Characterizing and Discriminating the Shape of Asbestos Particles

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The lengths and widths of approximately 1000 particles from each of four asbestos samples, two nonfibrous amphiboles, and one talc–serpentine sample were measured utilizing the SEM. The asbestos samples are commercially available and include chrysotile from Quebec, chrysotile from California, amosite from South Africa, and crocidolite from South Africa. The tremolite and talc–serpentine are from New York, and the riebeckite is from California. Beneficiation, including milling of amosite, crocidolite, and tremolite and air classifications of the two chrysotile samples, was done under commercial conditions; the riebeckite was milled in the laboratory. For comparison, the same measurements were made on the California chrysotile using TEM. Shape characterizations of the samples are compared using regression techniques. The usefulness of the various shape definitions including length, width, and aspect ratio (length/width) in characterizing and discriminating between samples is explored and evaluated. Significant results include: (i) Frequency distribution of log length, log width, and log aspect ratio show very apparent differences between asbestos and nonasbestos populations. (ii) Dimensional differences and accurate classification according to dimensions are enhanced by regressing log width and/or log aspect ratio against log length. (iii) Discriminant function analysis is able to quantify the distinction between asbestos and nonasbestos particle dimensions such that over 95% of the population assignments are correct. (iv) Log width is a more efficient classifier than log aspect ratio using either linear regression of discriminant function analysis for these particular samples. (v) The choice of instrumentation, i.e., TEM vs SEM, may affect the sample characterization. (vi) Quantitative descriptions of the dimensions of small particles may be related to the habit of the mineral and the structure of the mineral groups to which the particles belong. However, such mineralogical distinctions are probably not valid for particles whose longest dimension is less than about 1 μm.

INTRODUCTION

Morphology has often been used to characterize, define, and differentiate asbestos minerals. For example, the Occupational Safety and Health Administration defines an asbestos fiber as any particle of anthophyllite, tremolite, actinolite, chrysotile, amosite, or crocidolite longer than 5 μm with an aspect ratio (length/width) of 3 or greater (NIOSH, 1972). This morphological standard originated in England as the result of an air-monitoring program in an asbestos textile factory. The 5-μm length was chosen as a lower limit because the optical microscope was the instrument being used for monitoring. This choice can be justified based on reproducibility studies by Addingley (1966) and Lynch *et al.* (1970) which show that the counting of less than 5-μm fibers can lead to imprecise results. The choice of an aspect ratio of 3, however, was arbitrary, and not based on any systematic study. It has yet to be shown that this aspect ratio has any relationship to biological activity or disease, nor does such an aspect ratio uniquely define asbestos. Many materials break, cleave, or crystallize with aspect ratios in excess of 3.

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though asbestos possesses many unique properties, among them being ex-dinary tensile strength and flexibility, most are very difficult to measure oscopically. Dimensions, on the other hand, are readily measured. Therefore, question remains, can shape and size uniquely and quantitatively describe stos and distinguish it from other minerals, especially the more massive var-s of the same mineral? This study was undertaken to address this question.

MATERIALS AND METHODS

Sample Description

our samples of commerically available asbestos and three samples of nonas-tos were examined in this study (Table 1). All the samples except the riebeckite to be used by the National Institute of Environmental Health Sciences in nal oral ingestion studies. They are more completely described by Campbell *et* (1980). The two chrysotile samples were air classified, the amosite and idolite were air jet milled, and the tremolite and talc–serpentine were ground ball mill, all under commercial conditions. The riebeckite sample was ground e laboratory in a Wiley mill. None of the samples, except the riebeckite, were of contaminants. For the chrysotile, amosite, and crocidolite, however, mor-logy alone was generally sufficient to identify the asbestos; in the case of olite and talc–serpentine, however, the sample provided was a mixture of e three minerals. Each particle examined was identified either as tremolite or serpentine based on an energy-dispersive X-ray analysis (EDXA). EDXA used whenever morphology was insufficient in the other samples as well. It ld also be noted that amosite is properly a commerical term. This particular ple consisted of approximately 95% grunerite asbestos and 5% actinolite as-os. Crocidolite is the variety name for riebeckite asbestos.

Sample Preparation

r SEM examination of the samples, a solution of 4 ml distilled water and 1 ml washing liquid was mixed in a beaker. To this, 0.5 mg of sample was added dispersed by hand swirling the beaker. A mixture of 0.1 mg of sample per 1.0 of solution resulted. From this, a dilute solution of 0.005 mg of sample per 1.0 of solution was prepared.

0.1-μm Nucleopore filter was placed in a filtering apparatus. The dilute solu-(1.0 ml) was dispersed in distilled water of sufficient quantity to cover the r and poured down a glass rod onto the filter. The water was drawn through filter using a hand vacuum pump. After filtration, the sample was rinsed three s with distilled water to remove the soap.

hen completely dry, a square of approximately 25 mm^2 was cut from the r and mounted on a carbon disk with double-sided tape. This was in turn nted on an SEM specimen tab. A small drop of solution containing 1.099-μm x spheres was placed on one corner of the filter square; these were used for e. The specimen stub was then copper coated.

or TEM examination, a mixture of 20 ml of water and 0.5 mg of sample was

TABLE 1
SAMPLE CHARACTERISTICS

Name and locality	Log width			Log length			Log aspect ratio		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Maximum
Tremolite[a] St. Lawrence County, N.Y.	0.117	0.292	1.138 −0.481	0.464	0.344	2.217 −0.357	0.347	0.214	2.026
Talc−serpentine[a] St. Lawrence County, N.Y.	0.155	0.268	1.041 −0.357	0.388	0.283	1.380 −0.114	0.232	0.179	1.149
Riebeckite[b] Calif.	0.107	0.448	1.403 −1.301	0.784	0.526	2.201 −0.357	0.677	0.406	2.146
Short-fiber chrysotile[c] (SEM), Idria, Calif.	−0.780	0.255	0.477 −1.699	0.710	0.338	1.519 −0.481	1.590	0.383	2.723
Short-fiber chrysotile[c] (TEM), Idria, Calif.	−1.234	0.251	0.461 −1.699	0.002	0.561	1.653 −1.222	1.236	0.450	2.885
Long-fiber chrysotile[d] Thetford, Quebec	−0.870	0.225	0.121 −1.398	0.651	0.619	2.986 −0.451	1.580	0.383	4.008
Amosite[e] South Africa	−0.339	0.229	0.384 −1.046	1.197	0.592	3.255 −0.114	1.536	0.523	3.224
Crocidolite[f] South Africa	−0.606	0.203	0.456 −1.000	0.727	0.442	2.265 −0.415	1.332	0.426	2.944

[a] Courtesy USBM, Sample No. CP54-CP59.
[b] Courtesy Smithsonian Institution, Sample No. 119931.
[c] Courtesy USBM, Sample No. COF25.
[d] Courtesy USBM, Sample No. CP80-CP89.
[e] Courtesy USBM, Sample No. CP102A-G.
[f] Courtesy USBM, Sample No. CP117, 119, 121, 123, 125, 127, 129.

ared. The mixture was placed in a sealed jar and ultrasonically dispersed for oximately 10 min. After dispersal, several drops of the mixture were placed Collodion-coated, 200-mesh copper grid, and the water was allowed to orate. After evaporation, a fairly even distribution of particles adhered to the dian due to static charge.

may be that some of these preparation techniques could alter the population ily by breaking up a few fibers or fiber bundles. In designing the experiments, edures which would be more likely to alter the population characteristics, ultrasonification, were kept to a minimum. However, without the addition of persing agent and some agitation, clumping of the fibers made the collection eaningful length and width data impossible.

Data collection

wo SEMs were employed in this study: a Cambridge Mark IIa located at the itute of Physical Sciences and Technology, University of Maryland, College Maryland, and an AMR 1400 located at the Bureau of Mines, Avondale allurgy Research Center, Avondale, Maryland. Both instruments were pped with EDXA. SEM rather than TEM was chosen as the technique for of the data collection because of the extremely long lengths of some particles 00 μm). TEM was utilized only for the short-fiber chrysotile.

e lengths and widths of all particles were measured directly on the cathode tube (CRT) of the SEM using a scale based on the apparent size of latex res. Five spheres were measured and the average diameter was taken as 1.1 ± μm. A new scale was established for every specimen tab and magnification. nstruments were operated at approximately 10,000× to 15,000× but the ification was increased to approximately 20,000× for accurate width mea- ment. Widths were measured perpendicular to length at a point the operator d to be representative of the particle. Scale was established on the TEM by ument setting previously calibrated to an NBS standard.

or all samples studied by SEM, except the short-fiber chrysotile, particles to easured were chosen by moving the specimen tab in increments and record- the length and width of the particle whose center fell closest to the center of CRT. This approach effectively reduces all particles to points and generates that give the distributions of particle sizes according to particle numbers. In r words, a large particle and a small particle are each one particle and are ted the same. For the short-fiber chrysotile, TEM, all lengths and widths were sured from photographs; all particles falling in a given area were measured. also generates data that give distributions of particle dimensions according to icle numbers. The short-fiber chrysotile examined by SEM was treated differ- y. The lengths and widths of every particle that crossed a set of evenly spaced s were recorded. This approach generated data that closely reflect volume entages.[1]

[1] This approach accurately reflects volume only when the widths are constant. This is not strictly for chrysotile but the deviation is small and probably does not significantly affect the data.

Courtesy USBM, Sample No. COF25.
Courtesy USBM, Sample No. CP80-CP89.
Courtesy USBM, Sample No. CP102A-G.
Courtesy USBM, Sample No. CP117, 119, 121, 123, 125, 127, 129.

RESULTS

(*a*) *Frequency Distributions*

Histograms showing the frequency distributions of log length, log width, and log aspect ratio are shown in Figs. 1 through 6. They were tested for normality by the χ^2 goodness-of-fit test[2] as summarized in Table 2. While it is visually evident that most of the distributions are unimodal and approximately symmetrical, many of the computed χ^2 values are significant at the 95% level of probability; i.e., many of the sample frequency distributions imply nonnormal population distribution. These departures from normality could be real or reflect nonrandom sampling of the parent population of minerals, and such departures could present difficulties in the interpretation of statistical techniques where normality of the distribution is a critical assumption. However, differentiation of asbestos from nonasbestos by linear regression and/or discriminant function analysis is not sensitive to small departures from normality.

The summary statistics characterizing the frequency distributions in Table 1 strongly point to the conclusion that asbestos minerals have a significantly smaller but more uniform log width than do nonasbestos minerals; that they have longer but more varied log lengths; and that they have over twice the log aspect ratios of nonasbestos, but with significantly higher variation. Statistical techniques comparing variances and means (i.e., analysis of variance, multiple comparison tests of means) assume normal distributions, a condition not met by our data, so these

[2] The χ^2 statistic can be used to make statistical comparisons between a set of observed frequencies, f_i, in each of k categories and a set of theoretical frequencies (in this case from a normal distribution), F_i. The statistic computed is

$$\chi^2 = (f_i - F_i)^2/F_i.$$

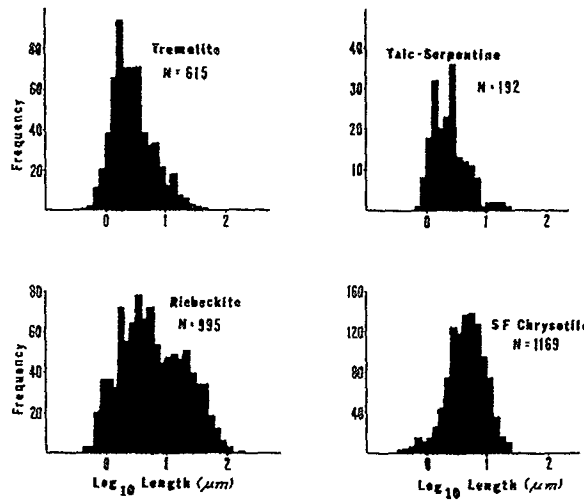
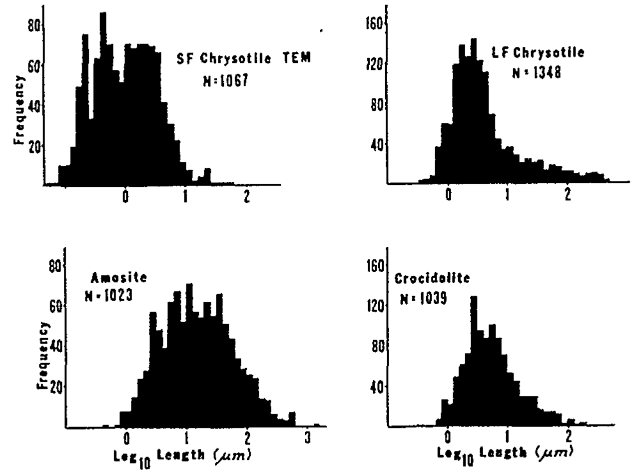


FIG. 1. Frequency distributions of log length for tremolite, talc–serpentine, riebeckite, and short-fiber chrysotile.



G. 2. Frequency distributions of log length for short-fiber chrysotile (TEM), long-fiber chrysotile, ite, and crocidolite.

clusions are only visual, albeit the differences are considered strong enough to valid.

Linear Regressions

ight least-squares linear regressions[3] of log aspect ratio (Y) versus log particle th (X) are plotted in Fig. 7 and described in Table 3. In each case the regres-s were significant at the 95% level of probability as indicated by the tabulated e of r, the correlation coefficient.[4] Also listed in Table 3 are the respective ndard errors of the estimates," which are the standard deviations of the log ect ratios around the computed regression line. The importance of the standard r as a descriptive statistic lies in the fact that approximately 95% of the ervations of log aspect ratio should be within ±2 standard error estimates of regression line. Large standard errors reflect the failure of the least-squares to explain the data (Chayes, 1971).

Aspect ratio comparisons may be considered valid by regulatory agencies, but equally impressive morphologic characterization and discrimination tool ap-rs to be the simple linear regression of log width (Y) on log length (X) (Fig. 8).[5]

We assume that within the size range measured, a linear model would describe the data, i.e., would ount for the variation in the dependent variable, log aspect ratio. The significant values of r, the relation coefficient, support the linear model.

The correlation coefficient, r, is an expression of the linear relationship between two variables vis, 1973). An r of 1 indicates a perfect direct relationship; an r of -1 indicates a perfect inverse tionship. The statistical significance of a given value of r for any number of observations can be essed from tables appearing in most elementary statistics texts.

It should be noted that this is not an independent relationship as shown by the following:

$$\text{log aspect ratio} = M \text{ log length} + B,$$

$$\text{log length} - \text{log width} = M \text{ log length} + B,$$

$$\text{log width} = (1 - M) \text{ log length} - B.$$

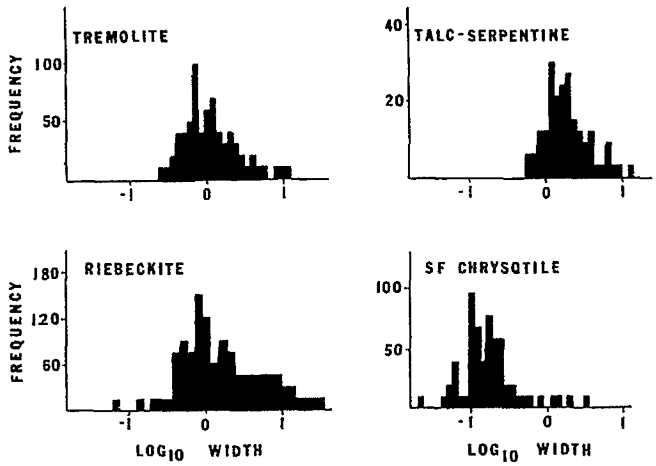


FIG. 3. Frequency distributions of log width for tremolite, talc–serpentine, riebeckite, and short-fiber chrysotile.

Stated more strongly, ratios do not add any appreciable information that is not already obvious from the dimensions themselves. On the contrary, and there are extensive examples of this in the literature (Davis, 1973; Chayes, 1971), taking ratios may either distort or at best cloud the true relationship. The regression lines of log width on log length are described in Table 4. They are all statistically significant.

(c) Discriminant Function Analysis

In discriminant function analysis, the problem is to find a linear function of the variables, in this case log length, log width, and log aspect ratio, which produces

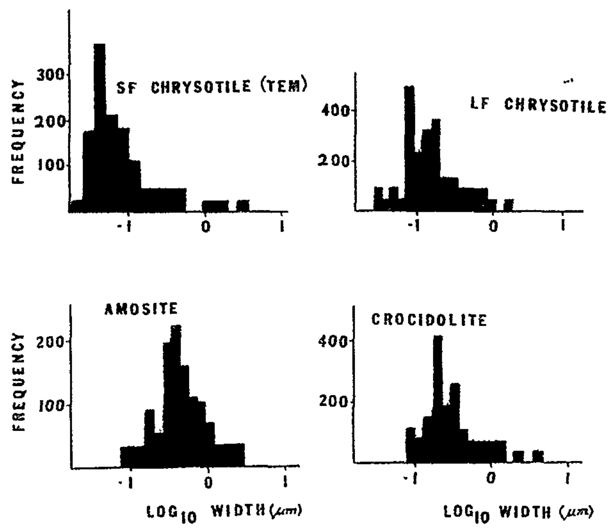


FIG. 4. Frequency distributions of log width for short-fiber chrysotile (TEM), long-fiber chrysotile, amosite, and crocidolite.

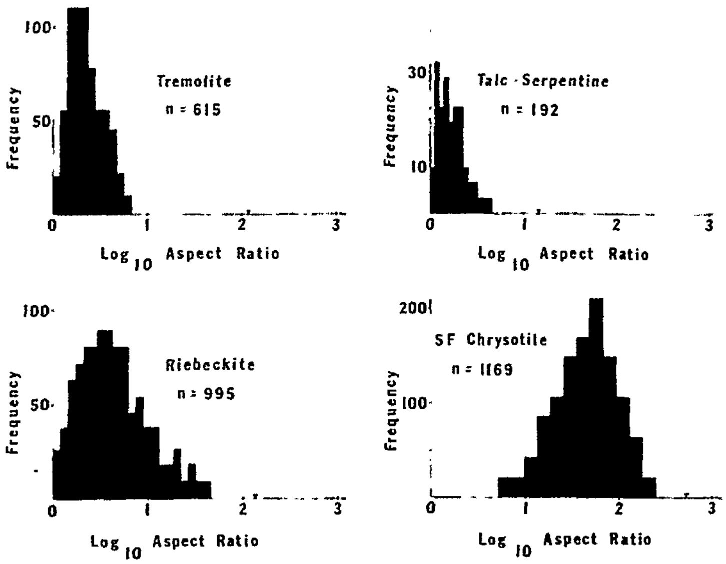


FIG. 5. Frequency distributions of log aspect ratio for tremolite, talc–serpentine, riebeckite, and short-fiber chrysotile.

the maximum difference between two previously defined groups, i.e., a population of asbestos particles and a population of nonasbestos particles. Discriminant function analysis depends upon an a priori knowledge that there are, in fact, two populations. It is not particularly sensitive to nonnormality in the population frequency distribution (Davis, 1973).

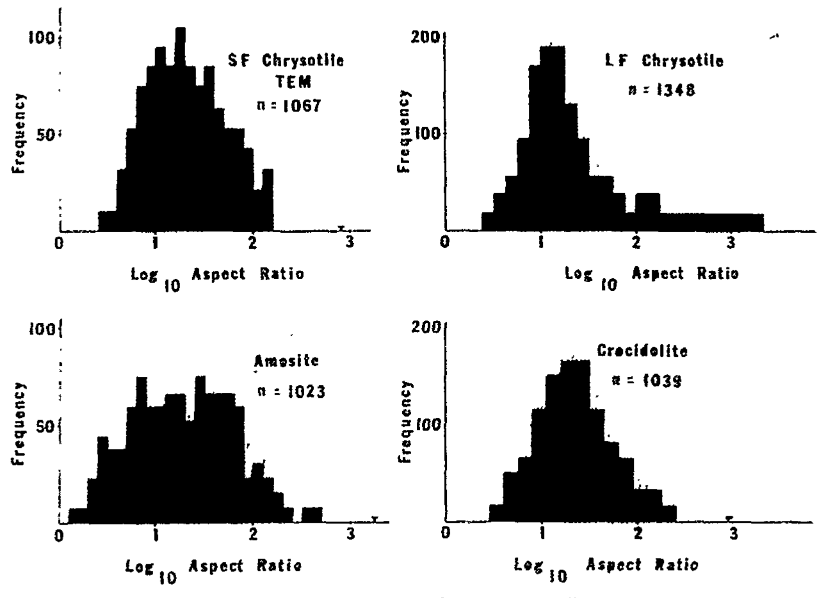


FIG. 6. Frequency distributions of log aspect ratio for short-fiber chrysotile (TEM), long-fiber chrysotile, amosite, and crocidolite.

TABLE 2
χ^2 GOODNESS-OF-FIT VALUES OF LOG LENGTH, LOG WIDTH, AND LOG ASPECT RATIO

Sample	Log length	Log width	Log aspect ratio
Tremolite	58.4	72.4[a]	125.2
Talc–serpentine	93.8[a]	60.4[a]	144.8[a]
Riebeckite	72.1[a]	53.0	112.5[a]
Short-fiber chrysotile	47.9	101.1[a]	24.3
Short-fiber chrysotile (TEM)	21.6	94.8[a]	18.1
Long-fiber chrysotile	106.9[a]	140.3[a]	68.5[a]
Amosite	31.8	29.2	139.7[a]
Crocidolite	61.4[a]	112.1[a]	10.4

[a] Significant at 95% level of probability (Davis, 1973).

The technique transforms an original set of measurements into a single discriminant "score" or transformed variable. In this work, the functions were calculated as follows,

$$Y_a = -2.57491 - 5.89958 \text{ (log width)}, \quad (1)$$

$$Y_n = -1.27804 + 0.87779 \text{ (log width)}, \quad (2)$$

where Y_a is the discriminant score for asbestos particles and Y_n is the respective score for nonasbestos particles using width as the sole criterion for discrimination. If log aspect ratio is introduced as an additional discriminating variable, the discriminant functions become

$$Y_a = -6.92419 - 5.79358 \text{ (log width)} + 6.12433 \text{ (log aspect ratio)}, \quad (3)$$

$$Y_n = -2.05436 + 0.91638 \text{ (log width)} + 2.22936 \text{ (log aspect ratio)} \quad (4)$$

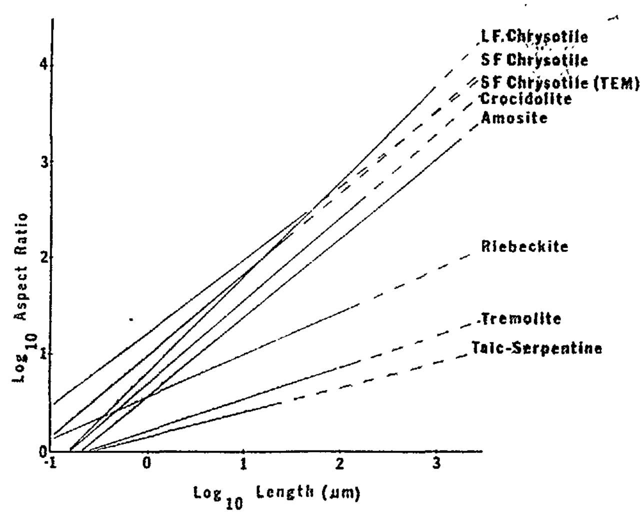


FIG. 7. Least-squares linear regression plots of log aspect ratio as a function of log length.

TABLE 3
REGRESSION EQUATIONS, CORRELATION COEFFICIENTS AND STANDARD ERROR OF LOG ASPECT RATIO VS LOG LENGTH

Sample	Regression equation Log (Aspect, = f(Log Length) ratio)	r^a	SE[b]
Tremolite	$Y = 0.334X + 0.192$	0.537	0.181
Talc–serpentine	$Y = 0.254X + 0.134$	0.401	0.165
Riebeckite	$Y = 0.436X + 0.336$	0.565	0.335
Short-fiber chrysotile (SEM)	$Y = 0.858X + 0.971$	0.757	0.251
Short-fiber chrysotile (TEM)	$Y = 0.763X + 1.234$	0.873	0.220
Long-fiber chrysotile	$Y = 0.985X + 0.819$	0.959	0.181
Amosite	$Y = 0.816X + 0.559$	0.923	0.201
Crocidolite	$Y = 0.858X + 0.709$	0.891	0.193

[a] r = correlation coefficient.
[b] SE = SD of observations around the regression line.

These functions can be reduced and rotated geometrically to a single function where the coefficients are independent, the so-called canonical form. It is found to be

$$Y = 2.75011 + 2.16673 \text{ (log width)} - 1.25773 \text{ (log aspect ratio)}. \quad (5)$$

By plugging in the dimensions of a particular particle, this canonical function can be used to allocate that particle to either an asbestos or nonasbestos population. The correctness of these allocations is given in Table 5. For example, given a particle came from a nonasbestos population, using this discriminant function (Chayes, 1971) we can correctly allocate that particle to the nonasbestos population 74.7% of the time using the sole criterion of log width or 87.9% of the time using the criteria combination of log width and log aspect ratio. The correct

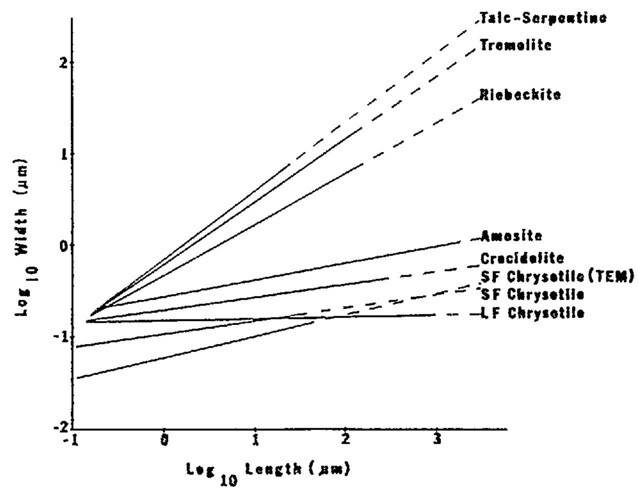


FIG. 8. Least-squares linear regression plots of log width as a function of log length.

TABLE 4
REGRESSION EQUATIONS, CORRELATION COEFFICIENTS AND STANDARD ERROR OF LOG WIDTH VS. LOG LENGTH

Sample	Regression equation Log width = f(Log length)	r[a]	SE[b]
Tremolite	$Y = 0.666X - 0.192$	0.785	0.181
Talc–serpentine	$Y = 0.746X - 0.134$	0.790	0.165
Riebeckite	$Y = 0.564X - 0.336$	0.663	0.335
Short-fiber chrysotile (SEM)	$Y = 0.142X - 0.971$	0.189	0.251
Short-fiber chrysotile (TEM)	$Y = 0.237X - 1.234$	0.487	0.220
Long-fiber chrysotile	$Y = 0.015X - 0.820$	0.050	0.181
Amosite	$Y = 0.184X - 0.560$	0.477	0.201
Crocidolite	$Y = 0.142X - 0.709$	0.309	0.193

[a] r = correlation coefficient
[b] SE = SD of observations around the regression line

allocations are respectively 95.9 and 97.8% if the particle is originally drawn from an asbestos population.

DISCUSSION

The first approach to morphology characterization, classification, and discrimination was attempted by comparison of the observed univariate frequency distributions and the summary statistics, i.e., means, standard deviations, and ranges, of log length, log width, and log aspect ratio. While from a visual comparison of these frequency distributions the differences among the populations are evident, the nonnormality of many of the sample distributions makes quantitative descriptions such as analyses of variance and probability statements inappropri-

TABLE 5
CLASSIFICATION EFFICIENCY OF DISCRIMINANT FUNCTIONS

(a) Criterion: width
Discriminant function: $Y = 2.75011 + 2.16673$ (log width)[a]

Group	Percentage correct	Number of cases classified: Nonasbestos	Asbestos
Nonasbestos	74.7	1332	450
Asbestos	95.9	233	5412

(b) Criteria: width and aspect ratio
Discriminant function: $Y = 2.75011 + 2.16673$ (log width) $- 1.25773$ (log aspect ratio)[a]

Group	Percentage correct	Number of cases classified: Nonasbestos	Asbestos
Nonasbestos	87.9	1566	216
Asbestos	97.8	122	5523

[a] Equation (5).

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. LENGTH

	r^a	SE^b
	0.785	0.181
	0.790	0.165
	0.663	0.335
	0.189	0.251
	0.487	0.220
	0.050	0.181
	0.477	0.201
	0.309	0.193

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FUNCTIONS

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hestos	Asbestos
32	450
33	5412

773 (log aspect ratio)^a

nber of cases classified	
estos	Asbestos
6	216
2	5523

However, even without these statistical tools, we think that the data in Table rongly support the conclusions that asbestos particles have longer and more ed lengths, thinner and less varied widths, and greater, more varied aspect s than do nonasbestos particles.

n excellent linear relationship exists between log aspect ratio and log length, ell as between log width and log length for all samples studied. Each of the t samples can be described by unique regression equations. Furthermore, the ession equations describing the samples fall into two groups, asbestos and asbestos, based upon slope. The differences between these two groups are easingly obvious as the length increases, implying that fewer observations are uired to differentiate, either on the basis of aspect ratio or width, between estos and nonasbestos when the particles are long. Conversely, differentiation hese populations in the shorter lengths demands a larger number of observa-s, especially when aspect ratio is used. Indeed if a population of particles were have lengths all less than approximately 1 μm, differentiation between the two ups would be very difficult if not impossible.

he discriminant function analysis suggests that log width is a more sensitive sifier of a sample particle than either log aspect ratio or log length. This clusion is stronger if the population being sampled is, in fact, asbestos. Stated erently, to correctly categorize an asbestos fiber as such, one theoretically d only measure log width; to correctly classify a nonasbestos cleavage frag-nt, log aspect ratio should be measured as well. It appears from our analysis t log length is a redundant measurement, except as needed to calculate the ect ratio; it contains almost no unique classifying information. It should be embered that these conclusions are based on classification of particles from samples. Extrapolation to the classification of air- or waterborne particles only be done with extreme caution because these two agents can sort particles efficiently, thereby altering the parent population.

he numerical relationships describing the morphology of the particles in these t samples are readily related to the structure and habit of these minerals. The aller, less variable widths of all the asbestos samples can be related to the fibril ucture of asbestos. In chrysotile, the fibrils are individual tubes produced by led sheets; in amphibole asbestos the fibrils are single or twinned crystals ich grow in bundles sharing a common C axis but which have no order in the er crystallographic directions. In both cases the fibrils are small and similarly ed. The fibril structure is best developed in chrysotile. The fibrils are larger and ow more variability in the amphiboles, especially amosite. It is interesting to te that amosite is commonly described as being more "harsh" and its fibers ve less flexibility than other types of asbestos. The data suggest that the larger il widths are probably the reason. Cleavage fragments have much larger more iable widths than does asbestos and possesses no flexibility.

The regression lines relating log aspect ratio or log width to log length readily tinguish asbestos from nonasbestos based on the slope of these lines. The value the slope is in part a measure of the degree of development of fibers and may be lled an index of fibrosity (Wylie, 1979). For example, considering log aspect tio vs log length, a slope of zero indicates all particles have identical aspect tios. Talc–serpentine particles most closely approximate this shape. They belong to the sheet silicate group and have similar crystallographic dimensions parallel to the sheets, producing nearly equidimensional cleavage fragments when crushed. At the other extreme is chrysotile with slopes of the regression lines relating log aspect ratio to log width that approach one. This implies a nearly constant particle width, a consequence of chrysotile's fibrillar structure. The other types of asbestos also have by this analysis very high slopes, also reflecting the fibril structure. In between are the amphibole cleavage fragments. These cleavage fragments have an elongated nature due to their double-chain structure. Although the longer particles tend to have higher aspect ratios, they do not approach the dimensions of asbestos and any population of such cleavage fragments should be distinguishable from asbestos provided some of their lengths are greater than approximately 1 μm.

There is some indication that the frequency distribution of log aspect ratio of amosite is bimodal. The amosite sample contains cleavage fragments of grunerite which were not distinguished from grunerite asbestos, the major component of the amosite sample in this study. In addition, the amosite sample contains about 5% actinolite asbestos which was included and counted as part of the amosite population. The apparent bimodal distributions may be due to either or both of these "contaminants." The fact that mineral samples are generally not pure must not be overlooked in sample population descriptions and great care must be exercised in attempting this type of analysis in other studies.

Finally, it is appealing to assign the obvious differences between the short-fiber chrysotile as characterized by SEM and TEM to the differences in instrumentation. However, the techniques used for gathering the data were different: the TEM was used to collect data based on particle number while the SEM was used to collect data based on particle volume. Therefore the frequency of log length by TEM should show a larger number of short particles. The regression equations relating log aspect ratio and/or log width to length are very similar and cannot be used to distinguish significantly the effects of instrumentation. The comparison of the frequencies of log width, however, presents a different case. For asbestos, width is practically independent of length. Therefore, width frequencies should not be affected by the nature of the data collection, i.e., number vs volume. It is evident that the frequency of log width by TEM shows many more particles of smaller widths than does the SEM characterization of the same sample. This is probably a real instrumentation effect. Two fibrils side by side would be seen, measured and recorded as two fibers by TEM but by SEM they would appear and be counted as one thicker fiber.

In summary, it appears from this study that populations can be classified as either asbestos or nonasbestos based on morphological considerations. However, there may be many mineral particle populations that may not be so clearly distinguished as those we studied. Moreover, the effects of grinding, sampling, instrumentation, and mineralogical characteristics on small particle morphology need to be more clearly described by future experiments.

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