thus, the critical measure of the stability or reproducibility of a geochemical map is the ratio of the total variance across the map, or some part of it, to the local variance which is due in varying part to analytical variation. If this ratio is large, the analytical variation and the local fluctuations are unlikely to obscure the regional geochemical pattern, and it is likely that the same regional pattern would emerge if the sampling and laboratory analysis were repeated. If this ratio is small, however, the pattern displayed by the map may be completely unreliable. The ratio suggested by Miesch (1976), referred to as v_m, is the variance among the sampling locality means over the error variances of the means. The sampling localities may be defined in various ways to examine map stability at different scales.

The v_m ratio was calculated using variance components that were derived from a 4-level nested analysis of variance (table 4) and that represented sources of variation within areas of diminishing size as follows: between groups of six contiguous counties, between pairs of counties within groups, between counties within county pairs, and between samples within each county. The equation for v_m was modified along the lines of the general equation of Cochran (1963, p. 286) to incorporate finite population correction factors. The general equation for the v_m of groups is

$$v_m(g) = \frac{s_g^2}{(1-f_p)\frac{s_p^2}{n_p} + (1-f_pf_c)\frac{s_c^2}{n_pn_c} + (1-f_pf_cf_s)\frac{s_s^2}{n_pn_cn_s}}, \quad (1)$$

where the s^2 terms are the variance components at the group (g), county pair (p), county (c), and sample (s) levels, the n's are the number of items selected from a population of N items, and f terms are the ratios of n/N for each of the above levels, respectively. The s_s^2 term contains variance due to both sampling error and laboratory error. Because the entire population of N items was selected for p and c levels and because the (1–f)-terms are nearly zero, the first two terms in the denominator drop out and the general equation (1) reduces to

$$v_m(g) = \frac{s_g^2}{s_s^2} \times 60 \quad \text{for groups of size counties,} \qquad (2)$$

$$v_m(p) = \frac{s_p^2}{s_s^2} \times 20 \quad \text{for county pairs, and} \qquad (3)$$

$$v_m(c) = \frac{s_c^2}{s_s^2} \times 10 \quad \text{for counties.} \qquad (4)$$

The v_m ratio may be viewed as a relative index of reproducibility of the map pattern at the scale for which the ratio was computed. By a Monte Carlo simulation technique, it was found that the general configuration of a map pattern is almost totally unreproducible if the computed ratio is less than 1 (Tidball, 1972, p. 20–21). Reproducibility increases as the ratio increases over 1, and good reproducibility is generally present if the ratio is about 3 or more.

RESULTS

Total element concentrations in the surface horizon of Missouri agricultural soils are summarized in table 2. The grand means, deviations, ranges, and measures of the analytical precision are shown for all elements except for those with severely censored distributions. The detection ratios for severely censored distributions (as for cadmium, molybdenum, silver, and tin) show that only a few of the 1140 samples analyzed contained detectable quantities of the element. For moderately censored distributions (for example, beryllium with a detection ratio of 520:1140) the mean and deviation are estimated by methods of Cohen (1959), described in Miesch (1976). Carbon is reported in three forms as carbonate, organic, and total, but nearly all of the carbon occurs in the organic form.

The grand means for Missouri agricultural soils are compared in table 3 with grand means that were calculated from the area means reported by Erdman, Shacklette, and Keith (1976b). The means for soils of the United States collected east of the 97th meridian (Shacklette and others, 1971a, b; 1973; 1974) are also included for comparison to show the relative position of Missouri soils.

The average concentrations of elements in cultivated soils reported in tables 2 and 3 are nearly the same as the averages given by Erdman, Shacklette, and Keith (1976b, tables 8, 9, 10, 11). Although the estimates of this report are considered to be more precise because they are based on 1140 samples, it is remarkable that the estimates by Erdman, Shacklette, and Keith that are based on only 40 samples are so similar. Compared with the soils of the eastern U.S., the soils of Missouri tend to have slightly larger amounts of barium, chromium, florine, lead, manganese, strontium, vanadium, and zinc.

TABLE 2.—*Average total concentrations of elements in Missouri soils*

[Detection ratio is number of samples with detectable concentration to total number analyzed. Geometric mean, geometric deviation, and geometric error given except as noted by asterisk (*) where arithmetic mean, standard deviation, and standard error are given. Mean values and ranges are in parts per million except as noted in percent. Leadered entries (--) mean insufficient data]

Element	Detection ratio	Geometric mean	Geometric deviation	Observed range	Geometric error
Ag	4:1140	<0.7	---	<0.7 - 3	---
Al, pct	1140:1140	4.1*	1.19*	1.1 - 7.9	0.34*
As	1140:1140	8.7	1.46	2.5 - 72	1.16
B	1113:1140	31	1.34	<20 - 700	1.40
Ba	1140:1140	580	1.46	100 - 1500	1.28
Be	520:1140	0.8	1.43	<1 - 2	1.16
C (as total), pct	1140:1140	1.30	1.50	0.24 - 5.2	1.07
C (as carbonate) pct	946:1140	0.028	2.85	<0.01 - 2.9	2.31
C (as organic) pct	1140:1140	1.25	1.53	0.08 - 5.2	1.11
Ca, pct	1114:1140	0.33	2.03	<0.07 - 5.6	1.12
Cd	12:1140	<1	---	<1 - 11	---
Ce	435:1140	115	1.27	<150 - 300	---
Co	1139:1140	10	1.50	<3 - 30	1.27
Cr	1140:1140	54	1.44	10 - 150	1.27
Cu	1140:1140	13	1.55	5 - 150	1.28
F	1140:1140	270	2.22	10 - 6400	1.86
Fe, pct	1140:1140	2.11*	0.64*	0.49 - 5.4	0.12*
Ga	1111:1140	11	1.49	<5 - 30	1.22
Hg	1124:1140	0.039	1.80	<.01 - 0.8	1.53
I	114:114	4.4*	1.65*	1.2 - 11.7	0.65*
K, pct	1140:1140	1.4*	0.40*	0.33 - 3.7	0.07*
La	1136:1140	41	1.39	<30 - 150	1.26
Li	1140:1140	22	1.28	7 - 47	1.05
Mg, pct	1140:1140	0.26	1.65	0.05 - 2.8	1.10
Mn	1140:1140	740	1.83	15 - 3000	1.30
Mo	16:1140	<3	---	<3 - 15	---
Na, pct	1140:1140	0.53*	0.23*	0.07 - 1.2	0.03*
Nb	375:1140	7.2	1.38	<10 - 15	1.11
Nd	739:1140	63	1.17	<70 - 150	---
Ni	1131:1140	14	1.59	<5 - 70	1.24
P, pct	1130:1140	0.059	1.61	<.01 - 0.61	1.30
Pb	1140:1140	20	1.55	10 - 7000	1.22
Sc	1092:1140	7.6	1.34	<5 - 15	1.16
Se	925:1140	0.28	2.54	<0.1 - 2.7	1.67
Si, pct	1140:1140	35*	2.77*	23 - 43	1.32*
Sn	9:1140	<15	---	<15 - 50	---
Sr	1140:1140	110	1.60	20 - 500	1.25
Th	199:228	9.6*	2.47*	3.2 - 21	2.29*
Ti	1140:1140	3300	1.31	1500 - 7000	1.20
U	228:228	3.8	1.34	1.1 - 15	1.26
V	1140:1140	69	1.50	15 - 150	1.25
Y	1138:1140	32	1.35	<10 - 70	1.25
Yb	1138:1140	3.2	1.31	<1 - 7	1.25
Zn	1140:1140	49	1.55	18 - 640	1.08
Zr	1140:1140	310	1.53	70 - 700	1.35

The geochemical patterns of the elements across the State are shown in figures 2 to 44 as gray-level symbol maps. Actual measured values rather than symbols are given for those elements where frequency distributions are severely censored and where histograms are not shown. Means, deviations, and measures of analytical precision from table 2 are repeated on the maps for the convenience of the reader. What confidence do we have that the map is faithfully portraying the true distribution of an element?

TABLE 3.—*Comparison of mean concentrations of elements in Missouri agricultural soils determined in this study with a previous study by Erdman, Shacklette, and Keith (1976b) and with the mean concentrations in parts of the eastern U.S.*

[Concentrations in parts per million, except where noted to be in percent. Geometric mean given, except where noted to be arithmetic means. Leadered entries (--), no data]

Element	Missouri soils This study[1]	 Other analyses[2]	Eastern United States[3]
Al, pct[4]	4.1	4.2	5.2
As	8.7	9.0	[5]5.4
B	31	30	32
Ba	580	680	300
Be	.8	1.0	.6
C, carbonate, pct	.03	<.01	---
C, organic, pct	1.25	1.5	---
Ca, pct	.33	.49	.32
Cd	<1	<1	<1
Co	10	8.4	7
Cr	54	64	36
Cu	13	17	14
F	270	260	[5]120
Fe, pct	2.1	2.2	2.5
Ga	11	12	10
Hg	.039	.046	[6].096
K, pct	1.4	1.6	1.6
La	41	43	33
Li	22	20	[4,7]22
Mg, pct	.26	.28	.23
Mn	740	550	290
Na, pct	.53	.62	.71
Nb	7.2	9	13
Ni	14	12	13
P, pct	.059	.054	.018
Pb	20	24	14
Sc	7.6	6.7	7
Se	.28	.44	[5].39
Si, pct	35	37	---
Sn	<15	<10	---
Sr	110	130	51
Ti, pct	.33	.31	.30
V	69	70	46
Y	32	25	23
Yb	3.2	3.0	3.0
Zn	49	52	36
Zr	310	250	250

[1] Based on 1140 samples.

[2] Erdman, Shacklette, and Keith (1976b), based on 40 samples.

[3] Shacklette, Hamilton, Boerngen, and Bowles (1971b), unless otherwise noted.

[4] Arithmetic mean.

[5] Shacklette, Boerngen, and Keith (1974). Based on 420 samples.

[6] Shacklette, Boerngen, and Turner (1971a). Based on 420 samples.

[7] Shacklette, Boerngen, Cahill, and Rahill (1973). Based on 420 samples.

The variance-mean ratios, v_m, as calculated from the variance components in table 4, are given in table 5; the ratios serve as indices of confidence so that the general character and the major features of the map patterns could be reproduced by a repetition of the sampling and laboratory analysis. In general, features of the maps that extend over about six counties or more are probably reproducible; the values of $v_m(g)$ are high for most elements. Less extensive features of the maps, those that extend over only one or two counties are generally nonreproducible, or at least unlikely to be reproducible; the values of $v_m(p)$ and $v_m(c)$ are generally small and many are less than 1.

The reason that the larger areas are more often reproducible is that they are represented by larger numbers of samples; this causes the variance of the area means to be small and, therefore, the values of $v_m(g)$ to be high. Variance-mean ratios were not calculated for iodine, thorium, and uranium because not all samples were analyzed for these elements nor for beryllium, cerium, molybdenum, niobium, neodymium, silver, and tin because these elements were not detected in many of the samples.

The analytical precisions (reproducibility) of the analyses for fluorine, mercury, ytterbium, and yttrium are poor (analytical error variance is greater than 50 percent of the total variance, see table 4). Except for mercury, the poor precision still does not completely diminish the reproducibility of the maps for these elements at the county-group level because the values of $v_m(g)$ are moderately high.

DISCUSSION

The regional distribution patterns for some elements are quite distinct, but other elements exhibit high degrees of local variation and no apparent regional variation. The regional patterns are of two contrasting types: sodium (fig. 34), a relatively mobile element, represents the first type and is more abundant in soils developed on geologically young materials; it is more depleted in soils on older land surfaces. Silicon (fig. 32), represents the second type and is a resistate element which appears to be enriched in soils after the more mobile elements have moved out during prolonged weathering.

TABLE 4.—*Variance components of soil elements*

[Variance based on $\log_{10}$ concentrations, except where noted. Asterisk (*), components are significantly greater than zero at 0.05 probability level]

Element	Variance Components				
	Between groups of 6 counties, s_g^2	Between pairs of counties, s_p^2	Between counties within pairs, s_c^2	Between samples[2] within county, s_s^2	
				s_e^2	s_a^2
Al[1]	0.63265*	0.07235*	0.08203*	0.56121	0.11498
As	.00434*	.00056	.00162*	.01677	.00413
B	.00047*	.00035	.00056*	0	.01127
Ba	.00697*	0	.00138*	.00792	.01138
C (tot.)	.00679*	.00089	.00160*	.02127	.00079
Ca	.03572*	.00536*	.00747*	.04643	.00244
Co	.00089*	.00055	.00271*	.01642	.01097
Cr	.00429*	.00064	.00132*	.00881	.01047
Cu	.00232*	.00158*	.00069	.02090	.01128
F	.00684*	0	.00627*	.03532	.07321
Fe[1]	.07339*	.02511*	.01771*	.28223	.01484
Ga	.01086*	.00200*	.00035	.01140	.00732
Hg	0	.00205*	.00086	.03090	.03370
K[1]	.05043*	.01898*	.01010*	.07525	.00546
La	.00110*	0	.00135*	.00201	.00985
Li	.00204*	0	.00129*	.00764	.00039
Mg	.02110*	.00195*	.00259*	.02134	.00160
Mn	.00690*	.00092	.00650*	.04275	.01265
Na[1]	.03458*	.00461*	.00231*	.01323	.00083
Ni	.00870*	.00279*	.00171*	.01950	.00884
P	.00472*	.00038	.00284*	.02325	.01269
Pb	.00212*	.00136	.00350*	.002248	.00745
Sc	.00325*	.00008	.00110*	.00943	.00435
Se	.01624*	.00473	.00465*	.07154	.04970
Si[1]	2.3282*	0.22463	0.28905*	3.141	1.730
Sr	.02353*	.00229*	.00085*	.00743	.00907
Ti	.00138*	.00068*	.00020	.00549	.00633
V	.00791*	.00024	.00225*	.01139	.00922
Y	.00158*	.00085*	.00031	.00514	.00950
Yb	.00153*	.00044*	.00034	.00217	.00955
Zn	.00509*	.00101	.00310*	.02563	.00123
Zr	.00481*	.00205*	.00152*	.00905	.01678

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[1] Variance based on nontransformed data.

[2] $s_s^2 = s_e^2 + s_a^2$, where s_s^2 = total between-sample variance, s_e^2 = sampling error, s_a^2 = analytical error

TABLE 5.—*Variance mean ratios for soil elements within areas of decreasing size*

[$v_m(g)$, ratio for groups of six counties. $v_m(p)$, ratio for county pairs. $v_m(c)$, ratio for counties]

Element	$v_m(g)$	$v_m(p)$	$v_m(c)$	Element	$v_m(g)$	$v_m(p)$	$v_m(c)$
Al-----	56	2.1	1.2	Mg-----	55	1.7	1.1
As-----	12	.54	.77	Mn-----	7.4	.38	1.2
B------	2.5	.63	.50	Na-----	150	6.6	1.6
Ba-----	22	0	.72	Ni-----	18	2.0	.60
C (tot)	18	.80	.73	P------	12	.21	.79
Ca-----	44	2.2	1.5	Pb-----	4.2	.91	1.2
Co-----	1.9	.40	.99	Sc-----	14	.12	.80
Cr-----	13	.67	.69	Se-----	8.0	.78	.38
Cu-----	4.3	.98	.21	Si-----	29	.92	.59
F------	3.8	0	.58	Sr-----	86	2.8	.52
Fe-----	15	1.7	.60	Ti-----	7.0	1.2	.17
Ga-----	35	2.1	.19	V------	23	.23	1.1
Hg-----	0	.64	.13	Y------	6.5	1.2	.21
K------	37	4.7	1.3	Yb-----	7.8	.76	.29
La-----	3.5	0	.73	Zn-----	11	.75	1.2
Li-----	15	0	1.6	Zr-----	11	1.6	.59

The bimodal frequency distribution of sodium (fig. 34) is unusual among the elements studied. The samples represented by each peak of the histogram occur within separate and distinct areas of the State: the higher concentrations occur in the northern part and the lower concentrations occur in the southern part. The eastern part of the Ozark Plateaus exhibits exceptionally low concentrations of sodium. The sharp boundary between the two populations coincides approximately with the 1½-meter-depth isopach for loess deposits that parallels both the southern limit of glaciation and the Mississippi River valley (Scrivner and others, 1966, p. 7).

The elements aluminum, calcium, magnesium, potassium, strontium and to a lesser extent lithium and nickel have distributions similar to that of sodium. Although other factors may have affected the general distribution of these elements, the principal factor appears to have been the distributions of at least three of the major types of underlying geologic materials: (1) glacial materials comprised of till, loess, and alluvium, (2) rocks of Precambrian, Mississippian, and Pennsylvanian ages, and (3) residuum from carbonate rocks of Cambrian and Ordovician ages.

Above-average concentrations of silicon occur in the southern part of the State, and below-average values occur in the northern part (fig. 32). The boundary between the two areas is less abrupt than that for sodium. Manganese, niobium, and zirconium exhibit distribution patterns similar to that of silicon.

Between the two extreme patterns represented by sodium and silicon, there are numerous elements (arsenic, barium, beryllium, boron, cerium, gallium, iron, lanthanum, neodymium, scandium, selenium, titanium and vanadium that exhibit large local variations and no distinct regional pattern.

Carbon (fig. 9) is another element with high local variation: carbon reflects in a general way the contrasting vegetation types of forest and grass under which the soils have developed. Grass vegetation results in moderately higher concentrations of carbon in the soils; whereas, forests promote lower concentrations. The approximate boundary between the original prairie and forest communities is irregular and trends diagonally northeast-southwest across the middle of the State (fig. 1) with the prairie to the northwest and the forests to the southeast (U.S. Geological Survey, 1970, sheet no. 90). The effect of climate tends to reinforce the effects of vegetation. Both precipitation and temperature, at least by present-day records, increase from north west to southeast (Scrivner and others, 1966), which provides increasingly favorable conditions for the oxidation of carbon toward the southeast.

Some elements may become concentrated either by natural processes of mineralization or by man-induced processes. Phosphorus, for example, occurs in rather uniform concentrations over large areas of the State (fig. 28), which suggests the likelihood of widespread application of P-containing fertilizer. Lead (fig. 19) is an element that may have been redistributed by both natural and man-induced processes. Concentrations are particularly high near the southeast Missouri lead district (Washington, St. Francois, and Jefferson Counties) where near-surface mineral deposits have been worked since the early 1700's (Kiilsgaard and others, 1967). Samples with the highest concentrations of lead were obtained from the flood plains of streams that flow through the district. The distribution pattern of lead was reconfirmed by subsequent sampling and analysis of alluvial soils along Big River and Mineral Fork in Iron, St. Francois, Washington, and Jefferson Counties (Tidball, 1973). These samples also contained high concentrations of barium that reflect the extensive mining of barite from surface deposits. Lead-mine tailings have been used as agricultural lime in some areas near the mining districts (W. F. Heidlage, written commun., 1971), a practice that introduces unusually large amounts of lead to agricultural soils. The distributions of copper and zinc (figs. 13, 43) are associated largely with the occurrence of significant loess deposits.

In summary the more mobile elements, such as calcium, magnesium, potassium, and sodium are more highly concentrated in areas with geologically young glacial till and loess. Less mobile elements, like silicon and zirconium, are enriched in soils on very old, nonglaciated, and deeply weathered geologic materials. The regional variation in the carbon content of the soils reflects the climatic and vegetation differences across the State, and locally high concentrations of lead and a few other metals appear to be related to mining activities. Many of the elements have predominantly local variation and fail to display regional patterns of variations across the State. The large number of samples collected in this study and their extensive distribution illustrate spatial patterns, but if the objective had been simply to estimate means then fewer samples would have been required: remarkably, Erdman, Shacklette, and Keith (1976b) reported similar means with only 40 samples.

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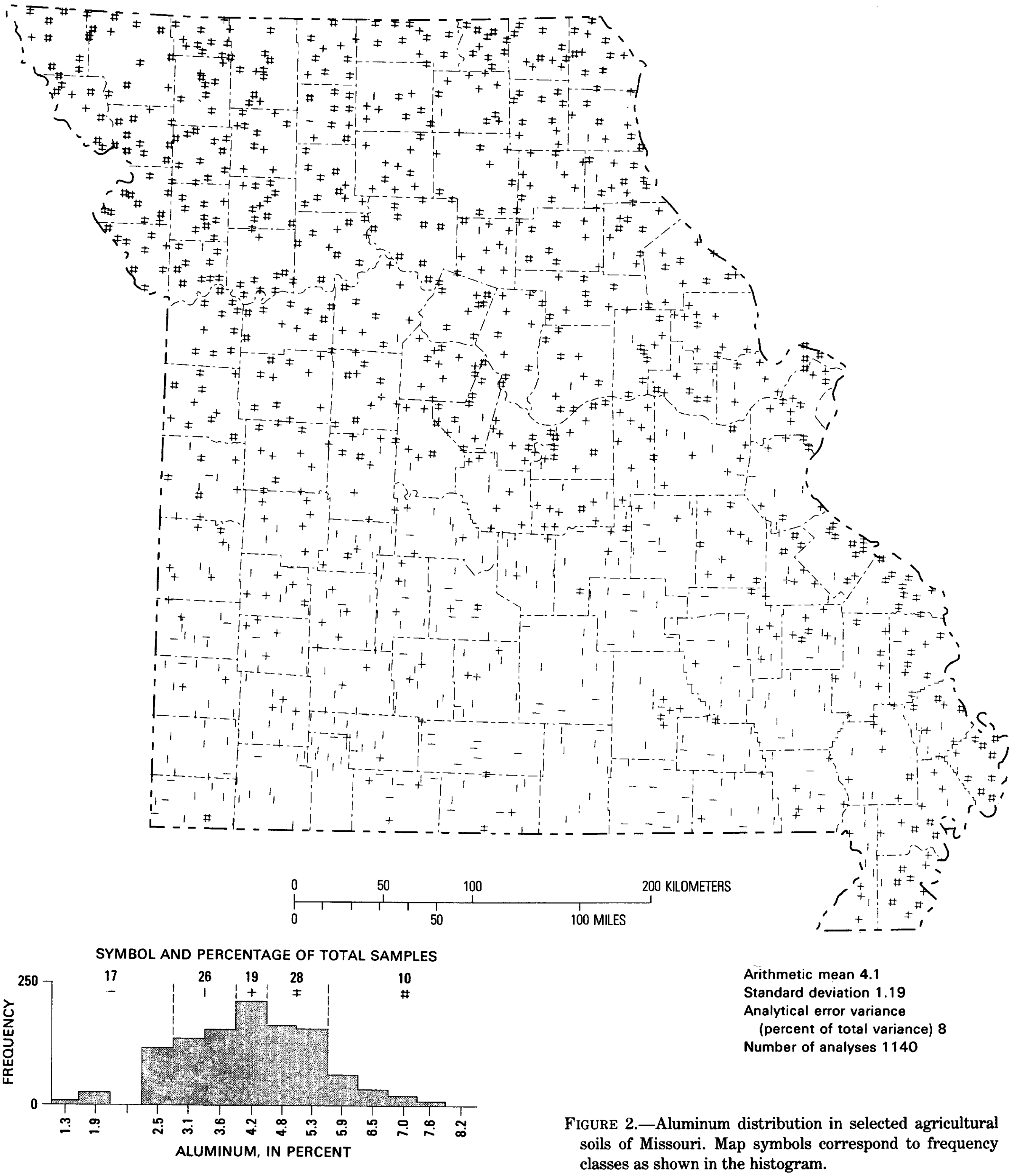
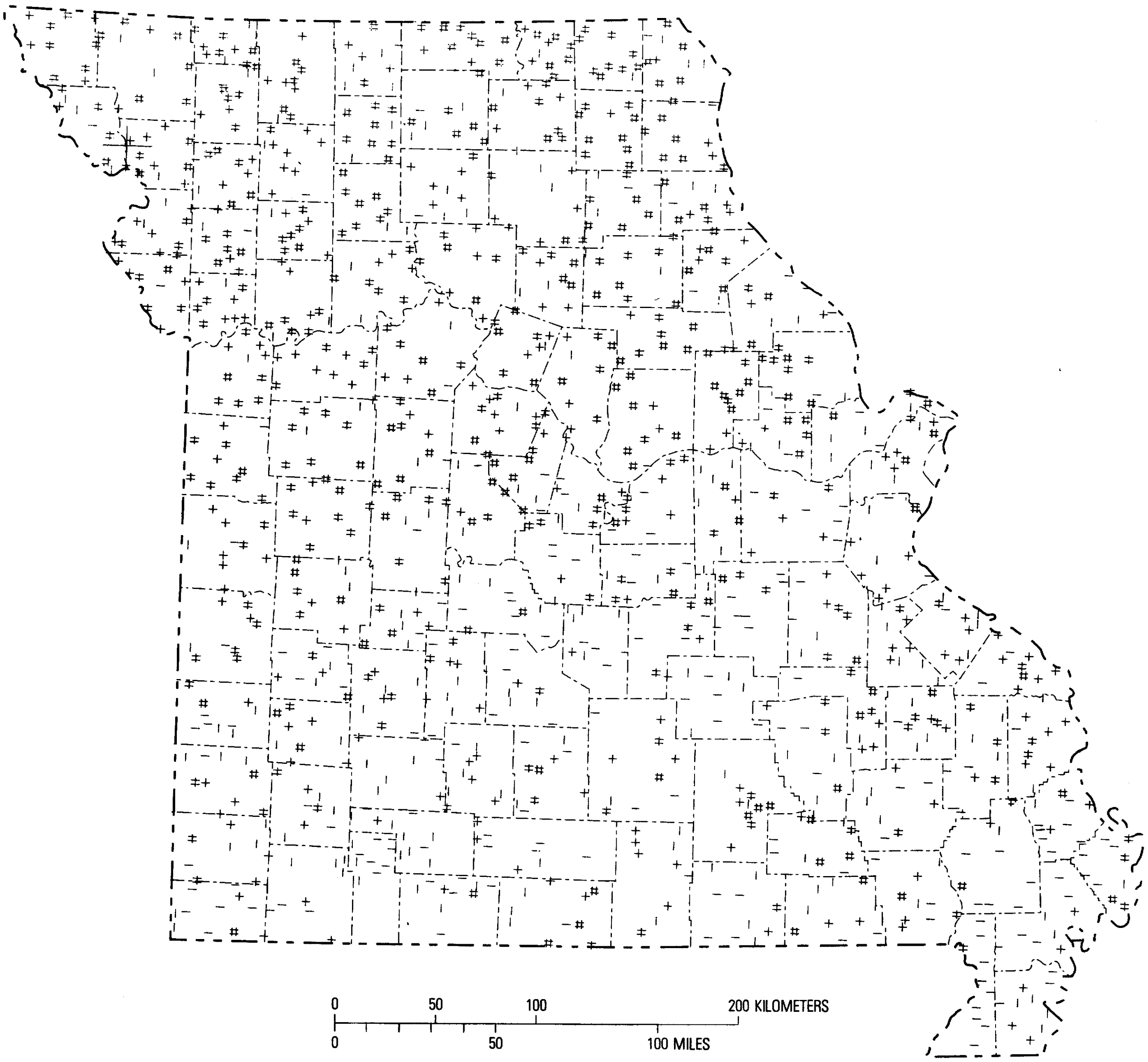
FIGURES 2–44.

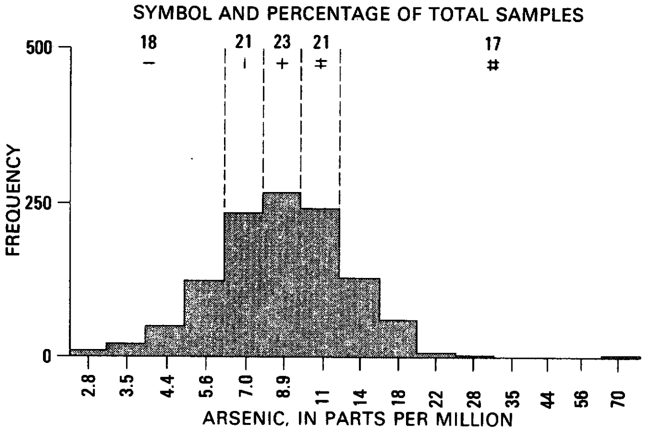
Element distributions in selected agricultural soils of Missouri



Arithmetic mean 4.1
Standard deviation 1.19
Analytical error variance
(percent of total variance) 8
Number of analyses 1140

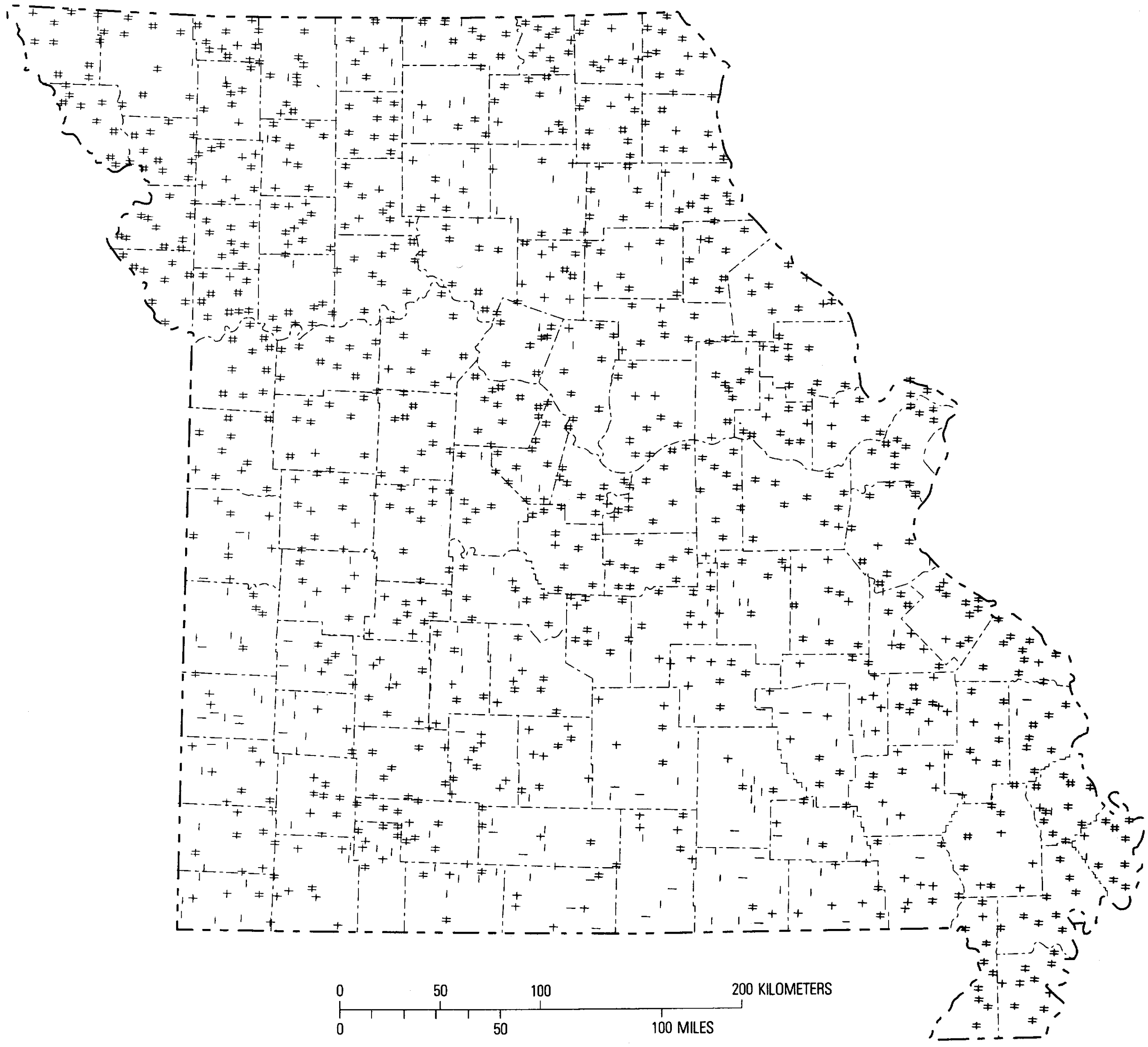
FIGURE 2.—Aluminum distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

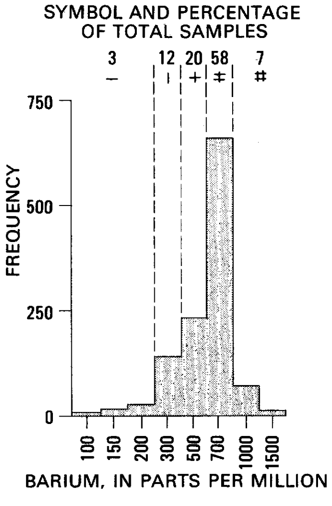




Geometric mean 8.7
Geometric deviation 1.46
Analytical error variance
(percent of total variance) 15
Number of analyses 1140

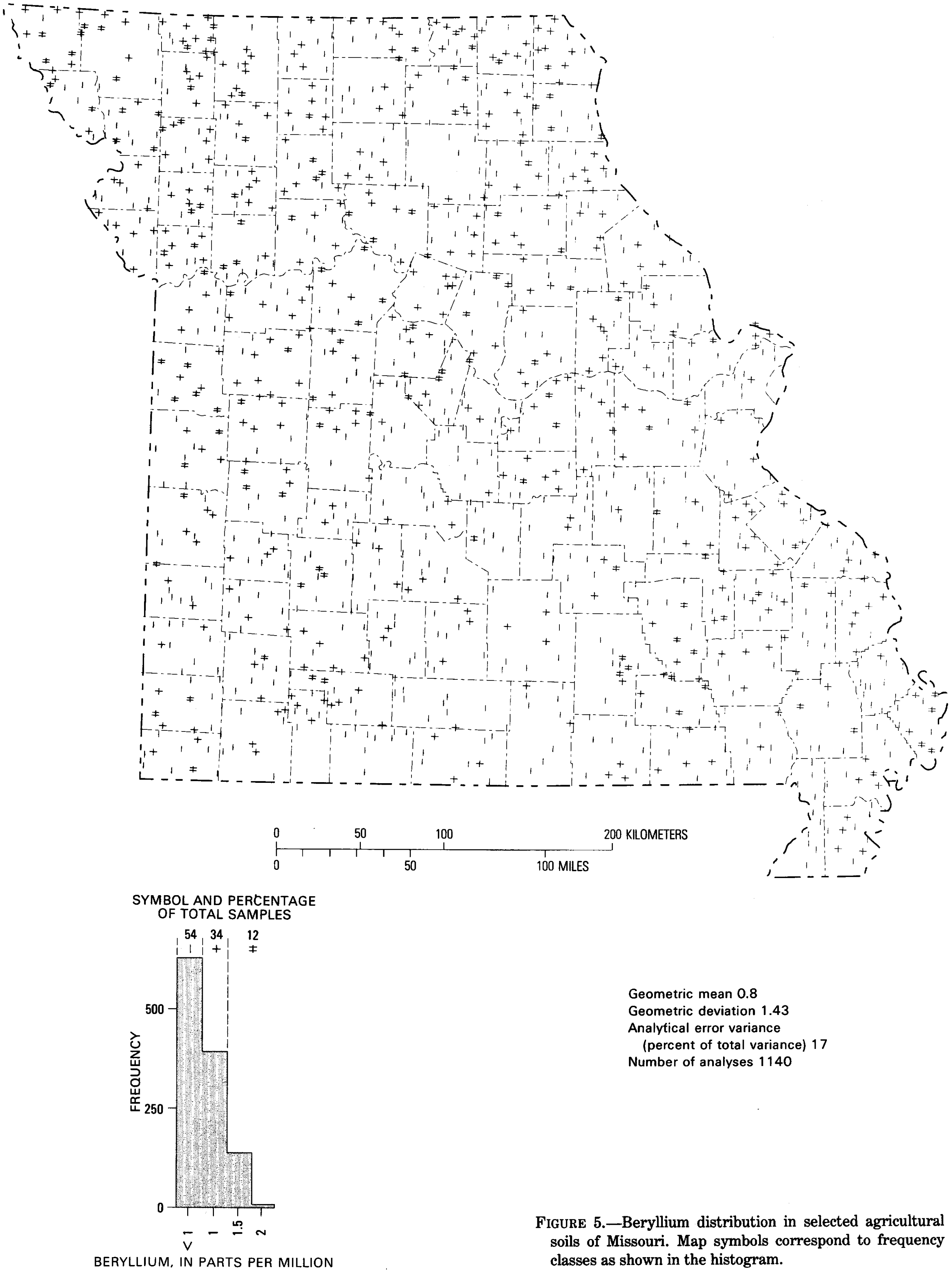
FIGURE 3.—Arsenic distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





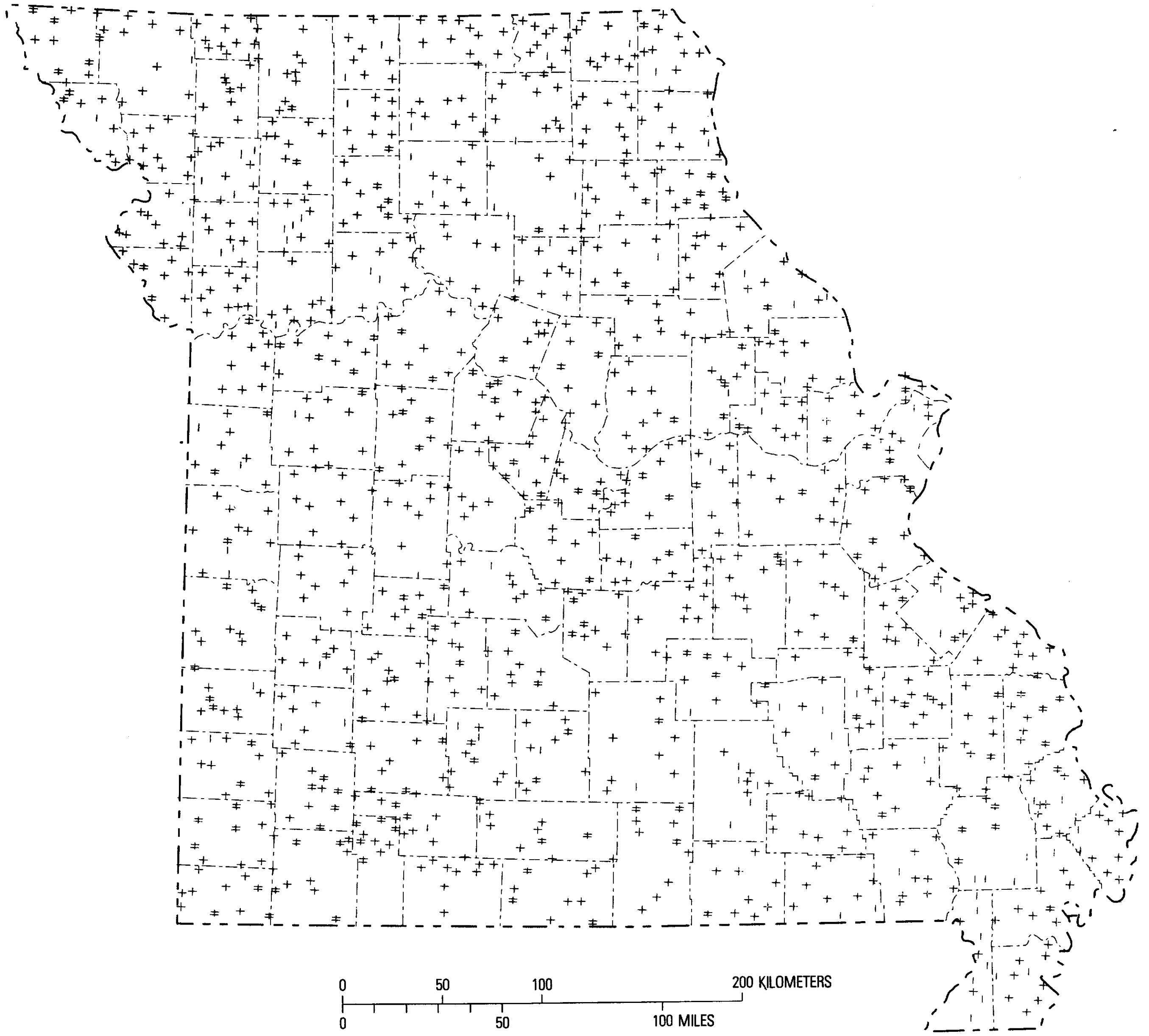
Geometric mean 580
Geometric deviation 1.46
Analytical error variance
(percent of total variance) 42
Number of analyses 1140

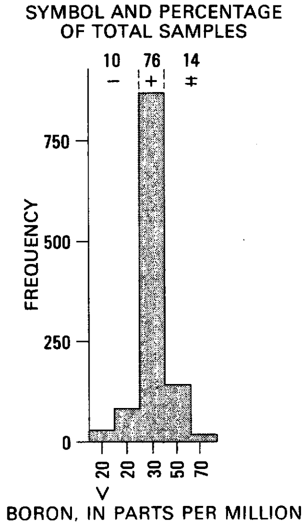
FIGURE 4.—Barium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 0.8
Geometric deviation 1.43
Analytical error variance
(percent of total variance) 17
Number of analyses 1140

FIGURE 5.—Beryllium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





Geometric mean 31
Geometric deviation 1.34
Analytical error variance
(percent of total variance) 100
Number of analyses 1140

FIGURE 6.—Boron distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

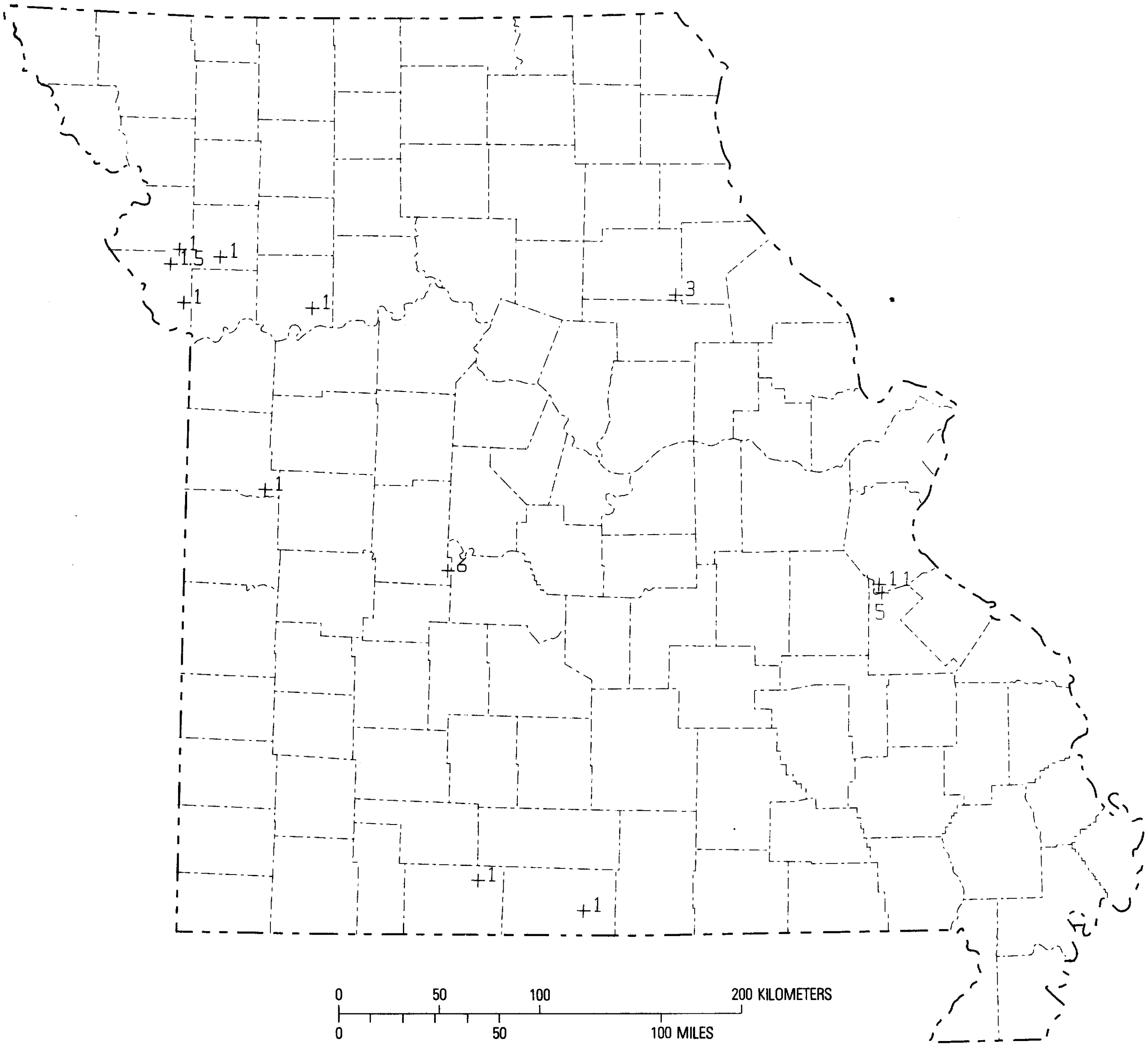
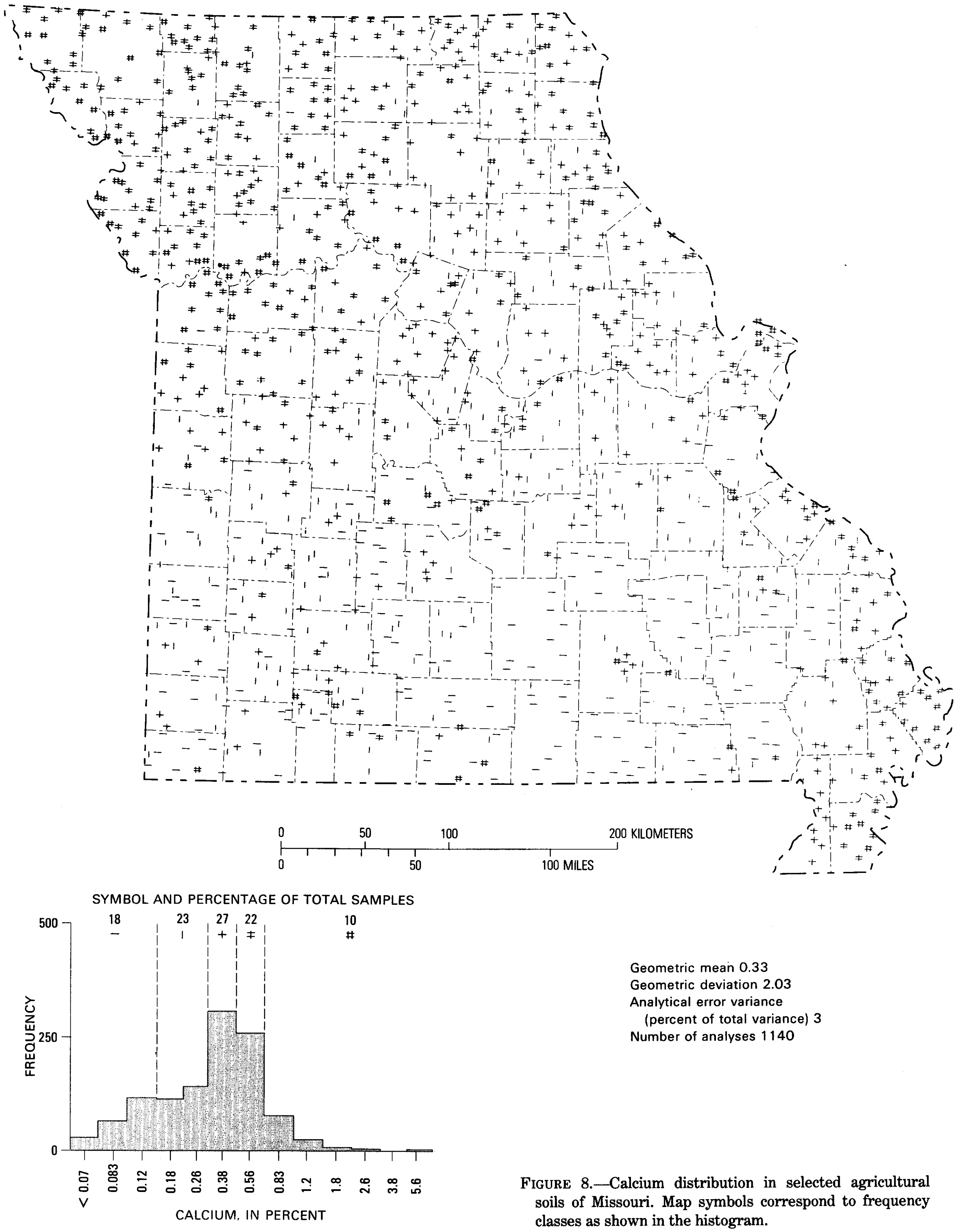
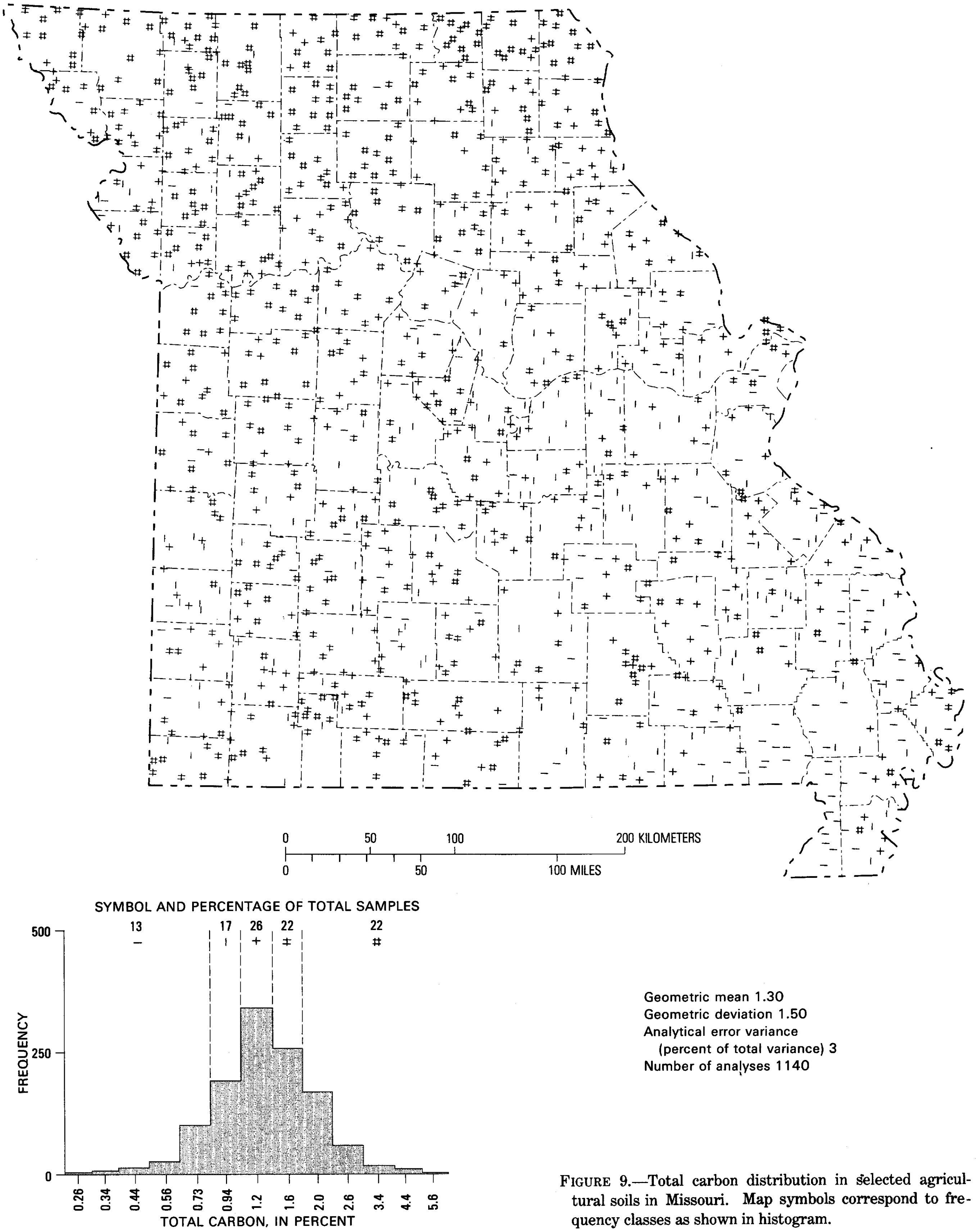


FIGURE 7.—Cadmium concentrations, in parts per million, in selected agricultural soils of Missouri. Only samples with concentrations above the lower limit of determination are shown. Location of sampling site is indicated by plus (+).



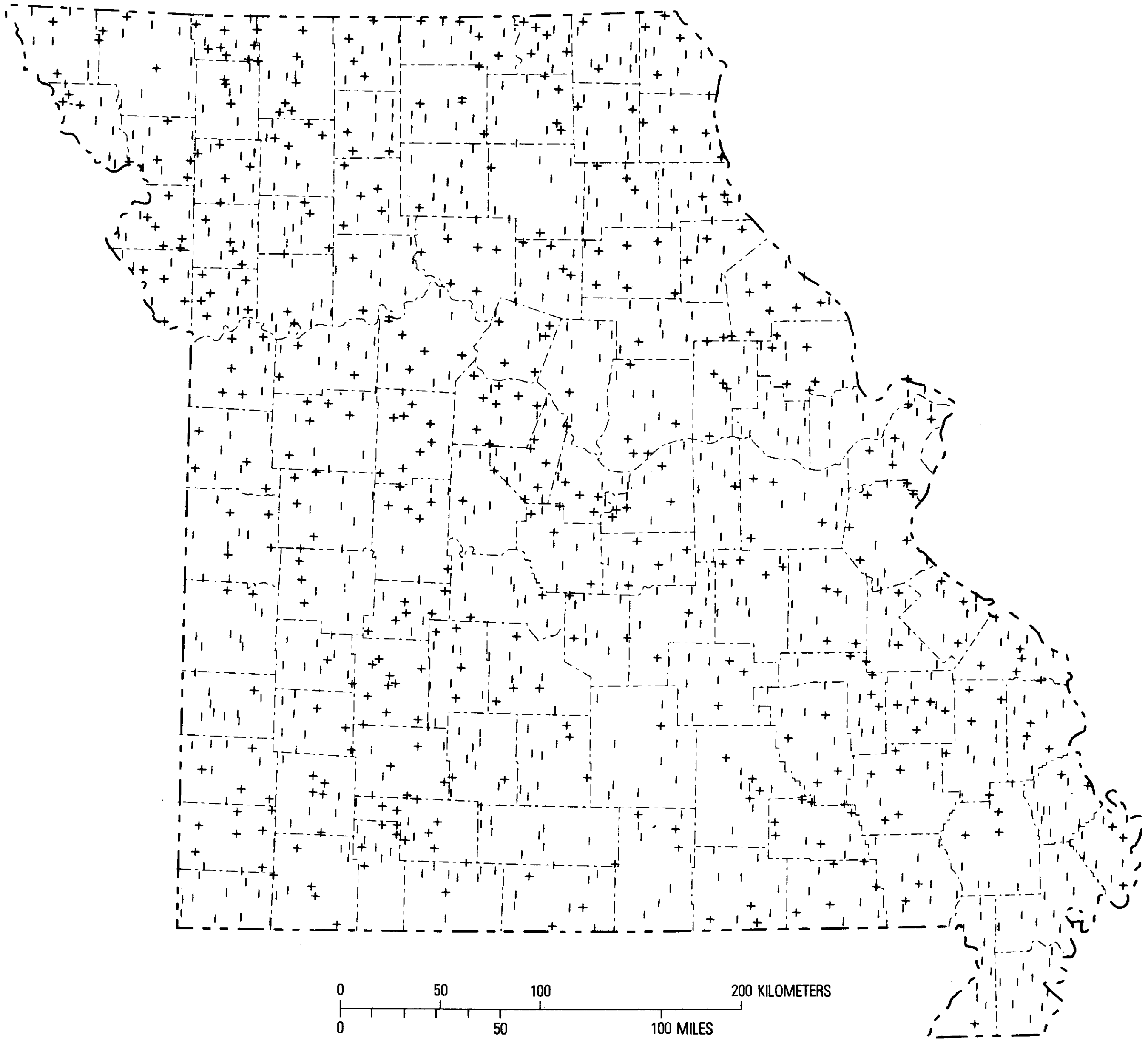
Geometric mean 0.33
Geometric deviation 2.03
Analytical error variance
(percent of total variance) 3
Number of analyses 1140

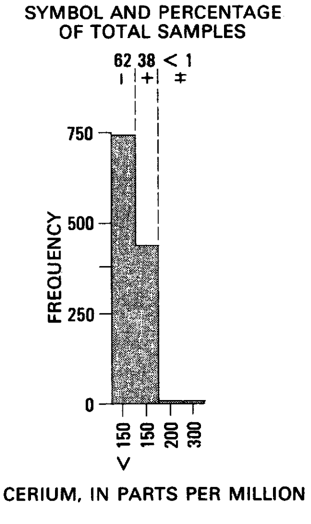
FIGURE 8.—Calcium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 1.30
Geometric deviation 1.50
Analytical error variance
(percent of total variance) 3
Number of analyses 1140

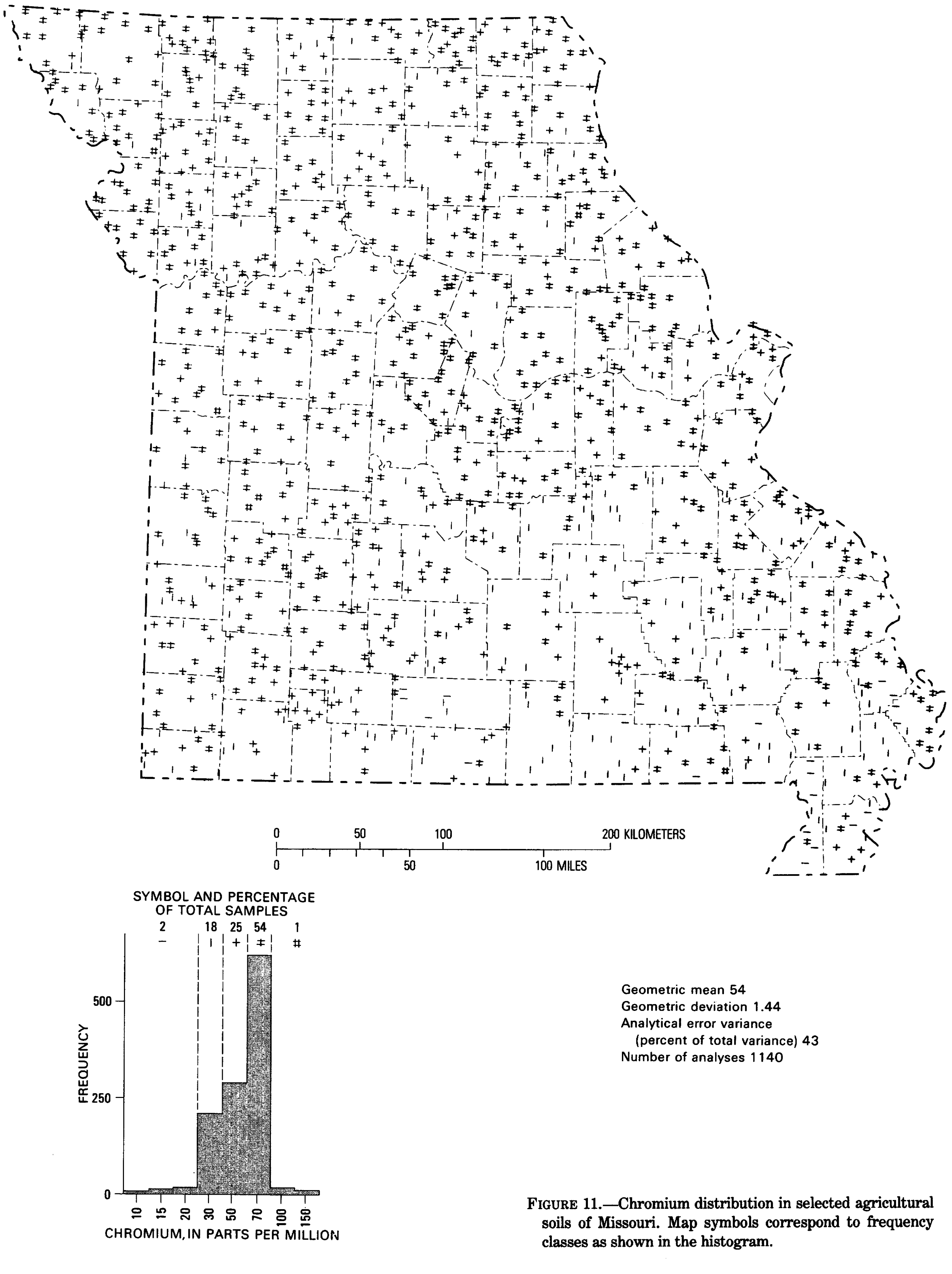
FIGURE 9.—Total carbon distribution in selected agricultural soils in Missouri. Map symbols correspond to frequency classes as shown in histogram.





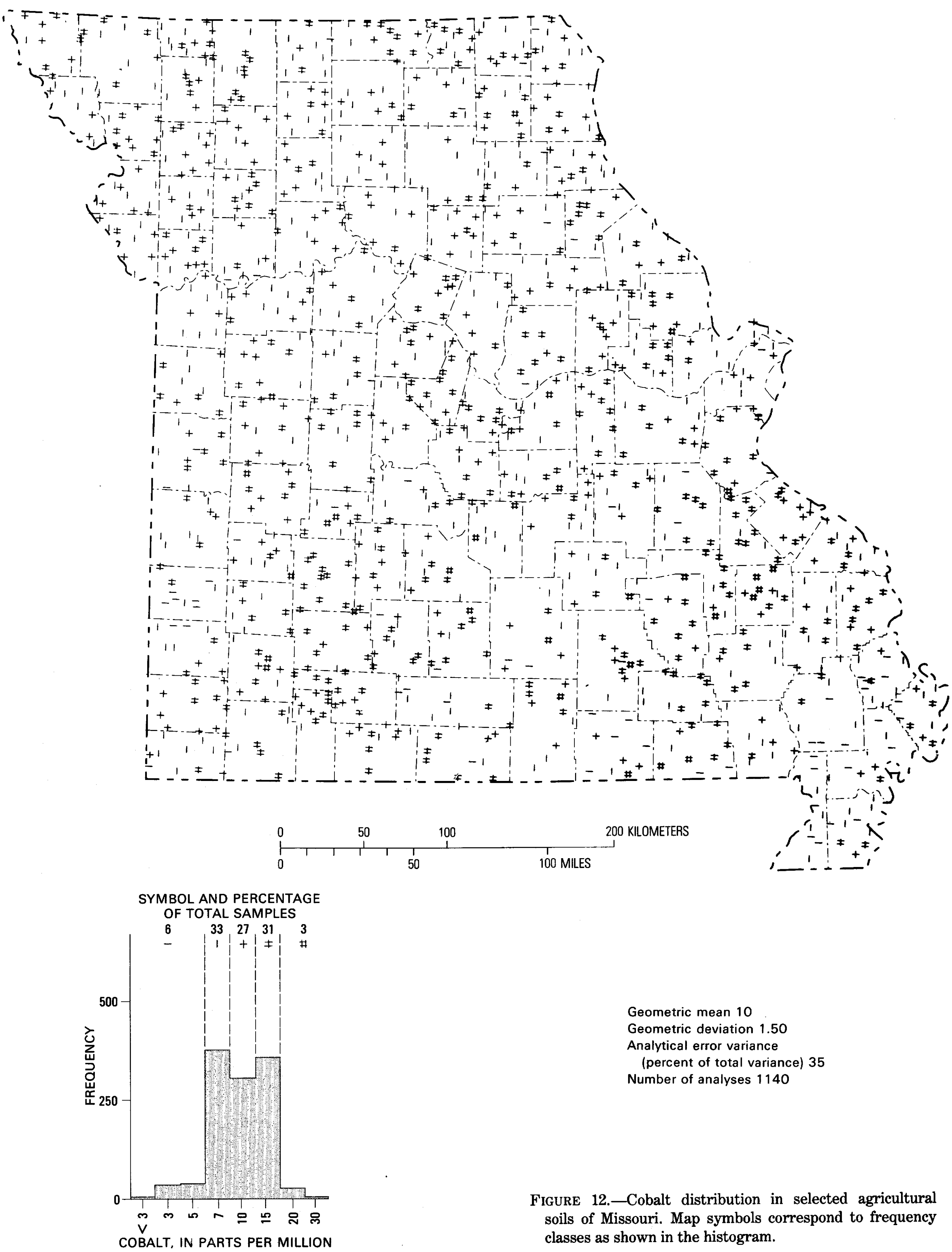
Geometric mean 115
Geometric deviation 1.27
Analytical error variance
(percent of total variance)
not determined
Number of analyses 1140

FIGURE 10.—Cerium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



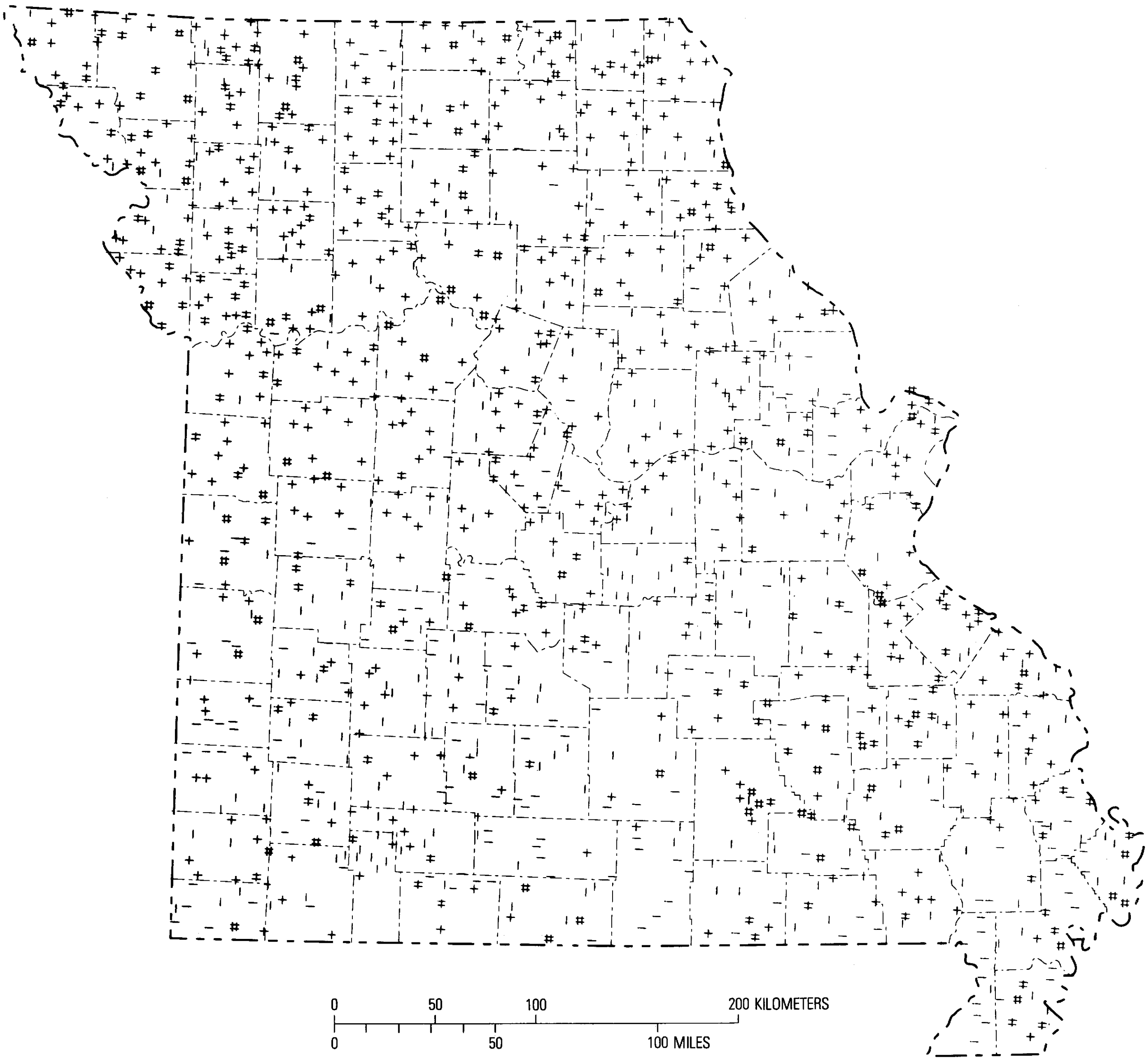
Geometric mean 54
Geometric deviation 1.44
Analytical error variance
(percent of total variance) 43
Number of analyses 1140

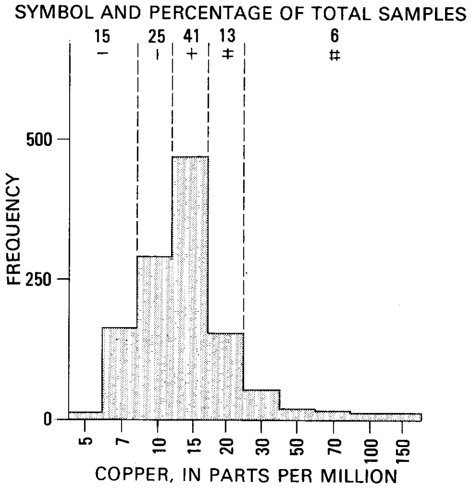
FIGURE 11.—Chromium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 10
Geometric deviation 1.50
Analytical error variance
(percent of total variance) 35
Number of analyses 1140

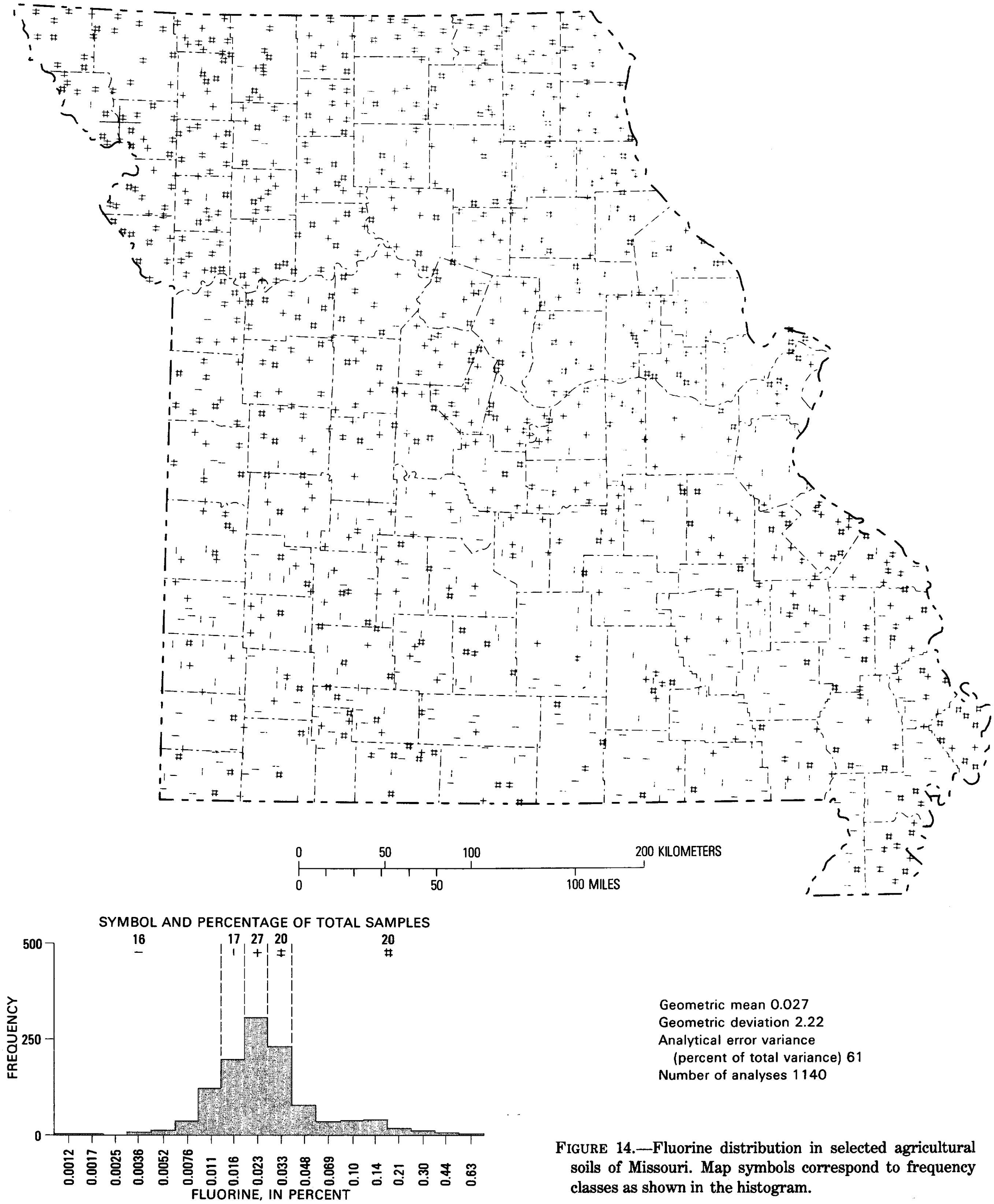
FIGURE 12.—Cobalt distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





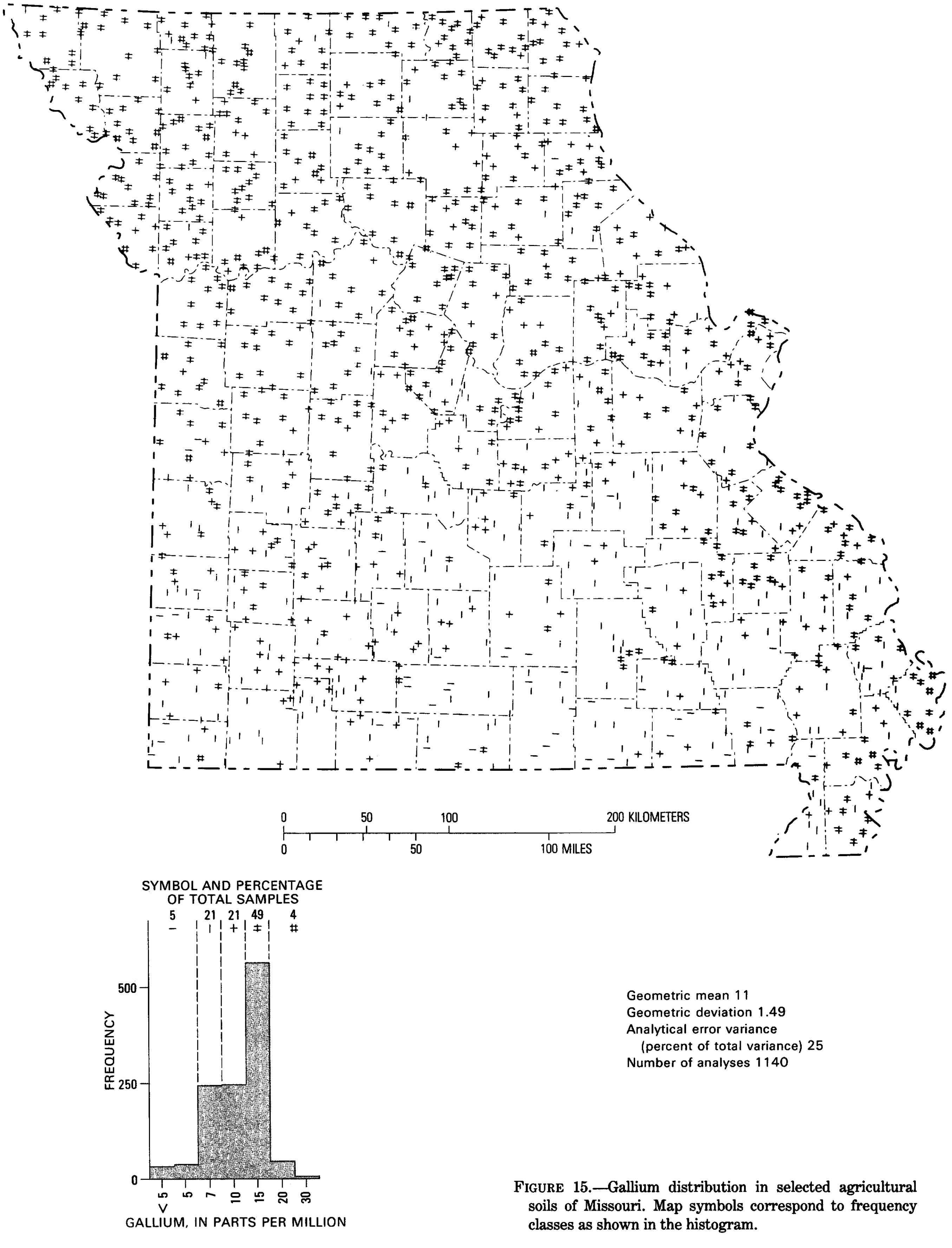
Geometric mean 13
Geometric deviation 1.55
Analytical error variance
(percent of total variance) 32
Number of analyses 1140

FIGURE 13.—Copper distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



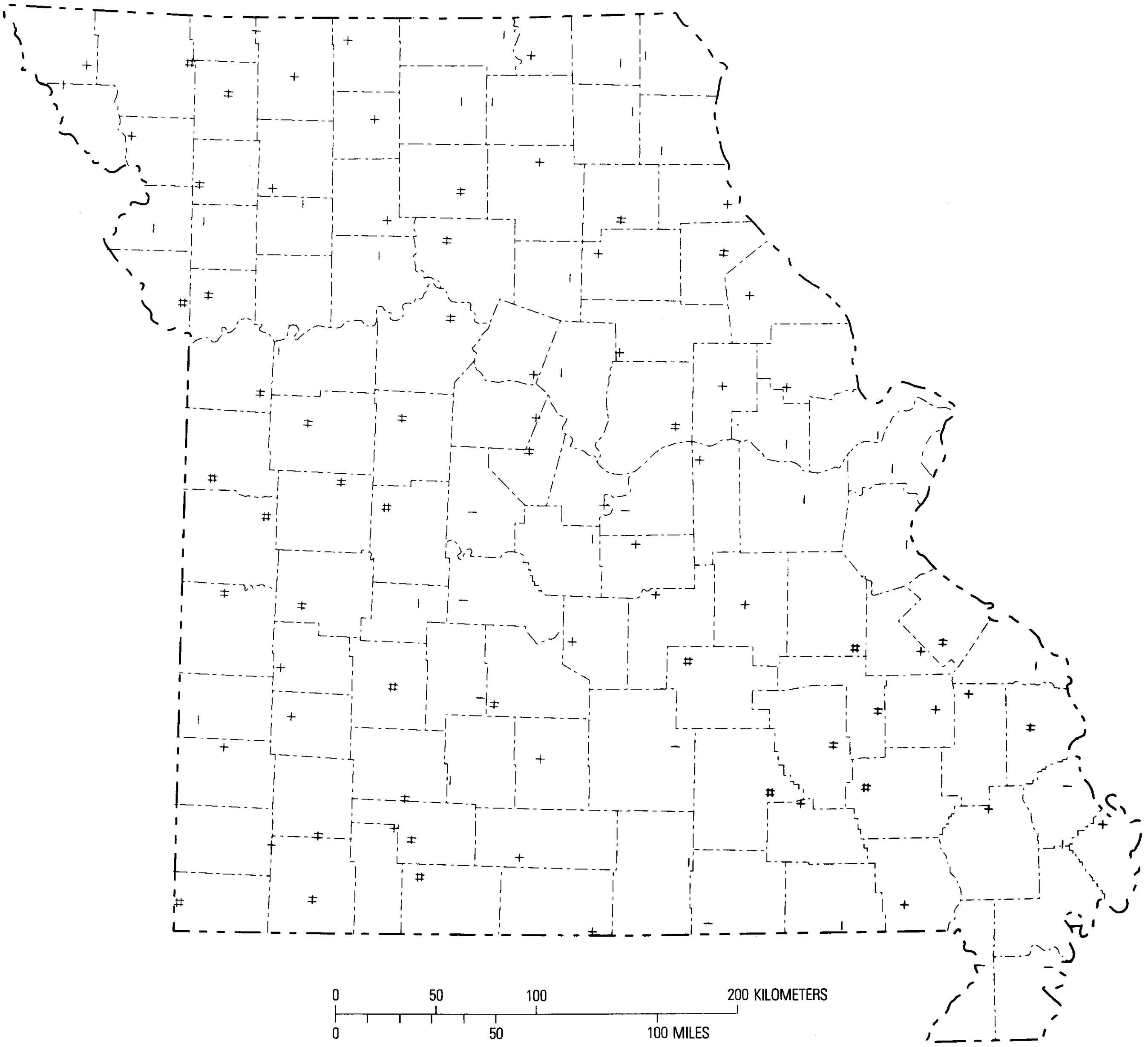
Geometric mean 0.027
Geometric deviation 2.22
Analytical error variance
(percent of total variance) 61
Number of analyses 1140

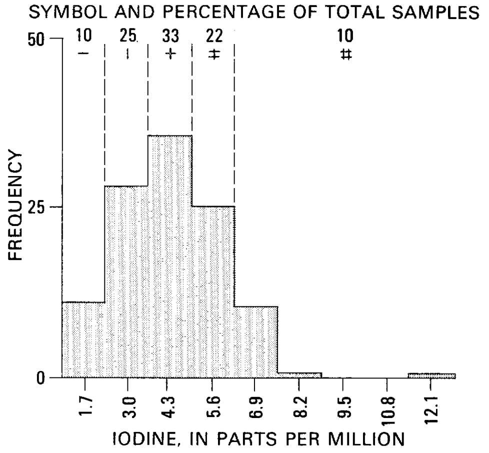
FIGURE 14.—Fluorine distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 11
Geometric deviation 1.49
Analytical error variance
(percent of total variance) 25
Number of analyses 1140

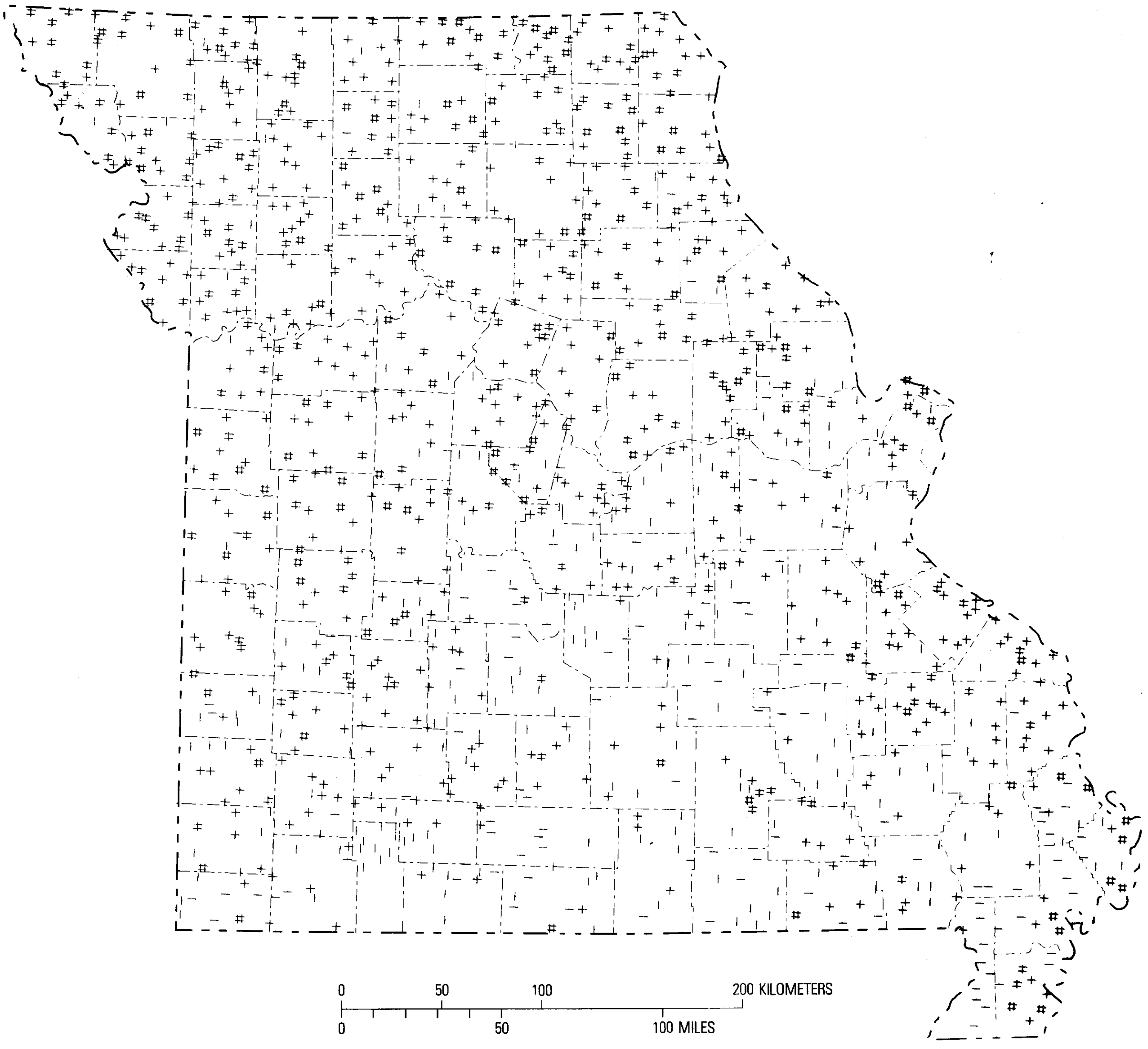
FIGURE 15.—Gallium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

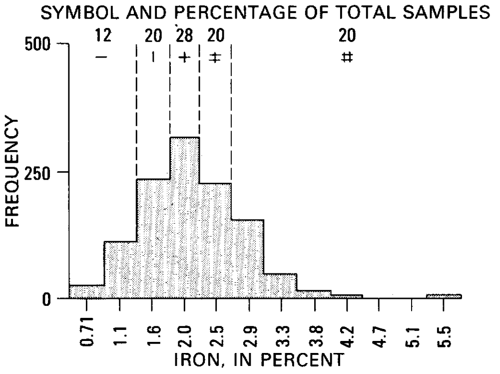




Arithmetic mean 4.4
Standard deviation 1.65
Analytical error variance
(percent of total variance) 16
Number of analyses 114

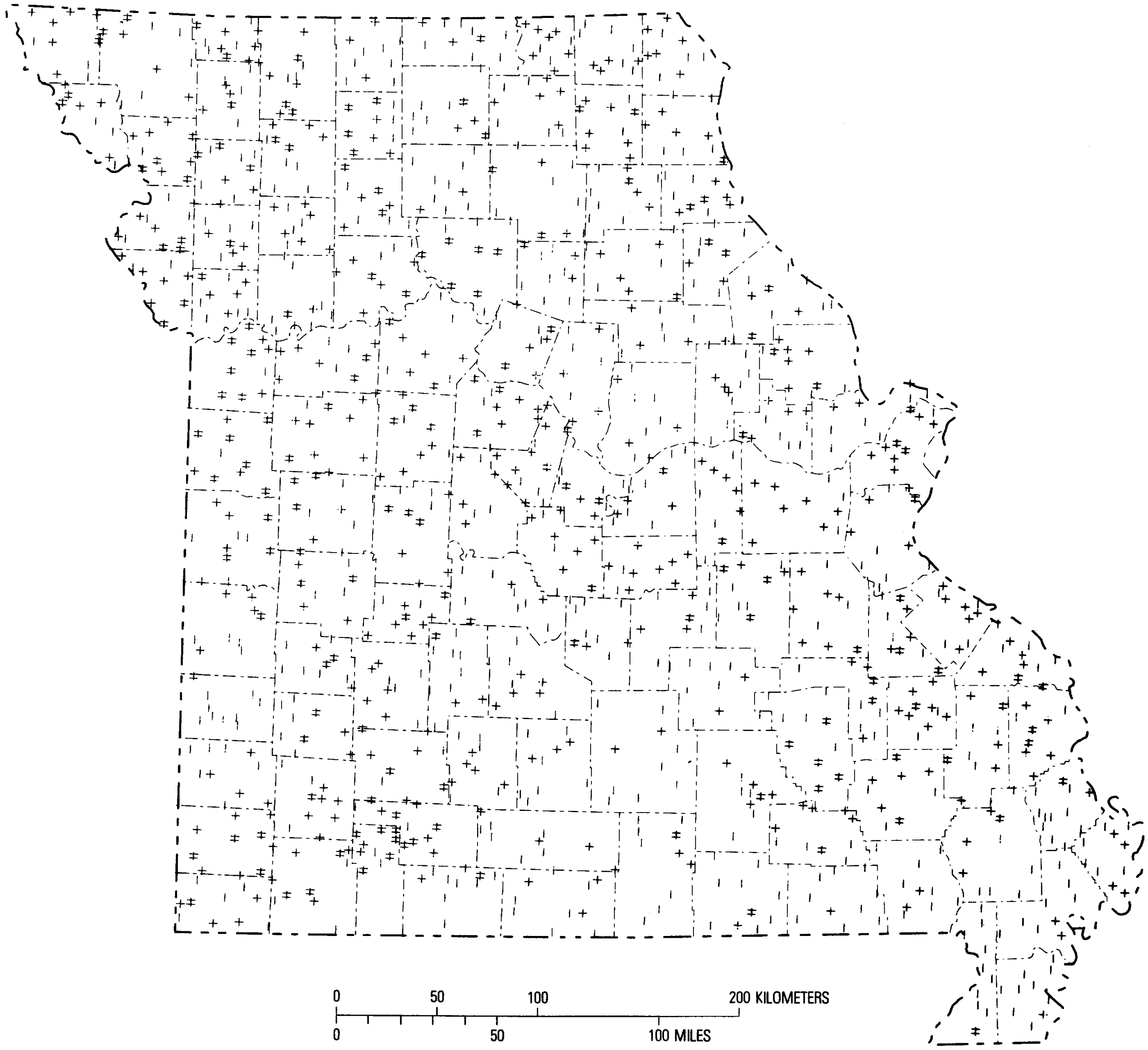
FIGURE 16.—Iodine distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

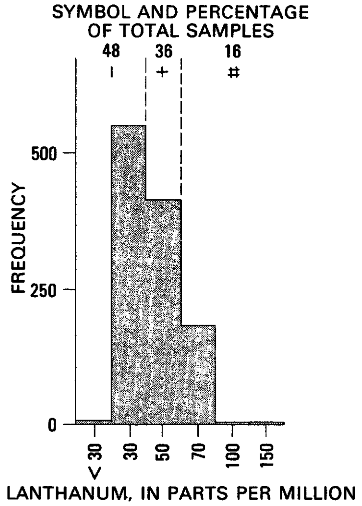




Arithmetic mean 2.11
Standard deviation 0.64
Analytical error variance
(percent of total variance) 4
Number of analyses 1140

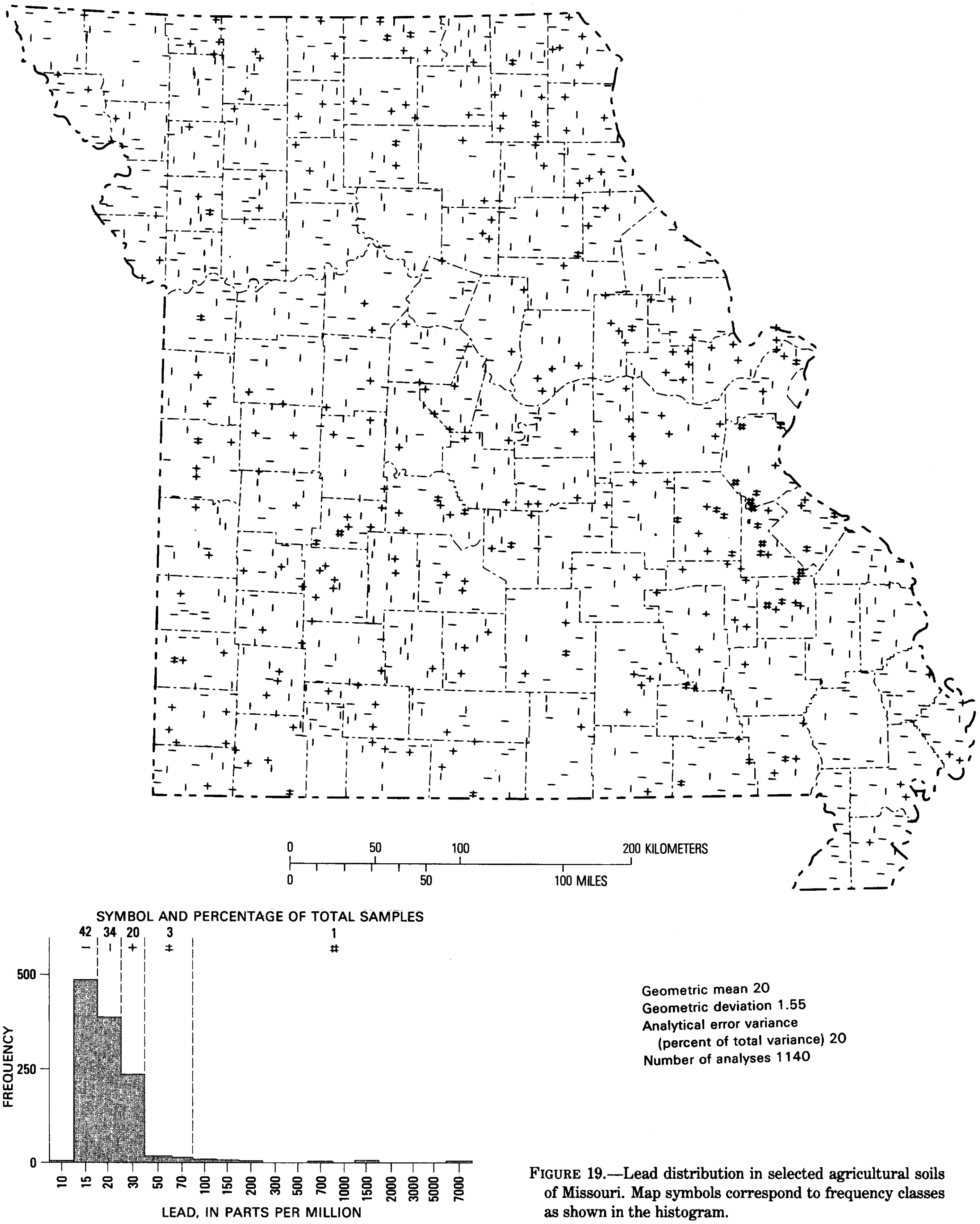
FIGURE 17.—Iron distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





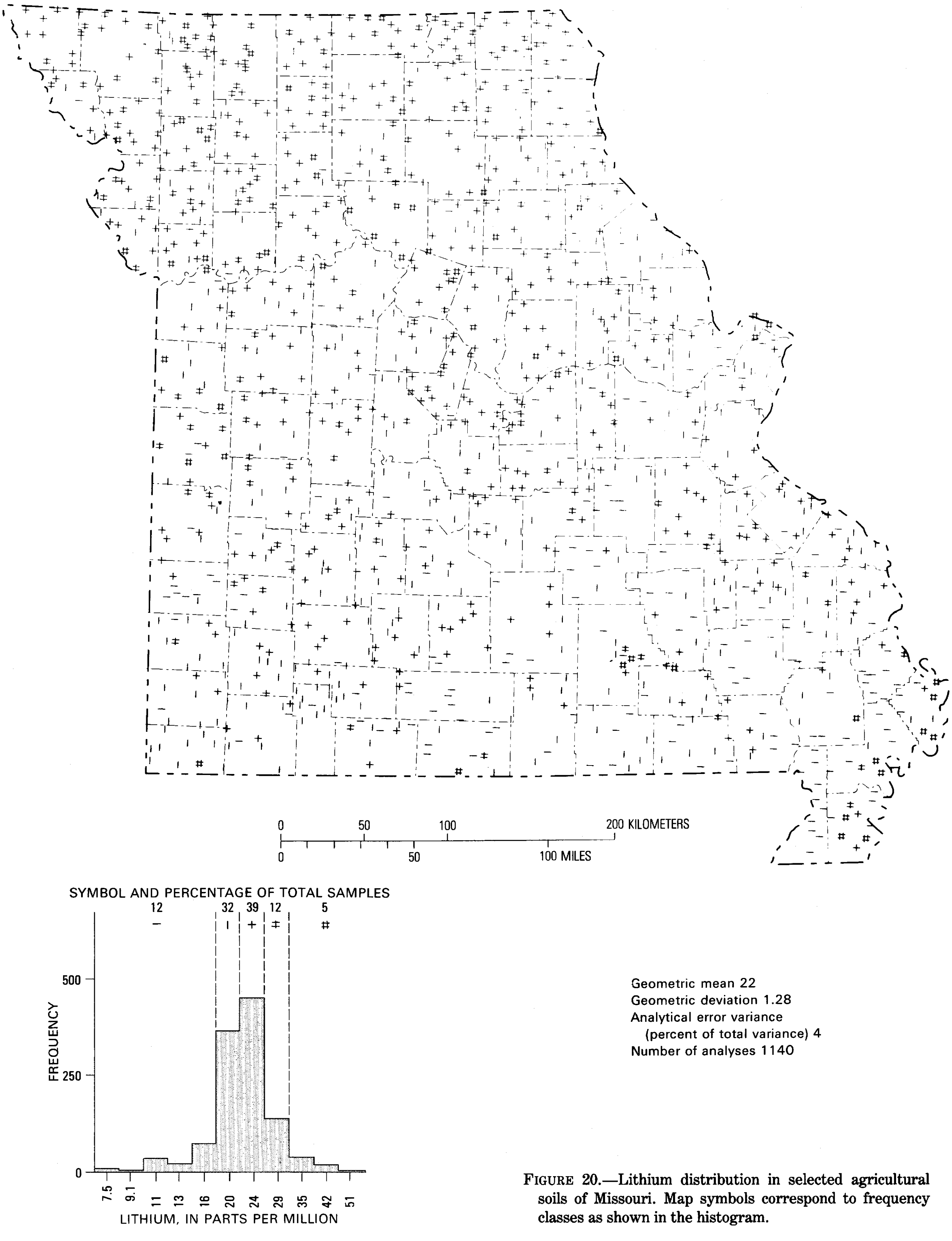
Geometric mean 41
Geometric deviation 1.39
Analytical error variance
(percent of total variance) 49
Number of analyses 1140

FIGURE 18.—Lanthanum distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



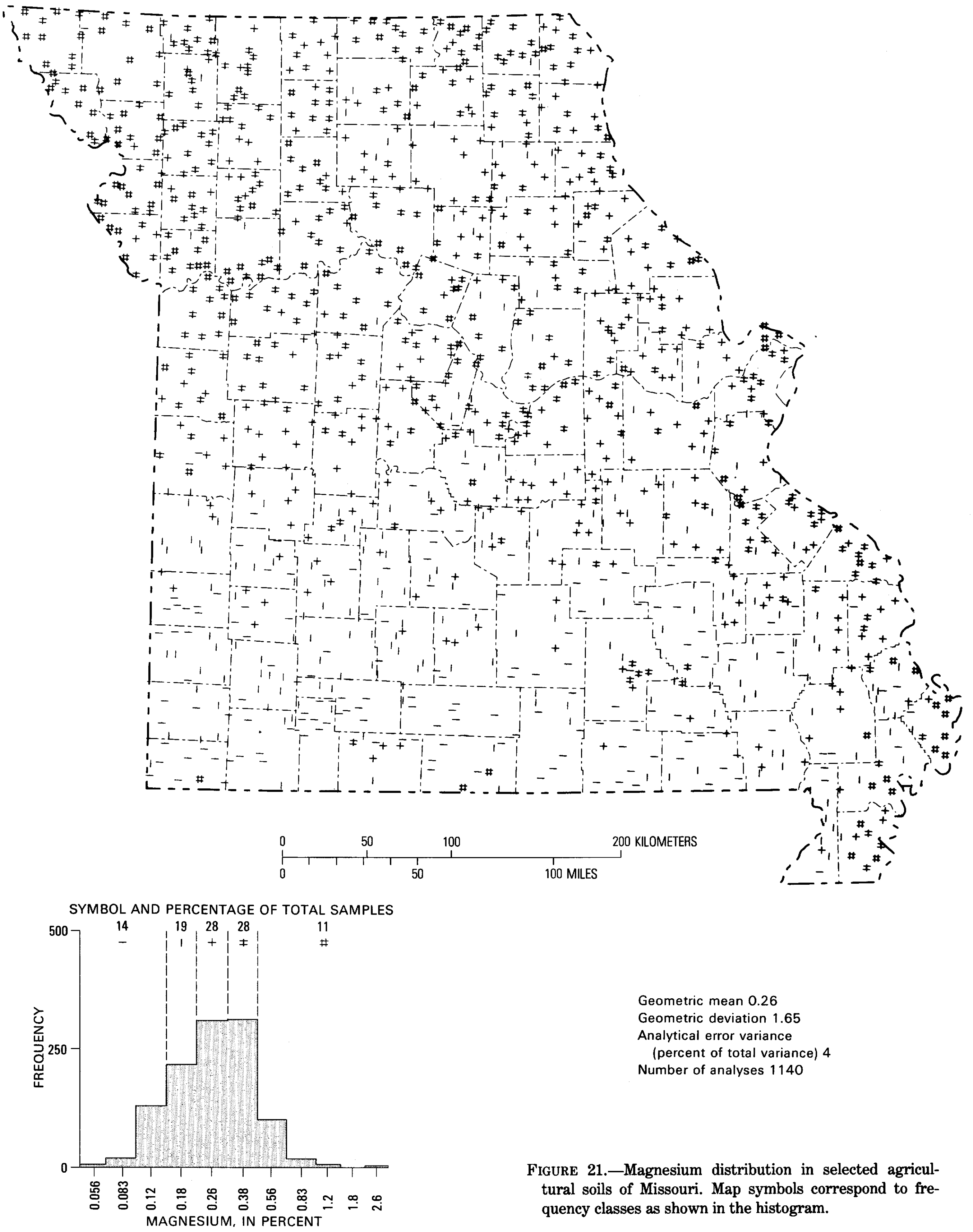
Geometric mean 20
Geometric deviation 1.55
Analytical error variance
(percent of total variance) 20
Number of analyses 1140

FIGURE 19.—Lead distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



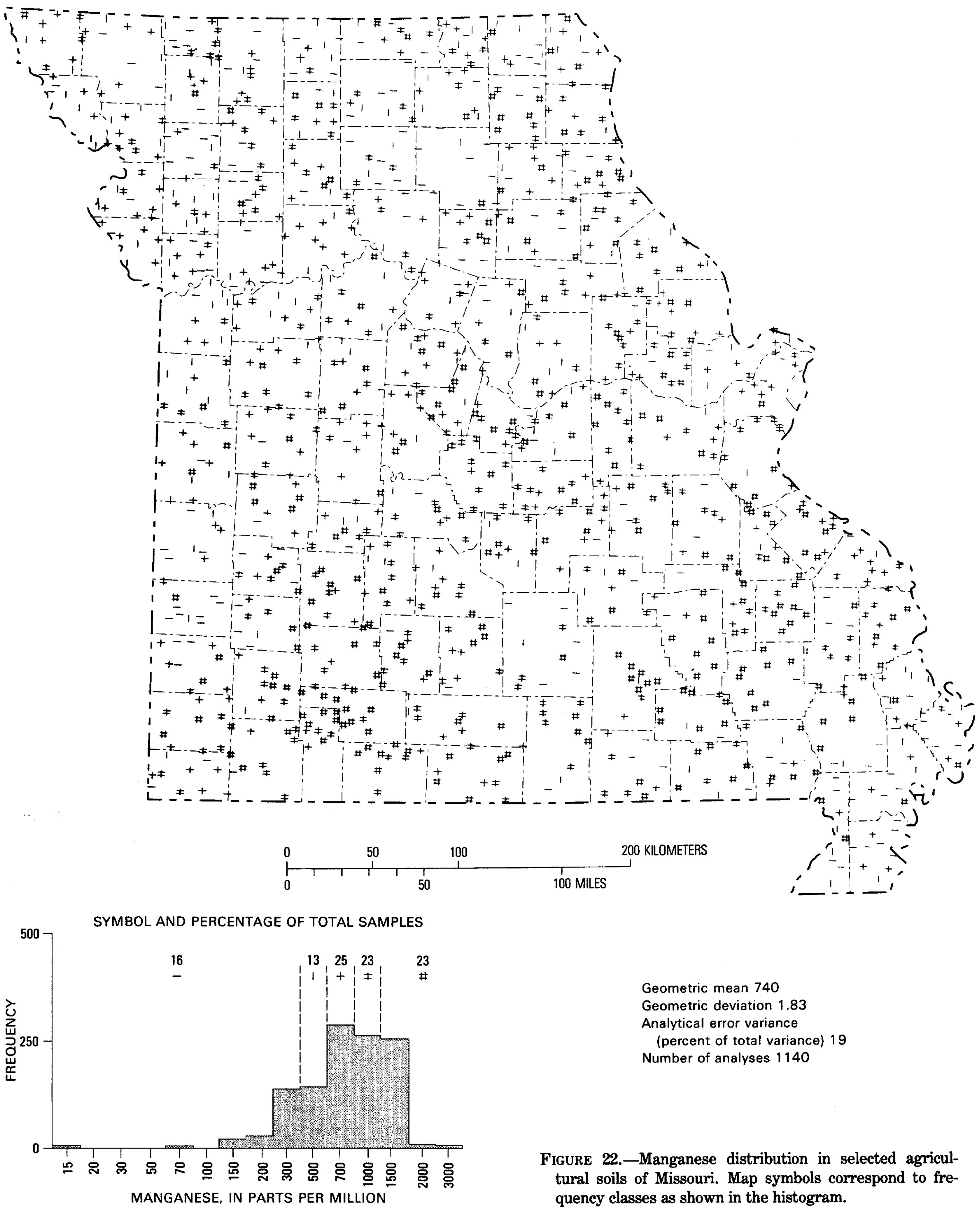
Geometric mean 22
Geometric deviation 1.28
Analytical error variance
(percent of total variance) 4
Number of analyses 1140

FIGURE 20.—Lithium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



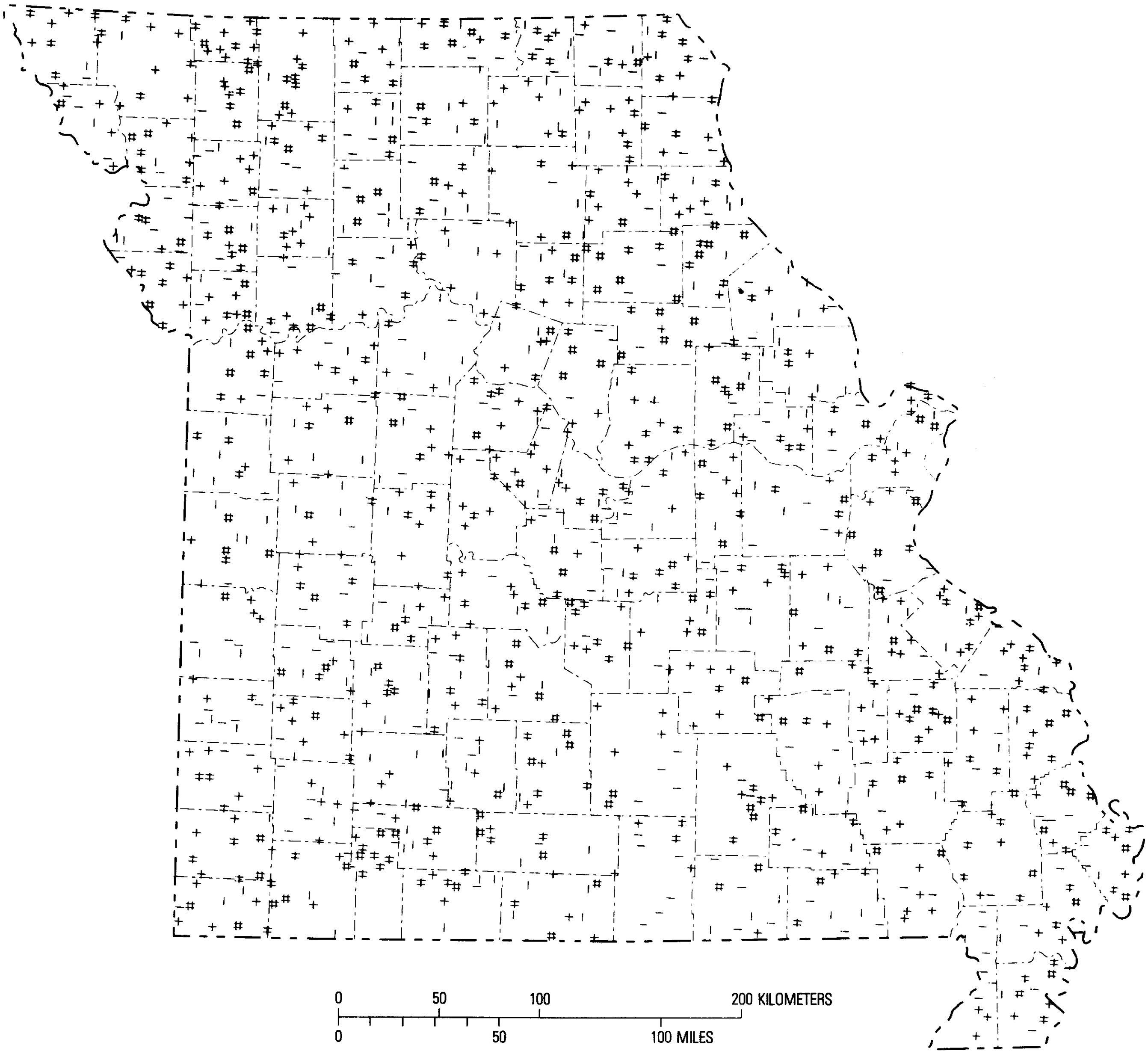
Geometric mean 0.26
Geometric deviation 1.65
Analytical error variance
(percent of total variance) 4
Number of analyses 1140

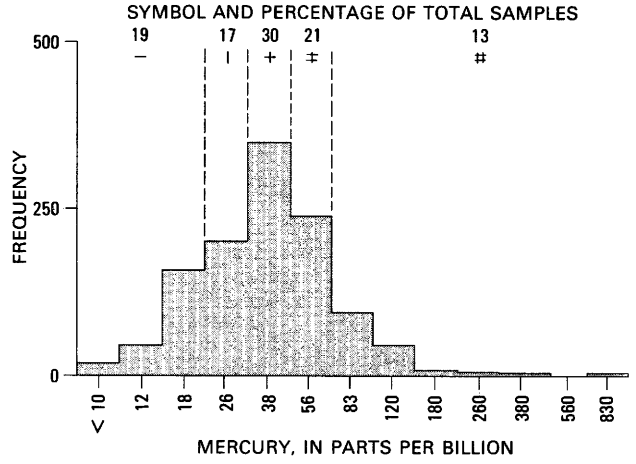
FIGURE 21.—Magnesium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 740
Geometric deviation 1.83
Analytical error variance
(percent of total variance) 19
Number of analyses 1140

Figure 22.—Manganese distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

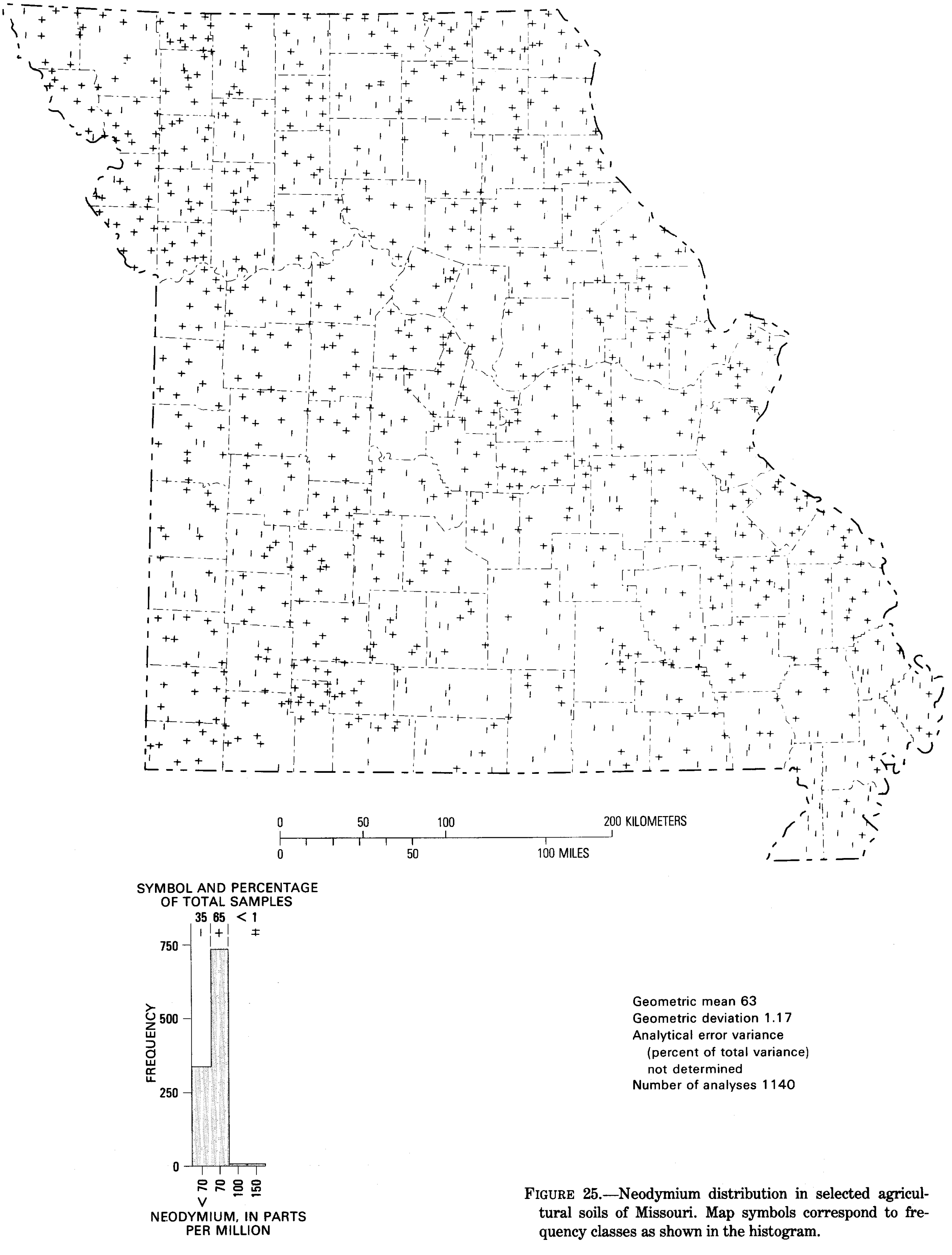




Geometric mean 39
Geometric deviation 1.80
Analytical error variance
(percent of total variance) 52
Number of analyses 1140

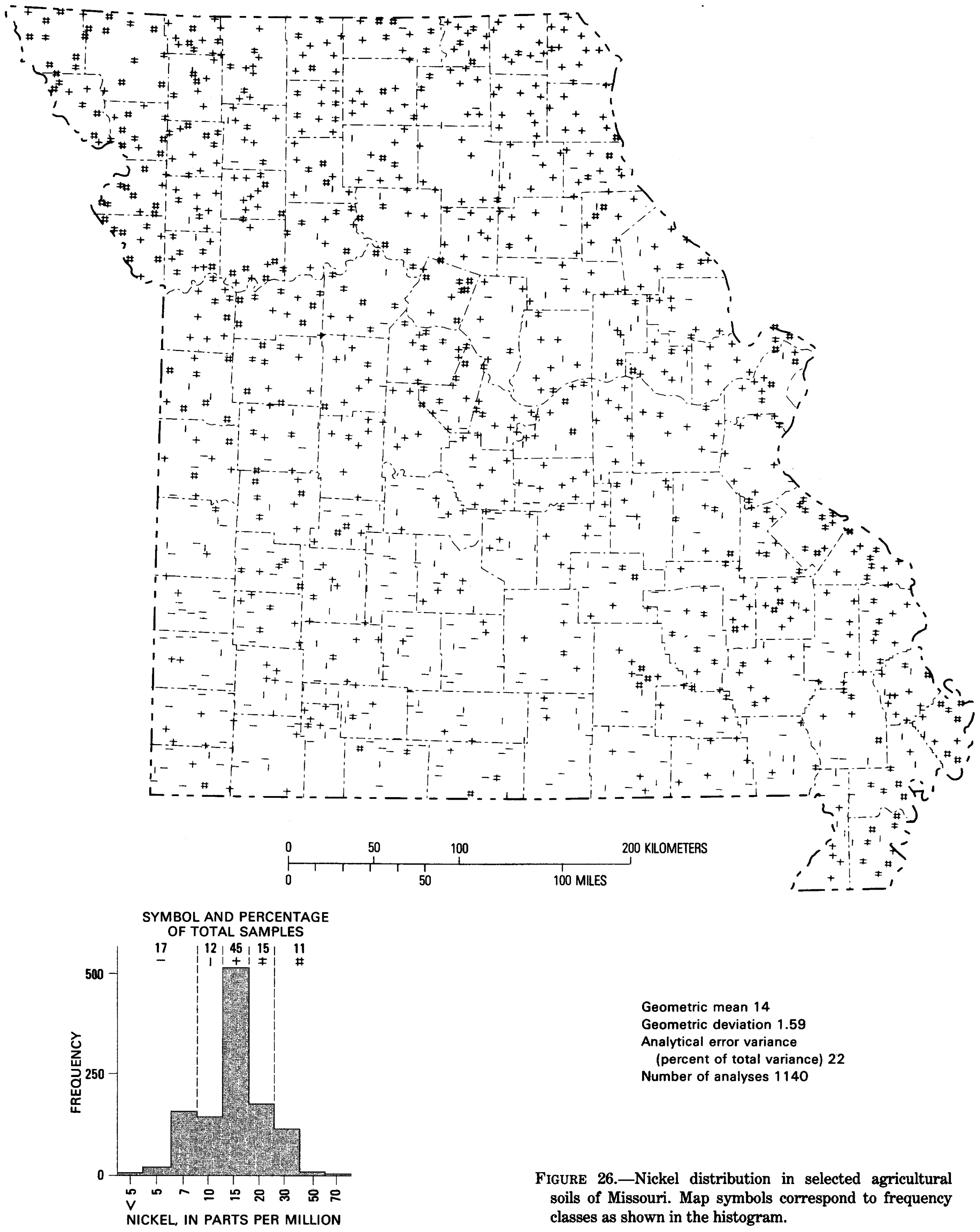
FIGURE 23.—Mercury distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

FIGURE 24.—Molybdenum concentrations, in parts per million, in selected agricultural soils of Missouri. Only samples with concentrations above the lower limit of determination are shown. Location of sampling site is indicated by plus (+).



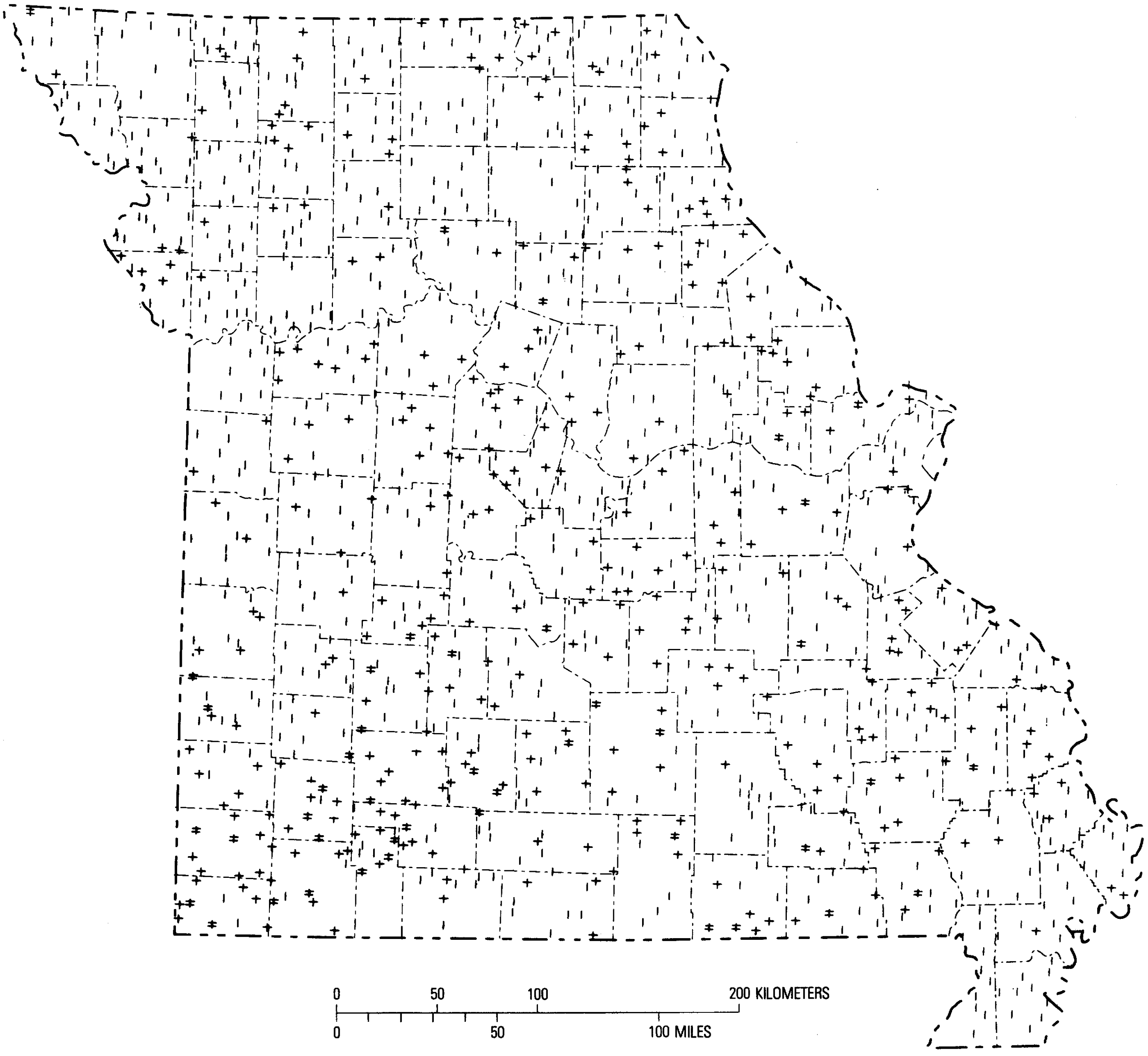
Geometric mean 63
Geometric deviation 1.17
Analytical error variance
(percent of total variance)
not determined
Number of analyses 1140

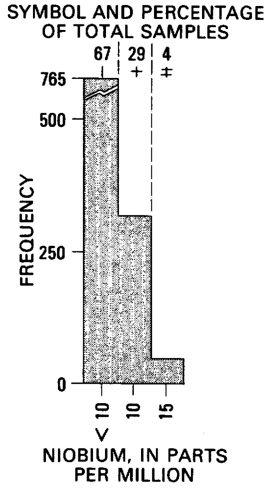
FIGURE 25.—Neodymium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 14
Geometric deviation 1.59
Analytical error variance
(percent of total variance) 22
Number of analyses 1140

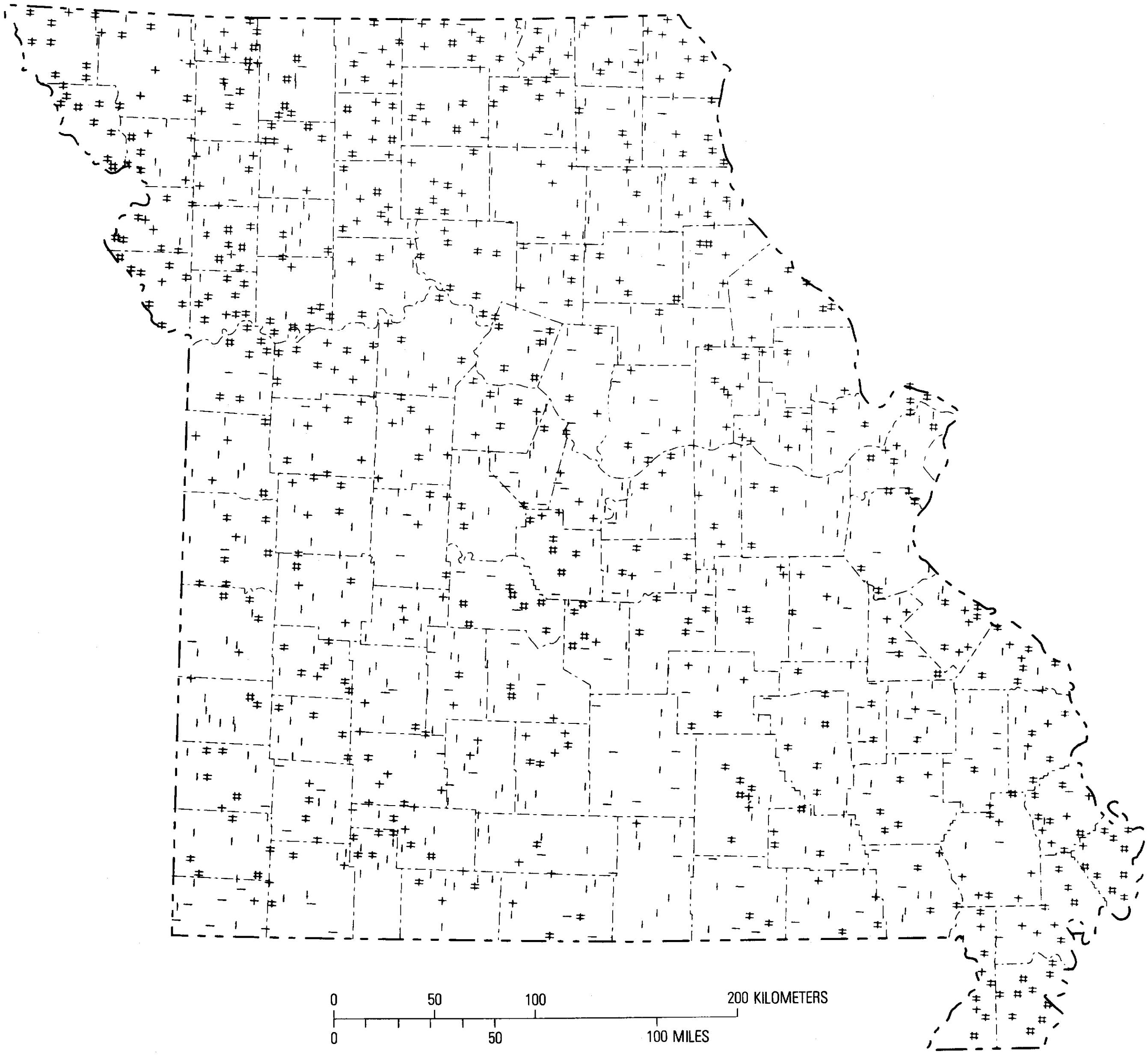
FIGURE 26.—Nickel distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

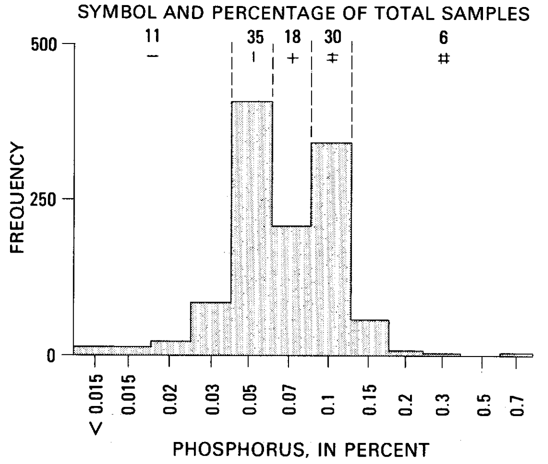




Geometric mean 7
Geometric deviation 1.38
Analytical error variance
(percent of total variance) 10
Number of analyses 1140

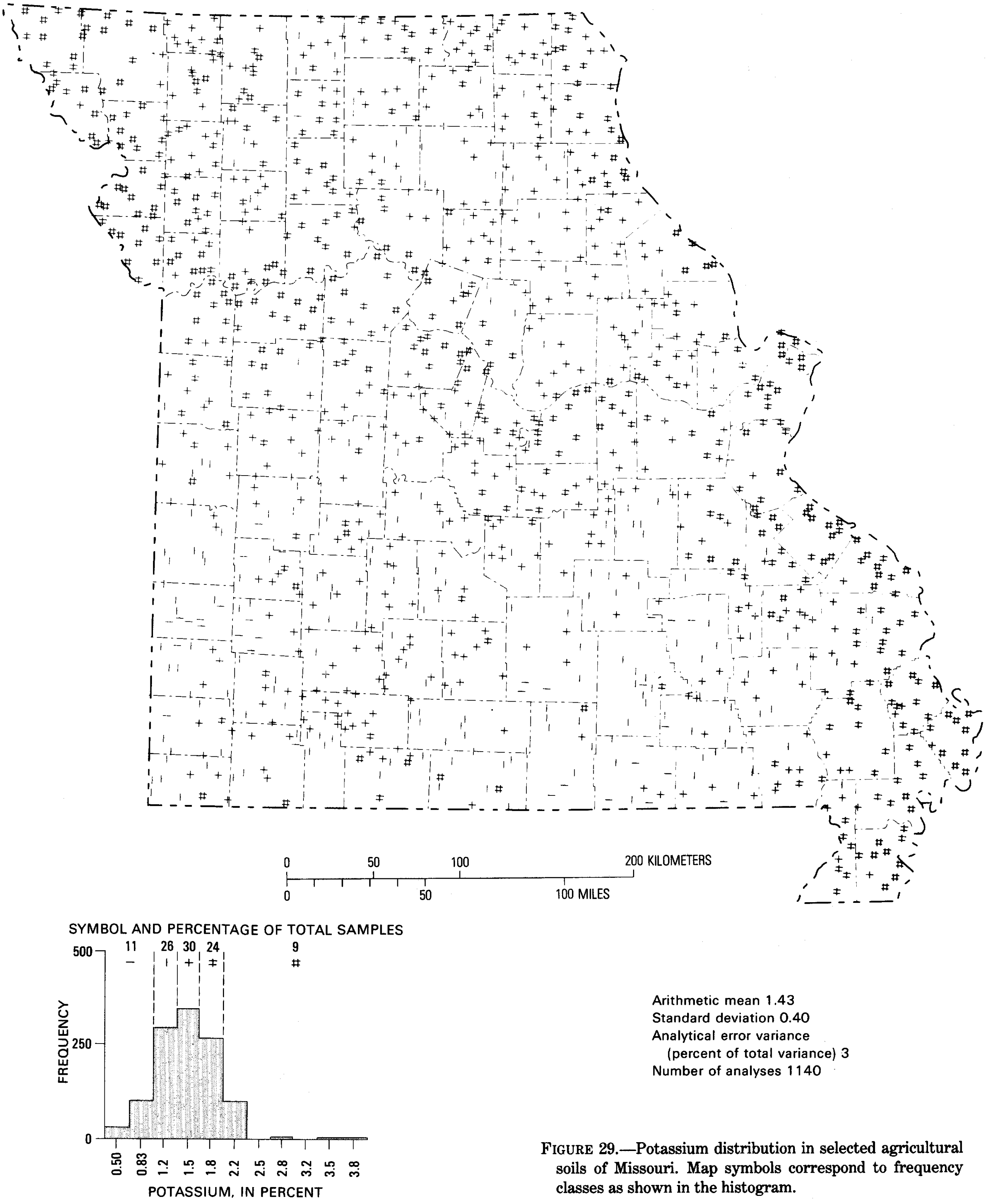
FIGURE 27.—Niobium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





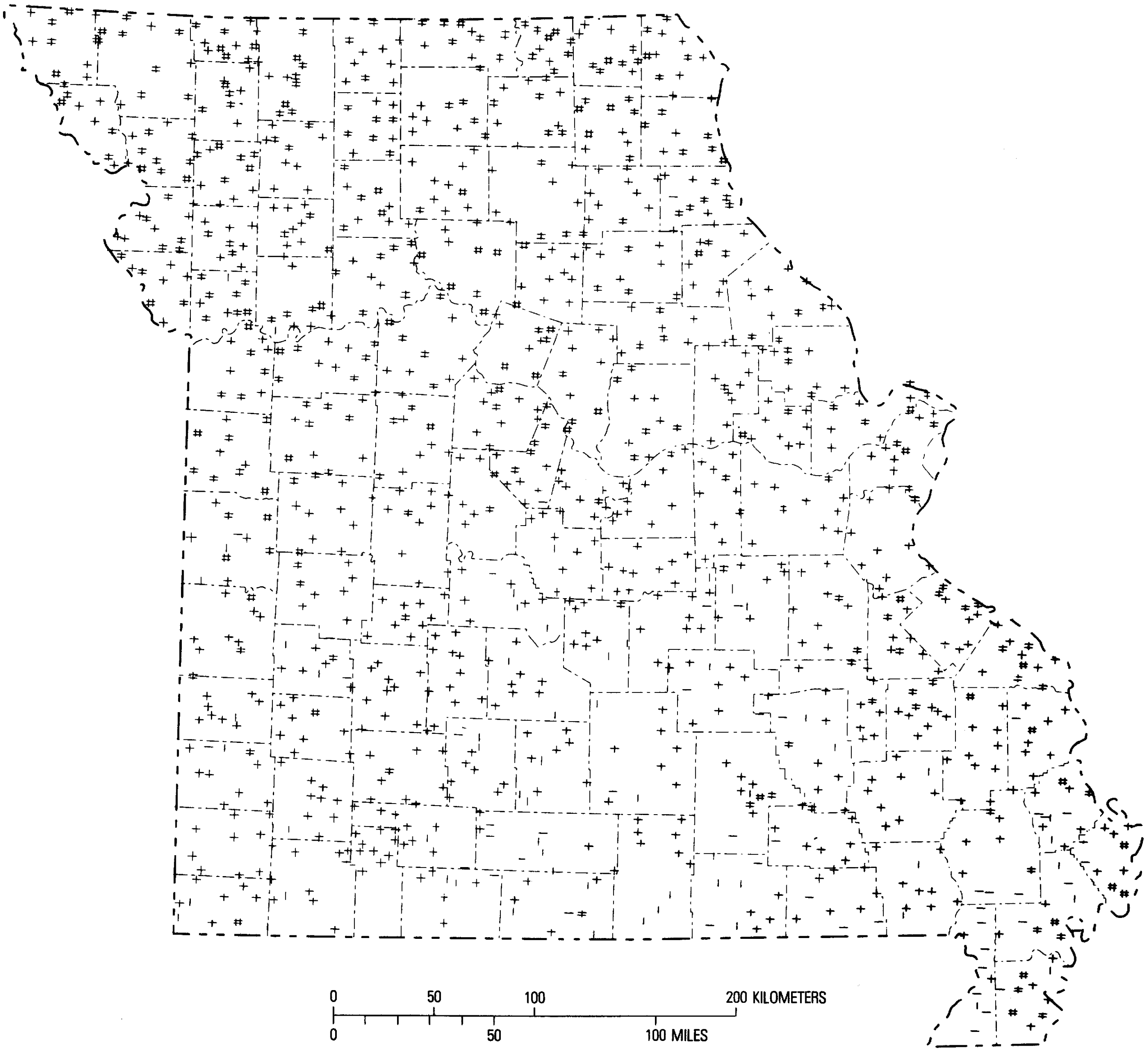
Geometric mean 0.059
Geometric deviation 1.61
Analytical error variance
(percent of total variance) 30
Number of analyses 1140

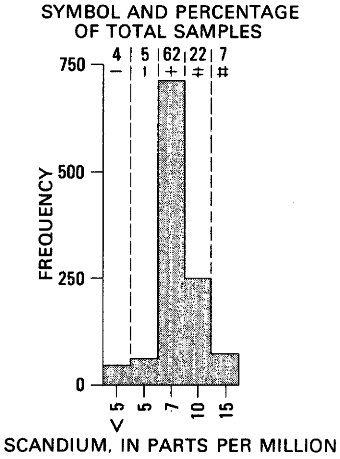
FIGURE 28.—Phosphorus distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Arithmetic mean 1.43
Standard deviation 0.40
Analytical error variance
(percent of total variance) 3
Number of analyses 1140

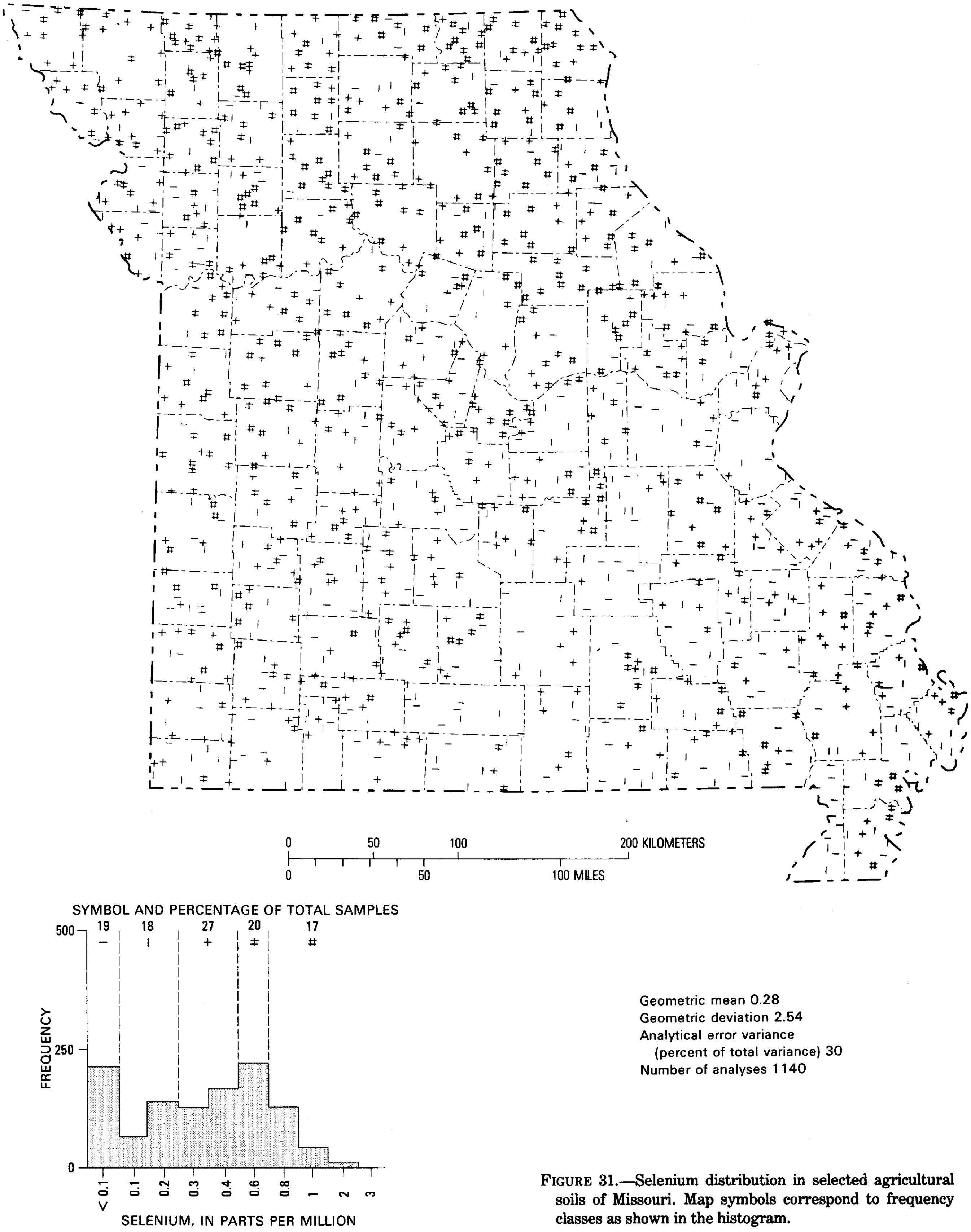
FIGURE 29.—Potassium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





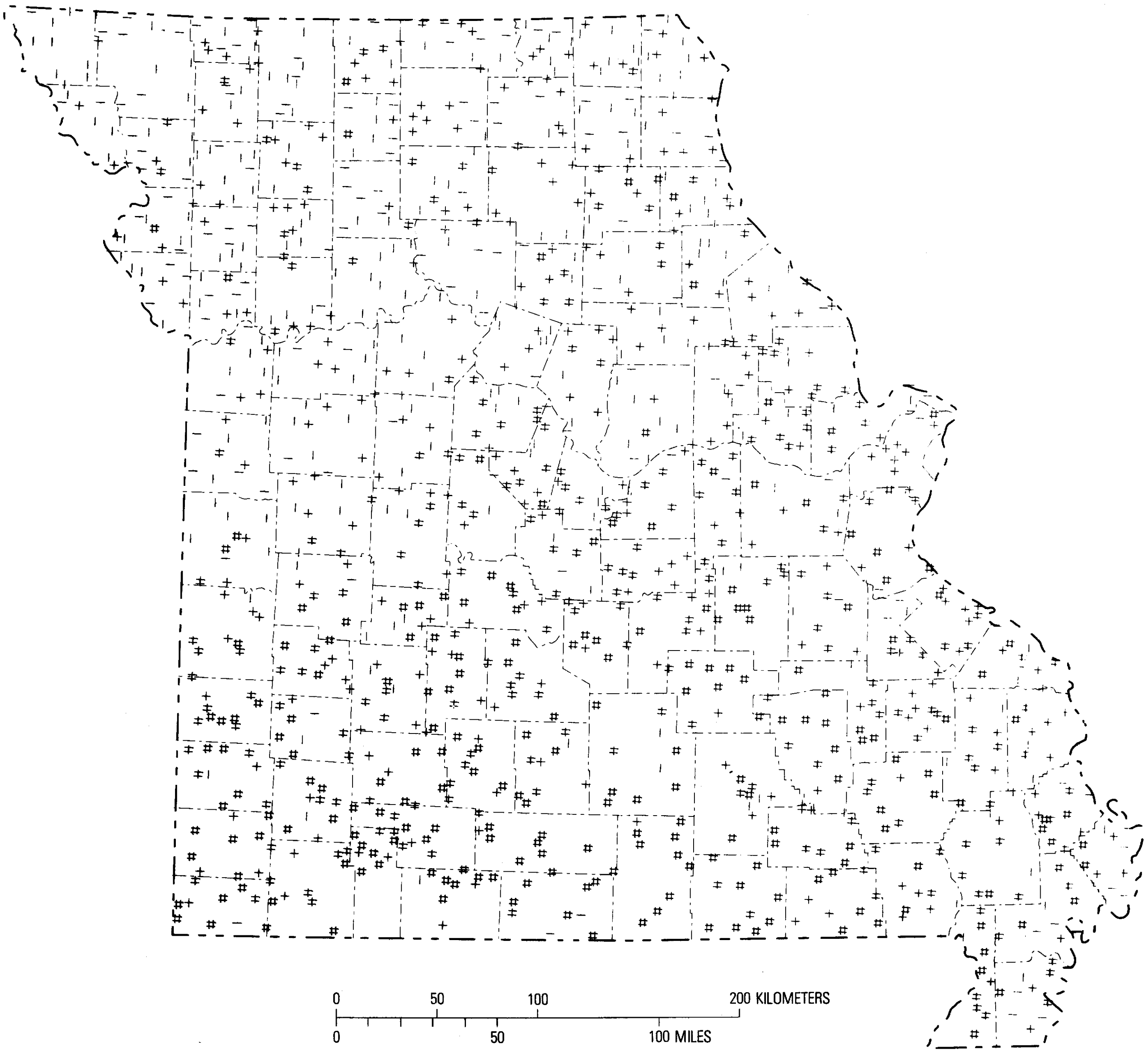
Geometric mean 8
Geometric deviation 1.34
Analytical error variance
(percent of total variance) 26
Number of analyses 1140

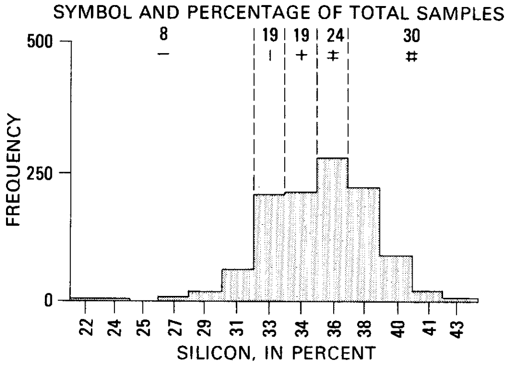
FIGURE 30.—Scandium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 0.28
Geometric deviation 2.54
Analytical error variance
(percent of total variance) 30
Number of analyses 1140

FIGURE 31.—Selenium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





Arithmetic mean 35
Standard deviation 2.77
Analytical error variance
(percent of total variance) 23
Number of analyses 1140

FIGURE 32.—Silicon distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

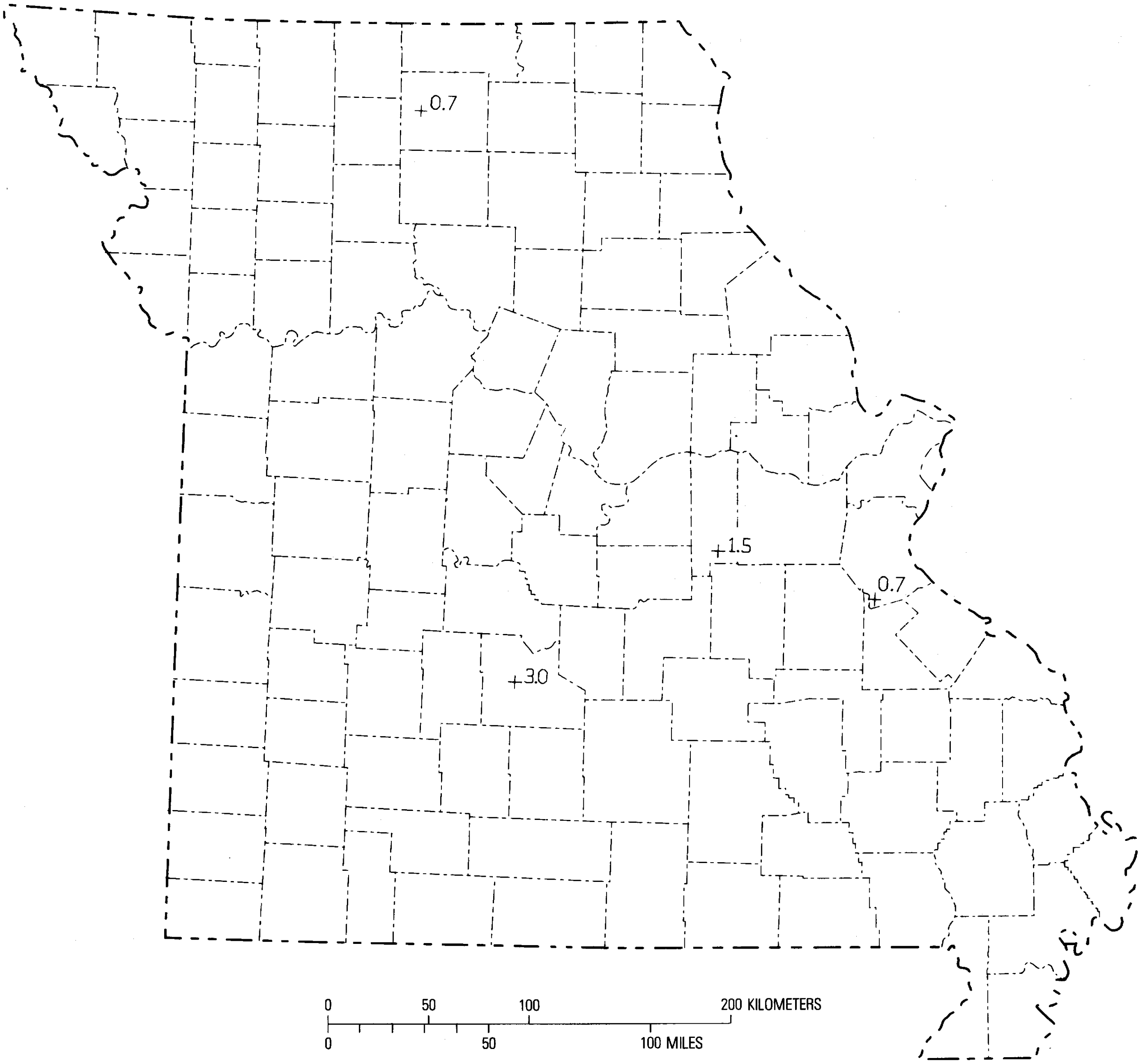
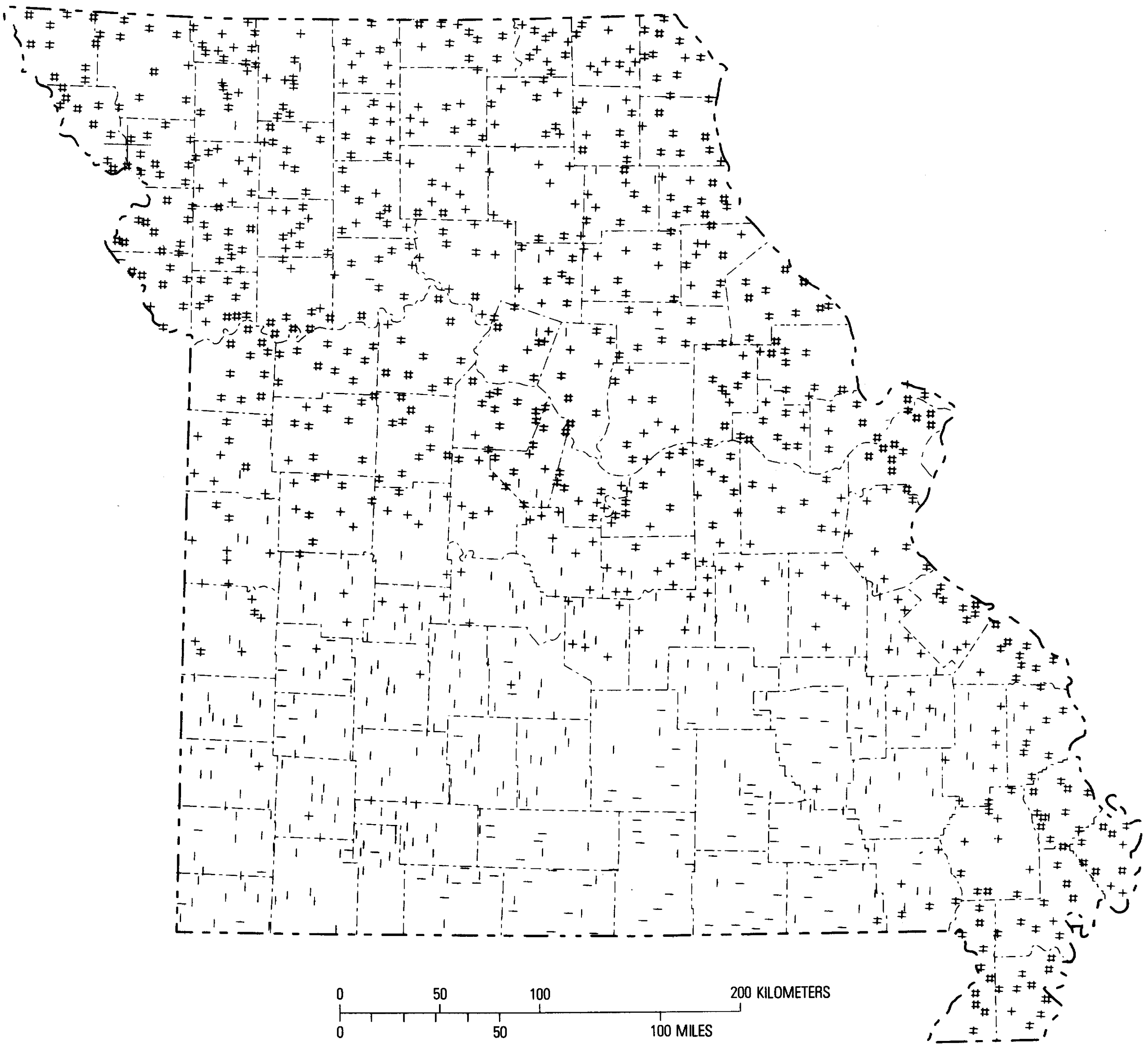
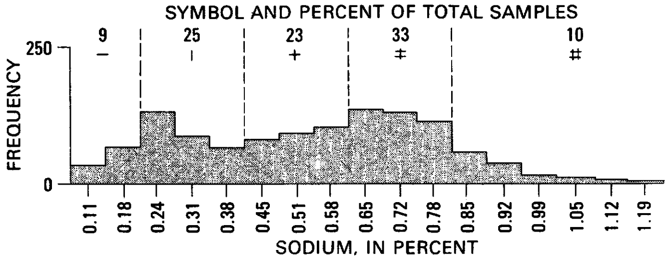


FIGURE 33.—Silver concentrations, in parts per million, in selected agricultural soils of Missouri. Only samples with concentrations above the lower limit of determination are shown. Location of sampling site is indicated by plus (+).



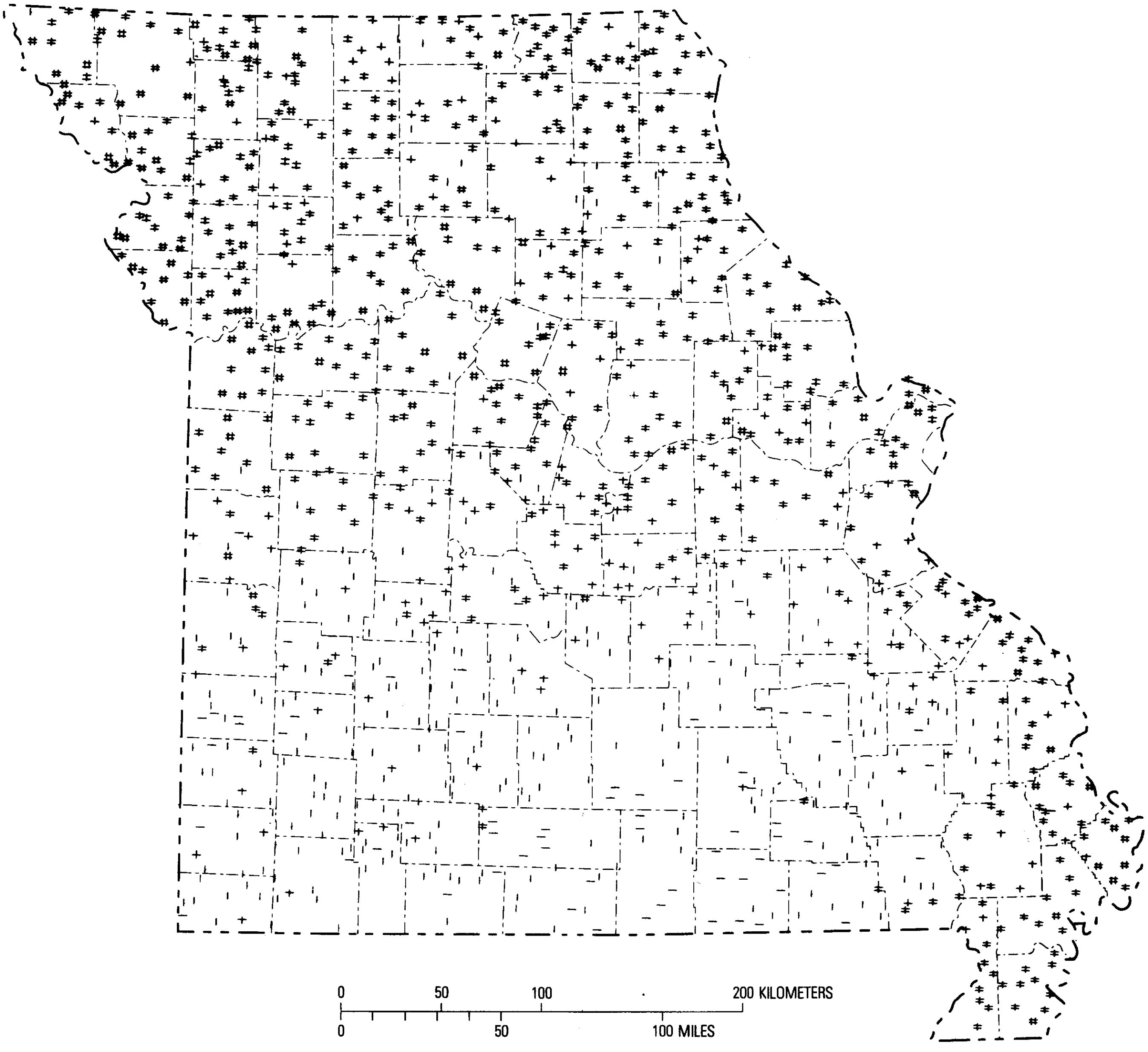


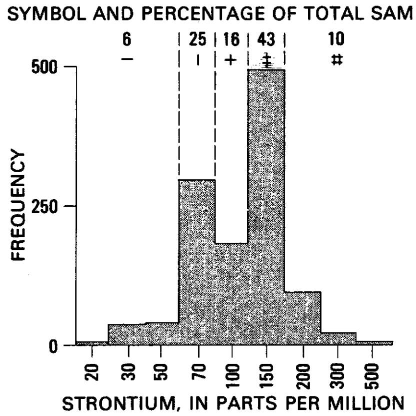
Whole population:
- Arithmetic mean 0.53
- Standard deviation 0.23
- Analytical error variance (percent of total variance) 2
- Number of analyses 1140

Lower population (<0.4):
- Arithmetic mean 0.26
- Standard deviation 0.08
- Number of analyses 380

Upper population (>0.4):
- Arithmetic mean 0.67
- Standard deviation 0.15
- Number of analyses 760

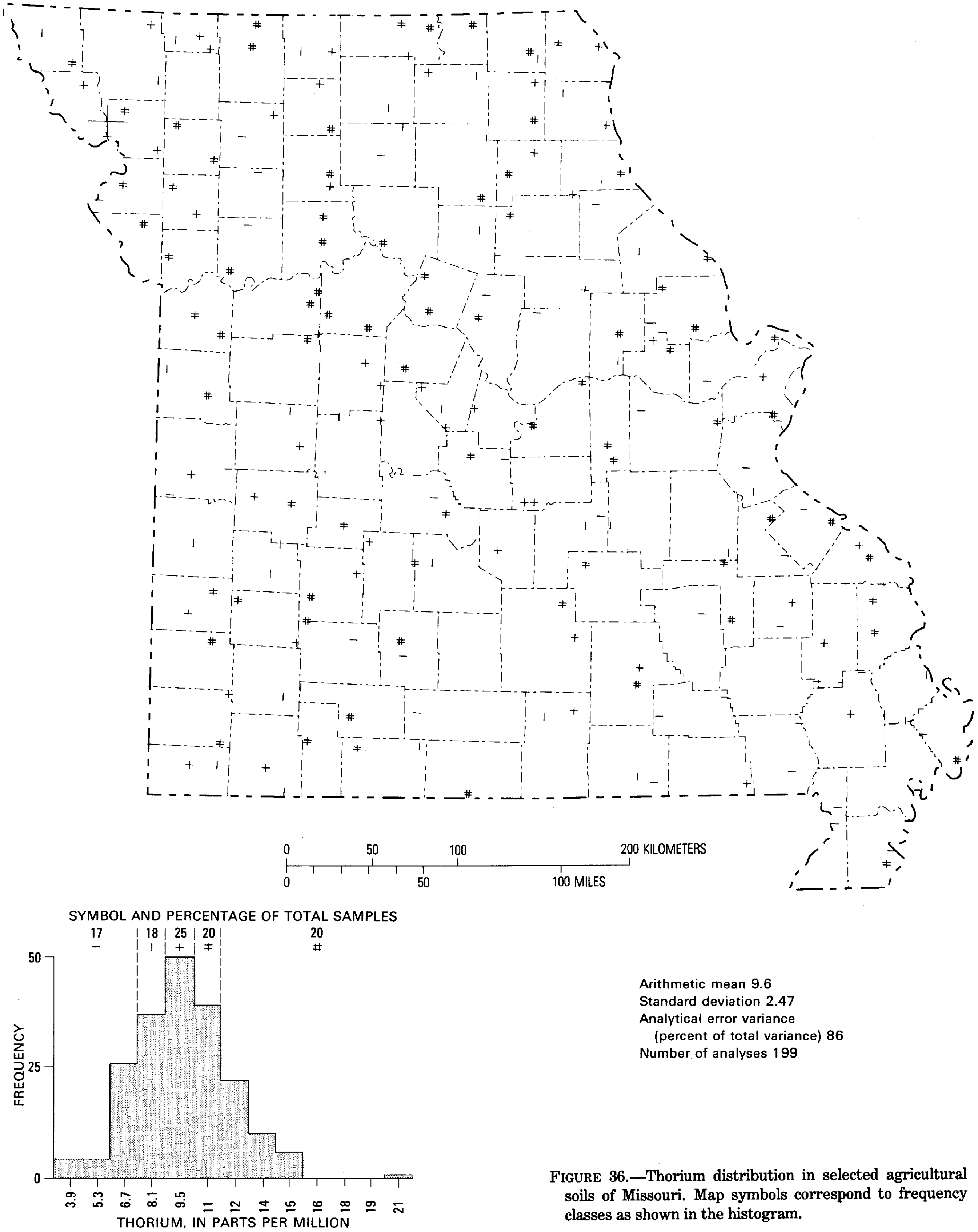
Figure 34.—Sodium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





Geometric mean 110
Geometric deviation 1.60
Analytical error variance
(percent of total variance) 23
Number of analyses 1140

Figure 35.—Strontium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Arithmetic mean 9.6
Standard deviation 2.47
Analytical error variance
(percent of total variance) 86
Number of analyses 199

FIGURE 36.—Thorium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

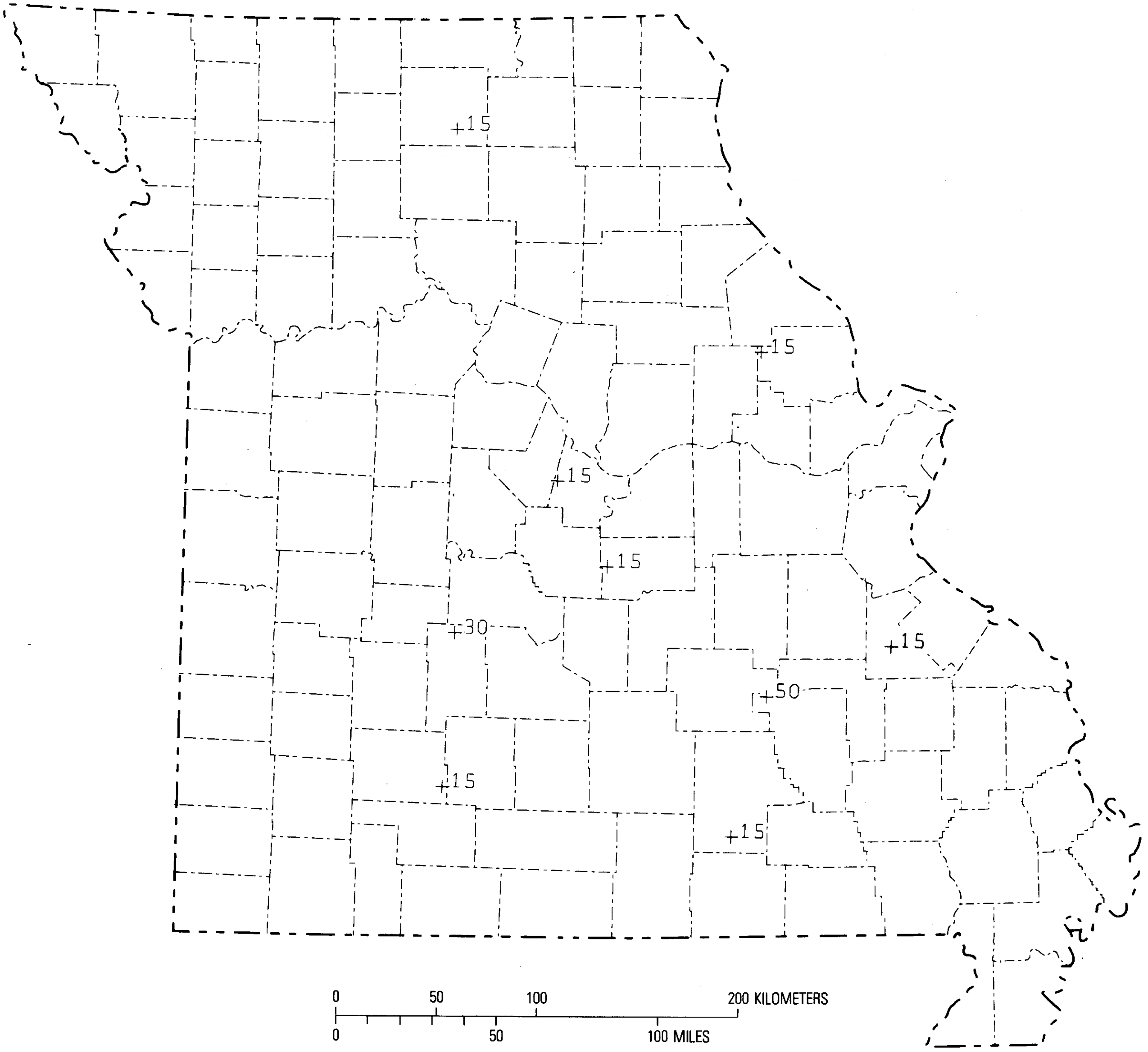
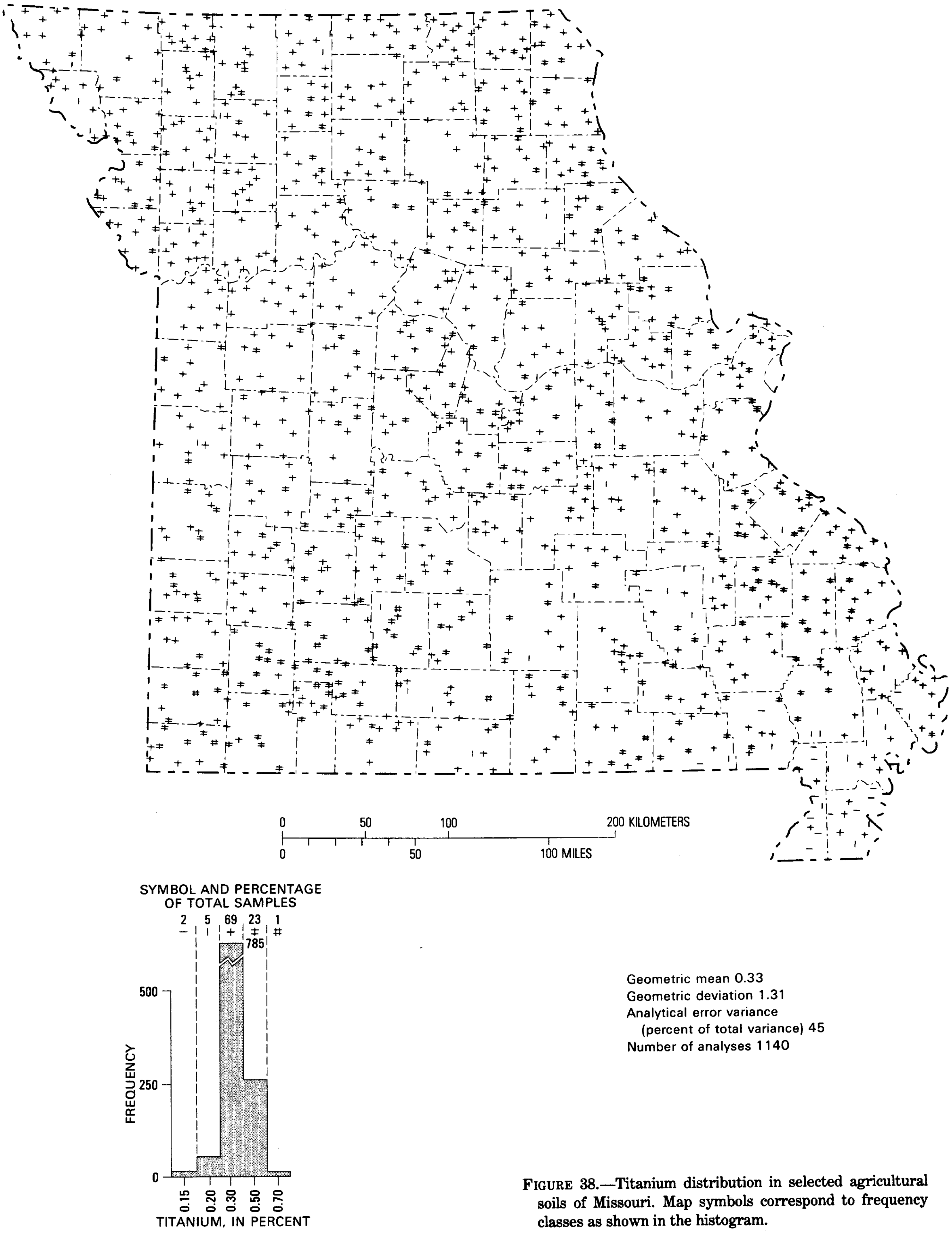
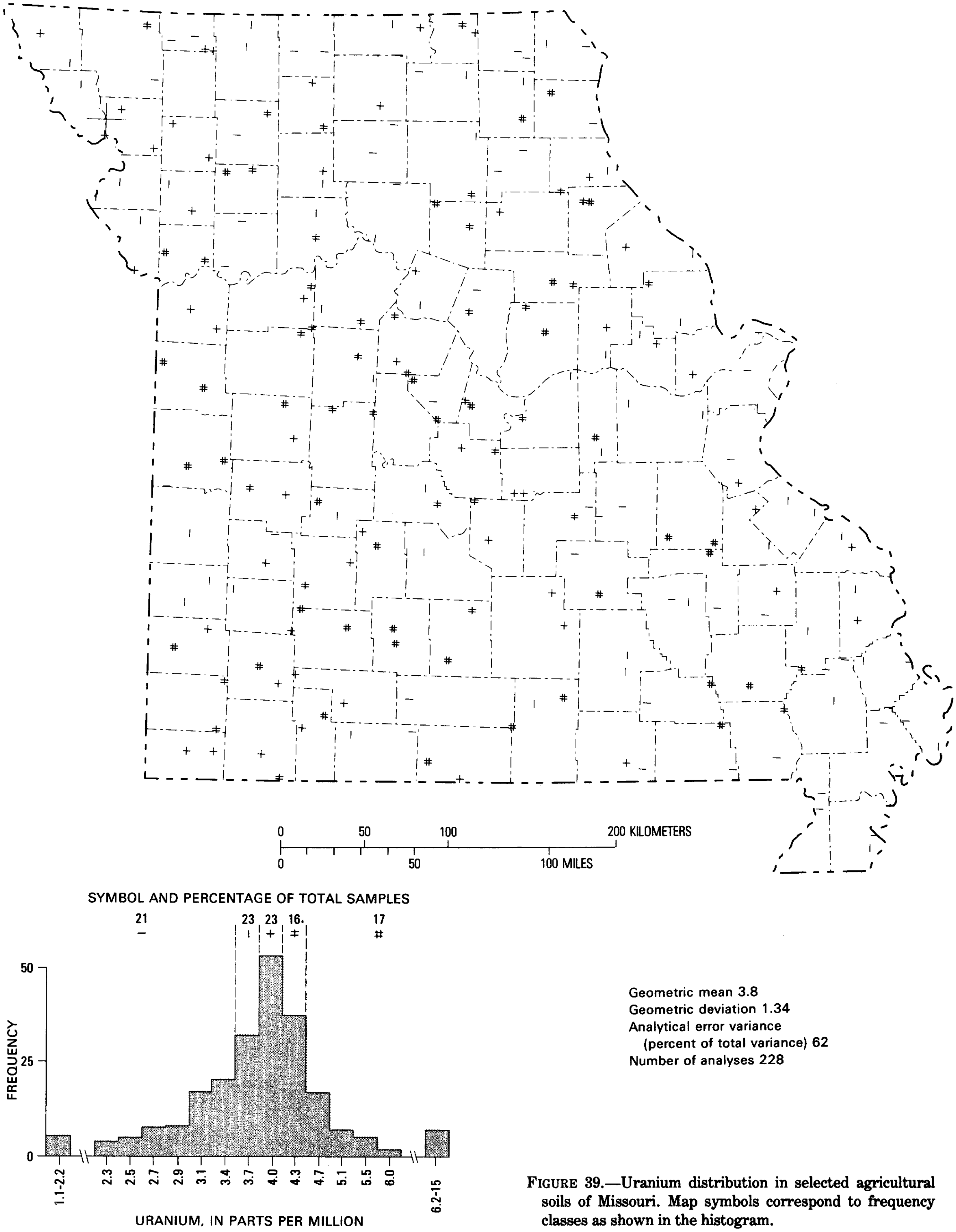


FIGURE 37.—Tin concentrations, in parts per million, in selected agricultural soils of Missouri. Only samples with concentrations above the lower limit of determination are shown. Location of sampling site is indicated by plus (+).



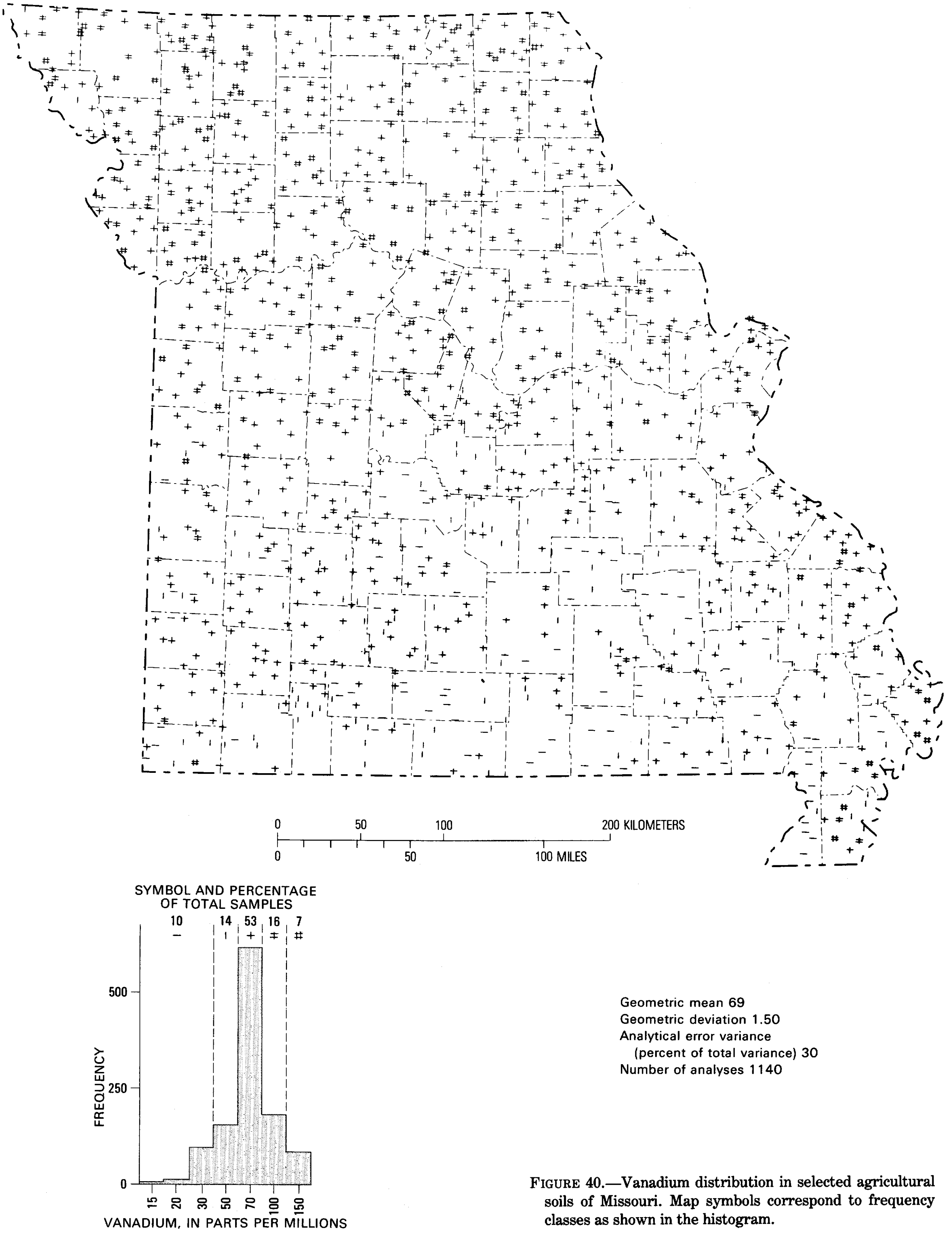
Geometric mean 0.33
Geometric deviation 1.31
Analytical error variance
(percent of total variance) 45
Number of analyses 1140

FIGURE 38.—Titanium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



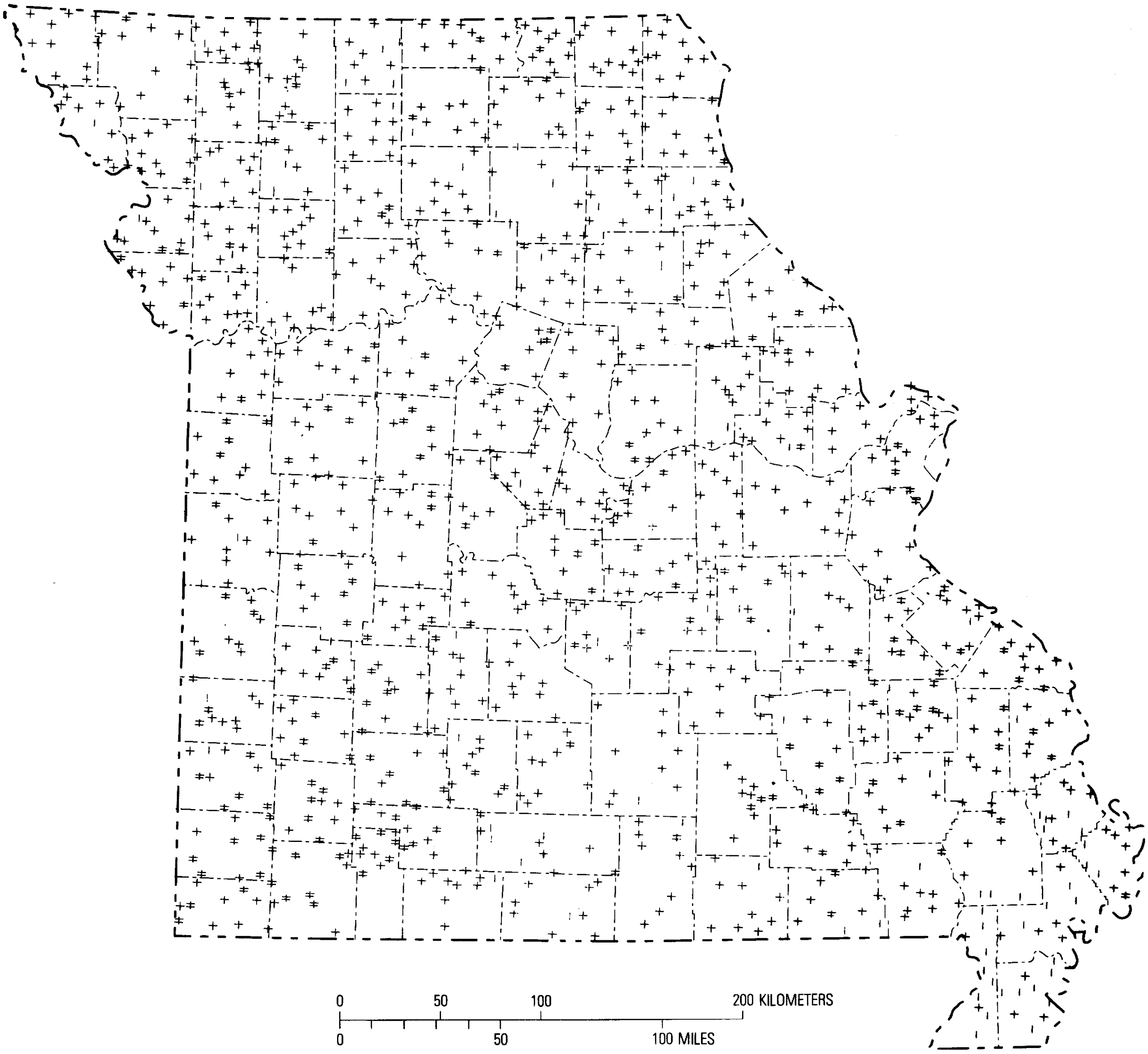
Geometric mean 3.8
Geometric deviation 1.34
Analytical error variance
(percent of total variance) 62
Number of analyses 228

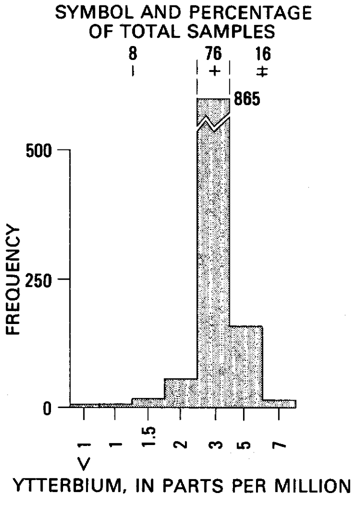
FIGURE 39.—Uranium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 69
Geometric deviation 1.50
Analytical error variance
(percent of total variance) 30
Number of analyses 1140

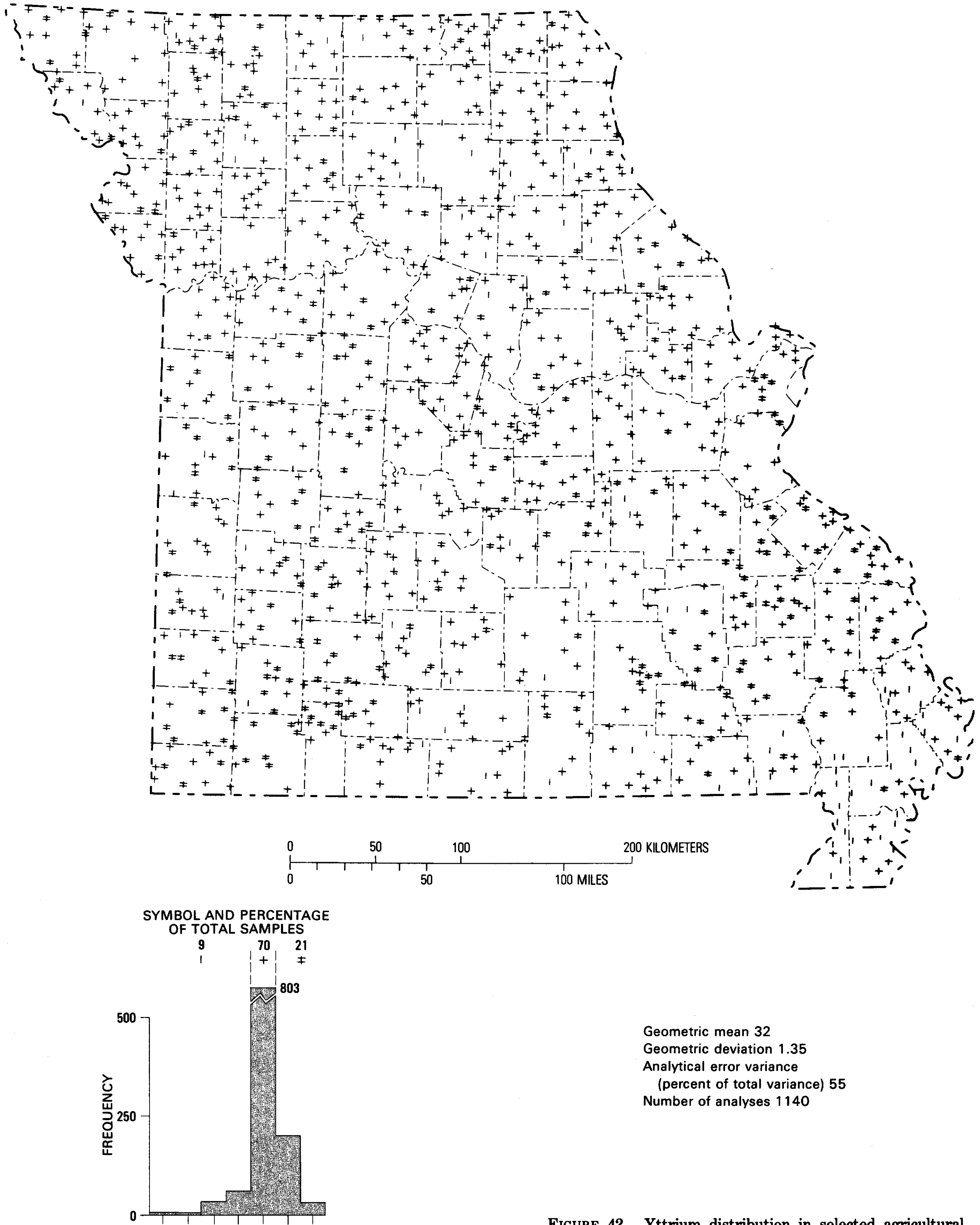
FIGURE 40.—Vanadium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





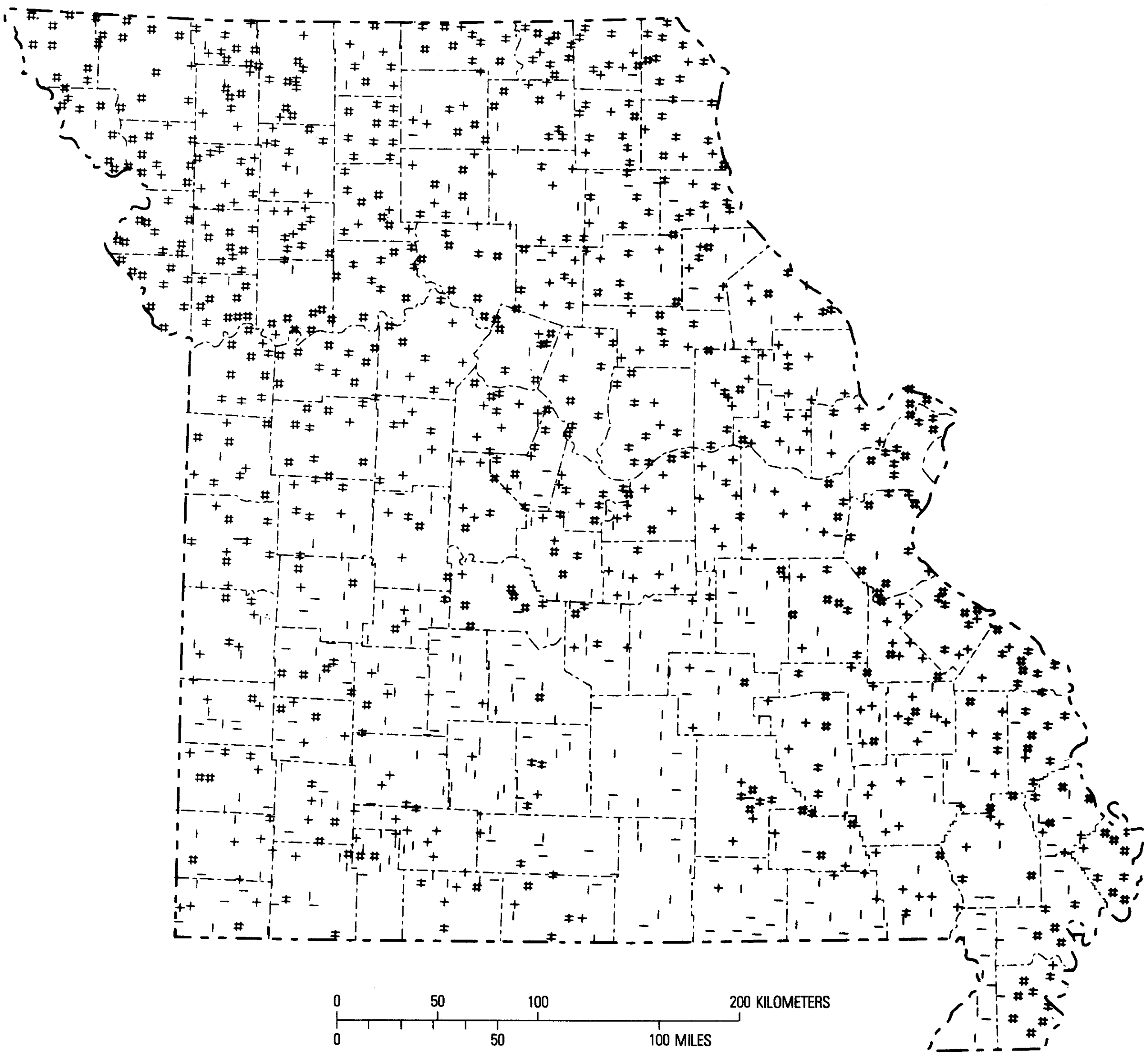
Geometric mean 3.2
Geometric deviation 1.31
Analytical error variance
(percent of total variance) 68
Number of analyses 1140

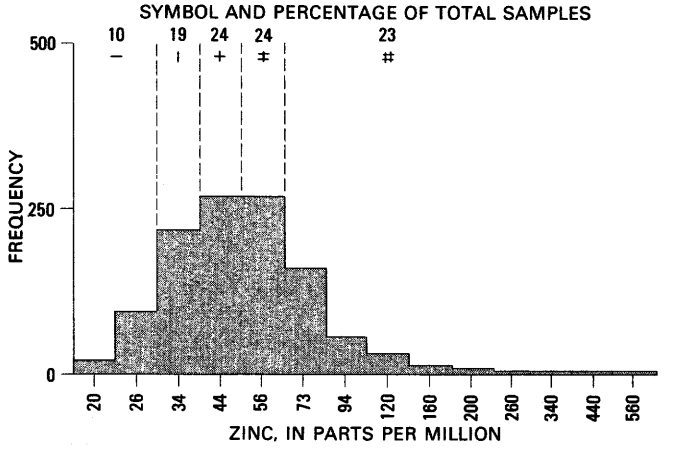
FIGURE 41.—Ytterbium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 32
Geometric deviation 1.35
Analytical error variance
(percent of total variance) 55
Number of analyses 1140

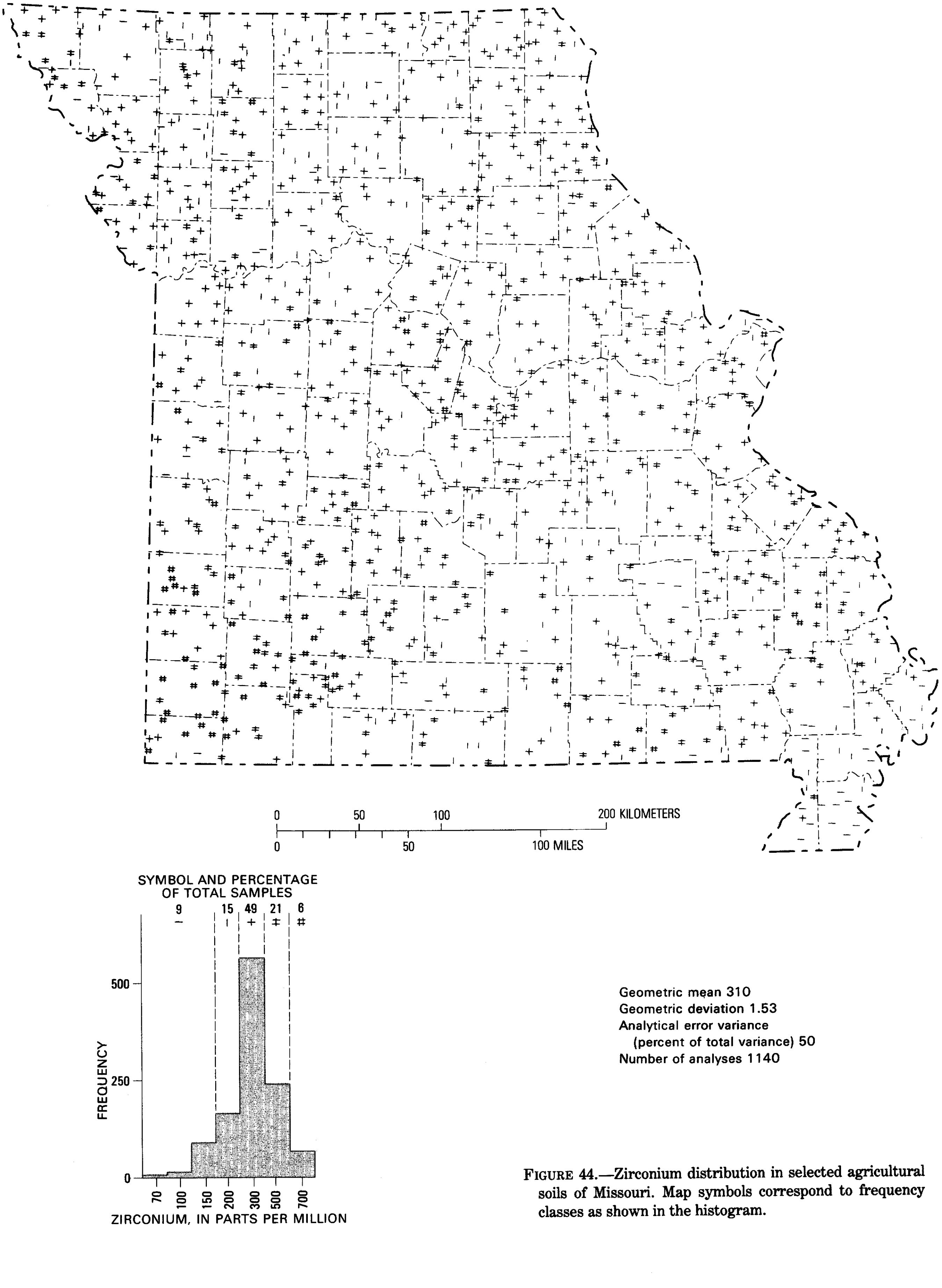
FIGURE 42.—Yttrium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.





Geometric mean 49
Geometric deviation 1.55
Analytical error variance
(percent of total variance) 3
Number of analyses 1140

FIGURE 43.—Zinc distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.



Geometric mean 310
Geometric deviation 1.53
Analytical error variance
(percent of total variance) 50
Number of analyses 1140

FIGURE 44.—Zirconium distribution in selected agricultural soils of Missouri. Map symbols correspond to frequency classes as shown in the histogram.

Geochemical Classification by Factor Analysis of Missouri Agricultural Soils

By RONALD R. TIDBALL

GEOCHEMICAL SURVEY OF MISSOURI

GEOLOGICAL SURVEY PROFESSIONAL PAPER 954–I

A multivariate study of agricultural soils from 1140 locations in Missouri by Q*-mode and* R*-mode factor analysis*

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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GEOCHEMICAL SURVEY OF MISSOURI

GEOCHEMICAL CLASSIFICATION BY FACTOR ANALYSIS OF MISSOURI AGRICULTURAL SOILS

By RONALD R. TIDBALL

ABSTRACT

Samples of 1140 agricultural soils from the State of Missouri were classified according to similarity of chemical composition by factor analysis. The samples were classified into four groups by *Q*-mode analysis using an oblique rotation. The factors are interpreted as clay, resistate, glacial material, and silica.

R-mode analysis was used to identify the suite of elements associated with each group of samples. Lithium, iron, and several trace elements are associated with the clay factor; lithium and iron are likely structural elements but adsorption is also a dominant mechanism especially for the trace elements. Zirconium, titanium, ytterbium, and yttrium are associated with the resistate factor. The alkalies and alkaline-earth elements and aluminum are associated with the glacial factor; feldspars are more abundant in this material. Silicon and zironcium are the principal elements associated with the silica factor.

Extreme samples in each group represented soils that were developed from (1) shale and clay alluvium, (2) residuum of limestone of Mississippian age, (3) loess, glacial till, and outwash, and (4) residuum of dolomite of Late Cambrian to Early Ordovician age.

INTRODUCTION

Samples of 1140 agricultural soils from throughout the State of Missouri were analyzed for total element concentrations. The geographic variations in the concentrations of each element are illustrated on maps in a companion paper (Tidball, 1984). With over 40 maps that represent individual elements it was most difficult to define associations among samples of similar composition or to suggest common origins or soil-forming processes. Clearly a multivariate approach that can examine the variations in all of the elements simultaneously was needed.

In this report, *Q*-mode factor analysis is used to classify the samples by defining the interrelationships or similarities between the samples on the basis of element concentrations. The assemblage of elements associated with each group of samples is determined by *R*-mode factor analysis. The extreme types of samples are characterized by their composition and by their probable mineralogy. The identity of the *Q*-mode factors is deduced from the geographic distributions of the sample-vector loadings.

ACKNOWLEDGMENTS

Soil samples were obtained through the cooperation of the Statewide staff of the Extension Division of the University of Missouri under the supervision of Dr. Walter F. Heidlage, Program Coordinator, Extension Environmental Health. Chemical analyses of all samples were done by the U.S. Geological Survey in Denver, Colorado and Reston, Virginia by the following: L. A. Bradley, semiquantitative spectrograph; Johnnie Gardner and Violet Merritt, magnesium, and sodium; I. C. Frost, G. T. Burrow, and G. D. Shipley, carbon; J. P. Cahill, cadmium; J. A. Thomas, lithium and zinc; J. S. Wahlberg, M. W. Solt, and Mike Brown, X-ray fluorescence; R. L. Turner, mercury; F. W. Brown, Joseph Budinsky, B. A. McCall, Leung Mei, and Roosevelt Moore, arsenic and fluorine; A. J. Bartel, iodine; A. J. Bartel, E. Brandt, J. P. Hemming, R. J. Knight, H. T. Millard, R. J. Vinnola, R. J. White, uranium and thorium. Computer programs for mechanical plotting were written by M. R. Mall. Discussions with A. T. Miesch concerning the use and interpretations of his computer programs for factor analysis are gratefully acknowledged.

SAMPLES

Methods of sample collection and methods of laboratory analyses were described previously (Tidball, 1984). The soil samples, which represent the plow zone (A horizon, 0–15 cm in depth), were collected in each of the 114 counties of the State at the rate of 10 per county. In most counties, the sampling localities were scattered extensively throughout the county. The sample-vector-loadings maps illustrate the locations of the sampling sites.

The samples represent soils that were developed from all of the major parent-material types that occur in the State. The glaciated terrain of the northern half of the State includes glacial till and loess (fig. 1) and outwash alluvium in the valleys of the Missouri and Mississippi Rivers. Surficial material on the Mississippi Alluvial Plain is alluvium from both the Mississippi and the Ohio Rivers (Krusekopf, 1966). The Ozark Plateaus province is a very old, deeply weathered, nonglaciated land surface developed on cherty carbonate rocks. The northern flanks of the plateaus near the southern limit of glaciation support a mantle of loess that diminishes in thickness toward the south.

Q-MODE FACTOR ANALYSIS

The general methodology and application of factor analysis in the geological sciences was reviewed by Jöreskog, Klovan, and Reyment (1976). The method of *Q*-mode analysis used here is the conventional form as described by Miesch (1976a, b, c) for use with geochemical and petrological data. *Q*-mode analysis was chosen as a tool for this study because one of its uses is that of classifying a large number of samples into a minimum number of common assemblages, particularly where each sample has numerous measured properties and where the genetic significance of those properties is unknown. The operational objectives of *Q*-mode analysis are (1) to determine the minimum number of end members (extreme sample types), (2) to find the compositions of the end members, and (3) to describe the proportions of each end member that are mixed in each sample. These proportions (sample loadings) become a new multivariate property of each sample that when mapped illustrate the geographic components that are associated with each end member.

It will be helpful to view each sample initially as a mixture of a number of actual or theoretical end members equal to the number of chemical properties measured. Several of these properties are probably correlated with each other because of one or more common controlling mechanisms. In a more concise model, therefore, the number of end members required to describe a given amount of variation in the data can be reduced to a much smaller number than the original number of properties.

Samples, for which a large number of properties (variables), M, have been determined, can be represented as vectors with a common origin in M-dimensional space where each dimension is represented by a reference axis (factor). It is common when numerous samples are so represented that the sample vectors tend to cluster into a space that can be described by fewer dimensions, m. The factors represent the compositions of theoretical end members. As each sample may be viewed as a mixture of the end-member compositions, so each sample vector is a linear combination of the end-member vectors (factors). The location of each sample vector in space is specified by the coordinates (loadings) of the vector as projected on each factor.

Factors that are orthogonal to each other are uncorrelated. That is, if two orthogonal factors each represent particular processes, then the two processes are independent of one another. If the factors are not orthogonal, then the processes are interdependent. A factor may be viewed as the end member of a mixture series or as a type sample for a classification system. The hypothetical composition of the factor (expressed in normalized units of measurement) is specified by inital factor "scores." The locations of the factors in relation to the sample vectors determine the magnitude of the factor scores, which appear in a scores matrix, F_{MM}. When the sample vectors are projected onto the factors, the initial loadings of the sample vectors become fixed and constitute the loadings matrix, A_{NM} (where N is the number of samples, M is the number of variables). According to the general *Q*-mode analysis model these two matrices are related to the normalized data matrix, Z_{NM}, with m equal to M,

$$Z_{NM} = A_{NM}F_{MM}, \tag{1}$$

but it is also possible to estimate Z_{NM} with fewer than M variables, that is, m is less than M,

$$\hat{Z}_{NM} = A_{Nm}F_{mN} \tag{2}$$

In either case, equations 1 and 2 estimate the normalized data matrix, Z_{NM}, which is not in the original units of measurement rather than the original data matrix, X_{NM}, which is in original units. Miesch (1976b) described a procedure whereby X_{NM} could be estimated,

$$\hat{X}_{NM} = P_{Nm}C_{mN}, \tag{3}$$

by transforming A_{Nm} to P_{Nm}, a matrix of sample-vector composition loadings and F_{mN} to C_{mN}, a matrix of com-

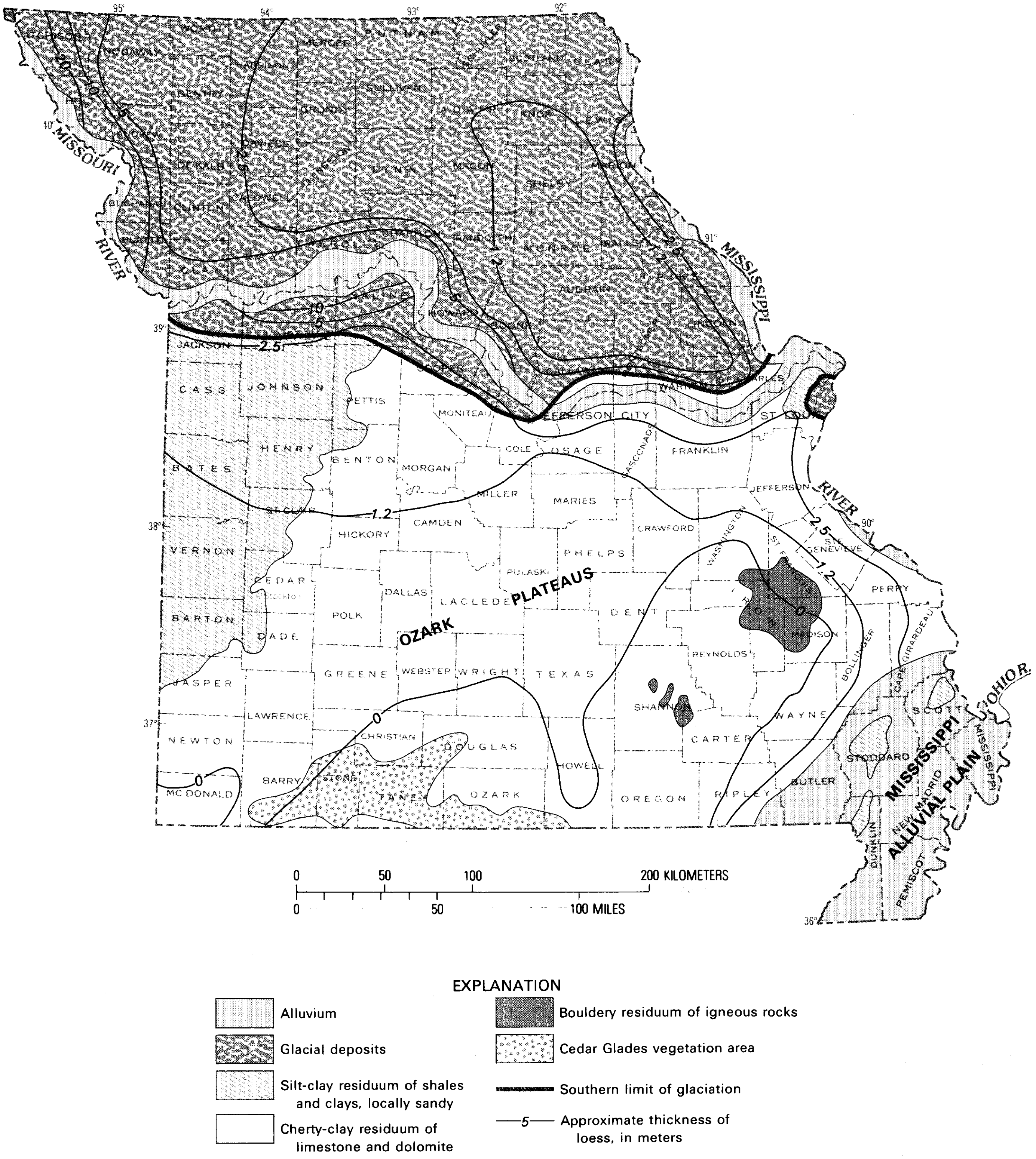
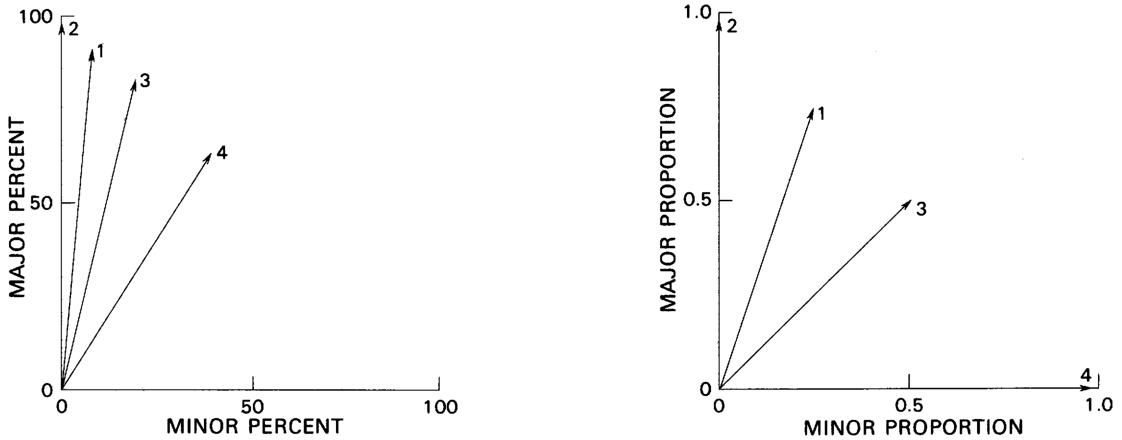
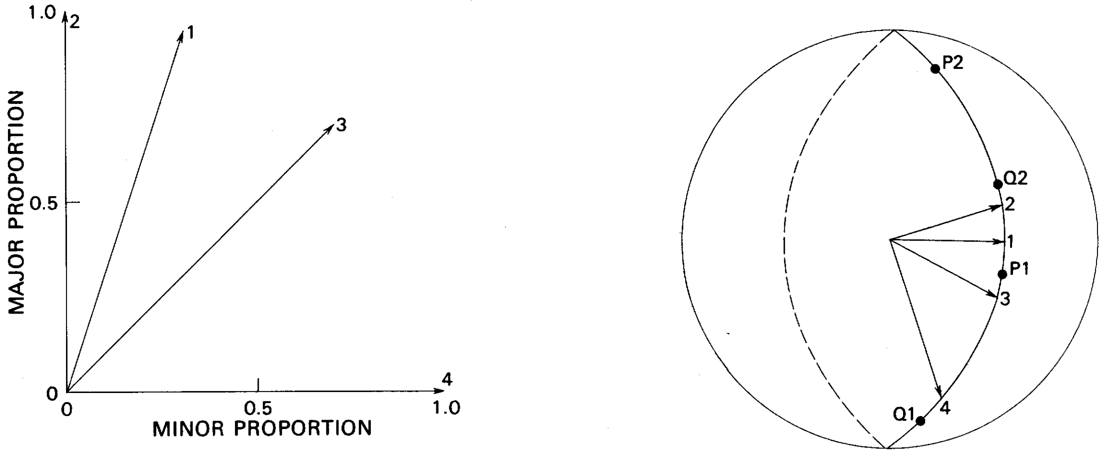


FIGURE 1.—Surficial deposits of Missouri (Stout and Hoffman, 1973; Küchler, 1964).



A. Original data

B. Scaled data



C. Normalized scaled data

D. Spherical projection (PI, principal components axis; QI, oblique axis)

FIGURE 2.—Geometry of sample vectors for different forms of the same hypothetical data.

position scores. P_{Nm} is derived by a transformation of A_{Nm} that fixes the signs of the loadings and changes them into true proportions that sum to unity across the rows. C_{mN} is derived through a transformation of F_{mN} that restores the original units of measurement to the scores. Recalling the operational objectives of *Q*-mode analysis stated previously, C_{mN} fulfills objective 2 and P_{Nm} fulfills objective 3.

The original chemical data are expressed as oxides and adjusted to sum to a constant of 100 percent for each sample (each row of the data matrix is one sample). Miesch (1976b) showed that the constant row-sum is desirable to be able to derive a *Q*-mode model in terms of the original data. The data are then transformed first, by columns (scaling) and second, by rows (normalizing). These transformations are illustrated by means of hypothetical data as shown in table 1, and the resulting geometry of the sample vectors for these data appears in figure 2.

The original data matrix, X_{NM}, in table 1*A* is scaled

TABLE 1.—*Methods of transformation with hypothetical data*

A. Original data, X_{NM} = matrix of x_{ij} values in *i*th row and *j*th colum

Samples = $N = 4$, Variables = $M = 2$.

	Oxides, percent		
Samples	Major	Minor	Row sum
1	90	10	100
2	100	0	100
3	80	20	100
4	60	40	100
$xmax_j$	100	40	
$xmin_j$	60	0	

B. Scaled data

$$x'_{ij} = (x_{ij} - xmin_i)/(xmax_j - xmin_j)$$

1	0.75	0.25	1.0
2	1.0	0	1.0
3	.5	.5	1.0
4	0	1.0	1.0

C. Normalized scaled data, Z_{NM} = matrix of x''_{ij}

$$x''_{ij} = x'_{ij}/(\sum_j x'^{2}_{ij})^{1/2}$$

			Row-sum squares
1	0.95	0.32	1.0
2	1.0	0	1.0
3	.71	.71	1.0
4	0	1.0	1.0

to range from zero to one within each column, as shown in table 1*B*, where x_{ij} is expressed as a proportion of the range. The purpose of scaling is to equalize the weighting of the variables so that oxides present in large amounts (major) do not have an inordinate effect on the factor model. Scaling has the effect of spreading out the original cluster of sample vectors; vectors 2 and 4, for which the samples each contain the largest amounts of the major and minor elements, respectively, now coincide with a factor. (See figs. 2*A* and 2*B*.)

The scaled data are then row normalized by dividing each scaled value, x'_{ij}, in the row by the square root of sum of squares for the row giving the matrix Z_{NM} in table 1*C*. The purpose of normalizing is to adjust the sample vectors to unit length (fig. 2*C*). The comparison of vectors is now more convenient because of being able to compute the communalities (communality equals the square of the vector length after projection into a smaller *m*-space). The diagram of sample vectors in figure 2*C* can also be viewed as a slice of a sphere as in figure 2*D*. The locations of the first two principal-components factors (Jöreskog and others, 1976, p. 74) are shown at *P*1 and *P*2; oblique factors, *Q*1 and *Q*2[1], are shown at one of many possible locations. These factors will be discussed later.

COMPOSITIONAL MODEL OF MISSOURI SOILS

Analyses of 31 elements were initially included in the factor analysis. These were aluminum*[2], arsenic, barium*, boron*, calcium*, carbon, chromium*, cobalt*, copper*, fluorine, gallium*, iron, lanthanum*, lead*, lithium*, magnesium*, manganese, mercury, nickel*, phosphorous, potassium*, scandium*, silicon*, sodium*, strontium*, titanium*, vanadium*, yttrium*, ytterbium*, zinc, and zirconium*. The ranges of concentration for most of the elements are well within the limits of determination of the analytical method that was used; that is, the elements have uncensored frequency distributions. The lower end of the ranges for a few elements, however, is less than the lower limit of determination of the method, and some of the values are indeterminate (censored). Where the number of censored values is small, they were replaced with arbitrarily small values (equal to 0.7 times the lower limit of determination) to complete the frequency distribution.

The analytical values of each element were expressed in percent of the common oxide except fluorine and mercury, which are assumed to occur in the soils either in ionic or in elemental form. All the values were first adjusted to a common sum of 100 percent, and then the data were scaled and normalized as described previously.

The minimum number of end members (fulfills objective 1), *m*, is determined from the factor-variance diagram (fig. 3), which is a plot of the proportion of variance accounted for (coefficient of determination from Miesch, 1976b, p. G19) against the number of factors in the model. Factors that explain the variation in several variables simultaneously are called common factors (Harman, 1967, p. 15; Miesch, 1976b, p. G21). A unique factor explains a large part of the remaining variance (including error) in only one variable. Conventionally, the factor model is simplified by retaining only the common factors.

The common factors may be very effective in describing the variance of some variables but ineffective for certain others. In order to enhance the effectiveness of the final model, after an initial computation those

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[1] Labels of *Q*1 and *Q*2 distinguish factors in demonstration from QI, QII, and so forth used later in actual factor model, but the concept remains the same.

[2] Elements with asterisk were retained in the final factor analysis after omitting elements that were poorly described by the factor model.

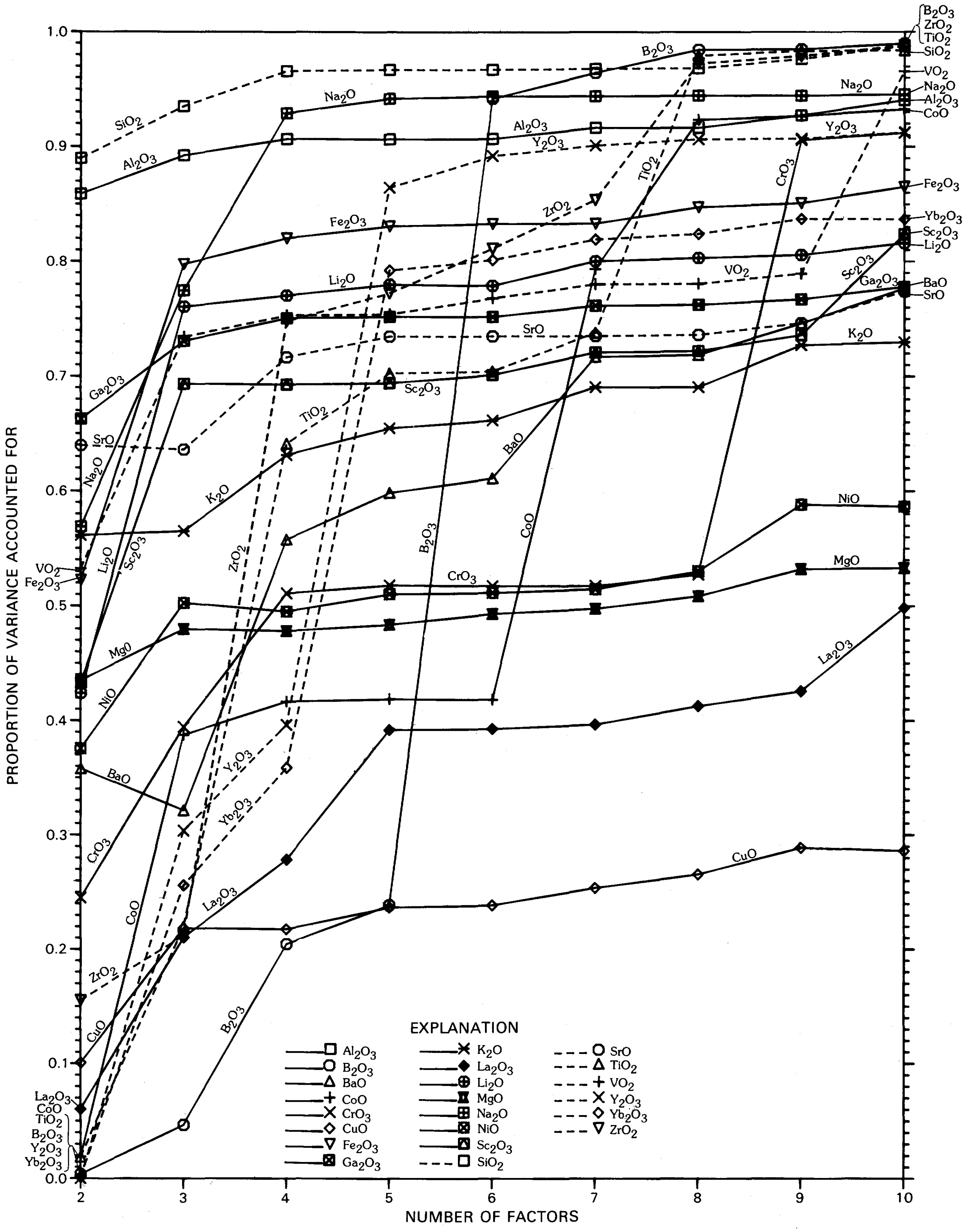

FIGURE 3.—Factor variance diagram for 22 oxides in Q-mode factor analysis.

oxides that were poorly described were removed to eliminate the possiblity of spurious or accidental effects. The criteria that were adopted for retaining an oxide were that (1) the variation in the data had to reflect mostly (arbitrarily set at 50 percent) natural variation rather than analytical error, and (2) the variation that was explained had to be on the common factors. Excess analytical error was the basis for most of the omissions (table 2). A total of 22 elements were retained for further analysis. (See footnote 2.) The factor-variance diagram in figure 3 indicates that four factors accommodate most of the variables explaining an average of 60 percent of the total variance. The few variables that are not well explained by four factors generally require numerous additional factors.

A factor model was derived initially using the varimax criterion in which the factors are orthogonal. The four sample vectors of most extreme composition were then identified (Miesch, 1976, p. G22). Because the composition scores of the varimax factors contain numerous negative values and were judged, therefore, to be unrealistic, an oblique model was derived by moving the factors to nonorthogonal positions that are very close to the extreme sample vectors, respectively. The compositions of the factors were then more nearly equivalent to those of nearby sample vectors which facilitates the interpretations of the factors. The oblique composition scores, C_{mN}, are given in table 3.

TABLE 2.—*Total and natural variation explained by a preliminary 4-factor model of Q-mode factor analysis and analytical error variance of Missouri agricultural soils*

[Values, percent. Asterisk (*), variable is included in the final factor analysis]

Oxide	Analytical error	Proportion of variance explained by the factor model	
		Total	Natural[1]
SiO_2	26	94	100*
Na_2O	2	92	94*
Al_2O_3	10	88	98*
Fe_2O_3	4	78	81*
VO_2	43	77	100*
Sc_2O_3	39	76	100*
Li_2O	4	75	78*
SrO	31	73	100*
Ga_2O_3	27	73	100*
ZrO	61	67	100*
K_2O	5	64	67*
TiO_2	48	60	100*
BaO	45	59	100*
MgO	5	55	58*
NiO	39	48	79*
CrO_3	38	46	74*
Y_2O_3	54	45	98*
CoO	49	44	86*
Yb_2O_3	63	40	100*
La_2O_3	51	35	71*
As_2O_3	17	31	37
MnO	17	27	33
CaO	4	26	27
CuO	56	25	57*
B_2O_3	76	24	100*
CO_2	3	24	25
ZnO	4	19	20
SeO_2	68	15	47
P_2O_5	20	8	10
F	89	3	27
PbO	56	1	2
Hg	65	1	3

[1] Percentage of natural variation explained is normalized to natural base:

$$\frac{\text{Total variance, pct}}{(100 - \text{anal. error, pct})} \times 100 = \text{natural variance explained, percent.}$$

TABLE 3.—*Oblique composition scores,* C_{mN}, *from Q-mode factor analysis of Missouri agricultural soils*

[Values in parts per million, except as noted in percent]

Oxide	Factors			
	Q-I	Q-II	Q-III	Q-IV
Al_2O_3, percent	19.7	5.0	10.6	3.0
B_2O_3	97	170	99	76
BaO	950	840	1040	170
CoO	34	18	6.8	7.2
CrO_3	240	140	110	30
CuO	59	15	14	7.9
Fe_2O_3, percent	9.2	2.3	2.8	1.2
Ga_2O_3	45	11	20	4.3
K_2O, percent	2.7	1.6	2.7	.79
La_2O_3	95	69	46	25
Li_2O	130	40	43	30
MgO, percent	1.7	.12	.68	.061
Na_2O, percent	.71	.51	1.7	.16
NiO	60	11	22	7.4
Sc_2O_3	33	10	11	5.4
SiO_2 percent	65.2	89.0	80.9	94.5
SrO	280	98	270	21
TiO_2, percent	.58	1.1	.45	.28
VO_2	370	97	120	20
Y_2O_3	75	68	28	24
Yb_2O_3	6.0	5.9	2.7	2.3
ZrO_2	-49	1200	360	190

RESIDUALS

Residuals represent the discrepancies between the original compositions of the samples, $\hat{X}_{NM}$, and the reproduced compositions, X_{NM}, as computed from the factor model by equation 3. Thus residuals serve as measures of how well the factor model represents the samples. The matrix of residuals, R_{NM}, is computed as,

$$R_{NM} = X_{NM} - \hat{X}_{NM} \cdot \qquad (4)$$

Even though four factors account for only 60 percent of the variation, the residuals for all samples were found to be small. Because the factor model is represented in fewer dimensions than the original data was, the residuals are associated with all of the unspecified factors that were omitted. To insure that none of the unspecified factors had an important and overlooked systematic geographic component, the residuals for all samples were plotted on maps (not shown here). The maps exhibit a more or less random pattern indicating that a systematic component is absent. Analytical error and sampling error are examples of random components.

NAMING THE FACTORS

The identity of each factor was judged by the character of the extreme sample vectors that lie close to the oblique factor. Character in this sense implies sample composition, sample locality, parent material, and inferred mineralogy. The original compositions of the 10 most extreme sample vectors for each factor are given in tables 4–7 in order of decreasing distance away from the factor. The scores will differ slightly from the original compositions of the most extreme sample vectors because the factors were projected into a space of fewer dimensions than that of the original data.

Within each sample group, the sample vectors have similar compositions and the samples were collected from similar sites or parent materials. Descriptive notes for each sample group are given in table 8.

Factor I represents a composition with comparatively large amounts of nearly all of the heavy metals plus Al_2O_3, Fe_2O_3, K_2O, and MgO, but a comparatively small amount of SiO_2. Sample vectors close to factor I represent soils developed from clayey alluvium that occurs on the flood plains of the major rivers, the Missouri and the Mississippi. The sample of the most extreme vector was collected from a soil developed from a black shale of the Chattanooga Formation. Factor I is, therefore, named the "clay factor."

Factor II represents a composition with comparatively large amounts of B_2O_3, SiO_2, TiO_2, and ZrO_2, and nearly all other oxides occur in intermediate concentrations. Sample vectors close to factor II represent soils on upland sites that were developed from cherty residuum of limestone in the Kaskaskia sequence that occurs in southwest Missouri. These strata range in age from Middle Devonian to Late Mississippian (Connor and Ebens, 1980). Factor II is named the "resistate factor."

Factor III represents a composition that is similar to that of factor I in terms of some oxides such as B_2O_3, BaO, K_2O, SrO, and TiO_2. There are comparatively large amounts of Na_2O and SiO_2 but all other oxides have concentrations equal to one-half or less of factor

TABLE 4.—*Original compositions of the 10 most extreme sample vectors near to factor Q–I*

[Sample vectors arranged in order of increasing distance from the factor. Values in parts per million, except as noted in percent]

Oxide	Sample vectors									
	D146417	D145447	D146005	D146278	D145813	D145956	D145610	D146518	D145457	D145734
Al_2O_3, percent	18.8	16.5	16.2	16.8	14.5	15.6	16.6	16.8	14.8	15.2
B_2O_3	120	76	120	120	110	120	120	54	180	100
BaO	420	920	970	940	870	940	930	940	640	850
CoO	24	22	16	23	21	23	15	11	22	21
CrO_3	170	160	170	160	150	160	160	120	150	150
CuO	47	44	110	110	70	75	45	30	28	20
Fe_2O_3, percent	6.7	6.4	7.1	6.1	6.3	6.5	5.9	6.6	6.5	5.7
Ga_2O_3	51	32	33	32	30	32	32	24	31	22
K_2O, percent	5.6	2.9	3.4	3.0	3.0	2.8	3.3	2.5	2.7	2.5
La_2O_3	74	97	73	70	65	98	98	99	93	89
Li_2O	89	120	99	120	110	100	100	110	110	98
MgO, percent	2.3	1.2	1.7	1.6	1.6	1.2	2.0	1.2	.92	1.1
Na_2O, percent	.23	.70	.78	.84	.77	.79	.80	.71	.81	.72
NiO	110	45	48	46	99	76	30	31	43	41
Sc_2O_3	29	27	29	28	26	28	27	18	26	25
SiO_2, percent	65.6	71.0	70.0	70.9	72.6	72.3	70.4	71.3	73.1	74.0
SrO	150	280	300	280	200	210	420	210	200	190
TiO_2, percent	.63	.98	.62	.60	.93	.60	.59	.60	.95	.54
VO_2	310	290	300	290	270	290	290	200	280	270
Y_2O_3	48	75	47	46	71	76	45	46	72	69
Yb_2O_3	4	4	4	4	6	7	4	4	4	4
ZrO_2	120	240	250	160	300	490	240	110	310	150

TABLE 5.—*Original compositions of the 10 most extreme sample vectors near to factor Q–II*

[Sample vectors arranged in order of increasing distance from the factor. Values in parts per million, except as noted in percent]

Oxide	Sample vectors									
	D145511	D145912	D145892	D145987	D146292	D145985	D145973	D145952	D145968	D145889
Al_2O_3, percent	5.59	6.09	5.28	6.18	5.37	6.02	5.55	7.81	7.03	6.42
B_2O_3	180	260	170	110	104	180	190	190	110	100
BaO	870	640	830	380	600	870	650	900	920	840
CoO	10	15	20	15	14	21	10	15	22	20
CrO_3	150	110	100	150	150	150	160	160	160	100
CuO	10	43	13	22	20	14	22	29	29	13
Fe_2O_3, percent	1.9	2.4	3.1	5.6	2.6	2.7	2.8	2.8	3.6	2.8
Ga_2O_3	11	11	10	15	10	15	11	15	16	10
K_2O, percent	1.6	1.8	1.6	1.3	1.3	2.0	1.6	2.0	1.4	1.6
La_2O_3	66	67	87	67	63	65	68	94	69	38
Li_2O	46	57	48	52	46	53	50	52	56	51
MgO, percent	.27	.32	.24	.30	.22	.29	.24	.34	.33	.29
Na_2O, percent	.39	.33	.38	.33	.48	.46	.39	.52	.42	.36
NiO	10	15	20	22	7	21	10	22	15	14
Sc_2O_3	12	12	11	12	12	12	12	12	13	11
SiO_2, percent	88.7	87.8	88.0	85.1	88.6	87.3	88.2	85.4	85.9	87.1
SrO	93	95	87	95	89	92	96	95	97	89
TiO_2, percent	1.3	.96	1.2	.96	1.3	.93	.96	.96	.98	1.2
VO_2	91	94	120	190	120	130	94	130	130	120
Y_2O_3	71	100	67	100	68	99	73	73	74	41
Yb_2O_3	4	9	6	9	6	9	7	7	7	4
ZrO_2	110	110	100	110	100	110	110	110	110	100

TABLE 6.—*Original compositions of the 10 most extreme sample vectors near to factor Q–III*

[Sample vectors arranged in order of increasing distance from the factor. Values in parts per million, except as noted in percent]

Oxide	Sample vectors									
	D146327	D146480	D145523	D145455	D146575	D146042	D146524	D146089	D145873	D146554
Al_2O_3, percent	9.55	9.62	11.9	9.89	11.1	6.87	10.7	8.25	8.63	12.5
B_2O_3	100	48	100	110	110	49	48	76	100	110
BaO	120	84	121	86	120	85	84	92	60	89
CoO	9	7	10	10	10	7	7	10	10	10
CrO_3	61	62	150	150	110	42	41	68	62	110
CuO	20	9	14	14	21	10	13	10	14	21
Fe_2O_3, percent	2.5	2.2	2.9	2.6	3.3	1.4	2.8	2.5	2.7	3.3
Ga_2O_3	21	14	22	22	22	10	10	24	22	23
K_2O, percent	2.7	2.5	2.7	2.5	2.9	2.1	2.6	2.1	2.6	2.8
La_2O_3	87	38	63	39	39	38	38	41	38	40
Li_2O	41	41	51	45	60	19	51	36	39	61
MgO, percent	.71	.90	.88	.90	1.1	.27	.75	.92	.64	1.6
Na_2O, percent	1.6	1.5	1.6	1.6	1.5	1.4	1.3	1.6	1.5	1.5
NiO	20	20	27	21	28	21	14	30	21	43
Sc_2O_3	11	8	12	12	12	6	11	13	12	12
SiO_2, percent	82.1	82.7	79.2	81.7	79.3	87.6	81.5	84.0	83.4	77.6
SrO	630	250	260	260	260	190	190	140	190	270
TiO_2, percent	.53	.36	.54	.55	.56	.27	.27	.39	.36	.57
VO_2	120	87	180	130	130	53	87	96	88	130
Y_2O_3	40	27	41	28	42	21	20	30	21	43
Yb_2O_3	4	2	4	4	4	2	2	3	2	4
ZrO_2	220	430	440	300	230	220	140	240	220	230

TABLE 7.—*Original compositions of the 10 most extreme sample vectors near to factor Q–IV*

[Sample vectors arranged in order of increasing distance from the factor. Values in parts per million, except as noted in percent]

Oxide	Sample vectors									
	D146537	D146569	D146399	D146229	D145828	D145533	D146550	D145750	D146237	D145958
Al_2O_3, percent	3.28	2.31	4.31	3.16	3.10	2.15	2.09	3.12	3.25	3.92
B_2O_3	70	74	69	100	100	100	67	100	110	110
BaO	183	193	181	176	230	240	180	170	240	250
CoO	7	3	4	9	9	4	9	7	10	28
CrO_3	42	160	62	41	30	31	100	40	31	32
CuO	10	10	9	13	13	13	7	9	9	28
Fe_2O_3, percent	1.1	1.5	2.3	1.6	1.3	.75	1.6	1.2	1.1	1.5
Ga_2O_3	5	5	5	5	5	5	5	5	5	5
K_2O, percent	.55	.46	.65	.42	1.3	1.1	.42	.83	1.3	.56
La_2O_3	38	41	38	37	36	<35	37	37	38	39
Li_2O	24	17	42	27	29	23	22	34	28	29
MgO, percent	.13	.10	.15	.18	.18	.18	.10	.12	.18	.17
Na_2O, percent	.12	.13	.14	.12	.12	.19	.10	.19	.22	.15
NiO	10	7	10	13	20	10	9	7	7	21
Sc_2O_3	6	<4	8	6	6	6	6	6	6	6
SiO_2, percent	94.5	95.1	92.0	94.1	93.5	95.2	95.3	93.9	93.5	93.3
SrO	26	41	38	37	37	38	37	37	38	40
TiO_2, percent	.27	.29	.36	.35	.35	.36	.35	.52	.36	.37
VO_2	27	28	53	51	34	26	34	34	35	36
Y_2O_3	21	15	27	40	26	21	26	20	21	43
Yb_2O_3	2	1	2	4	2	2	2	2	2	4
ZrO_2	220	230	220	210	210	290	420	210	220	230

I. Sample vectors close to factor III represent soils developed either from sandy or silty alluvium on the major river flood plains or from loess. It is probable that the prominent deposits of loess that occur on the bluffs along the river valleys are the source of at least part of this type of alluvium. Factor III is named the "glacial factor" because the samples distinctly outline (fig. 6) the glaciated terrain and deposits of glacial outwash.

We see there are some differences between the oblique composition scores of factors I and III (see table 3) but some similarities in the sites (flood plains) of the extreme samples that are associated with each factor. The differences are believed to be due to the mineralogical compositions: samples near factor I contain about 60 percent clay minerals, 30 percent quartz, and 10 percent feldspar; samples near factor III contain about 25 percent clay minerals, 50 percent quartz, and 25 percent feldspar. (Percentages were derived from X-ray diffraction analysis.) These feldspars surely explain the relatively large Na_2O and K_2O scores of factor III.

Factor IV represents the lowest concentrations of all the oxides except SiO_2 and ZrO_2. Sample vectors close to factor IV represent soils on upland sites that were developed from cherty residuum of dolomite of the Sauk sequence (mostly Jefferson City Formation) that ranges in age from Late Cambrian to Early Ordovician (Connor and Ebens, 1980). This residuum is the most thoroughly weathered material in the study area as suggested by the highest concentration of SiO_2 and the lowest concentrations of most other elements. Factor IV is named the "silica factor." The large concentration of SiO_2 represented by both factors II and IV reflects the contribution of chert, which is a significant constituent of the residuum.

OBLIQUE COMPOSITION LOADINGS

The oblique composition loadings, P_{Nm}, are too numerous to tabulate but are plotted as gray-level symbol maps in figures 4–7. The frequency distributions of loadings for each factor were divided into five classes with approximately 20 percent of the loadings being placed in each class. A symbol identifying each sample appropriate to the class of its loading is plotted on the

TABLE 8.—*Descriptive notes for extreme samples near to each Q-mode factor*

Sample Number	County	Site	Parent material	Other remarks[1]
		Samples associated with factor Q-I		
D146417	McDonald	upland	black shale	Chattanooga Shale.
D145447	Bates	flood plain	alluvium	Osage silt.
D146005	Mississippi	do	do	Mississippi Alluvial Plain, Sharkey clay.
D46278	do	do	do	Do.
D145813	do	do	do	Do.
D145956	Lewis	do	do	Mississippi valley.
D145610	Saline	do	do	Missouri valley, Wabash clay.
D146518	Grundy	do	do	Glaciated area, probable Sarpy series.
D145457	Livingston	do	do	Do.
D145734	Pike	do	do	Missouri valley.
		Samples associated with factor Q-II		
D145511	McDonald	upland	cherty residuum of limestone	
D145912	Lawrence	do	do	
D145892	Newton	do	do	
D145987	do	do	do	
D146292	do	do	do	
D145985	Dade	do	do	
D145973	Barry	do	do	
D145952	Lawrence	do	do	
D145968	Greene	do	do	
D145889	do	do	do	
		Samples associated with factor Q-III		
D146327	Jackson	do	probable loess	
D146480	Ray	flood plain	alluvium	Missouri valley, Sarpy very fine soil.
D145523	Mississippi	do	do	Mississippi Alluvial Plain.
D145455	do	do	do	Missouri valley, probable Sarpy series.
D146575	Platte	do	do	Missouri valley, Sarpy sandy loam.
D146042	Dunklin	terrace	do	Mississippi Alluvial Plain, Dexter fine sandy loam.
D146524	Pemiscot	flood plain	do	Mississippi Alluvial Plain, probable Sarpy series.
D146089	Holt	terrace	loess	Missouri valley.
D145873	Pemiscot	flood plain	alluvium	Mississippi Alluvial Plain, probable Sarpy series.
D146554	Perry	do	do	Mississippi valley, probable Sarpy series.
		Samples associated with factor Q-IV		
D146537	Ripley	upland	cherty residuum of dolomite	Probable loess mixture.
D146569	Reynolds	do	do	
D146399	Texas	do	do	
D146229	Carter	do	do	
D145828	Douglas	do	do	
D145533	Ozark	do	do	
D146550	Cedar	do	sandstone	Krebs Formation (Pennsylvanian).
D145750	Oregon	do	cherty residuum of dolomite	
D146237	Douglas	do	do	
D145958	Dent	do	do	

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[1] Soil series name given when known; for example Osage silt.

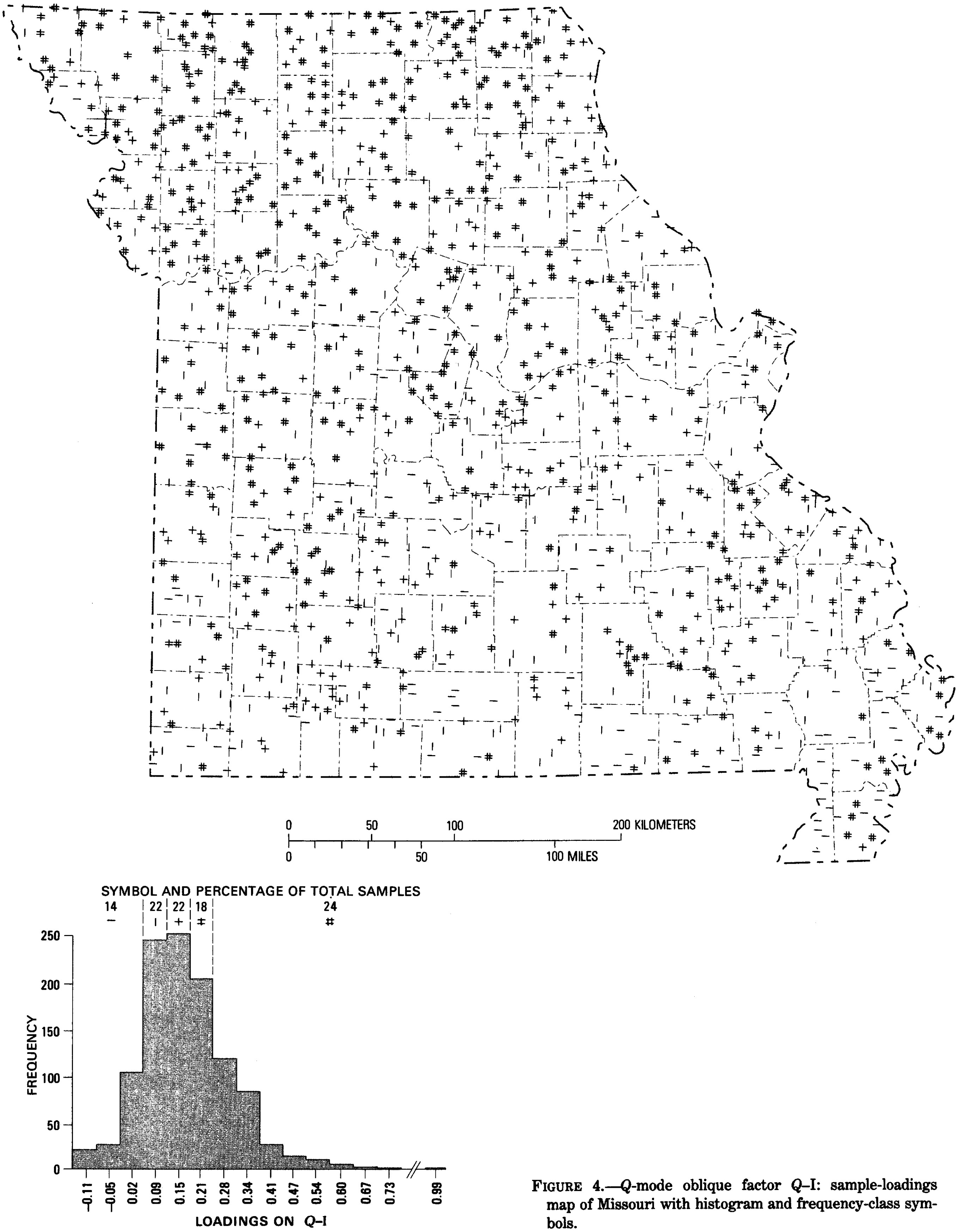
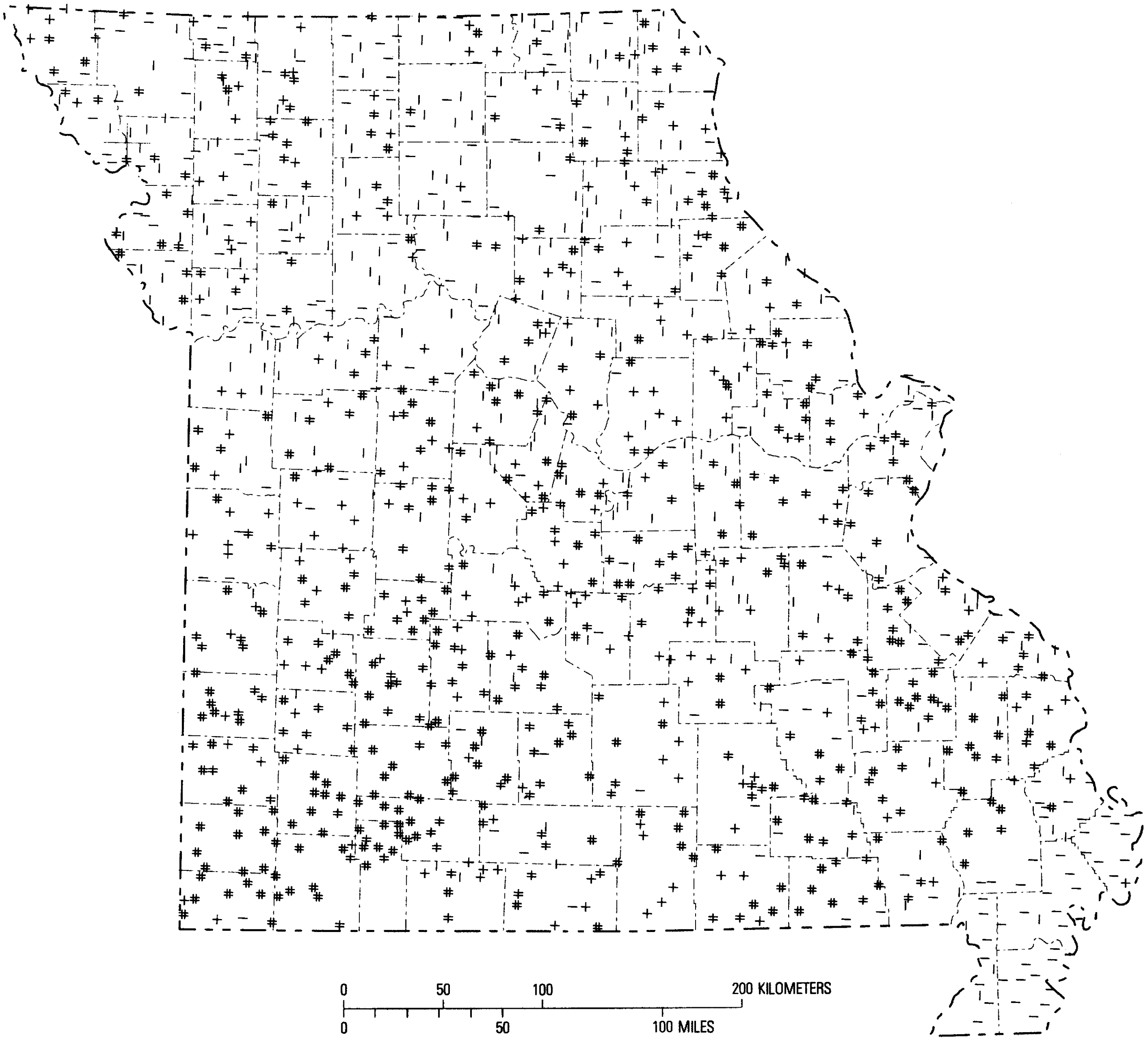


FIGURE 4.—Q-mode oblique factor Q-I: sample-loadings map of Missouri with histogram and frequency-class symbols.



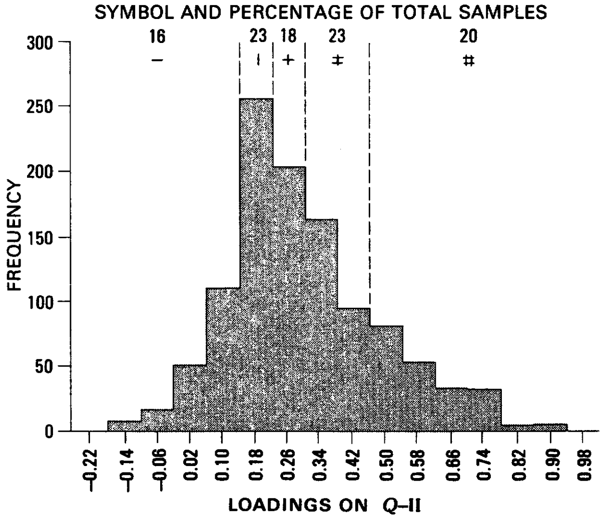
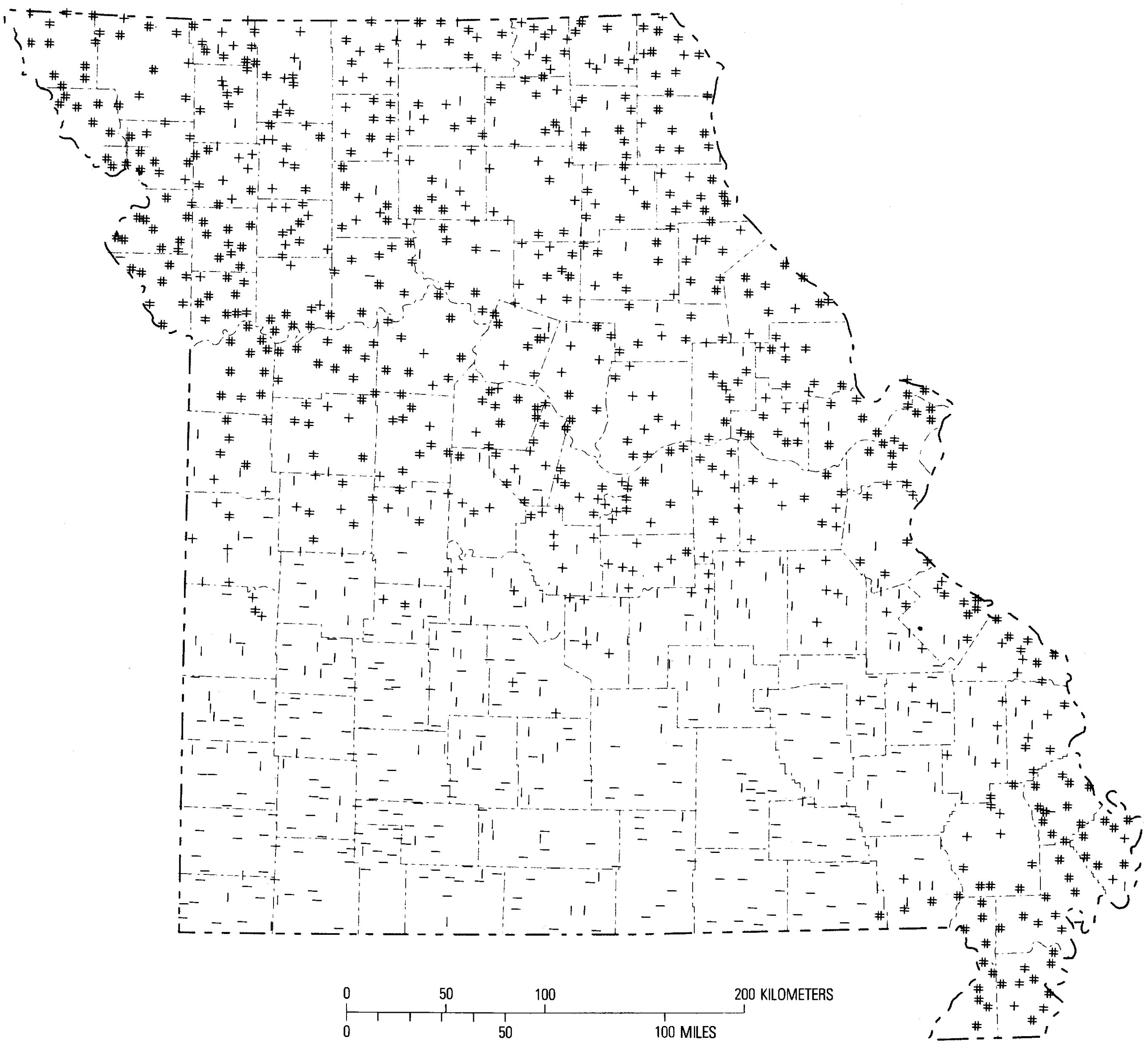


FIGURE 5.—*Q*-mode oblique factor *Q*-II: sample-loadings map of Missouri with histogram and frequency-class symbols.



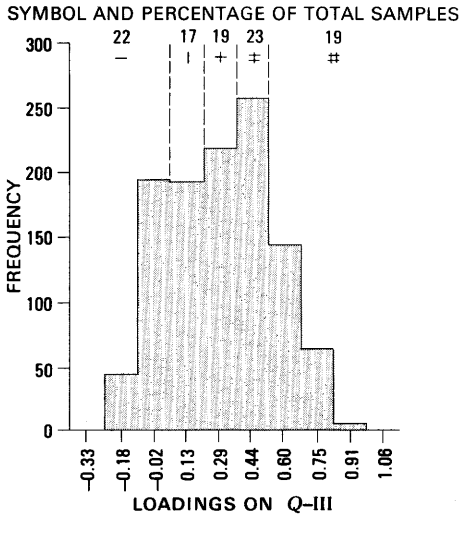
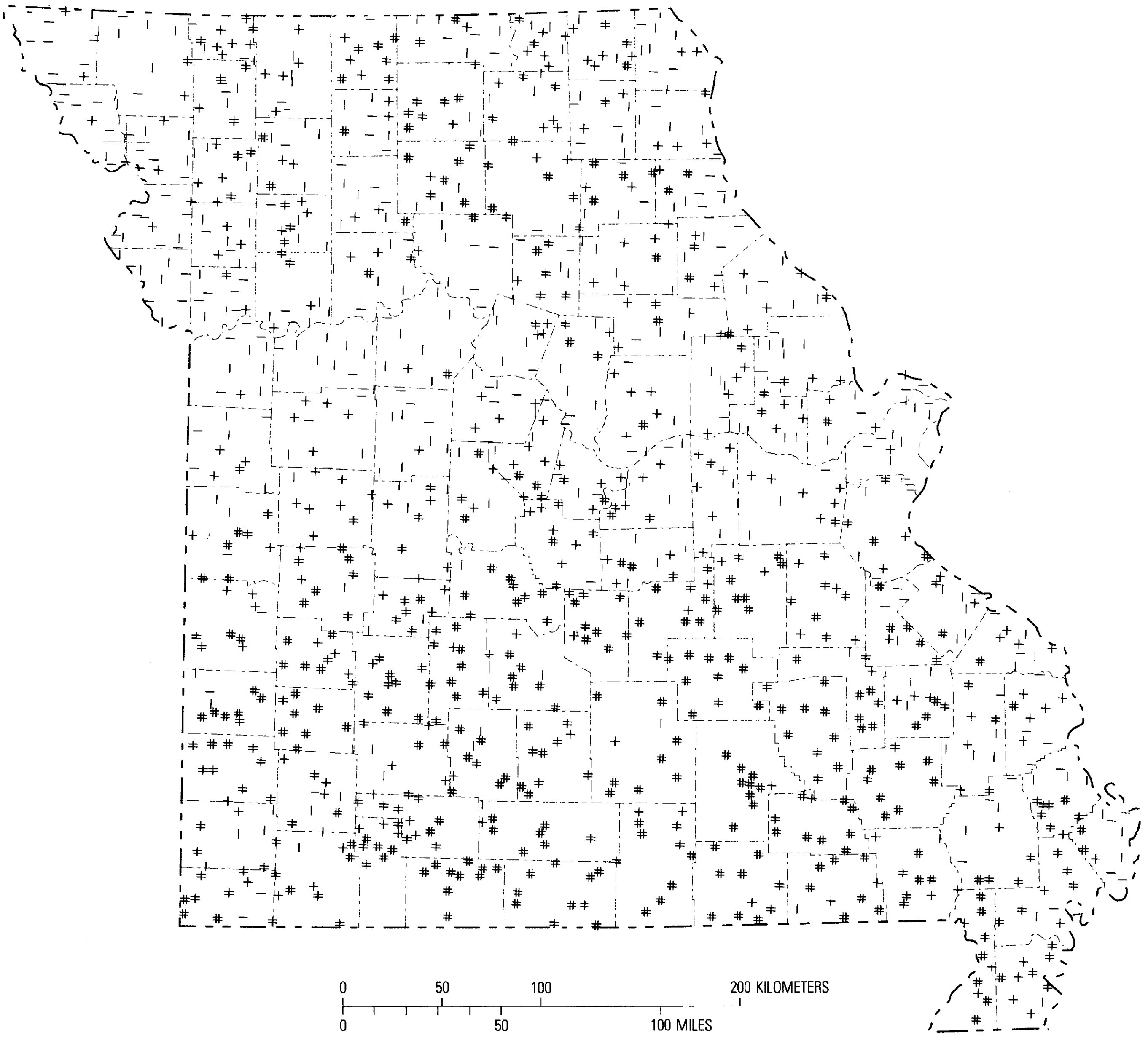


FIGURE 6.—*Q*-mode oblique factor *Q*–III: sample-loadings map of Missouri with histogram and frequency-class symbols.



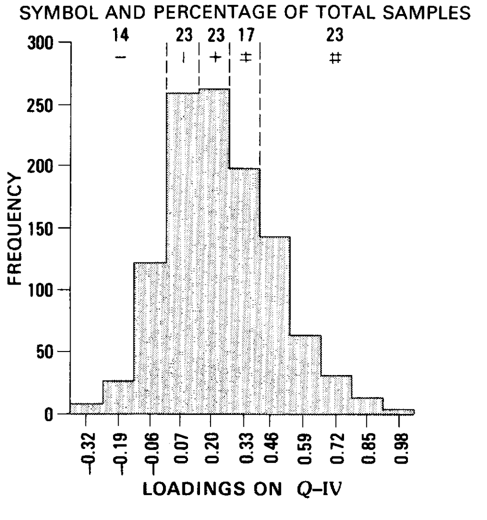


FIGURE 7.—*Q*-mode oblique factor *Q*–IV: sample-loadings map of Missouri with histogram and frequency-class symbols.

map at the location of collection. The maps, therefore, illustrate the locations of samples and their degree of similarity in composition to that of the factor.

Samples closely associated (large loadings) with the clay factor (I) exhibit a wide distribution across several types of parent material, although the glaciated terrain of northern Missouri is slightly better represented than the nonglaciated terrain of southern Missouri (fig. 4). There must be some common feature throughout the region that results in a similar composition among soils that represent an apparent diversity of parent materials and possible contrasting ages. That common feature could be the widespread effect of loess superimposed over the effect of the residual parent materials.

Samples closely associated with the resistate factor (II) occur predominantly in southwest Missouri on cherty residuum of the Kaskaskia sequence (fig. 5). These soils contain moderately large amounts of SiO_2 (about 88 percent) and comparatively large amounts of TiO_2 (about 1.1 percent) and ZrO_2 (about 0.1 percent). Samples with dissimilar compositions occur on the Mississippi Alluvial Plain and throughout northwest Missouri and tend to be associated with factor III.

Samples related to the glacial factor (III) form the most distinctive distribution pattern of all the sample groups (fig. 6). The most closely related samples outline the Missouri and Mississippi River valleys and adjacent terrain where the most prominent deposits of loess and glacial outwash occur. Other samples with moderately large loadings fill in other parts of the glaciated terrain. This distribution pattern is markedly similar to that of the individual elements: aluminum, calcium, magnesium, potassium, sodium, and strontium, (Tidball, 1984). Samples that are not related to factor III define the area of the Ozark Plateaus and are related to factors II or IV.

Samples that are similar to the silica factor (IV) are largely confined to the Ozark Plateaus where cherty residuum of carbonate rocks occurs (fig. 7). Other similar samples in the Mississippi Alluvial Plain and in northern Missouri represent sandy alluvium or sandstone parent materials. Samples with compositions that are unrelated to factor IV are coincident with the prominent loess deposits and associated alluvium of northwest Missouri.

R-MODE FACTOR ANALYSIS

The *Q*-mode factors represent the compositions of the most extreme sample types, and they were named by interpretation of a small group of extreme sample vectors. Each sample group, however, includes sample vectors with compositions that diverge evermore from that of the factor until eventually a sample vector represents an intergrade of two or more factors. In order to determine the association of oxides that are unique to each of these more extended groups of samples, the associations of 1140 *Q*-mode sample loadings with the 22 chemical variables was expressed by a correlation matrix. With the inclusion of the *Q*-mode loadings as "new variables" in the data matrix, it was no longer closed. The chemical variables, except SiO_2, were transformed to logarithms (base 10) to achieve more nearly normal distributions. The correlation matrix served as input to *R*-mode factor analysis (Miesch, 1980, method 2), which was used to simplify the analysis and interpretation of the matrix. In *R*-mode analysis,

$$X_{NM} = P_{mN}\, C_{Nm} \tag{5}$$

which differs from equation 3 only by the subscripts, m and N. P_{mN} is the small matrix of loadings, and C_{Nm} is the large matrix of scores.

The eigenvalues and the eigenvalue ratios (Miesch, 1980, p. 532) for the first six factors are as follows:

No.	*Eigenvalues*	*Ratio*
1	11.7	0.45
2	4.61	.63
3	2.54	.73
4	1.05	.77
5	.77	.79
6	.74	.82

The ratios multiplied by 100 express the average cumulative percentage variance accounted for by each additional factor. A three-factor model with a varimax rotation was adopted.

In the varimax solution, the matrix of loadings, P_{mN}, is also a matrix of correlations between the varimax scores, C_{Nm}, and the variables. Correlations larger than 0.2 are shown in table 9. Under each *R*-mode factor all those variables with a large positive correlation tend to be associated or behave in a similar manner. Any one factor may represent a process that directly controls the amount of the oxide in the sample, and therefore the several variables with a large correlation on that factor all reflect a common controlling process. Some oxides with intermediate correlations are simultaneously controlled by two or more processes. Oxides with small correlations tend to behave more independently; the process represented by the factor has little effect on these oxides. A large negative correlation indicates that an oxide is still controlled by the process but the behavior is opposite to that of variables with positive correlations.

Under *R*–I the clay factor, *Q*–I, is positively associated with LiO_2, Fe_2O_3, and so forth, and most negatively associated with SiO_2. If the interpretation of *Q*–I as a clay factor is correct, then the abundance of the highly correlated oxides under *R*–I is very responsive

TABLE 9.—*Coefficients of correlation between* R-*mode sample scores and chemical values and* Q-*mode sample loadings*

[Only coefficients of correlation greater than 0.2 are given]

R-mode factors					
I		II		III	
Variable	Correlation	Variable	Correlation	Variable	Correlation
Q-I	0.98	Q-I		Q-I	
Q-II		Q-II	0.93	Q-II	
Q-III		Q-III		Q-III	0.92
Q-IV	-.33	Q-IV		Q-IV	-.81
Li_2O	.86	ZrO	.77	Na_2O	.93
Fe_2O_3	.85	TiO_2	.76	SrO	.84
Sc_2O_3	.80	Yb_2O_3	.67	K_2O	.78
VO_2	.75	Y_2O_3	.66	BaO	.74
Ga_2O_3	.69	B_2O_3	.56	Al_2O_3	.64
CaO	.68	La_2O_3	.46	MgO	.60
MgO	.68	Cr_2O_3	.41	Ga_2O_3	.54
Al_2O_3	.67	CoO	.40	VO_2	.43
NiO	.66	BaO	.27	NiO	.37
CoO	.57			Cr_2O_3	.33
Cr_2O_3	.55			SiO_2	-.62
Y_2O_3	.42				
La_2O_3	.42				
SrO	.38				
Yb_2O_3	.37				
SiO_2	-.73				
ZrO	-.27				

to the abundance of clays and suggests that either adsorption or crystalline structural positions are domininant. The "clays" include as reactive colloids, the clay minerals, organic matter, and the sesquioxides of Fe and Al that are common in oxidizing environments (Rose and others, 1979, p. 144) often as coatings on other mineral grains. The high correlation for Fe_2O_3 suggests that sesquioxides are a dominant part of the colloidal complex. Li^{+1} is a relatively mobile cation in the surficial environment (Rose and others, 1979, p. 24) and is often dispersed in clays (Norton, 1973, p. 366). Thus, the principal process of enrichment for Li^{+1} as well as the other trace oxides associated with *R*–I is probably adsorption (Krauskopf, 1967, p. 593). The large correlation for Sc_2O_3, however, may not relate to adsorption because Sc^{+3} is a relatively immobile cation (Rose and others, 1979, p. 24). Sc_2O_3 typically occurs as a trace constituent in the ferromagnesian minerals, pyroxenes, hornblendes, and biotites (Adams, 1973, p. 568); these minerals may be redistributed into sedimentary deposits where concentrations of Sc_2O_3 can exceed crustal abundance.

Under *R*–II the resistate factor (*Q*–II) is most highly associated with resistate-type oxides, ZrO_2, TiO_2, Yb_2O_3, and Y_2O_3. Minerals that could be present in the resistate-group of soils include zircon (ZrO_2), sphene (TiO_2, Yb_2O_3, Y_2O_3), tourmaline (B_2O_3), and ferromagnesian minerals (carriers of rare earths, La_2O_3 and Y_2O_3) (Adams and Staatz, 1973, p. 550). Although tourmaline contains B_2O_3, this oxide is also adsorbed from sea water onto argillaceous sediments (Deer and others, 1966, p. 96) that may be incorporated in some carbonate rocks.

Under *R*–III the glacial factor (*Q*–III) is most highly associated with the bases, Na_2O, SrO, K_2O, BaO, and MgO, and also with Al_2O_3; there is a negative association with SiO_2 and *Q*–IV. Most of these oxides are principal constituents of the feldspars including both the plagioclase series and the alkali feldspars. Barium may substitute for potassium in feldspar and mica-group minerals (Deer and others, 1966; Krauskopf, 1967), or it may be adsorbed to clays or occur as barite minerals (Brobst, 1973, p. 77). Most of the glacial material was probably derived from local source rocks, which would be chiefly sedimentary rocks of Pennsylvanian age and to a lesser degree cherty, interbedded limestone of Mississippian age. The dominant rocks of Pennsylvanian age, shales and sandstones of the Absaroka sequence, were found by Connor and Ebens (1980) to be enriched in many elements compared to limestones and dolomites.

The silica factor (*Q*–IV) is negatively associated with *R*–III and also to a minor extent with *R*–I. In both cases, SiO_2 is the dominant oxide, and ZrO_2 is a minor one under *R*–I. SiO_2 in samples of the *Q*–IV group occurs largely in the form of chert, a major component of the weathered residuum of carbonate rocks over much of southern Missouri. Otherwise, SiO_2 in samples of group *Q*–I occurs as small grains of quartz or as a component of silicate minerals.

DISCUSSION

Q-mode analysis has identified four extreme types of soils; and accordingly, all the soil samples may be classified as belonging to one of the four groups or as intergrades between groups depending on their degree of compositional similarity to that of the end members. Each end member represents a unique aggregation of constituents: these are the end products of not only particular mixes of original minerals but also differing duration of weathering.

The *R*-mode factor analysis indicates that a unique assemblage of oxides characterizes each group of samples. The basic pattern is that soils associated with relatively little weathered parent materials have relatively abundant amounts of alkali and alkaline-earth oxides (bases) and oxides of the aluminosilicates, Al_2O_3 and Fe_2O_3; resistate oxides, SiO_2, TiO_2, and ZrO_2 are present in minor amounts. Soils associated with highly weathered parent materials have an abundance of resistates and little or none of the bases and silicates.

Factors *R*–I and *R*–III represent the case of limited weathering where the presence of bases (positive association) is contrasted with the absence of resistates (negative association). The positive assemblage of *R*–I undoubtedly reflects the mechanism of adsorption which accounts for the inclusion of the several trace oxides. Adsorption may also apply to the positive assemblage of *R*–III, but a reservoir of primary minerals, such as the feldspars, may be a more important feature.

Factor *R*–II and negative associations of *R*–I and *R*–III represent the case of advanced weathering. Factor *R*–II is characterized by resistates and rare-earth oxides. Soils having this assemblage are derived mostly from residuum of limestones, calcareous shale, and sandstone of the Kaskaskia sequence of Mississippian age (Connor and Ebens, 1980). The assemblage of resistates associated with *R*–I and *R*–III, however, is found in soils developed from residuum of mostly dolomite of the Sauk sequence of Late Cambrian to Early Ordovician age (Connor and Ebens, 1980).

The results of this study based on the A horizons (or plow zone) of agricultural soils of Missouri may be compared to a study of the B horizons of 60 native soils of Missouri by Erdman, Shacklette, and Keith (1976, p. C19–C23). The samples of native soils were classified by *Q*-mode factor analysis with a varimax rotation, and four factors were interpreted as being related to parent material, although the samples were collected from within vegetation-type areas which often cross over parent-material types. Their factor-variance diagram suggests that perhaps five factors should have been selected, and the varimax factors had numerous negative scores. Their first factor, which they related to Al-rich parent materials on the prairies of northern and western Missouri (area of shales, sandstones, and limestones of Pennsylvanian age) is similar to the clay factor (*Q*–I). Their second factor, which represents silicon-rich compositions and was associated with cherty residuum of carbonate rocks in the Ozark plateaus, is similar to both the resistate (*Q*–II) and the silica factors (*Q*–IV). Their third factor represents soils developed from dolomitic rocks in the Cedar Glades vegetation area near the southern border of Missouri—there are no similar samples in the present study. Their fourth factor was related to a feldspathic- sand facies in the Mississippi Alluvial Plain and is vaguely similar in composition to the glacial factor (*Q*–III), but the distribution of the sample loadings is not at all similar. Their X-ray diffraction analysis of factor-four samples indicates feldspars rather than feldspathic minerals; feldspars were found in *Q*–III samples.

There are two widely occurring parent materials, loess and carbonate residuum, in which the contrasting duration of weathering has resulted in the two basic patterns of either limited or advanced weathering. The original compositions of these two parent materials are given by Ebens and Connor (1980). They sampled parts of the parent material from strata well below the soil profile and reported as follows: (1) the mineralogy of loess consists mostly of quartz and clay plus minor amounts of dolomite, potassium-feldspar, and plagioclase; (2) loess contains more of the bases, K_2O, Na_2O, MgO, CaO, strontium, and barium, and more boron and SiO_2 than residiuum; (3) residuum is comprised mostly of quartz and clay with the quartz being concentrated in large fragments of chert rather than being disseminated as small grains; (4) residuum contains larger amounts of Al_2O_3, Fe_2O_3, lithium and manganese than loess; and (5) there are about equal amounts of gallium, scandium, yttrium, ytterbium, and zirconium in these two parent materials.

Comparing the compositions of these two principal parent materials with those of the soils developed therefrom (Tidball, 1984), there are some marked reversals in the proportions of some elements as a result of soil development. The principal reversal is that of silicon: residuum parent material contains a smaller amount of silicon than loess parent material, but residuum soil contains a larger amount of silicon than loess soil. I believe that the reason is that the large fragments of chert, which are scattered as lenses throughout the residuum parent material, become concentrated in the soil profile as a resistant lag material; thus, the apparent proportion of silicon is increased. Residuum parent material contains nearly twice more Al_2O_3, Fe_2O_3, and lithium than loess parent material, but loess soils contain larger amounts of these elements than residuum soils. Loess is younger, less weathered, and less leached than residuum; thus, the original composition of the loess parent material—particularly in respect to calcium, potassium, magnesium, and sodium—is more nearly preserved in the soil.

EPILOGUE

As one travels throughout Missouri, it is soon apparent that regions with more chemically diverse soils also tend to exhibit the better looking farms and tend to produce a higher level of agricultural income (Missouri Crop and Livestock Reporting Service, 1972). Also, some evidence suggests that better health may be expected among people living on the more fertile soils (Albrecht, 1957, p. 102–103). One of the original motivations for conducting this study was to provide geochemical information toward understanding the role of the environment in the health and nutrition of animals and humans (Connor and others, 1972; Miesch, 1976c). Because diseases and premature mortality exhibit a geographic distribution (Sauer and Donnell, 1970), it is appealing to presume that soils may have a role (this is supported by an extensive literature, for example, Armstrong, 1962, 1964; Losee, 1962), but no significant relationship was found between soil composition and human-mortality rates in Missouri (Tidball and Sauer, 1975). Perhaps a more sensitive experiment using only the extreme soil types as identified by this study would provide an alternative conclusion.

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