Clays and Clay Minerals, Vol. 34, No. 4, 488–495, 1986.

VANADIUM CHLORITE FROM A SANDSTONE-HOSTED VANADIUM-URANIUM DEPOSIT, HENRY BASIN, UTAH

GENE WHITNEY AND H. ROY NORTHROP
U.S. Geological Survey, Federal Center, Denver, Colorado 80225

Abstract—An unusual vanadium chlorite precipitated during the formation of a vanadium-uranium ore deposit in the Henry Basin, southeastern Utah. The ore deposit formed by reduction and precipitation of U and V in the presence of organic matter at the interface between a stagnant brine and overlying, circulating meteoric water. Some samples of the vanadium chlorite (heated before analysis) contain ≥ 10% V_2O_5. In fresh samples, most of the vanadium is in the trivalent oxidation state. X-ray powder diffraction data suggest that Fe and V are concentrated preferentially in the interlayer hydroxide sheets of the chlorite. A d(060) value of 1.52 Å indicates that the chlorite probably has a dioctahedral structure which is distended by the presence of octahedral Fe and V. The vanadium ore zone is flanked by peripheral zones containing perfectly ordered chlorite/smectite. This chlorite/smectite contains much less V than the pure chlorite. This chlorite may have formed by the progressive precipitation of vanadium-rich interlayer hydroxide sheets in the mixed-layer chlorite/smectite in the most reducing portion of the ore zone. The pure chlorite is a *IIb* polytype, which, for nonvanadiferous analogs, is ordinarily found in high-temperature environments; however, no evidence exists to show that these rocks have ever been exposed to elevated temperatures. In fact, the presence of unreacted smectite in a potassium-rich setting and the low vitrinite reflectance of coalified plant debris indicate a low-temperature history for these sediments.

Key Words—Chlorite, Chlorite/smectite, Corrensite, Diagenesis, Tosudite, Uranium, Vanadium, X-ray powder diffraction.

INTRODUCTION

The chlorites constitute a widespread and diverse group of minerals. Varieties of chlorite have been found in such dissimilar geologic materials as soils, evaporites, and greenschist-facies metamorphic rocks. This widespread geologic occurrence is partly the result of the chemical diversity of the minerals, as described by Bailey (1975) and Foster (1962), among others. Chlorite contains one octahedral cation sheet in the 2:1 layer, plus an interlayer octahedral sheet. This structure permits substantial amounts of substitution which gives rise to several rather exotic chlorites which contain large amounts of chromium, nickel, lithium, or vanadium.

Vanadium-rich chlorites were first identified in sandstone-hosted uranium deposits in the late 1950s. Hathaway (1959) described a vanadium chlorite as one of the clay minerals associated with uranium in Colorado Plateau deposits, and Foster (1959) reported detailed chemical studies of these minerals. Subsequent studies of Colorado Plateau uranium deposits indicate that such vanadium chlorites are commonly, and almost exclusively, found with uranium mineralization (Granger, 1962; Keller, 1962; Schultz, 1963; Brookins, 1982). They therefore provide another means of inferring the chemical composition of the ore-forming fluid inasmuch as they were produced by that same fluid.

The purpose of the present study is to examine the chemistry and mineralogy of some ore-zone vanadium chlorites and their relationship to other phases in order to understand their origin.

GEOLOGIC SETTING

Tabular vanadium-uranium deposits have been found in several locations throughout the Colorado Plateau. Most of these deposits occur in the terrestrial sandstones of the Triassic Chinle Formation or in the Salt Wash Member of the Jurassic Morrison Formation (Nash *et al.*, 1981). The deposit under consideration here is in the Salt Wash Member of the Morrison Formation in the Henry structural basin of southern Utah (Figure 1). The stratigraphy and general geology of the area were described by Peterson (1977, 1978, 1980).

The distribution, geochemistry, and origin of this deposit were discussed in considerable detail by Northrop (1982). Briefly, the deposit consists of four distinct mineralized intervals, each of which may be composed of several uranium-enriched horizons. The mineralized intervals are peneconcordant with the bedding within the host rock, and some are laterally continuous over distances of 5 km. Although the mineralized intervals are roughly planar, they show considerable dependance on small-scale sedimentological features such as crossbedding and pockets of organic debris. Detailed studies of carbonate mineralogy, clay mineral distribution, stable isotope geochemistry, and ore geochemistry by Northrop (1982) show that the ore was deposited at the horizontal interface between a stagnant Mg-rich brine and overlying circulating meteoric water. The meteoric water leached the U and V from the overlying ash-bearing strata and transported them to the brine-freshwater interface where the U was precipitated as coffinite, the primary uranium mineral, and

Copyright © 1986, The Clay Minerals Society

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press

the V was precipitated as vanadium oxides and as vanadium clays. The presence of organic matter apparently played a key role in the reduction and precipitation of the uranium and vanadium minerals. The four mineralized intervals represent four positions at which the brine-freshwater interface was stable for sufficient lengths of time for significant mineralization to occur.

ANALYTICAL TECHNIQUES

One hundred forty samples were collected from drill core, and a separate suite of samples was collected underground from the active Tony M Mine. Several samples were obtained from above the water table to assess the effects of oxidation on the authigenic minerals. Samples were ultrasonically disaggregated by placing coarsely crushed sandstone into distilled water and sonifying for approximately 10 min. Samples were washed until dispersed, and the <0.5- and 0.5–5-μm fractions were isolated by centrifugation.

All size fractions were X-rayed using either a Picker or Philips diffractometer, at scan speeds of ½° or ⅛°2θ/min using Ni-filtered CuKα radiation. The <0.5- and 0.5–5-μm fractions were made into oriented mounts using the technique of Pollastro (1982) and X-rayed untreated, glycolated, and after heating to 550°C.

Major element composition was determined by atomic absorption spectrophotometry and by inductively coupled plasma-emission spectroscopy using standard lithium metaborate fusion and digestion procedures. Minor element composition was determined by inductively coupled plasma-emission spectroscopy. All samples were heated to 900°C in air before analysis to drive off structural water and to oxidize the Fe and V. Fe and V are reported in their most oxidized forms, even though both occur in mixed valence states in the fresh samples. The structural water content was determined thermogravimetrically.

Thermogravimetric analysis (TGA) was made with a Perkin-Elmer TGS-2 thermogravimetric analyzer. Samples (~10 mg) were heated both in nitrogen and oxygen atmospheres at heating rates of 10°, 20° or 40°C/min. A first derivative computer accessory on the TGA simultaneously provided the differential thermogravimetric (DTG) curve. Special heat treatment of bulk sample for X-ray powder diffraction (XRD) analysis was carried out in a standard muffle furnace.

Spectra in the mid-infrared region were obtained with a Perkin-Elmer Model 580B infrared spectrophotometer. About 0.5 mg of sample was added to 300 mg of KBr in a mechanical shaker, mixed, and then pressed into a transparent pellet in a hydraulic press. Data were collected over the spectral range 4000–200 cm^{-1}.

Scanning electron microscope (SEM) examination was made with a Cambridge instrument with an attached energy dispersive fluorescence analyzer for qualitative chemical analysis. Samples were coated with gold or silver.

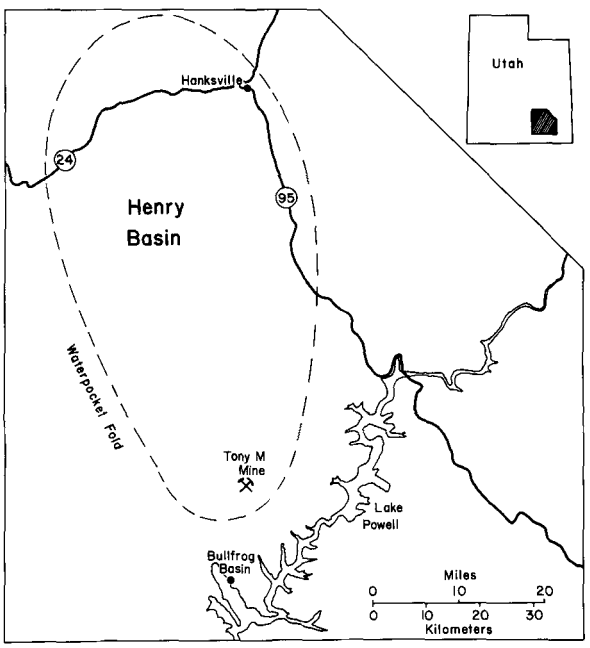


Figure 1. Map showing location of study. Mine samples were taken from the Tony M Mine; core samples were taken from the area surrounding the mine.

RESULTS

Mineralogy and distribution of clays

Away from the mineralized intervals, the authigenic clays in the Salt Wash sandstone are predominantly smectite, mixed-layer illite/smectite, kaolinite, and mixed-layer chlorite/smectite. From textural evidence, the smectite predates the vanadium-uranium mineralization and forms a thin grain coating in the sandstones. The smectite was largely removed from the ore zones when the ore was formed. The illite/smectite is detrital and occurs in mud clasts and mudstones. The kaolinite precipitated after ore formation and accompanied the oxidation of portions of the ore.

A d(060) value of 1.50 Å for the well-crystallized chlorite/smectite indicates that it is dioctahedral. Even though the chlorite/smectite coexists with a significant amount of illite/smectite, there is no trace of a separate trioctahedral 060 peak. Some samples of chlorite/smectite approach true tosudite (perfectly ordered, 50% expandable dioctahedral chlorite/smectite) in ordering and expandability and exhibit several orders of very sharp basal reflections. Sample WC6-1554 (Figure 2) has a coefficient of variation of 0.43 and is therefore tosudite, according to Bailey *et al.* (1982). Other chlorite/smectite samples have expandabilities ranging from 10 to 40%; thus, the proportion of smectite layers in the chlorite/smectite covers the range from 50% to pure

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press

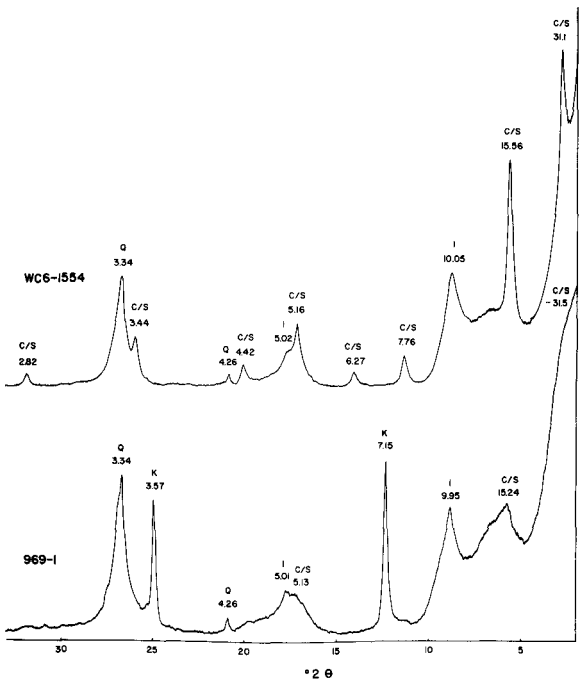


Figure 2. X-ray powder diffraction patterns for two mixed-layer chlorite/smectites. Sample WC6-1554 (top) is from sandstone adjacent to, and immediately below the most strongly mineralized zone. The chlorite/smectite is dioctahedral and is sufficiently well ordered to be called tosudite. Sample 969-1 is from an ore zone which has been exposed to oxidizing conditions and probably represents the degradation product of vanadium chlorite. C/S = mixed-layer chlorite/smectite; I = illite; K = kaolinite; Q = quartz. Both samples are the <2-μm fraction and were X-rayed using CuKα radiation.

chlorite. The chlorite/smectite occurs in stratigraphically equivalent rocks away from the ore deposit and represents a lateral extension of the mineralized interval or it occurs immediately below the mineralized interval. Chlorite/smectite and discrete chlorite have never been found as separate phases in the same sample.

The vanadium chlorite occurs only within the mineralized zones. Furthermore, mineralized rock always contains at least some vanadium chlorite. No other clay minerals are abundant in the unaltered mineralized intervals. Where mineralized rock was exposed to oxidizing conditions, however, the chlorite was progressively degraded into an ordered chlorite/smectite having very broad peaks, in contrast to the corrensite-like chlorite/smectite which occurs on the periphery of pristine ore (Figure 2).

Other authigenic minerals include quartz, potassium feldspar, dolomite, calcite, and, in the ore zones, cofinite and vanadium oxides. The vanadium oxides have a fan-like, bladed morphology and most closely resemble montroseite or paramontroseite.

Texture

The authigenic vanadium chlorite exhibits two distinct textures (Figure 3). The first is the familiar "house-of-cards" grain-coating texture common in authigenic sedimentary chlorites (Wilson and Pittman, 1977). This texture is by far the most abundant chlorite texture noted. The second texture is similar, but the individual blades or flakes of chlorite are more compact, blocky, and rounded. The relationship between the two textures indicates that the unusual rounded-flake chlorite precipitated after the house-of-cards chlorite; however, the two textural varieties give identical spectra from the SEM energy dispersive analyzer, which indicates that both contain significant amounts of V, Fe, and Mg. In certain places, the rounded-flake chlorite seems to have precipitated as a continuation, or overgrowth of the house-of-cards chlorite.

The textural relationship between the house-of-cards chlorite and certain other authigenic minerals is obvious, because authigenic quartz, potassium feldspar, and vanadium oxides clearly lie on top of this chlorite (Figure 3). Where the rounded-flake chlorite has postdated the house-of-cards chlorite, however, its relationship to other minerals is not clear, and in some specimens the rounded-flake chlorite has postdated the vanadium oxides. Also, the texture of the tosudite (in sample WC6-1554) is similar to the rounded-flake chlorite, but the relationship between them is not well defined inasmuch as they do not occur in the same samples.

Chemical analysis

Chemical compositions of two of the purest samples of vanadium chlorite are shown in Table 1. Like the samples used by Foster (1959), these chlorite samples could not be completely separated from other minerals, and contain small amounts of quartz, potassium feldspar, and mixed-layer illite/smectite. Because of the presence of these impurities, the chemical analyses were not cast into rigorous structural formulae. It is instructive, however, to examine the atomic ratios of Al, Fe, Mg, and V in these samples as an indication of their relative octahedral abundance (no free vanadium oxide was detected in these particular samples). These cation ratios were calculated on the basis of an anion charge of -28, and are included in Table 1. The ratios show that both samples contain almost equal amounts of Fe and V (on an atomic basis) and approximately twice as much Mg per formula unit as either Fe or V. About 75% of the vanadium in these chlorites is present as the trivalent cation and 25% is present as the quadrivalent cation, according to wet-chemical analyses (Richard Wanty, U.S. Geological Survey, Federal Center, Denver, Colorado, personal communication, 1984). Based on these analyses, there appears to be an insufficient number of cations to form two trioctahedral

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press

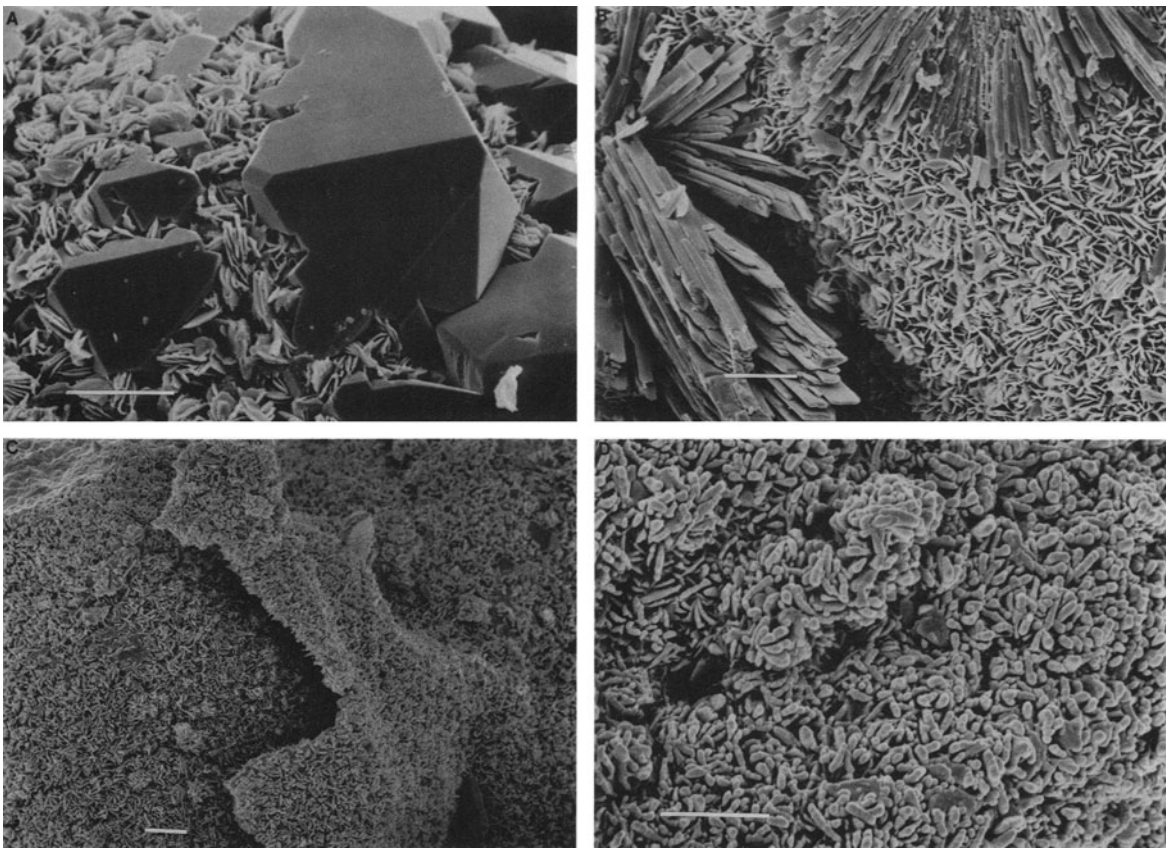


Figure 3. Textures of authigenic minerals. (A) Thin-flake chlorite with overgrowths of quartz. (B) House-of-cards vanadium chlorite with fan-shaped vanadium oxide crystals overgrowing it. (C) A layer of rounded-flake vanadium chlorite on top of the thin-flake house-of-cards vanadium chlorite. (D) Closer view of the rounded-flake vanadium chlorite. Bar scale on each photo is 10 μm.

sheets. In fact, the chlorite appears to be almost perfectly dioctahedral (i.e., two cations per three sites in each of the two octahedral sheets). Because both samples contain small amounts of impurities, it is somewhat fortuitous that the cation totals are so nearly ideal; the actual formulae must differ somewhat from these values.

X-ray powder diffraction results for vanadium chlorite

The XRD analysis of these vanadium chlorites provides information about (1) the octahedral cations based on the *b*-dimension of the chlorite, (2) the octahedral cations based on relative intensities of basal reflections, and (3) the polytype, or stacking arrangement, of the chlorite based on *hkl* reflections.

Measurement of the *b*-axis dimension of a clay mineral is a simple way to gain information about its octahedral cation population. Dioctahedral and trioctahedral clays produce distinctly different positions for the 060 peak because they have markedly different *b*-axis dimensions. Dioctahedral clays have *b*-axis dimensions of about 8.9–9.0 Å and therefore exhibit an 060 spacing of about 1.48–1.50 Å, with a somewhat larger spacing if octahedral Fe is present. Because all octahedral sites are filled and because larger cations predominate, trioctahedral clays have larger *b*-axis dimensions (about 9.2–9.3 Å) and therefore exhibit 060 spacings of about 1.53–1.54 Å. Chlorites possess two octahedral sheets per structural layer; the two layers may have different numbers and species of cations. For example, chlorite having a dioctahedral 2:1 layer and a trioctahedral interlayer sheet have been reported with 060 spacings near 1.51 Å (Hayashi and Oinuma, 1964; Bailey, 1975). The vanadium chlorites in the present study gave 060 spacings of about 1.52 Å (Figure 4). This value is not appropriate for a dioctahedral or a trioctahedral chlorite of usual composition. It could be reasonably interpreted as a di,trioctahedral chlorite, but the observed 060 values are most suggestive of the *b*-axis measurements made by Heinrich and Levinson (1955) for roscoelite, the vanadium-rich mica. They reported a value of 1.52 Å for the 060 of the dioctahedral mica in which V substitutes for octahedral Al.

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press

Table 1. Chemical compositions and cation ratios for vanadium chlorites.

	Sample TM05	Sample TM6
Wt. %		
SiO_2	44.40	44.89
Al_2O_3	26.46	25.14
TiO_2	0.45	0.35
Fe_2O_3[1]	8.01	8.29
MgO	9.63	8.47
CaO	0.98	0.84
Na_2O	0.27	0.27
K_2O	1.94	2.18
Li_2O	0.13	0.16
UO_3[1]	0.27	0.92
V_2O_5[1]	7.69	9.14
Total	100.23	100.65
ppm		
Cr	10	10
Mn	200	200
Co	110	150
Ni	45	58
Cu	10	10
Zn	110	140
Cation ratios (based on a formula with $O_{10}(OH)_8$)[2]		
Si	3.54	3.59
Al	0.46	0.41
Total tetrahedral	4.00	4.00
Al	2.02	1.96
Mg	1.14	1.01
Fe	0.48	0.50
V	0.40	0.48
Li	0.04	0.05
Total octahedral	4.08	4.00

[1] All samples were fired at 900°C before analysis. Fe, U, and V are reported in their most oxidized forms.

[2] Samples contain small amounts of quartz, K-feldspar, and mixed-layer illite/smectite.

The distortion of the *b*-axis of the chlorite is further complicated by the presence of significant amounts of octahedral Fe and Mg.

To gain some further insight into the octahedral cation occupancy of these chlorites, the intensities of the 00*l* XRD peaks were examined using the techniques of Petruk (1964). Although Petruk's technique was developed for trioctahedral chlorites, it still provides useful information about the balance of heavy cations between the two octahedral sheets. The relative intensities of the second- through fifth-order basal reflections indicate that the distribution of heavy cations (Fe and V) is asymmetrical, with about 0.5–0.6 more heavy atoms in the interlayer hydroxide sheet than in the 2:1 layer octahedral sheet of sample TM6 (Figure 4). Petruk's technique also yielded a total of 0.7 heavy atoms in octahedral sites per $O_{10}(OH)_8$. This number is reasonable for the determined chemical composition listed in Table 1. Some variation in peak intensities was noted in different samples of vanadium chlorite,

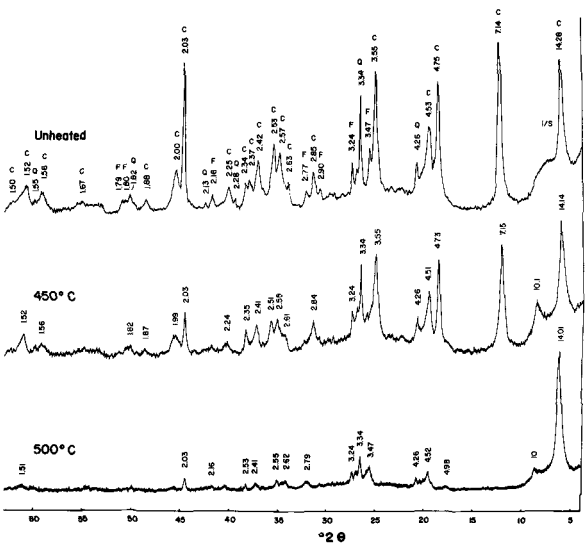


Figure 4. X-ray powder diffraction patterns for unheated and heated vanadium chlorite sample TM6. All patterns are for random powder mounts; peak labels are in Å.

and a few samples exhibited equal intensities for the first four 00*l* peaks, a phenomenon noted by Hathaway (1959).

The structural polytype of these chlorites was determined by examining the position and intensities of the 20*l* peaks in the 2–3-Å spacing range on the XRD patterns (Figure 4) and comparing them with published patterns (Bailey, 1975). These data show that the vanadium chlorites are of the *IIb* structural type of Bailey and Brown (1962). Bailey and Brown (1962) and Hayes (1970) suggested that *IIb* structural type chlorites are generally associated with a medium-to-high temperature environment; however, evidence that these vanadium chlorites formed in a low-temperature diagenetic environment is presented later in this paper.

Thermal analysis

Thermogravimetric analysis of the vanadium chlorite shows some adsorbed water which is lost below 100°C and a major dehydroxylation event between 500° and 600°C. The point of maximum inflection is at 552°C (Figure 5). The differential thermogravimetric (DTG) curve exhibits a small subsidiary event at about 450°C which may be due to the preferential dehydroxylation of some octahedral cations at a lower temperature than the main dehydroxylation. This chlorite lacks the distinctively separate dehydroxylation events for the 2:1 layer and the interlayer hydroxide sheet which has been reported for some chlorites (Mackenzie and Caillere, 1975). The total weight loss at 900°C for sample TM6 is 9.16%. Of this total, approximately 2.75% is adsorbed water and 6.41% is hydroxyl water.

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press

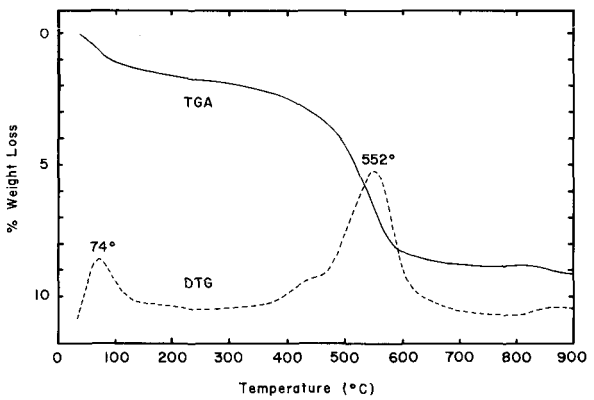


Figure 5. Thermogravimetric data for vanadium chlorite sample TM6. The upper curve (TGA) registers percent weight loss and the bottom curve (DTG) is the differential thermogravimetric curve which indicates points of maximum rate of weight loss.

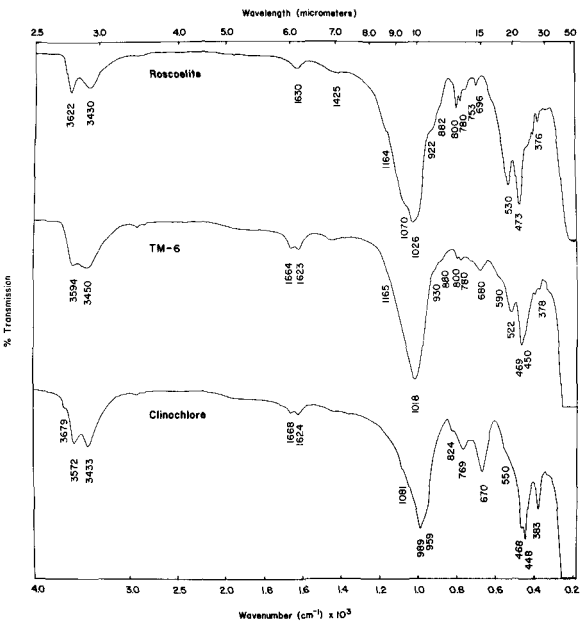


Figure 6. Infrared spectra for roscoelite (Rifle, Colorado) (upper spectrum), vanadium chlorite sample TM6 (middle spectrum), and clinochlore (Silver Peak, Montana) (bottom spectrum). Absorption bands are labeled in wave numbers.

Infrared analysis

Figure 6 compares the vanadium chlorite with roscoelite (vanadium mica) and clinochlore. It is notable that many of the absorption bands of the vanadium chlorite fall between those of the roscoelite and clinochlore, both in position and intensity. For example, roscoelite exhibits two strong bands at 530 and 473 cm^{-1}. This pair of bands is typical of muscovite and other aluminous dioctahedral 2:1 layer silicates, although the precise positions may vary somewhat because of variations in composition (Farmer and Palmieri, 1975). The trioctahedral layer silicates, on the other hand, have a deep band near 450–470 cm^{-1} and only a very small band near 530 cm^{-1}. The clinochlore spectrum in Figure 6 shows typical trioctahedral clay features in the 450–550-cm^{-1} range. The vanadium chlorite spectrum is intermediate between the two, suggesting a predominantly dioctahedral 2:1 layer, but the unequal intensities of the bands at 522 cm^{-1} and 469 cm^{-1} indicate that this layer is not a typical mica-like layer. Furthermore, the absence of a distinct Al_2OH-libration band at 920 cm^{-1} indicates that the 2:1 layer is not strictly an aluminous dioctahedral layer but probably contains other cations as well. Finally, the position of the main OH band at 3594 cm^{-1} suggests that significant amounts of Fe and/or V occupy octahedral sites. It is assumed here that the presence of Fe and V would produce similar spectral effects because of their similarity of mass and ionic radius.

DISCUSSION AND CONCLUSIONS

Octahedral cation distribution

The structural formulae calculated for roscoelite by Wells and Brannock (1946) show that their samples were almost perfectly dioctahedral, having octahedral cation populations ranging from 1.97 to 2.08 per $O_{10}(OH)_4$. Of that number, V occupied from 0.4 to 1.41 octahedral sites and Al, Mg, and Fe constituted the remainder. The samples analyzed by Foster (1959), which consisted of vanadium-rich mica, mica/smectite mixed-layer minerals, and small amounts of impurities, generally contained about 2.00 octahedral cations per formula unit, but certain samples contained as few as 1.84 octahedral cations. Like the samples of Wells and Brannock (1946), Foster's samples also contained a mixed combination of Fe, Mg, Al, and V in the octahedral sheet.

The vanadium chlorites in the present study also contain significant amounts of Al, Fe, Mg, and V in the octahedral sheets. Attempts to apportion these cations precisely was complicated by the fact that chlorite has two octahedral sheets; hence, the cations may be unevenly distributed between the 2:1 layer and the interlayer hydroxide sheet. The variability in oxidation states of the Fe and V also complicate the apportionment process.

Based on the XRD data, most of the Fe and V are located in the interlayer hydroxide sheet; however, the IR data indicate that the octahedral sheet of the 2:1 layer is not entirely aluminous. If some Mg and small amounts of Fe and V are in the 2:1 layer, this chlorite has a phengite-like 2:1 layer.

The presence of the corrensite-like chlorite/smectite on the periphery of the ore zones and the existence of

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press

an ordered chlorite/smectite in oxidized ore are also important indicators of cation distribution. For example, both the well-crystallized chlorite/smectite and the oxidized, degraded chlorite/smectite contain several hundred parts-per-million V. This value is well above background levels for V, but dramatically lower than the 6–10% V_2O_5 commonly found in the ore zone chlorites. Mg values are commonly higher in the ore-zone chlorites than in the chlorite/smectites, as well. Therefore, the formation of the vanadium chlorite may be envisioned as incremental addition of interlayer vanadium-magnesium-iron hydroxide to authigenic chlorite/smectite. If this is indeed the mechanism of formation, then V not only must be concentrated in the interlayer hydroxide sheet, but it must be concentrated in alternate interlayer hydroxide sheets. This hypothesis is supported by the nature of the poorly crystalline chlorite/smectite in oxidized ore, which appears to have formed by degradation of the ore-zone chlorite. The fact that it is depleted in V relative to the ore-zone chlorite suggests that the degradation proceeded by oxidation and leaching of the alternate V-rich interlayer hydroxide sheets. In other words, the V-rich interlayer hydroxide sheets were the last to precipitate in the chlorite/smectite and the first to be removed when the chlorite was exposed to oxidizing conditions.

This mode of formation helps explain some of the complex structural chemistry of these chlorites but it does not adequately explain the two episodes of chlorite formation which are manifested in the two different textures. A simple conversion reaction would produce a single texture. Therefore, the conversion and precipitation reactions must be related in some complex way which cannot, at present, be defined.

Environmental significance of the IIb *polytype*

The stacking arrangement, or polytype, of nonvanadiferous chlorites has been used as a general indicator of the environment of formation (Bailey and Brown, 1962; Hayes, 1970). High-temperature igneous and metamorphic chlorites are almost exclusively the *IIb* polytype, whereas authigenic diagenetic chlorite is generally the *Ia* or *Ib* polytype. Hayes (1970) identified only one exception to this generalization, but urged caution in interpreting authigenic chlorites as necessarily low-temperature phases, because some sandstones have experienced elevated temperatures sufficient for incipient metamorphism. The fact that the vanadium chlorites examined here are the *IIb* polytype is significant inasmuch as they are authigenic and the rocks have apparently never been deeply buried, nor have they experienced elevated temperatures.

Evidence in support of a low-temperature formation of these chlorites consists primarily of unreacted smectites surrounding the ore and the presence of coalified organic matter which exhibits low vitrinite reflectance. The smectites coat sand grains throughout much of the Salt Wash Member and are found both above and below the ore horizons. The smectites are known, from textural relationships, to predate the ore (the ore has been assigned a Late Jurassic age (Northrop, 1982)). The rocks have been exposed to Al- and K-bearing fluids, as evidenced by the existence of post-ore authigenic potassium feldspar, and yet the smectites are largely unreacted. Because smectite is known to react to mixed-layer illite/smectite under conditions of elevated temperatures in many geologic environments (Hoffman and Hower, 1979), the persistance of smectite in a K-rich setting suggests that these sandstones have never been exposed to elevated temperatures.

The organic matter associated with the deposit is detrital plant debris, and the vitrinite reflectance covers a wide range of values (M. B. Goldhaber, U.S. Geological Survey, Federal Center, Denver, Colorado, written communication, 1984). Anomalously high reflectance values have been found for materials in close association with the ore because of prolonged alpha particle bombardment (Sassem, 1981), but the existence of vitrinite with low reflectance nearby at least suggests that the rocks have not been significantly heated. These data do not prove that the rocks have always been cool, but no evidence exists, other than the type *IIb* chlorite itself, that would indicate elevated temperatures in these rocks.

ACKNOWLEDGMENTS

We gratefully acknowledge the assistance of M. S. Hanson and L. R. Mahrt, Jr., of the U.S. Geological Survey Energy Minerals Laboratory, for preparing and analyzing samples. D. B. Hatfield and J. L. Seeley of the Branch of Analytical Chemistry provided some of the chemical analyses. We thank Fred Peterson of the U.S. Geological Survey and the geologists of Plateau Resources Ltd. for background information and samples. This paper is dedicated to the memory of John Hower, who was a good friend and a guide in the study of clays.

REFERENCES

Bailey, S. W. (1975) Chlorites: in *Soil Components, Volume 2, Inorganic Components,* J. E. Gieseking, ed., Springer-Verlag, New York, 191–263.

Bailey, S. W., Brindley, G. W., Kodama, H., and Martin, R. T. (1982) Report of the Clay Minerals Society nomenclature committee for 1980–1981—nomenclature for regular interstratifications: *Clays & Clay Minerals* **30,** 76–78.

Bailey, S. W. and Brown, B. E. (1962) Chlorite polytypism: 1. Regular and semi-random one-layer structures: *Amer. Mineral.* **47,** 819–850.

Brookins, D. G. (1982) Geochemistry of clay minerals for uranium exploration in the Grants Mineral Belt, New Mexico: *Mineral. Deposita* **17,** 37–53.

Farmer, V. C. and Palmieri, F. (1975) The characterization of soil minerals by infrared spectroscopy: in *Soil Components, Volume 2, Inorganic Components,* J. E. Gieseking, ed., Springer-Verlag, New York, 573–670.

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press

Foster, M. D. (1959) Chemical study of the mineralized clays: *U.S. Geol. Surv. Prof. Pap.* **320,** 121–132.

Foster, M. D. (1962) Interpretation of the composition and a classification of the chlorites: *U.S. Geol. Surv. Prof. Pap.* **414-A,** 33 pp.

Granger, H. C. (1962) Clays in the Morrison Formation and their spatial relation to the uranium deposits at Ambrosia Lake, New Mexico: *U.S. Geol. Surv. Prof. Pap.* **450-D,** D15–D20.

Hathaway, J. C. (1959) Mixed-layer structures in vanadium clays: *U.S. Geol. Surv. Prof. Pap.* **320,** 133–138.

Hayashi, H. and Oinuma, K. (1964) Aluminian chlorite from Kamikita Mine, Japan: *Clay Sci.* **2,** 22–30.

Hayes, J. B. (1970) Polytypism of chlorite in sedimentary rocks: *Clays & Clay Minerals* **18,** 285–306.

Heinrich, E. W. and Levinson, A. A. (1955) Studies in the mica group; X-ray data on roscoelite and barium-muscovite: *Amer. J. Sci.* **253,** 39–43.

Hoffman, J. and Hower, J. (1979) Clay mineral assemblages as low grade metamorphic geothermometers: application to the thrust faulted Disturbed Belt of Montana, U.S.A.: *Soc. Econ. Paleo. Min. Spec. Pub.* **26,** 55–79.

Keller, W. D. (1962) Clay minerals in the Morrison Formation of the Colorado Plateau: *U.S. Geol. Surv. Bull.* **1150,** 89 pp.

Mackenzie, R. C. and Caillere, S. (1975) The thermal characteristics of soil minerals and the use of these characteristics in the qualitative and quantitative determination of clay minerals in soils: in *Soil Components, Volume 2, Inorganic Components,* J. E. Gieseking, ed., Springer-Verlag, New York, 529–571.

Nash, J. T., Granger, H. C., and Adams, S. S. (1981) Geology and concepts of genesis of important types of uranium deposits: *Econ. Geol.* **75th Anniversary Volume,** 63–116.

Northrop, H. R. (1982) Origin of the tabular-type vanadium-uranium deposits in the Henry Structural Basin, Utah: Ph.D. dissertation, Colorado School of Mines, Golden, Colorado, 340 pp. (unpublished).

Peterson, Fred (1977) Uranium deposits related to depositional environments in the Morrison Formation (upper Jurassic), Henry Mountains mineral belt of southern Utah: *U.S. Geol. Surv. Circ.* **753,** 45–47.

Peterson, Fred (1978) Measured sections of the lower member and Salt Wash Members of the Morrison Formation (upper Jurassic) in the Henry Mountains mineral belt of southern Utah: *U.S. Geol. Surv. Open-file Rep.* **78-1094,** 95 pp.

Peterson, Fred (1980) Sedimentology as a strategy for uranium exploration: concepts gained from analysis of a uranium bearing depositional sequence in the Morrison Formation of south-central Utah: in *Uranium in Sedimentary Rocks: Application of the Facies Concept to Exploration:* C. E. Turner-Peterson, ed., Rocky Mountain Section, Society of Econ. Paleo. Min., Denver, Colorado, 65–126.

Petruk, W. (1964) Determination of the heavy atom content in chlorite by means of the X-ray diffractometer: *Amer. Mineral.* **49,** 61–71.

Pollastro, R. M. (1982) A recommended procedure for the preparation of oriented clay-mineral specimens for X-ray diffraction analysis: modifications to Drever's filter-membrane peel technique: *U.S. Geol. Surv. Open-file Rep.* **82-71,** 10 pp.

Sassem, R. (1981) Increased vitrinite reflectance associated with uranium mineralization: in *Advances in Organic Geochemistry, 1981,* Wiley, New York, 94–98.

Schultz, L. G. (1963) Clay minerals in Triassic rocks of the Colorado Plateau: *U.S. Geol. Surv. Bull.* **1147-C,** 71 pp.

Wells, R. C. and Brannock, W. W. (1946) The composition of roscoelite: *U.S. Geol. Surv. Bull.* **950,** 121–127.

Wilson, M. D. and Pittman, E. D. (1977) Authigenic clays in sandstones: recognition and influence on reservoir properties and paleoenvironmental analysis: *J. Sed. Pet.* **47,** 3–31.

(Received 24 May 1984; accepted 31 December 1984; Ms. 1379)

https://doi.org/10.1346/CCMN.1986.0340416 Published online by Cambridge University Press