

## “MAUFITE” DISCREDITED: NOT A MINERAL SPECIES BUT AN IMPORTANT INTERSTRATIFIED Ni-BEARING LIZARDITE + CLINOCHLORE

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### ABSTRACT

The mineral name “maufite” was proposed in 1930 to describe a “bright emerald green” nickeliferous vein material occurring within a serpentinite of the Great Dyke in the Umvukwe Range of Zimbabwe, then Southern Rhodesia. Study of this material shows that it is not a distinct species but rather an interstratified nickel-bearing lizardite-clinochlore, with lizardite dominant over clinochlore. The name “maufite” is discredited. The lizardite is a Group-A polytype, and the clinochlore is a Ia polytype in the nomenclature developed by S.W. Bailey. The formula calculated on the basis of 14 negative charges is  $(\text{Mg}_{1.74}\text{Al}_{0.88}\text{Ni}_{0.13}\square_{0.25})\Sigma_{3.00}(\text{Si}_{1.60}\text{Al}_{0.40})\Sigma_{2.00}\text{O}_5(\text{OH})_4$ ; on the basis of nine oxygen atoms including 14.6 wt.%  $\text{H}_2\text{O}$  determined thermogravimetrically, the formula is  $(\text{Mg}_{1.68}\text{Al}_{0.78}\text{Ni}_{0.13}\square_{0.41})\Sigma_{3.00}(\text{Si}_{1.55}\text{Al}_{0.45})\Sigma_{2.00}\text{O}_{4.51}(\text{OH})_{4.49}$ . Analytical electron microscopy shows that the composition is variable on a fine scale. The randomly interstratified lizardite-clinochlore occurs as a pseudomorph after amphibole and plagioclase and is a product of serpentinization. The material is poorly crystalline and very fine grained, producing broad reflections on powder diffraction and microbeam X-ray diffraction patterns. Unlike most of the interstratified serpentine-chlorite described in the literature, lizardite is here dominant over clinochlore.

**Keywords:** interstratified lizardite-clinochlore, serpentine-chlorite, nickel-bearing lizardite, powder XRD, microbeam XRD, TEM-AEM, TGA, evolved gas analysis, electron-microprobe analysis, “maufite”, discreditation, Zimbabwe.

### INTRODUCTION

“Maufite” was originally described by Keep (1930a, b) and named after Mr. Herbert Brantwood Maufe (1879–1946), director at the Southern Rhodesia Geological Survey (Foshag 1930). It occurs “as a quarter inch seam” of “a peculiar ... bright emerald green rock” within “a dark red, speckled, serpentine rock adjacent to a small dolerite dyke” (Keep 1930b, p. 26). The serpentine rock forms part of the Great Dyke in the Umvukwe Range of Zimbabwe, formerly Southern Rhodesia. The specific occurrence was located 1.5 miles northeast of the Umvukwe geodetic station, on the Ruorka Ranch in the Mazoe District. Keep was meticulous about the deposition of the type material, and sent it to the Smithsonian Institution. His letter of deposition indicates that it exists as only one specimen and admirably states: “I enclose it

herewith, as with you it will be a permanent record whereas with me it might get lost.” The specimen bears the number 4558, which is likewise the number cited in his publication. Thus, the type material is of high integrity. It is catalogued as Smithsonian Institution #NMNH 96398. A fragment from this specimen is catalogued at the Royal Ontario Museum (ROM) as ROM #M45039.

The results of the study described below indicate that “maufite” is not a unique species, but a random interstratification of Ni-bearing lizardite with clinochlore. The lizardite is a Group-A polytype (Bailey 1969, 1988b), and the clinochlore is polytype Ia (Bailey 1988a, 1988c). The lizardite is the dominant phase, with lesser and variable amounts of clinochlore. Our recommendation to discredit “maufite” as a mineral name was accepted by the International Mineralogical Association, Commission

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on New Minerals and Mineral Names on May 13, 1993 (Nickel & Grice 1998). “Maufite” was included in a mass discreditation of mineral names by Burke (2006).

Most of our work on this material was done in the early 1990s. Publication of a new study of interstratified lizardite-clinocllore (Cressey *et al.* 2008a) was reminiscent of our earlier study of “maufite” from Ruorka Ranch, and a reminder that the study of the interstratified lizardite-clinocllore formerly known as “maufite” needed to be published.

Although it was scientifically necessary to discredit “maufite”, it was unpleasant to do so, as “maufite” was meant to honor Herbert B. Maufe and his significant contribution to the development of the Southern Rhodesian Geological Survey (Lightfoot 1947, Spencer 1947), now the Geological Survey of Zimbabwe. It was a relief to learn that the Geological Survey of Zimbabwe is located in the Maufe Building at the corner of Selous Avenue and 5th Street in Harare. This is undoubtedly a more significant memorial, seen by more people, than the small, single specimen of “maufite”, a portion of which is stored at the Smithsonian and a portion at the ROM.

#### INVESTIGATIONS

##### *Optical study*

In thin section, Keep found that the centimetric pale apple green to emerald green seam in the serpentine rock seems to be composed solely of a light green, length-fast mineral occurring in “fibrous sheaves aligned at acute angles

with one another” (Keep 1930a, p.104). Examination of a new thin section cut from the original specimen indicates that the mineral is texturally more complex than described by Keep. The vein is composed of typical serpentine pseudomorphs after amphibole and feldspar. As no primary minerals survived serpentinization, their identification is based solely on the morphology of the pseudomorphs (Wicks & Whittaker 1977). The amphibole pseudomorphs are made up of sheaves of length-fast apparent fibers with minor patches of length-slow apparent fibers and isotropic featureless serpentine (Fig. 1). The isotropic serpentine is rimmed by zones of fine-grained, length-fast apparent fibers arranged in rosettes. It is very likely that these rosettes are small spheres of polyhedral lizardite similar to those recently characterized by Cressey *et al.* (2008b, 2010). This assemblage of textural units is fairly typical of the amphibole bastite described by Wicks & Whittaker (1977). The plagioclase pseudomorphs commonly show a rectangular outline and are composed of interlocking grains of length-slow or, in some cases, length-fast serpentine (Fig. 1). The veins seem to have been composed initially of radiating, interpenetrating sprays of amphibole crystals up to  $1.5 \times 0.5$  mm, and a few percent of euhedral plagioclase crystals, up to  $0.15 \times 0.85$  mm. The plagioclase was either enclosed by, or interstitial to, the amphibole.

##### *Chemical composition*

The Ruorka Ranch vein material was chemically analyzed using an ARL-SEMQ electron microprobe utilizing an operating voltage of 15 kV and a sample

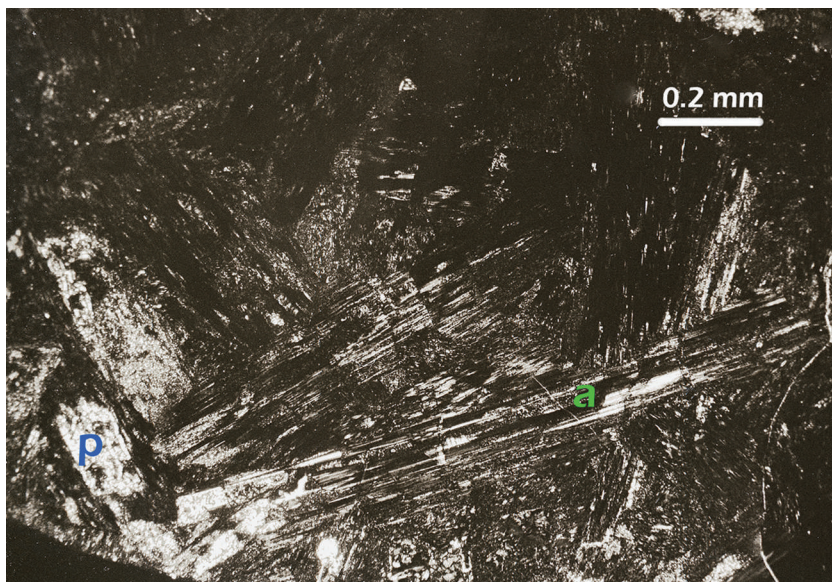


FIG. 1. Interstratified lizardite-clinocllore pseudomorphs formed after elongate, bladed amphibole (a) and euhedral plagioclase grains (p). As no primary minerals survived serpentinization, their identification is based on the morphology of the pseudomorphs (Wicks & Whittaker 1977). Sample NMNH 96398, crossed nicols.

TABLE 1. CHEMICAL COMPOSITION OF "MAUFITE", LIZARDITE-CLINOCLORE

Oxides	Keep (1930a, b)	Microprobe
SiO <sub>2</sub> wt.%	33.26	33.6
Al <sub>2</sub> O <sub>3</sub>	36.81	22.8
Fe <sub>2</sub> O <sub>3</sub>	0.79	n.d.
FeO	0.68	n.d.
NiO	4.28	3.4
MgO	4.78	24.4
CaO	tr.	n.d.
H <sub>2</sub> O <sup>+</sup>	13.67	14.6
H <sub>2</sub> O <sup>-</sup>	5.71	4.4
Total	99.98	98.8*

n.d.: not detected, tr.: trace.

\* Excludes 4.4 wt.% H<sub>2</sub>O<sup>-</sup>.

current, measured on brass, of 0.025 Å. We used the following standards in the analysis: hornblende for Si, Al, and Mg, and Ni,Fe alloy for Ni. The analyses, made at seven points from a variety of textural units, yielded SiO<sub>2</sub> 33.6, Al<sub>2</sub>O<sub>3</sub> 22.8, MgO 24.4, NiO 3.4 wt.%, for a total of 84.2 wt.%. Iron was sought but not detected. The new composition differs from the original findings (Keep 1930a, b) principally in higher MgO (24.4 versus 4.78 wt.%) and lower Al<sub>2</sub>O<sub>3</sub> (22.8 versus 36.81 wt.%) values (Table 1). Clearly, the original analytical work was flawed.

The amount of H<sub>2</sub>O was determined using a Mettler TA-1 thermoanalyzer by thermogravimetric analysis (TGA). It was coupled to an Inficon IQ 200 quadrupole

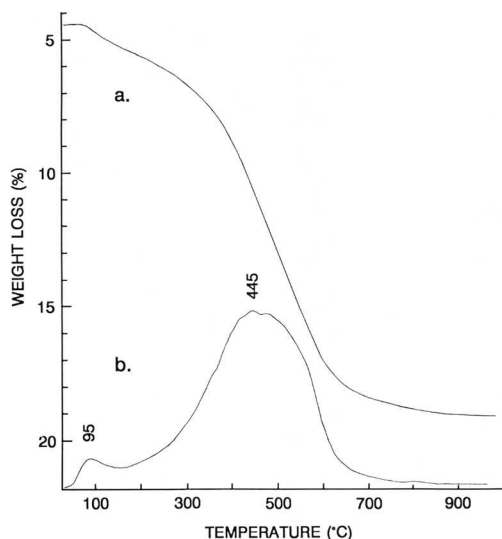


FIG. 2. Thermal gravimetric curve (a) and total pressure curve, principally H<sub>2</sub>O (b), of randomly interstratified lizardite-clinocllore. The total pressure curve is in arbitrary units.

mass spectrometer for identification of the evolved gas species (EGA) using the methods described by Wicks & Ramik (1990). A finely crushed 5.769 mg sample of the vein material was weighed at 40% relative humidity at 23 °C, placed in a Pt-10% Rh crucible and allowed to stabilize for 19 hours in the thermoanalyzer at an ultimate vacuum of  $4 \times 10^{-8}$  torr. During this period in vacuum, the sample lost  $4.4 \pm 0.2$  wt.%, presumably adsorbed H<sub>2</sub>O. Following this measurement, the sample was heated at a rate of 10 °C/min to a maximum temperature of 1000 °C. A loss of  $14.6 \pm 0.2$  wt.%, principally H<sub>2</sub>O, occurred between 22 and 1000 °C (Fig. 2). This was composed of a minor loss of approximately 0.8 wt.% between 22 and 150 °C with a peak at 95 °C, and a major loss of 13.8 wt.% between 150 and 950 °C, with a peak at 445 °C.

The total weight-loss of 19.0 wt.% H<sub>2</sub>O (4.4 wt.% in vacuum prior to heating plus 14.6 wt.% during heating) is similar to the total weight loss of 19.38 wt.% (5.71 H<sub>2</sub>O<sup>-</sup>, 13.67 wt.% H<sub>2</sub>O<sup>+</sup>) reported by Keep (Table 1). The loss in vacuum of 4.4 wt.% adsorbed H<sub>2</sub>O is significantly greater than the loss of 0.1 to 1.8 wt.% that we have observed in many other serpentines that we have analyzed. This likely reflects the small size of the particles and a high surface-area available for adsorption.

The H<sub>2</sub>O lost in vacuum prior to the thermal analysis is not essential to the lizardite or clinocllore structures, and need not be included in the empirical formula. The major loss in H<sub>2</sub>O during heating of 14.6 wt.% is produced by the destruction of the crystal structures and loss of hydroxyl ions as H<sub>2</sub>O. The lowered peak temperature of 445 °C, compared to 600 to 700 °C for similar sheet silicates analyzed at one atmosphere, is partly due to the high vacuum (Wicks & Ramik 1990), but also may be due to the small particle-size (Mackenzie 1970). The analytical total of the microprobe results (84.2 wt.%) plus the structural water present (14.6 wt.%) combine for a total of 98.8 wt.% (Table 1).

An average formula for the interstratified lizardite-clinocllore mixture,  $(\text{Mg}_{1.74}\text{Al}_{0.88}\text{Ni}_{0.13}\square_{0.25})\Sigma 3.00(\text{Si}_{1.60}\text{Al}_{0.40})\Sigma 2.00\text{O}_5(\text{OH})_4$ , can be calculated from the

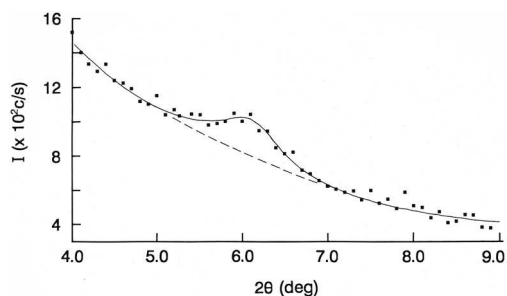


FIG. 3. An X-ray powder-diffraction pattern of the 14 Å (6.1° 2θ) peak of interstratified lizardite-clinocllore recorded in a step scan from 4° to 9° 2θ. The experimental conditions are given in the text.

results of the electron-microprobe analysis based on 14 negative charges and assuming the presence of  $\text{Ni}^{2+}$ . With so many mineral analyses being done with an electron microprobe and with  $\text{H}_2\text{O}$  determinations rarely available, this method of calculating the formula is the norm. However, using the amount of  $\text{H}_2\text{O}^+$  determined by TGA-EGA analysis (14.6 wt.%  $\text{H}_2\text{O}^+$ ) combined with the analytical results acquired with an electron microprobe, an alternative average formula, based on nine atoms of oxygen can be calculated:  $(\text{Mg}_{1.68}\text{Al}_{0.78}\text{Ni}_{0.13}\square_{0.41})\Sigma 3.00(\text{Si}_{1.55}\text{Al}_{0.45})\Sigma 2.00\text{O}_{4.51}(\text{OH})_{4.49}$ .

### X-ray diffraction

Several X-ray powder-diffraction patterns were recorded with a 114.6 mm Debye-Scherrer camera at the Smithsonian and at the Royal Ontario Museum (ROM), and with a Nonius Guinier-de Wolff camera at the ROM. We used  $\text{CuK}\alpha$  radiation in all cases. Data for representative powder-diffraction patterns are presented in Table 2. All the diffraction patterns are composed of fairly broad reflections suggesting poor crystallinity or fine grain-size or both. Some of the ROM powder-diffraction patterns were produced using a Philips clay-mineral collimator to enhance the possibility of recording

low-angle reflections. Strong scattering in the low-angle region recorded on all the films made observation and measurement of the 14 Å reflection difficult. However, a weak, broad, unambiguous 14 Å peak was recorded at  $14.5 \pm 0.3$  Å by making a step scan through  $4^\circ$  to  $9^\circ$   $2\theta$  of a small sample smear, mounted on a quartz plate (Fig. 3). A step-scan interval of  $0.100^\circ$   $2\theta$ , an integration time of 15 seconds per step, a  $0.25^\circ$  divergence slit, a  $0.25^\circ$  antiscatter slit, and a 0.3 mm receiving slit on a Philips automated diffractometer at the University of Manitoba were used to record this peak.

A series of heating experiments was made to further define the 14 Å structure. The limited amount of material available precluded a regular diffractometer-based heating study, so a small amount of powder was heated in a 0.2 mm capillary. The product was examined by Debye-Scherrer powder diffraction using clay-mineral collimators. Heating in air for 2.5 hours at  $550^\circ\text{C}$  increased the intensity of the 14.5 Å reflection and decreased the intensity of all other  $00l$  reflections. Heating at  $630^\circ\text{C}$  produced a shift from 14.5 to 13.8 Å. This step confirmed that the 14 Å phase is chlorite and not vermiculite (Brindley & De Souza 1975).

At this point in the study, it appeared that the material might well be a Ni-bearing clinochlore (Bayliss 1975), with

TABLE 2. X-RAY-DIFFRACTION DATA FOR "MAUFITE", LIZARDITE-CLINOCHLORE

Clinochlore 1a*	Debye Scherrer 114.6 mm		Guinier-de Wolff		Microbeam Lz + Cch		Microbeam Lz only		Lizardite Group A <sup>†</sup>
	<i>d</i> (Å)	<i>l</i> (est)	<i>d</i> (Å)	<i>l</i> (est)	<i>d</i> (Å)	<i>l</i> (est)	<i>d</i> (Å)	<i>l</i> (est)	
001	14.3	m	14.4	3	14	m			
002	7.12	s	7.12	10	7.17	s	7.13	s	001
003	4.81	vw	4.84	<1	4.82	m			
020, 110	4.54	s	4.57	9	4.47	s	4.52	s	020
111	4.23	vw?							11 $\bar{1}$
022			3.88	1					021
004	3.56	s	3.57	7	3.54	s	3.55	s	002
005					2.83	w			
20 $\bar{1}$ , 200	2.61	m	2.631	4	2.58	m	2.61	m	20 $\bar{1}$ , 200
20 $\bar{2}$	2.56	m	2.573	4					20 $\bar{2}$
202	2.376	s	2.376	5	2.37	m	2.36	ms	003
20 $\bar{4}$							2.24	w	201
204	2.000	w	2.001	1	2.00	m	2.00	m	20 $\bar{3}$
20 $\bar{7}$	1.725	vw	1.732	<1					
206	1.664	vw	1.67	<1					20 $\bar{4}$
060, 207	1.529	s	1.53	6					060
062	1.493	w	1.497	1					061
064	1.403	w							062
20 $\bar{10}$	1.318	w							204
066	1.285	w							063

\* Bailey (1988c),

<sup>†</sup> Bailey (1988b).

Symbols used: Lz: lizardite, Cch: clinochlore.

similarities to the other Ni-bearing chlorites studied by Brindley & De Souza (1975) and by Bailey & Riley (1977). The powder-diffraction patterns can be indexed as clinochlore (Table 2), and the intensities of the  $h0l$  reflections best match a monoclinic 1a polytype (Bailey 1988a, c). This is the structure generally found in other Ni-bearing chlorites (Brindley & De Souza 1975, Bailey & Riley 1977). However, we discovered that the Ruorka Ranch vein material is not simply a Ni-bearing clinochlore. Five microbeam X-ray diffraction patterns, taken from various textural units in three small fragments of vein material using the procedures of Wicks & Zussman (1975) and Wicks *et al.* (1995), indicated that there are two distinct phases present: a 14 Å and a 7 Å phase. In one diffraction pattern, the  $00l$  reflections of clinochlore with  $l$  odd are absent, leaving a lizardite pattern (Table 2) and in the other four patterns, the reflections of clinochlore with  $l$  odd were found to vary in intensity with respect to those with  $l$  even. The diameter of the X-ray microbeam is 50 µm; the diffraction results thus indicate that the abundance of clinochlore varies over relatively short distances.

The spacing and the intensities of the reflections of the 7 Å lizardite structure (Table 2) indicate that it is a Group-A polytype (Bailey 1969, 1988b). As both the 7 Å Group-A polytype and the 14 Å 1a polytype (Bailey 1988a, 1988c) involve shifts of  $\pm a/3$ , there are basic similarities in the two diffraction patterns, so that diffraction patterns of the mixture can be indexed as the chlorite polytype 1a (Table 2).

These diffraction results raise the question of whether the material is a mechanical mixture of the two phases or a regular interstratification of the 7 Å and 14 Å layers. The recorded 003 and 005 diffraction peaks are too weak (Table 1) for us to measure half-peak widths for comparison with half-peak widths for the  $00l$  reflections with  $l$  even. However, the half-peak width of the 001 reflection (Fig. 3) could be estimated, and it is approximately twice as wide as the half-peak widths of the 002 and 004 reflections. Reynolds (1988), Moore & Reynolds (1989), and Reynolds *et al.* (1992) have demonstrated, using calculated diffraction patterns, that this effect is produced by diffraction from a random interstratification of serpentine and chlorite.

In order to understand the nature of the interstratification, we used the program NEWMOD (Reynolds & Reynolds 1996) to estimate the relative abundance of lizardite and clinochlore and the nature of the interstratification. The program was modified, as instructed in the manual, to adjust for the nickel content, vacancies, and lack of iron in the structure, although this did not profoundly affect the results. Use of the *Reichweite* routine of the program indicated that the lizardite and clinochlore are randomly interstratified. When a series of calculated diffraction patterns were compared to the recorded diffraction patterns, the maximum clinochlore content recorded was on the order of 25%. We found that the NEWMOD program is not sensitive to clinochlore

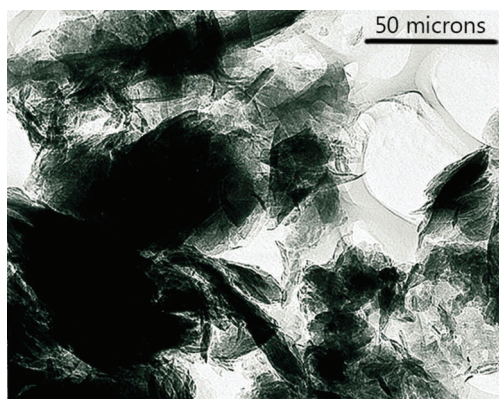


FIG. 4. A low-magnification transmission electron microscope image of crushed and dispersed composite grains of the lizardite-clinochlore fragments deposited on a holey carbon film.

contents of less than 10%. However, some of the microbeam diffraction patterns of the Group-A polytype (Table 2) revealed an absence of clinochlore; the clinochlore content thus seems to vary from near 0 up to 25% among the various samples.

In most of the natural occurrences cited by Reynolds (1988), chlorite is the dominant phase. The mineral dozyite has a regular interstratification of amesite and clinochlore occurring in equal amounts (Bailey *et al.* 1995). However, the Ruorka Ranch vein material seems to be unusual in that lizardite, the serpentine component, is the dominant phase. In order to further understand this problem, we used transmission electron microscopy.

#### Transmission electron microscopy

An attempt was made to thin two vein fragments by ion milling, but the material tended to break away rather than thin. One sample survived milling, but it had thick edges and was of limited use for our study. Two additional samples of grains, picked from the vein center and from the vein margin, were crushed and the dispersed fragments were mounted on holey carbon films on Cu specimen grids for transmission electron microscopy (TEM). A Philips CM12 scanning-transmission electron microscope (STEM) fitted with a Kevex Quantum solid-state detector for analytical electron microscopy (AEM) was used for this study.

Crushing and dispersing the samples produced a range of fragments from anhedral composite grains to smaller elongate grains (Fig. 4). The larger grains are an assemblage of smaller grains, some of which occasionally have what might be partially and weakly developed crystal outlines. The features of the grains seen by TEM (Fig. 4) bear little resemblance to the original pseudomorphic textures seen in thin section (Fig. 1). The elongate grains tend to be smaller than the

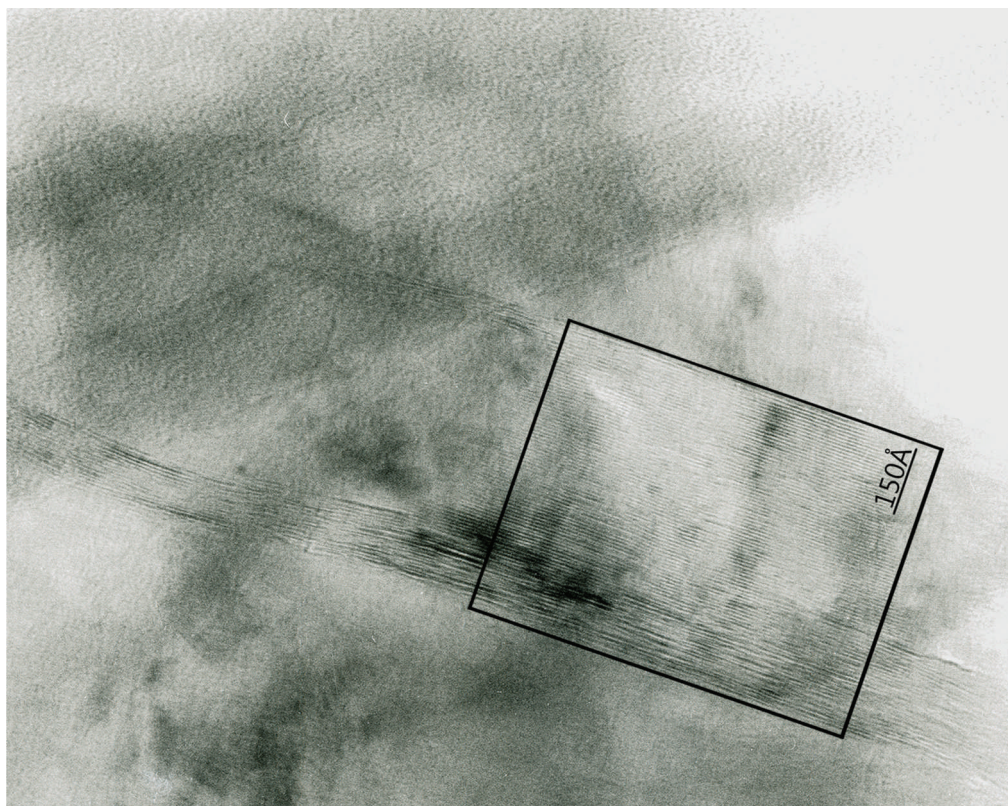


FIG. 5. A transmission electron microscope image of a slightly elongate grain with long slim arms extending from the corners. Well-developed 7 Å structural fringes occur throughout, with 14 Å fringes mainly occurring in the marginal zones and less frequently within the grain. This is probably a part of the randomly interstratified Ni-bearing lizardite-clinoclchlore pseudomorphs after the original amphibole. The outlined area is Figure 6.

composite grains and probably come from the elongate parts of the pseudomorphs after amphibole, but this is speculation.

The diameter of the individual grains that make up the larger composite grains is approximately 200 Å. This fine grain-size explains the broad reflections of the X-ray diffraction patterns, the high level of the low-angle scattering, the high content of adsorbed H<sub>2</sub>O, and the lower and broader-than-normal range of decomposition temperatures during TGA-EGA.

Numerous selected-area electron-diffraction patterns were examined. We found that lizardite is dominant in the samples examined by TEM. Most of the selected-area electron-diffraction patterns are in a classic, although rarely perfectly oriented, hexagonal array, showing that most of the lizardite-clinoclchlore particles are lying on the 001 basal cleavage plane with the **c** axis parallel, or nearly parallel, to the electron beam (Wicks 1979, Fig. 1.34). Closely spaced pairs of diffraction spots and occasional arcs associated with the diffraction spots indicate that successive cleavage packets of lizardite are slightly rotated with respect to one another. The grinding and dispersion of the sample have not

only fractured the lizardite-clinoclchlore particles in the pseudomorphic textures, but have also cleaved them along the basal cleavage plane to produce thin platy particles. Within these thin platy particles, adjacent cleavage packets are slightly rotated within the cleavage plane with respect to adjacent cleavage packets.

Selected-area electron-diffraction patterns from the elongate particles were less frequently recorded and have the **c** axis of lizardite-clinoclchlore perpendicular to the axis of elongation, and either the **a** or **b** axes parallel to the direction of elongation (see Wicks 1979, Fig. 1.32, for the basic orientation of these patterns; note that these are fiber-diffraction patterns, and the diffraction spots from the cylindrical fibrous structure should be ignored). One pattern had the **a** axis parallel to the axis of elongation and the **c** and the **b** axes perpendicular to it. The diffraction patterns were rarely well oriented, showing tilting, as might be expected from an irregular elongate particle. These electron-diffraction patterns generally show streaking of reciprocal lattice rows with  $k \neq 3n$ , indicating interlayer disorder.

Eight 00 $l$  structural fringe images were recorded from elongate particles that are probably from the

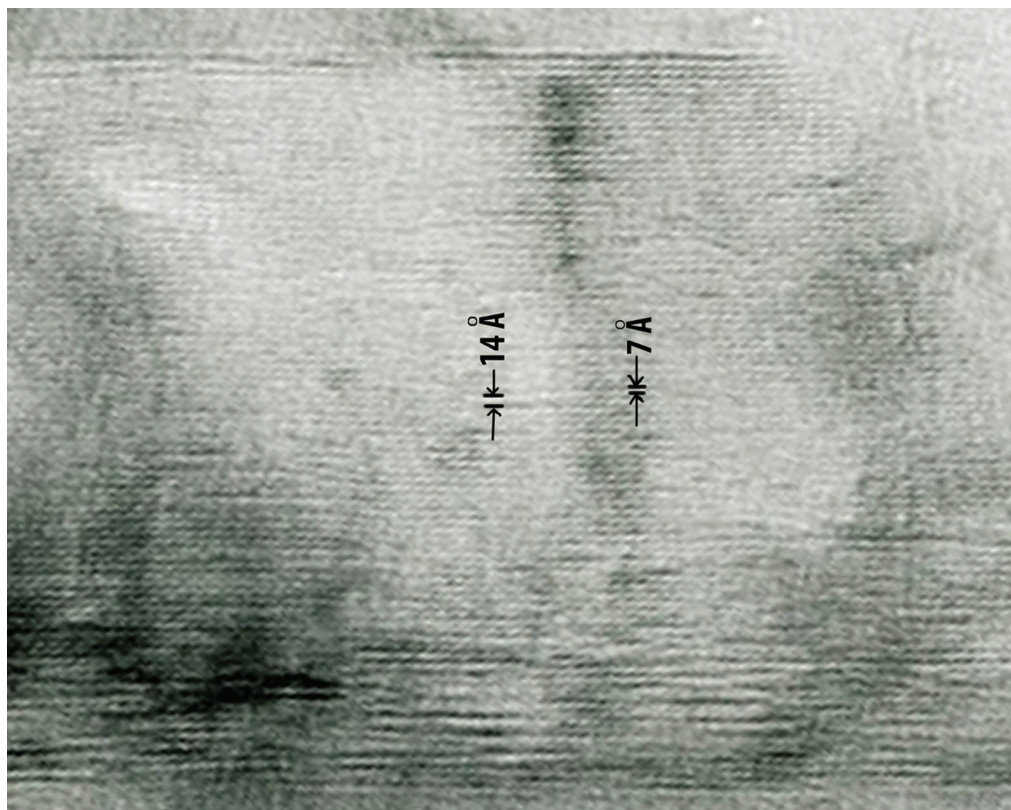


FIG. 6. A closer view of the structural fringes in the transmission electron microscope image in Figure 5. Clinochlore (14 Å) dominates across the bottom of the image, and lizardite (7 Å) dominates in the central area and across the top. Two layers of lizardite that pass into a single layer of clinochlore can be seen in several places throughout the image as well as at the transition labeled in the center of the image.

elongate parts of the amphibole pseudomorphs. The areas of fringes is usually small. The largest area is shown in Figure 5. This blocky, slightly elongate grain has slim arms of variable length extending from the corners. The fringes show that the sample is dominated by the lizardite layers, but that interstratified clinochlore or packets of clinochlore layers also are present (Figs. 5, 6), although not in all images. The lizardite and clinochlore structures often pass from one structure to the other laterally (Fig. 6), two layers of lizardite becoming one of clinochlore (Cressey *et al.* 2008a). The TEM results provide direct evidence (along with the X-ray data) that the material is randomly interstratified and lacks long-range periodicity.

Numerous areas examined by AEM show that the material has a heterogeneous composition. The nickel content of most particles varies from 2 to 8 wt.% NiO, and one contained 12 wt.% NiO (discussed below), but on average is close to the average value, 3.4 wt.% NiO, obtained by electron-microprobe analysis. Iron is, in general, absent or present at less than 1 wt.% FeO in most grains, but a few grains contain significant amounts of iron,

corresponding to 2 to 12 wt.% FeO. One unusual grain has a Mn content of 11 to 12 wt.% MnO. This grain also has the highest Ni content, 12 wt.% NiO, and 0 to 3 wt.% FeO. In general, the composition determined by the electron microprobe, but also illustrates the heterogeneous chemical composition of the material on the very fine scale. This latter point was not obvious in the electron-microprobe study.

A single grain of chlorite was identified and analyzed with the AEM. This grain produced sharp electron-diffraction spots, is Fe-rich and Ni-poor, has some edges typical of a hexagonal crystal, and is slightly coarser than the associated lizardite-clinochlore mixture. In contrast to the composition of the interstratified lizardite-clinochlore, this chlorite is a Mg-bearing chamosite with almost no nickel. This chamosite is an extraordinary grain, possibly associated with the contact zone of the vein. It is not interstratified with the lizardite, and its Fe-rich, Ni-poor composition does not represent the chlorite in the Ni-rich, Fe-poor interstratified lizardite-clinochlore.

The difficulty in finding clinochlore in the two samples examined by TEM confirms the X-ray microbeam results,

and indicates that the clinochlore content is variable and may be nil, at least in the volume sampled in the 50  $\mu\text{m}$  diameter beam of the microbeam X-ray-diffraction camera.

#### DISCUSSION AND CONCLUSIONS

“Maukite” is discredited as a mineral name. The Ruorka Ranch vein material is a Ni-bearing lizardite of Group A (Bailey 1969, Bailey 1988a, 1988b) with a variable amount, 0 to 25%, of randomly interstratified clinochlore polytype Ia (Bailey 1988a, 1988c). The average formula for the interstratified lizardite-clinochlore mixture ( $\text{Mg}_{1.74}\text{Al}_{0.88}\text{Ni}_{0.13}\square_{0.25}\Sigma_{3.00}(\text{Si}_{1.60}\text{Al}_{0.40})\Sigma_{2.00}\text{O}_5(\text{OH})_4$ ), can be calculated from the electron-microprobe results based on 14 negative charges. An alternative average formula, ( $\text{Mg}_{1.68}\text{Al}_{0.78}\text{Ni}_{0.13}\square_{0.41}\Sigma_{3.00}(\text{Si}_{1.55}\text{Al}_{0.45})\Sigma_{2.00}\text{O}_{4.51}(\text{OH})_{4.49}$  based on nine atoms of oxygen, can be calculated from the electron-microprobe analytical results combined with the TGA-EGA results (14.6 wt.%  $\text{H}_2\text{O}^+$ ). This is probably the more accurate formula, but the first formula is helpful for researchers using microprobe analyses. Although the AEM results indicate that the composition of individual grains is variable, both formulae, in a general way, represent the essential features of the randomly interstratified Ni-bearing lizardite-clinochlore. Aluminum is the principal minor element substituting in both the sheets of octahedra and tetrahedra; the distribution of this trivalent ion requires that some vacancies occur in the sheet of octahedra, although the material is essentially trioctahedral. There is no significant amount of iron present; the bright emerald green color may be a result of the minor and variable nickel content. The variable nature of the composition of grains suggests that differences among or within grains may be greater than differences between adjacent 7  $\text{\AA}$  and 14  $\text{\AA}$  structures within a grain. All evidence indicates that this is a poorly crystalline, non-equilibrium product of serpentinization.

It is not possible to determine whether or not the clinochlore composition differs significantly from the lizardite composition. The interstratification is at too fine a scale (Figs. 5, 6) to test for differences with the AEM. Although Al is essential for the clinochlore structure, it is not essential for the lizardite structure. The crystal structure of a practically Al-free, end-member lizardite has been refined by Mellini *et al.* (2010), demonstrating that lizardite can crystallize without Al. It would appear that clinochlore does incorporate Al at the expense of lizardite in an Al-poor system.

It is important to note that where the serpentine-chlorite solid-solution system is Al-rich, the serpentine mineral that forms is the Al-rich serpentine amesite,  $\text{Mg}_2\text{Al}(\text{SiAl})\text{O}_5(\text{OH})_4$ . In fact, the amesite is more aluminous than the associated clinochlore (Bailey *et al.* 1995). Where the system is Al-poor, the serpentine mineral that forms is the relatively Al-poor lizardite,

and the clinochlore is more aluminous than the lizardite (Cressey *et al.* 2008a).

The dominance of lizardite over clinochlore in the “maufite” material is the reverse of most other interstratified serpentine-chlorite described in the literature (Reynolds 1988, Moore & Reynolds 1989, Banfield *et al.* 1994, Bailey *et al.* 1995, Banfield & Bailey 1996). The lizardite-dominant interstratification thus is rare, but Cressey *et al.* (2008a) have proposed that small amounts of clinochlore (2 to 5%) interstratified with lizardite may be common within lizardite but simply goes unrecognized. Thin packets of clinochlore would not coherently diffract X-rays. This inference is supported to some degree by 14  $\text{\AA}$  structures associated with lizardite occasionally found in an extensive microbeam X-ray camera study of serpentine textures after olivine and pyroxene (Wicks 1969, Wicks & Plant 1979). Note, however, that these 14  $\text{\AA}$  structures have not been characterized in detail.

The study of this material provides an example of the difficulties encountered in the study of fine-grained materials. If the identification had been based only on the X-ray powder-diffraction study and electron-microprobe results, an erroneous conclusion would have been drawn. The microbeam X-ray diffraction and TEM/AEM study provided the basis for a quite different conclusion.

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