CASE REPORT

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Identification of Stolen Rare Palm Trees by Soil Morphological and Mineralogical Properties*

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ABSTRACT: The San Diego County District Attorney's office requested our help to investigate the theft of palm trees from a private collection of exotic plants. Circumstantial evidence led investigators to the suspect's residence where 33 palm trees were found. Because the victim raised all palms from seed in the same potting mix, we compared morphologic and mineralogic properties of soil samples collected from the root balls of palms that were at the victim's and suspect's residences. Analyses of soil color, reaction with dilute hydrochloric acid, particle size, heavy:light mineral ratios, and mineral speciation of the >2.86 g cm^{-3} fine sand fraction, indicated that 25 of 33 soil samples collected from palm trees at the suspect's residence were very similar to soil samples from palm trees at the victim's residence. After a pretrial hearing at which the soil evidence was presented, the suspect changed his innocent plea to guilty.

KEYWORDS: forensic science, soil science, forensic mineralogy, soil color, particle-size analysis, palm trees, heavy:light mineral ratios, potting soil

Soil and geologic materials have served as critical evidence in a number of criminal investigations. In these instances, earth scientists become involved in forensic cases. For example, scientists with the California Division of Mines and Geology assisted in the identification of a kidnapper by analyzing a diatomaceous earth footprint found in the back seat of the kidnap vehicle. Identification of the specific diatoms and their distribution led investigators to the quarry where the victim was previously held (1). More recently, the California Division of Mines and Geology assisted prosecutors in the identification of a murder suspect. Mineralogical analysis of the clastic material found in a suspect's vehicle linked him to the location of a victim's body (2).

In a recent lawsuit involving a plane crash, plaintiffs argued that soil adhering to the plane's engine contributed to the crash. A plaintiff expert witness testified that the energy dispersive X-ray (EDX) spectra of the soil material adhering to the engine wreckage was consistent with soil on the runway from which the plane departed. A soil scientist serving as an expert for the defense argued that major element contents, as determined by EDX, do not distinguish soils effectively. He found color analysis of heat-treated samples to be a more sensitive method for soil comparison. The court agreed with the defense expert's conclusion that the soil on the engine-wreckage was not consistent with the runway, but was similar to soil found in the storage yard where the plane wreckage was stored (3).

Geologic materials and soils have also been used as evidence in environmental regulatory compliance cases. For example, in 1993, the Mississippi Office of Geology assisted the Office of Pollution Control by determining the sources of sediment pollution in a small Mississippi lake. Investigators evaluated a sediment column in the lake and correlated the strata within the column with specific localities within the drainage basin and with specific ages corresponding to known historical events since the lake was constructed. The results indicated that the lack of erosion controls during construction of a new subdivision upstream was responsible for the contamination (4).

In April of 1997, upon request from the San Diego County District Attorney's Office, we assisted in an investigation involving stolen exotic palm trees. The victim raised exotic palm trees from seed in a potting mix that was purchased in large lots from a southern California bulk distributor of potting soil. The missing palm trees had an estimated value of \$40 000. Eyewitness accounts and an informant led investigators to the suspect's residence, however physical evidence was required to make an arrest. The suspect had 33 palm trees of similar size, age (approximately seven-years-old), and species as those of the victim. The palms were planted in the yard around his residence and in plant pots on the patio.

Our investigation hinged on being able to distinguish or match potting soils. Commercial bulk potting mixes are variable and depend on the local availability of material. For example, in southern California decomposed granite is readily available due to the abundance of granitic rock outcrops in the region. When mixed with organic matter and other amendments, decomposed granite provides a favorable medium for plant growth. Effective potting mixes should provide plant support, possess nutrient holding capacity, possess large moisture retention, provide aeration, and be free of pathogens. Generally, native soils are not ideal media for potting plants because they lack adequate drainage and water holding ca-

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pacity. In addition, native soils typically need to be amended with organic matter and perlite or quartz-rich sand to improve their physical structure and water and nutrient retention capacities. Perlite (formed by heating volcanic glass) is a lightweight, sponge-like, material that is inert and porous. Vermiculite (expanded mica) can absorb nutrients, as well as water, and will contribute some potassium and magnesium, which are essential to plant growth. Some packaged potting mixes can be bought at local nurseries and garden supply dealers. Usually these soil mixes are composed of a sterilized sandy soil amended with vermiculite, organic matter, and perlite. Potting mixes that do not incorporate native soil material commonly include varying concentrations of peat moss, perlite, and vermiculite.

Because of the single source of potting mix at the victim's residence, we hypothesized that all palm trees raised at the victim's residence would have similar soil within the root ball of each tree. If tree root balls at the suspect's residence had potting soils similar to those at the victim's residence, this evidence would support the charge against the suspect. We performed a series of analyses to characterize and compare the root ball potting soils to determine if palm trees collected from the suspect's residence had been stolen from the victim.

Materials and Methods

Soil samples were collected in the spring of 1997 in conjunction with the San Diego County Sheriff's Department. At the suspect's residence, soils from the root balls of 33 palm trees were collected. Palms planted in the suspect's yard were excavated and the soil from the root ball was collected with a soil knife. Soil samples from the root ball of potted palms were collected with an Oakfield Soil Sampler (push tube). In addition to the palm tree soil samples, three samples were collected by push tube from the suspect's yard for comparison. Ten soil samples (two potted plants of each of five species) from the victim's palm tree collection were used for comparison. In total, 46 soil samples were collected for analyses: 33 palm soils from suspect, three samples of native soil from the suspect's yard, and ten palm soil from the victim's collection.

Seven species of palm trees were excavated and sampled at the suspect's residence: *Butia capitata, Chamaerops humilis, Cycas revoluta, Jubaea chilensis, Livistona mariae, Phoenix roebillini, Trithrinax acanthocoma.* The victim raised all of these species at his residence except *Phoenix roebillini.* Although the six *Phoenix roebillini* were not stolen from the victim, soil samples from the root balls of these trees were analyzed to test the effectiveness of our methods in differentiating samples.

Samples were stored in polyethylene sample bags for transport from the sampling sites to the laboratory. All soils were then air-dried and sieved to remove gravel (>2 mm size fraction). The <2-mm-soil fraction was analyzed to determine carbonate presence, soil color, particle-size distribution, and mineralogical profile. These latter three techniques are the standard practice of laboratories that perform forensic geologic analyses (5,6).

We set out to eliminate any soils collected from the suspect's palm trees that were dissimilar to the victim's palms. The analysis techniques and order in which they were used is detailed by a flow chart in Fig. 1 and are described below. All soil samples were analyzed for their color and reaction with carbonates. Any of the suspect's samples that were dissimilar to the victim's soils, were excluded from further analyses. From the remaining group of similar soils, a subset of 11 samples: five palm tree soils from the suspect's residence, five palm tree soils from the victim's residence, and one sample from the suspect's yard, were selected randomly and analyzed for their mineralogic properties. This smaller set of samples was used at the request of the District Attorney's office in order to moderate the high cost and length of time required to perform detailed analyses.

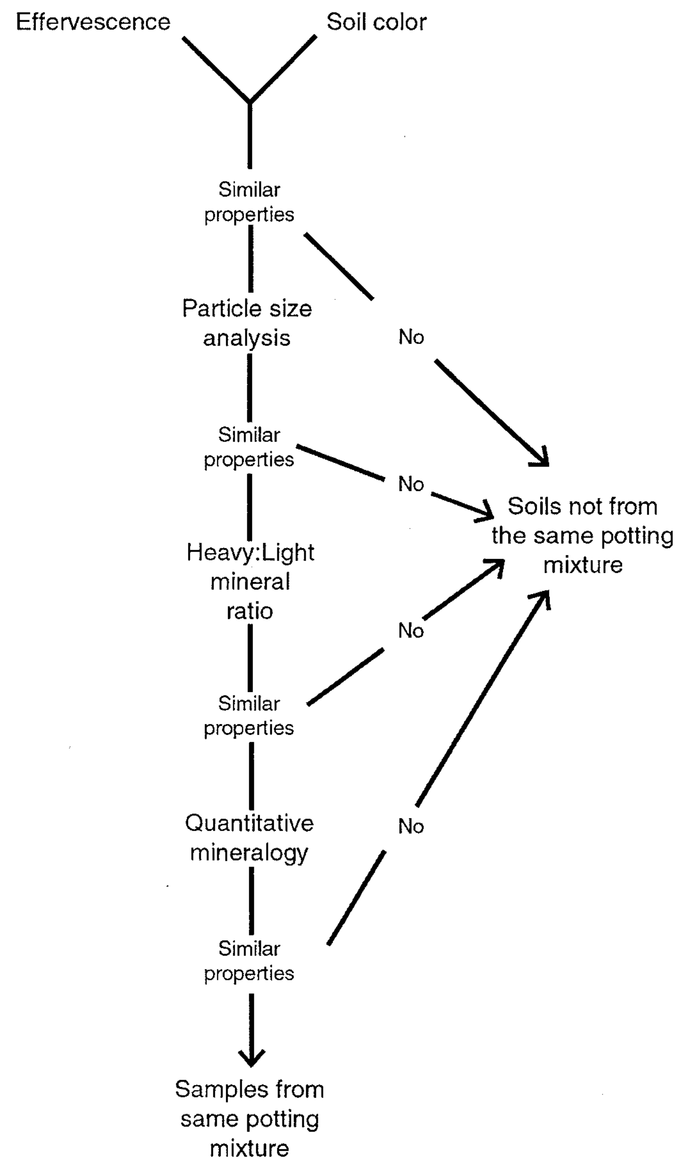

FIG. 1—*Methods and sequence of analyses used to differentiate soil samples collected from the root ball of victim's and suspect's palm trees.*

Carbonate Determination

Cold 1 M (about a 1:10 dilution of concentrated HCl) hydrochloric acid is used to test for calcium carbonates ($CaCO_3$) in soils. When $CaCO_3$ is treated with HCl, carbon dioxide (CO_2) is released and bubbles rise from the sample. The amount and expression of effervescence is affected by grain size and mineralogy of the carbonates, as well as quality. Consequently, effervescence cannot be used to estimate the amount of carbonate, however it can be used to qualitatively compare carbonate behavior during acid treatments. Four qualitative classes of effervescence are used: (a) very slightly effervescent (few bubbles seen), (b) slightly effervescent (bubbles readily seen), (c) strongly effervescent (bubbles from low foam), and (d) violently effervescent (thick foam forms quickly) (7).

Color Determination

Soil color relates to soil properties that include organic matter, iron mineralogy, and moisture content of soils. Soil color was determined on all samples utilizing a spectrophotometer (Minolta Chromameter CR-200) which expresses reflected energy from the visible portion of the spectrum as Munsell hue (spectral color), value (light or darkness of soil), and chroma (intensity of spectal color). This instrument gives a highly reproducible, non-subjective color determination that is much preferable to the traditional subjective color-chip matching process (8), particularly for forensic work.

Two subsamples of each soil were heated in a muffle furnace to 400°C for 16 h and 800°C for 6 h. The resulting color data for the heated subsamples were averaged for each soil at each temperature. Heating removes organic matter by oxidation, and causes mineralogical transformation that can yield diagnostic color changes (9,10). More specifically, ignition of soils at 400 to 450°C for 8 to 16 h results in the removal of most organic matter (11), while heating soils to 800°C results in the decomposition of carbonate minerals (12). In addition, at high temperatures the soil mineral goethite, a common yellowish-orange colored iron oxide, is converted to hematite, a reddish iron oxide mineral (10). To simplify the color data from three numerical components (hue (H), value (V), chroma (C)) to a single index, we combined the color components into a redness rating (RR) (14) to evaluate how color of the samples changed with heating (3).

$$RR = (10 - (\text{YR Hue})) \times \text{Chroma/Value}$$

Particle Size Analysis

Ten grams of each sample were treated with 30 mL of 30% H_2O_2 in 5 mL increments to remove organic matter (14). The sample was then dispersed by thoroughly mixing with approximately 400 mL of distilled water and 10 mL of 10% Na-hexametaphosphate solution (15). The soil solution was wet sieved through a 0.05-mm-mesh sieve. Both the sand (2 to 0.05 mm) and silt + clay (<0.05 mm) fractions were oven dried. The sand fraction was further partitioned by dry sieving through a nest of sieves (1.00, 0.500, 0.250, 0.100, and 0.050 mm mesh sizes). The contents of each fraction were weighed, and percentages of the total were calculated. The fine sand fraction (0.250 to 0.100 mm) was retained for mineralogical analysis.

Mineralogical Analysis

The fine sand fraction was treated with citrate-bicarbonate-dithionite (CBD) to remove free iron oxides that coat the grains and interfere with satisfactory heavy mineral separation (14). A sink or float with a 2.86 specific gravity Na-polytungstate solution was used to partition the CBD-treated fine-sand fraction into heavy (>2.86 g cm^{-3}) and light (<2.86 g cm^{-3}) mineral fractions (16), which were then weighed. The heavy:light mineral ratio was then used for comparison between samples.

The fine sand heavy fraction was mounted on slides in a 1.68 refractive index medium. Minerals were identified by their morphology, birefringence, color, refractive index, and optical sign using polarized light microscopy techniques (17). Three-hundred grains per sample were quantified by the ribbon transect method (18). A count of 300 grains is considered the optimum number of grains to count for speed and statistical significance in a forensic investigation (19).

Results and Discussion

Carbonate and Color

Two of the victim's samples (*Butia capitata*) effervesced slightly with 1 M HCl treatment, while the remaining eight samples did not react. These results show that the victim's potting mix contains at most very little $CaCO_3$. Three of the suspect's samples (1 *Chamaerops humilis* and 2 *Cycas revoluta*) also had a very slight or slight reaction, while two others (one *Chamaerops humilis* and one *Cycas revoluta*) effervesced violently when treated with the acid. Two of the samples from the suspects yard contained enough $CaCO_3$ to effervesce violently. This $CaCO_3$ formed in the native soil, a common process in southern California.

The color of the victim's samples ranged from a hue of 8.9YR to 0.2Y, a value of 3.8 to 4.1, and a chroma of 1.9 to 2.5, while the color of the suspect's samples ranged from 6.3YR to 1.5Y (hue), 3.1 to 5.3 (value) and 1.1 to 3.1 (chroma). Samples from the suspect's six *Phoenix roebillini* plants were particularly variable in color. Disregarding these samples, since the *Phoenix roebillini* were not stolen from the victim, the color parameters of the soils from the suspect's palms were 8.6YR to 0.2Y (hue), 3.9 to 5.3 (value) and 1.8 to 3.1 (chroma), which are much closer to the range of the victim's samples.

The RR of samples at 25 and 400°C (including *Phoenix roebillini* soils) did not aid in the discrimination of any palm trees. However, after samples were heated to 800°C, the six soils from the *Phoenix roebillini* were differentiated by their lower RR (Fig. 2). The remaining suspect's samples (excluding the *Phoenix roebillini* soils) had colors very similar to those of the victim's at 25,400 and 800°C.

Violent effervescence of two of the suspect's samples (from a *Chamaerops humilis* and a *Cycas revoluta*) suggests that these samples were not from the same source as the victim's soil sam-

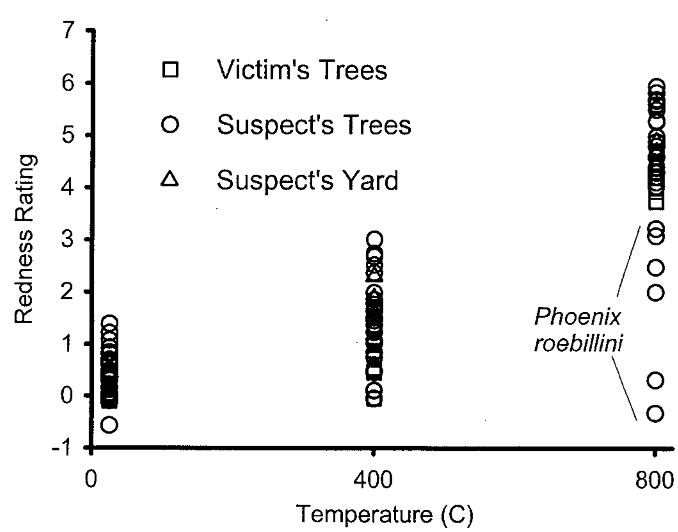

FIG. 2—*Calculated redness rating (RR) of soil samples at 25,400, and 800°C. Samples could not be differentiated at 25 and 400°C, however, 6 potting soils from suspect's* Phoenix roebillini *could be differentiated at 800°C.*

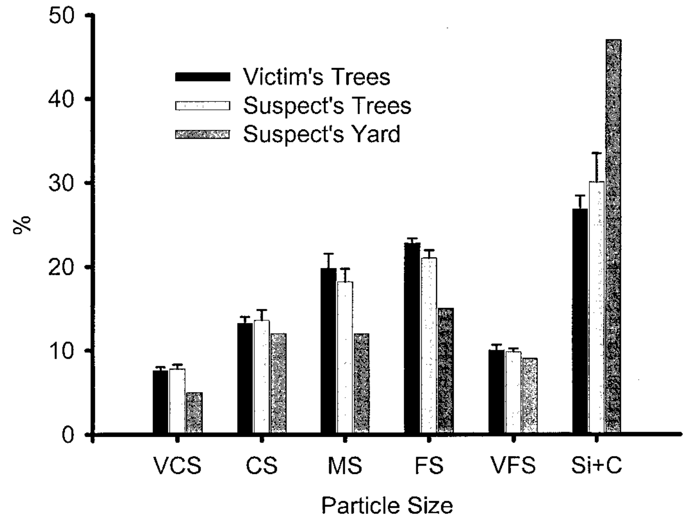

FIG. 3—*Average and standard error of particle size distribution of soil samples collected from 5 palm trees each at the victim's and suspect's residences, and particle size distribution of 1 soil sample from suspect's yard. (Particle size classes (mm): VCS = 1.00–2.00, CS = 0.50–1.00, MS = 0.25–0.50, FS = 0.10–0.25, and VFS = 0.05–0.10).*

ples. In addition, these soils had a color value of 5.3, one unit greater than the lightest color from the victim's residence. The differences in color of these two soils compared to the victim's samples are due to the presence of calcium carbonate. The suspect's native soil in the yard had high color values (5.0 and 5.3) and abundant calcium carbonate as indicated by violent effervescence. The carbonate-rich yard soil may have contaminated root balls composed of victim's potting mix when the trees were planted in the yard, causing violent effervescence and lighter color, thus differentiating the *Chamaerops humilis* and *Cycas revoluta* from the victim's. However, taking a conservative view we did not speculate on the contamination of the root ball of these to samples, but opted to remove them from any further analysis.

Particle Size and Mineralogy

The results from the particle size analysis of the five palm soil samples from the suspect's residence are very similar to those from the five palms at the victim's residence (Fig. 3). The slightly effervescing native soil sampled from the suspect's yard can be discriminated from the potting soils by its much higher silt plus clay content and generally lower sand fraction contents (Fig. 3).

The heavy:light mineral ratios of the fine sand fraction are also similar for the victim's and suspect's samples. The heavy:light ratios of the suspect's palms range from 0.10 to 0.22 with an average of 0.16, while the victim's palm soils heavy:light ratios range from 0.10 to 0.18 with an average of 0.14.

The mineralogy of the heavy fraction of both sample groups includes hornblende, biotite, zircon, epidote, and opaque minerals (assumed to be magnetite). These minerals are common accessory minerals of granite, a common rock type in southern California. All grains are angular, a characteristic that is consistent with the mineralogical source of the victim's potting mix, decomposed granite.

Because hornblende made up the largest percentage of the samples, it was used for quantitative comparison between sample groups. The remaining minerals were present in concentrations too low for valid comparison, given the number of grains counted (20). The hornblende concentration in the heavy fraction ranged from 63 to 81% in the suspect's soils, and 58 to 70% in the victim's soils. The wide range of hornblende values for the suspect's samples is due to one sample (81% hornblende in heavy fraction). Contamination with native soil from the victim's yard, where hornblende is 86% of heavy fraction, could account for the high value for this one sample. The remaining four samples from the suspect's residence had fine-sand hornblende concentrations of 63 to 69% in the heavy fraction, which falls clearly within the range for the victim's potting soil.

Summary

We concluded that 25 of the 33 palms seized for evidence at the suspect's residence were planted in potting soil that was characteristic of the potting soil at the victim's residence. The analyses accurately discriminated six palms (*Phoenix roebillini*) that were not raised at the victim's residence. Of the remaining palms, two were discriminated by effervescence and soil color determination, and were not stolen from the victim. Results of the mineralogical analyses did not discriminate any other palm trees, indicating that their potting soils were from the same source.

The case against the suspect was based on several types of evidence. The similarity between potting soils of palm trees collected at the victim's and suspect's residences was just one important piece of physical evidence. After a pretrial hearing at which the results from the potting soil analyses were presented, the suspect changed his innocent plea to guilty.

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