

Microstructures of cylindrical tochilinites

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ABSTRACT

Individual fibers of tochilinite—ideally $2\text{Fe}_{0.9}\text{S} \cdot 1.67[(\text{Mg}, \text{Fe})(\text{OH})_2]$ —from Cornwall, Pennsylvania, and the Jacupiranga mine, Brazil, have been examined using scanning electron microscopy (SEM), analytical electron microscopy (AEM), and high-resolution transmission-electron microscopy (HRTEM). Dominant morphologies for tochilinite from these locations are filled and hollow cylinders. The HRTEM of Cornwall tochilinite cylinders reveals that they are composed of laths stacked into polygonal sectors around the cylinder axis. Within each polygonal section, the curvature of the tochilinite sheets does not exceed 10^{-2} radian. Adjacent laths are slightly rotated about the cylinder axis, which provides the effective curvature responsible for the cylindrical morphology. Greater effective sheet curvature results in cylinders, as shown by the material from Cornwall. Tochilinite from the Jacupiranga mine has a smaller effective sheet curvature, which results in a cladded morphology. Similar morphologies can be observed for the “poorly characterized phases” within C2 carbonaceous chondrite meteorite matrices.

INTRODUCTION

Tochilinite, ideally $2\text{Fe}_{0.9}\text{S} \cdot 1.67[(\text{Mg}, \text{Fe})(\text{OH})_2]$, was noted at both the Muskox intrusion, Northwest Territories, Canada (Jambor, 1969), and the Lizard ultramafic body in Cornwall, England (Clark, 1970) before being successfully described as a new species by Organova et al. (1971), from the Mamonovo deposit, Voronezh Region, USSR. Tochilinite has subsequently been recognized as a relatively common mineral in sulfide-rich serpentinized ultramafic bodies (Jambor, 1976; Sabina, 1978).

Detailed characterization of tochilinite phases in terrestrial rocks has been made difficult by their commonly fine grain size and their optical properties being similar to other common sulfides. For example, confusion regarding tochilinite occurrences sometimes arose because valleriite, a double-layer sulfide with a yellow-gray color in reflected light, often occurs in similar environments (Clark, 1970; Jambor, 1969). Ramdohr (1973) also noted that tochilinite (identified by him as an unknown layer-structure mineral) is very difficult to distinguish optically from mackinawite and valleriite, with which it commonly occurs.

The excellent descriptions of various layer phases in carbonaceous chondrites by Ramdohr (1973) has provided a firm basis for subsequent optical and electron-beam studies of the group of incompletely described minerals termed “poorly characterized phases” (PCPs; Fuchs et al., 1973). Electron-microprobe studies identified three basic types of PCP within C2M carbonaceous chondrites (Bunch and Chang, 1980), and subsequent analytical electron microscopy (AEM) studies provided evidence for the identification of at least one type of PCP as a variety of to-

chilinite and another as a coherent intergrowth of tochilinite and serpentine (Mackinnon and Zolensky, 1984). This suggestion by Mackinnon and Zolensky (1984) was based upon a series of AEM and HRTEM studies by Mackinnon and Buseck (1979a, 1979b), Mackinnon (1980a, 1980b, 1982), and Barber et al. (1983). More recent publications, though incompletely referenced, give detailed textural data on the occurrence of tochilinite phases in carbonaceous chondrites (Tomeoka and Buseck, 1983, 1985). The presence of tochilinites in meteorites may prove to be an important indicator of paragenesis (Zolensky, 1984; Tomeoka and Buseck, 1985) as has been suggested for certain terrestrial environments (Van de Vusse and Powell, 1983).

Characterization of terrestrial tochilinite using AEM has received little attention apart from the pioneering electron-diffraction work of Organova et al. (1972, 1973, 1974). In light of the importance of tochilinite to meteorite studies and to strengthen our suggestion that most PCPs are varieties of the tochilinite-group minerals, we have initiated a detailed chemical and structural study of tochilinite from two major terrestrial localities initially described by Smith (1978) and Boctor and Svisero (1978). This paper is a more detailed account of preliminary data given by Zolensky and Mackinnon (1984, 1985).

EXPERIMENTAL PROCEDURE

Samples of tochilinite were collected by one of the authors (M.E.Z.) from the open pit iron mine at Cornwall, Pennsylvania, in 1979. Tochilinite from this locality occurs in cavities and open fractures within lizardite and is often in contact with colorless calcite crystals. The Cornwall tochilinite is associated also with

Table 1. Compositional data for tochilinite (in wt%)

	Cornwall	Jacupiranga
Fe	37.01	46.05
S	24.19	23.05
Mg	12.81	5.67
Al	3.56	4.85
OH*	22.43	20.38
Total	100.0	100.0

* Water estimated by difference.

pyrrhotite and pyrite. Magnetite is very abundant at Cornwall, but it is not genetically related to the tochilinite (Van de Vusse and Powell, 1983; Zolensky, 1984). The tochilinite at Cornwall occurs in two basic forms. One morphological form consists of tufts of black-to-bronze, fine, acicular fibers up to 1 cm in maximum length. The other form consists of bronze-to-black tabular crystals and thin coatings on calcite. Tochilinite specimens from the Jacupiranga mine, São Paulo, Brazil, were provided by Luiz Alberto Dias Menezes, Jr., and Eugene Foord. This material, originally identified as valleriite (Boctor and Svisero, 1978; Menezes and Martins, 1984), occurs in association with dolomite, pyrrhotite, and chalcopyrite and, although all fibers are similar in color and gross morphology to the acicular tochilinite from Cornwall, they are stubbier, nowhere exceeding 3 mm in length.

All samples used in this study were identified using powder X-ray diffraction, which compared favorably with the diffraction patterns for tochilinite given by Organova et al. (1971) and Jambor (1976). Chemical compositions of all samples were obtained with a CAMECA CAMEBAX scanning electron microprobe. A low beam current of 20 nA was used in order to minimize sample volatilization. Standard calibration procedures at the Johnson Space Center, Solar System Exploration Division, were employed using forsterite for Mg, troilite for Fe and S, and kaersutite for Al. OH abundance was determined by difference. In addition, selected tochilinite specimens were mounted onto a graphite disk and coated with Au-Pd before examination in a JEOL 35C scanning electron microscope (SEM). Specimens were imaged at 40 kV and ~100 mA to obtain maximum resolution.

Electron-transparent sections of tochilinite fibers were prepared by ion-thinning and ultramicrotomy. To enable viewing normal to the fiber axis, individual tochilinite fibers were transferred to thin copper slot (0.66 mm) grids and secured across the slot with glue. Tochilinite fibers were then ion-thinned using a GATAN ion-mill. Ion-beam damage to the thin regions of tochilinite occurs during the initial high-angle (30°), high voltage (4–5 kV) ion-beam thinning process. Therefore, this initial thinning was followed by more gentle thinning at a reduced incidence angle (10–15°) and lower voltage (1 kV), to minimize the extent of ion-beam damage (e.g., Mackinnon, 1982). In order to view the tochilinite fibers along the fiber axis, individual fibers were first impregnated with low-viscosity embedding resin (Spurr, 1969), and microtomed in approximately 500 Å serial sections. Samples were then placed directly onto 150 mesh beryllium grids and 400 mesh copper grids for AEM and HRTEM imaging. All transmission microscopy was performed using JEOL 100CX, 200CX, and 2000FX AEMs with standard side-entry goniometers. Short exposures and low beam currents were used in all cases in order to minimize electron-beam damage. Thin-film energy-dispersive spectroscopy (EDS) analyses were obtained with a Tracor-Northern TN 5500 detector and analyzer attached to a JEOL 2000 FX AEM. The

diameter of the electron beam for these thin-film analyses ranged from 40 to 200 Å at the specimen.

OBSERVATIONS

Microprobe analyses

Twelve analyses of one tochilinite sample from the Cornwall mine gave the average composition shown in Table 1. From this average analysis, the calculated formula for this tochilinite is $2\text{Fe}_{0.88}\text{S} \cdot 1.75[\text{Mg}_{0.80}\text{Al}_{0.20}(\text{OH})_2]$, assuming that all Fe is present as a sulfide and that none is present in the hydroxide layer. The concentration of oxygen and hydrogen was calculated by difference. These electron-microprobe analyses are considered precise to within 0.5 wt% for the value indicated in Table 1, as instrument drift was quite low. Microprobe analysis of the Jacupiranga tochilinite was more difficult owing to the ubiquitous presence of fine-grained calcite and Al-rich serpentine. However, three areas on one sample showed no detectable contaminants and gave an average composition of $2\text{Fe}_{0.89}\text{S} \cdot 1.67[\text{Mg}_{0.39}\text{Fe}_{0.31}\text{Al}_{0.30}(\text{OH})_2]$ (see Table 1), keeping the amount of Fe in the sulfide layer consistent with that in the Cornwall material.

Scanning electron microscopy

Individual tochilinite fibers occur up to 1 cm in length, although fiber diameters are often only 10 to 30 μm. A typical low-magnification view of Cornwall tochilinite fibers is shown in Figure 1a. SEM imaging at higher magnification clearly reveals that the fibers consist of individual sheets rolled into cylinders, in a manner analogous to chrysotile fibers (Yada and Iishi, 1977) and cylindrite (Makovicky and Hyde, 1981). Individual sheets vary in thickness from 450 to 750 Å. For many of the Cornwall tochilinite fibers, these sheets spiral into the center and completely fill the interiors of the cylinders. A small fraction (~10%) of these tochilinite cylinders are also hollow. Both filled and hollow cylinder morphologies are shown in Figures 1b and 1c. Many hollow tochilinite cylinders from Cornwall showed length-to-width aspect ratios up to 1000.

The Jacupiranga tochilinite also consists of 450–750-Å-thick individual sheets rolled into cylinders. In contrast, however, no tochilinite fibers examined from the Jacupiranga mine are hollow. These fibers are usually wider at the midpoint and taper off in thickness at either end. Detailed SEM images show that the Jacupiranga tochilinite fibers are not composed of individual sheets spiraling inward evenly toward the cylinder center, but contain additional parasitic laths, horseshoe shapes, and smaller cylinders of tochilinite, as shown in Figure 2a. This morphology was also noted for some of the tochilinite from the Grace mine, Berks County, Pennsylvania, by Jambor (1976), who described it as resembling a rolled-up newspaper. In some instances, Jacupiranga tochilinite fibers do not consist of individual rolled sheets, but rather contain a cladding of gently curved discontinuous sheets. This cladding morphology is shown in Figure 2b.

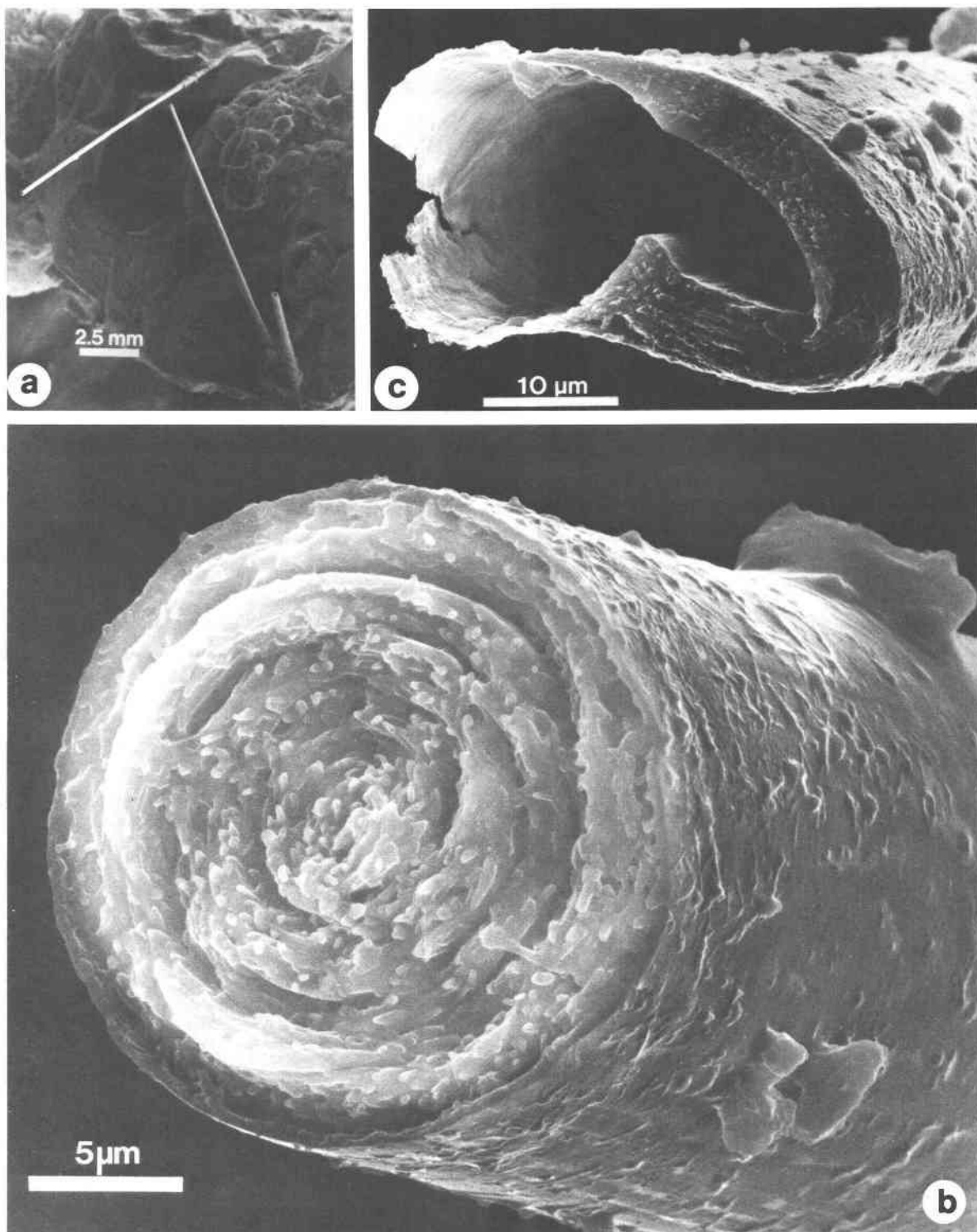


Fig. 1. (a) Low-magnification SEM image of tochilinite fibers from Cornwall, Pennsylvania. (b) SEM image of Cornwall tochilinite cylinder, with sheets spiraling inward to completely fill up space. (c) SEM image of hollow Cornwall tochilinite cylinder.

Transmission-electron microscopy

Low-magnification TEM images from a section of the Cornwall tochilinite, cut normal to the fiber axis, show a distinct en echelon texture (Fig. 3). In these sections the

cylindrical morphology of tochilinite is not preserved because neighboring sheets become detached during the microtome procedure. Individual en echelon sheets vary in thickness from approximately 450 to 750 Å. This sheet

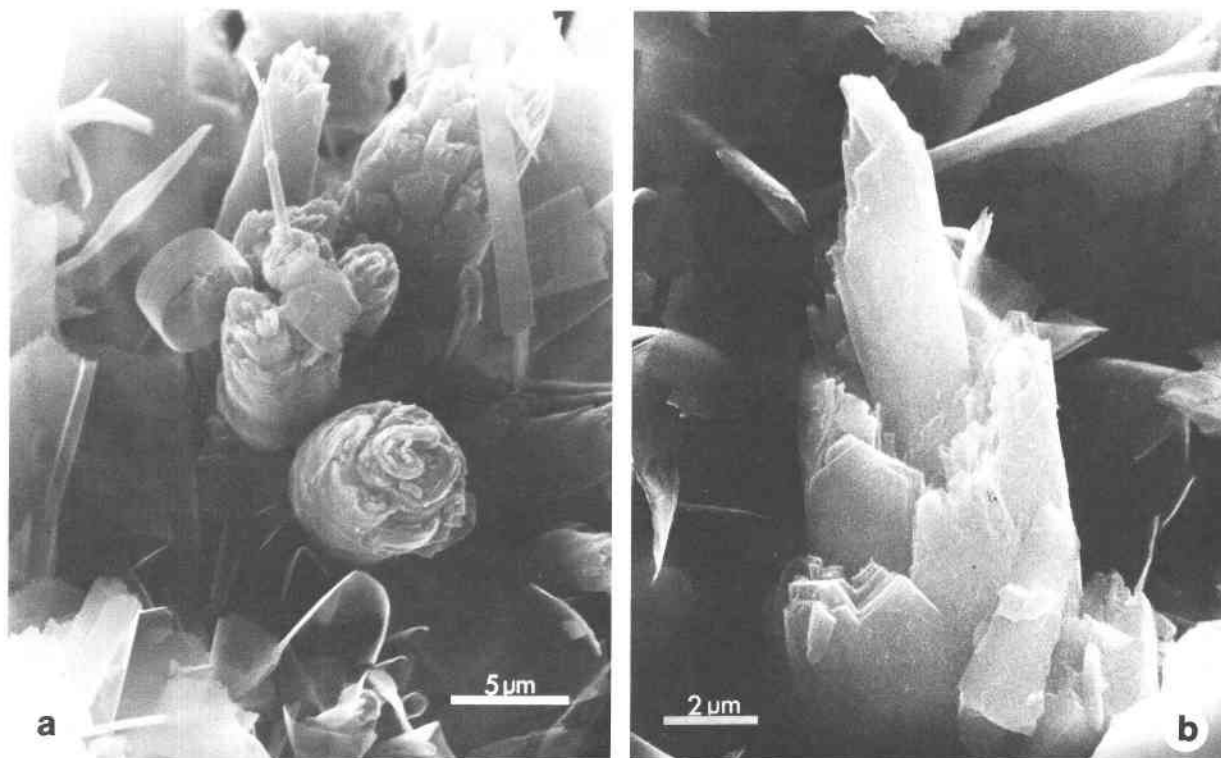


Fig. 2. (a) SEM image of tochilinite cylinders from the Jacupiranga mine showing how the larger cylinders are filled with laths, horseshoe shapes, and smaller parasitic cylinders. (b) SEM image of Jacupiranga tochilinite showing cladded morphology.

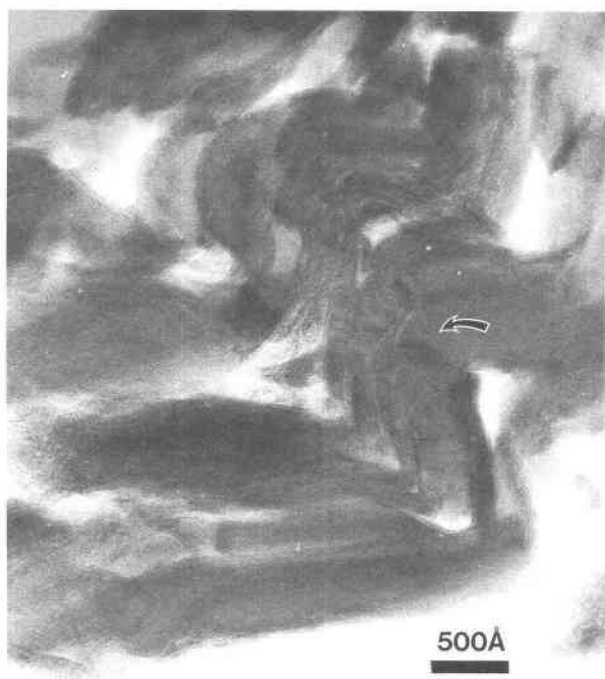


Fig. 3. HRTEM image of Cornwall tochilinite microtomed normal to the cylinder axis, showing en echelon texture. Arrow indicates region where the lattice fringes of the characteristic 10.8-Å spacing of tochilinite are visible.

thickness compares favorably with thicknesses observed using lower-magnification SEM imaging. The lattice fringes visible in Figure 3 correspond to the 10.8-Å basal planes characteristic of tochilinites (Organova et al., 1971, 1972, 1974). HRTEM of tochilinite fibers, along the long-axis direction (c), reveals sublattice fringes spaced at 5.4 Å, in addition to the basal lattice fringes spaced at 10.8 Å. These 5.4 and 10.8 Å fringes are more clearly shown in Figures 4a and 4b. Tochilinite sheets from the Cornwall mine occur in a wide range of forms as shown by the high-resolution images of microtomed sections in Figure 4. The extreme "hairpin" curvature shown in Figure 4b is common in sections cut normal to the fiber axis and is always associated with layer misfit or planar faults. A wide range of sheet curvature accompanied by layer misfit is also observed for the ~10-Å and ~17-Å varieties of PCPs in carbonaceous chondrites (Akai, 1980; Mackinnon and Zolensky, 1984; Tomeoka and Buseck, 1985).

The distinct curved and rolled nature of tochilinite fibers evident in the SEM images can be explained by an examination of the HRTEM images in Figures 3 and 4. These images reveal that individual tochilinite sheets are curved to only a very minor extent. The radius of curvature of individual sheets is not observed to exceed 10^{-2} radian, using HRTEM images. Basal lattice fringes often terminate abruptly along lines normal to the tochilinite lattice planes, i.e., there are dislocations of edge character (see Fig. 4). Each array of these dislocations constitutes a

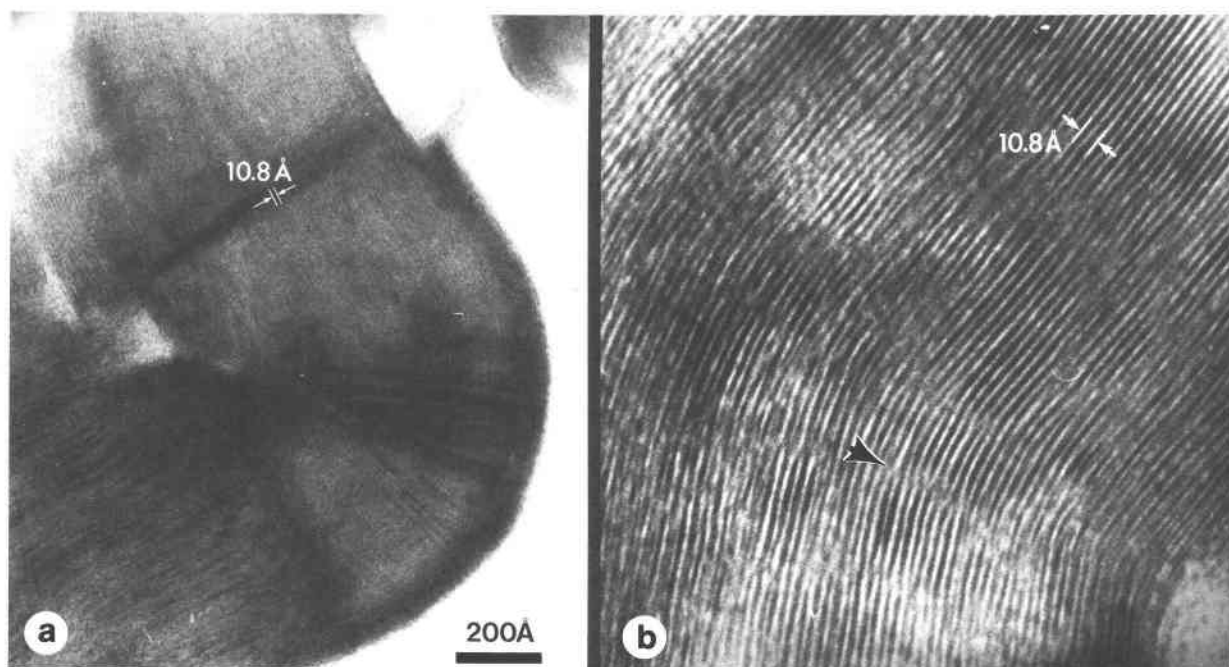


Fig. 4. (a) HRTEM image of Cornwall tochilinite microtomed normal to the cylinder axis. Small arrows indicate the 10.8-Å basal lattice fringes, and the intermediate 5.4-Å basal sublattice fringes are visible between them. (b) Image as in 4a, but at higher magnification. Also visible in this image are polygonal sections bounded by planar arrays of growth dislocations (indicated by the larger arrow). In addition to these planar arrays of dislocations, separate dislocations with edge character may be observed.

low-angle tilt boundary, the cumulative effects of which impart to the tochilinite fibers a polygonal (sectored) appearance in cross section. Thus, each polygonal tochilinite segment consists of a lath of flat or gently curving plates arranged tangentially around the fiber axis. The orientation of the plates is rotated across each of the planar arrays of dislocations that compose the polygonal boundaries. This rotation exceeds the curvature of the individual plates, making the greatest contribution to the curvature of the tochilinite fiber as a whole. Images indicate the presence of dislocations with edge character at the polygonal boundaries, appearing as plane bifurcations, and introduce stacking faults into the tochilinite layer sequence.

Approximately 50 thin-film EDS elemental analyses of Cornwall tochilinite were obtained from sections cut normal to the fiber axis. Individual sheets showing a range of curvature were probed with a beam-size equal to or less than the width of each tochilinite sheet. Well-defined sheets, oriented with the *c* axis approximately normal to the electron beam, showed major-element spectra containing primarily Fe, S, Mg, and minor amounts of Al. A typical example of EDS spectra from these tochilinite sheets is shown in Figure 5a. Semiquantitatively, these element abundances agree well with the electron-microprobe analyses for Cornwall tochilinite shown in Table 1. The small Al peak to the right of the Mg peak in Figure 5a confirms that Al may substitute into the tochilinite structure as suggested by the electron-microprobe analyses in Figure 1.

Figure 5b shows another type of EDS analysis obtained

from individual sheets within the Cornwall tochilinite microtomed sections. This spectrum shows significant Si and Al peaks and reduced intensities of the Mg and S peaks relative to Fe. Using the average electron-microprobe analysis for Cornwall tochilinite in Table 1, a set of thin-film *k* factors (Cliff and Lorimer, 1975) can be calculated for the analysis conditions used on these Si-rich sheets. Unlike some conventional thin-film analyses (e.g., Cliff and Lorimer, 1975; Nord, 1982), these *k* factors are calculated relative to Fe, as it is the most abundant element in these analyses. Thus, taking the average of integrated peak ratios from seven EDS spectra of tochilinite, such as shown in Figure 5a, $k_{\text{Mg,Fe}} = 0.69$ and $k_{\text{S,Fe}} = 1.049$. The relative precision of these calculated ratios cannot be considered better than ~10% owing to the difficulty in obtaining accurate electron-microprobe analyses of individual tochilinite fibers. Nevertheless, using these *k* factors, atom ratios calculated on an average set of values from two spectra such as shown in Figure 5b gives Fe:Mg = 5:1 and Fe:S = 3.6:1.

The above atom ratios calculated for these relatively uncommon Si-rich sheets are considerably different from the electron-probe values for Cornwall tochilinite: Fe:Mg = 2.85 and Fe:S = 1.53. The atom ratios for Mg and S (relative to Fe) obtained from these Si-rich sheets are consistent with values expected for a phase showing coherent intergrowths of serpentine $[(\text{Fe,Mg})_3\text{Si}_2\text{O}_5(\text{OH})_4]$ and Fe-rich tochilinite. A serpentine-tochilinite structure has been proposed for the ~17-Å PCP phase commonly

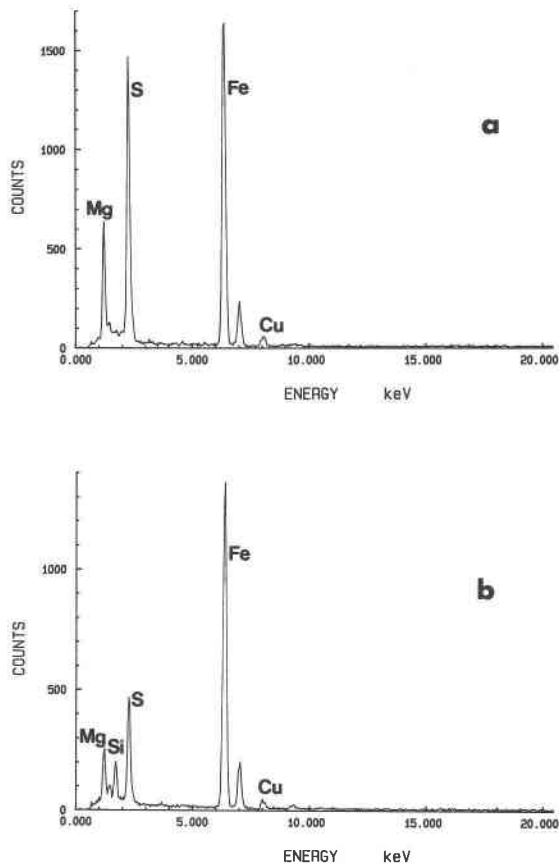


Fig. 5. Thin-film EDS analyses of Cornwall microtomed sections from (a) common sheets ($\sim 400\text{--}700\text{-\AA}$ width) showing typical tochilinite major-element abundances and (b) uncommon, Si-rich sheets that have element abundances consistent with a serpentine-tochilinite intergrowth. The small Cu peak to the right of the Fe $K\alpha$ and $K\beta$ peaks (at ~ 8.1 keV) is an instrument artifact due to spurious column X-rays.

observed in carbonaceous chondrites (Mackinnon and Zolensky, 1984). Alternatively, the spectrum shown in Figure 5b may be due to the presence of discrete serpentine (along with tochilinite) on a scale much less than the size of the AEM probe beam ($\sim 200\text{ \AA}$). Unfortunately, electron-beam damage is rapid and so severe in these Si-rich sheets that the samples could not be examined by high-resolution imaging after EDS analysis. The presence of $\sim 7\text{-\AA}$ or $\sim 17\text{-\AA}$ lattice fringes in sheets from other areas of the microtomed sections could not be confirmed.

Thin-film EDS analyses from other areas with different morphologies (e.g., clumps or bundles of sheets) in the Cornwall tochilinite sections showed a range of compositions including Fe and S only, combinations of the elements present in the data of Figures 5a and 5b in variable proportions, and Mg, Fe, and Si only. The first two types of spectra suggest that some individual tochilinite sheets are broken into their component mackinawite and/or brucite layers during the microtome procedure. The spectra showing only Mg, Fe, and Si probably represent ser-

pentine present as a discrete phase in minor amounts within the individual tochilinite fibers.

DISCUSSION

The structures of the tochilinite group minerals have been determined by Organova and co-workers (Organova et al., 1972, 1973, 1974). The poor quality of all macroscopic tochilinite crystals necessitated the use of electron diffraction, rather than X-ray diffraction, in these structure determinations. Electron diffraction is a less-precise technique than X-ray diffraction for structure analysis. Thus, cation-ordering arrangements proposed for the various tochilinites may require independent confirmation. For the purpose of this discussion, we use structure descriptions of tochilinite based on the work of Organova et al. (1972, 1973, 1974).

Tochilinite is a coherently interstratified iron sulfide and magnesium-iron hydroxide phase. The sulfide layer has a defect structure with cation vacancies similar to that in mackinawite and can tolerate a variable density and distribution of vacancies. In general, the hydroxide layer is similar to the brucite structure-type. The sulfide/hydroxide ratio has also been observed to vary. A comprehensive review of structural data by Makovicky and Hyde (1981) has demonstrated the existence of a homologous series of tochilinites. Mg and/or Cu may replace Fe in the sulfide layers, and Al or Ca may substitute into the hydroxide layers for Mg or Fe. Taking all of the reported compositions of terrestrial tochilinite into consideration (summarized in Makovicky and Hyde, 1981) the general formula for the observed tochilinite homologous series is



where \square represents the cation vacancies within the sulfide layer.

Ideally, in double-layer structures the two layer types provide charge balance for any uncompensated valency and usually stack with strict regularity. However, Organova et al. (1972, 1973, 1974) described a variable degree of incommensurability between the interlayer periodicities of composite mackinawite- and brucite-type sheets in tochilinites. In other words, the intralayer unit vectors of the mackinawite-type layers do not correspond with those of the brucite-type layers. Consequently, interlayer bonding between the component mackinawite- and brucite-type layers consists predominantly of long-range, easily adjustable, weak H bonding between apical hydroxyl H and S atoms.

Sheet curvature

The weak interlayer bonding between component mackinawite- and brucite-type layers in tochilinite suggests that a high degree of sheet curvature cannot be accommodated before detachment along the basal planes would occur. In extreme cases of curvature the individual sheets would slip by each other. The maximum amount of sheet curvature that stable tochilinite can accommodate

is dependent on the composition of the individual mackinawite- and brucite-type layers. This composition-dependent layer curvature is analogous to the serpentine structures (Wicks and Whittaker, 1975). Thus far, tochilinites with cylindrical morphologies (those from the Cornwall, Jacupiranga, and Grace mines) have the highest reported Al contents of any tochilinites, with up to about 12 wt% Al (Jambor, 1976; this paper). Al may substitute into the brucite layer, where its small size ($\sim 0.67 \text{ \AA}$, Shannon and Prewitt, 1969) and trivalent charge serve to decrease the thickness of the brucite-type layer. This Al substitution must be accompanied by the coupled substitution of lower charge cations or the introduction of cation vacancies elsewhere in the structure in order to maintain charge balance. The lack of precise structural information for tochilinite does not permit precise predictions of the influence that such cation substitutions could have on the curvature of tochilinite layers.

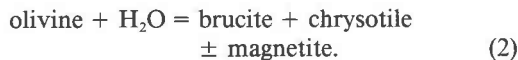
The radius of curvature of tochilinite basal planes has not been observed to exceed 10^{-2} radian. With this maximum degree of curvature, the minimum inside diameter for a tochilinite cylinder of one sheet thickness is approximately $100 \mu\text{m}$. Tochilinite cylinders from Cornwall have inner diameters varying from $0 \mu\text{m}$ (for completely filled cylinders) to a maximum of $50 \mu\text{m}$. The increased curvature necessary for the observed tightly rolled tochilinite cylinders is provided by the growth dislocations shown in HRTEM images (Figs. 3 and 4). Cross sections of individual tochilinite cylinders reveal that they are composed of laths stacked in sectors about a common axis (the cylinder axis). These laths appear in cross section as polygons of flat or gently curved plates arranged tangentially about the cylinder axis. These polygons are bounded by planar arrays of growth dislocations and appear to be accompanied by dislocations with edge character and faults in the tochilinite stacking sequence. In cross section, these polygons decrease in width toward the center of the cylinders, giving the planar arrays of dislocations forming the subboundaries a radial appearance. This structural arrangement is very similar to that described for Povlenor polygonal-type serpentine (Middleton and Whittaker, 1976; Cressey and Zussman, 1976) and observed in carbonaceous chondrite meteorite matrices (Mackinnon, 1980a). An important distinction between polygonal tochilinite and serpentine is that in the former case the segmentation is less distinct and may extend to the cylinder center. Where the segmentation density of cylindrical tochilinite remains low, the radius of curvature for tochilinite sheets, correspondingly, remains low. Cladded structures, such as those observed from the Jacupiranga mine, would be produced under these circumstances.

Growth conditions

The cylindrical tochilinite morphology is probably due to rapid growth in a supersaturated solution. Supersaturated solutions of the required composition are present in serpentinizing sulfide-rich ultramafic bodies (Zolensky, 1984), where dissolution of the primary ultramafic min-

erals proceeds at a far greater rate than the consequent growth of the hydrous alteration phases (Nesbitt and Bricker, 1978). The growth rate of tochilinite would be expected to be greater in the plane of the layers than in the direction normal to them, owing to stronger intralayer bonding. Dislocations introduced into the rapidly growing tochilinite sheets would encourage the development of cylinders, although cylinder growth only occurs if the edge dislocations occur predominately of one sign to yield low-angle tilt boundaries. The relatively weak interlayer bonding would permit the introduction of frequent edge dislocations and errors in the tochilinite stacking sequence. These stacking errors can be readily observed in HRTEM images viewed normal to the fiber axis. Similarly, these stacking errors help to explain some of the compositional variation reported for tochilinites (Makovicky and Hyde, 1981). Other growth dislocations, such as those associated with the incorporation of foreign grains within the growing fiber, probably account for the parasitic tochilinite forms found within the Jacupiranga fibers.

Although there has been no experimental investigation of the stability range of the tochilinites, some estimate of their stability may be attempted in an indirect manner. This involves analyzing the stability conditions for the constituent brucite and mackinawite layers and observing conditions of overlapping stability (Zolensky, 1984). Brucite forms from the breakdown of olivine, as can be illustrated by the reaction



Various studies have placed the temperature at which this reaction takes place at 350 to 450°C, at pressures below 20 kbar (Moody, 1976). The pH of solutions in equilibrium with brucite-containing serpentinites is generally 10 to 12, in the temperature range 10 to 330°C and at pressures to 1.5 kbar (Moody, 1976; Barnes et al., 1972). In altered ultramafic bodies, mackinawite forms by the breakdown of pyrrhotite under conditions of decreasing temperature (below 170°C) and low oxygen fugacity; mackinawite is favored by increasing sulfur fugacity (Takano, 1965). Mackinawite also forms as the first corrosion product of Fe at low temperatures in H₂S-saturated solutions (Shoesmith et al., 1980). Thus, tochilinites probably grow from solutions characterized by low oxygen fugacity, high sulfur fugacity, pH in the range 10 to 12, and a temperature at or below 170°C.

In conclusion, AEM and HRTEM reveal that some terrestrial tochilinites form rolled to cylindrical structures, resembling fibers in visual appearance. These morphologies probably result from rapid growth in a supersaturated solution, which results indirectly in complex dislocation structures. Phases with identical chemistry, structure, and morphology are common in the matrices of C2M carbonaceous chondrites. Thus, this study supports the suggestion (Mackinnon and Zolensky, 1984) that meteoritic matrix phases (the PCPs) include tochilinites as a major component. In several papers, Tomeoka and Buseck (1983,

1985) have called the meteoritic equivalent of tochilinite "FESON." In light of the evidence presented in this and earlier papers (Mackinnon and Zolensky, 1984; Zolensky and Mackinnon, 1984, 1985) the use of the ambiguous and unnecessary term "FESON" should be abandoned, to be replaced with the term "tochilinite" or "meteoritic tochilinite."

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