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Fiber Dimensions of Crocidolites From Western Australia, Bolivia, and the Cape and Transvaal Provinces of South Africa

By Kim B. Shedd

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CONTENTS

ILLUSTRATIONS

TABLES

TABLES--Continued

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	µA	microampere
cm^3	cubic centimeter	µm	micrometer
kV	kilovolt	pct	percent
mL	milliliter	wt pct	weight percent
mm	millimeter		

FIBER DIMENSIONS OF CROCIDOLITES FROM WESTERN AUSTRALIA, BOLIVIA, AND THE CAPE AND TRANSVAAL PROVINCES OF SOUTH AFRICA

By Kim B. Shedd[1]

ABSTRACT

The Bureau of Mines measured fiber dimensions on crocidolites (riebeckite-asbestos and magnesioriebeckite-asbestos) from the world's four crocidolite mining regions. The objective of the study was to determine whether there are measurable morphological differences between crocidolite fibers that correlate with the high reported incidence of mesothelioma in miners and mill employees in the Cape Province of South Africa and Western Australia, as compared with little or no reported incidence of this cancer in the Transvaal Province of South Africa or Bolivia. Fiber dimensions measured with the scanning transmission electron microscope showed that crocidolites from Western Australia and the Cape Province have more thin fibers than crocidolites from Bolivia and the Transvaal Province.

INTRODUCTION

Precise and objective mineral particulate characterizations are essential to help clarify some of the health-related problems associated with occupational and environmental exposure to fibrous minerals. By providing these characterizations the Bureau of Mines is able to assist regulatory agencies and industry by furnishing mineralogical information upon which more informed decisions can be based.

The question addressed in this report is, "Are there differences in fiber dimensions of crocidolites from different mining regions that might correlate with reported differences in the incidence of mesothelioma?" Crocidolite is a general term for alkali amphibole asbestos (12).[2] The two forms of crocidolite examined in this study are riebeckite-asbestos and magnesioriebeckite-asbestos, based on chemical compositions reported in the literature. Crocidolite samples were examined from four locations where it has been produced commercially (14) to determine if there are measurable differences in fiber dimensions. The results are evaluated in view of the differences in mesothelioma incidence as reported in the literature. The basis for this correlation is reviewed in appendix A.

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[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

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SAMPLE DESCRIPTIONS

GEOLOGIC SETTING

Ten crocidolite samples were examined in this study (table 1). The samples were obtained from the four geographic regions where crocidolite has been mined commercially: the Cape and Transvaal Provinces in South Africa, the Hamersley Range of Western Australia, and Bolivia. Detailed descriptions of the geology and mineralogy of the four regions have been published (1-2, 4-5, 11, 14). Geologically the crocidolite deposits can be divided into two types. The South African and Western Australian deposits occur in banded iron formations of Precambrian age. The crocidolite is present as "seams" parallel to the bedding planes of the banded ironstone. The fibers lie perpendicular to the plane of the seam (cross fiber). Based on their chemical composition, crocidolites from South Africa and Western Australia are riebeckite-asbestos. Magnetite is commonly reported in association with the crocidolite from these locations (2, 11, 14). In contrast, the Bolivian deposit occurs in younger slates and quartzites of Devonian age. The crocidolite in this deposit is present as veins parallel to the bedding, and as fracture fillings at irregular angles to the bedding, forming a "stockwork" type deposit. The fiber lies at an acute angle to the veins (slip fiber) and is a magnesioriebeckite-asbestos because of replacement of ferrous iron by magnesium (32). A similar deposit has been described near Lusaka, Zambia (4), but has not been worked commercially.

A systematic sampling within mines or regions was beyond the scope of this project and was not attempted. Samples were primarily raw fibers within host rock, or in some cases fibers removed from the host rock. A few of the samples were received in a milled form. Specific comments from hand-sample examination of the samples follow a general discussion of chemical composition.

TABLE 1. - Crocidolite sample descriptions and source locations

Sample	Description	Source location
A1....	Crude fiber from mill circuit; GSWA #57408.[1]	Colonial Mine, Wittenoom, Hamersley Range, Western Australia.
A2....	Fiber in rock from spoil heap; GSWA #57409.[1]	Do.
B.....	Fiber bundles..................	Wormald Mine, Bolivia.
C1....	Fiber in rock..................	Mined near Kuruman, northern Cape Province, Republic of South Africa.
C2....	Air-jet milled fiber;[2] CP#130, 05303.	Mined in Kuruman Hills, northern Cape Province, Republic of South Africa.
T1....	Fibers removed from rock labeled "crude ore."[3]	Voorspoed Mine (Good Luck Mine), northeast Transvaal, Republic of South Africa.
T2....	Fiber in rock..................	Do.
T3....	Milled fiber...................	Transvaal, Republic of South Africa.
T4....	Fiber in rock; #WS42[1]..........	Dublin, Pietersburg, Transvaal, Republic of South Africa.
T5....	Fiber in rock..................	Do.

[1]Sample numbers provided by sample donors.
[2]Sample prepared for the National Institute of Environmental Health Studies.
[3]Sample from the collection of the late Mearl F. Stanton.

CHEMICAL COMPOSITION

Results from selected chemical analyses reported in the literature for crocidolites from four regions are presented in tables 2 through 5. Semiquantitative chemical analyses on the samples in the present study confirm the following trends in chemical composition.

TABLE 2. - Chemical composition of Cape Province crocidolites, weight percent

Oxides	I	II	III	IV	V	VI
SiO_2..............	50.90	50.70	52.00	50.50	51.94	50.18
Al_2O_3............	Nil	.70	Nil	NA	.20	2.58
Fe_2O_3............	16.85	18.30	16.05	20.20	18.64	17.43
FeO..............	20.50	17.50	17.65	15.40	19.39	15.51
MnO..............	.05	.06	Tr	NA	NA	.09
MgO..............	1.06	3.05	4.28	3.65	1.37	3.87
CaO..............	1.45	1.30	1.20	.80	.19	.92
Na_2O.............	6.20	5.30	6.21	4.40	6.07	5.25
K_2O..............	.20	Tr	.06	NA	.04	.05
H_2O^+.............	2.37	2.53	2.43	4.15	2.58	3.03
H_2O^-.............	.22	.29	.26	1.05	.31	.43
TiO_2..............	NA	NA	NA	NA	NA	.14
CO_2..............	.20	.45	.09	NA	NA	.36
P_2O_5.............	NA	NA	NA	NA	NA	.14
Total.......	100.00	100.18	100.23	100.15	100.73	99.98

NA Not available. Tr Trace.
I Koegas (9).
II Kuruman (9).
III Pomfret (9).
IV Kuruman, Bechuanaland (5).
V Kliphuis, northwest Cape Province (5).
VI Average of 9 analyses, Kuruman iron formation (2).

TABLE 3. - Chemical composition of Transvaal Province crocidolites, weight percent

Oxides	I	II	III
SiO_2...............	56.27	59.40	59.41
Al_2O_3..............	NA	NA	Nil
Fe_2O_3..............	NA	14.40	14.03
FeO................	33.78	15.10	15.11
MnO................	NA	NA	Tr
MgO................	1.67	3.40	3.53
CaO................	1.70	.55	.49
Na_2O...............	3.92	4.05	4.63
K_2O................	NA	NA	.28
H_2O^+...............	NA	3.25	2.07
H_2O^-...............	NA	.10	.14
TiO_2...............	NA	NA	NA
CO_2................	NA	NA	.09
Total...........	97.34	100.25	99.78

NA Not available. Tr Trace.
I Malips River, east of Pietersburg (5), total reported as 99.84.
II East of Malips River (5).
III Malips drift (9).

TABLE 4. - Chemical composition of Western Australian crocidolites, weight percent

Oxides	I	II	III	IV	V
SiO_2...	53.66	53.10	51.86	51.94	52.85
Al_2O_3..	.08	.88	.03	.24	.18
Fe_2O_3..	17.73	16.95	20.26	18.93	18.55
FeO....	14.67	17.54	14.84	15.25	14.95
MnO....	.07	NA	.01	.01	Tr
MgO....	4.54	3.13	3.26	3.94	4.64
CaO....	.23	.52	.49	.40	1.07
Na_2O...	5.01	6.21	6.12	6.00	5.97
K_2O....	.07	.14	.28	.26	.05
H_2O^+...	2.81	[1]1.66	1.97	2.67	2.77
H_2O^-...	.33	NA	.68	.72	.22
TiO_2...	.02	NA	.03	.01	NA
CO_2....	.57	NA	.02	Nil	.23
P_2O_5...	.36	NA	.05	Nil	NA
FeS_2...	.02	NA	NA	NA	NA
Total	100.17	100.13	99.90	100.37	100.48

NA Not available. Tr Trace.
[1]Total water.
I Wittenoom (25).
II Location unknown (25).
III Mount Margaret (25).
IV Weeli Wolli (25).
V Hamersley Range (25).

TABLE 5. - Chemical composition of Bolivian crocidolites, weight percent

Oxides	I	II	III	IV
SiO_2.....	55.65	56.1	54.68	55.16
Al_2O_3....	4.00	.66	3.90	3.10
Fe_2O_3....	13.01	15.6	13.98	14.02
FeO......	3.84	4.06	7.40	7.93
MnO......	Tr	Nil	.21	.09
MgO......	13.09	14.5	12.25	11.78
CaO......	1.45	1.11	1.27	.98
Na_2O.....	6.91	5.05	5.55	5.92
K_2O......	.39	.71	.46	.60
H_2O^+.....	1.78	[1]2.21	[3].72	[3]1.07
H_2O^-.....	Tr	[2].03	NA	NA
TiO_2.....	NA	Tr	Tr	NA
CO_2......	Tr	NA	NA	NA
P_2O_5.....	NA	NA	NA	NA
Total..	100.12	100.03	100.42	100.65

NA Not available. Tr Trace.
[1]Water [theoretical 2(OH)/mol].
[2]Loss at 105° C.
[3]Total water.
I Cochabamba (9).
II Cochabamba (32).
III Philadelphia Mine, Cristalmayu, Cochabamba (1).
IV Philadelphia Mine, Cristalmayu, Cochabamba (1).

The Bolivian crocidolite is magnesioriebeckite-asbestos (12). This crocidolite has higher content of Al_2O_3, MgO, CaO, and K_2O, and lower total iron content than the riebeckite-asbestos from the other three regions.

Keep (11) reports that the Transvaal Province crocidolite has higher silica and lower iron and sodium than crocidolite from the Cape Province. The crocidolites reported in tables 2 through 5 have fairly consistent SiO_2 contents within regions, but these values differ from region to region. The four regions can be ranked from lowest to highest concentration of SiO_2 as follows: Cape Province (50 to 52 pct), Western Australia (52 to 54 pct), Bolivia (55 to 56 pct), Transvaal Province (56 to 59 pct).

Total iron content in crocidolites from the Cape Province and Western Australia is generally higher than that reported for crocidolites from the Transvaal Province and Bolivia. The low iron content in the Bolivian crocidolite is the result of replacement of ferrous iron by magnesium (32).

Webster (31) also reports lower concentrations of Na_2O in the Transvaal Province and higher concentrations in the Cape Province. Na_2O contents of crocidolites from Western Australia and Bolivia are similar to those reported for Cape Province crocidolites. MnO and MgO concentrations of crocidolites from the Cape and Transvaal Provinces and Western Australia are similar. Values of K_2O are variable; they appear to be about 0.04 to 0.06 for most Cape Province samples and Western Australian samples labelled Wittenoom and Hamersley Range (table 4), but are generally higher in the Transvaal Province (0.28 pct), and in other samples from Western Australia and Bolivia.

WESTERN AUSTRALIAN SAMPLES

Samples A1 and A2 are from the Colonial Mine at Wittenoom in the Hamersley Range in Western Australia. Sample A1 is crude fiber from the mill circuit, and is composed of gray-blue fiber bundles, 2 to 2.5 cm long and 1 to 15 mm wide. No accessory minerals were observed during hand sample examination.

Sample A2 is a raw sample from the spoil heap of the Colonial Mine. It consists of four pieces of crocidolite seams. Each piece measures approximately 3 to 4 cm^3 and is capped at both ends by host rock. The host rock on one end of the seam is blue-black massive riebeckite; on the other end it is reddish-brown ironstone. The fibers themselves are gray blue and range in length from about 1 mm where the seam fingers into the host rock to a maximum length of about 3 cm. Most fibers are about 2.5 cm in length. The crocidolite seams are cross fiber (fibers perpendicular to the plane of the seam) and have a satiny luster. Upon careful examination small equidimensional opaque crystals of magnetite are visible among the fibers, although these occur rarely. No other obvious accessory minerals were seen.

BOLIVIAN SAMPLE

Sample B is from the Wormald Mine in Bolivia. This sample is strikingly different from the others in terms of color and fiber length. It is composed of a pale blue fiber bundle, approximately 18 cm long and 1.5 cm wide. No other minerals or evidence of host rock were seen in the hand specimen.

CAPE PROVINCE SAMPLES

Sample C1 is a raw sample mined near Kuruman in the northern Cape Province. It is a cross-fiber seam of slightly curved, blue-black fibers capped by blue-black massive riebeckite. The fibers are approximately 8.5 cm in length and exhibit a satiny luster on some surfaces of the sample. Magnetite is visible in layers of the host rock, in a curved vein intersecting the fibers, and as rare individual crystals among the fibers.

Sample C2 is a blended sample prepared by the Bureau for the National Institute of Environmental Health Studies (NIEHS) Oral Ingestion Studies. It is from the Kuruman Hills of the Cape Province. The sample was airjet milled for the NIEHS study, resulting in balls of loose fiber, gray blue in color. Individual fibers or bundles of fibers up to 1 cm in length are present in the sample. No other minerals are visible in hand-sample examination. Chemical and physical properties of this sample are reported by Campbell, Huggins, and Wylie (3).

TRANSVAAL PROVINCE SAMPLES

Sample T1 is from the collection of the late Mearl F. Stanton of the National Cancer Institute, National Institutes of Health. The sample was from the Voorspoed Mine of the northeast Transvaal. It is composed of a few fiber bundles of gray-blue, slightly iron-stained fiber. The bundles are 2 to 10 mm in length. Brown, iron-stained host rock is present at the ends of some bundles. Magnetite grains are visible extending from the host rock into the fiber.

Sample T2 is also from the Voorspoed Mine. It is a raw sample of a cross-fiber seam, approximately 3 by 2 by 1.5 cm in size. The fibers are slightly curved and gray blue in color with some iron oxide staining. Fiber lengths range from about 5 mm to 2 cm. Magnetite is present as thin layers crosscutting the fibers and as individual grains extending from the host rock into the fibers. The host rock is a mottled brown and black magnetite-rich layer of iron stone.

Transvaal sample T3 was received in a milled form. The sample is a gray-blue powder. Most fibers are submicroscopic, but rare fibers up to 5 mm in length are present.

Samples T4 and T5 were raw samples from the same location or mine in the Transvaal Province. "Dublin" is the name either of the mine or of the farm on which the mining took place. The samples consist of sections of magnetite-rich host rock containing crocidolite seams 3.5 to 4 cm in width. The fiber in the seams is gray blue and curved or wavy. Magnetite extends from the host rock into the fibers as individual grains. Portions of the fiber and host rock are stained reddish brown by iron oxide. Some surfaces of the fiber have a satiny luster; others have a dull luster.

MICROSCOPY

SPECIMEN PREPARATION

Because the objective of the study was to compare the fiber dimensions of crocidolites from their source deposits, unprocessed rock samples were obtained wherever possible. Characterization of fibers from the original rocks has advantages over characterization of air filter samples in that the bulk samples can all be treated in the same way, eliminating possible variations due to differing mining and processing techniques, air sampling conditions, etc. Questions may be raised as to how fibers prepared in the laboratory relate to airborne fibers in the mining environment, and whether sample preparation techniques such as milling cause different particle size distributions. Sample preparation in the present study was kept to a minimum. A comparison of the results from this study with results from other TEM studies shows similar crocidolite fiber size distributions within geographic areas such as the Cape Province regardless of method of particle size reduction, or whether the fibers were from rock or air samples.

Raw samples of crocidolite seams were prepared by first breaking the host rock with a hammer and chisel, then removing the fibers with tweezers. Whenever possible, fresher fiber from inside a seam was chosen over weathered fiber from the surface. This first step was not necessary for samples A1, B, C2, T1, and T3, which were received either as loose fiber bundles or in a milled form. Fiber from each sample was then milled to minus 20 mesh in a Wiley[3] mill.

While it was desirable to alter particle size as little as possible, milling was necessary to break apart fiber bundles and reduce the fiber lengths to allow mounting on 3-mm specimen grids. The Wiley mill uses rotating knife blades to "chop" the fibers into smaller sizes. The fibers then pass through a screen, which removes them from the action of the blades. The large mesh size (approximately 830-µm openings) was chosen to allow rapid liberation of fibers without excess reduction of fiber lengths. This method of particle size reduction is preferred over conventional ball milling techniques, which have been shown to alter crystal structure (19, 33).

Two of the samples were not processed in the Wiley mill. Sample T1 did not contain enough material to be milled, so the fiber bundles were teased apart with tweezers. Sample T3 was already well below minus 20 mesh as received.

Microgram quantities of the milled fiber from each sample were suspended in approximately 30 mL of filtered distilled water and subjected briefly to ultrasonic

[3]Reference to specific products does not imply endorsement by the Bureau of Mines.

vibration to disperse the fibers. Ultrasonic treatment for these brief time periods should not alter the crystal structure or fiber size distributions of these samples (19). Drops of each suspension were placed on Formvar-coated copper transmission electron microscope grids. After drying on a hotplate, the samples were carbon-coated.

FIBER MEASUREMENT

Fiber lengths and widths were measured directly from the cathode ray screen of a Hitachi H600 scanning transmission electron microscope (STEM) in the scanning-transmission mode at a 75-kV accelerating voltage and a 20-μA emission current. Measurement from the cathode ray screen (CRT) allowed the long fiber lengths and narrow widths to be measured over a wide range of magnifications (X 2,000 to X 60,000). The STEM was calibrated at each magnification using a carbon grating replica with 1,134 lines/mm. Measurements of the magnified image on the CRT were made to ±1/2 mm. The accuracy in micrometers was that fraction of a micrometer that 1/2 mm represents at a given magnification. The range in accuracy for the length measurements was from approximately ±0.2 μm for measurements of long fibers at X 2,000 to ±0.01 μm for measurements of short fibers at X 60,000. Widths were measured at X 12,000 to X 60,000. No attempt was made to distinguish between fibers or fibrils. The range of accuracy associated with the width measurements was approximately ±0.01 for the narrowest fibers to ±0.04 for the wider fibers.

Two sets of fiber measurements were made for each sample. In the first set, lengths and widths of all fibers within a given area were measured. At least 300 fibers was measured for each sample. When a fiber intersected a grid bar, the STEM was switched to the secondary electron mode so the full length could be measured. In this set of data small fibers were as likely to be counted as large fibers. Frequency distributions from this particle measurement technique represent particle number percent rather than weight percent.

For the second set of data a minimum length threshold of 2 μm was imposed. By restricting the data set to fibers greater than 2 μm in length, more of the "longer" fibers in the samples were measured. This allowed more fibers within dimensional categories emphasized by health scientists to be examined. Approximately 250 to 300 fibers were measured for each sample. As in the first data set, percentages reported from these results represent particle number percent.

FIBER DIMENSIONS

The number of fibers in specific length and width categories is presented in appendix B for both sets of measurements on each sample.

General similarities and differences in crocidolites from the four geographic regions can be observed from frequency distributions for fiber length, width, and aspect ratio (length/width). Lengths and widths from the measurement of all particles in each sample are combined into one set of lengths and one set of widths for each region. The frequency distributions are presented as log values to show the full range of data (fig. 1). The position of the modes (highest point in the curve), the relatively symmetrical distribution, and the positive kurtosis (peakedness) of the log width distributions for the Cape Province crocidolites are similar to the log width distribution of Western Australian fibers. The log width distributions of samples from these two regions can be contrasted with those from the Transvaal Province and Bolivia, which are less symmetrical and have modes shifted towards larger widths.

Differences in the log length distributions for the four regions are less obvious. All log length distributions are asymmetrical, with tails in the direction of longer fibers. Samples from Western Australia and the Cape Province tend to have more short fibers than those from the Transvaal Province and Bolivia. The similarities in length distributions may be the result of milling. Fiber width, which is a more fundamental mineralogical characteristic (21), is less affected by milling, and the differences in width between samples remain more pronounced.

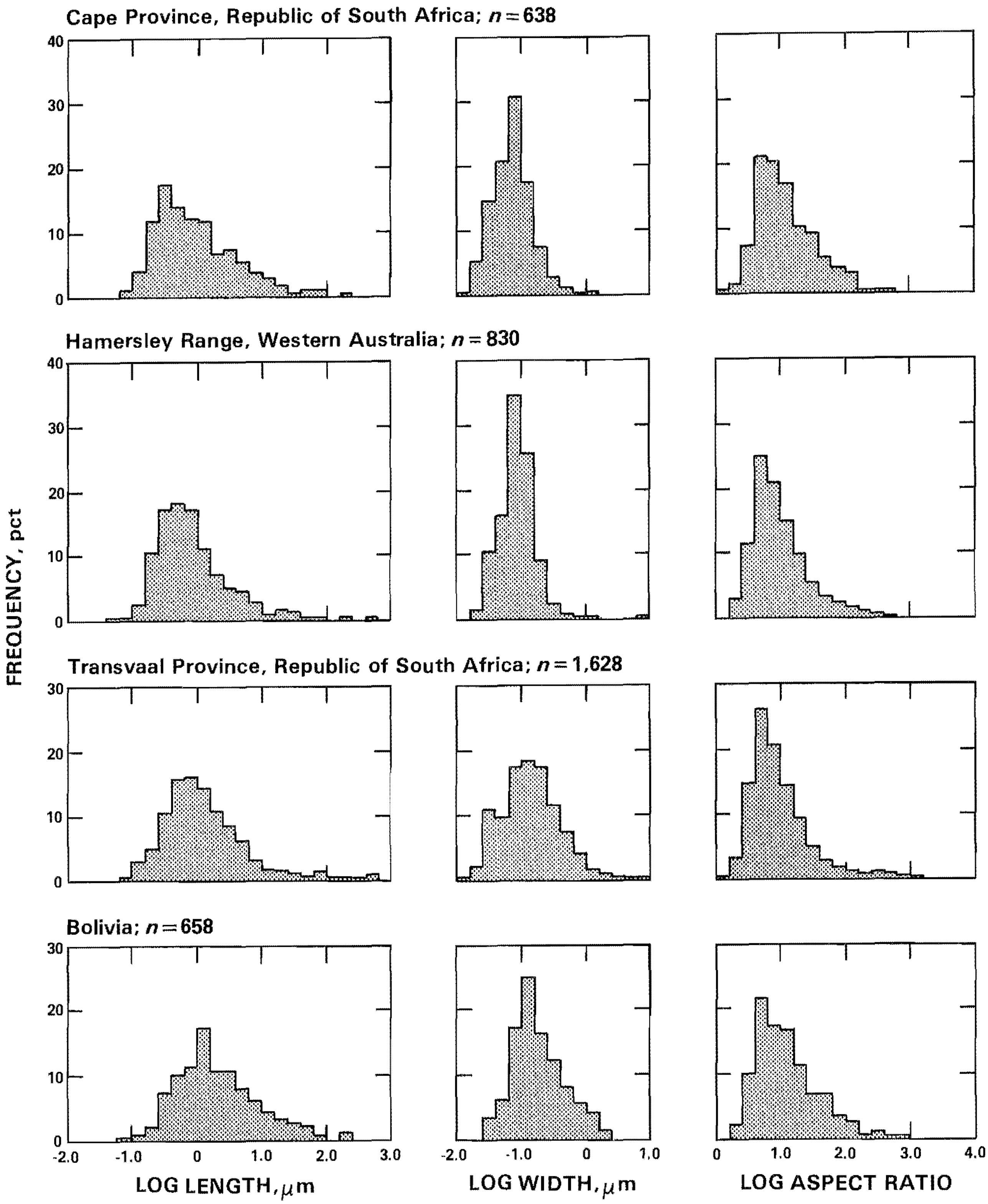

FIGURE 1. - Frequency distributions of log length, log width, and log aspect ratio (length/width), showing full range of dimensions measured, from measurement of fibers of all lengths. Results from individual samples were combined by geographic region. Cape Province = samples C1 and C2; Hamersley Range = samples A1 and A2; Transvaal Province = samples T1, T2, T3, T4, and T5; Bolivia = sample B (data B1 and B2). n = number of fibers.

An important difference in crocidolite fibers from the four regions is evident in portions of the length and width distributions presented in figures 2*A* and 2*B*. The fiber distributions are similar in terms of the positions of their modal lengths and widths. However, the percentage of fibers in the mode differs between regions for both length and width. In terms of length, the approximate percent of fibers in the mode for each sample is as follows: Cape Province 12 pct, Western Australia 11.5 pct, Transvaal Province 8.3 pct, and Bolivia 5.5 pct. The percent of fibers in the modal width for each sample is Western Australia 45 pct, Cape Province 41 pct, Transvaal Province 23 pct, and Bolivia 19 pct. Therefore, by particle number percent, the Bolivian and Transvaal Province samples have about half as many short or thin fibers in their modes as do samples from the Cape Province and Western Australia.

Fiber dimension data (mean, minimum, maximum, and standard deviations, where applicable, for fiber length, fiber width, log length, and log width) are presented for each sample in table 6. Because the length and width distributions approach normal distributions on a log scale (fig. 1), the geometric means (calculated as the antilog of the mean log length or mean log width) are presented along with the arithmetic means. Although there is some variation within regions, in general the regions can be ranked by particle size from largest to smallest mean length and mean width in the following order: Bolivia, Transvaal Province, Western Australia, and Cape Province (with the exception of sample C2). Therefore, based on the means, the Bolivian sample has the largest fibers (both the widest and longest), followed by the Transvaal Province samples, then the Western Australian samples, and the Cape Province samples with the shortest and narrowest fibers.

Minimum fiber lengths range from 0.05 to 0.14 µm, but minimum fiber widths are fairly constant at approximately 0.02 µm for all samples. The majority of fibers present in the samples are small, so large fibers are less likely to be encountered before the predesignated number of fibers is measured. Therefore, the maximum lengths and widths are not as well established as the minimum lengths and widths.

The results on fiber length and width can be compared with fiber dimensions reported in the literature. Hwang and Gibbs (10) studied airborne crocidolite from the Kuruman area of the Cape Province. Fiber dimensions of crocidolite on air filters are very similar to those on bulk Cape Province crocidolite samples in the present study. The airborne fibers are short (<1.6 pct longer than 10 µm) and narrow (<1.5 pct wider than 0.4 µm), and the widths are fairly constant with increasing fiber length. The width distributions of these fibers are characterized by minimum widths of 0.01 µm, geometric mean widths ranging from 0.08 to 0.10 µm, and modes at 0.1 to 0.2 µm.

In their study comparing fibers from the Cape and Transvaal Provinces, Timbrell, Griffiths, and Pooley (23) also note that Cape Province crocidolites have shorter fibers than crocidolite and amosite from the Transvaal Province. Timbrell, Pooley, and Wagner (24) report similar minimum widths to those reported here: approximately 0.04 µm for Cape Province crocidolite (Union International Contre le Cancer material) and 0.02 µm for Western Australian crocidolite. In the present study, the larger mean widths of fibers from the Transvaal Province as compared with those from the Cape Province follow the same trend reported by Timbrell, Griffiths, and Pooley (23). Their values of 0.073 µm mean width for Cape Province crocidolite and 0.212 µm for Transvaal Province crocidolite are very close to the mean widths reported here. The similarity between fiber dimensions reported previously (10, 23-24) and those in the present study is notable, considering that different samples were examined, perhaps from different mines within the regions, different sampling and sample preparation methods were used [samples in (10) were collected on air filters; samples in (23) were ground by mortar and pestle], and measurement techniques may also have differed.

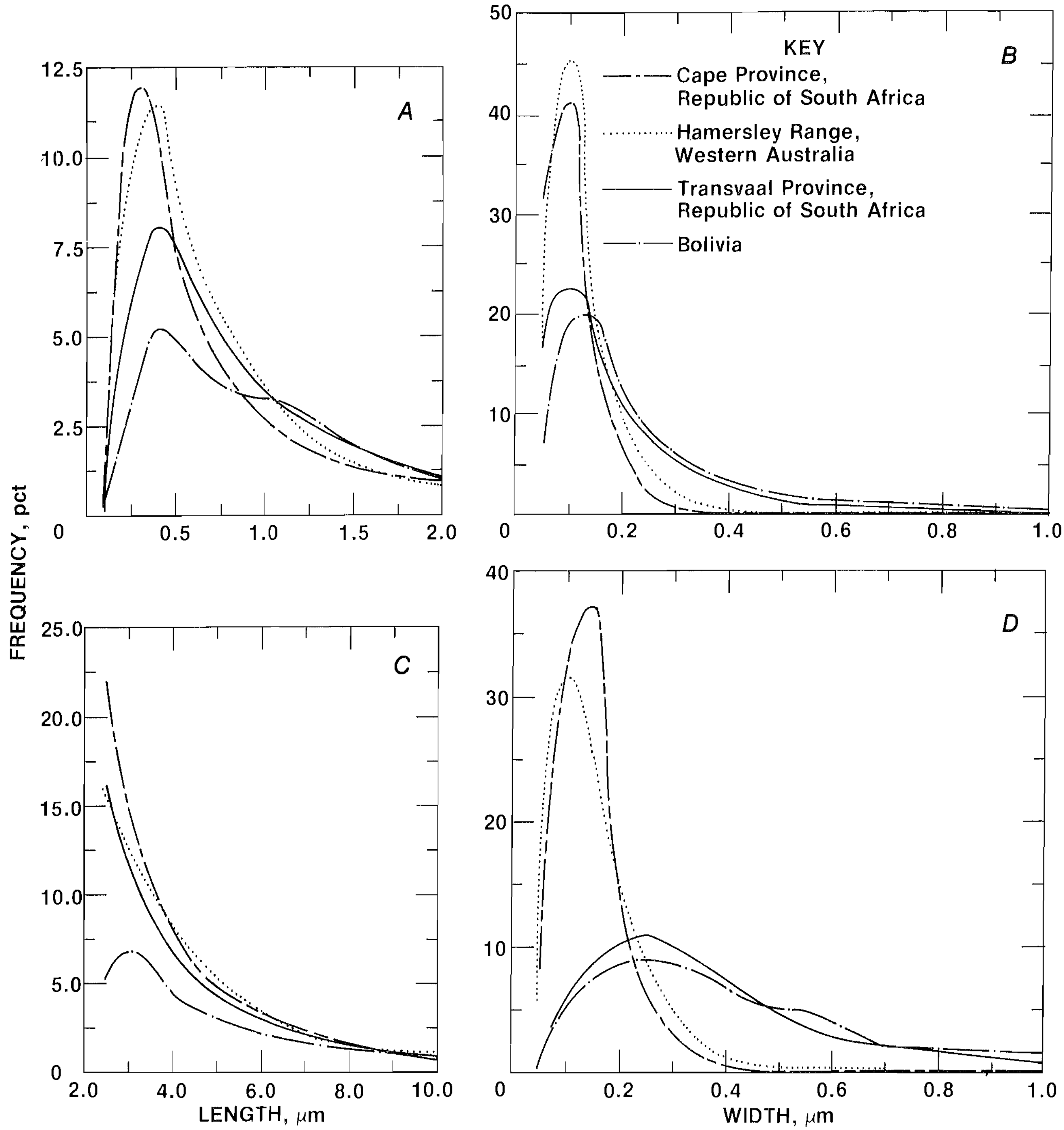

FIGURE 2. - Frequency distributions of length and width, combined samples from each of the four geographic regions. *A*, *B*, lengths and widths from the measurement of fibers of all lengths. *C*, *D*, lengths and widths from the measurement of fibers longer than 2 μm. Note that the full length and width ranges are not displayed in these figures.

TABLE 6. - Fiber dimension data for individual crocidolite samples, all lengths, micrometers

	Hamersley Range, Western Australia		Northern Cape Province, Republic of South Africa		Transvaal Province, Republic of South Africa					Bolivia
					Voorspoed Mine		T3--Milled fiber	Dublin, Pietersburg		B--Wormald Mine
	A1--Colonial Mine mill circuit	A2--Colonial Mine spoil heap	C1--Kuruman raw	C2--Kuruman Hills (NIEHS)	T1--Stanton	T2--raw		T4	T5	
Length:										
Mean (geometric)..	0.77	0.94	0.43	1.77	1.87	1.03	1.20	1.14	0.96	2.28
Mean (arithmetic).	2.53	3.83	.93	5.65	12.01	2.36	2.15	9.19	6.80	12.58
Minimum..........	.05	.08	.08	.14	.12	.10	.09	.10	.07	.09
Maximum..........	473.7	163.4	70.6	229.2	492.9	49.4	48.0	551.3	493.2	542.1
Width:										
Mean (geometric)..	.09	.08	.06	.09	.12	.13	.20	.12	.13	.18
Mean (arithmetic).	.12	.09	.07	.11	.19	.16	.29	.26	.28	.29
Minimum..........	.02	.02	.01	.02	.02	.02	.02	.02	.02	.02
Maximum..........	7.73	.51	.49	1.17	.98	.79	2.47	9.22	4.41	2.37
Log length:										
Mean.............	-.112	-.027	-.363	.247	.271	.011	.075	.058	-.019	.359
Standard deviation	.468	.617	.401	.596	.707	.482	.447	.639	.608	.675
Minimum..........	-1.316	-1.096	-1.118	-.856	-.925	-.999	-1.027	-1.017	-1.134	-1.023
Maximum..........	2.676	2.213	1.849	2.360	2.693	1.694	1.681	2.741	2.693	2.734
Log width:										
Mean.............	-1.041	-1.109	-1.234	-1.048	-.912	-.900	-.692	-.914	-.891	-.741
Standard deviation	.273	.242	.257	.285	.410	.304	.381	.448	.497	.402
Minimum..........	-1.793	-1.795	-1.852	-1.798	-1.808	-1.783	-1.805	-1.795	-1.833	-1.687
Maximum..........	.888	-.296	-.311	.069	-.010	-.105	.393	.965	.644	.375
Total particles counted...........	505	325	311	327	368	320	313	320	307	658

Results from selected samples in the present study can be used for an indication of the variations that can be expected from sampling a mine, sample preparation, and the measurement technique. A thorough study would be necessary to examine the effect that each of these sources of variation independently contributes to the final result. In the present study the combined effect of two or more of these sources of variation can be observed. The comparisons that follow are based on results from the first set of data, in which fibers of all lengths were measured. The measurement technique was the same for all samples; however, some of the variation in the results can probably be attributed to variations in the reproducibility of the measurement technique. Similarly while most of the samples underwent identical sample preparations, this may also be a source of variation.

Bolivian sample B was divided into subsamples B1 and B2. The subsamples were milled separately, then prepared and measured as independent samples. Results on subsamples B1 and B2 (table 7 and fig. 3) represent variations originating from milling, preparation of the suspension and specimen grids, and measurement technique.

Two sets of samples give an indication of the variation originating from sampling a mine, then preparing and analyzing samples using the same techniques. Samples A1 and A2 are both from the Colonial Mine in Western Australia, and samples T4 and T5 are from Dublin in the Transvaal Province. Results for these samples are presented in table 6 and figure 3. In contrast, samples T1 and T2 are both from the Voorspoed Mine, but were prepared differently for analysis. (Sample T1 was not milled.) The results for T1 and T2 (fig. 3 and the values in table 6) include variations from sampling, from different methods of sample preparation, and from the measurement technique.

TABLE 7. - Particle measurement data on two preparations of the Bolivian crocidolite sample, all lengths, micrometers

	B1	B2
Length:		
Mean (geometric).....	3.20	1.62
Mean (arithmetic)....	19.13	5.86
Minimum.............	.14	.09
Maximum.............	542.1	251.2
Width:		
Mean (geometric).....	.21	.16
Mean (arithmetic)....	.32	.26
Minimum.............	.03	.02
Maximum.............	2.37	2.19
Log length:		
Mean................	.505	.209
Standard deviation...	.724	.583
Minimum.............	-.856	-1.023
Maximum.............	2.734	2.400
Log width:		
Mean................	-.675	-.808
Standard deviation...	.378	.415
Minimum.............	-1.507	-1.687
Maximum.............	.375	.340
Total particles counted	333	325

The linear least squares regression of log width versus log length allows the relationship between fiber width and length to be examined. Previous studies have used the relationship

$$\text{log width} = F \text{ log length} + b,$$

where F is the slope of the regression line, termed the "fibrosity index," and b is the intercept on the log width axis, to compare asbestos fibers with amphibole cleavage fragments from bulk samples (16) and occupational air monitor filters (28), and to compare asbestos and nonasbestos fibers (15). The regression of log width versus log length has been shown to be independent of sample preparation for a bulk sample of wollastonite (33).

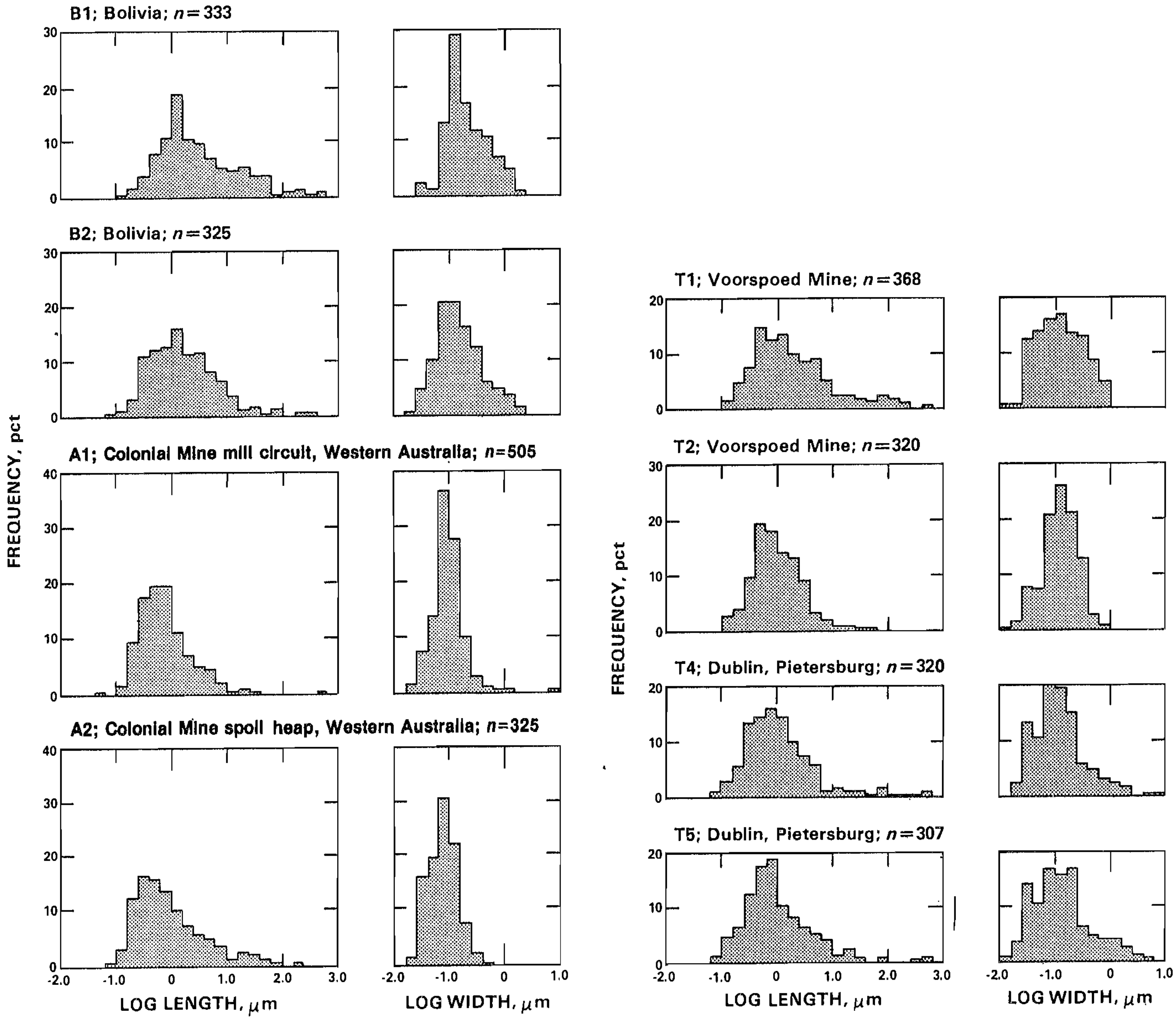

FIGURE 3. - Examples of variation with sampling and sample preparation. Frequency distributions of log length and log width for selected samples. These data are from the measurement of fibers of all lengths. B1 and B2 are results from two portions of the Bolivian sample milled and prepared separately. A1 and A2, samples from the Colonial Mine in Western Australia, were milled and prepared separately. T1 and T2 are samples from the Voorspoed Mine, Transvaal Province; T1 was not milled. T4 and T5, samples from Dublin, Transvaal Province, were milled and prepared separately. n = number of fibers.

Because all samples in the present study are crocidolite (riebeckite-asbestos, or magnesioriebeckite-asbestos in the case of the material from Bolivia), one would not expect large differences in the regression analyses. The regression of log width versus log length on the combined data for the four regions shows a slight division of the samples into two groups (fig. 4 and table 8). The Transvaal Province and Bolivian samples have larger "fibrosity indices" (steeper slopes) and higher intercepts than the Western Australian and Cape Province samples. Fibers in the former samples show a greater dependence of width on length; the longer fibers are generally wider than those of the same length from Western Australia or the Cape Province.

TABLE 8. - Linear least squares regression of the log width versus log length, combined samples, all lengths

Region[1]	F[2]	b[3]	Standard error[4]
Transvaal Province..........................	0.478	-0.905	0.309
Bolivia....................................	.406	-.886	.295
Western Australia..........................	.294	-1.045	.212
Cape Province..............................	.330	-1.122	.210

[1]Fiber dimension data from each region are combined to obtain these results. Transvaal Province = samples T1 + T2 + T3 + T4 + T5, Bolivia = subsamples B1 + B2, Western Australia = samples A1 + A2, Cape Province = samples C1 + C2.

[2]F is termed the "Fibrosity index" and represents the slope of the regression line.

[3]b is the intercept of the line on the log width axis.

[4]Standard error of estimate of width on length = square root of the variance.

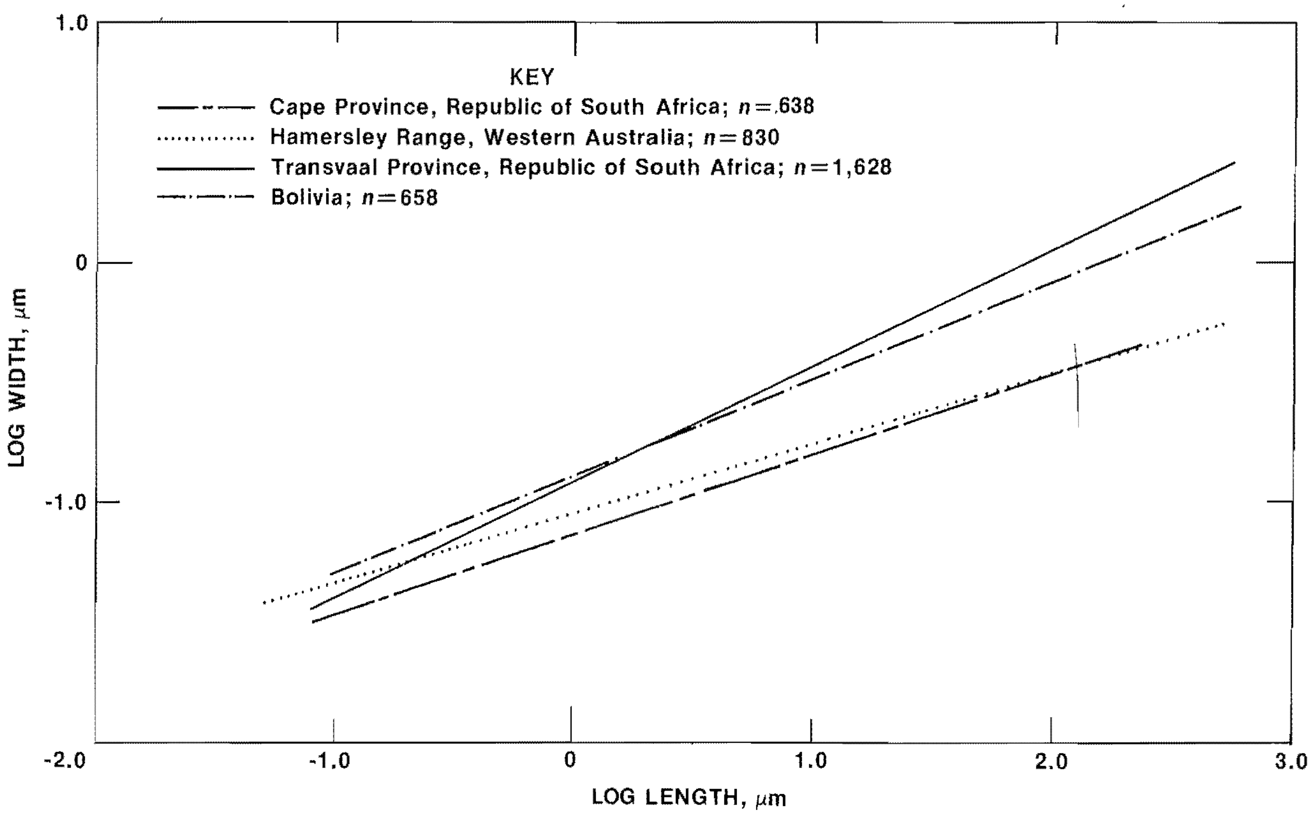

FIGURE 4. - Linear least squares regression of log width versus log length of the combined samples from the four geographic regions. These data are from the measurement of fibers of all lengths. Lines represent the full range of lengths measured. n = number of fibers.

The second set of data is the result of the measurement of 250 to 300 fibers with lengths greater than 2 µm. Frequency distributions showing the full ranges of length, width, and aspect ratio are presented on logarithmic scales for combined samples from each region in figure 5. The maximum lengths observed in this data set are about the same as those in the first data set (fig. 1). However, more fibers in the tails of the length distributions have been measured to provide better sampling of these long fibers. The log length distributions for fibers from the Cape Province, Western Australia, and Transvaal Province are similar, although the Transvaal Province has more fibers longer than 2.0 (100 µm). The Bolivian log length distribution is quite different from the other three, with a high proportion of fibers longer than 1.0 (10 µm). These similarities and differences are more evident in the 2.0- to 10.0-µm length ranges presented in figure 2*C*.

The general shapes and ranges of the log width distributions for fibers longer than 2 µm (fig. 5) and fibers of all lengths (fig. 1) are similar. The 0- to 1.0-µm portion of the width distributions of the longer fibers (fig. 2*D*) shows the same regional similarities as the widths of fibers of all lengths (fig. 2*B*). Cape Province and Western Australian crocidolites are similar with more narrow fibers; Transvaal Province and Bolivian crocidolites are similar with broader width distributions and more wide fibers. Differences between the width distributions for the fibers longer than 2 µm and fibers of all lengths reflect the dependence of width on length given in figure 4. The Cape Province and Western Australian fiber widths are not very dependent on fiber length. The shapes of the width distributions, positions of the modal widths, and mean widths are nearly the same for both fibers longer than 2 µm and fibers of all lengths (fig. 2, tables 6 and 9). In contrast, fiber widths from the Transvaal Province and Bolivia are more dependent on the fiber length. For these two regions the width distributions for fibers longer than 2 µm are quite different than those for fibers of all lengths. The fibers longer than 2 µm have much broader width distributions with modes shifted towards wider fibers. The difference in mean widths for the longer fibers as compared with fibers of all lengths are also greater for the Transvaal Province and Bolivian crocidolites than for crocidolites from the Cape Province or Western Australia.

The results from this second data set can also be viewed in terms of the dimensional categories cited by health scientists as having a high correlation with carcinogenicity (appendix A). In the present study, the Cape Province and Western Australian crocidolites are distinguished from the Transvaal Province and Bolivian crocidolites by a higher percent of thin fibers. Between 85 and 95 pct of the fibers longer than 2 µm from the Cape Province and Western Australia are ≤0.25 µm wide, as compared with only 21 to 57 pct from the Transvaal Province and Bolivia (table 10). Another difference between the regions is that the fibers from the Cape Province and Western Australia are thin regardless of their lengths. From 67 to 88 pct of the fibers longer than 8 µm from the Cape Province and Western Australia are <0.25 µm wide. Transvaal Province and Bolivian crocidolites have a greater dependence of width on length; long fibers tend to be wider. Because of this only 6 to 54 pct of the fibers longer than 8 µm from these locations are <0.25 µm wide. Therefore, Cape Province and Western Australian crocidolites have a higher percent of fibers that meet Stanton's length and width criteria (see appendix A and (20)) because the fibers are thin regardless of length, while the Transvaal Province and Bolivian crocidolites have fewer fibers that meet Stanton's criteria because their long fibers are wide.

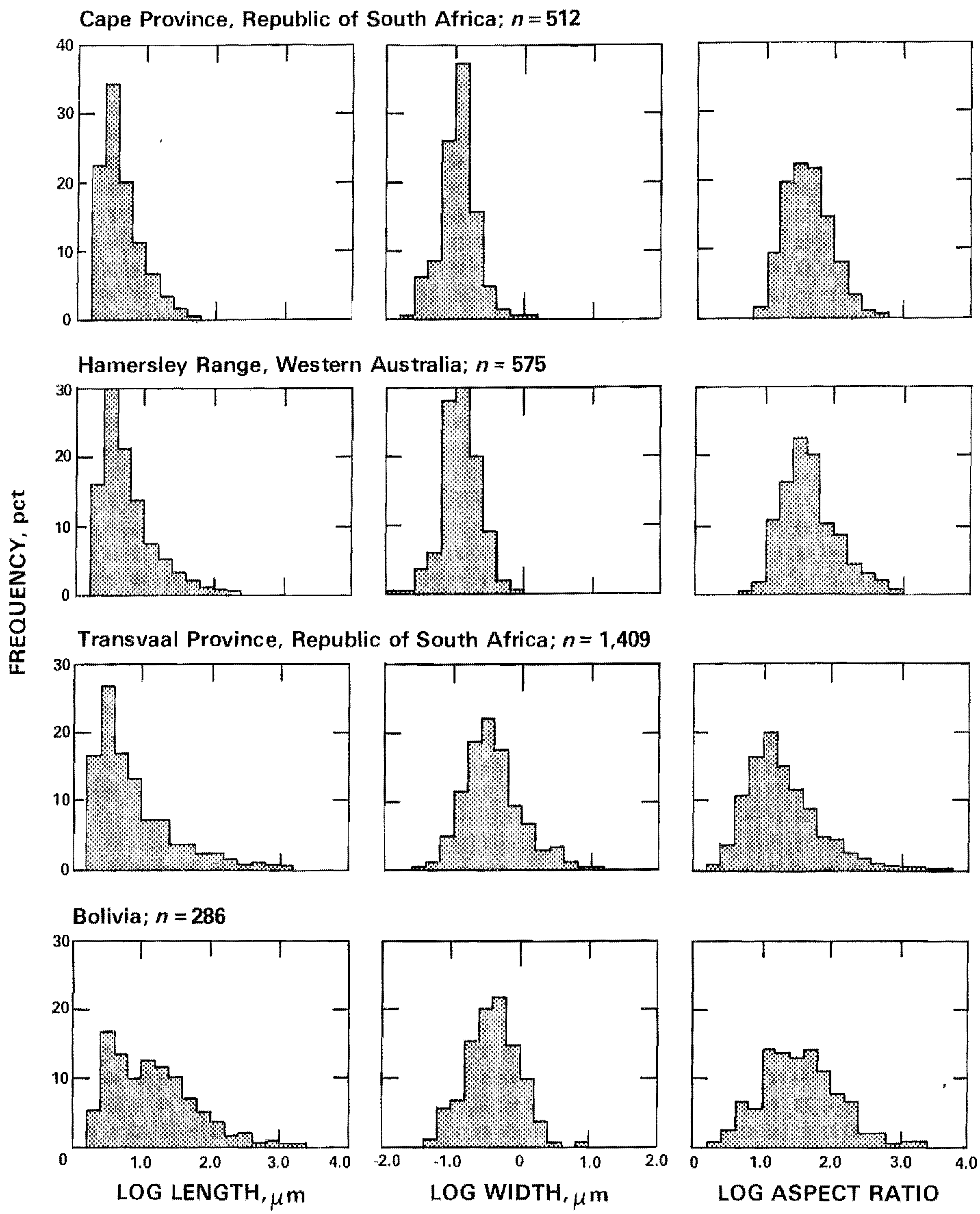

FIGURE 5. - Frequency distributions of log length, log width, and log aspect ratio (length/width), showing full range of dimensions measured, from measurement of fibers longer than 2 μm. Results from individual samples were combined by geographic region. Cape Province = samples C1 and C2; Hamersley Range = samples A1 and A2; Transvaal Province = samples T1, T2, T3, T4, and T5; Bolivia = sample B. n = number of fibers.

TABLE 9. - Fiber dimension data for individual samples, fibers longer than 2 μm, micrometers

	Hamersley Range, Western Australia		Northern Cape Province, Republic of South Africa		Transvaal Province, Republic of South Africa					Bolivia
					Voorspoed Mine		T3--Milled fiber	Dublin, Pietersburg		
	A1--Colonial Mine mill circuit	A2--Colonial Mine spoil heap	C1--Kuruman raw	C2--Kuruman Hills (NIEHS)	T1--Stanton	T2--raw		T4	T5	B--Wormald Mine
Length:										
Mean (geometric)..	4.38	6.73	3.54	5.07	10.10	5.70	4.32	9.63	7.26	13.58
Mean (arithmetic).	5.75	12.59	4.17	6.75	38.96	9.62	5.98	36.94	20.54	45.47
Minimum...........	2.00	2.04	2.03	2.06	2.05	2.01	2.05	2.03	2.02	2.04
Maximum...........	65.71	321.9	31.67	57.33	1,136	141.1	87.42	1,059	557	1,598
Width:										
Mean (geometric)..	.14	.11	.11	.10	.23	.25	.36	.47	.60	.40
Mean (arithmetic).	.16	.13	.13	.12	.29	.31	.44	.84	1.11	.58
Minimum...........	.03	.03	.02	.03	.03	.06	.06	.04	.04	.04
Maximum...........	.67	.50	.64	1.38	2.13	2.69	1.76	4.62	11.47	9.70
Log length:										
Mean..............	.642	.828	.549	.705	1.004	.756	.636	.984	.861	1.133
Standard deviation	.275	.420	.219	.301	.614	.381	.298	.595	.509	.581
Minimum...........	.302	.309	.307	.313	.312	.303	.311	.307	.306	.309
Maximum...........	1.818	2.508	1.501	1.758	3.055	2.149	1.942	3.025	2.746	3.204
Log width:										
Mean..............	-.867	-.962	-.956	-.986	-.644	-.610	-.439	-.326	-.220	-.403
Standard deviation	.249	.258	.257	.249	.314	.284	.268	.467	.481	.377
Minimum...........	-1.465	-1.479	-1.632	-1.470	-1.474	-1.234	-1.239	-1.405	-1.416	-1.399
Maximum...........	-.173	-.304	-.197	.139	.328	.429	.247	.665	1.059	.987
Total particles counted...........	298	277	239	273	274	285	285	280	285	286

TABLE 10. - Percent of fibers meeting Stanton's and Harington's length and width criteria, fibers longer than 2 μm

	Hamersley Range, Western Australia		Northern Cape Province, Republic of South Africa		Transvaal Province, Republic of South Africa					Bolivia
					Voorspoed Mine			Dublin, Pietersburg		
	A1--Colonial Mine mill circuit	A2--Colonial Mine spoil heap	C1--Kuruman raw	C2--Kuruman Hills (NIEHS)	T1--Stanton	T2--raw	T3--Milled fiber	T4	T5	B--Wormald Mine
FIBERS MEETING STANTON'S CRITERIA										
Total fibers ≥2 μm long..............	298	277	239	273	274	285	285	280	285	286
Pct of total ≥8 μm long..............	16.4	35.7	9.2	21.2	44.2	28.4	16.5	43.2	34.4	60.5
Pct of total ≤0.25 μm wide...........	85.2	92.8	93.3	94.9	56.6	48.4	31.6	27.1	21.1	28.7
Pct of total ≥8 μm long and ≤0.25 μm wide..............	11.1	31.4	7.9	17.2	23.7	13.0	1.4	5.0	2.1	11.2
Pct of fibers ≥8 μm long that are ≤0.25 μm wide...........	67.3	87.9	81.0	81.0	53.7	45.7	8.5	11.6	6.1	18.5
FIBERS MEETING HARINGTON'S CRITERIA										
Total fibers ≥2 μm long..............	298	277	239	273	274	285	285	280	285	286
Pct of total ≥3 μm long..............	68.1	79.1	53.1	72.5	78.1	71.9	61.4	81.8	74.0	87.8
Pct of total ≤0.05 μm wide...........	3.4	8.7	10.0	7.3	1.8	0	0	0.7	0.7	0.7
Pct of total ≥3 μm long and ≤0.05 μm wide..............	0.7	6.5	4.6	4.4	1.5	0	0	0.7	0.4	0.3
Pct of fibers ≥3 μm long that are ≤0.05 μm wide...........	1.0	8.2	8.7	6.1	1.9	0	0	0.9	0.5	0.4

The second data set was collected to contain a high percent of fibers longer than 3 µm in all samples. Based on data from these long fibers Harington's stringent width criterion of 0.05 µm (see appendix A and (6)) divides the regions into two groups: Cape Province and Western Australia with 3 to 10 pct fibers narrower than 0.05 µm, and Transvaal Province and Bolivia with only 0 to 2 pct (table 10). The percent of fibers in this data set that meet both Harington's >3-µm length and <0.05-µm width criteria is low for both groups: 4 to 6.5 pct for most Cape Province and Western Australian samples, and 0 to 1.5 pct for samples from the Transvaal Province and Bolivia. The second Western Australian sample had only 0.7 pct meeting both criteria, owing to fewer narrow fibers in the sample. With this exception, these data agree with Harington's threshold values for fiber dimensions present in areas of high mesothelioma incidence and virtually absent in areas lacking mesothelioma.

SUMMARY AND CONCLUSIONS

Physical and chemical properties of crocidolites from the four geographic regions discussed in this report can be divided into two groups: properties present in regions where the incidence of mesothelioma has been reported to be high (Cape Province and Western Australia); and properties present in regions with little or no reported incidence of mesothelioma (Transvaal Province and Bolivia).

Chemically, crocidolites from the four regions can be distinguished by their total iron, silica, K_2O, and Na_2O contents. Cape Province and Western Australian crocidolites have higher total iron, lower silica, and generally lower K_2O contents than crocidolites from the Transvaal Province and Bolivia. The Transvaal Province crocidolite has lower Na_2O than crocidolites from the other three regions. The Bolivian crocidolite is a magnesioriebeckite with high magnesium, lower ferrous iron than the other three crocidolites, and a silica content higher than that of crocidolites in the Cape Province and Western Australia but lower than that of crocidolites in the Transvaal Province.

Crocidolites from areas of high reported mesothelioma incidence are dimensionally different from crocidolites in areas with little or no reported mesothelioma. Cape Province and Western Australian crocidolites are characterized by thin fiber widths that are relatively independent of fiber length. Because of this a high percent of the long fibers in crocidolites from these regions meet the length and width dimensions proposed by health scientists as having a high correlation with carcinogenicity. In contrast, the crocidolites from the Transvaal Province and Bolivia have more long and wide fibers. The widths of these fibers have a greater dependence on their lengths. Longer fibers tend to be wider, so fewer long fibers meet the length and width categories proposed to have a high correlation with carcinogenicity.

While this study is limited by the small number of samples examined and the number of fibers measured for each sample, the general trends in fiber width are in agreement with those reported elsewhere.

SUGGESTIONS FOR FURTHER RESEARCH

Further research should include thorough chemical analysis to determine similarities and differences not only in major elements, but in trace elements as well, and the relationship, if any, between chemical composition and fiber dimensions, particularly width. Finally, additional studies by biomedical researchers are needed to determine if tumor production is indeed independent of properties other than fiber size and shape. Before this can be done, research on how to prepare size-segregated samples of fibrous materials is needed. Spurny, Stober, Opiela, and Weiss (18) have had some success in the preparation of sized fibers. With the ability to separate fibrous samples into well-defined size categories, the biological effects of fiber morphology and various physiochemical properties could be examined independently. Cooperative research between biomedical and minerals scientists would assist in solving some of the outstanding questions on which properties contribute to carcinogenesis. Once this is determined, it will be clearer which materials should be regulated to ensure occupational and environmental health.

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APPENDIX A.--BRIEF REVIEW OF PREVIOUS RESEARCH ON CROCIDOLITE AND MESOTHELIOMA

The first correlation between pleural mesothelioma and crocidolite exposure was made by Wagner, Sleggs, and Marchand in 1960 (30).[1] In almost all of the cases examined the individual had been exposed to crocidolite from the Cape Province of South Africa, either from an association with the asbestos fields or from exposure in industry.

The relationship between incidence of mesothelioma and crocidolite exposure has also been shown in epidemiologic studies of crocidolite miners and millers from Western Australia (8) and by studies of populations exposed to crocidolite during gas-mask manufacture during World War II (13). However, while the incidence of mesothelioma is reported to be significantly high in the crocidolite mining areas of Western Australia and the Cape Province (22), there are only a small number of cases of mesothelioma reported from the Transvaal Province of South Africa, where both crocidolite and amosite are mined (7, 14), and no reports have been found on mesothelioma associated with the crocidolite mining region of Bolivia (14).

Various possibilities for the apparent difference in mesothelioma incidence between the two Provinces in South Africa have been investigated. Sluis-Cremer (17) reports that medical facilities in the two areas are the same, and that while occupational dust levels from mines and mills in the Cape Province were higher than dust levels in the Transvaal Province, both areas had high incidence of asbestosis, indicating that "dust levels in the [Transvaal Province] were adequate to be potentially carcinogenic." He points out that the exposed population in the Cape Province is larger, but that the "areas surrounding the mines in the [Transvaal Province] are more densely populated than their equivalents in the [Cape Province]." Annual production of crocidolite in the Cape Province has been significantly higher than annual production of this mineral in the Transvaal Province (7, 17, 26). However, annual crocidolite production in the Transvaal Province was similar to that of Western Australia from the late 1950's to the late 1960's (25, 27), and prior to the late 1950's, annual crocidolite production in the Transvaal Province was actually greater than that in Western Australia (17, 25, 27). Therefore, annual production does not appear to correlate with mesothelioma incidence when Western Australian production is considered. Bolivian production has been significantly lower than production in either South Africa or Western Australia (26).

Finally, the fibers themselves were examined for differences in mineralogy, chemical composition, and fiber size and shape. Mineralogically the asbestos deposits in South Africa grade from pure crocidolite in the Cape Province, to crocidolite and amosite in the Pietersburg field of the Transvaal Province, to pure amosite east of Pietersburg (31). Chemical trends related to the changes in mineralogy are described as follows: "The manganese content increases from the south of the Cape crocidolite field to the north and through the Transvaal crocidolite field to the amosite area, where it is approximately 5%; the sodium content decreases in the same way (31)."

Wagner, Berry, and Timbrell (29) addressed the relationship between chemical composition and carcinogenicity in in vivo studies with various types of asbestos. They found that all types of asbestos could produce mesotheliomata in test animals. Results from the Union International Contre le Cancer (UICC) reference samples of asbestos showed crocidolite to be the most carcinogenic. However, a "superfine" Canadian chrysotile was found to be very carcinogenic in test animals. This is in contrast to epidemiological studies, which show crocidolite to be the asbestos type most commonly associated with mesothelioma in humans. From in vivo studies with Canadian chrysotile they concluded that "carcinogenicity was not related to the content

[1] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

of iron, chromium, cobalt, nickel, scandium or manganese" (29). They add, "the fact that all the types of asbestos, having very different chemical compositions, produce mesotheliomata makes it unlikely that the carcinogenicity of asbestos could be due to chemical properties."

The possibility that natural or contaminating oils might be a factor in the carcinogenicity of asbestos was also examined by Wagner, Berry, and Timbrell (29). Benzene-extracted samples of asbestos, including crocidolite, showed no detectable change in carcinogenicity. In their conclusions the authors stress the hypothesis that finer fibers appear to be more carcinogenic.

The relationship between fiber dimension and carcinogenicity was also studied by Stanton, Layard, Tegeris, Miller, May, Morgan, and Smith (20). Stanton and his coworkers studied pleural tumor production in rats by implanting various types of particles. From the results of their experiments, they conclude that "a wide variety of compounds that seem to have only dimension and durability in common are carcinogenic for the pleura of the rat," and that "probability of pleural sarcoma correlates best with fibers that measure ≤0.25 by >8 µm, but that relatively high correlations were also observed with fibers in other categories having a diameter up to 1.5 µm and a length greater than 4 µm (20)."

Timbrell, Griffiths, and Pooley (23) have attributed the difference in mesothelioma incidence in the two Provinces in South Africa to a difference in fiber size and shape. They report that the crocidolite fibers from the Cape Province have a lower mean width than the crocidolite and amosite fibers from the Transvaal Province. In another study Timbrell, Pooley, and Wagner (24) show that Western Australian crocidolite is morphologically similar to the crocidolite from the Cape Province, but has a higher proportion of narrow fibers.

In a review of literature on the subject of fiber carcinogenesis (6), Harington discusses some of the studies that support the hypothesis that fiber dimension is the major factor in the production of mesothelioma. He uses unpublished data from Timbrell on Cape Province crocidolite (significant mesothelioma) and Finnish anthophyllite from Paakkila (no reported mesothelioma in nearly 60 years of mining) to distinguish fiber dimensions present primarily in areas with significant mesothelioma incidence. From these data he suggests that the minimum fiber widths delineated from in vivo studies such as Stanton's are too wide to explain the differences in mesothelioma reported for human populations. He proposes that fiber dimensions present in regions of high reported mesothelioma incidence and absent in regions with no reported mesothelioma could be the dimensions necessary for mesothelioma to occur. From Timbrell's data, Harington proposes 0.05 µm as a minimum width threshold, because only 0.1 pct of the Paakkila fibers are less than 0.05 µm wide as compared with 17 pct of the Cape Province fibers. Similarly, he points out that "a length of 8 µm is too high a threshold for fiber carcinogenicity. In the northwestern Cape only about 1% of the fibers are longer than 8 µm. A much smaller percentage, approximately 0.1%, is both longer than 8 µm and narrower than 0.05 µm in diameter. These percentages are probably insufficient to explain the northwestern Cape mesotheliomas. If the threshold diameter is about 0.05 µm, then the threshold length must be reduced to 3 µm for inclusion of a few percent of the fibers in the carcinogenic range." While these values for threshold length and width are speculative, and not based on biological experimentation, they may be a useful way to compare samples in the present study.

In the present study particle dimensions of crocidolite from the four regions where it has been produced commercially (14) are compared with results from other characterization studies and evaluated in view of the differences in mesothelioma incidence as reported in the literature.

APPENDIX B.--PARTICLE SIZE DISTRIBUTION DATA FOR INDIVIDUAL SAMPLES

TABLE B-1. - Particle size distribution for sample A1, Hamersley Range, Western Australia, all lengths

Length interval..................µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-474
Number of particles per interval[1]...	424	38	21	7	4	11
Percent of all particles............	84.0	7.5	4.2	1.4	0.8	2.2
Cumulative percent, all particles...	84.0	91.5	95.6	97.0	97.8	100.0
Mean length.....................µm..	0.66	2.89	4.93	7.18	9.17	63.24
Mean width......................µm..	0.09	0.17	0.21	0.21	0.21	1.01
Particles per length by width, µm:						
0 to 0.025........................	9	0	0	0	0	0
>0.025 to 0.05....................	51	1	1	1	1	1
>0.05 to 0.075....................	113	4	2	0	0	0
>0.075 to 0.1.....................	103	6	1	0	0	0
>0.1 to 0.2.......................	139	19	8	2	0	4
>0.2 to 0.5.......................	9	7	8	4	3	4
>0.5 to 1.0.......................	0	1	1	0	0	0
>1.0 to 5.0.......................	0	0	0	0	0	1
>5.0..............................	0	0	0	0	0	1

[1]Total particles = 505.

TABLE B-2. - Particle size distribution for sample A1, Hamersley Range, Western Australia, fibers longer than 2 µm

Length interval..................µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1]...	199	65	20	5	3	2
Percent of all particles............	66.8	21.8	6.7	1.7	1.0	0.7
Cumulative percent, all particles...	66.8	88.6	95.3	97.0	98.0	98.7
Mean length.....................µm..	3.15	6.87	11.43	17.04	22.13	27.52
Mean width......................µm..	0.14	0.19	0.18	0.28	0.14	0.12
Particles per length by width, µm:						
0 to 0.025........................	0	0	0	0	0	0
>0.025 to 0.05....................	8	2	0	0	0	0
>0.05 to 0.075....................	33	6	5	0	2	0
>0.075 to 0.1.....................	17	4	1	0	0	1
>0.1 to 0.2.......................	99	27	8	1	0	1
>0.2 to 0.5.......................	42	24	5	4	1	0
>0.5 to 1.0.......................	0	2	1	0	0	0
>1.0 to 5.0.......................	0	0	0	0	0	0
>5.0..............................	0	0	0	0	0	0
Length interval..................µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-66	
Number of particles per interval[1]...	0	1	1	0	2	
Percent of all particles............	0	0.3	0.3	0	0.7	
Cumulative percent, all particles...	98.7	99.0	99.3	99.3	100.0	
Mean length.....................µm..	0	39.69	40.50	0	61.74	
Mean width......................µm..	0	0.67	0.38	0	0.23	
Particles per length by width, µm:						
0 to 0.025........................	0	0	0	0	0	
>0.025 to 0.05....................	0	0	0	0	0	
>0.05 to 0.075....................	0	0	0	0	0	
>0.075 to 0.1.....................	0	0	0	0	0	
>0.1 to 0.2.......................	0	0	0	0	1	
>0.2 to 0.5.......................	0	0	1	0	1	
>0.5 to 1.0.......................	0	1	0	0	0	
>1.0 to 5.0.......................	0	0	0	0	0	
>5.0..............................	0	0	0	0	0	

[1]Total particles = 298.

TABLE B-3. - Particle size distribution for sample A2, Hamersley Range, Western Australia, all lengths

Length interval..............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-164
Number of particles per interval[1].	248	25	15	6	7	24
Percent of all particles..........	76.3	7.7	4.6	1.8	2.2	7.4
Cumulative percent, all particles.	76.3	84.0	88.6	90.5	92.6	100.0
Mean length..................µm..	0.64	2.92	5.10	6.87	8.85	34.75
Mean width...................µm..	0.07	0.12	0.12	0.12	0.11	0.20
Particles per length by width, µm:						
0 to 0.025.....................	2	0	1	0	0	0
≥0.025 to 0.05.................	68	2	0	0	0	1
≥0.05 to 0.075.................	46	1	1	0	0	0
≥0.075 to 0.1..................	78	8	6	1	2	4
≥0.1 to 0.2....................	53	10	5	5	5	10
≥0.2 to 0.5....................	1	4	2	0	0	8
≥0.5 to 1.0....................	0	0	0	0	0	1
≥1.0 to 5.0....................	0	0	0	0	0	0
≥5.0...........................	0	0	0	0	0	0

[1]Total particles = 325.

TABLE B-4. - Particle size distribution for sample A2, Hamersley Range, Western Australia, fibers longer than 2 µm

Length interval..............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	133	67	23	13	8	7
Percent of all particles..........	48.0	24.2	8.3	4.7	2.9	2.5
Cumulative percent, all particles.	48.0	72.2	80.5	85.2	88.1	90.6
Mean length..................µm..	3.25	7.06	12.57	17.41	21.95	27.72
Mean width...................µm..	0.11	0.13	0.12	0.12	0.17	0.10
Particles per length by width, µm:						
0 to 0.025.....................	0	0	0	0	0	0
≥0.025 to 0.05.................	14	8	1	1	0	0
≥0.05 to 0.075.................	26	5	1	3	2	0
≥0.075 to 0.1..................	41	16	8	3	0	3
≥0.1 to 0.2....................	34	24	10	5	3	4
≥0.2 to 0.5....................	18	14	3	1	3	0
≥0.5 to 1.0....................	0	0	0	0	0	0
≥1.0 to 5.0....................	0	0	0	0	0	0
≥5.0...........................	0	0	0	0	0	0
Length interval..............µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-322	
Number of particles per interval[1].	6	3	4	1	12	
Percent of all particles..........	2.2	1.1	1.4	0.4	4.3	
Cumulative percent, all particles.	92.8	93.9	95.3	95.7	100.0	
Mean length..................µm..	32.61	38.37	42.23	49.83	97.24	
Mean width...................µm..	0.18	0.20	0.20	0.33	0.25	
Particles per length by width, µm:						
0 to 0.025.....................	0	0	0	0	0	
≥0.025 to 0.05.................	0	0	0	0	0	
≥0.05 to 0.075.................	1	0	1	0	0	
≥0.075 to 0.1..................	1	0	1	0	1	
≥0.1 to 0.2....................	3	1	1	0	6	
≥0.2 to 0.5....................	1	2	1	1	5	
≥0.5 to 1.0....................	0	0	0	0	0	
≥1.0 to 5.0....................	0	0	0	0	0	
≥5.0...........................	0	0	0	0	0	

[1]Total particles = 277.

TABLE B-5. - Particle size distribution for sample B, Bolivia, all lengths

Length interval...............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-544
Number of particles per interval[1].	355	107	43	26	19	108
Percent of all particles..........	54.0	16.3	6.5	4.0	2.9	16.4
Cumulative percent, all particles.	54.0	70.2	76.7	80.7	83.6	100.0
Mean length..................µm..	0.89	2.81	4.85	6.80	8.69	65.83
Mean width...................µm..	0.14	0.32	0.34	0.45	0.36	0.68
Particles per length by width, µm:						
0 to 0.025......................	1	1	0	0	0	0
≥0.025 to 0.05..................	43	0	2	0	0	0
≥0.05 to 0.075..................	51	6	0	0	0	1
≥0.075 to 0.1...................	54	7	2	1	1	4
≥0.1 to 0.2.....................	135	40	10	6	5	17
≥0.2 to 0.5.....................	65	31	20	13	10	29
≥0.5 to 1.0.....................	6	17	7	3	2	30
≥1.0 to 5.0.....................	0	5	2	3	1	27
≥5.0............................	0	0	0	0	0	0

[1]Total particles = 658.

TABLE B-6. - Particle size distribution for sample B, Bolivia, fibers longer than 2 µm

Length interval...............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	81	49	32	21	14	15
Percent of all particles..........	28.3	17.1	11.9	7.3	4.9	5.2
Cumulative percent, all particles.	28.3	45.5	57.3	64.7	69.6	74.8
Mean length..................µm..	3.26	7.10	12.47	17.55	21.93	27.10
Mean width...................µm..	0.38	0.36	0.64	0.54	0.61	0.62
Particles per length by width, µm:						
0 to 0.025......................	0	0	0	0	0	0
≥0.025 to 0.05..................	2	0	0	0	0	0
≥0.05 to 0.075..................	1	1	0	0	0	0
≥0.075 to 0.1...................	8	4	2	0	0	1
≥0.1 to 0.2.....................	17	12	3	4	1	3
≥0.2 to 0.5.....................	28	23	12	8	7	3
≥0.5 to 1.0.....................	20	5	10	7	4	5
≥1.0 to 5.0.....................	5	4	7	2	2	3
≥5.0............................	0	0	0	0	0	0

Length interval...............µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-1598
Number of particles per interval[1].	5	9	10	4	44
Percent of all particles..........	1.7	3.1	3.5	1.4	15.4
Cumulative percent, all particles.	76.6	79.7	83.2	84.6	100.0
Mean length..................µm..	33.70	37.80	43.09	46.64	221.8
Mean width...................µm..	0.97	0.43	0.76	0.92	1.07
Particles per length by width, µm:					
0 to 0.025......................	0	0	0	0	0
≥0.025 to 0.05..................	0	0	0	0	0
≥0.05 to 0.075..................	0	0	0	0	0
≥0.075 to 0.1...................	0	0	0	0	0
≥0.1 to 0.2.....................	0	1	0	1	3
≥0.2 to 0.5.....................	1	5	5	1	6
≥0.5 to 1.0.....................	1	3	2	1	22
≥1.0 to 5.0.....................	3	0	3	1	12
≥5.0............................	0	0	0	0	1

[1]Total particles = 286.

TABLE B-7. - Particle size distribution for sample C1, Cape Province, Republic of South Africa, all lengths

Length interval..............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-72
Number of particles per interval[1].	293	7	6	3	1	1
Percent of all particles..........	94.2	2.3	1.9	1.0	0.3	0.3
Cumulative percent, all particles.	94.2	96.5	98.4	99.4	99.7	100.0
Mean length..................µm..	0.47	2.78	5.01	6.87	8.23	70.56
Mean width...................µm..	0.06	0.15	0.15	0.16	0.10	0.49
Particles per length by width, µm:						
0 to 0.025.....................	27	0	0	0	0	0
≥0.025 to 0.05..................	115	0	1	0	0	0
≥0.05 to 0.075..................	40	1	0	0	0	0
≥0.075 to 0.1...................	72	3	1	1	1	0
≥0.1 to 0.2.....................	37	1	3	2	0	0
≥0.2 to 0.5.....................	2	2	1	0	0	1
≥0.5 to 1.0.....................	0	0	0	0	0	0
≥1.0 to 5.0.....................	0	0	0	0	0	0
≥5.0............................	0	0	0	0	0	0

[1]Total particles = 311.

TABLE B-8. - Particle size distribution for sample C1, Cape Province, Republic of South Africa, fibers longer than 2 µm

Length interval..............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9	30-32
Number of particles per interval[1].	190	34	13	0	0	1	1
Percent of all particles..........	79.5	14.2	5.4	0	0	0.4	0.4
Cumulative percent, all particles.	79.5	93.7	99.2	99.2	99.2	99.6	100.0
Mean length..................µm..	2.95	6.55	12.11	0	0	25.75	31.67
Mean width...................µm..	0.12	0.17	0.16	0	0	0.09	0.14
Particles per length by width, µm:							
0 to 0.025.....................	1	0	0	0	0	0	0
≥0.025 to 0.05..................	20	3	0	0	0	0	0
≥0.05 to 0.075..................	38	7	3	0	0	0	0
≥0.075 to 0.1...................	19	4	1	0	0	1	0
≥0.1 to 0.2.....................	86	10	6	0	0	0	1
≥0.2 to 0.5.....................	26	8	2	0	0	0	0
≥0.5 to 1.0.....................	0	2	1	0	0	0	0
≥1.0 to 5.0.....................	0	0	0	0	0	0	0
≥5.0............................	0	0	0	0	0	0	0

[1]Total particles = 239.

TABLE B-9. - Particle size distribution for sample C2, Cape Province, Republic of South Africa, all lengths

Length interval...............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-230
Number of particles per interval[1].	192	50	20	19	8	38
Percent of all particles..........	58.7	15.3	6.1	5.8	2.4	11.6
Cumulative percent, all particles.	58.7	74.0	80.1	85.9	88.4	100.0
Mean length...................µm..	0.88	2.97	4.79	7.06	9.01	32.29
Mean width....................µm..	0.08	0.11	0.14	0.17	0.14	0.25
Particles per length by width, µm:						
0 to 0.025.....................	7	0	0	0	0	0
≥0.025 to 0.05..................	45	5	3	1	0	0
≥0.05 to 0.075..................	58	12	2	1	2	1
≥0.075 to 0.1...................	36	10	2	5	1	3
≥0.1 to 0.2.....................	43	19	9	7	5	20
≥0.2 to 0.5.....................	3	4	4	5	0	11
≥0.5 to 1.0.....................	0	0	0	0	0	2
≥1.0 to 5.0.....................	0	0	0	0	0	1
≥5.0............................	0	0	0	0	0	0

[1]Total particles = 327.

TABLE B-10. - Particle size distribution for sample C2, Cape Province, Republic of South Africa, fibers longer than 2 µm

Length interval...............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	152	77	20	10	7	3
Percent of all particles..........	55.7	28.2	7.3	3.7	2.6	1.1
Cumulative percent, all particles.	55.7	83.9	91.2	94.9	97.4	98.5
Mean length...................µm..	3.17	6.84	12.89	18.17	22.33	27.16
Mean width....................µm..	0.10	0.13	0.14	0.30	0.14	0.29
Particles per length by width, µm:						
0 to 0.025.....................	0	0	0	0	0	0
≥0.025 to 0.05..................	14	4	1	0	1	0
≥0.05 to 0.075..................	54	22	2	1	1	0
≥0.075 to 0.1...................	7	2	2	0	0	0
≥0.1 to 0.2.....................	70	36	11	5	2	1
≥0.2 to 0.5.....................	7	13	4	3	3	1
≥0.5 to 1.0.....................	0	0	0	0	0	1
≥1.0 to 5.0.....................	0	0	0	1	0	0
≥5.0............................	0	0	0	0	0	0

Length interval...............µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-58
Number of particles per interval[1].	3	0	0	0	1
Percent of all particles..........	1.1	0	0	0	0.4
Cumulative percent, all particles.	99.6	99.6	99.6	99.6	100.0
Mean length...................µm..	33.15	0	0	0	57.33
Mean width....................µm..	0.33	0	0	0	0.26
Particles per length by width, µm:					
0 to 0.025.....................	0	0	0	0	0
≥0.025 to 0.05..................	0	0	0	0	0
≥0.05 to 0.075..................	0	0	0	0	0
≥0.075 to 0.1...................	0	0	0	0	0
≥0.1 to 0.2.....................	1	0	0	0	0
≥0.2 to 0.5.....................	1	0	0	0	1
≥0.5 to 1.0.....................	1	0	0	0	0
≥1.0 to 5.0.....................	0	0	0	0	0
≥5.0............................	0	0	0	0	0

[1]Total particles = 273.

TABLE B-11. - Particle size distribution for sample T1, Transvaal Province, Republic of South Africa, all lengths

Length interval..............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-494
Number of particles per interval[1].	222	46	32	12	7	49
Percent of all particles..........	60.3	12.5	8.7	3.3	1.9	13.3
Cumulative percent, all particles.	60.3	72.8	81.5	84.8	86.7	100.0
Mean length..................µm..	0.80	2.82	5.05	7.13	9.14	77.59
Mean width...................µm..	0.11	0.27	0.33	0.24	0.20	0.39
Particles per length by width, µm:						
0 to 0.025.....................	4	0	0	0	0	0
>0.025 to 0.05.................	62	1	4	2	0	2
>0.05 to 0.075.................	44	2	4	1	0	0
>0.075 to 0.1..................	25	5	0	1	1	3
>0.1 to 0.2....................	61	14	3	3	4	8
>0.2 to 0.5....................	26	14	12	3	2	21
>0.5 to 1.0....................	0	10	9	2	0	15
>1.0 to 5.0....................	0	0	0	0	0	0
>5.0...........................	0	0	0	0	0	0

[1]Total particles = 368.

TABLE B-12. - Particle size distribution for sample T1, Transvaal Province, Republic of South Africa, fibers longer than 2 µm

Length interval..............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	112	56	13	20	9	4
Percent of all particles..........	40.9	20.4	4.7	7.3	3.3	1.5
Cumulative percent, all particles.	40.9	61.3	66.1	73.4	76.6	78.1
Mean length..................µm..	3.04	7.15	12.43	17.15	22.41	27.07
Mean width...................µm..	0.25	0.28	0.45	0.24	0.32	0.15
Particles per length by width, µm:						
0 to 0.025.....................	0	0	0	0	0	0
>0.025 to 0.05.................	5	0	0	0	0	0
>0.05 to 0.075.................	13	1	0	1	0	1
>0.075 to 0.1..................	4	5	2	0	0	0
>0.1 to 0.2....................	26	16	2	9	1	1
>0.2 to 0.5....................	59	31	4	10	7	2
>0.5 to 1.0....................	4	3	3	0	1	0
>1.0 to 5.0....................	1	0	2	0	0	0
>5.0...........................	0	0	0	0	0	0

Length interval..............µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-1136
Number of particles per interval[1].	6	5	4	4	41
Percent of all particles..........	2.2	1.8	1.5	1.5	15.0
Cumulative percent, all particles.	80.3	82.1	83.6	85.0	100.0
Mean length..................µm..	31.87	36.43	43.13	47.38	204.5
Mean width...................µm..	0.19	0.26	0.56	0.30	0.40
Particles per length by width, µm:					
0 to 0.025.....................	0	0	0	0	0
>0.025 to 0.05.................	0	0	0	0	0
>0.05 to 0.075.................	0	1	0	0	1
>0.075 to 0.1..................	0	0	0	0	1
>0.1 to 0.2....................	4	1	0	1	6
>0.2 to 0.5....................	2	3	2	3	25
>0.5 to 1.0....................	0	0	2	0	6
>1.0 to 5.0....................	0	0	0	0	2
>5.0...........................	0	0	0	0	0

[1]Total particles = 274.

TABLE B-13. - Particle size distribution for sample T2, Transvaal Province, Republic of South Africa, all lengths

Length interval...............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-50
Number of particles per interval[1].	242	47	10	5	3	13
Percent of all particles..........	75.6	14.7	3.1	1.6	0.9	4.1
Cumulative percent, all particles.	75.6	90.3	93.4	95.0	95.9	100.0
Mean length..................µm..	0.78	2.72	4.59	7.05	8.97	25.39
Mean width...................µm..	0.13	0.22	0.22	0.28	0.29	0.33
Particles per length by width, µm:						
0 to 0.025.....................	4	0	0	0	0	0
>0.025 to 0.05.................	31	1	0	0	0	0
>0.05 to 0.075.................	17	2	0	0	0	0
>0.075 to 0.1..................	53	7	2	1	0	0
>0.1 to 0.2....................	95	14	5	0	0	4
>0.2 to 0.5....................	42	22	2	4	3	7
>0.5 to 1.0....................	0	1	1	0	0	2
>1.0 to 5.0....................	0	0	0	0	0	0
>5.0...........................	0	0	0	0	0	0

[1]Total particles = 320.

TABLE B-14. - Particle size distribution for sample T2, Transvaal Province, Republic of South Africa, fibers longer than 2 µm

Length interval...............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	152	69	23	14	8	3
Percent of all particles..........	53.3	24.2	8.1	4.9	2.8	1.1
Cumulative percent, all particles.	53.3	77.5	85.6	90.5	93.3	94.4
Mean length..................µm..	3.10	6.87	12.36	18.03	22.30	27.05
Mean width...................µm..	0.26	0.34	0.49	0.35	0.24	0.34
Particles per length by width, µm:						
0 to 0.025.....................	0	0	0	0	0	0
>0.025 to 0.05.................	0	0	0	0	0	0
>0.05 to 0.075.................	4	1	0	1	2	0
>0.075 to 0.1..................	9	0	1	0	0	0
>0.1 to 0.2....................	51	21	3	1	1	2
>0.2 to 0.5....................	73	38	11	11	4	0
>0.5 to 1.0....................	14	7	6	1	1	1
>1.0 to 5.0....................	1	2	2	0	0	0
>5.0...........................	0	0	0	0	0	0

Length interval...............µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-142
Number of particles per interval[1].	0	3	3	1	9
Percent of all particles..........	0	1.1	1.1	0.4	3.2
Cumulative percent, all particles.	94.4	95.4	96.5	96.8	100.0
Mean length..................µm..	0	38.26	41.37	48.51	79.16
Mean width...................µm..	0	0.56	0.34	0.25	0.27
Particles per length by width, µm:					
0 to 0.025.....................	0	0	0	0	0
>0.025 to 0.05.................	0	0	0	0	0
>0.05 to 0.075.................	0	1	0	0	1
>0.075 to 0.1..................	0	0	0	0	1
>0.1 to 0.2....................	0	0	1	0	3
>0.2 to 0.5....................	0	1	1	1	3
>0.5 to 1.0....................	0	0	1	0	1
>1.0 to 5.0....................	0	1	0	0	0
>5.0...........................	0	0	0	0	0

[1]Total particles = 285.

TABLE B-15. - Particle size distribution for sample T3, Transvaal Province, Republic of South Africa, all lengths

Length interval...............μm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-48
Number of particles per interval[1].	220	52	22	7	5	7
Percent of all particles..........	70.3	16.6	7.0	2.2	1.6	2.2
Cumulative percent, all particles.	70.3	86.9	93.9	96.2	97.8	100.0
Mean length..................μm..	0.86	2.76	4.82	6.76	8.92	19.38
Mean width...................μm..	0.21	0.43	0.49	0.70	0.42	0.48
Particles per length by width, μm:						
0 to 0.025.....................	4	0	0	0	0	0
≥0.025 to 0.05.................	18	0	0	0	0	0
≥0.05 to 0.075.................	20	0	0	0	0	0
≥0.075 to 0.1..................	26	1	0	0	0	0
≥0.1 to 0.2....................	56	9	0	0	1	0
≥0.2 to 0.5....................	83	26	15	5	2	6
≥0.5 to 1.0....................	12	15	6	1	2	0
≥1.0 to 5.0....................	1	1	1	1	0	1
≥5.0...........................	0	0	0	0	0	0

[1]Total particles = 313.

TABLE B-16. - Particle size distribution for sample T3, Transvaal Province, Republic of South Africa, fibers longer than 2 μm

Length interval...............μm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	190	61	16	8	4	2
Percent of all particles..........	66.7	21.4	5.6	2.8	1.4	0.7
Cumulative percent, all particles.	66.7	88.1	93.7	96.5	97.9	98.6
Mean length..................μm..	2.99	6.86	12.90	18.07	22.86	27.32
Mean width...................μm..	0.35	0.59	0.61	0.76	0.39	0.32
Particles per length by width, μm:						
0 to 0.025.....................	0	0	0	0	0	0
≥0.025 to 0.05.................	0	0	0	0	0	0
≥0.05 to 0.075.................	2	0	0	0	0	0
≥0.075 to 0.1..................	4	0	0	0	0	0
≥0.1 to 0.2....................	38	2	0	0	1	0
≥0.2 to 0.5....................	115	28	6	2	2	2
≥0.5 to 1.0....................	28	22	9	5	1	0
≥1.0 to 5.0....................	3	9	1	1	0	0
≥5.0...........................	0	0	0	0	0	0

Length interval...............μm..	30-34.9	35-39.9	40-44.9	45-49.9	50-88
Number of particles per interval[1].	1	1	0	0	2
Percent of all particles..........	0.4	0.4	0	0	0.7
Cumulative percent, all particles.	98.9	99.3	99.3	99.3	100.0
Mean length..................μm..	30.87	37.49	0	0	76.12
Mean width...................μm..	1.76	1.52	0	0	0.69
Particles per length by width, μm:					
0 to 0.025.....................	0	0	0	0	0
≥0.025 to 0.05.................	0	0	0	0	0
≥0.05 to 0.075.................	0	0	0	0	0
≥0.075 to 0.1..................	0	0	0	0	0
≥0.1 to 0.2....................	0	0	0	0	0
≥0.2 to 0.5....................	0	0	0	0	0
≥0.5 to 1.0....................	0	0	0	0	1
≥1.0 to 5.0....................	1	1	0	0	0
≥5.0...........................	0	0	0	0	0

[1]Total particles = 285.

TABLE B-17. - Particle size distribution for sample T4, Transvaal Province, Republic of South Africa, all lengths

Length interval...............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-552
Number of particles per interval[1].	235	39	17	1	4	24
Percent of all particles..........	73.4	12.2	5.3	0.3	1.3	7.5
Cumulative percent, all particles.	73.4	85.6	90.9	91.3	92.5	100.0
Mean length..................µm..	0.74	2.75	4.90	6.07	8.57	105.6
Mean width...................µm..	0.11	0.27	0.47	0.11	0.17	1.52
Particles per length by width, µm:						
0 to 0.025.....................	8	0	0	0	0	0
≥0.025 to 0.05.................	54	1	1	0	0	0
≥0.05 to 0.075.................	25	1	0	0	0	1
≥0.075 to 0.1..................	49	7	1	0	1	0
≥0.1 to 0.2....................	76	8	5	1	2	1
≥0.2 to 0.5....................	21	18	4	0	1	5
≥0.5 to 1.0....................	2	4	4	0	0	4
≥1.0 to 5.0....................	0	0	2	0	0	12
≥5.0...........................	0	0	0	0	0	1

[1]Total particles = 320.

TABLE B-18. - Particle size distribution for sample T4, Transvaal Province, Republic of South Africa, fibers longer than 2 µm

Length interval...............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	120	54	21	16	8	11
Percent of all particles..........	42.9	19.3	7.5	5.7	2.9	3.9
Cumulative percent, all particles.	42.9	62.1	69.6	75.4	78.2	82.1
Mean length..................µm..	3.25	7.04	12.20	17.16	21.88	26.62
Mean width...................µm..	0.35	0.65	1.06	1.00	1.31	1.80
Particles per length by width, µm:						
0 to 0.025.....................	0	0	0	0	0	0
≥0.025 to 0.05.................	0	2	0	0	0	0
≥0.05 to 0.075.................	10	2	2	0	0	0
≥0.075 to 0.1..................	4	1	0	0	1	0
≥0.1 to 0.2....................	22	13	1	2	0	0
≥0.2 to 0.5....................	60	17	7	4	0	1
≥0.5 to 1.0....................	18	5	2	1	4	3
≥1.0 to 5.0....................	6	14	9	9	3	7
≥5.0...........................	0	0	0	0	0	0

Length interval...............µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-1060
Number of particles per interval[1].	2	3	3	5	37
Percent of all particles..........	0.7	1.1	1.1	1.8	13.2
Cumulative percent, all particles.	82.9	83.9	85.0	86.8	100.0
Mean length..................µm..	32.64	37.26	43.82	47.10	217.0
Mean width...................µm..	2.01	1.91	0.88	1.93	1.82
Particles per length by width, µm:					
0 to 0.025.....................	0	0	0	0	0
≥0.025 to 0.05.................	0	0	0	0	0
≥0.05 to 0.075.................	0	0	0	0	0
≥0.075 to 0.1..................	0	0	0	0	0
≥0.1 to 0.2....................	0	0	0	0	0
≥0.2 to 0.5....................	1	1	1	1	0
≥0.5 to 1.0....................	0	0	1	0	13
≥1.0 to 5.0....................	1	2	1	4	24
≥5.0...........................	0	0	0	0	0

[1]Total particles = 280.

TABLE B-19. - Particle size distribution for sample T5, Transvaal Province, Republic of South Africa, all lengths

Length interval..............µm..	0-1.9	2-3.9	4-5.9	6-7.9	8-9.9	10-494
Number of particles per interval[1].	230	35	13	8	5	16
Percent of all particles..........	74.9	11.4	4.2	2.6	1.6	5.2
Cumulative percent, all particles.	74.9	86.3	90.6	93.2	94.8	100.0
Mean length..................µm..	0.65	2.72	4.98	7.25	8.48	104.9
Mean width...................µm..	0.12	0.41	0.59	0.81	0.97	1.61
Particles per length by width, µm:						
0 to 0.025.....................	14	0	0	0	0	0
≥0.025 to 0.05.................	51	3	0	0	0	0
≥0.05 to 0.075.................	30	2	0	1	0	0
≥0.075 to 0.1..................	36	2	0	0	0	0
≥0.1 to 0.2....................	61	6	2	0	1	1
≥0.2 to 0.5....................	34	12	5	3	2	2
≥0.5 to 1.0....................	4	7	4	1	0	1
≥1.0 to 5.0....................	0	3	2	3	2	12
≥5.0...........................	0	0	0	0	0	0

[1]Total particles = 307.

TABLE B-20. - Particle size distribution for sample T5, Transvaal Province, Republic of South Africa, fibers longer than 2 µm

Length interval..............µm..	2-4.9	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9
Number of particles per interval[1].	142	59	20	11	12	4
Percent of all particles..........	49.8	20.7	7.0	3.9	4.2	1.4
Cumulative percent, all particles.	49.8	70.5	77.5	81.4	85.6	87.0
Mean length..................µm..	3.13	7.08	12.28	17.84	22.87	27.34
Mean width...................µm..	0.44	0.85	1.83	1.23	1.59	1.81
Particles per length by width, µm:						
0 to 0.025.....................	0	0	0	0	0	0
≥0.025 to 0.05.................	2	0	0	0	0	0
≥0.05 to 0.075.................	1	1	0	0	0	0
≥0.075 to 0.1..................	9	1	0	0	0	0
≥0.1 to 0.2....................	22	7	1	1	1	0
≥0.2 to 0.5....................	63	14	1	1	2	0
≥0.5 to 1.0....................	33	17	7	2	2	1
≥1.0 to 5.0....................	12	19	11	7	6	3
≥5.0...........................	0	0	0	0	1	0

Length interval..............µm..	30-34.9	35-39.9	40-44.9	45-49.9	50-557
Number of particles per interval[1].	3	3	6	1	24
Percent of all particles..........	1.1	1.1	2.1	0.4	8.4
Cumulative percent, all particles.	88.1	89.1	91.2	91.6	100.0
Mean length..................µm..	33.22	36.82	41.86	48.95	152.3
Mean width...................µm..	1.41	3.37	2.79	3.09	3.89
Particles per length by width, µm:					
0 to 0.025.....................	0	0	0	0	0
≥0.025 to 0.05.................	0	0	0	0	0
≥0.05 to 0.075.................	0	0	0	0	0
≥0.075 to 0.1..................	0	0	0	0	0
≥0.1 to 0.2....................	0	0	0	0	0
≥0.2 to 0.5....................	0	0	0	0	1
≥0.5 to 1.0....................	1	1	1	0	1
≥1.0 to 5.0....................	2	1	5	1	15
≥5.0...........................	0	1	0	0	7

[1]Total particles = 285.

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