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I. Purpose of the Project

Although it is well-recognized that criminals track dusts to and from every crime scene, dust particles on a suspect's shoes are very seldom used as evidence linking the accused to the crime. The major obstacle preventing the use of this type of evidence is that the shoes have mixtures of particles arising from activity before, during and after the crime itself.[1,2] Methods separating the evidentiary particle "signal" from background noise would enable a powerful new and widely-applicable forensic capability. This capability would augment traditional footwear pattern evidence with objective quantitative associations, addressing one of the specific issues raised in the 2009 NAS report.

Our prior NIJ research showed (1) that corresponding particle sets provide extremely strong, objective, quantitative, associative evidence,[3] and (2) that a walk of 250 m in a new environment is sufficient to remove and replace particles present on the contact surfaces of footwear.[4] However, other research [2,5,6] has shown that particles from prior exposures persist on footwear soles much longer. Given the rapid loss of particles from contact surfaces[4] we hypothesized that it is non-contact, recessed areas of footwear that retain particles from prior exposures.

The purpose of the present project was to test the ability of quantitative differential analyses of very small particles (VSP) on the contact surfaces and recessed areas of footwear to separate trace evidence signals attributable to different exposures. Towards this end 1) a series of sequential test exposures were designed and conducted in known environments, 2) computational methods were developed and tested for the quantitative differential analysis of VSP, and 3) these methods were applied to specimens collected from the contact surfaces and recessed areas of footwear.

II. Project Design

Three well-characterized environmental sites (Figures 1-3) were used for footwear exposures. Each site had a characteristic VSP profile, distinguishable by defined qualitative and quantitative particle characteristics (Table 1).

To test the effect of sole type, two distinctly different and commonly encountered types of shoe soles were employed for all tests: athletic shoes (with flexible rubber soles) and work boots (with hard rubber soles).

Exposures to measure rates of loss and replacement of VSP on footwear contact surfaces were made by loading footwear for a walk of 250 m in one environment (approximately 175 steps/shoe) followed by walking in a second environment for varying numbers of steps (5, 10, 25, 50, and 100). VSP were recovered from the contact surfaces by swabbing, analyzed by polarized light microscopy and interpreted using (1) a chi-square measure of distance and (2) a Dirichlet allocation model (a hierarchical probability model characterizing mixtures of multinomial distributions).

Exposures for the differential analysis of VSP from the contact and recessed surfaces of footwear were made by sequential exposures of pairs of footwear to each of the three test environments (250 m walk in each). VSP were first recovered from the contact surfaces by swabbing. Subsequently, VSP were recovered from recessed surfaces by a combination of swabbing and localized washing. VSP were analyzed by polarized light microscopy and interpreted using (as above) the chi-square measure of distance and the Dirichlet allocation model.

III. Methods

A. Recovery of VSP from Footwear Soles by Swabbing

Swabbing was performed using a polyurethane swab wetted with particle-free distilled water and a small amount of ethanol (2%). For each sample a single, disposable swab was used, with periodic transfer of recovered particles from the swab to a small volume of distilled water in a 1.5 ml centrifuge tube (Figure 4). Localized washing of more restricted recessed areas was performed by rapidly pipetting a small quantity of the distilled water/alcohol mixture onto and then immediately off of the recessed surface, followed by transferring the liquid+particles to a 10 ml centrifuge tube. Settled particles were recovered from the centrifuge tube as described in the next section.

B. Particle Isolation and Mounting for Microscopical Analysis

Particles were separated by settling velocity in water,[7] recovering particles settling 3 cm in 9 sec or less. (Allowing particles with a density of 2.61 and diameter greater than 62.5 μm to settle.[8]) Particles were mounted on a microscope slide using standardized Cargille liquid with a refractive index of 1.540.

C. Polarized Light Microscopy (PLM).

Particles were characterized optically and morphologically. Mineral identifications or group classifications minerals were made using the PLM by comparison to known samples and reference data as in prior work on specimens from these environments.[4] The number percent of each particle type (such as a particular mineral) was measured by point counting (> 300 grains) using the ribbon method.[9]

D. Data Reduction and Statistical Methods

Following established procedures for these environmental sites[4] mineral data were binned into the 13 categories shown in Table 1, with a 14th category as “other.” This data reduction retains clear quantitative distinctions among the three sites, while simplifying subsequent computational methods.

The proportion of two sites in a binary mixture, or of three sites in ternary mixture, was measured using a Dirichlet allocation model, developed under this project in cooperation with Madeline Ausdemore (under the advisement of Dr. Cedric Neumann) at South Dakota State University. This is a hierarchical probability model characterizing mixtures of multinomial distributions. The mixture proportion is itself characterized by a multinomial distribution with a Dirichlet distribution for its parameters. The multinomial characterizing the mixture proportion can be used to represent the relative proportions of the different sites, while the Dirichlet distribution is used to characterize the uncertainty on these proportions for an observed mixture.

To visualize the resulting percentages for each of the three sites a ternary diagram was used following the method of Graham and Midgely.[10]

IV. Data Analysis

A. Loss and Replacement of VSP from Contact Surfaces of Footwear

Table 2 shows the percentage loss and replacement of VSP on the contact surfaces for 18 pairs of each of the two footwear types that were (1) exposed to one site for 175 steps/shoe (equivalent to a 250 m walk) to “load” the contact surfaces and (2) exposed for differing numbers of steps to 0, a second (site LQ: 5, 10, 25, 50 and 100 steps). Figure 5 shows a chart of these data. Rapid loss of loading site particles, and replacement with the second site, is seen within the first 25 steps. By 50 steps there is nearly complete replacement of the loading site particles with those from the second site.

B. Differential Analysis of VSP Signals from Successive Exposures

Table 3 shows the results of the analysis of VSP recovered from the contact surfaces and recessed surfaces of shoes and boots after sequential walks of 250 m in each of the three environmental sites. Figure 6 shows a ternary diagram of these data.

There are four principle findings. Firstly, and as expected given the previous results, the contact surfaces of the footwear are universally dominated by VSP attributable to the last (third) site. (This can be seen in the dark green shaded cells in Table 3, as well as the clustering of the blue and red data points to the lower left in Figure 6.)

Secondly, VSP recovered from the recessed surfaces of the boots showed major percentages of VSP attributable to the first and second sites of exposure. For all boots this was more than 25% of the VSP, with an average of 43% and a high of 64%. (The orange data points in Figure 6, well dispersed into the central portion of the ternary diagram, are an excellent illustration of this finding.)

Thirdly, a markedly different effect was seen for the athletic shoes. Although there were detectable percentages of VSP attributable to the first and second sites of exposure, the amounts were much less than for boots. These included a low of 8% (well within the range for contact surfaces), an average of only 13% and a high of 22%. (The range of the green data points in Figure 6, falling far short of the orange and well-mixed with the red and blue, are an excellent illustration of this finding.)

Fourthly, when VSP were found attributable to the first and second sites, there was no clear trend for dominance of either the first or second site. Rather, it may be that the character of the site is more of a factor. Table 4 shows the instances where more than 15% of the VSP were attributable to the first and second sites. Dominance of either the first or second site is shown where highlighted in blue. Site PR is dominant over AT in all cases (6). Site LQ and PR are comparable in nearly all cases (4 of 5, LQ dominates in one). AT and LQ show a mix (LQ dominant in two cases, AT dominant in one and no clear dominance in the remaining three).

V. Scholarly Products Produced or in Process

A. Presentations

1. Stoney, DA, Bowen, AM, Ausdemore, M, Stoney, PL and Neumann, C. Particle Combination Analysis in Footwear Investigations; NIJ Impression, Pattern and Trace Evidence Symposium, Arlington, VA, January 24, 2018 (upcoming)

2. Ausdemore, M, Neumann, C and Stoney, D. Location Detection and Characterization in Mixtures of Dust Particles; NIJ Impression, Pattern and Trace Evidence Symposium, Arlington, VA, January 24, 2018

3. Stoney, DA, Bowen, AM, Ausdemore, M, Stoney, P and Neumann, C. Rates of Loss and Replacement of Very Small Particles (VSP) on the Contact Surfaces of Footwear During Successive Exposures; American Academy of Forensic Sciences 70th Annual Meeting, Seattle, WA, February 22, 2017. (Upcoming)

4. Stoney, DA. Application of Particle Characterization Methods (Such as SEM/EDS) in Support of Particle Combination Analysis; Pittcon 2018 Conference & Expo, Orlando, FL, March 1, 2018. (Upcoming)

B. Publications

1. Stoney, DA, Bowen, AM, Ausdemore, M, Stoney, PL and Neumann, C. "Contact Surface Retention and Loss of Very Small Particles on Footwear," (in progress)

2. Stoney, DA, Bowen, AM, Ausdemore, M, Stoney, P and Neumann, C. "Differential Analysis of Very Small Particles on Footwear," (in progress)

VI. Implications for Criminal Justice Policy and Practice in the United States

This research has provided (1) a greater understanding of how particles adhere to the soles of footwear, how they can be separated, and whether sequential exposures can be determined on this basis; (2) a set of computational methods applicable to VSP mixtures, allowing determination of proportions in mixtures, estimation of a proportion of a designated source in a mixture, and estimation of the parameters of an unknown source within a mixture; and (3) progress toward implementation of a new forensic capability that is widely applicable, with objective, quantifiable associations.

Specific findings included

- that the contact surfaces of the footwear are dominated by VSP attributable to the most recent site of exposure
- that walking in a new location rapidly removes and replaces VSP from the contact surfaces of footwear, with major replacement occurring in 5 to 10 steps and nearly complete replacement occurring by 50 steps

- that while the VSP on contact surfaces is lost, the recessed surfaces of footwear retain VSP from prior exposures
- that the type of sole appears to be a source of major differences in the amount of VSP from prior exposures that remains in recessed areas
- that when VSP were found attributable to the prior exposures, there was no clear trend for dominance between earlier exposures

More broadly, signals from VSP exist on many other forms of evidence. These VSP allow significant, objective, quantitative associations between transferred VSP and their sources.[11] The process of separating discrete signals of interest through quantitative differential analysis has the potential to extend the application of these methods to surfaces and items where a physical mixture of sources has occurred.

There is also a potentially high impact of this research from a criminal justice policy and practice perspective. The frequent occurrence of shoeprints at crime scenes, and the ubiquitous presence of footwear associated with suspects, means that there are many cases where linkages from VSP evidence could be applied. Currently, the probative value of shoeprints is tied directly to (1) the contingencies of the quality reproduction of the sole's pattern in the shoeprints, and (2) subjective expert determinations of correspondence between these patterns. Methods enabling objective corroboration of comparisons using VSP can directly improve the quality and reliability of current methods, and methods that are applicable to less distinct shoeprints (not considered of value for pattern evidence) can increase the number of cases where useful evidence is found.

VII. Appendix: Tables, Figures and References

A. Tables

Table 1. Overall fractions of mineral categories for single-site exposures showing differences among the three sites.

	SITE AT		SITE LQ		SITE PR	
	BOOTS	SHOES	BOOTS	SHOES	BOOTS	SHOES
Alkali feldspar	0.556	0.561	0.085	0.076	0.115	0.115
Alterite	0.065	0.046	0.025	0.015	0.027	0.017
Biotite	0.003	0.006	0.056	0.040	0.050	0.049
Epidote	0.019	0.019	0.031	0.026	0.139	0.138
High index	0.007	0.009	0.002	0.004	0.052	0.053
Hornblende	0.005	0.008	0.219	0.200	0.019	0.015
Iron oxides	0.020	0.015	0.001	0.000	0.004	0.010
Lithic Fragments	0.008	0.013	0.016	0.015	0.364	0.340
Muscovite	0.002	0.002	0.006	0.004	0.069	0.083
Opaques	0.064	0.047	0.015	0.014	0.002	0.002
Plagioclase	0.013	0.009	0.068	0.129	0.083	0.081
Quartz	0.217	0.228	0.452	0.453	0.046	0.069
Titanite	0.001	0.000	0.010	0.011	0.015	0.010
Other	0.021	0.037	0.012	0.013	0.015	0.018
Total	1.000	1.000	1.000	1.000	1.000	1.000

>0.25	0.10-0.25	0.05-0.10	0.02-0.05	<0.02

Table 2. Percentage Loss and Replacement of VSP after Loading in One Site and Walking a Number of Steps in a Second Site

	Shoes					
	AT to PR		PR to LQ		LQ to AT	
Steps	Left	Right	Left	Right	Left	Right
0	0.00	0.01	0.06	0.02	0.02	0.01
5	0.57	0.46	0.75	0.84	0.83	0.97
10	0.77	0.67	0.87	0.91	0.90	0.96
25	0.92	0.93	0.94	0.89	0.95	0.97
50	0.96	0.89	0.96	0.94	0.99	0.98
100	0.96	0.99	0.96	0.99	0.99	0.99
	Boots					
	AT to LQ		PR to AT		LQ to PR	
Steps	Left	Right	Left	Right	Left	Right
0	0.00	0.00	0.07	0.01	0.07	0.04
5	0.67	0.82	0.70	0.75	0.86	0.79
10	0.93	0.84	0.85	0.80	0.95	0.82
25	0.97	0.99	0.92	0.90	0.94	0.95
50	0.94	0.99	0.93	0.95	0.93	0.96
100	0.99	0.98	0.97	0.96	0.96	0.98

Table 3. Percentages of VSP Attributable to Each of the Three Test Sites after Sequential Walks of 250m.

PR AT LQ

			Site (Order of Exposure)		
			PR (1)	AT (2)	LQ (3)
Shoes	Contact	Left	0.02	0.01	0.97
		Right	0.05	0.02	0.92
	Recessed	Left	0.17	0.05	0.78
		Right	0.09	0.05	0.86
Boots	Contact	Left	0.09	0.01	0.90
		Right	0.04	0.01	0.95
	Recessed	Left	0.43	0.21	0.36
		Right	0.36	0.24	0.40

PR LQ AT

			Site (Order of Exposure)		
			PR (1)	LQ (2)	AT (3)
Shoes	Contact	Left	0.01	0.01	0.98
		Right	0.02	0.01	0.97
	Recessed	Left	0.07	0.11	0.82
		Right	0.03	0.05	0.92
Boots	Contact	Left	0.02	0.01	0.97
		Right	0.02	0.01	0.97
	Recessed	Left	0.08	0.20	0.72
		Right	0.13	0.12	0.74

LQ AT PR

			Site (Order of Exposure)		
			LQ (1)	AT (2)	PR (3)
Shoes	Contact	Left	0.00	0.03	0.97
		Right	0.01	0.00	0.98
	Recessed	Left	0.02	0.13	0.85
		Right	0.06	0.05	0.89
Boots	Contact	Left	0.02	0.10	0.87
		Right	0.02	0.10	0.87
	Recessed	Left	0.31	0.28	0.40
		Right	0.21	0.36	0.43

LQ PR AT

			Site (Order of Exposure)		
			LQ (1)	PR (2)	AT (3)
Shoes	Contact	Left	0.01	0.01	0.98
		Right	0.01	0.00	0.99
	Recessed	Left	0.00	0.04	0.95
		Right	0.05	0.03	0.92
Boots	Contact	Left	0.05	0.02	0.93
		Right	0.05	0.03	0.91
	Recessed	Left	0.20	0.22	0.58
		Right	0.22	0.22	0.57

AT LQ PR

			Site (Order of Exposure)		
			AT (1)	LQ (2)	PR (3)
Shoes	Contact	Left	0.05	0.01	0.94
		Right	0.02	0.01	0.97
	Recessed	Left	0.07	0.10	0.83
		Right	0.08	0.02	0.90
Boots	Contact	Left	0.02	0.05	0.93
		Right	0.02	0.04	0.94
	Recessed	Left	0.09	0.25	0.66
		Right	0.06	0.24	0.70

AT PR LQ

			Site (Order of Exposure)		
			AT (1)	PR (2)	LQ (3)
Shoes	Contact	Left	0.01	0.06	0.94
		Right	*	*	*
	Recessed	Left	0.04	0.11	0.85
		Right	*	*	*
Boots	Contact	Left	0.02	0.08	0.90
		Right	0.00	0.02	0.97
	Recessed	Left	0.12	0.24	0.64
		Right	0.12	0.25	0.62

*Missing data

> 0.90	0.50 to 0.90	0.10 to 0.50	< 0.10

Table 4. Instances where More than 15% of VSP in Recessed Areas were Attributable to the First and Second Sites. (Blue cells indicate dominance of one of the two sites over the other).

			PR (1)	AT (2)
Shoes	Recessed	Left	0.17	0.05
Boots	Recessed	Left	0.43	0.21
Boots	Recessed	Right	0.36	0.24
			PR (1)	LQ (2)
Shoes	Recessed	Left	0.07	0.11
Boots	Recessed	Left	0.08	0.20
Boots	Recessed	Right	0.13	0.12
			LQ (1)	AT (2)
Shoes	Recessed	Left	0.02	0.13
Boots	Recessed	Left	0.31	0.28
Boots	Recessed	Right	0.21	0.36
			LQ (1)	PR (2)
Boots	Recessed	Left	0.20	0.22
Boots	Recessed	Right	0.22	0.22
			AT (1)	LQ (2)
Shoes	Recessed	Left	0.07	0.10
Boots	Recessed	Left	0.09	0.25
Boots	Recessed	Right	0.06	0.24
			AT (1)	PR (2)
Shoes	Recessed	Left	0.04	0.11
Boots	Recessed	Left	0.12	0.24
Boots	Recessed	Right	0.12	0.25

B. Figures

Figure 1. Top: Overview of the location of the Piney River site, an improved hiking trail in a wooded site along the Virginia Blue Ridge Railway Trail (37.7078, -79.0220).Bottom: View of the Piney River trail site.

Figure 2. Top: Overview of the location of the Appalachian Trail site, an unimproved minor trail just off of the main Appalachian Trail leading along the Tye River (37.8384, -79.0220). Bottom: View of the Appalachian Trail site.

Figure 3. Top: Overview of the location of the Luck Stone Quarry site, along the edges of a public access road outside of the Luck Stone Quarry in Fredericksburg, VA (38.2128, -77.5488). Bottom: View of the Luck Stone Quarry site.

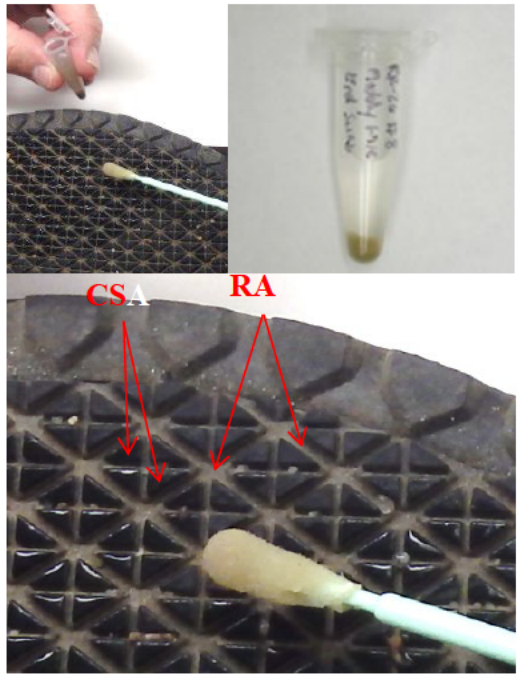

Figure 4. Contact surfaces (CS) are being sampled in the figure. Recessed areas (RA) are sampled subsequently after VSP are removed from the contact surfaces.

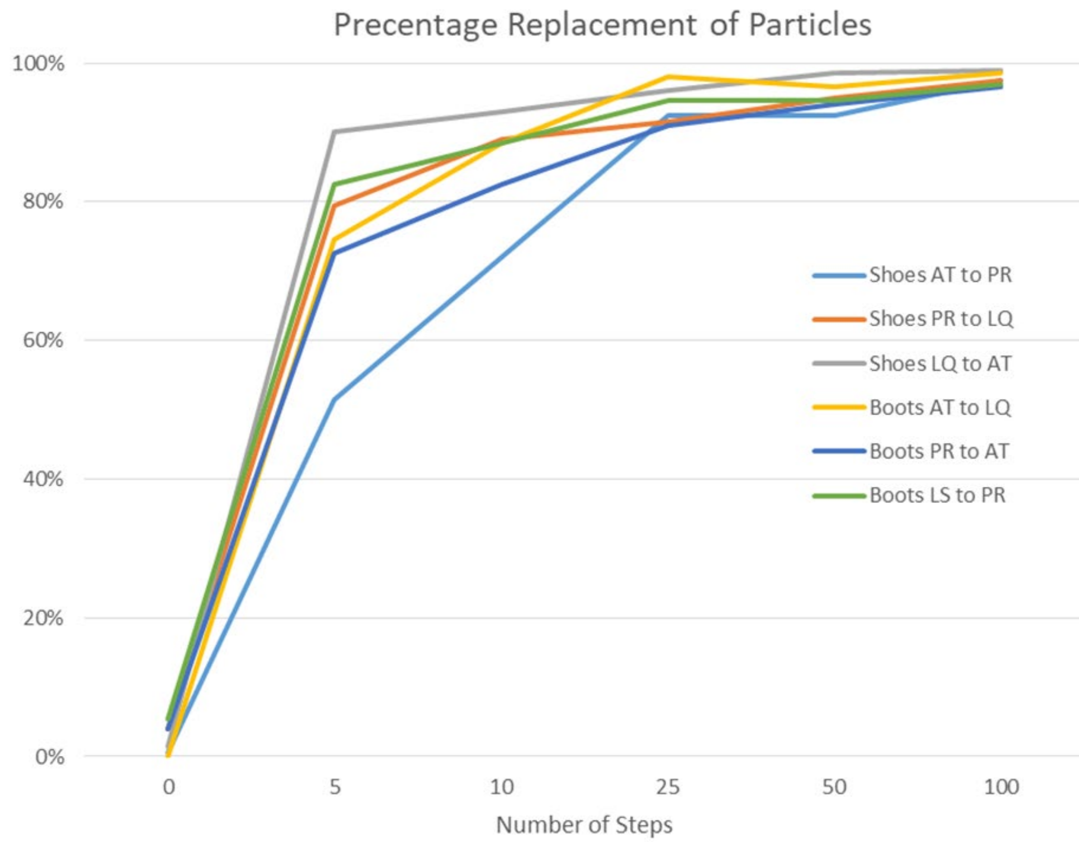

Figure 5. Loss and replacement of VSP on the contact surfaces of footwear following an initial walk of 250 meters (~175 steps/shoe) at the first “loading” site and a subsequent walk of varying length in a second site.

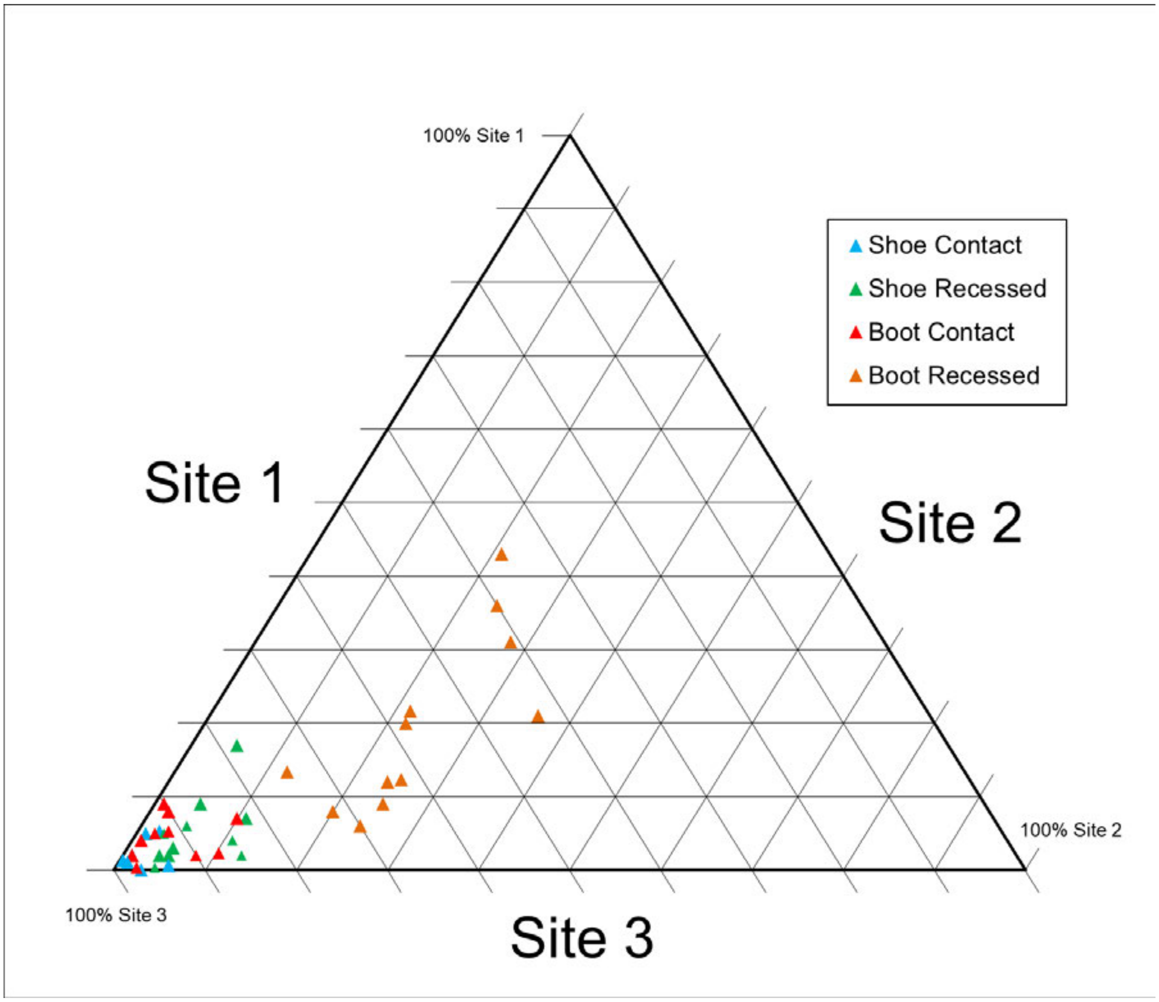

Figure 6. A ternary diagram showing the proportions of VSP attributable to the first, second and third sites while walking 250 m in each site.

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