

**Identification of Illite Polytype Zoning in
Disseminated Gold Deposits Using
Reflectance Spectroscopy and X-Ray
Diffraction—Potential For Mapping
With Imaging Spectrometers**

**Fred A. Kruse
Phoebe L. Hauff**

**Reprinted from
IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING
Vol. 29, No. 1, January 1991**

Identification of Illite Polytype Zoning in Disseminated Gold Deposits Using Reflectance Spectroscopy and X-Ray Diffraction—Potential For Mapping With Imaging Spectrometers

Fred A. Kruse and Phoebe L. Hauff

Abstract—X-ray diffraction studies of clay minerals from disseminated gold deposits in Nevada demonstrate that illite polytypes are often laterally and vertically zoned around ore bodies. Polytypes act as geothermometers indicating temperatures of ore deposition and thus proximity to the hydrothermal fluids during deposition. Visible/infrared reflectance spectroscopy for field identification and mapping of the illite polytypes is evaluated. Laboratory spectral measurements demonstrate that systematic changes occur as the illites progress from the lower temperature, less ordered *1M* variety through the higher temperature *2M* type. Distinctive absorption features near 1.90 and 2.20 μm and between 2.3–2.5 μm differentiate interlayer water, structural water (OH^-), and some octahedral layer characteristics. These changes were also observed in the laboratory using a field portable spectrometer and *in situ* at a major disseminated gold deposit. The results demonstrate that reflectance spectroscopy can be used to assist gold exploration efforts by providing detailed mineralogical information in real time at the field location. As the new generation of imaging spectrometers is developed, it is likely that subtle spectral differences such as those between the illite polytypes will become useful for remote exploration for gold deposits.

I. INTRODUCTION

THIS PAPER describes a technique utilizing X-ray diffraction and reflectance spectroscopy for identification of potential economic ore zones in precious metal deposits. The deposits being studied are those termed “disseminated gold” as the gold found within them is distributed through a high volume of rock and is usually submicroscopic in grain size. A large number of these systems are found concentrated near or within the mountain ranges in the state of Nevada. The Carlin–Trend disseminated gold deposits of north-central Nevada are ideal for study of alteration assemblages. The geology is generally well-known, and gold assays already exist for many areas. The Carlin Gold mine in Eureka County, Nevada, was selected for the initial study because it is recognized as the type locality for the original sediment hosted disseminated gold deposit.

The clay mineral illite is associated with the gold mineralization in many disseminated gold systems [1]. Illite is an important mineral species in these deposits as it can reflect lat-

eral and vertical zonation around gold ore bodies. Illites change crystal structure with temperature [2], [3] and may act as geothermometers indicating temperatures of ore deposition and proximity to hypogene and supergene fluids. The exploration method described here utilizes the structural ordering of the illite crystal lattice to predict zonal relationships within disseminated gold deposits.

Reflectance spectroscopy and multispectral remote sensing are proven tools for locating and mapping hydrothermally altered rocks [4]–[11]. Broad-band systems such as the Landsat Multispectral Scanner (MSS, four spectral bands) and Thematic Mapper (TM, six spectral bands) provide an operational capability that can be used by the exploration geologist to identify areas for more detailed study. These instruments, however, identify only general mineral groups such as carbonates, clays, and iron oxides. New imaging spectrometer systems with higher spatial and spectral resolution (up to 224 narrow spectral bands) make identification of individual minerals and mineral assemblages possible, thus permitting detailed site-specific mapping of alteration mineralogy.

II. X-RAY DIFFRACTION DETERMINATION OF ILLITE POLYTYPES

X-ray diffraction studies indicate that illite is an important mineral species in disseminated gold deposits, reflecting lateral and vertical temperature zonation around gold ore bodies [12]. To understand better what changes were occurring in the alteration zones of the deposits studied, a reference set of illites was assembled. Fig. 1 is a compilation of X-ray diffractograms showing the two most common illite species or polytypes. These range from the higher temperature well-ordered *2M* to the poorly ordered lower temperature *1M* variety.

Illite polytypes can be differentiated by automated X-ray diffraction [12]. Several diagnostic polytype peaks occur between 23° – 32° 2θ (Fig. 1). The *2M* from Japan (Fig. 1, scan A) is a classic high-temperature hydrothermal illite [13]. The *2M* illite from the Marblehead location (Fig. 1, scan B) is of sedimentary origin. It is quite different from the Japanese sample in that its structure contains considerably more water from interstratified smectite. This is shown by the broad asymmetrical profile of its 10\AA (8.9°) peak and the higher background from 2° to 7° . The Silver Hill sample (Fig. 1, scan D), also sedimentary, has

Manuscript received November 10, 1989; revised March 20, 1990. This work was supported in part by NASA under Grant NAGW-1601.

The authors are with the Center for the Study of Earth from Space, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309.

IEEE Log Number 9038750.

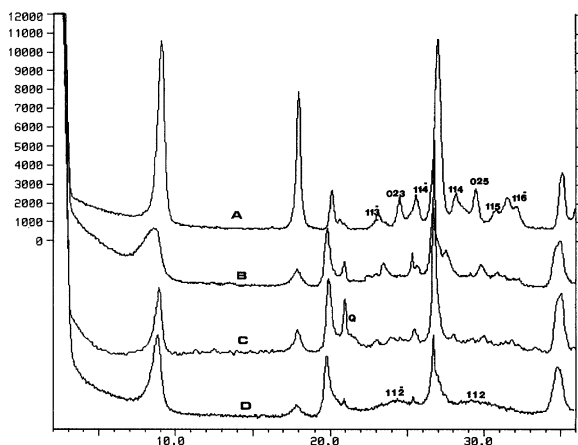


Fig. 1. X-ray diffraction scans of reference illites showing polytype differences. Vertical scale shows intensities. Q indicates presence of quartz. Horizontal scale is in degrees 2θ . Peaks marked with numerical hkl values indicate some diagnostic polytype reflections. A: Japanese hydrothermal $2M$ [13]. B: sedimentary $2M$ from Marblehead, WI. C: sedimentary $1M$ from Fithian, IL. D: disordered $1M$ from Silver Hill, MN. Instrument is the modified automated Philips system with Nicolet software running with copper tube.

been identified as a $1M_d$, which indicates disorder in its stacking. The smaller peaks at $\sim 25.5^\circ$ and $\sim 27^\circ$, diagnostic of the $1M$ polytype, are not as well-defined as in the Fithian sample (Fig. 1, scan C) which is considered to be $1M$. It becomes obvious that extensive variation exists among the illites, and the lower temperature, more disordered varieties are not as easy to identify using X-ray diffraction as the $2M$ polytypes.

III. SPECTRAL MEASUREMENTS

Although several authors [13]–[17] have briefly discussed illites, no attempt has been made in the literature to document the spectral variation in polytypes systematically. Fig. 2 shows high spectral resolution (3.8 nm resolution, 1 nm sampling) laboratory reflectance spectra of the reference illites shown in Fig. 1. Changes in the illite reflectance spectra are observed as the illites progress from the lower temperature, less ordered $1M$ variety through the higher temperature $2M$ type. Distinctive absorption features for illites are summarized in Table I. Features near 1.40, 1.90, and 2.20 μm and between 2.3–2.5 μm differentiate interlayer water, structural water (OH^-), and some octahedral layer characteristics. The reflectance spectrum for the $2M$ illite polytype is similar in appearance to that of muscovite [15]–[18]. The $2M$ illites typically have a sharp absorption feature at 2.2 μm caused by OH^- in the mineral structure [18]. In the $1M$ polytype, this band is broader and asymmetrical toward longer wavelengths. The $1M_d$ spectrum from Silver Hill suggests that a secondary absorption feature near 2.25 μm may be the cause of the absorption band asymmetry. The presence of absorption bands at both 1.4 and 1.9 μm is indicative of molecular water as water of hydration or water trapped in the mineral lattice [18]. If the 1.4 and 1.9 μm bands are sharp, as they are in the $2M$ polytype (spectra A and B, Fig. 2), this indicates that the water molecules are located in well-defined well-ordered sites. When these bands are broad and asymmetrical, as they are in the $1M$ illite polytypes (spectra C and D, Fig. 2), then they indicate that the mineral is relatively disordered [18]. The occurrence of the 1.4- μm band without the 1.9- μm absorption band indicates the presence of hydroxyl (OH^-) and the absence of molecular water. Additional weak absorption bands at 2.35

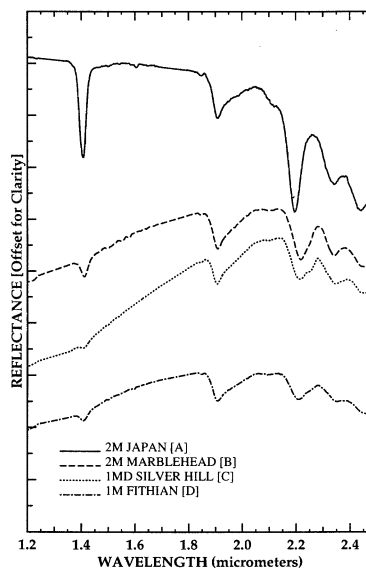


Fig. 2. Laboratory reflectance spectra of illite reference standards showing polytype differences. Note how absorption features at 1.4, 1.9, 2.2, and between 2.3 and 2.5 μm change with polytype. A: high-temperature hydrothermal $2M$ from Japan. B: sedimentary $2M$ from Marblehead, WI. C: sedimentary $1M$ from Silver Hill, MN. D: disordered $1M$ from Fithian, IL. Spectra were collected on the Beckman 5270 spectrometer with integrating sphere.

TABLE I
DIAGNOSTIC ABSORPTION FEATURES FOR ILLITE POLYTYPES

Feature Position	Physical Basis	Strength ($2M$)	Strength ($1M$)
1.4 μm	molecular water + structural water	$2M$ = sharp	$1M$ = broad asymmetrical
1.9 μm	molecular water	$2M$ = sharp	$1M$ = broad asymmetrical
2.2 μm	OH^-	$2M$ = sharp	$1M$ = broad asymmetrical
2.3–2.5 μm	structural octahedral layer cations	$2M$ = better definition	

and 2.45 μm in illites are also better developed in the $2M$ polytypes (Fig. 2).

Additional illite spectra (Fig. 3) were measured in the laboratory using a field portable spectrometer: the Geophysical and Environmental Research (GER) dual-beam visible infrared intelligent spectroradiometer (VIRIS). The VIRIS has lower spectral resolution (~ 10 nm, with 5 nm sampling in the 2.0–2.5 μm range) than the laboratory instrument used for Fig. 2. This resolution is comparable to that used on NASA's airborne visible/infrared imaging spectrometer (AVIRIS) and proposed for the high-resolution imaging spectrometer (HIRIS) to be launched during the late 1990's [19]–[20]. The spectral variability between the $2M$ and $1M$ polytypes is still visible at the lower IRIS spectral resolution. The difference between the sharp 2.2- μm band in the $2M$ polytype versus the markedly asymmetrical 2.2- μm band in the $1M$ polytype is particularly clear and potentially could be used for remote identification of the polytypes using the imaging spectrometers.

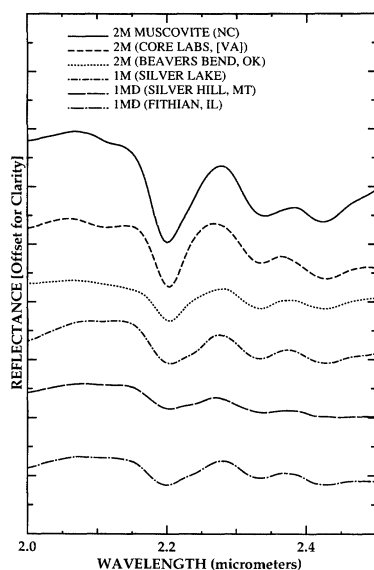


Fig. 3. Reflectance spectra of illite reference standards measured in the laboratory using the field spectrometer. Note sharpness of 2.2- μm band in 2M polytypes versus broad asymmetrical 2.2- μm band in 1M polytypes. Note decreased depth and increased width of 2.35- and 2.45- μm bands in 1M polytypes. Spectra were collected in the laboratory using the Geophysical Environmental Research VIRIS, dual-beam portable reflectance spectrometer. (Spectra measured by R. Lyon of Stanford University.)

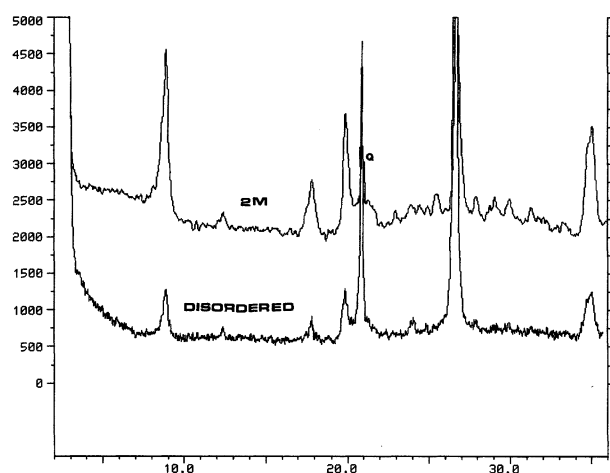


Fig. 4. X-ray diffraction patterns for samples from the main Carlin pit. Vertical scale shows intensities in counts per time interval. Horizontal scale is in degrees 2θ . Q indicates presence of quartz. Sample C-24 is well-developed 2M illite from ore zone and shows high gold values. Sample C-47 (1M) is a disordered illite from the barren zone.

IV. CARLIN DEPOSIT ILLITES

X-ray diffraction work at Carlin indicates that the 2M illite polytype is associated with proximity to high grade gold ore zones [12]. Fig. 4 contrasts the X-ray diffraction data for a 2M illite (upper scan) from a high gold bearing zone with a disordered illite (lower scan) from a barren silica-flooded alteration zone at the Carlin Mine. The contrast between the polytypes is striking.

Reflectance spectra were measured *in situ* in the main Carlin pit with another GER portable reflectance spectrometer: the single-beam visible/infrared intelligent spectroradiometer (SIRIS) (Fig. 5). The spectral resolution of this instrument is nearly identical to that of the VIRIS instrument used for the laboratory

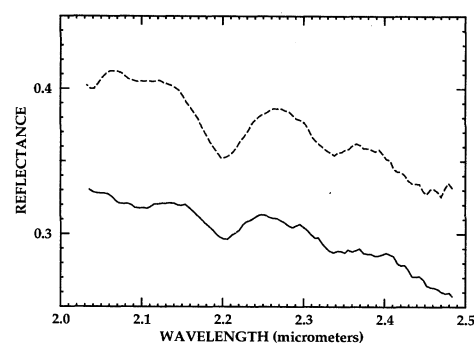


Fig. 5. Illite reflectance spectra collected with SIRIS portable reflectance spectrometer in the main Carlin pit. Dotted line is 2M illite; solid line is 1M. Note differences in definition of features at 2.2, 2.35, and 2.45 μm . Spectra were measured in October with low sun angle and therefore tend to have a low signal-to-noise ratio.

spectra shown in Fig. 3. The spectra were measured in October, however, with a low sun angle and therefore tend to have a lower signal-to-noise ratio. Field spectrum C10885 is from alteration zone 3 of Bakken and Enaudi [14] (moderately silicified laminated beds), a typically high gold zone. The well-developed absorption bands at 2.2, 2.35, and 2.45 μm indicate that it is a 2M polytype. Field spectrum CAR88B, which exhibits less well-developed spectral features, is from alteration zone 5 (strongly silicified clastic beds) [14], a zone typically having low gold values. Both of these identifications are substantiated by the X-ray diffraction measurements. Although the difference between the reflectance spectra are quite subtle in this case, they do show that the polytypes can be identified and mapped in the field and that, with higher resolution field instruments, this method has potential as an exploration and mapping tool.

V. CONCLUSION

This combined X-ray diffraction/reflectance spectroscopy study of illite polytypes has established that sufficient spectral differences exist to allow identification using near-infrared reflectance spectroscopy. Field spectrometers have been used successfully to identify subtle distinctions between the polytypes. Additional work is required to develop this into a routine method, however, field reflectance spectroscopy can eventually be used operationally to assist exploration efforts by providing detailed mineralogical information in real time at the field location. The potential exists, given sufficient spectral and spatial resolution and instrument signal-to-noise ratio, to identify these polytypes from aircraft or satellite imaging spectrometers such as AVIRIS or HIRIS.

ACKNOWLEDGMENT

The authors would like to acknowledge the gracious cooperation and interests of the Newmont Gold Company for granting access to the Carlin property for the field study portion of this project and to thank B. Bakken for providing access to her sample suite and assisting us to locate her alteration zones in the field. Dr. R. Lyon of Stanford University was especially helpful in the initial stages of this project by giving us encouragement, sharing his knowledge and data base, and running the VIRIS reference illite spectra for us. R. J. Madrid has also shared his knowledge and expertise on these deposits.

REFERENCES

- [1] B. M. Bakken, M. F. Hochella, Jr., A. F. Marshall, and A. M. Turner, "High-resolution microscopy of gold in unoxidized ore from the Carlin mine, Nevada," *Economic Geol.*, vol. 84, no. 1, pp. 171-179, 1989.
- [2] D. Duba and A. E. Williams-Jones, "The application of illite crystallinity, organic matter reflectance and isotopic techniques to mineral exploration: A case study in Southwestern Gaspe, Quebec," *Economic Geol.*, vol. 78, pp. 1350-1363, 1983.
- [3] M. Boiron and M. Cathelineau, "Hydrothermal clay mineral alteration related to gold deposition: mineralogy and physical chemical conditions," *Abstracts, AIPEA 9th Int. Clay Conf.*, Strasbourg, France, Aug. 28-Sept 2, 1989, p. 49.
- [4] L. C. Rowan, P. H. Wetlaufer, A. F. H. Goetz, F. C. Billingsley, and J. H. Stewart, "Discrimination of rock types and detection of hydrothermally altered areas in south-central Nevada by the use of computer enhanced ERTS images," U.S. Geological Survey Professional Paper 883, 1974.
- [5] S. E. Marsh and J. B. McKeon, "Integrated analysis of high-resolution field and airborne spectroradiometer data for alteration mapping," *Economic Geol.*, vol. 78, no. 4, pp. 618-632, 1983.
- [6] A. F. H. Goetz, G. Vane, J. E. Solomon, and B. N. Rock, "Imaging spectrometry for earth remote sensing," *Science*, vol. 228, pp. 1147-1153, 1985.
- [7] K. Lee, "Interactive digital image analysis of Landsat images for mapping hydrothermal limonite," in *Proc. Int. Symp. Remote Sensing of Environment, 4th Thematic Conf. Remote Sensing for Exploration Geology*. Environmental Res. Inst. of Michigan, Ann Arbor, 1985, pp. 293-307.
- [8] A. Hutsinpillar, "Discrimination of hydrothermal alteration mineral assemblages at Virginia City, Nevada, using Airborne Imaging Spectrometer data," *Remote Sensing of Environment*, vol. 24, no. 1, pp. 53-66, 1988.
- [9] S. Feldman and J. V. Taranik, "Identification of hydrothermal alteration assemblages using Airborne Imaging Spectrometer data," in *Proc. 2nd Airborne Imaging Spectrometer (AIS) Data Analysis Workshop*, May 6-8, 1986, JPL Jet Propulsion Lab., Pasadena, CA, Pub. 86-35, 1986, pp. 96-101.
- [10] F. A. Kruse, "Use of airborne imaging spectrometer data to map minerals associated with hydrothermally altered rocks in the northern Grapevine Mountains, Nevada and California," *Remote Sensing of Environment*, vol. 24, no. 1, pp. 31-51, 1988.
- [11] F. A. Kruse, K. S. Kierein-Young, and J. W. Boardman, "Mineral mapping at Cuprite, Nevada with a 63 channel imaging spectrometer," *Photogrammetric Eng. Remote Sensing*, vol. 56, no. 1, pp. 83-92, 1990.
- [12] P. L. Hauff, F. A. Kruse, and R. J. Madrid, "Gold exploration using illite polytypes defined by X-ray diffraction and reflectance spectroscopy," in *Proc. World Gold '89*, Reno NV, Nov. 5-9, 1989, ch. 9, pp. 76-82.
- [13] S. Shimoda, "A hydromuscovite from the Shakanai mine, Akita Prefecture, Japan," *Clays Clay Minerals*, vol. 18, pp. 269-274, 1970.
- [14] B. M. Bakken and M. T. Enaudi, "Spatial and temporal relations between wall-rock alteration and gold mineralization, main pit, Carlin Gold Mine, Nevada," in *Proc. "Gold 86," Vancouver, BC, Canada*, vol. 1, Willowdale, ON, Canada: Knosult Int., 1986, pp. 388-403.
- [15] K. Lee and G. L. Raines, "Reflectance spectra of some alteration minerals—A chart compiled from published data 0.4-2.5 μm ," U.S. Geological Survey Open-File Rep. 84-96, 1984.
- [16] R. N. Clark, T. V. V. King, M. Klejwa, and G. A. Swayze, "High spectral resolution spectroscopy of minerals," *J. Geophys. Res.*, in press.
- [17] J. K. Crowley and N. Vergo, "Visible and near-infrared (0.4 to 2.5 μm) reflectance spectra of selected mixed-layer clays and related minerals," in *Proc. 6th Thematic Conf. Remote Sensing for Exploration Geology*, Houston, TX, vol. 2, 1988, pp. 597-606.
- [18] G. R. Hunt and J. W. Salisbury, "Visible and near-infrared spectra of minerals and rocks: I: Silicate minerals," *Mod. Geol.*, vol. 2, pp. 283-300, 1970.
- [19] W. M. Porter and H. T. Enmark, "A system overview of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," in *Proc., 31st Annu. Int. Technical Symp., Soc. of Photo-Optical Instrumentation Eng.*, vol. 834, pp. 22-31, 1987.
- [20] NASA, "HIRIS, High-resolution imaging spectrometer: Science opportunities for the 1990s," Earth Observing Syst., Instrument panel Rep. vol. IIC, Nat. Aeronautics and Space Admin., 1987.



Fred A. Kruse received the B.S. degree in geology from the University of Massachusetts, Amherst, in 1976. He earned both the M.S. (1984) and Ph.D. degrees (1987) in geology from the Colorado School of Mines, Golden.

He served in the United States Army Corps of Engineers (1976-1981) and with the Remote Sensing Section of the U.S. Geological Survey, Branch of Geophysics (1982-1987). He is currently a Research Associate at the Center for Study of Earth from Space (CSSES) at the University of Colorado, Boulder. His research includes developing models and techniques for use of multispectral remote sensing for mineral exploration, characterization and quantification of the electromagnetic properties of Earth-surface materials, development of artificial intelligence for geologic mapping, and investigating geologic applications of imaging spectrometers and Geographic Information Systems (GIS).



Phoebe L. Hauff did undergraduate work at the University of California at Berkeley and Colorado State University, and has done graduate work at the University of Colorado, Boulder.

She worked for the U.S. Geological Survey (1968-1983) as a Mineralogist and supervised the Geologic Division Mineral Analysis Laboratory (1977-1983). Presently, she is a Professional Research Assistant and Supervisor of the Mineralogical Research Laboratory for the Center for the Study of Earth from Space at the University of Colorado. She is a Clay Mineralogist with interest in economic geology, specifically clays in mineralized, hydrothermal systems concentrating in disseminated gold deposits. Her specific areas of instrumental expertise are in X-ray spectroscopy and electron-beam microscopy. She has worked extensively in illitic and mixed layer clay suites, with particular emphasis on paragenetic sequences and resolution of polytypes. One current and important emphasis is on the integration of reflectance spectroscopy with detailed mineral characterization and the application of this to field-based problems.