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TECHNICAL NOTE

Criminalistics

Soil survey laboratory grain count data to substantiate the rarity of mineral grains in forensic soil reports of examination

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Abstract

The Natural Resources Conservation Service-Kellogg Soil Survey Laboratory has a large publicly available database of laboratory analyses of soil horizons collected from soil profiles largely from the United States. Among these soil properties are mineral grain counts from selected sand and silt fractions of soil horizons, performed by polarized light microscopy (PLM). These grain counts of over 20,000 fractions from 7534 sites provide a substantial reference that a forensic soil examiner could use to substantiate the rarity or commonness of a mineral species. The statement of the rarity or commonness of various minerals provide juries with additional context for the interpreting the results of a forensic soil comparison within the framework of a trial. The grain count data at specific locations can also be assessed to aid in soil provenance investigations, for cases where there are grain-counted sites in relevant locations. Two examples of application of these to data to soil evidence are included, one relating soil the rarity of a mineral (andalusite) to provide context in a soil comparison and one to aid in narrowing target regions in a soil provenance investigation.

KEYWORDS
forensic geology, grain counts, grain mount, minerals, petrographic microscopy, PLM, polarized light microscopy, soils, trace evidence

Highlights

- Soil survey mineral grain count data are compiled and culled for citation in soil evidence cases.
- Over 20,000 fractions from 7534 sites have mineral variety occurrence and count observations.
- Soil mineral rarity can be compared to soil evidence to provide context in reporting.
- These grain count data are applied to a soil comparison and a soil provenance case.

1 | INTRODUCTION

Microscopical examination of soil grains is central to the characterization of forensic soil evidence. Polarized light microscopy permits characterization of the optical properties of mineral grains and thereby identification of mineral species/classes. In addition, microscopy provides critical capacity for observing grain morphology that can indicate the history of crystallization, transport, and weathering.

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In a forensic soil comparison, for example, comparison of soil on a suspect's shoe to soil from a crime scene, the examiner will document soil characteristics that could provide exclusionary differences. Polarized light microscopy is one of several methods of soil examination that might be used in forensic soil comparison. If the features observed in the two soils are unusual/rare, then the probative value of the soil comparison is greater. Three particle types that strengthen a forensic soil comparison are anthropogenic particles, botanical components, and distinctive mineral particles. These distinctive mineral grains could be a common mineral that exhibits unusual morphology or could be a mineral type that is either uncommon in soils in general or rare within an area of interest.

Most microscopical mineral studies focus on largely unweathered rocks in thin section, whereas forensic soil examinations typically characterize fine sand, which has been washed of its adhering clay coatings and mounted in refractive index oil (1). The populations and distribution of minerals in soils differ from rocks due to preferential weathering of some minerals and pedogenic formation of other minerals. Because of these differences, there are few large compilations of the frequency of soil minerals. The mineral grain count data reported by the USDA (United States Department of Agriculture) NRCS (Natural Resources Conservation Service) Kellogg Soil Survey Laboratory (KSSL) is analogous to the mineral grain characterization commonly generated for forensic evidence. This paper describes mineral grain count data in the KSSL database and its relevance for reporting the rarity of minerals in soils in forensic examination reports.

2 | METHODS

The NRCS KSSL offers soil mineral grain counts among their analytical services (2,3). Approximately 5% of soil horizons analyzed by the KSSL include mineral grain count data. Grain count data that have been validated by KSSL quality control processes and have associated site information with no specific restrictions are compiled in the National Cooperative Soil Survey Characterization Database (4,5). Within this database, the mineral grain count data are reported in the "MINERALOGY_PETRO" table.

2.1 | Laboratory methods

The MINERALOGY_PETRO table reports percent of grain types determined by polarized light microscopy (PLM) or petrographic microscopy. The KSSL methods of sample preparation include removal of organic matter with hydrogen peroxide (H_2O_2), dispersing the sample, then washing sand and coarse silt grains of adhering particles. Particles are separated in size fractions by sieving (sand fractions) and by aqueous gravitational sedimentation (coarse silt fraction). The coarse silt (0.02–0.05 mm), very fine sand (0.05–0.1 mm), and fine sand (0.1–0.25 mm) from selected horizons are permanently mounted, unpolished, in epoxy with a refractive index of 1.54 (2,3). Minerals from one or more of these fractions (typically the most abundant fraction is selected) are identified by PLM analysis. The criteria for grain identification used by the KSSL are described in (3) and (6). This method of sample preparation is similar to most forensic examinations except that in forensic analysis, size fractionation might not be quantitative, mineral grains are seldom subjected to H_2O_2, and mineral grains are typically mounted in refractive index oils instead of epoxy to permit recovery of grains for additional analysis. Commonly, oils with refractive indices of 1.54 and 1.66 are used to aid in mineral identification and to enhance visualization of grain surface texture (1).

3 | DATA DESCRIPTION

The September 2018 version of the KSSL data is used in this paper. 20,776 grain-counted fractions comprise this version of the MINERALOGY_PETRO Table, but these data were filtered to remove 197 grain-counted fractions that *only* report glassy and non-specific grain types (GS-Glass, GC-Glass-Coated Grain, GA-Glass Aggregates, BG-Basic Glass, GM-Glassy Materials, NX-Non-Crystalline, PA-Palagonite, AR-Weatherable Aggregates, RA-Resistant Aggregates, OW-Other Weatherable Minerals, OT-Other, RE-Resistant Minerals, FM-Ferromagnesian Mineral, WE-Weatherable Mineral, OR-Other Resistant Minerals, MD-Resistant Mineraloids). The data discussed and summarized in this paper represent 20,579 grain-counted fractions. The standard method for PLM characterization by the KSSL is to systematically count a minimum of 300 grains. In addition to objectively counting grains, all slides are scanned for other grain varieties present, not already recorded in the grain count. These additional grain types are reported as a zero, to capture all of the grain varieties present within the fraction, even if they are sufficiently rare to be unobserved in the grain count (3). Fewer than 0.2% of the grain-counted fractions in the KSSL database include under 200 grains counted.

These 20,579 grain-counted fractions represent 20,190 unique horizons, reflecting that a small proportion of the samples include grain counts from multiple grain size fractions. These 20,190 horizons are from 7534 unique sites. Of these sites, 664 are outside of the United States (1854 grain-counted fractions) (Figure 1).

These samples are derived from a range of depths, represented in Figure 2. For most sites, grain counts are only performed on a limited section of the soil profile. This is commonly a representative subsurface layer prescribed by *Soil Taxonomy* (7) with the rationale that the layer is free from alteration such as tillage, addition of soil amendments, removals or additions by erosion or sedimentation. The great majority of the samples are from the coarse silt, very fine sand, and fine sand fractions (Table 1).

4 | RESULTS AND DISCUSSION

The rarity or commonness of mineral species in soil can be used to convey the importance of observing a mineral type in soil evidence.

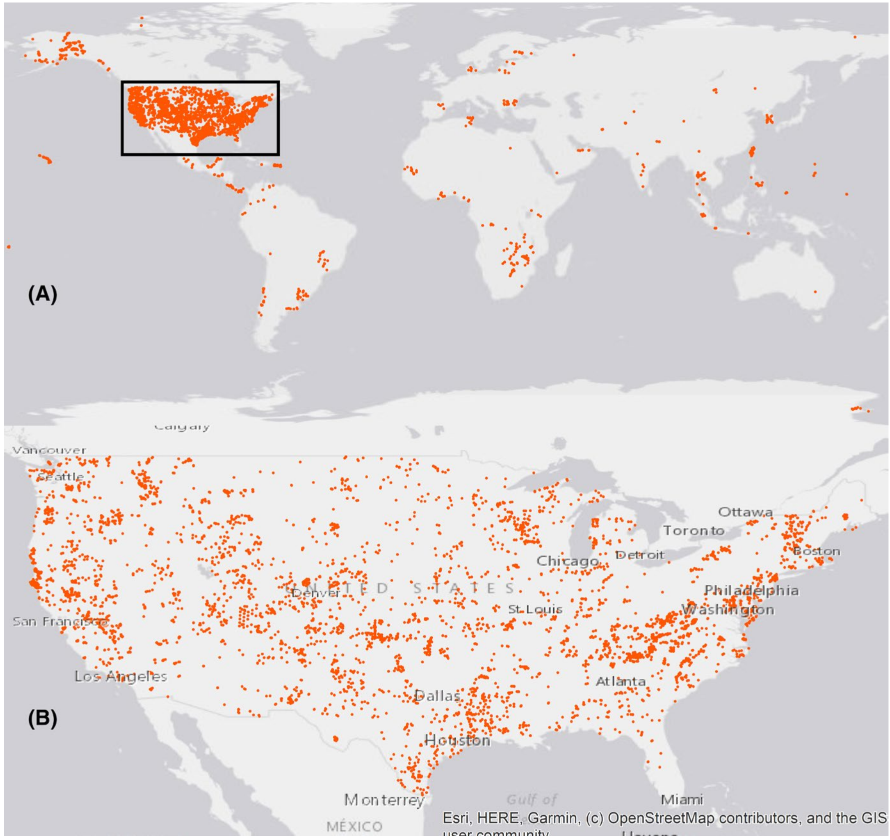

FIGURE 1 Locations where KSSL grain-counted soil horizons were collected, (A) globally and (B) within the conterminous USA [Color figure can be viewed at wileyonlinelibrary.com]

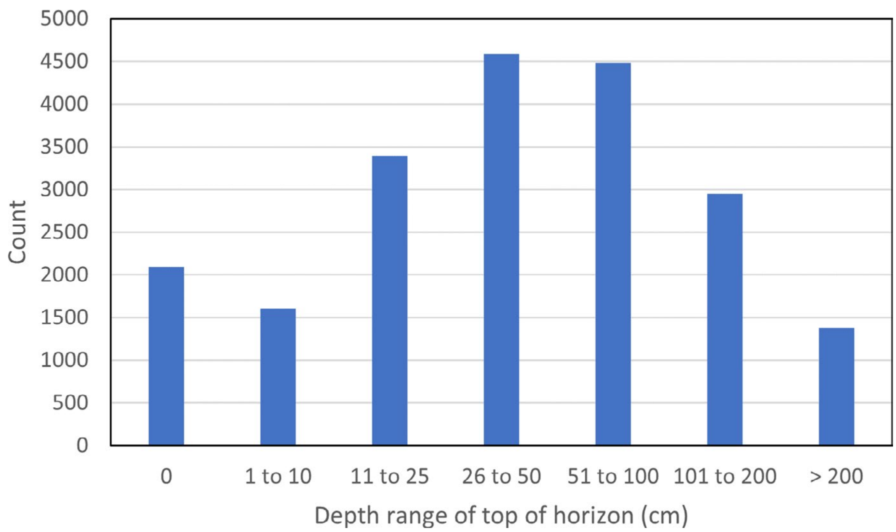

FIGURE 2 Distribution of depths of the top of the soil horizons among the grain mounts in the KSSL database [Color figure can be viewed at wileyonlinelibrary.com]

The grain counts in the KSSL database are summarized in the Appendix S1/Excel spreadsheet. The primary data have 169 categories, some of which are less relevant for application to forensic soil analysis (e.g., the category of "other weatherable minerals"), and other categories that are partially duplicative (e.g., a category of plagioclase and other categories that are varieties of plagioclase). To make the primary data from the KSSL more usable, some of the categories are removed or merged as shown in Table 2.

The frequency of observing these mineral varieties by polarized light microscopy in fine sand to coarse silt sized fractions of soil is visualized in Figure 3A,B. Table 2 and Figure 3 could be used in a forensic report of examination to substantiate the statement that a mineral is generally rare in soils. The KSSL-reported rarity of a mineral variety could strengthen the conclusion in a forensic soil comparison. For example, the observation of kyanite particles in soil on a suspect's shoes and at a crime scene would strengthen the forensic comparison, particularly if the soils at the suspect's residence and work site lack kyanite; kyanite is observed in only ~0.8% of the soils characterized by polarized light microscopy by the KSSL. Likewise, the *absence* of grain types like quartz, and perhaps potassium feldspar or opaque grains, could strengthen a forensic soil comparison as these grain types are extremely common in KSSL grain counts.

TABLE 1 Distribution of size fractions among the grain mounts in the KSSL database

Size fraction	Name of size fraction	% of grain-counted samples in this size fraction
0.02–0.05 mm	Coarse Silt	39.03
0.05–0.1 mm	Very Fine Sand	22.57
0.1–0.25 mm	Fine Sand	37.02
0.25–0.5 mm	Medium Sand	0.28
0.5–1 mm	Coarse Sand	0.02
1–2 mm	Very Coarse Sand	0.02
0.05–2 mm		1.01
0.02–2 mm		0.03
<2 mm		0.02

The population of soil horizons with grain counts in the KSSL database is a statistical sample of convenience, rather than representative statistical sample of soils for application to forensic soil reports. In an attempt to assess the sampling biases, the grain count data are segregated into subpopulations summarized in Table 2. These subpopulations are horizons with tops within 10 cm of the soil surface; soil horizons excluding those with *any* glassy grains; and excluding soils with volcanic parent material as indicated by notation as belonging to the Andisol soil order. The soil horizons nearer to the soil surface are often more relevant for the types of soils encountered in the majority of forensic scenarios.

The compilation of mineral occurrence frequency is of most use as reference data for forensic soil examinations. However, it may be useful to create a subset of these to make these data to a more case-pertinent based on the region, horizon depth, or other factors. A user can access a subset of the KSSL mineral grain data by using the primary data in the KSSL database (4,5), the appended spreadsheet, or by web enabled map by selecting the "sampled pedon," "Primary_Lab_Report" (8).

5 | LIMITATIONS OF THE KSSL GRAIN COUNTS FOR FORENSIC APPLICATIONS

The KSSL mineral grain count data are the largest collection of soil grain count data that we are aware of, and as such, are quite valuable for providing context for forensic soil examinations. However, there are some important limitations to this data set.

- Bias toward soils with glassy components: Several of the NRCS taxonomic distinctions require quantifying the proportion of glassy grains. For example, one criterion for andic soil properties is having greater than 5% glassy material by grain count, among other chemical and physical properties (7). The soil survey has a method for just counting glassy components and a separate table for reporting this, but there is still likely an over-representation of soils with glassy constituents in the data present in this paper, with ~45% of fractions reporting a glassy component. To assess the effects of this bias, Table 2 has a column of data, excluding grain counts in which a variety of glassy particle is observed and another excluding those with Andisol affiliation. There are additional uses of grain counts in USDA-NRCS soil taxonomy relating to percent of quartz, percent micas, and proportion of resistant minerals, and these too could overrepresent certain soils in the KSSL database over the general population of soils.
- Project-driven biases: The soils characterized in the KSSL and those subjected to grain counts may be motivated by specific local or regional project needs. Reasons for sampling and analyzing a particular site may be to acquire specific information to classify a soil within Soil Taxonomy (7), or to make a practical interpretation for use and management of a soil for agronomic, engineering, or environmental applications. There is no overall scheme to randomize or otherwise produce a statistically representative database; however, because of the time and expense of conducting a complete soil characterization analytical suite, there is a general goal of selecting representative sites. These sites may represent extensive areas, or they may represent unique previously unsampled areas. Therefore, the sites and horizons subjected petrographic grain counts are not a randomized statistical sampling of any soil population. Moreover, the specificity of mineral variety categories (e.g., FD-feldspar, FK-potassium feldspar, FC-microcline) might have been dictated by project-specific requirements, potentially limiting the utility of the narrowest mineral variety categories.
- The U.S. National Cooperative Soil Survey and the KSSL efforts are strongly focused on the soils in the United States and, therefore, the mineral frequencies may be less relevant for other regions with parent material or chemical weathering regimes that are dissimilar to the soils of the United States.
- Minerals that are rare in general may be common within the area of interest: The compilation of mineral occurrence frequency in Table 2 is objective, despite the likely bias in sampling. But for forensic reports of examination, it is critical to recognize that a mineral that is generally rare may be common within the area(s) of interest for a particular case. Therefore, if using the mineral frequency data reported in this paper for supporting the rarity or commonness of a mineral variety, it is important to assess reference data on the geology and soils of the area of interest, including the KSSL mineral data specifically for the area of interest, and local studies and maps of the surficial geology.
- Forensic soil examinations may include density separation and microscopical examination of the high density "heavy" minerals. The mineral grain proportions in the KSSL database are not directly relevant to the mineral grain observed in the heavy mineral fraction of soils, but because all minerals observed are recorded, the presence of rare heavy minerals is represented in the tabulated data.
- Analytical Biases: Alternative methods of mineral identification within soil evidence, for example by scanning electron microscopy (SEM-EDS), Raman microscopy, or X-ray diffraction (XRD), have differing abilities to differentiate among mineral species/classes than polarized light microscopy. Therefore, to apply the frequency of

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TABLE 2 Summary of grain counts in the KSSL database. The grain categories are listed in decreasing frequency of occurrence. Some categories are binned to create potentially more relevant categories for forensic soil examinations

Grain category[a]	Subcategory[b]	Code[c]	% with any, all depths[d]	% with any,[d] top within 10 cm	% with any,[d,e] those with glass excluded	% with any,[d,f] no Andisols	Mean %[g]
Quartz			97.84	97.41	98.54	98.51	
	Quartz	QZ	97.80	97.30	98.53	98.49	53.96
	Iron-Coated Quartz	QI	5.78	6.08	6.58	5.91	0.20
	Clay-Coated Quartz	QC	3.09	3.59	3.67	3.05	0.14
	Glass-Coated Quartz	QG	1.51	3.24	0.00	1.07	0.02
Opaques			86.91	87.59	82.80	86.77	
	Opaques	OP	84.41	84.59	81.11	84.49	1.61
	Glass-Coated Opaque	OG	1.47	3.24	0.00	0.96	0.01
Potassium Feldspar			85.69	85.24	82.64	86.70	
	Potassium Feldspar	FK	85.60	85.14	82.56	86.61	11.04
	Feldspar	FD	6.02	7.38	7.13	6.08	0.89
	Glass-Coated Feldspar	FG	4.28	8.68	0.00	3.25	0.13
	Microcline	FC	1.40	2.16	1.51	1.45	0.01
	Sanidine	FS	0.20	0.46	0.05	0.21	0.01
	Orthoclase	FR	0.03	0.05	0.05	0.03	0.00
Biotite			77.25	78.49	68.33	77.62	
	Biotite	BT	76.84	78.19	67.91	77.22	4.04
	Vermiculite-Mica	VM	4.67	4.16	4.01	4.66	0.06
	Hydrobiotite	HB	2.66	2.97	1.56	2.65	0.04
	Vermiculite-Hydrobiotite	VH	0.82	0.84	0.51	0.83	0.01
	Phlogopite	PL	0.23	0.08	0.38	0.24	0.00
	Biotite-Chlorite	BC	0.11	0.05	0.11	0.11	0.00
Pyroxene			71.99	76.54	60.12	71.35	
	Pyroxene	PR	71.55	75.70	59.86	71.02	1.42
	Enstatite	EN	0.60	0.49	0.46	0.59	0.00
	Hypersthene	HY	0.40	0.89	0.17	0.28	0.02
	Augite	AU	0.21	0.43	0.04	0.13	0.00
	Diopside	DP	0.06	0.11	0.05	0.07	0.01
Muscovite			71.44	70.22	64.30	72.25	
	Muscovite	MS	68.65	67.32	60.93	69.51	3.03
	Mica	MI	5.15	5.43	4.97	5.14	0.21
	Sericite	SR	1.14	1.19	0.81	1.16	0.05
	Illite (hydromuscovite)	IL	0.00	0.00	0.00	0.01	0.00
Hornblende			70.36	73.76	57.58	70.20	
	Hornblende	HN	63.70	67.95	50.81	63.46	1.06
	Amphibole	AM	12.86	12.11	11.21	12.95	0.15
	Lamprobolite	LA	2.11	2.05	0.81	2.05	0.01
	Glass-Coated Hornblende	HG	1.34	2.41	0.00	1.12	0.01

(Continues)

TABLE 2 (Continued)

Grain category[a]	Subcategory[b]	Code[c]	% with any, all depths[d]	% with any,[d] top within 10 cm	% with any,[d,e] those with glass excluded	% with any,[d,f] no Andisols	Mean %[g]
Iron Oxides			63.58	65.62	56.02	63.24	
	Iron Oxides (GE,HE,LM)	FE	61.21	63.78	53.31	60.81	2.88
	Hematite	HE	1.89	1.92	1.68	1.89	0.04
	Goethite	GE	1.43	0.95	1.77	1.48	0.07
	Schwertmannite	SI	0.37	0.22	0.45	0.39	0.00
	Limonite	LM	0.28	0.19	0.32	0.29	0.00
Plagioclase			57.58	64.54	41.73	56.58	
	Plagioclase	FP	57.37	64.49	41.44	56.36	2.94
	Albite	FB	0.18	0.00	0.31	0.19	0.02
	Oligoclase	FO	0.05	0.03	0.02	0.06	0.01
	Labradorite	FL	0.01	0.03	0.01	0.02	0.00
	Anorthite	FN	0.01	0.00	0.01	0.01	0.00
	Andesine	FA	0.00	0.00	0.01	0.01	0.00
Chert			55.49	56.24	48.28	56.21	
	Chalcedony (Chert)	CD	55.36	55.95	48.24	56.07	2.50
	Siliceous Aggregates		0.56	0.57	0.38	0.58	0.06
Zircon		ZR	50.76	49.16	44.75	51.72	0.06
Tourmaline		TM	44.36	47.35	38.74	44.59	0.05
Glass			43.64	59.05	0.00	42.01	
	Glass	GS	42.37	57.95	0.00	40.87	2.20
	Glass-Coated Grain	GC	10.73	18.59	0.00	9.19	0.23
	Glass Aggregates	GA	7.97	12.05	0.00	6.95	0.53
	Glassy Materials	BG	1.64	2.08	0.00	1.30	0.20
	Basic Glass	GM	0.87	1.65	0.00	0.68	0.04
	Non-Crystalline	NX	0.19	0.51	0.00	0.20	0.01
	Palagonite	PA	0.00	0.00	0.00	0.01	0.00
Garnet		GN	41.71	42.70	35.95	42.51	0.07
Plant Opal		PO	37.51	47.57	23.40	37.38	0.31
Calcite			28.27	27.76	24.94	29.12	
	Calcite	CA	24.77	24.62	21.69	25.53	1.86
	Carbonate Aggregates	CB	17.73	17.03	15.81	18.32	1.25
Beryl		BY	23.62	25.27	14.90	23.84	0.02
Chlorite		CL	22.05	22.32	17.81	22.40	0.29
Rutile		RU	18.08	15.38	15.88	18.55	0.01
Epidote		EP	12.87	11.32	12.44	13.04	0.07
Zeolite			10.45	12.38	4.95	10.62	
	Zeolite	ZE	10.39	12.27	4.94	10.56	0.06
	Analcime	LC	0.01	0.03	0.00	0.02	0.00
	Stilbite	ST	0.13	0.16	0.03	0.14	0.00
Monazite		MZ	8.00	9.65	4.90	8.04	0.00
Sponge Spicule		SS	5.96	7.65	2.05	5.93	0.01
Magnetite		MG	4.55	5.95	2.68	4.20	0.22

(Continues)

TABLE 2 (Continued)

Grain category[a]	Subcategory[b]	Code[c]	% with any, all depths[d]	% with any,[d] top within 10 cm	% with any,[d,e] those with glass excluded	% with any,[d,f] no Andisols	Mean %[g]
Apatite			4.38	4.16	2.48	4.47	
	Apatite	AP	4.36	4.16	2.45	4.45	0.00
	Collophane	CO	0.02	0.00	0.03	0.02	0.00
Kaolinite		KK	4.02	3.62	5.00	3.80	0.22
Cassiterite		CT	3.76	3.92	3.01	3.74	0.00
Sphene		SP	3.70	3.46	3.68	3.82	0.01
Foraminifera		FF	2.61	2.00	2.02	2.69	0.02
Cristobalite		CR	2.60	3.84	0.45	2.51	0.06
Feldspathoids			2.26	3.41	0.77	2.20	
	Feldspathoids	FZ	2.20	3.35	0.71	2.13	0.02
	Nepheline	NE	0.07	0.08	0.06	0.07	0.00
Diatoms		DI	2.14	3.43	0.58	2.10	0.02
Tremolite		TE	2.04	1.89	1.17	2.02	0.00
Zoisite		ZO	1.59	1.92	0.98	1.59	0.00
Chlorite-Mica		CM	1.47	0.92	0.73	1.50	0.02
Andalusite		AN	1.27	1.43	0.85	1.25	0.00
Gypsum		GY	1.09	1.22	1.22	1.13	0.08
Talc		TA	1.01	0.70	0.53	1.00	0.04
Glauconite		GL	0.84	0.54	1.12	0.87	0.02
Kyanite		KY	0.79	0.84	0.81	0.78	0.00
Piemontite		PD	0.76	1.00	0.27	0.75	0.01
Sillimanite		SL	0.700	0.84	0.576	0.72	0.003
Spinel		SN	0.603	0.49	0.646	0.63	0.001
Pollen		PN	0.554	0.49	0.305	0.55	0.000
Aragonite		AO	0.525	0.54	0.480	0.54	0.023
Olivine			0.81	1.14	0.21	0.53	
	Olivine	OV	0.491	0.76	0.096	0.222	0.023
	Iddingsite	ID	0.321	0.38	0.113	0.313	0.005
Glaucophane		GO	0.481	0.49	0.314	0.469	0.000
Antigorite		KH	0.452	0.78	0.393	0.408	0.112
Halloysite		GI	0.437	0.38	0.340	0.434	0.151
Gibbsite		VR	0.355	0.46	0.288	0.333	0.051
Vermiculite		AG	0.350	0.27	0.201	0.297	0.011
Dolomite		DL	0.321	0.32	0.419	0.328	0.041
Leucoxene		LU	0.311	0.16	0.550	0.323	0.001
Staurolite		SO	0.248	0.43	0.227	0.25	0.000
Corundum		CN	0.248	0.22	0.323	0.257	0.000
Coal		CC	0.199	0.16	0.227	0.207	0.009
Pyrite		PI	0.194	0.22	0.157	0.171	0.001
Sphalerite		SG	0.146	0.05	0.262	0.151	0.001
Cliachite (Bauxite)		CH	0.136	0.03	0.209	0.136	0.009
Vermiculite-Chlorite		VC	0.112	0.00	0.105	0.116	0.003
Clinozoisite		CZ	0.102	0.08	0.026	0.106	0.000
Chrysotile		CY	0.083	0.14	0.096	0.086	0.014

(Continues)

TABLE 2 (Continued)

Grain category[a]	Subcategory[b]	Code[c]	% with any, all depths[d]	% with any,[d] top within 10 cm	% with any,[d,e] those with glass excluded	% with any,[d,f] no Andisols	Mean %[g]
Actinolite		AC	0.083	0.14	0.105	0.086	0.008
Montmorillonite		MT	0.068	0.00	0.070	0.071	0.016
Anthophyllite		AH	0.058	0.03	0.096	0.060	0.003
Topaz		TP	0.058	0.03	0.052	0.060	0.000
Anhydrite		AY	0.044	0.11	0.035	0.045	0.013
Dumortierite		DU	0.044	0.08	0.026	0.045	0.000
Brucite		BR	0.029	0.00	0.035	0.030	0.000
Perovskite		PK	0.024	0.14	0.000	0.025	0.000
Magnesite		ME	0.015	0.00	0.026	0.015	0.000
Fluorite		FU	0.015	0.00	0.026	0.015	0.000
Galena		GG	0.015	0.00	0.017	0.015	0.000
Pyrophyllite		PY	0.015	0.03	0.026	0.015	0.000
Melilite		ML	0.010	0.00	0.000	0.010	0.000
Jarosite		JO	0.010	0.03	0.009	0.010	0.000
Sulfur		SU	0.005	0.03	0.000	0.000	0.000
Anatase		AE	0.005	0.00	0.009	0.005	0.000
Brookite		BK	0.005	0.00	0.009	0.005	0.000

The grain-counted fractions for which the horizon top is within 10 cm of the soil surface. The soils closer to the soil surface are more relevant for forensic soil cases that do not involve digging or excavated soils (n=3705).

[a]This table omits the following categories that lack the specificity to be more relevant: Weatherable Aggregates (AR), Resistant Aggregates (RA), Other Weatherable Minerals (OW), Other (OT), Resistant Minerals (RE), Ferromagnesian Mineral (FM), Weatherable Mineral (WE), Other Resistant Minerals (OR), Resistant Mineraloids (MD). Counts of these grain categories can be assessed in the KSSL database or in the Appendix S1.

[b]Subcategories are binned in the paper into the grain categories for select grain types. The fourth through seventh columns (% with any) tally only a single grain category when more than one of the subcategories of the same category are reported within a mineral fraction.

[c]These codes indicate the way these grain categories are recorded in the KSSL database.

[d]All columns indicated with "d" represent the percent of the grain-counted fractions containing any amount of the mineral variety, either among the counted grains or elsewhere on the microscopy slide.

[e]Grain-counted fractions, excluding those in which glassy components are observed (GS-Glass, GC-Glass-Coated Grain, GA-Glass Aggregates, BG-Basic Glass, GM-Glassy Materials, NX-Non-crystalline, PA-Palagonite, HG-Glass-Coated Hornblende, QG-Glass-Coated Quartz, FG-Glass-Coated Feldspar, OG-Glass-Coated Opaque). The purpose of this subset of the data is to de-emphasize the inherent bias in the data set toward volcanic soils. (n=11,465)

[f]Grain-counted fractions, excluding those designated as Andisols in samp_taxorder, corr_taxorder, or KSSL_taxorder fields. The purpose of this subset of the data is to de-emphasize the inherent bias in the data set toward volcanic soils. (n = 20,105)

[g]The mean % column is the average percent of each grain category, calculated by summing the reported grain percentages and dividing by the 20,587 grain fractions.

mineral observation from the KSSL database, derived from polarized light microscopy to mineral observation by alternative methods, the user should understand the limitation of each technique for mineral species identification. For example, SEM-EDS cannot differentiate among polymorphs, but may be better at distinguishing among mineral along solid solution series and XRD of bulk material has higher limit of detection than microscopy.

6 | EXAMPLE APPLICATIONS OF GRAIN COUNT DATA TO CASES

Two example applications of the KSSL grain count data to forensic soil cases are described here: the first simply cites of the compilation of the mineral occurrence frequency to substantiate the rarity of a mineral within soil evidence, and the second assesses the grain count percentages from sites near potential clandestine burial locations.

6.1 | Example 1, rare minerals observed in a soil comparison

Trace soil was extracted from four items at a suspect's home, two dirty socks recovered from a trash can and two digging tools. These soil samples were compared to soil samples recovered from a victim's clandestine grave (Table 3). The mineral grains were characterized, and their general abundance noted as

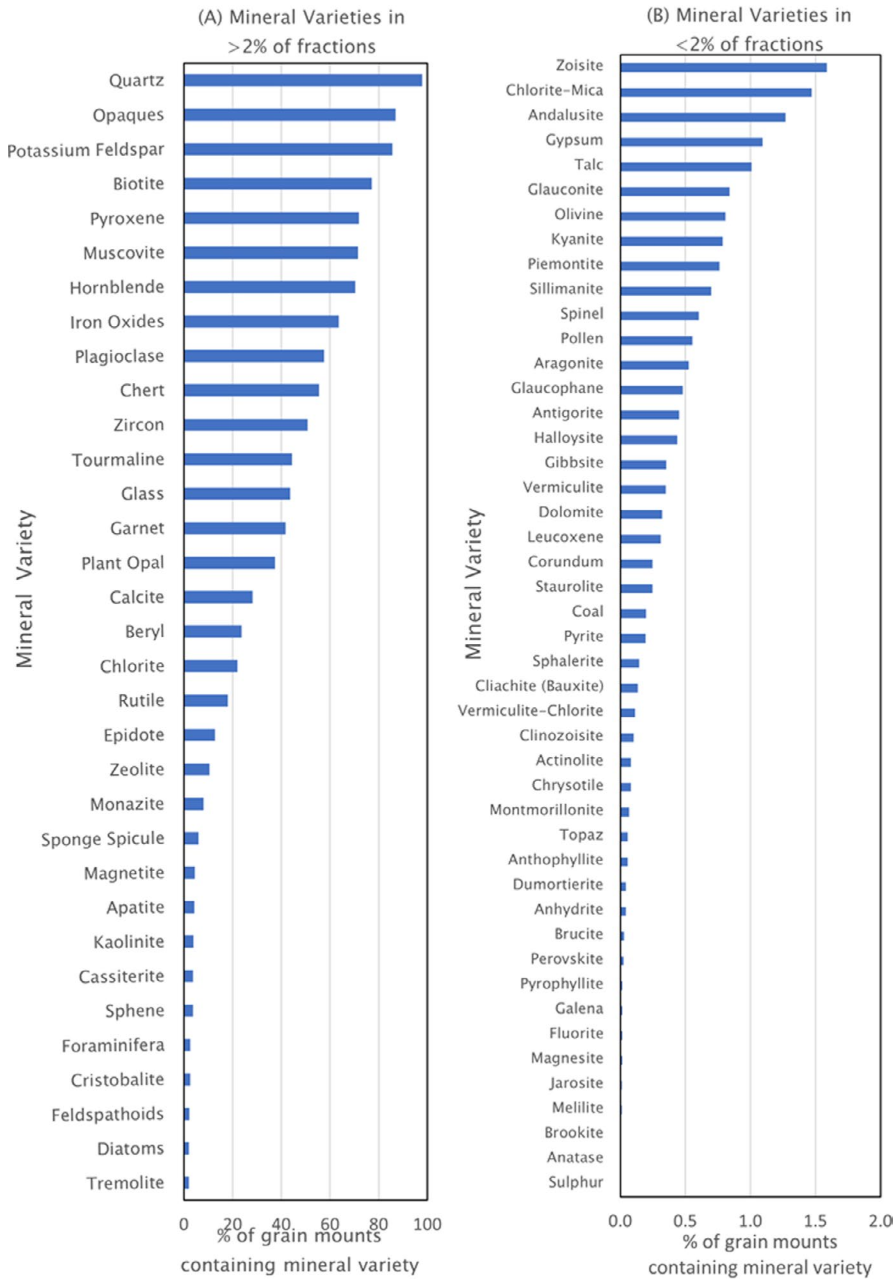

FIGURE 3 Graphical representation of the frequency of occurrence of mineral grain varieties in the KSSL database, separated by those occurring in more than (A) and less than (B) 2% of the grain mounts [Color figure can be viewed at wileyonlinelibrary.com]

major, minor, and trace. All samples contained common minerals (quartz, feldspar, unidentified opaque minerals, micas, pyroxene, and amphiboles), but many of the minerals found in trace abundance were absent in some of the examined items. Andalusite, which is found in only 1.27% of the grain-counted fractions of the KSSL database, was observed in all seven soils. The presence of this normally rare mineral adds strength to report of examination because this mineral is seldom observed in soil grain mounts. This case was examined prior to compilation of the KSSL grain count data presented in this paper, so the data were not cited in the forensic laboratory report, but in future similar cases, the examiner could use this reference to objectively provide conclusion statements about rarity or commonness of mineral grains in soil.

6.2 | Example 2, unusually abundant micas in a soil provenance examination

A suspect purchased a new shovel immediately before stopping at four separate regions where the suspect could have disposed of the victim's body. Soil on the shovel was examined to narrow the search areas and was found to have an unusually high proportion of unweathered euhedral dark and light micas (tens of percent of grains). One of these four regions is within ~8 km of two soil survey sites with mineral grain count data reported to have "biotite" and "muscovite" in excess of tens of percent of the counted grains. Soils with such high biotite contents are observed in less than 1% of the grain-counted fractions in the KSSL database. This assessment indicated that this region near the high mica soil survey sites

TABLE 3 Comparison of mineral grains observed by PLM in a case in which mineral grains extracted from items at a suspect's home (dirty socks in the trash can and digging tools) were compared to soil collected from the victim's clandestine grave

	From Suspect's home				From Clandestine Grave			
Mineral descriptions observed by PLM[a]	Sock 1	Sock 2	Shovel	Rake	Grave Soil 1	Grave Soil 2	Grave Soil 3	% of KSSL grain-counted fractions with mineral[b]
Quartz	Ma[a]	Ma	Ma	Ma	Ma	Ma	Ma	97.8
Magnetite plus other unidentified opaque minerals	Mi	Mi	Mi	Mi	Mi	Mi	Mi	86.91
Weathered Feldspar, including Microcline	Mi	Mi	Mi	Mi	Mi	Mi	Mi	85.7
Pyroxene	Mi	Mi	Mi	Mi	Mi	Mi	Mi	72.0
Biotite/Phlogopite	Tr	Tr	Tr	Tr	Tr	Tr	Tr	77.3
Muscovite	Tr	Tr	Tr	Tr	Tr	Tr	Tr	71.4
Amphibole with pleochroism of blue-green to green	Tr	Tr	Tr	Tr	Tr	Tr	Tr	70.36
Tourmaline with pleochroism of pink to dark grayish-blue to black			Tr	Tr		Tr		44.36
Garnet (pink)		Tr	Tr	Tr	Tr	Tr	Tr	41.7
Rutile			Tr?[c]	Tr		Tr		18.1
Epidote	Tr		Tr	Tr	Tr	Tr	Tr	12.9
Zircon		Tr	Tr	Tr	Tr	Tr	Tr	5.76
Sphene	Tr	Tr?					Tr?	3.5
Andalusite	Tr	Tr	Tr	Tr	Tr	Tr	Tr	1.27

[a]Unlike the KSSL grain count data, the mineral grains were only reported semi-quantitatively as major (Ma, >~10% of grains), minor (Mi, ~1 to ~10%), and trace (Tr, <~1%) in relative abundance and were characterized in oil with RI of 1.54.

[b]The percent of grain-counted fractions in the KSSL database with these mineral types, from Table 2. The percentages in right column are for the more general mineral categories rather than the full morphological descriptions (right column is percent of the grain-counted fraction with ANY amphibole variety, not specifically those with blue-green to green pleochroism).

[c]The notation of "?" indicates that this is a provisional mineral identification resulting from limitation to the observable properties in the evidentiary grains.

was the most likely source of the soil on the shovel. Subsequently, reference soils were collected from the four target regions and only the region near the high mica soil survey sites had soils similar to the evidentiary soil.

This example verifies the potential use of the KSSL mineral grain count data in aid of soil provenance investigations for cases where soil survey grain-counted fractions are available in the vicinity of case-relevant locations. The details of this case are intentionally omitted because this case remains open, as the victim's body has not yet been found. The presence of soil on the new shovel indicates that the suspect attempted to dig a clandestine grave, but it is quite possible that the grave was never completed, and the victim's body was disposed in some other manner.

7 | CONCLUSIONS

The grain counts of soil minerals tabulated in the KSSL database represent a very large reference data set that could be used to provide context for forensic soil comparison and potentially to aid in a forensic soil provenance investigation. This paper does not intend to be prescriptive on the appropriate ways to use these data in a forensic soil report of examination, but it does intend to raise awareness about this excellent resource, and its limitations, and to make these data easily accessible and usable for the forensic soil examiner.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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