INTRODUCTION

Aluminum-poor ferromagnesian amphiboles are either monoclinic (cummingtonite-grunerite) or orthorhombic (anthophyllite-ferroanthophyllite), and in most instances the distinction is readily made using the polarized light microscope. However, at least for iron-rich compositions, the observation of parallel extinction still leaves open three possibilities: sub-microscopically twinned or fibrillar (Wylie 1979) \( C_2/m \) grunerite, \( Pnmn \) protoferroanthophyllite (Sueno et al. 1998), or \( Pnma \) ferroanthophyllite. Near end-member grunerite, formed by replacement of fayalite in granite from Rockport, Massachusetts, is a case in point. It was described as a member of the anthophyllite series (parallel extinction) by Warren (1903; see also Evans and Medenbach 1997) and as grunerite (\( Z_c = 10^\circ \)) by Bowen and Schairer (1935). In a thin section of the same sample studied by Bowen and Schairer (National Museum of Natural History R7702), we found both inclined and parallel extinction. A single-crystal examination by Hexiong Yang (personal communication 1998) confirmed grunerite, but also indicated the presence of submicroscopic twinning on (100). We embarked on a transmission electron microscopy (TEM) study of this sample to determine if the twinning fully accounted for the parallel extinction. If not, we believed that the results could be informative with regard to the stability relations of the iron-rich ferromagnesian amphiboles. It transpired that, in addition to imaging the very fine-scale twinning, we are able to confirm unambiguously for the first time the existence in nature of near end-member \( Pnma \) ferroanthophyllite.

The TEM investigation also provided a clue to the relative timing of growth of ferroanthophyllite and grunerite. However, we did not find protoamphibole in the Rockport sample. For comparison, we also studied a sample of the protoferroanthophyllite from Cheyenne, Colorado (American Museum of Natural History 10928) described by Sueno et al. (1998).

AMPHIBOLE STRUCTURES

The structures of amphiboles are well known and have been described in great detail in several papers and a number of reviews (e.g., Veblen 1981; Hawthorne 1983; Deer et al. 1997). The basic structure consists of double chains of linked \( (Si,Al)O_4 \) tetrahedra parallel to the \( c \) axis and octahedral cations of larger size sandwiched between the tetrahedral ribbons. Ferromagnesian amphibole with a composition close to the iron end-member is now known to crystallize in three space groups: \( C_2/m \) grunerite, \( Pnmn \) protoferroanthophyllite (Sueno et al. 1998), or \( Pnma \) ferroanthophyllite. Near end-member grunerite, formed by replacement of fayalite in granite from Rockport, Massachusetts, is a case in point. It was described as a member of the anthophyllite series (parallel extinction) by Warren (1903; see also Evans and Medenbach 1997) and as grunerite (\( Z_c = 10^\circ \)) by Bowen and Schairer (1935). In a thin section of the same sample studied by Bowen and Schairer (National Museum of Natural History R7702), we found both inclined and parallel extinction. A single-crystal examination by Hexiong Yang (personal communication 1998) confirmed grunerite, but also indicated the presence of submicroscopic twinning on (100). We embarked on a transmission electron microscopy (TEM) study of this sample to determine if the twinning fully accounted for the parallel extinction. If not, we believed that the results could be informative with regard to the stability relations of the iron-rich ferromagnesian amphiboles. It transpired that, in addition to imaging the very fine-scale twinning, we are able to confirm unambiguously for the first time the existence in nature of near end-member \( Pnma \) ferroanthophyllite.

The TEM investigation also provided a clue to the relative timing of growth of ferroanthophyllite and grunerite. However, we did not find protoamphibole in the Rockport sample. For comparison, we also studied a sample of the protoferroanthophyllite from Cheyenne, Colorado (American Museum of Natural History 10928) described by Sueno et al. (1998).

ABSTRACT

A transmission electron microscopy study reveals the microstructure of polysynthetically twinned, near end-member grunerite from Rockport, Massachusetts. A small percentage of \( Pnma \) ferroanthophyllite of similar composition is present as thin slabs intergrown parallel to (100) of grunerite and as individual \( \mu \)-size crystals. HRTEM imaging shows that grunerite is free of chain-multiplicity faults. The observed microstructures are interpreted as a result of partial transformation of ferroanthophyllite to grunerite, a mechanism that is also supported by microstructures observed in the \( Pnmn \) protoferroanthophyllite from Cheyenne, Colorado, with similar composition. This study supports the possibility that grunerite, ferroanthophyllite, and protoferroanthophyllite may all possess true stability fields.
Starting with the C2/m amphibole the systematic repeat of the n-glide plane for every other silicate layer will produce the Pnma amphibole whereas operating the glide plane for every silicate tetrahedral layer produces the Pnmm structure. Isolated operation of n-glide translation between two adjacent tetrahedral layers will create a stacking fault in the clinoamphibole with apparent vector of displacement ~c/5 (Fig. 1c). In this respect each (100) twin plane in clinoamphibole could also be regarded as a slab of orthoamphibole half a unit cell wide along a* (Fig. 1b). Similarly, the stacking fault in clinoamphibole could also be described as protoamphibole half a unit cell wide along a* (Fig. 1c).

RESULTS

Electron microprobe

Electron microprobe analysis was done by wavelength-dispersive spectrometry with a JEOL 733 microprobe at the University of Washington, Department of Geological Sciences, using natural mineral standards, 15 kV accelerating potential, 10 to 40 min integration times, and the a-factors of Armstrong (1988). The average composition of the Rockport amphibole (sample R7702) calculated from the microprobe analysis (Table 1) assuming 23 anhydrous O atoms per formula unit is: Na0.03Mg0.02Al0.03Mn0.23Zn0.06Fe6.68Si7.97O22(OH)2. Thus, the only significant end-member components are Fe (95.5%) and Mn (3.3%), in agreement with the wet-chemical analysis in Bowen and Schairer (1935). This composition reflects that of the fayalite from which it formed by addition of SiO2 and H2O. Additional minerals found in the sample are magnetite, fayalite, and traces of minnesotaite and fluorite. The only significant difference between the composition of the Rockport amphibole and the Cheyenne amphibole (Table 1; also Sueno et al. 1998) is the increased amount of Mn in the latter. Both samples contain small amounts of Zn, but F was not detected in either.

Transmission electron microscopy

Transmission electron microscopy (TEM) was performed at the Central Facility for Advanced Microscopy and Microanalysis of the University of California at Riverside with a Philips CM300 microscope operating at 300 kV accelerating voltage, equipped with a LaB6 electron gun, twin objective lens, a CompuStage eucentric side-entry goniometer allowing a high degree of tilt (±70°), a low-background double-tilt specimen holder, a Gatan anti-contamination device, and an EDAX energy dispersive spectrometer (EDS).

Samples of R7702 from Rockport, Massachusetts and 10928 from Cheyenne, Colorado were prepared by gently crushing

**TABLE 1.** Microprobe analyses of R7702 Rockport grunerite/ferroanthophyllite and 10928 Cheyenne protoferroanthophyllite

<table>
<thead>
<tr>
<th></th>
<th>NMNH R7702</th>
<th>AMNH 10928</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>47.73 (27)</td>
<td>48.05 (34)</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.01 (01)</td>
<td>0.02 (02)</td>
</tr>
<tr>
<td>Al2O3</td>
<td>0.17 (07)</td>
<td>0.07 (05)</td>
</tr>
<tr>
<td>FeO*</td>
<td>47.90 (43)</td>
<td>46.95 (39)</td>
</tr>
<tr>
<td>MnO</td>
<td>1.65 (06)</td>
<td>2.48 (12)</td>
</tr>
<tr>
<td>MgO</td>
<td>0.07 (02)</td>
<td>0.14 (03)</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.49 (03)</td>
<td>0.43 (06)</td>
</tr>
<tr>
<td>CaO</td>
<td>0.02 (01)</td>
<td>0.07 (04)</td>
</tr>
<tr>
<td>Na2O</td>
<td>0.10 (04)</td>
<td>0.06 (02)</td>
</tr>
<tr>
<td>K2O</td>
<td>0.01 (01)</td>
<td>0.01 (01)</td>
</tr>
<tr>
<td>F</td>
<td>0.00 (02)</td>
<td>0.00 (02)</td>
</tr>
<tr>
<td>Cl</td>
<td>0.01 (01)</td>
<td>0.07 (02)</td>
</tr>
<tr>
<td>H2O+fCl</td>
<td>1.80</td>
<td>1.79</td>
</tr>
<tr>
<td>Less O = F, Cl</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>99.96</td>
<td>100.09</td>
</tr>
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</table>

Proportions of atoms based on anion charge of 46

<table>
<thead>
<tr>
<th></th>
<th>NMNH R7702</th>
<th>AMNH 10928</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>7.965</td>
<td>7.993</td>
</tr>
<tr>
<td>Fe</td>
<td>6.685</td>
<td>6.532</td>
</tr>
<tr>
<td>Mn</td>
<td>0.233</td>
<td>0.347</td>
</tr>
<tr>
<td>Mg</td>
<td>0.017</td>
<td>0.035</td>
</tr>
<tr>
<td>Zn</td>
<td>0.060</td>
<td>0.053</td>
</tr>
<tr>
<td>Ca</td>
<td>0.004</td>
<td>0.012</td>
</tr>
<tr>
<td>Na</td>
<td>0.032</td>
<td>0.016</td>
</tr>
<tr>
<td>K</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Cl</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>F</td>
<td>15.033</td>
<td>15.006</td>
</tr>
<tr>
<td>OH</td>
<td>1.997</td>
<td>1.980</td>
</tr>
</tbody>
</table>

* Iron as FeO.
† Calculated % H2O.
the crystal aggregates without any grinding, dispersing the material in distilled water and depositing it onto Cu grids coated with a thin (5 nm thick) holey carbon support film. Selected area electron diffraction (SAED) patterns and high-resolution (HRTEM) images were obtained from about 30 crystals of R7702 and about 10 crystals from 10928 in order to study their structure and defects. The HRTEM images were obtained with a 50 µm diameter condenser aperture, effective objective aperture radius of 0.86 nm⁻¹, spherical aberration (Cₐ) of 2.00 mm, at defocus values of −60 to −160 nm and a beam convergence angle of 0.8 mrad. Images were recorded digitally using a Gatan MultiScan CCD camera and DigitalMicrograph 2.5 software running on a Macintosh Power PC G3/333 computer utilizing the MacTempas software.

NMNH sample R7702 from Rockport, MA. This amphibole is in the form of sub-radiating aggregates of needles that appear to range up to 1 cm in length. Optical microscopy and SEM imaging reveal grains with typical dimensions on the order of 50 × 100 × 1000 µm, subparallel with respect to their c axes, and much fractured along the cleavage planes. Crystal fragments prepared for TEM by gentle crushing include a greater proportion of small grains, but their aspect ratios (5 to 15, Fig. 2) are comparable to the original sample. Harlow et al. (1984) showed that only excessive grinding of grunerite amphiboles significantly reduces the average aspect ratio.

The compositions of 30 individual crystals determined by EDS analyses, following the procedure described in Bozhilov et al. (1999), do not show significant variation. The average composition calculated assuming 23 anhydrous O atoms per formula unit is Mg₀.₀₉Al₀.₀₆Mn₀.₂₅Zn₀.₀₈Fe₆.₅₃Si₇.₉₉O₂₂(OH)₂. The variation in concentration of the individual elements in terms of formula units is: Mg ± 0.09, Al ± 0.03, Mn ± 0.08, Zn ± 0.04, Fe ± 0.1, Si ± 0.01. These minor compositional variations do not correlate with structure type, twinning, or defect density of the individual grains. The composition is within error limits the same as obtained by electron microprobe.

All SAED patterns obtained from the crystals are consistent with the amphibole structure. To reliably identify the structure type, usually several (up to 12) SAED patterns were obtained from individual crystal fragments. The phase identification was done after indexing all zone axis SAED patterns from one crystal and matching the angle of tilt between the experimentally determined and theoretically calculated zone axes.

The electron diffraction results unambiguously show that the sample consists mainly of C2/m grunerite with minor amounts of Pnma ferroanthophyllite. Four types of SAED patterns were revealed: (1) defect free C2/m grunerite, (2) twinned C2/m grunerite, (3) twinned grunerite intergrown with Pnma ferroanthophyllite and (4) Pnma ferroanthophyllite (Fig. 3). Out of 30 characterized crystals 5 are of type 1, 8 of type 2, 15 of type 3, and 2 of type 4. The grunerite and anthophyllite are intergrown in such a manner that their b and c axes are parallel, respectively. Such relationships cause the orientations of many zone axes to be extremely close together (Fig. 4). This results in extra reflections and produces complex SAED patterns. Many SAED patterns show streaking of the reflections parallel to a* (Fig. 3b and 3c). Some selected SAED patterns could be identified with the Pnma protoamphibole structure, but no single crystal was found for which all obtained SAED patterns could be identified with the Pnma structure, and the geometry between the zone axis patterns does not correspond to protoamphibole. These observations unambiguously show that individual crystals of protoamphibole structure type are not present in the amphibole of sample R7702.

HRTEM imaging was used to reveal the microstructural details of intergrowths and twinning in sample R7702. Images were obtained along the main crystallographic axes to reveal the structural details at the atomic scale. HRTEM images down the [100] axis show that the studied crystals are free of chain-multiplicity faults and possess perfect double-chain structure (Fig. 5). In this respect, our sample differs from previous studies of asbestiform grunerite, which have found the occurrence of chain-multiplicity faults to be common (Hutchison et al. 1975; Cressey et al. 1982).

The [011] zone axis was chosen for HRTEM imagining because it offers superior ability to distinguish between different amphibole polymorphs, reveal twin planes and stacking faults, compared to imaging along the b axis, where the image contrast is much more complex. For comparison, in Figure 6 we show calculated HRTEM images of anthophyllite and grunerite with the electron beam respectively parallel to [010] and [011], as well as the corresponding patterns of the projected potentials. Due to the specific arrangements of the O atoms around the tetrahedral and octahedral sites a localized gap of low potential density is formed by tilting the amphibole so that the [011] axis is parallel to the electron beam. The places of low charge density are visualized as dark areas on the images of the projected potential (Spence 1988) and as bright spots on

![Figure 2](image-url) - A low magnification TEM image showing the morphology of the amphibole crystals fragments from Rockport, Massachusetts.
FIGURE 3. SAED patterns with the beam parallel to the $b$ axis from four different amphibole crystals from Rockport, Massachusetts. The indices of the reflections are placed so that the number in the middle is positioned directly under the corresponding reflection. An arrow points to the indexed reflection, where the pattern is complex. (a) This image is from an individual defect-free crystal of grunerite, (b) and (c) are from individual crystals of intergrown and twinned grunerite and ferroanthophyllite, representing different degrees of defectiveness, and (d) is from an individual crystal of ferroanthophyllite. The streaking of the reflections parallel to $a^*$ in (b) and (c) is due to the presence of planar defects and narrow intergrowth domains.

FIGURE 4. Stereographic projection down [010] of intergrown grunerite and ferroanthophyllite. The zone axes of grunerite and ferroanthophyllite are plotted as open circles and filled squares, respectively. The coinciding zone axes are shown as filled circles. The indices of grunerite are positioned above the symbol and the indices for ferroanthophyllite below the symbol.
the corresponding HRTEM images, where the symmetry and mutual disposition of the bright spots reflect very closely the arrangement between the octahedral and tetrahedral layers in the structure. Experimental structure images obtained with the electron beam parallel to the [011] zone axis show the structural details of the intimate intergrowths and twinning (Figs. 7 and 8). The composition plane of the twinned grunerite is parallel to (100) and this is also the contact plane of the intergrown ortho- and clinoamphibole. The twinning of grunerite is based on reflection across the (100) glide plane with a glide component of \( \frac{c}{2} + \frac{b}{2} \). Image interpretation is based on comparison with simulated HRTEM images. Simulated HRTEM images were generated for twinned grunerite based on the model of twinning shown in Figure 1b, as well as for ideal ferroanthophyllite and protoferroanthophyllite. The simulated images match very closely the experimental ones (Fig. 7). Shown in Figure 7d and Figure 8 are typical HRTEM images down [011] in two crystals of grunerite. Both crystals consist of wide bands of twinned grunerite parallel to the \( c \) axis, intergrowths of \( Pnma \) ferroanthophyllite with variable thickness and stacking faults in grunerite with displacement vector \( c/5 \) (the latter are not shown). The polysynthetic grunerite twins are usually between 5 and 500 nm wide. The ferroanthophyllite intergrowths are narrow slabs about 3 to 15 unit cells wide along the \( a^* \) axis. The twin boundaries and the intergrowths usually intersect the whole examined crystal fragments along their \( c \) axis. Since no terminations within the crystals were observed, we conclude that the intergrowths originally transected the whole crystals, an inference supported by SEM imaging of the microstructures. The stacking faults have similar distribution and also transect the whole grain fragments parallel to the \( c \) axis. They can be described as narrow bands with

**Figure 5.** HRTEM image of Rockport grunerite down [100] showing perfect amphibole double-chain structure. No chain-width errors or other defects are present.

**Figure 6.** Simulated HRTEM (b, d, f, h) and calculated projected potential (PP) (a, c, e, g) images of anthophyllite (a, b, c, d) and grunerite (e, f, g, h) with beam parallel to [010] and [011], respectively. Assumed thickness of the crystals along the electron beam direction is 50 nm.
protoamphibole structure arrangement half a unit-translation wide along the $a^*$ axis. The fact that such a band does not extend more than one unit cell in all three dimensions suggests that it should be classified as a planar defect rather than an intergrowth with unique structure.

**AMNH sample 10928 from Cheyenne, Colorado.** Transmission electron microscope data, EDS, and microprobe analysis confirm the structure and composition as determined by Sueno et al. (1998). The amphibole in this sample is Mn-bearing protoferroanthophyllite. The structure was confirmed by electron diffraction. The HRTEM imaging revealed the presence of isolated stacking faults, and intergrown narrow slabs of grunerite and ferroanthophyllite (Fig. 9). The width of the intergrowths perpendicular to $a^*$ is variable but narrower than in the Rockport amphibole. The intergrown slabs are made of even and odd numbers of octahedral layers present in almost equal amounts.

**DISCUSSION**

The clear difference in the microstructures of grunerite from Rockport and protoferroanthophyllite from Cheyenne suggests that the microstructures are characteristic for the corresponding sample and are not introduced mechanically during preparation. Further evidence of the original character of the observed microstructures is the lack of stacking faults or (100) twinning in samples of ferroactinolite MS2825 from the UCLA collection and tremolite from Val Malenco, Italy, both prepared by gentle crushing and examined under similar conditions in the TEM. The multiple twinning on (100) of metamorphic cummingtonite-grunerite has long been known as a valuable diagnostic feature (e.g., Deer et al. 1997), although its fine scale in the Rockport sample is perhaps unusual. The origin of the complex intergrowths and twinning in the Rockport grunerite can be interpreted in terms of its growth and evolution. Theoretically, there are three possibilities for the origin of the observed microstructures: (1) growth of grunerite thermodynamically close to the stability field of orthoamphibole, so that both structures nucleate simultaneously with quantitative dominance of grunerite; (2) initial growth of grunerite and subsequent partial transformation to ferroanthophyllite; (3) initial growth of ferroanthophyllite with later transformation to grunerite. Of these hypotheses the third one matches most closely the observed microstructures. This is because the transformation from grunerite to ortho- or protoamphibole and vice versa is constrained by certain geometrical relationships. If we look closely at the grunerite structure (Fig. 1a) we notice that one unit cell of grunerite encompasses two tetrahedral and two octahedral layers along...
a*. The same is true for protoamphibole whereas the anthophyllite structure consists of four tetrahedral and four octahedral layers along a*. The configuration of the composition plane of (100) twins and the stacking faults parallel to (100) in grunerite resemble the configuration around the n-glide planes in orthoamphibole as discussed earlier (Fig. 1). During transformation from clinoamphibole to orthoamphibole the composition planes of (100) twins and stacking faults if present will be the preferable nucleation sites for the n-glide planes because the short-range order is preserved and minimum rearrangement is required. In the case of the reverse transformation path, namely from orthoamphibole to clinoamphibole, the present n-glide planes would be preferred nucleation sites for (100) twins and stacking faults for the same reason stated above.

If an originally perfect grunerite is transformed to ferroanthophyllite by solid-state transformation, because of the random occurrence of the nucleation of the Pnma structure, the newly formed orthoamphibole domains will be separated by domains consisting of even and odd numbers of octahedral layers in similar proportions. If grunerite is formed by transformation from protoamphibole, because of the separation of the n-glide planes by one octahedral layer, the final intergrown structure and twin domains will also consist of domains of odd and even numbers of octahedral layers in similar proportions. Only transformation from ferroanthophyllite to grunerite will produce intergrowths and twins separated mostly by even numbers of chains; this is because the n-glide planes are separated by two octahedral layers and any two n-glide planes in the precursor anthophyllite will be separated by octahedral layers in multiples of two, that is, even-numbered layers. In such a scenario two neighboring domains which transform simultaneously will meet either in registry or misregistry and in the latter case a stacking fault will be generated. The observations from this study show that twin domains in the Rockport grunerite are usually separated by even numbers of octahedral layers. The ratio of observed domains with even and odd numbers of octahedral layers is close to 15:1 in favor of the former. This suggests strongly that the twinning in grunerite and the intergrown...
orthoamphibole are the result of solid state transformation of ferroanthophyllite to grunerite rather than twinning of grunerite during growth and consequent partial transformation to ferroanthophyllite. Further support of the hypothesis of transformation of ferroanthophyllite to grunerite is provided by the presence of minor amounts of individual ferroanthophyllite crystals. In contrast, the intergrown slabs in the Cheyenne amphibole do not show a predominant presence of domains consisting of odd or even number of octahedral layers, which suggests a different origin compared to the Rockport grunerite. In this latter sample most probably the presence of defects is not due to transformation but rather it is a growth phenomenon.

**CONCLUDING REMARKS**

Assuming that the mutual phase relations of ferroanthophyllite and grunerite are analogous to those of anthophyllite and cummingtonite (Finger 1970; Ross et al. 1969; Evans et al. 1974; Carpenter 1982; Evans et al. 2001), then a stability field for ferroanthophyllite, if one exists at all, occurs at a lower temperature than that of grunerite. The inversion of ferroanthophyllite to twinned grunerite observed for the Rockport sample can then be explained in at least two ways: (1) nucleation and growth of metastable ferroanthophyllite followed at some later time by conversion to stable grunerite, or (2) nucleation and growth of stable ferroanthophyllite followed by inversion to grunerite as a consequence of an increase in temperature. An inversion temperature of approximately 450 °C has been postulated by Evans et al. (2001), based on an analysis of thermodynamic and field constraints in the FeMg-amphibole system. An event of fenitization by late magmatic peralkaline fluids was believed by Martin (1977) to have taken place in the Cape Ann non-orogenic plutonic complex that hosts the Rockport fayalite. There is otherwise no indication of a pervasive thermal event, although the complex resulted from a series of plutonic events. The hydration of fayalite in the presence of quartz and H₂O by means of the reaction 7 Fa + 9 Qtz + 2 H₂O = 2 Fe-Ath liberates 160 kJ at 550 °C; the C_p of Fe-Ath at this temperature is 1.0 kJ/mol. Therefore, the potential temperature rise due to the reaction is as much as 80 °C; of course, it will be much smaller depending on the relative rates of reaction and dispersion of heat.

At least by demonstrating the existence in nature of end-member ferroanthophyllite, the present study lends some support to the proposed stability field for ferroanthophyllite. However, the temperature minimum in the T-XFe relations of cummingtonite-grunerite and anthophyllite-ferroanthophyllite (Evans at al. 2001) may still preclude a stability field for intermediate FeMg-anthophyllites with respect to sheet-silicate assemblages.

Similar reasoning could also be used to infer some sort of stability field for Pnnm protoferroanthophyllite. It is possible that the proto structure might be favored by the presence of Mn (Sueno et al. 1998). Protoferroanthophyllite from Cheyenne, Colorado and Hiruka River Village, Japan, contains 2.5–2.7 and 3.0 wt% MnO respectively (Sueno et al. 1998), whereas the Rockport ferroanthophyllite contains 1.5–1.7 wt% MnO. HRTEM images of the Colorado sample confirm that it is com-
posed largely of protoferroanthophyllite (but with narrow slabs of grunerite and ferroanthophyllite). Clearly, there is scope for further work on the relative stabilities of the three polymorphs of Fe₇Si₈O₂₂(OH)₂, and their dependence on the presence of other components such as Mn and Mg.

ACKNOWLEDGMENTS

We greatly appreciate the loan of specimens from the National Museum of Natural History, the American Museum of Natural History, G.V. Gibbs, and S. Sueno. Thoughtful reviews by Alain Baronnet and Huifang Xu are appreciated. This work was supported by NSF grant EAR 9706236.

REFERENCES CITED


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