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# A Mineralogical Soil Classification Technique for the Forensic Scientist

Mineral grains form the largest component of most soils. These grains are quite stable and undergo no significant change over the periods of time in which the forensic scientist is normally interested. In most naturally occurring soils, there is a large variety of different minerals whose relative proportions vary from one area to another [*1,2*]. These factors make the mineralogy of soils an attractive property for the forensic scientist to investigate.

A detailed procedure for the quantitative petrographic examination of soil minerals was devised by Dell [*3*]. Included with this procedure was a description of 33 soil minerals and rock fragments occurring in the soils of the province of Ontario, Canada. Several other useful lists and descriptions of rock-forming minerals have also been compiled [*4-8*].

None of the conventional methods for determining quantitative mineralogy is entirely suitable for forensic science work. Brewer [*9*] suggested that counts of more than 1000 grains were necessary to obtain accurate quantitative results for mineral grains composing 5% of the sample. The traditional methods for identifying and counting so many mineral grains require up to 20 h. This limitation makes these methods tedious and also makes impractical any study involving more than a small number of samples.

Some investigators of soil mineralogy have shortened sample examination time by concentrating on the heavy mineral fraction [*10*]. Since these minerals exhibit considerable variety, both in sediments and in some soils, they have been used extensively in studies of provenance where they are more significant than the ubiquitous quartz and feldspar. However, the forensic scientist cannot make much use of the heavy minerals as they usually occur in small amounts in soils and are useful only where large samples are available. The forensic analyst who deals with very small samples must rely on the total assemblage of minerals.

To determine the forensic science usefulness of soil mineralogy, it was first necessary to develop a rapid quantitative method for classifying and comparing the content of small soil samples. A method and classification system developed for this purpose are presented here. By using this procedure, in conjunction with color analysis, a large number of soil samples from the southern portion of the province of Ontario have been examined to assess the usefulness of soil as it relates to forensic science. The results of this survey will be published in a subsequent paper.

## Sample Preparation

A representative sample of 10 to 50 mg of the soil was taken. The amount used was dependent on the grain size of the soil with a lesser quantity required from silty sands than from coarse sandy soils or silty clays. This sample was placed in a 5-ml beaker and dispersed in 3 ml of water with a small propeller driven at about 8000 rpm. A pair of

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stainless steel sieves with rim diameters of 76 mm (3 in.) and with mesh openings of 0.149 and 0.105 mm (100 and 150 mesh) were nested and placed over a Buchner funnel containing a Whatman No. 4 filter paper. The beaker contents were wet-sieved with the soil particles being retained by the sieves or filter paper according to grain size. The sieves were then separated and placed at the bottom of the tank of a 100-W ultrasonic cleaner with a water level reaching to a point just below the upper rims of the sieves. The cleaner was operated for 4 min before the sieves and their contents were removed and dried in an oven at 105°C for 20 min.

Three drops of Cargille[2] oil with a refractive index $n$ of 1.54 were separated in the center of a flat microscope slide. A camel-hair brush was used to transfer the very fine sand from the 0.105-mm (150-mesh) sieve onto a piece of paper. A representative subsample of 3 mg was transferred to the oil on the slide; when 3 mg or less was available, the whole sample was transferred to the slide. The grains were thoroughly mixed and then spread evenly over the central portion of the slide with a wooden applicator stick. The mount was completed by placing a cover glass over the mixture of oil and sand.

## Rapid Counting Procedure

A Zeiss petrographic microscope with a binocular viewing head was used to classify and count the soil particles (Fig. 1). One of the wide-angle oculars in the viewing head was equipped with cross hairs; the other was provided with a black matte mask in which a rectangular aperture had been cut (Fig. 2). The dimensions of this aperture (8 by 5 mm) were chosen so that the corners of the rectangle were just within the circular field of the oculars. The mask was positioned in the same plane as the cross hairs in the other ocular so that the edges of the aperture were in focus. A two-way mechanical stage, mounted on the standard rotating stage of the polarizing microscope, was used to hold the glass slide on which the soil particles were mounted. The mechanical stage was positioned with its two arms (north-south and east-west) parallel respectively to the vertical and horizontal cross hairs when the microscope stage was in the initial 0-deg position. The rotating stage was provided with stops at 0 deg and at each 90-deg interval thereafter, enabling the operator to rotate the slide back to the initial position without removing his eyes from the oculars. In addition to the usual transmitted light source, oblique illumination was provided by a high intensity lamp suspended above the stage and to one side of the nosepiece holding the objectives.

The general optical setting of the microscope was arranged as follows. The upper polarizing filter (analyzer) was out, the condenser diaphragm was open, and the lower polar was rotated 8 to 10 deg out of its usual alignment to provide a dark gray rather than a black background when the analyzer was inserted. This was found to be more restful for the eyes and it allowed a better view of particle shape and inclusions during those times when the analyzer was in. Two sources of illumination were used in conjunction, one below the stage for transmitted light and one above and to one side of the stage as a source for reflected light.

Deviations from this general setting were used frequently as different categories of soil particles were identified. Particle shape and twinning were often better defined with the analyzer inserted. The Becke line was best observed by closing down the condenser diaphragm and raising or lowering the stage until the grains were slightly out of focus. For determination of birefringence or wavy extinction, the analyzer was inserted. Rotation of the stage was used to check for pleochroism or variable relief and to observe extinction, isotropy, and birefringence under crossed polars (analyzer in). To observe grains in reflected light it was only necessary to cover the substage light source with one hand.

[2] R. P. Cargille Laboratories, New York, N. Y.

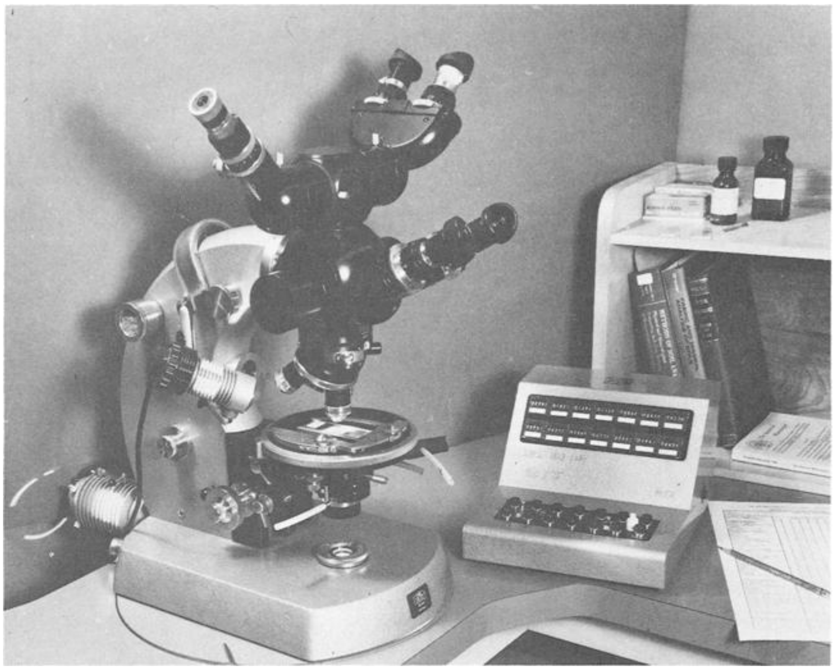

FIG. 1—*Apparatus as set up for the rapid counting procedure showing microscope slide on mechanical stage, transmitted and incident light sources, push-button counter, and counting sheet. Microscope control levers have been modified for ease of manipulation.*

The rapid counting of soil particles was accomplished in the following manner. When some central portion of the slide was brought into view, the vertical (front to rear) motion of the mechanical stage was arrested with a screw clamp and the reading on the corresponding vernier scale was recorded on the counting sheet (Fig. 3). The slide was then

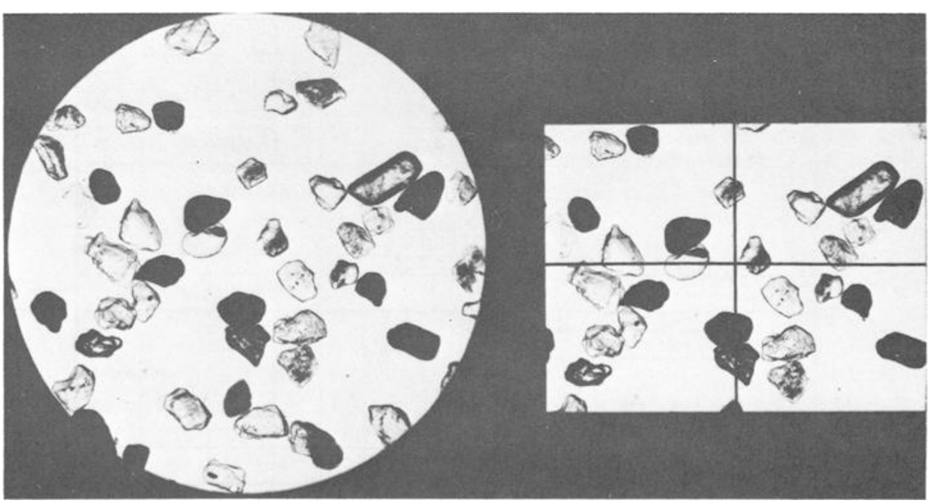

FIG. 2—*Typical view seen through left and right oculars with a rectangular mask inserted in the right binocular tube (transmitted light, analyzer out).*

**MICROSCOPIC SOIL ANALYSIS COUNTING SHEET**

Sample No:  Oven Dry Colour (105°C):

Remarks:

| MINERAL OR PARTICLE CLASSIFICATION | Stage Ordinates(mm) | | | | | Totals No. | Totals % | Totals Rounded % |
|---|---|---|---|---|---|---|---|---|
| **MINERAL GRAINS** | | | | | | | | |
| COMMON MINERALS | | | | | | | | |
| Quartz + Feldspar* | | | | | | | | |
| Microcline (Twinned)* | | | | | | | | |
| Plagioclase (Twinned)* | | | | | | | | |
| Perthite* | | | | | | | | |
| Quartz | | | | | | | | |
| Alkali Feldspar | | | | | | | | |
| Plagioclase | | | | | | | | |
| Carbonate: Microcrystalline | | | | | | | | |
| Macrocrystalline | | | | | | | | |
| LESS COMMON MINERALS | | | | | | | | |
| Garnet: Red | | | | | | | | |
| Colourless | | | | | | | | |
| Purple | | | | | | | | |
| Clinopyroxene: Green | | | | | | | | |
| Colourless | | | | | | | | |
| Orthopyroxene | | | | | | | | |
| Amphibole: Olive Green | | | | | | | | |
| Bluish Green | | | | | | | | |
| Brown | | | | | | | | |
| TRACE MINERALS | | | | | | | | |
| Biotite, Phlogopite | | | | | | | | |
| Apatite | | | | | | | | |
| Gypsum | | | | | | | | |
| Talc, Muscovite | | | | | | | | |
| Chlorite | | | | | | | | |
| Epidote | | | | | | | | |
| Tourmaline | | | | | | | | |
| Zircon, Sphene, Rutile | | | | | | | | |
| OPAQUE PARTICLES | | | | | | | | |
| Pyrite, Marcasite | | | | | | | | |
| Magnetite, Ilmenite | | | | | | | | |
| Cinders | | | | | | | | |
| Hematite | | | | | | | | |
| Limonite | | | | | | | | |
| Black Opaque | | | | | | | | |
| Shale: Brown and Grey | | | | | | | | |
| Red | | | | | | | | |
| Feldspar (Highly Altered) | | | | | | | | |
| OTHER PARTICLES | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| Cumulative Mineral Totals | | | | | | | | |
| **PLANT PARTICLES** | | | | | | | | |
| Structured | | | | | | | | |
| Spores and Seeds | | | | | | | | |
| Unstructured: Translucent | | | | | | | | |
| Opaque | | | | | | | | |
| Cumulative Plant Totals | | | | | | | | |

FIG. 3—*Microscopic soil analysis counting sheet (asterisk designates those minerals not to be included separately in the cumulative mineral totals).*

moved horizontally to view a ribbon traverse extending across the slide. As a grain entered the rectangular frame, one or more quick optical tests were made to classify the particle before it reached the vertical cross hair and was counted. By using the optical conditions listed in Table 1, the grains belonging to any group could be easily counted in the course of one traverse. Several optical categories were usually counted during one pass by using the keyboard counter shown in Fig. 1. Upon completing the ten to fifteen passes necessary to count all grains in one ribbon traverse, the slide was moved 2 mm or more so that the objective was positioned over another ribbon. Usually three to five such ribbons were traversed to give a total count of 1000 to 1500 grains. The ordinate of each ribbon was marked on the counting sheet to ensure that no grain would be counted twice and to enable grains of special interest to be located again.

In a well-dispersed slide, about 300 to 500 grains were contained within the borders of a ribbon traverse when $\times 60$ to $\times 80$ magnification was used. With the rotating stage in its initial position at 0 deg this traverse is parallel to the horizontal cross hair, and the edges of the ribbon are delineated by the upper and lower edges of the mask aperture. It was found to be advantageous to include within the ribbon all grains that touched the edge of the mask. This was more precise and faster than deciding whether or not more than half of a grain was within the frame. Any grain partially obscured by the mask could be clearly seen through the other unmasked ocular.

Table 1 gives a typical sequence used for counting soil particles and assigning them to the 38 optical categories shown in Fig. 3. This table also summarizes the deviations made from the general optical setting while these categories, here combined into 14 groups, were examined. With the exception of trace minerals and plant particles, the categories within each group are optically similar such that one optical setting allowed identification of all optical categories within any one group. Although 14 groups are listed in Table 1, the actual number of passes required to classify any given soil usually varied from 10 to 15. Some soils contained no carbonate, shale, or badly weathered feldspar. In other soils, abundant quantities of less common particles made it more convenient to increase the number of passes.

Four to six traverses were usually required to count those particles listed under "Common Minerals" on the counting sheet (Fig. 3). On the first traverse all grains of quartz and feldspar were counted; this entailed counting all colorless translucent grains with low relief and appropriate morphology. On the next pass, the analyzer was inserted while microcline, twinned plagioclase, and perthite grains were counted. The grains counted in the first two passes, marked with asterisks on the counting sheet, are also included in other optical categories. For this reason, they are not included in the cumulative totals. The quartz and feldspar count is not one of the 38 optical categories since it has been further subdivided into three categories: quartz, alkali feldspar, and plagioclase. Quartz grains were counted on the third traverse and the alkali feldspars ($n < 1.54$) followed on the next pass by making use of the Becke line. Then the totals of the third and fourth passes were deducted from the count for the first traverse. This figure gave the number of plagioclase grains with a refractive index greater than 1.54. The microcrystalline carbonates were examined under polarized and reflected lighting conditions with the analyzer inserted and the transmitted light blocked intermittently. During the sixth pass, the stage was rotated periodically while in the general optical setting to observe the variable relief of the macrocrystalline carbonates.

Three traverses were needed to classify the categories designated "Less Common Minerals" on the counting sheet. The three main groups were subdivided primarily on the basis of color. The general optical setting was used while grains of garnet were counted on the seventh pass, though the analyzer was occasionally inserted to check for isotropy. Pyroxene and amphibole grains were counted essentially under the standard optical setting with only occasional use being made of the analyzer. In the case of the amphiboles the

TABLE 1—*Sequence and optical conditions for particle classification during ribbon traverses.*

| Pass No. | Optical Category or Group | Optical Conditions |
|---|---|---|
| 1 | quartz and feldspars | general setting |
| 2 | microline (twinned); plagioclase (twinned); perthite | analyzer in, rotation of stage |
| 3 | quartz | analyzer alternately in and out, rotation of stage when analyzer inserted |
| 4 | alkali feldspar ($n < 1.54$) | condenser lens out, stage diaphragm closed down, stage raised or lowered to give Becke line |
| ...[a] | plagioclase ($n > 1.54$) | no count required |
| 5 | microcrystalline carbonate | transmitted light blocked intermittently, analyzer alternately in and out while in transmitted light |
| 6 | macrocrystalline carbonate | rotation of stage, analyzer alternately in and out |
| 7 | garnet | analyzer alternately in and out, slight rotation of stage when analyzer inserted |
| 8 | pyroxene | analyzer alternately in and out, slight rotation of stage when analyzer inserted |
| 9 | amphibole | rotation of stage while in general setting, analyzer inserted periodically |
| 10 | trace minerals | variable according to properties of each optical category |
| 11 | opaque particles (except magnetite, ilmenite, shale, and altered feldspar) | transmitted light blocked |
| 12 | magnetite, ilmenite | general setting, magnetized rod held in field of view above slide |
| 13 | shale and highly altered feldspars | transmitted light blocked intermittently, analyzer alternately in and out while in transmitted light |
| 14 | plant particles | variable according to properties of each optical category |

[a] Note: The number of plagioclase grains is calculated by subtraction of Passes 3 and 4 from 1.

stage was rotated to observe the pleochroism; grains showing a bluish green color in any orientation were classified as "bluish green," those showing green to brown pleochroic colors were classified as "olive," and those grains that were brown in all orientations were denoted as "brown."

One pass was usually sufficient for the trace minerals. As opposed to the categories within the other groups of Table 1, the trace minerals were not all similar to one another with respect to optical properties. Many of these, however, were often absent entirely or were present in such small amounts that all could easily be counted during one traverse. As would be expected, the optical conditions varied substantially in the course of this traverse depending on the distinguishing characteristics of the various minerals as given in the Appendix.

Up to three passes were required for the opaque minerals depending on whether or not shale and highly altered feldspar were present. During the count of the magnetite-ilmenite group, a thin iron rod was used. The rod rested against both poles of a small horseshoe magnet with one tip projecting to a point just above the slide and within the field of view. As the traverse was run magnetic particles were shifted and could be readily counted. Grains of shale and highly altered feldspar were examined in both reflected light and transmitted light with polars crossed, as was done with the microcrystalline carbonates. The remaining opaque particles were counted and classified as the transmitted light was intermittently blocked to view the color and appearance of these grains in reflected light.

In most cases plant particles could be counted in one pass. As was the case with trace minerals, the optical setting varied according to the types of plant material in the soil. On the counting sheet the cumulative totals for the counts of plant particles were kept separate from the totals for the mineral grains.

With the exception of plant particles, cinders, and some particles of the magnetite-ilmenite category, Fig. 3 includes only naturally occurring rock and mineral grains. In some soils, less common rock-forming minerals or industrial particles may be found. Descriptions of many such particles have been provided by Winchell and Winchell [*11*] and by McCrone and Delly [*12*]. When these particles are found in soils they can be of great significance but the diversity and scarcity of these contaminants preclude any attempt to describe them here. However, space is provided for listing particles other than those specifically referred to on the counting sheet.

## Discussion

### *Rationale of Method*

In the foregoing sections, the mechanical steps for the preparation and classification of soil samples have been presented with little consideration of the rationale behind the procedure. Basically the method evolved from an attempt to achieve a practical, and at the same time rapid, method for classifying small soil samples on the basis of their mineralogical composition. A discussion of the principles involved in attaining this objective is helpful in understanding the reasoning behind the sample preparation and rapid counting methods previously outlined.

The purpose of the sample preparation procedure was to isolate a convenient size range from the soil. The 0.149- to 0.105-mm fraction was selected for several reasons. It is a nearly ubiquitous fraction of soils with even most gravels and silty clays containing a small percentage of this size fraction. For most soils, 20- to 50-mg samples yielded 3 mg of very fine sand. This quantity amounted to about 1500 grains, a number which provided a counting accuracy to within 5% for all categories composing 5% or more of the sample [*9*]. This same fraction was very convenient for mounting and viewing under the microscope. In this size range most grains consisted of one mineral or optical category and were transparent or translucent, with the exception of some grains listed under "Opaque Minerals" on the counting sheet. Magnification of ×60 to ×80 provided a depth of field in which most of each grain was in focus. The near uniformity of the grain diameters permitted consistent estimation of relief and birefringence. Finally, the grains were not so small as to make identification difficult and interference figures could be obtained when required.

The surfaces of mineral and other solid grains in soils are very often covered in part by deposits of iron oxides and other clay-size materials and by stains of organic materials. These coatings prevent or cause difficulty in the optical identification of the grains. In general these deposits and stains were not removed by the vigorous stirring undergone by the grains during the dispersion process. Removal by cavitation in an ultrasonic bath was found to be superior in speed and cleaning power to chemical methods. Additionally, the grains were not altered chemically and the mechanical effects upon the grains seemed to be minimal.

Cargille oil was used in preference to Canada Balsam[3] or Permount[3] for mounting the very fine sand on the glass slides for the following reasons: its refractive index was known with considerable accuracy; it was less viscous and allowed a more even and more random mixing of grains; special grains could be rolled to different positions so that their optical properties could be better measured; and magnetic particles could be detected by their movement as a magnet was passed over the slide.

[3]Fisher Scientific Co., Fair Lawn, N. J.

In the rapid counting procedure much time was saved by placing the mineral, rock, and plant particles into such categories as could be differentiated without resorting to extensive optical tests. On the counting sheet, the 40 or more mineral species and rock particles found in Ontario soils were reclassified into 33 optical categories to which were added five additional categories including cinders and four optical types of plant particles. Several mineral species were not classified individually on the counting sheet. For example, the green clinopyroxene category includes augite, diopside, actinolite, and aegirine, minerals that cannot always be quickly distinguished from one another. In this case, the optical category "green clinopyroxene" includes several mineral species, one of which belongs to the amphibole group. In other instances, the categories were subdivided on the basis of some readily distinguishable property. Thus the carbonate grains were put into different categories on the basis of morphology, and the amphibole grains were subdivided according to their pleochroic colors. It was possible to obtain this increased efficiency because an exact mineralogical breakdown of a soil is not required by the forensic scientist. What is important is that a comparison of the contents of two or more soils can be made according to a rapid, yet consistent and unambiguous, classification scheme. The descriptions of soil particles contained in the Appendix reflect this modified approach to soil mineralogy and vary at times from standard mineralogical classifications [*4-7*]. Other variations in these descriptions arise as a consequence of the procedure used and the attempt to concentrate on those optical properties that can be quickly determined. For these reasons, the Appendix should be a valuable guide to anyone attempting to use this method of soil analysis.

Further time was saved by combining optically similar categories into the 14 groups of Table 1. By making use of a push-button counter several categories could be counted at one time under the same optical conditions. This greatly reduced the number of passes required to classify all soil particles in any ribbon traverse.

As a result of these modifications to a conventional mineralogical examination, the amount of time required to quantify the composition of one sample by counting 1000 to 1500 grains was reduced from 15 h or more to about 2 h.

*Utility and Scope of Method*

The procedure for classifying soils presented in this paper is especially suited to comparisons of the very small soil samples usually encountered by forensic scientists. By employing this procedure it has been possible to show that there are a large number of soils in Ontario which can be distinguished on the basis of composition and that the mineral composition of a soil within a footprint-size area is nearly homogeneous in most instances. It has also been determined that the small differences found between two soil samples from the same location are greater than would be introduced by the random counting error alone. For this reason the time spent counting 1000 to 1500 grains for increased accuracy is not necessary for routine case work. A count of 300 grains per sample suffices to differentiate between two soils with significant quantitative differences and offers considerable time savings; a 1200-grain count increases the time factor by four, yet increases by only a two-fold margin the accuracy obtained by counting 300 grains [*13*]. Where qualitative or major quantitative differences are noted between two samples, a preliminary examination can replace the counting procedure. As a result of these findings, the microscopic determination of soil composition has been an integral part of soil examinations in this laboratory for the past several years.

Although the quantitative mineral composition is an important point of comparison between soils, the same is not true for plant particles whose proportions in soils were found to vary abruptly over very small distances. For this reason, the totals for plant particles were kept separately from those of the mineral constituents. Only qualitative comparisons of plant particles were found to be of significance.

Before this classification scheme can be applied to areas other than Ontario, two possible difficulties must be recognized: some localities may not have a large number of different soils (as is the case in Ontario), and the soil mineralogy of other regions may vary from that outlined on the counting sheet. With respect to the first of these problems, the usefulness of soil composition as a forensic property would be greatly diminished. Although the classification scheme could still be used in areas where soil mineralogy was uniform over considerable distances, the forensic significance of such comparisons would be very limited. The second problem is more easily resolved. Where the mineralogy is significantly different from Ontario soils, a preliminary survey should reveal such differences. The counting sheet could then be modified by the addition or deletion of particle classifications as required.

Most parts of Europe and large portions of northern Asia and America have experienced the same recent geological history as Ontario. The glacial advances and retreats that have helped shape the present topography of Ontario have been at work in these other areas as well. It is, accordingly, very probable that the soils within these recently glaciated regions will, like the soils of Ontario, display large variations in mineralogy. Thus the soil analysis method proposed here should be adaptable to many different areas, provided adjustments are made for regional variations in mineralogy.

**Summary**

A method for the rapid quantitative mineralogical classification of soils is presented. This method is oriented towards the examination of small soil samples and is therefore well suited to the needs of forensic scientists. Soil particles are identified with the polarizing microscope using the fraction within the 0.149- to 0.105-mm (100- to 150-mesh) size range. Sample preparation and a rapid counting technique are described in detail, and the optical properties of commonly occurring soil particles are appended, with emphasis being placed on their distinguishing characteristics. This classification scheme has been instrumental in determining the forensic science usefulness of soil mineralogy. Although developed in Ontario, the method should be adaptable to many other geographical locations by adjusting for regional variations in mineralogy.

*Acknowledgments*

The author is indebted to Mr. O. J. Frenkel, M.Sc., who initiated a mineralogical approach to soil analysis at this laboratory and who originated the concept of a rapid counting technique.

# APPENDIX

Soils contain mineral and rock fragments formed by the mechanical and chemical weathering of pre-existing rocks. It is important to bear in mind that the following descriptions apply to a given size range of these detrital particles and that the properties listed for each will often not be applicable to particles of greater or lesser size or to the same grains mounted in thin section.

Each optical category is divided into the following sections: color, morphology, relief, birefringence, and distinguishing features. The color or colors of the grains are given as seen in both transmitted and reflected light. Pleochroic color variations are included since the lower polarizer is in place at all times. The typical morphology of the particles follows with a listing of such properties as degree of alteration, shape of grains, cleavage, fracture, and twinning. A value designating the relief of a grain represents the difference between the refractive indices of the particle and the immersion medium, a value which may be either positive (when the refractive index of the particle is higher) or negative (when the refractive index of the immersion medium is higher). Included with the birefringence is a description of the observed interference colors. Each particle description ends with a summary of those properties that best serve to distinguish that category from other optically similar categories.

**Quartz** is colorless in transmitted light. Under reflected light the quartz grains are very slightly lighter than the background. *Morphology:* The great majority of grains are anhedral, angular to subangular in shape, and are characterized by conchoidal fracture and lack of cleavage. Small inclusions are common, the predominant type being spherical liquid and gas inclusions, usually arranged in well-defined planes. *Relief* is very low (+0.004 to +0.013). *Birefringence* is 0.009. Grains typically have one or two broad edges that are gray but the interference colors range from gray to first- or second-order colors near the center of the grains. About one grain in 500 will show third-order colors. A wavy extinction is shown by many of the grains. *Distinguishing Features:* Quartz is distinguished from apatite by its low relief and conchoidal fracture, and from the feldspars by clearness of the grains, lack of cleavage, conchoidal fracture, and, frequently, by wavy extinction and aligned inclusions.

**Alkali Feldspars** ($n < 1.54$) include potassium feldspars and sodium feldspars (albite). Distinctions between albite grains and grains of the potassium feldspars cannot be made rapidly and both are therefore classified under the general name "alkali feldspars." This arbitrary division between sodic plagioclase and the more calcic feldspars is established by the use of an immersion medium with a refractive index of 1.54. The alkali feldspars are colorless in transmitted light; weathered portions vary from light yellow to light brown. Under reflected light, the altered portions are grayish to yellowish or light brown, whereas the unweathered areas reflect almost no light. *Morphology:* The potassium feldspars occur as anhedral, subhedral, or broken grains in nearly equal proportions. Most grains are equant and display good cleavage in one or two directions. Microcline is distinguished from orthoclase and sanidine by polysynthetic twinning in two perpendicular directions. Albite has a morphology similar to the other plagioclase feldspars. Perthite, an intergrowth of albite and potassium feldspar, is characterized by its intergrowth structures, best seen under crossed polars. These structures take many forms such as veinlets, rods, spindles, or patches. *Relief* is low (0.000 to −0.018). *Birefringence* is 0.007 to 0.008. Interference colors range from a typical gray at the edges of the grains up to the top of the first order at their centers. *Distinguishing Features:* The alkali feldspars are distinguished from quartz and plagioclase feldspars by their lower refringence.

**Plagioclase** ($n > 1.54$) is colorless in transmitted light; altered portions vary from light yellow to dark brown. Under reflected light the altered areas range from light gray to white. *Morphology:* Prismatic subangular grains showing good cleavage in one or two directions are common. Alteration is less common than for the alkali feldspars and is often localized along partings and traces of cleavage planes. Polysynthetic twinning is observed in many grains. *Relief* is very low (0.00 to +0.04). *Birefringence* ranges from 0.007 to 0.012. Interference colors range up to lower second-order colors at the centers of the grains. *Distinguishing Features:* Plagioclase is distinguished from alkali feldspar by its higher refringence. It is differentiated from quartz by good cleavage, prismatic habit, and, for a proportion of the grains, by altered surfaces or twinning.

**Microcrystalline Carbonates** include rock fragments of both limestone and dolostone. In transmitted light the grains are light to dark gray or brownish gray and range from translucent to nearly opaque. The degree of opaqueness increases with increasing fineness of the particles composing each grain and with content of argillaceous matter. Under reflected light the grains range from gray to very light gray and white (cloud-like), buff, or occasionally greenish yellow. *Morphology:* The fragments are mostly rounded to subrounded. They have a granular appearance in both transmitted and reflected light. Individual crystals are always discernible at the edges of the grains at a magnification of ×200 or more. *Relief* is highly variable and can be observed in the individual crystals. *Birefringence* is extreme. High-order white interference colors are shown by the translucent fragments; in the more opaque grains, the crystals at the edges of the fragments will usually show first- to third-order colors. *Distinguishing Features:* The granular appearance and the colors in transmitted and reflected light are distinctive. Limestone and dolostone are distinguished from calcareous shale by the relative quantities of calcite and feldspar grains among the individual crystals at the edges of the fragments.

**Macrocrystalline Carbonates** (calcite and dolomite) are colorless in transmitted light although fine bands of iridescent colors are sometimes visible. Under reflected light the grains are very dark gray. *Morphology:* The grains are frequently euhedral to subhedral rhombic crystals, but they are also found as angular to rounded fragments. (Twinning is displayed by some grains.) *Relief* is highly variable (−0.05 to +0.14). Most grains are oriented so as to show this marked variation as the microscope stage is rotated. *Birefringence* is 0.18. White interference colors of the 6th to 20th order are shown by the grains. *Distinguishing Features:* The variable relief and the very high birefringence are distinctive.

**Garnets** are light red to orange, pale violet, or colorless in transmitted light. Under reflected light the grains vary from very dark gray to dark reddish or violet gray. Specular reflections from external or internal planes may cause parts of the grains to appear lighter in color. *Morphology:* Garnets are found as equant euhedral crystals or as subrounded grains. The latter usually show pitting and conchoidal fracture surfaces. Inclusions are found frequently. *Relief* is very high (+0.26 to +0.46). *Birefringence:* Garnet is isotropic but anomalous and weak birefringence is sometimes observed. *Distinguishing Features:* The isotropy and the dark borders resulting from the high relief are distinctive.

**Clinopyroxenes** also include grains of such optically similar species as kyanite and two of the amphiboles (actinolite and tremolite). The grains are colorless to pale or bright green in transmitted light. Under reflected light the grains are very dark gray to very dark greenish gray with weathered portions light gray or brown. *Morphology:* Grains are usually stubby subangular prismatic cleavage fragments with ragged (dentate) terminations. Inclusions or cloudy alteration products are seen occasionally. Good cleavage in two nearly perpendicular directions is shown by most grains. *Relief* is moderate to high (+0.06 to +0.20). *Birefringence* ranges from 0.02 to 0.04. Second-, third-, and fourth-order interference colors are most common. *Distinguishing Features*: Clinopyroxenes are distinguished from amphiboles by their higher birefringence, absence or weakness of pleochroism, a greater degree of angularity, and greater translucence. They are distinguished from the orthopyroxenes by their color and higher birefringence.

**Orthopyroxenes** also include grains of andalusite and staurolite. In transmitted light some grains are colorless, but most are pleochroic in colors of pale pink, red, and yellow. Almost no light is reflected by the orthopyroxenes, but light gray to brown weathered portions are seen occasionally. *Morphology:* The grains are typically equant or stubby prismatic cleavage fragments. Striations paralleling the cleavage, cut by cross fractures at about 90 deg, are conspicuous. *Relief* is high (+0.12 to +0.19). *Birefringence* ranges from 0.009 to 0.016. First- and second-order interference colors are typical. *Distinguishing Features:* Orthopyroxenes are differentiated from clinopyroxenes by pleochroism and birefringence.

**Amphiboles** consist of hornblende grains, generally pleochroic in colors of green, bluish green, olive, and brown. Some of the thicker grains appear opaque except near their thinnest edges. Under reflected light amphibole grains differ from most other grains in being very often darker than the background illumination of the immersion medium. *Morphology:* The grains are generally subhedral elongate prisms with rounded ends. Good cleavage in two directions is seen as longitudinal traces on the prismatic faces. Cross fractures are common. *Relief* is moderate to high (+0.07 to +0.22). *Birefringence* ranges from 0.016 to 0.030 for the great majority of the amphibole grains found in soils. Basaltic (brown) hornblende has a higher birefringence but is rare. Second-order interference colors are typical, and in almost all cases they are partly masked by the colors of the mineral, giving them a "muddy" appearance. *Distinguishing Features:* The amphiboles are distinguished from the clinopyroxenes by their deeper colors, pleochroism, elongate shapes, and lower birefringence. The extremely dark appearance of the grains in reflected light distinguishes the opaque amphiboles from the other opaque grains.

**Biotite** and **Phlogopite** range from colorless to pale brown, orange brown, or dark brown in transmitted light. Pleochroism is not usually well displayed by grains on the microscope slide since they are generally lying on the flat basal cleavage planes. Grains appear very dark gray to very dark brownish gray under reflected light. *Morphology:* All grains have one perfect basal cleavage, almost always oriented parallel to the microscope slide. Flakes lying on this plane have equant hexagonal or subrounded to irregular shapes. *Relief* is low to moderate (+0.04 to +0.11) for almost all flakes. *Birefringence* of biotite and phlogopite is high but again, because of their preferred orientation, the grains show typical dark gray interference colors with some wavy extinction. *Distinguishing Features:* Biotite and phlogopite are distinguished from amphibole by their more equant outlines and by their apparent lack of cleavage traces, pleochroism, and birefringence.

**Apatite** is colorless in transmitted light and is very dark gray under reflected light. *Morphology:* Most apatite grains are equant and rounded. Less commonly it shows somewhat worn elongated prismatic forms. Inclusions arranged in rows or planes may be present. The surface of the grains is often very finely pitted and appears like frosted glass. *Relief* is moderate (+0.09 to +0.11). *Birefringence* is very weak (0.003 to 0.005). Interference colors are typically first-order gray to orange. *Distinguishing Features*: Apatite is differentiated from colorless pyroxenes by its very low birefringence, high degree of rounding, and frosted surfaces. It is distinguished from quartz and feldspar by the much higher relief and lack of conchoidal fracture.

**Gypsum** (selenite) is colorless in transmitted light. Under reflected light, grains with aggregate texture are light to medium gray; the others are dark gray. *Morphology:* Euhedral to subhedral prismatic to rhombic-shaped grains and grains with irregular shapes are equally common. Parallel streaks of included fine matter are often found in both types of grains. Fibrous or aggregate textures and ragged edges are typically shown by those grains that have irregular shapes. *Relief* is low (−0.02 to −0.01). *Birefringence* is 0.009. First- and second-order interference colors are typical for euhedral grains, and grays or yellows of the first order are typical in the aggregate grains. *Distinguishing Features:* Euhedral grains of gypsum are distinguished from alkali feldspars by their crystal form and parallel streaks of included material. The irregular grains are distinguished from grains of alkali feldspars by their aggregate or fibrous appearance and are differentiated from talc grains by their lower refringence.

**Talc** and **Muscovite** are colorless in transmitted light and dark gray under reflected light. Weathered portions are gray to white under reflected light. *Morphology:* Talc occurs in fibrous aggregates, shreds, and plates, which often have a parallel arrangement. The grains may be bent. Muscovite occurs in thin plates which, like those of other micas, appear equant when lying flat on the microscope slide. It occurs also in aggregates or shreds. Both talc and muscovite have perfect cleavage in one direction. *Relief* is low to moderate (0.00 to +0.07). *Birefringence* ranges from 0.03 to 0.05. Flakes lying on their basal faces show first-order interference colors. Grains in other orientations show brilliant colors of second and higher orders. *Distinguishing Features:* Talc and muscovite are differentiated from biotite, phlogopite, and chlorite by their lack of color and from fibrous gypsum by their higher birefringence and refringence.

**Chlorites** are weakly pleochroic in colors of pale green to yellowish green in transmitted light. Under reflected light the grains are very dark gray. *Morphology:* Chlorite grains, like the micas, are most commonly thin flakes that lie with their basal cleavage faces on the microscope slide. In this orientation the grains appear equant, occasionally showing pseudo-hexagonal outlines. *Relief* is low to moderate (+0.02 to +0.11). *Birefringence* shown by basal plates is very low. Gray to dark gray interference colors are common. *Distinguishing Features:* Chlorites are distinguished from the amphiboles by lighter colors and an apparent lack of cleavage. They are distinguished from the pyroxenes by their micaceous habit and very low birefringence.

**Epidote** is usually weakly pleochroic in transmitted light in colors of brown to yellowish green or pale yellow; some grains are colorless. Colors are usually patchy, both in transmitted and reflected light, because of extensive weathering. Grains range from very dark gray to pale shades of yellow and green under reflected light. *Morphology:* Most grains show angular to subrounded equant shapes but euhedral prismatic grains are occasionally seen. *Relief* is very high (+0.18 to +0.24). *Birefringence* varies from 0.02 to 0.05. The high interference colors are sometimes masked by the greenish shades of the epidote grains but anomalous brilliant red and green interference colors are frequently seen, especially in the clear grains. *Distinguishing Features:* Epidote is distinguished from clinopyroxene by its yellow tint, extent of alteration, very high relief, and anomalous interference colors.

**Tourmaline** is pleochroic in transmitted light in various combinations of yellow, pale brown, pale violet, indigo, black, and colorless. Under reflected light the grains are very dark gray. *Morphology:* Tourmaline occurs most often as irregular, fractured pieces but also as elongated prismatic grains and rounded oval grains. The prismatic grains have fractured ends and prominent striations. *Relief* is moderate to high (+0.08 to +0.16). *Birefringence* varies from 0.02 to 0.04. Interference colors range from second to fifth order but these may be masked in the darker grains. *Distinguishing Features:* Tourmaline is distinguished from the pyroxenes and from detrital biotite by its pleochroism, morphology, and prominent striations.

**Rutile, Sphene,** and **Zircon** are frequently indistinguishable as detrital grains. In transmitted light, rutile is weakly pleochroic in yellow and reddish brown; sphene is also weakly pleochroic, varying from colorless to pale yellow and light brown; zircon is usually colorless but some grains are yellow to brown and the darker grains are pleochroic. Under reflected light, rutile is yellow or brown; sphene and zircon vary from very dark gray to light yellowish gray. *Morphology:* Rutile often occurs as short euhedral prisms that may have rounded pyramidal ends or less frequently as irregular grains; sphene is commonly irregular and subangular but is sometimes found as euhedral diamond-shaped grains; zircon varies in morphology from euhedral prisms with pyramidal terminations to elongated rounded grains. The grains of all three minerals commonly contain inclusions. *Relief* varies from very high to extreme: rutile (+1.06 to +1.46), sphene (+0.35 to +0.51), and zircon (+0.38 to +0.45). *Birefringence* is very high to extreme: rutile (0.29), sphene (0.09 to 0.14), and zircon (0.06). High-order white interference colors are usually masked by the absorption colors of the grains. Anomalous extinction colors, especially deep blue, are shown by many grains of sphene. *Distinguishing Features:* These three minerals are distinguished from epidote and pyroxene by their very high relief and apparent lack of interference colors.

**Pyrite** and **Marcasite** are opaque to transmitted light. Under reflected light they show a metallic brassy yellow color often tarnished in part to a dull dark-brown veneer. *Morphology:* The grains are commonly equant and may be subhedral to irregular in shape. Less frequently the grains consist of aggregates of minute crystals or globular clusters. They occasionally display ragged edges. *Distinguishing Features:* Pyrite and marcasite are distinguished from cinders by their metallic yellow colors in reflected light.

**Magnetic Particles** include magnetite, most ilmenite, iron, and rust particles with iron cores. All of these are opaque to transmitted light. Under reflected light magnetite, ilmenite, and iron particles are grayish, bluish, and brownish black with metallic luster; rust particles are dark brown to reddish brown with many small reflecting surfaces. *Morphology:* Magnetite and ilmenite are found as equant, angular to subrounded grains showing some crystal facets; iron particles vary from irregular jagged fragments to well-rounded spherules; rust particles often show elongated wedge-like shapes and frequently have ragged edges. *Distinguishing Features:* Magnetic properties distinguish these particles from other opaque grains.

**Cinders** are generally opaque to transmitted light although some grains may be translucent in part. Under reflected light the grains vary from white through yellow, brown, reddish brown, and occasionally black. There is no metallic luster; the surfaces are typically matte. *Morphology:* Cinders are the products of fusion often followed by fragmentation. Most cinders have highly irregular shapes characterized by holes (resulting from gas bubbles), and by re-entrants with round or ragged outlines. Globular clusters, or a single globule fused to a particle of irregular shape, may be seen occasionally. *Distinguishing Features:* Cinders are distinguished from other opaque particles by their highly irregular shapes and matte surfaces.

**Hematite** and nonmagnetic rust particles are reddish where translucent. Hematite grains generally appear to be opaque, but the small grains may show some translucence along thin edges; rust particles are almost always opaque. Under reflected light both particles are commonly dark reddish brown and often display reflections from many small surfaces. *Morphology:* Hematite grains are commonly found as irregular equant particles; rust particles are often elongate, display wedge-like shapes, and frequently have ragged edges. *Distinguishing Features:* These grains are distinguished from other opaque particles by their lack of magnetism and by their color.

**Limonite** is brown when translucent but is usually opaque in transmitted light. Under reflected light it varies from earthy to metallic bright yellow, orange, or brown. *Morphology:* Rounded particles or powdery aggregates are common. *Distinguishing Features:* Limonite is distinguished from other opaque particles by its colors in reflected light.

**Black Opaque Particles** are opaque to transmitted light and are black under reflected light. This classification includes black cinder particles that do not show characteristic outlines, grains of ilmenite that are nonmagnetic, and other less commonly occurring particles having the same optical properties. *Distinguishing Features:* The black color under reflected light and lack of magnetism distinguish these grains from the other opaque particles.

**Shales** are colorless where translucent. Although grains of shale are largely opaque, transmitted light usually can be seen at the edges of grains. Under reflected light shales display various shades of earthy brown, gray, and red and are characterized by nonuniform colors within a single grain. Brown and gray shales may show black bituminous inclusions. *Morphology:* Grains are equant to slightly elongate, often platy, and subrounded to rounded in form. The aggregate nature of the grains is usually apparent, especially at higher magnifications. Silt-sized single crystals of quartz and feldspar can usually be found at the edges of the grains where their relief can be observed. *Relief* is low for most of the silt-sized crystals. When highly variable relief is shown by some of the individual crystals, then the aggregate consists of a calcareous shale. *Birefringence* is low. Single crystals of quartz and feldspar at the edges of the grains are characterized by dark gray to gray interference colors. Silt-sized carbonate particles at the edges of calcareous shale grains show bright first- to third-order colors. *Distinguishing Features:* Shale is distinguished from other opaque particles by the aggregate nature of the fragments. It is distinguished from argillaceous limestone grains by the lack of variable relief shown by most of the single crystals.

**Highly Altered Feldspars** are light brown to grayish brown where transparent to transmitted light and light gray to light brown under reflected light. *Morphology:* The grains tend to be more rounded than the fresher feldspars. Alteration and pitting of the surfaces are often visible. *Relief* is the same as for fresh feldspar but is more difficult to determine because of the extensive weathering of the grains. *Birefringence:* First- and second-order interference colors are often visible despite alteration, sometimes only in part of a grain and often with the colors partly masked. *Distinguishing Features:* The altered feldspars are distinguished from limestone particles by their low relief and birefringence, from brown opaque particles by their partial translucence, and from shale by their nonaggregate nature.

**Plant Particles:** Structured particles, including nonopaque spores and seeds, range from pale gray to yellow and brown in transmitted light. The color is often variable across a particle. Translucent unstructured particles are brown in color, often having a dull turbid appearance. In reflected light structured particles and spores and seeds are dark gray. Unstructured particles range from dark gray (translucent) to dull turbid grayish brown (opaque). *Morphology:* Structured particles are typically elongate with fibrous, cellular, or other internal structures; spores and seeds are usually present as broken fragments of spheres, ellipsoids, or other seed-like shapes; unstructured particles vary from equant to elongated and from irregular to subrounded. *Relief* is generally low; the index of refraction of most plant particles is close to 1.54. *Birefringence* ranges up to 0.01 for the structured particles and the spores and seeds; first-order interference colors are most common. The unstructured particles are isotropic; no interference colors are shown. *Distinguishing Features:* The structured plant particles are distinguished from mineral grains by their pale and uneven color and by their external and internal structures. Spores and seeds are differentiated from structured plant particles by their external shape. The unstructured plant particles are distinguished from brown shale by their lack of aggregate structure and interference colors. They are distinguished from rust and limonite by their turbid appearance and by their lack of bright reflections from small surfaces.

## References


[1] Dell, C. I., *Canadian Journal of Soil Sciences*, Vol. 39, 1959, pp. 185-196.
[2] Dell, C. I., *Canadian Journal of Soil Sciences*, Vol. 43, No. 2, 1963, pp. 189-200.
[3] Dell, C. I., *Canadian Mineralogist*, Vol. 6, No. 3, 1959, pp. 363-371.
[4] Larsen, E. S. and Berman, H., *The Microscopical Determination of the Non-Opaque Minerals*, 2nd ed., U. S. Geological Survey Bulletin 848, Washington, D. C., 1934.
[5] Krumbein, W. C. and Pettijohn, F. J., *Manual of Sedimentary Petrography*, Appleton-Century-Crofts, New York, 1938.
[6] Rogers, A. F. and Kerr, P. F., *Optical Mineralogy*, 2nd ed., McGraw-Hill, New York, 1942.
[7] Milner, H. B., *Sedimentary Petrography*, Vol. 2, Macmillan, New York, 1962.
[8] Hewitt, D. F. and Karrow, P. F., *Sand and Gravel in Southern Ontario*, Queen's Printer, Toronto, 1963.
[9] Brewer, R., *Fabric and Mineral Analysis of Soils*, Wiley, New York, 1964, pp. 45-50.
[10] Dreimanis, A., Reavely, G. H., Cook, R. J. B., and Knox, K. S., *Journal of Sedimentary Petrology*, Vol. 27, No. 2, 1957, pp. 148-161.

[11] Winchell, A. N. and Winchell, H., *The Microscopic Characters of Artificial Inorganic Solid Substances*, Academic Press, New York, 1964.
[12] McCrone, W. C. and Delly, J. G., *The Particle Atlas*, 2nd ed., Ann Arbor Science Publishers, Ann Arbor, Mich., 6 vol., 1973-1979.
[13] Dryden, A. L., *Proceedings of the National Academy of Sciences*, Vol. 17, No. 5, 1931, pp. 233-238.

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