PB87234662

PHYSICAL AND CHEMICAL CHARACTERISTICS OF AIRBORNE FIBERS

Howard E. Ayer

Institute of Environmental Health

University of Cincinnati

Cincinnati, Ohio 45267

and

Ralph D. Zumwalde

National Institute for Occupational Safety & Health

U.S. Public Health Service

Cincinnati, Ohio 45226

April 5, 1979

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No. PB87 234662/AS

4. Title and Subtitle
Physical and Chemical Characteristics of Airborne Fibers

5. Report Date
79/04/05

6.

7. Author(s)
Ayer, H. E., and R. D. Zumwalde

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Institute of Environmental Health, University of Cincinnati, Cincinnati, Ohio

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address
Same as box 9.

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The chemical and physical properties of fibers commonly found in the air were reviewed, and a definition of a fiber was developed. An aspect ratio of 5 was considered to eliminate most nonfibrous particles. Fiber types discussed included organic fibers, mineral wool, fibrous glass, phytoliths, asbestos (1332214), chrysotile (12001295), crocidolite (12001284), amosite (12172735), anthophyllite (17068789), tremolite (14567738), actinolite (13768008), attapulgite (12174117), wollastonite (13983170), and other mineral fibers. Most of the organic fibers commonly found in indoor air were of animal and vegetable origin, while monofilamentous synthetic fibers were less frequently found. Airborne organic fibers may be of importance only in mills processing such materials. Amorphous fibers were found in the lungs of humans at autopsy and in air samples from urban areas. The methods of production of amorphous fibers such as glass and slag fibers, and crystalline fibers such as asbestos, resulted in inherent size differences. Chrysotile asbestos accounted for over 95 percent of current commercial asbestos production. Studies indicated that amphibole asbestos fibers are stiffer and straighter than chrysotile. Attapulgite and wollastonite have been known to occur in microfibrous form. The authors recommend that controls be instituted to limit exposures to any airborne fibrous dust.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms
NIOSH-Author, Airborne-dusts, Mineral-dusts, Chemical-properties, Physical-properties, Airborne-fibers, Asbestos-fibers, Synthetic-fibers

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages 41
	20. Security Class (This Page)	22. Price

(See ANSI–Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4–77) (Formerly NTIS–35) Department of Commerce

INTRODUCTION

In this presentation, chemical and physical properties of fibers commonly present in the air are reviewed. For purposes of classification, a reasonable definition of a fiber is presented. The presence of organic fibers is noted, and their predominance in some circumstances is pointed out. The principal emphasis, however, is on inorganic, mineral fibers, because of their commercial importance, their persistence in the air, and their potential health hazards.

DEFINITION

A common definition of a fiber, e.g., "a slender and greatly elongated natural or synthetic filament (as of wool, cotton, asbestos, gold, glass or rayon) typically capable of being spun into yarn" refers to an object too large to remain airborne for any length of time. Airborne fibers are objects which are slender and greatly elongated, but of microscopic dimensions. Thin flat crystals can appear to meet the definition if seen on their side in a two-dimensional view, but would not be considered fibers. Thus a regular cross-section would appear to be implicit in the definition of a fiber; a cross-sectional width-to-height ratio greatly exceeding 3 would probably exclude a particle from definition as a "fiber". The definition of a "fiber" in terms of length versus average diameter might most reasonably be made by considering departure from the terminal falling velocity of regular particles which approximate spheres. Timbrell's empirical equation for falling speed of glass fibers[1]

$$D_e/D_f = 66 \left[\frac{L_f/D_f}{2 + 4\ L_f/D_f}\right]^{2.2}$$ where D_e = equivalent diameter of spheres,

D_f = fiber diameter, and

L_f = fiber length

demonstrates that beyond a length to diameter ratio of 5, length as a factor in falling speed becomes relatively unimportant, resulting in only a one-sixth decrease in falling speed, which then becomes a function of diameter only. Beyond an aspect ratio of 10 there is only a seven percent decrease in falling speed for glass fibers, with similar values for the major types of asbestos. An aspect ratio of 5 would eliminate most non-fibrous particles such as quartz crystals, some of which meet a criterion of 3, though they do not appear "fibrous".

The foregoing operative definition will distinguish those cylindrical particles which behave aerodynamically and biologically as do spheres, from those which behave differently because of their extreme length to diameter ratios.

ORGANIC FIBERS

The organic fibers most commonly found in indoor air are of animal and vegetable origin. Examination of a home furnace filter, or a space where relatively quiescent air permits dust to preferentially settle, e.g., under a bed, reveals a significant proportion of fibers. Air sampling throughout a home shows that these fibers occur in highest concentration where clothing or household linen is handled, suggesting their origin.[2] Concentrations of these macroscopic fibers are low by number, so that they do not significantly contribute to a number count as determined by optical microscopy of filter samples. The monofilamentous synthetic fibers are more resistant to wear, and thus less frequently found. Although of far greater economic importance than inorganic fibers, in domestic air their size tends to retard their becoming airborne and to cause their removal by settling, so that the importance of organic fibers in the air is primarily as a nuisance, usually of concern only in clean rooms.

Industrially, airborne organic fibers are only of importance in mills processing these materials, where they may contribute to the fire hazard if allowed to accumulate.

Microscopic organic fibers may be observed in very low concentrations in samples from ambient air, where they apparently are primarily of vegetable origin, with occasional insect fragments.[3] They have not been reported to be of significance as an air pollutant from either a nuisance aspect or as a potential health hazard.

Organic fibers in the air have a density of approximately 1 g/cm^3. Few are found with a diameter of less than 10 μm, and the shape of the fiber is usually ribbon-like or irregular, rather than that of a smooth elongated cylinder.

BIOLOGICAL EFFECTS OF FIBERS

This review will not deal with the potential health hazards of fibrous aerosols. Nevertheless, if it were not for the excesses of lung cancer, mesothelioma of the pleura and peritoneum, and cancer of the gastrointestinal tract among some groups of asbestos workers there would be little or no interest in airborne fibers. Almost all the sources in this review are papers dealing in one way or another with real or potential health hazards. The review will cover physical and chemical properties which may be related to potential health hazards. A great deal of emphasis will be placed on size and shape of airborne fibers. Not only do these properties determine which fibers might reach the air spaces in the lung, but they may determine the degree of cancer hazard as well. A frequently quoted paper by Stanton[4] suggests that on the basis of implantation experiments in animals, small diameter long fibers present a greater cancer hazard than other fibers. If this should prove to be so, then the proportion of a fibrous aerosol in this biologically significant fraction should have to be determined to estimate health hazard. Such information is presented for some of the materials covered in this review.

AMORPHOUS MINERAL FIBERS

Mineral wool

Mineral wools are made from the slag byproduct of iron blast furnaces, or from rock such as argillaceous limestone by passing a stream of molten rock or slag in front of a steam jet, by throwing a molten material off a cylindrical rotor at high speed, or by throwing molten material off a spinning concave rotor at high speed.[5] In either case an organic binder may be added to cause the fiber to adhere. In none of these processes is all the rock or slag fiberized, so that the fibers are accompanied by "shot", unfiberized or partially fiberized mineral which must be removed. Currently about 70% of the mineral wool sold in the United States is produced from blast furnace slag, with most of the remainder from copper, lead, and iron smelter slag. Although average fiber diameters are in the range of 3.5 to 7.0 µm, there is a broad distribution of fiber diameters. In a study of two mineral wool manufacturing facilities Corn et al[6] found that 78% and 66% of the fibers had diameters <3 μm respectively, although only 16% and 15% of fibers had diameters <1 μm. Lengths of airborne fibers in the two facilities were longer than 20 μm 41% and 39% of the time, but 79% and 71% respectively were longer than 10 μm.

A larger survey of mineral wool producers and users was reported by Fowler.[7] Both bulk and airborne fibers were measured, and results are summarized in Table I. Typical bulk fiber had geometric mean diameters of 3-4 μm, but airborne fibers typically had geometric mean fiber diameters of 2 μm, with geometric standard deviations near 2. Fiber lengths were quite variable by operation, but geometric mean lengths of 15-20 were often encountered, with geometric standard deviations near 3.

Inasmuch as slag wool is a by-product, with additions to balance properties, its chemical composition can be expected to vary between manufacturers, depending upon the source of slag. Four analyses over a 2 year period by one producer reported by Fowler[10] showed relatively consistent composition: Silica, 35.8-41.4%; alumina, 9.3-11.6%; ferric oxide, 0.8-1.8%; CaO, 34.7-37.2%; MgO 7.0-9.8%; and sulfur trioxide, 0.5-1.9%. Electron microprobe analyses of fiber show the same elements to be the major components of the fibers as well. Trace metals were in relatively low concentration with the exception of one facility which used lead smelter slag and thus had a relatively high lead content.

TABLE I

Mineral Wool Fiber Diameters and Lengths

Facility	Fiber Diameters (μm)				Airborne Fiber Lengths (μm)	
	Bulk		Airborne			
	Mg*	Sg**	Mg's*	Sg's**	Mg's*	Sg's*
Mfg A	3.9	1.8	1.2-2.4	1.8-2.7	6.7-20	2.3-4.3
Mfg B	3.7	2.0	1.0-2.5	1.6-2.0	8.9-26	2.5-3.3
Mfg C	3.4	2.7	1.6-3.0	1.6-2.2	7.4-36	2.2-4.4
Mfg D	3.6	2.3	1.5-3.2	1.6-2.9	7.5-33	1.6-3.3
Mfg E	2.2	2.1	1.6-2.6	1.4-3.1	8.3-21	2.3-3.3
User F	4.8	1.7	1.6	1.8	12	3.3
User G	3.2	2.7	--	--	--	--
User H	--	--	2.3-2.4	1.7	17-28	2.8-3.1
User I	--	--	1.2-2.8	1.3-2.1	4.2-26	1.5-3.1
User J	2.3	2.2	2.2-2.7	1.8-1.9	28-45	3.9
User K	3.4	2.0	1.9	1.7	12	2.8

Mg = geometric mean (μm) Sg = geometric standard deviation

Adapted from Fowler[7]

Fibrous glass

Although a dress fabricated from glass fibers for the Empress Eugenie was exhibited at the St. Louis World's Fair in 1893, textile fiber was not made in the U.S. until 1934. Preceding the large scale development of the textile fibers was the development of air filters and thermal insulation starting in 1930.[8] A wide range of fibers of different compositions and fiber sizes are now available. Some of the chemical and physical properties of the various fibers are summarized in Table II adapted from Shand.[9] It may be noted that only the "fine wool" and "ultra-fine wool" in this table have average diameters that would lead to fibers which could be airborne for any significant length of time. However, in addition to the perhaps 1% of production going into the "ultra-fine" fibers averaging about 1 μm in diameter, there is a wide range of fiber diameters produced at many of the manufacturing operations. Further, the smaller diameter particles are separated by elutriation, so that at a construction site, mean fiber diameters in parent insulating material of 4.0 to 10.2 μm can result in mean airborne fiber diameters of 2.3 to 8.4 μm.[10] Likewise, Dement[11] found median airborne fiber diameters of 1.1 to 2.1 μm in three facilities manufacturing large diameter glass fibers, with a fourth plant having median diameters from 2.1 to 4.3 μm in four operations. These results may be contrasted with those of Balzer[12] who found geometric mean glass fiber diameters of 2.2 μm in ambient air, 1.3 μm from fibrous glass lined ventilation ducts, and 8.4 μm at occupational exposures. There are undoubtedly sampler entry biases on particle sizes as determined in some of the foregoing studies.

TABLE II

Chemical and Physical Properties of Some Commercial Fibrous Glass

Glass type	Component (% by weight)							Fiber diameter range (μm)	Density g/cm^3	Refractive Index
	SiO_2	Al_2O_3	CaO	MgO	B_2O_3	Na_2O	Other			
Low alkali, lime-alumina borosilicate	54.5	14.5	22.0	--	8.5	0.5		6-9.5	2.60	1.548
Soda-lime borosilicate (textile)	65.0	4.0	14.0	3.0	5.5	8.0	K_2O 0.5	6-9.5	2.54	1.541
Soda-lime borosilicate (wool)	50.0	4.5	16.0	5.5	3.5	11.0	0.5	7.5-15	2.61	1.549
Soda-lime	73.0	2.0	5.5	3.5	--	16.0		115-250	2.47	1.512
Lime-free borosilicate (fine wool)	59.5	5.0	--	--	7.0	14.5	ZrO_2, TiO_2, F 16.0	0.75-5	2.57	1.537
Lime free borosilicate (ultra-fine wool)	59.5	5.0	--	--	7.0	14.5	ZrO_2, TiO_2, F 16.0	0.25-0.75	2.57	1.537
High lead silicate	34.0	3.0	--	--	--	0.5	K_2O 3.5 PbO 59.0	6-9.5	4.30	--

Adapted from Shand[9]

None of the biases compare with that of Gross et al[13] who found mean fiber diameters determined by optical microscopy in lungs at autopsy to range from 1.4 to 2.8 µm, with most mean fiber diameters around 2 um. As noted previously, the aerodynamic diameter of fibers is primarily a function of fiber diameter, so that fiber lengths tended to reflect the operation and any sampler size selection bias. Dement,[11] for example, reported median lengths of airborne fibers at wool insulation manufacturing operations to range from 19 to 70 µm, while Gross et al[13] found mean lengths of fibers in human lungs at autopsy to range from 17-28 µm with the majority of the fibers between 5 and 25 µm in length. These figures are not unlike those reported for airborne slag wool fibers.

Phytoliths

An observation by Gross et al,[14] confirmed by Langer et al,[15] was that in the lungs at autopsy of persons not occupationally exposed to fibrous dust were numerous fibers which resembled those obtained from burning paper or leaves. These fiber diameters were most frequent at 1.5 um, with lengths most frequently between 15 and 20 µm. The amorphous nature and numerous potential sources for such fibers does not render them susceptible to ready identification. The tendency of the lung to concentrate fibers far above the proportion in which they exist in air breathed, suggests that these fibers would not be seen in high concentrations in ambient air. Their presumed vegetable origin, however, would tend to make their existence perhaps as much a factor in rural as in urban air.

Fragments of diatoms, which may be considered to be of animal origin are also seen in human lungs; small fragments are sometimes difficult to distinguish from fibers. These particles are composed entirely of amorphous silica.

Summary: Amorphous fibers

These materials can be found in urban air samples, and in the lungs of humans at autopsy. Both fibrous glass and slag wool products usually have mean fiber diameters on the order of 3-7 μm. However, the airborne fibers are smaller in diameter, averaging about 2 μm. The lengths of airborne fibers sampled from the air directly or from lungs will have a greater variance than the diameter. If a fiber is defined by a 5 to 1 ratio as suggested here, the minimum length will be about 6 μm, with maximum lengths greater than 50 μm.

CRYSTALLINE MINERAL FIBERS

The definitions of fibers as related to minerals can be somewhat circular; a fiber being defined in one dictionary[16] as "thread-like", while "mineral fiber" is defined by Campbell et al[17] as "the smallest elongated crystalline unit ..... that exhibits a resemblance to organic fibers", "fibril" as "a single fiber, which cannot be separated into smaller components without losing its fibrous properties or appearences", being distinguished from "prismatic" and "acicular" by their fiber-like appearance. The crystalline shapes and patterns as shown by Campbell et al[17] are presented in Figure 1. Although such distinctions may be useful mineralogically, they will not necessarily be observed in this review, for the properties of aerosols may be only incidentally related to such distinctions. In defining asbestos, however, this resemblance to organic fibers was explicit in the classification, and the minerals included as asbestos are recognized by this definition.

Asbestos

Asbestos is classified into two main classes, serpentine, of which the only member is chrysotile, and amphiboles of which the five recognized varieties are crocidolite, amosite*, anthophyllite, tremolite and actinolite. Approximate chemical formulae for these minerals, as presented by Gilson[18] after Hodgson[19] and idealized chemical formulae indicating their variable composition from Speil and Leineweber[20] are shown in Table III. The most abundant cation is shown first in the latter categorization. Chrysotile is by far the more common of the two asbestiform mineral classes and accounts for more than 95% of current commercial asbestos production.[20]

Being crystalline, asbestos can be determined chemically by x-ray diffraction in bulk samples. Quantitative analysis has been achieved in laboratory samples by enhancing the x-ray diffraction pattern using electrostatic alignment of the fibers,[21] but for routine analysis the limit of detection is on the order of 5 per cent.[22] As reported by Timbrell,[23] asbestos fibers of the sizes which become airborne can be aligned magnetically when suspended in air or liquid. Differing modes of alignment are observed, with samples from some asbestos mining areas aligning parallel to the applied magnetic field, others normal to the field, and still others showing a mixture of normal and parallel alignment. Individual fibers can be identified by electron microscopy using either selected area electron diffraction or electron microprobe analyses using energy dispersive x-ray detectors.[22,24,25] Optically, larger

*Although perhaps more correctly categorized mineralogically as cummingtonite-grunerite,[17] the common name amosite will be used here.

TABLE III

Idealized Chemical Formulae for Asbestos Minerals

Type	Approximate Formulae	
	Average[18,19]	Indicating Variability[20]
Chrysotile	3 MgO, 2 SiO_2, 2 H_2O	
Amphiboles		
Crocidolite	Na_2O, Fe_2O_3, 3 FeO, 8 SiO_2, H_2O	$(Na_2Fe_2^{2+}Fe_2^{3+})\ Si_8O_{22}(OH)_2$
Amosite	5.5 FeO, 1.5 MgO, 8 SiO_2, H_2O	$(Fe^{2+},Mg)_7\ Si_8O_{22}\ (OH)_2$
Anthophylite	7 MgO, 8 SiO_2, H_2O	$(Mg,Fe^{2+})_7\ Si_8O_{22}\ (OH)_2$
Tremolite	2 CaO, 5 MgO, 8 SiO_2, H_2O	$Ca_2Mg_5\ Si_8O_{22}\ (OH)_2$
Actinolite	2 CaO, 4 MgO, FeO, 8 SiO_2, H_2O	$Ca_2(Mg,Fe^{2+})_5\ Si_8O_{22}\ (OH)_2$

crystalline fibers can be distinguished from amorphous fibers by polarizing microscopy, but many, perhaps most airborne asbestos fibers are too small in diameter for them to be so distinguished.

A principal distinction between the amorphous glass and slag fibers on the one hand, and the crystalling fibers including asbestos on the other, is that the method of production leads to inherent size differences. The drawing or blowing of the molten mineral most easily produces large fibers of several μm diameter, while the formation of acicular or fibrous crystals can start with fibrils of a few nm diameter.

Chrysotile

Chemically, chrysotile from different sources varies about the theoretical composition of 43.4% SiO_2, 43.5% MgO and 13.1% H_2O, with SiO_2 from 34-44%, MgO from 40-42%, and H_2O from 13-14%.[20] Iron oxides are from 0.6-4%, alumina from 0.3-0.8%, CaO from a trace to 1%, Cr_2O_3 from not reported to 0.3%, and other trace elements usually less than 0.1% in the general decreasing order: NiO, Mn_2O_2, TiO_2, Na_2O, and K_2O.[20] Chrysotile is the most soluble of the forms of asbestos. The surface of the fibrils is magnesium hydroxide, which is readily dissolved by acid. Strong acids rapidly decompose chrysotile leaving 40% of the mass with a fragile fibrous morphology.[20] Both in vitro and in vivo studies have shown that chrysotile tends to break down chemically and physically in biological fluids as magnesium is leached away.[15] This characteristic of chrysotile can be used as an index of the airborne concentration of chrysotile in the absence of other magnesium containing minerals, as the amount of magnesium in air samples of asbestos can readily be analyzed by atomic absorption spectroscopy, and chrysotile is approximately 25% magnesium.[26]

Physically, the individual fibrils of chrysotile are 30-40 nm in diameter. The fibers that consist of bundles of these fibrils may be as large in diameter as a mm in crudely processed specimens, and fibers may be 5 cm or more in length.[27] Airborne chrysotile fibers are thus bundles of varying numbers of fibrils. At the ends of these bundles, and in fact all along the fiber, smaller bundles of fibrils may project themselves subdividing into still smaller bundles, as shown schematically in Figure 1, and in an electron micrograph of typical fibers collected during air sampling in Figure 2.[28] Aerodynamically, it is not possible to describe chrysotile fibers as easily as, say, glass fibers. The "curliness" of these fibers, as well as the many frayed and projecting fibers greatly increase the probability of capture or removal of these fibers by interception with a surface or with other fibers. Investigators have recognized this problem, and treated chrysotile differently in deposition models. Dement and Harris,[29] for example, assume chrysotile to be one-half single curved rods, and one-half crossed rods, following the method of Harris and Timbrell.[30]

The difference in size of chrysotile fibers from different operations may be seen in fibers sized in studies conducted by the National Institute for Occupational Safety and Health. Two examples condensed from these data as used by Dement and Harris[29] are presented in Table IV. In both examples most of the fibers are in the finest diameter category, but for the cement pipe finishing, more

TABLE IV

Fiber Size Distribution for Chrysotile

Twisting Asbestos Yarn[29]

Fibers per Thousand (n = 5817)

Length (midpoint interval) in µm

Diameter (µm) (midpoint)	0.15	0.45	1.75	3.25	4.75	>15
0.15	11	330	290	110	69	43
0.45	0	1	19	20	22	27
0.75	0	0	2	5	5	6
1.50	0	0	1	4	14	23

Cement Pipe Finishing

Fibers per Thousand (n = 4846)

Length (midpoint interval) in µm

Diameter (µm) (midpoint)	0.15	0.45	1.75	3.25	4.75	>15
0.15	51	510	270	73	46	9
0.45	0	1	10	6	11	9
0.75	0	0	0	0	2	1
1.5	0	0	0	0	1	3

Note: Totals do not equal 1000 because of rounding.

than half of the fibers are shown in one length-diameter category. In the original table, 53% of the fibers were in the interval centered at 0.08 μm diameter, and 0.35, 0.45, 0.75 and 1.75 length. For long, small diameter fibers, 4.6% of the cement finishing fibers were in the 7.5 μm and 15 μm length category with diameter <0.75 μm, as compared with 12.6% of the textile twisting fibers. It is evident that if length and diameter are important biological factors, then an equivalent concentration of these two fiber clouds would present different hazards.

These differing length-diameter distributions also make meaningful specification of concentration by any single number difficult. The most widely used concentration for airborne mineral fibers is number longer than 5 μm per cm^3 as determined by optical microscopy using a 4 mm objective. Regression equations between electron and optical microscopic counts for three operations each in asbestos friction, cement and textile operations showed that a 2 fiber/cm^3 count of fibers longer than 5 μm by optical microscope would correspond to from 1.7 to 5.6 fibers/cm^3 longer than 5 μm by electron microscope.[31] However, five of the nine operations were within 50%, and only two differed by more than a factor of two. It appears that if fibers longer than 5 μm are indeed the most significant criterion, then the optical counting method provides a satisfactory index of concentration. However, from 4.5 to 20.6% of total fibers were counted at the nine operations,[31] so the optical index does not well describe the concentration of total fibers.

In a rather different evaluation, asbestos was measured downwind from a mill processing Coalinga chrysotile asbestos in

California.[32] The asbestos in ambient air downwind of the plant, believed to be mainly resuspended from ore and tailings piles, ranged in concentration of total fibers up to 1 fiber/cm^3 as determined by electron microscopy. Of these fibers, roughly half were longer than 5 μm. Optical counts were much lower and essentially uncorrelated with the electron microscope counts.

Chrysotile fibers were also collected one to two miles from a serpentine rock quarry which contained no commercial asbestos.[17] For these samples, 95% of the fibers were 0.12 μm or less in diameter, and more than 90% were less than 5 μm in length.

The size distribution of chrysotile fibers in human lungs at autopsy is believed to be unrepresentative of the distribution in ambient air because of the physical modification resulting from dissolution of the relatively soluble chrysotile in the biological fluids.[15]

Amphiboles

Crocidolite was used in the U.S. most recently as a constituent of some asbestos cement pipe for pressure applications. It has been used for acid resistant filters, packings and certain types of lagging.[34] It has also been used for respirator filters and, at least in pilot applications, for cigarette filters. It has been used elsewhere as a reinforcing fiber for battery boxes, because of its high acid resistance. Crocidolite is found in Bolivia and Australia as well as in South Africa. Crocidolite has a tensile strength similar to that of chrysotile, but fibers are much "harsher", i.e., stiffer and straighter even in the finest fibers. The difference in "curliness" of crocidolite and thus of ability to penetrate the lung between the two deposits in South Africa has been postulated as a reason for the differences in mesothelioma incidence between the two areas.

Amosite was widely used in the U.S. for thermal insulation, particularly for naval insulation. Like the other amphiboles, the fibers are straighter and stiffer than chrysotile. Data of Table V from Dement and Harris[29] show that fibers are considerably coarser than those encountered in chrysotile manufacture. In their calculations they assumed amosite to be a straight fiber ordered with the streamlines of air flow.

Although amosite does not occur in the United States in commercial amounts there are exposures to cummingtonite-grunerite fibers as contaminants in other rock.[33] These could be expected to behave as amosite fibers in their chemical, physical and aerodynamic properties.

Anthophyllite has been mined in Georgia and the Carolinas[34] and has been used as a reinforcing fiber in polypropylene[20] as well as in automobile manufacture. Anthophyllite also occurs as a contaminant in talc. Some data on fiber size distribution are available from surveys of a talc mine in upper New York State. Median airborne fiber lengths were 1.5 μm in the mine and 1.4 μm in the mill, with geometric standard deviations of 2.6 and 2.9 respectively.[35] Median diameters were 0.13 at both locations, with geometric standard deviations of 2.4 and 2.9 respectively. The median aspect ratio of anthophyllite fibers was 9.5 to 1. The distribution is summarized in Table VI from Dement and Harris,[29] and typical fibers are shown in Figure 3. It is not known to what extent this size

TABLE V

Fiber Size Distribution for Amosite (Micrometers)

Pipe Insulation Mfg. - Finishing

Fibers per thousand (n = 229)

Length (interval midpoint) in μm

Diameter (μm) (midpoint)	0.15	0.45	1.75	3.25	4.75	15
0.15	0	9	120	92	110	4
0.45	0	4	92	61	120	31
0.75	0	0	22	70	87	39
1.5	0	0	0	22	48	70

Pipe Insulation Mfg. - mixing

Fibers per thousand (n = 373)

Length (interval midpoint) in μm

Diameter (μm) (midpoint)	0.15	0.45	1.75	3.25	4.75	15
0.15	0	35	120	94	83	29
0.45	0	3	62	51	130	59
0.75	0	0	29	35	86	40
1.5	0	0	3	21	46	70

Note: Because of rounding, totals do not equal 1000.

distribution resembles that of airborne fibers from the commercial asbestos.

Tremolite fibers from the same samples in the talc mine were also identified and sized by electron microscopy.[35,36] In this talc mine and mill, tremolite fibers had slightly larger median diameters than the anthophyllite, 0.19 μm with geometric standard deviations of 2.3 and 2.4 respectively and similar median fiber lengths, 1.6 and 1.5 respectively. With lower geometric standard deviations, however, 1.8 and 1.9 respectively, there were fewer long fibers and a median aspect ratio of 7.5. Only 30% of the fibers had an aspect ratio greater than 10 to 1. The fiber size distribution is summarized in Table VII and typical fibers are shown in Figure 4. Tremolite has been processed and repurified by acid treatment for special uses in the filtration field.[34]

Actinolite, with tremolite, is classified by Hendry[34] as the least important of the asbestos minerals from an economic standpoint. No data on airborne fiber characteristics were available for this report.

As a group, the amphibole fibers, while much less important than chrysotile economically, are found in significant numbers in human lungs at autopsy.[37] As indicated by Cralley et al[3] and by Hendy,[34] the less common forms of asbestos, when available in a relatively pure state, have found such uses as inexpensive fillers, reinforcing fibers, and thixotropic agents. They can be expected in ambient air from both industrial and commercial uses and from weathering of rock. Their "harsher", i.e., stiff and straight nature makes them easier to detect in an instrument such as that reported by Lilienfeld and

TABLE VI

Anthophyllite Fiber Size Distribution

Talc Mining and Milling

Fibers per thousand (n = 849)

Length (interval midpoint) in μm

Diameter (μm) (midpoint)	0.4	1.3	2.2	3.2	5.0	15
0.09	270	200	61	22	16	4
0.3	8	78	58	82	26	5
0.4	1	14	15	15	16	14
0.8	0	2	6	25	45	14

TABLE VII

Tremolite Fiber Size Distribution

Talc Mining and Milling

Fibers per thousand (n = 241)

Length (interval midpoint) in μm

Diameter (μm) (midpoint)	0.4	1.3	2.2	3.2	5.0	15
0.09	180	200	74	3	4	0
0.3	17	150	87	25	8	0
0.4	0	21	66	29	8	4
0.8	0	4	33	62	21	4

Elterman[38] which rotates fibers by means of an electric field for synchronous detection of the resulting modulation of the light scattered from a continuous wave laser beam by the rotating particles.

Attapulgite

Of the 36 non-asbestos minerals listed by Zumwalde and Dement[22] as examples which may occur in a fibrous state, attapulgite and wollastonite have recently been studied by the National Institute for Occupational Safety and Health,[39,40] and will be discussed. These minerals are both mined, processed and sold in the United States, and their commercial value is at least partially because of their microfibrous structure.

Attapulgite is the principal mineral component of attapulgus clay. It is a crystalline hydrated magnesium aluminum silicate of the approximate formula: $(MgAl)_2 [OH\ Si_4O_{10}] \cdot 4H_2O$. It is found in the Soviet Union and India as well as the Georgia-Florida area of the United States and is also known as palygorskite. Both colloidal and sorptive grades are marketed for a wide variety of industrial applications. Airborne fibers were sized by electron microscopy. The median fiber diameter was 0.07 µm, with a geometric standard deviation of 3.14; the largest diameter observed was 0.1 µm. The median fiber length was 0.4 µm with a geometric standard deviation of 3.0; the longest fiber observed was 2.5 µm. The diameters given are for individual fibers, which were observed, however there was a strong tendency for the fibers to agglomerate into jagged particulates that ranged in diameter from 0.5 to 5 µm. This may be seen in Figure 5.

It may be noted from the above description that unlike asbestos, this material would not appear fibrous with either the naked eye or the optical microscope. The designation as fibrous is solely because of the possibility of biological effect when inhaled or ingested.

Wollastonite

Wollastonite is a naturally occurring calcium silicate, $Ca_3(Si_3O_9)$ mined in Willsboro, N.Y. It has been used in ceramics, paints, welding fluxes, plastics, cements, wallboards and glass.[40] In the two surveys of the mine and mill reported on by Zumwalde,[40] air samples were taken for subsequent fiber counting and characterization. Samples were counted for fibers longer than 5 μm by the NIOSH standard procedure using a 45x phase contrast objective and examined by transmission electron microscopy at 10,000x. Selected area electron diffraction and energy dispersive x-ray analysis was used for fiber identification. Some typical fibers are shown in Figure 6.

The median fiber diameter was 0.22 μm, with a range of 0.1-5.2 μm. Fiber length median was 2.5 μm with a range of 0.3-41 μm. The fiber size distribution is summarized in Table VIII. Some 21% of the fibers were longer than 5 μm by optical microscopy, and 17% were longer than 4.75 μm by electron microscopy. Unlike the attapulgite, there were a number of fibers in these dust clouds which compared in dimension to those longer fibers seen in asbestos dust clouds. If, as the sum of biological, physiological and aerodynamic evidence seems to be suggesting, the carcinogenic properties of airborne fibers are more related to their size, shape, and aerodynamic behavior than to their chemical or physical properties, then wollastonite should be treated with as much respect as asbestos.

TABLE VIII

Airborne Fiber Size Distribution

Wollastonite Mining and Milling

Fibers per thousand (n = 1320)

Length in µm (midpoint)

Diameter (µm) (midpoint)	0.15	0.45	1.75	3.25	4.75	15
0.15	0	110	260	52	8	0
0.45	0	0	150	130	32	3
0.75	0	0	2	48	54	9
1.50	0	0	0	4	82	58

Other Mineral Fibers

As noted by Cralley et al[3] and amplified by Zumwalde and Dement[22] there are many minerals which may occur in fibrous form. These particles when airborne can, at least in certain sizes, result in the development of ferruginous bodies in the lung.[13] With sufficient exposure and an adequate latent period they may result in an increased probability of lung cancer or cancer of the gastrointestinal tract. The biological and epidemiological evidence is not available to even state with any certainty which of these fibers would create a health hazard. There is certainly no reason to limit the use of materials which are useful in manufacture, commerce and agriculture. It would, however, be foolhardy to treat any airborne fibrous dust as "inert". Wherever significant exposure to such dusts in the working atmosphere or release of the dusts to ambient air is occurring, controls should be instituted to minimize such exposure or release. Measurements of airborne fibers should be made to ascertain the degree of exposure, with help from the National Institute for Occupational Safety and Health or the State Environmental Protection Agency or State Health Department as appropriate. Let us hope our precautions are adequate so that we never can determine with certainty whether these materials are human carcinogens.

References:

1. Timbrell, V. "The Inhalation of Fibrous Dusts." Ann. N.Y. Acad. Sci. 132 (1), 255-273 (1965).
2. Whitby, K.T., A.B. Ahlgren and R.C. Jordan. "Size Distribution and Concentration of Air-Borne Dust." ASHAE Journal Section, Heating Piping and Air Conditioning (August 1955).
3. Cralley, L.J., R.G. Keenan, J.R. Lynch and W.S. Lainhart. "Source and Identification of Respirable Fibers." Am. Ind. Hyg. Assn. J. 29, 129-135 (1968).
4. Stanton, M.F., M. Layard, M. Miller, M. May and E. Kent. "Carcinogenicity of Fibrous Glass: Pleural Response in the Rat in Relation to Fiber Dimension." J. Natl. Cancer Inst. 58, 587-603 (1977).
5. Pundsack, F.L. "Fibrous Glass - Manufacture, Use and Physical Properties." In Occupational Exposure to Fibrous Glass. National Institute for Occupational Safety and Health, HEW Pub No. (NIOSH) 76-151 (Washington, D.C., U.S. Government Printing Office, 1976) p. 11-18.
6. Corn, M., Y. Hammad, D. Whittier and N. Kotsko. "Employee Exposure to Airborne Fiber and Total Particulate Matter in Two Mineral Wool Facilities." Environ. Res. 12, 59-74 (1976).
7. Fowler, W.P. Industrial Hygiene Surveys of Occupational Exposure to Mineral Wool. National Institute for Occupational Safety and Health, Cincinnati, (June 1978).

8. Smith, H.V. "History, Processes and Operations in the Manufacturing and Uses of Fibrous Glass," in Occupational Exposure to Fibrous Glass, National Institute for Occupational Safety and Health, HEW Pub. No. (NIOSH) 76-151 (Washington, D.C., U.S. Government Printing Office, 1976) p. 19-26.

9. Shand, E.B. Composition and Properties of Fibers. In: Glass Engineering Handbook, 2nd ed. (New York, McGraw Hill Book Co. 1958) p. 375-425.

10. Fowler, D.P., J.L. Balzer and . C. Cooper. "Exposure of Insulation Workers to Airborne Fibrous Glass." Am. Ind. Hyg. Assn. J. 32:86-91 (1971).

11. Dement, J.M. "Environmental Aspects of Fibrous Glass Production and Utilization." In: Occupational Exposure to Fibrous Glass. National Institute for Occupational Safety and Health, HEW Pub. No. (NIOSH) 76-151 (Washington, D.C., U.S. Government Printing Office, 1976) p. 97-109.

12. Balzer, J.L. "Environmental Data: Airborne Concentrations Found in Various Operations" In: Occupational Exposure to Fibrous Glass. National Institute for Occupational Safety and Health, HEW Pub. No. (NIOSH) 76-151 (Washington, D.C. U.S. Government Printing Office, 1976) p. 83-89.

13. Gross, P., J. Tuma and R.T.P. deTreville. "Fibrous Dust Particles and Ferruginous Bodies," Arch. Envir. Health 21:38-46 (1970).

14. Gross, P., L.J. Cralley, J.M.G. Davies, R.T.P deTreville and J. Tuma, "A Quantitative Study of Fibrous Dust in the Lungs of City Dwellers." In: Inhaled Particles III. W.H. Walton, Ed. (Unwin Bros. Ltd., Old Woking, England, 1971) p. 671-679.

15. Langer, A.M., V. Baden, E.C. Hammond and I.J. Selikoff. "Inorganic Fibers, Including Chrysotile, in Lungs at Autopsy." In: Inhaled Particles III, W.H. Walton, Ed., (Unwin Bros. Ltd., Old Woking, England, 1971) p. 683-692.

16. Guralnik, D.B. and J.H. Friend, Eds. Webster's New World Dictionary, (World Publishing Co., Cleveland 1962).

17. Campbell, W.J., R.L. Blake, L.L. Brown, E.E. Cather and J.J. Sjoberg. "Selected Silicate Minerals and Their Asbestiform Varieties" (U.S. Dept. of the Interior, Bureau of Mines, Washington 1977).

18. Gilson, J.C. "Asbestos" In: Encyclopedia of Occupational Safety and Health (International Labour Organization, Geneva, Switzerland 1971) p. 120-124.

19. Hodgson, A.A., "Fibrous Silicates," Royal Inst. Chem. London Lectures, Monographs, Rept., (London, 1965).

20. Speil, S. and J.P. Leineweber. "Asbestos Minerals in Modern Technology." Environ. Research 2, 166-208 (1969).

21. Birks, L.S., M. Fatemi, J.V. Gilfrich and E.T. Johnson. "Quantitative Analysis of Airborne Asbestos by X-Ray Diffraction": Final Report on Feasibility Study" (U.S. Environmental Protection Agency, Washington, D.C. January 1975).

22. Zumwalde, R.D. and J.M. Dement. "Review and Evaluation of Analytical Methods for Environmental Studies of Fibrous Particulate Exposures." National Institute for Occupational Safety and Health, (U.S. Government Printing Office, Washington, D.C. May 1977).

23. Timbrell, V. "Alignment of Respirable Asbestos Fibers by Magnetic Fields." Ann. Occup. Hyg. 18, 299-311 (1975).

24. Pooley, F.D. "The Identification of Asbestos Dust with an Electron Microscope Microprobe Analyzer." Ann. Occup. Hyg. 18, 181-186 (1975).

25. Mueller, P.K., A.E. Alcocer, R.L. Stanley, and G.R. Smith "Asbestos Fiber Atlas," U.S. Environmental Protection Agency, (Washington, D.C., April 1975).

26. Lynch, J.R., H.E. Ayer and D.L. Johnson, "The Interrelationships of Selected Asbestos Exposure Indices." Am. Ind. Hyg. Assn. J. 31, 598-604 (1970).

27. Gaze, R. "The Physical and Molecular Structure of Asbestos." Ann. N.Y. Acad. Sci. 132. 23-30 (1965).

28. Anon. "Determination of Magnitude of Exposure to Asbestos Fibers Associated with a Woman's Coat Containing 8% Asbestos." Unpublished report, National Institute for Occupational Safety and Health, Cincinnati, Ohio (June 30, 1971).

29. Dement, J.M. and R.L. Harris, "Estimates of Pulmonary and Gastrointestinal Deposition for Occupational Fiber Exposure." National Institute for Occupational Safety and Health, (Cincinnati, Ohio, In Press).

30. Harris, R.L. and V. Timbrell. "The Influence of Fiber Shape in Lung Deposition—Mathematical Estimates." In: Inhaled Particles IV, W.H. Walton, Ed., (Pergamon Press, Oxford, England 1977) p. 75-89.

31. Wallingford, K.M., J.M. Dement, R.D. Zumwalde and D.R. Roberts, "Comparison of Phase Contrast and Electron Microscopic Methods for Evaluation of Asbestos Fiber Exposure." Presented at Annual American Industrial Hygiene Conference, New Orleans, LA, May 24, 1977.

32. John, W., A. Berner, G. Smith and J.J. Wesolowski. "Experimental Determinations of the Number and Size of Asbestos Fibers in Ambient Air." Air and Industrial Hygiene Laboratory, (California Dept. of Health, Berkeley, Calif. Jan. 1976).

33. Gillam, J.D., J.M. Dement, R.A. Lemen, J.K. Wagoner, V.E. Archer and H.P. Blejer. "Mortality Patterns Among Hard Rock Gold Miners Exposed to an Asbestiform Mineral." Ann. N.Y. Acad. Sci. 271, p. 345-352, (1976).

34. Hendry, N.W. "The Geology, Occurrence and Major Uses of Asbestos," Ann. N.Y. Acad. Sci. 132. p. 12-21 (1965).

35. Dement, J.M. and R.D. Zumwalde, "Occupational Exposure to Talcs Containing Asbestiform Minerals." Presented at the Society of Occupational Environment and Health, Washington, D.C., Dec. 4-7, 1977.

36. Dement, J.M. and R.D. Zumwalde. "Industrial Hygiene Study of the Gouverneur Talc Company, Number One Mine and Mill," National Institute for Occupational Safety and Health, Cincinnati, Ohio (June 8, 1977) p. 105.

37. Langer, A.M. "Inorganic Fibers, Including Chrysotile, in Lungs at Autopsy : Discussion", In: Inhaled Particles III, W.H. Walton, Ed., (Unwin Brothers, Ltd., Old Woking, England 1971) p. 693.

38. Lillienfeld, P. and P.B. Elterman. "Development and Fabrication of a Prototype Fibrous Aerosol Monitor." National Institute for Occupational Safety and Health, Cincinnati, Ohio, HEW (NIOSH) Pub. No. 78-125 (1977). (Springfield, Va., National Technical Information Service).

39. Zumwalde, R.D. "Industrial Hygiene Study of the Engelhard Minerals and Chemicals Corporation." Unpublished report. (National Institute for Occupational Safety and Health, Cincinnati, Ohio, April 29, 1977) p. 76.

40. Zumwalde, R.D. "Industrial Hygiene Study of the Interpace Corporation" Unpublished report. (National Institute for Occupational Safety and Health, Cincinnati, Ohio, July 29, 1977) p. 79.

CAPTIONS FOR FIGURES

Figure 1

Various mineral crystal and aggregate shapes.
(from Campbell et al[17]).

Figure 2

Typical chrysotile fibers from an air sample.
Electron micrograph.

Figure 3

Typical anthophyllite fibers by electron microscope
at 20,000 X.

Figure 4

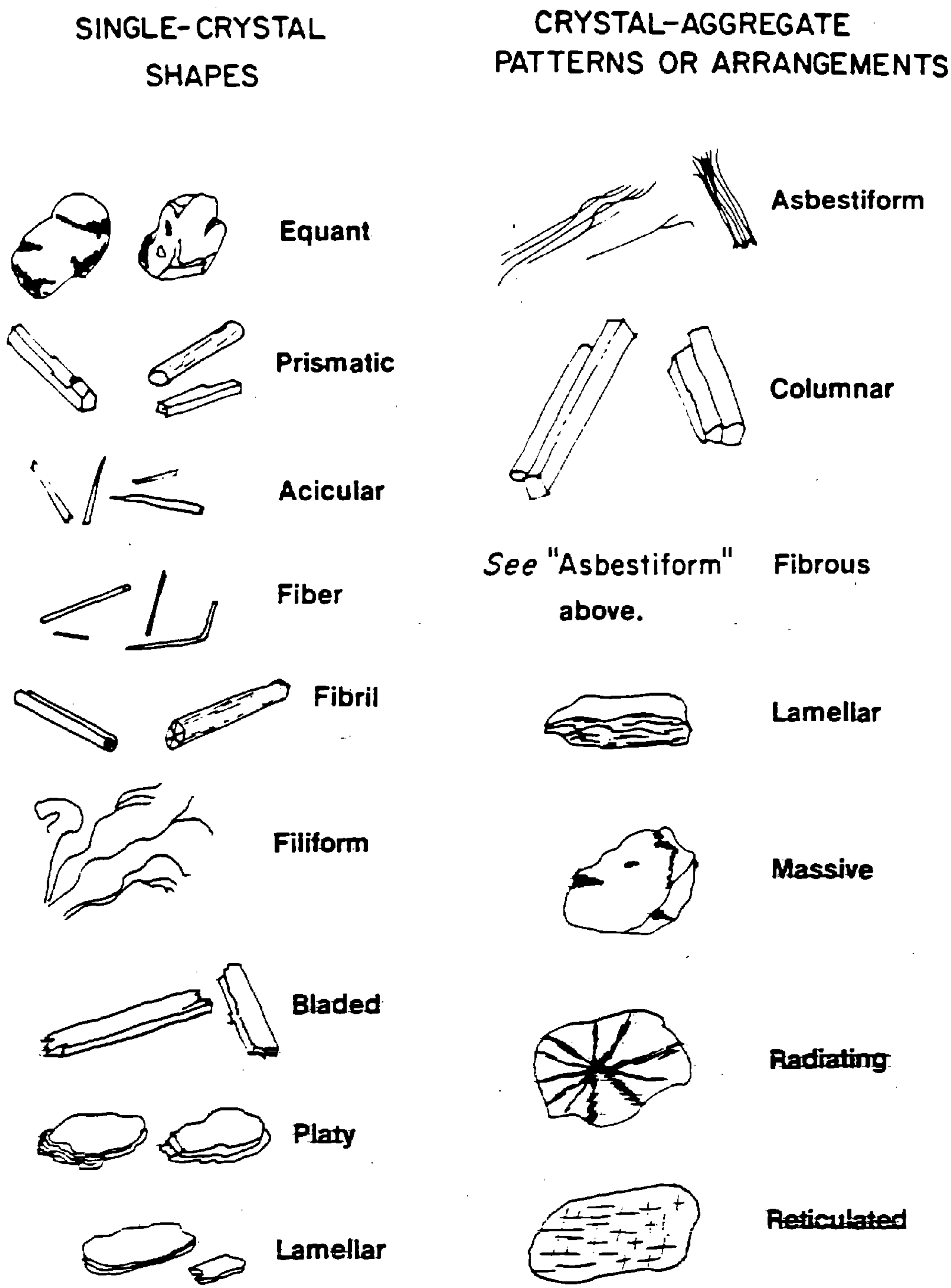
Typical tremolite fibers by electron microscope at 20,000 X.

Figure 5

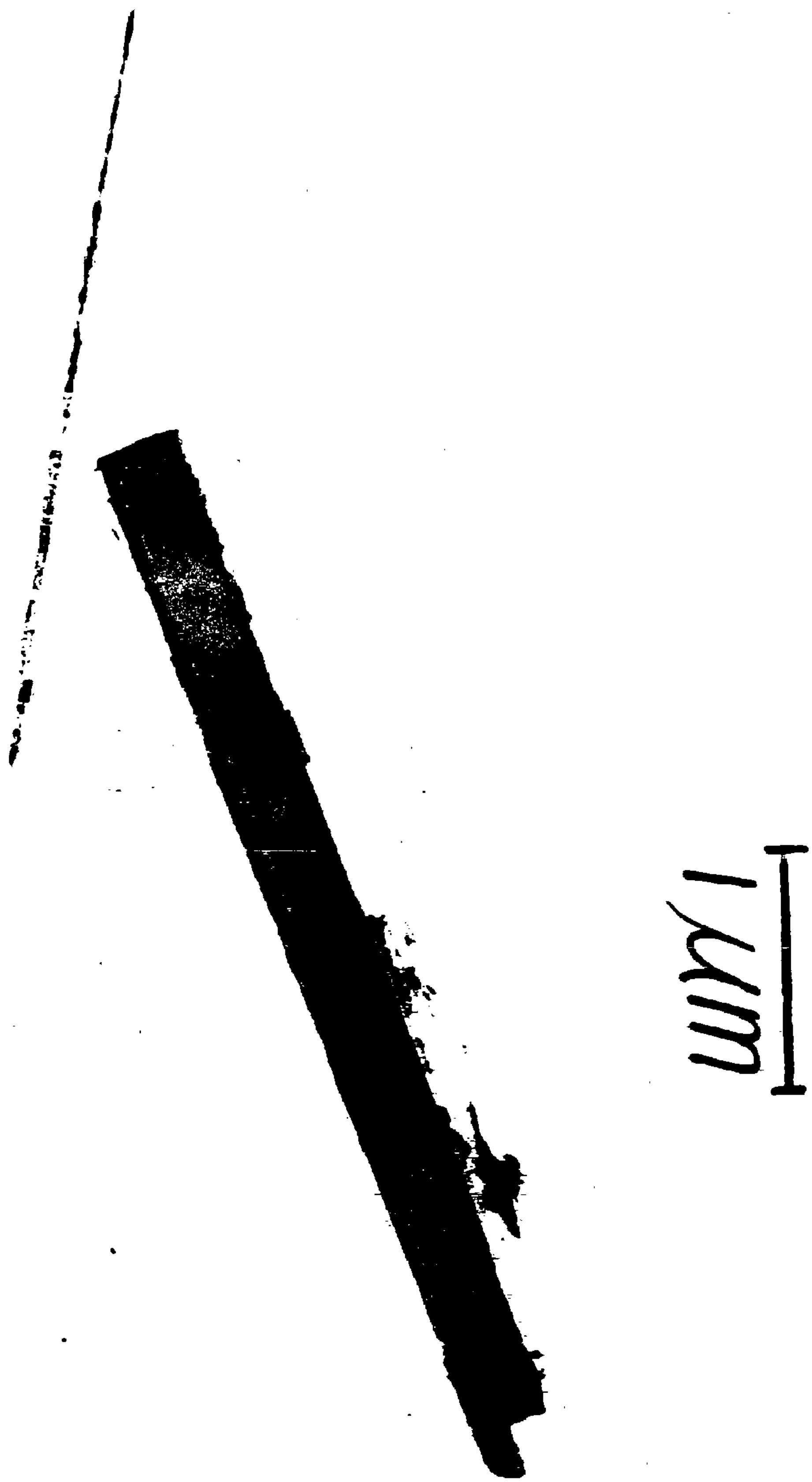
Attapulgite fibers by electron microscope at 20,000 X.

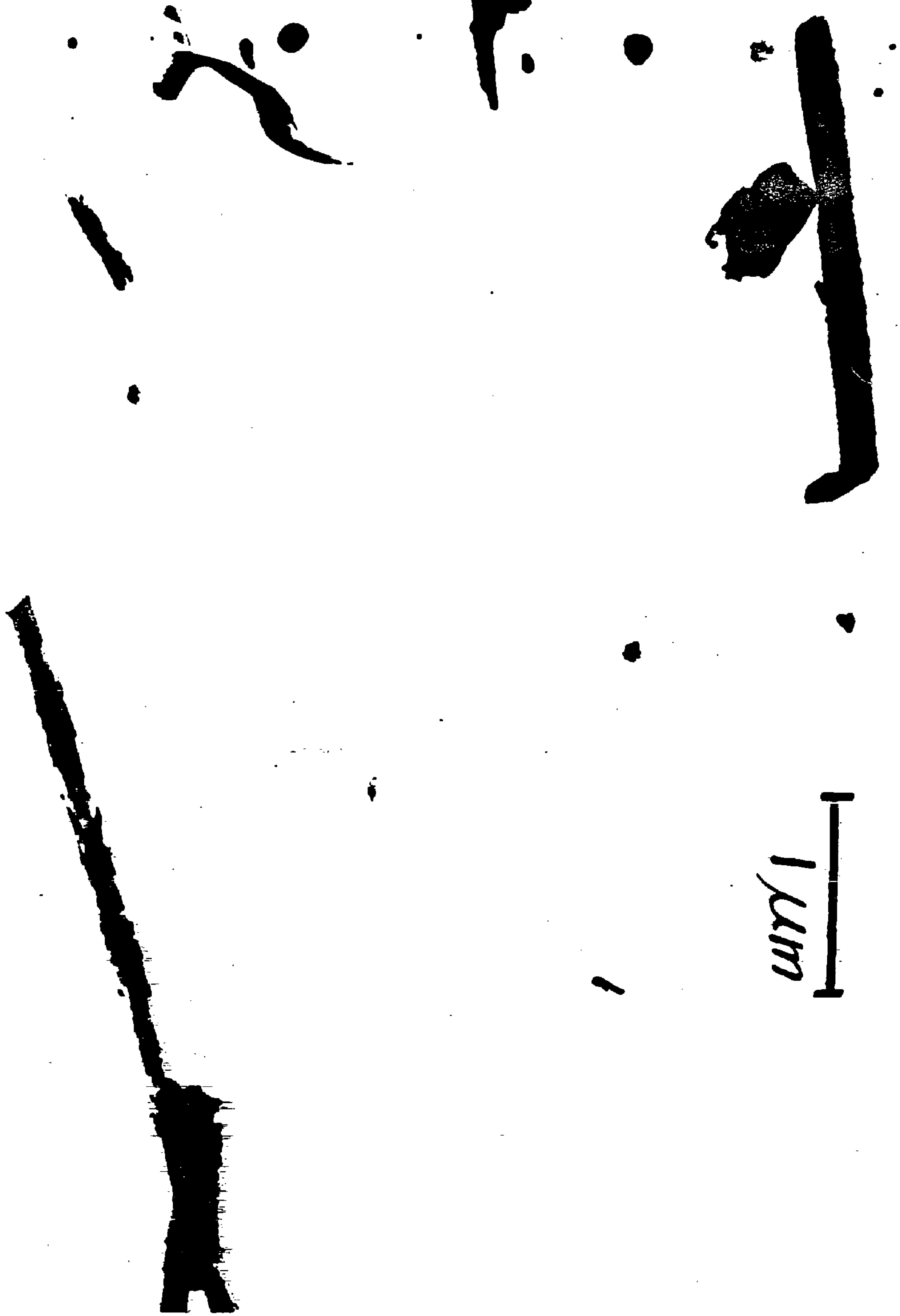
Figure 6

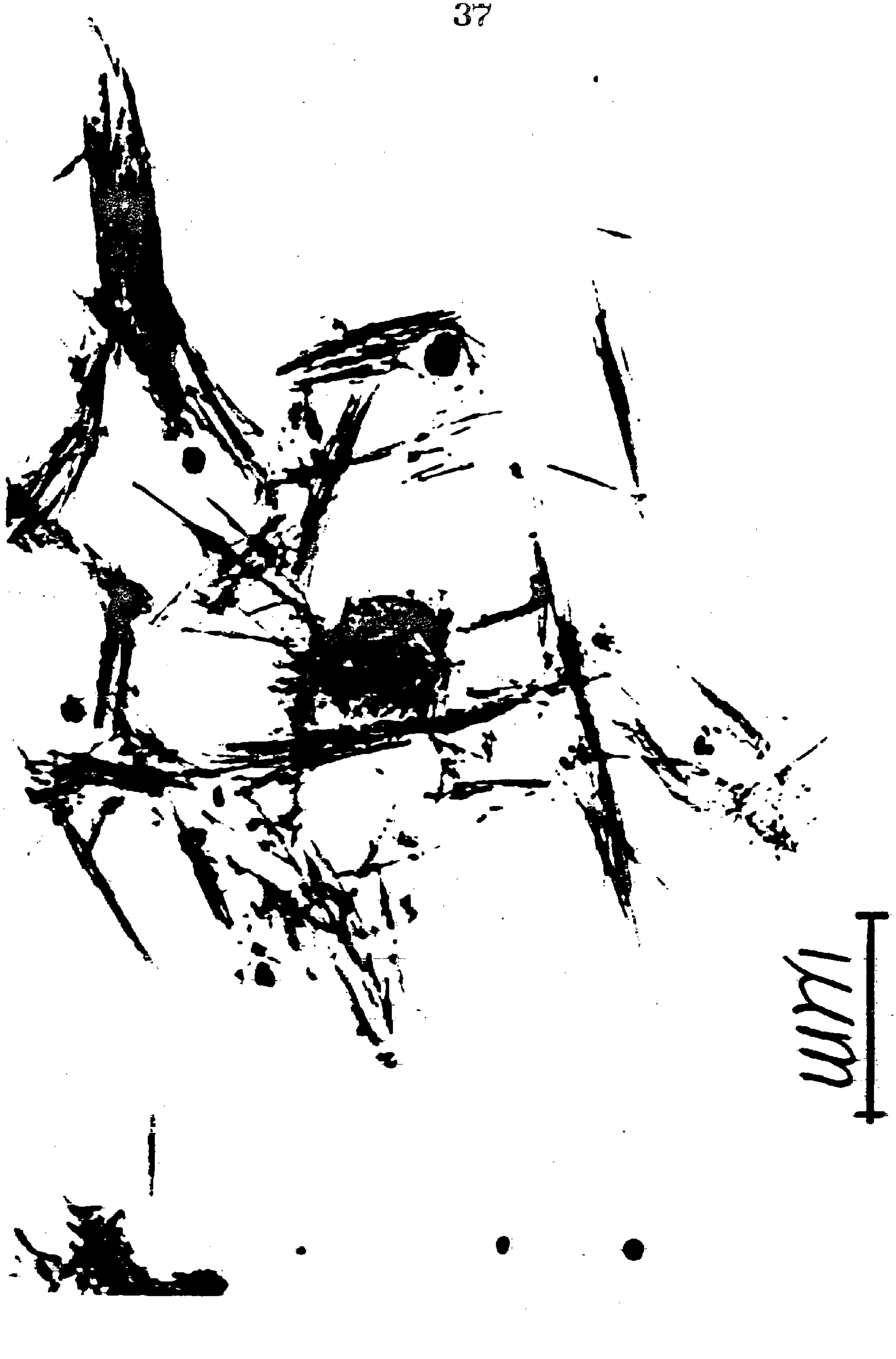
Wollastonite fibers by electron microscope at 20,000 X.

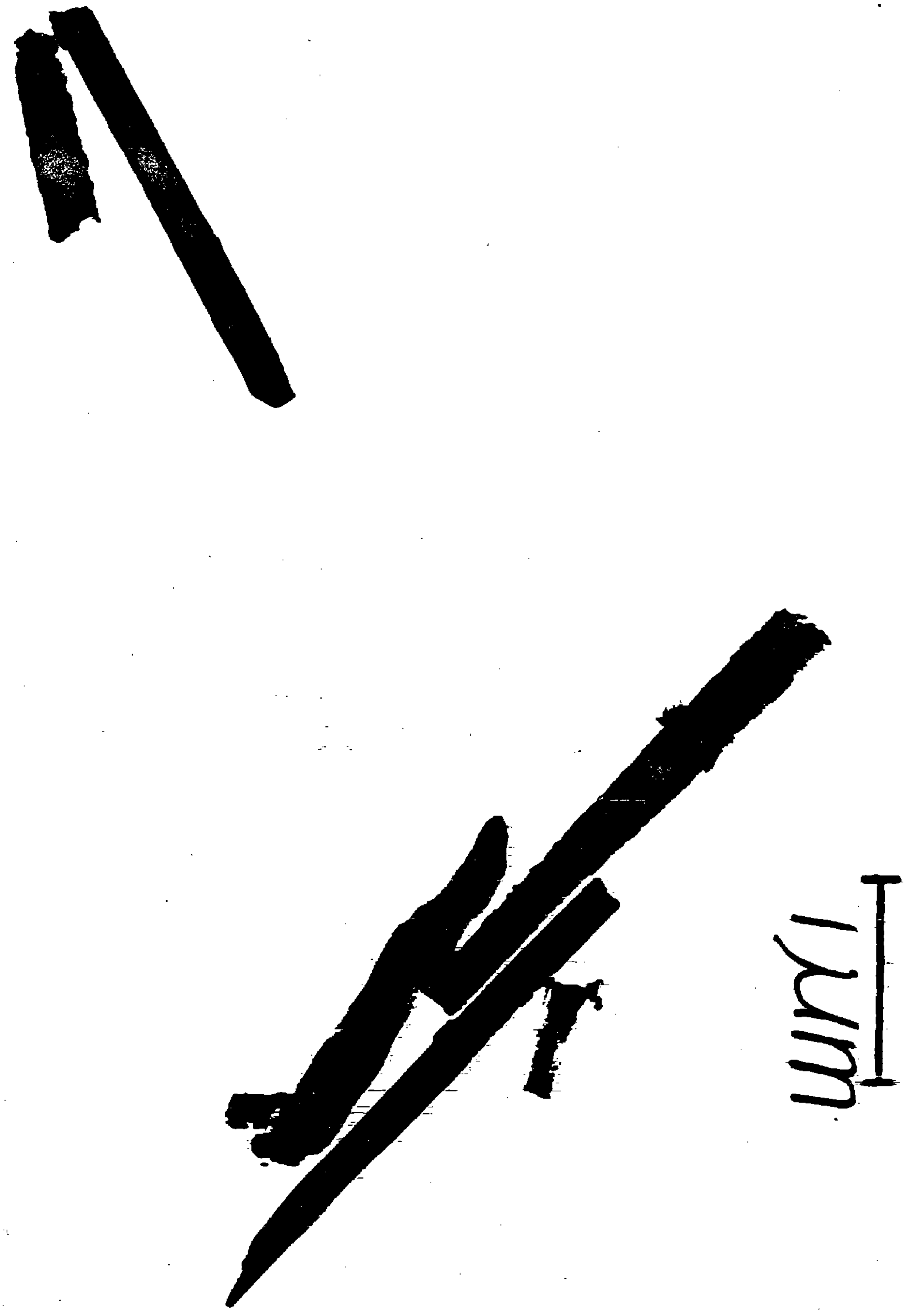

SINGLE-CRYSTAL SHAPES
CRYSTAL-AGGREGATE PATTERNS OR ARRANGEMENTS
Equant
Prismatic
Acicular
Fiber
Fibril
Filiform
Bladed
Platy
Lamellar
Asbestiform
Columnar
See "Asbestiform" above.
Fibrous
Lamellar
Massive
Radiating
Reticulated


1µm


1 mm


1 μm


1μm


1μm