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Bulk asbestos reference minerals for optical microscope identification

Preparation, evaluation and validation

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Bulk asbestos reference minerals for optical microscope identification

Preparation, evaluation and validation

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Suitable samples of asbestos have been obtained in quantities of up to 10 kilograms from a variety of sources and prepared for use as Reference Asbestos Minerals for identification of asbestos in bulk materials using optical microscopy. Seven asbestos samples (chrysotile (2), amosite, crocidolite, tremolite, actinolite and anthophyllite) have been prepared to be representative of the grades of fibre typically found in commercial products and insulation materials.

Each asbestos type has been fully described in terms of its optical properties and has been compared to published data and other well-known asbestos mineral samples. Each asbestos type has also been evaluated for purity and for its general suitability by testing with infrared spectrophotometry, X-ray diffractometry and electron microscopy with chemical analysis using energy dispersive X-ray spectrometry in comparison to well-known asbestos minerals and to published data.

The samples were homogenised and split into subsamples and have been packed into tough polythene bottles with tightly fitting screw caps, and labelled appropriately. Sets of the seven asbestos minerals are now available to bona-fide analytical laboratories for the purpose of meeting NAMAS requirements for Reference Materials.

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INSTITUTE OF OCCUPATIONAL MEDICINE**BULK ASBESTOS REFERENCE MINERALS FOR OPTICAL
MICROSCOPE IDENTIFICATION:
PREPARATION, EVALUATION AND VALIDATION****By****J Addison, LST Davies, C McIntosh and RH Porteous****SUMMARY**

A range of possible geological and commercial sources were identified for each of the different asbestos varieties and representative samples were evaluated initially.

Suitable samples of asbestos were obtained in quantities of up to 10 kilograms from selected sources and prepared for use as Reference Asbestos Minerals for identification of asbestos in bulk materials using optical microscopy. Seven asbestos samples (chrysotile (2), amosite, crocidolite, tremolite, actinolite and anthophyllite) have been prepared to be representative of the grades of fibre typically found in commercial products and insulation materials.

Each asbestos type has been fully described in terms of its optical properties and has been compared to published data and other well-known asbestos mineral samples. In addition, each asbestos type has also been evaluated for purity and for its general suitability by testing with infrared spectrophotometry, X-ray diffractometry and electron microscopy with chemical analysis using energy dispersive X-ray spectrometry. All of these data are fully compatible with previous reference materials such as the UICC asbestos varieties and with other published physico-chemical data.

The samples were homogenised and split into subsamples and have been packed into tough polythene bottles with tightly fitting screw caps, and labelled appropriately. Sets of the seven asbestos minerals are now available to bona-fide analytical laboratories for the purpose of meeting NAMAS requirements for Reference Materials.

1. INTRODUCTION

Asbestos in bulk materials is usually identified using optical microscopy. The techniques used rely on comparing a range of optical properties of minerals displayed in polarised light microscopy and dispersion staining microscopy with those of other minerals in published data or visually with reference asbestos minerals.

According to the UK National Measurement Accreditation Service (NAMAS, NIS 45), reference materials are essential for the maintenance of traceability of chemical measurements. NIS 45 states that it is important that the certified reference material has been produced and characterised in a technically valid manner and details of homogeneity trials, stability trials, the methods used in certifications and the uncertainties and variations in the stated analyte values provided by the supplier should be used to judge the pedigree of the reference material.

The aim of this project was to produce sufficient quantities of fibre of the asbestos materials amosite, chrysotile, crocidolite, tremolite, actinolite and anthophyllite to satisfy the criteria for their use as reference materials for identification of asbestos in bulk samples.

There are a number of existing sources of asbestos as reference materials but none are entirely satisfactory.

The US National Institute of Standards and Technology (NIST) have a set of minerals for the common asbestos varieties but these are small quantities only, are very expensive and are not available outside the USA. The less common varieties, also being planned by NIST, are probably not going to be available for some time.

The International Union Against Cancer (IARC) asbestos minerals were produced in Johannesburg in 1966. The descriptions of their physical and chemical properties would make them perfectly suitable as reference materials but, since the original intention had been to provide them for use in inhalation and injection experiments, they were all heavily milled to produce fine dust. These are not very appropriate for the identification of coarse mine-grade fibre by optical microscopy. In addition, the IARC reference standards did not include actinolite or tremolite varieties. The minerals and their data sheets have nevertheless been extremely useful as guides in the past and to the selection of the materials described in this paper.

Rendall (1979) was also involved in preparation of a further set of amphibole asbestos minerals which were intended as forms of European reference materials but although available from the Museum National d'Histoire Naturelle in Paris, in practice they were difficult to obtain and, of course, did not represent the full range of minerals.

Walter C McCrone Associates produced a set of mine grade samples of the three common asbestos minerals on a commercial basis. These were of excellent quality but are now no longer available.

No other suitable reference materials for the full set of the main asbestos minerals are available anywhere and it was to fill this gap that the proposal to collect, prepare, evaluate and validate suitable reference asbestos minerals was devised and submitted to the UK Health and Safety Executive (HSE).

2. METHODS

2.1 Identification of Sources

Possible sources for potentially suitable materials were identified by searching geological literature databases, by examination of British Geological Survey Memoirs, records and mineralogical texts and finally by personal contacts with individual scientists and companies.

The potential of the individual materials to meet the requirements of the reference minerals in terms of quality, purity and quantity was evaluated. Only when it was apparent that these conditions were likely to be met, or that other cost constraints would be unlikely to be exceeded, were attempts made to obtain full stocks of materials.

2.2 Methods of Preparation

All of the materials required a considerable amount of handling before the final sets of reference materials were ready. All handling was carried out in the most tightly controlled conditions practically available. This was usually a totally enclosed negative pressure glove box fitted with vacuum cleaner, water supply and waste disposal port. Otherwise, air-stream cabinets were used or the samples being handled were wet or had other forms of dust suppression.

Some of the materials required very little laboratory preparation before full evaluation and splitting. The amosite and crocidolite although apparently homogeneous in the first place having effectively been obtained directly from the mills, were each thoroughly mixed in a totally enclosed glove box before repacking in sealed 2 plastic containers for storage.

Other samples, including the actinolite asbestos and the tremolite asbestos required careful purification in the laboratory before the evaluation. The actinolite asbestos was collected from the rock face of a disused quarry and required washing, wet sieving and extensive hand picking of rock material, vein quartz and other minerals and of organic debris before it was suitable.

The tremolite asbestos initially contained considerable amounts of calcium carbonate which required soaking in dilute hydrochloric acid for a few hours before thorough washing and rinsing.

Drying of samples was carried out in small batches in a standard laboratory oven at 110°C with a porous cover fitted to the container. When dry the samples were teased out by hand in the glove box to separate any matted lumps of fibre and to hand pick any remaining rock or mineral fragments before homogenisation and packing for storage.

Individual subsamples were packed in batches of 100 into 25ml plastic bottles fitted with screw tops and airtight inner seals.

2.3 Optical Microscopy

All of the reference types were subject to detailed optical microscope examination using both phase contrast optical microscopy (PCOM) with optional polarised light microscopy (PLM) and with PCOM and McCrone objective lens dispersion stain microscopy. Observations were made using Nikon Labophot and Olympus BH2 optical microscopes.

Microscope preparations were made by mounting small bundles of fibres on standard glass microscope slides in High Dispersion Cargille Refractive Index Liquids selected to match each particular fibre type as detailed below:-

Fibre Type	RI Liquid
Chrysotile	1.550
Amosite	1.670
Crocidolite	1.700
Actinolite	1.640
Anthophyllite	1.605
Tremolite	1.605

The optical properties of all of the fibre types were observed with the microscopes in the operating modes as described below:

1. Plane polarised light:
Morphology, colour and any pleochroic colour changes
2. Plane polarised light with crossed polarisers:
Morphology, birefringence, interference colours, extinction position (pleochroism).
3. As in 2 but with first order red (530nm) compensator plate (sensitive tint plate):
Morphology, interference colours, optic orientation (sign of elongation; length fast or length slow).
4. Plane polarised light with matching phase contrast objectives and sub-stage annular condenser aperture OR McCrone dispersion staining objective lens with pin-hole sub-stage diaphragm.
Morphology and assessment of refractive indices from dispersion staining colours.

Detailed records were made of the optical properties as shown in Table 1.

2.4 X-ray Diffractometry (XRD)

X-ray diffraction patterns of all of the minerals were prepared on a Philips 1710 powder diffractometer.

Aqueous suspensions of dispersed fibres were prepared and aliquots from these containing about 10 milligrams of mineral were filtered on to 25mm cellulose nitrate membrane filters. The filters were mounted on to 26mm diameter aluminium discs by collapsing them with acetone vapour. This effectively bound the asbestos fibres to the filter and disc and the fibres on the upper surface were

sealed with a fine spray of lacquer which resulted in a strong pad of asbestos capable of being handled safely in the X-ray diffractometry. The dimensions of the aluminium disc were such that it just fitted the standard Philips circular sample holder with the upper surface of the asbestos level with the top of the rim.

Diffraction patterns were recorded with Copper $K\alpha$ radiation from $5^\circ 2\theta$ to $65^\circ 2\theta$ using a 1° divergence slit, a 0.1mm receiving slit and a graphite monochromator. Philips Analytical PC-APD software was used for pattern recording and diffraction peak searching and measuring for identification of possible contaminant minerals.

2.5 Infrared Spectrophotometry

Small samples of the minerals, around 1mg were ground under alcohol by hand with an agate mortar and pestle and mixed with 250mg of potassium bromide. The mixtures were pressed into discs using the procedures described by Dodgson & Whittaker (1973). Infrared absorbance spectra from 4000cm^{-1} to 400cm^{-1} wavenumbers were recorded on a Perkin Elmer 1720X Fourier Transform IR spectrophotometer.

2.6 Electron Microscopy

Aqueous suspensions of dispersed fibre were prepared and aliquots were deposited on to $0.1\mu\text{m}$ pore size 25mm diameter polycarbonate filters. Different fibre loadings on each filter were prepared to provide samples suitable for Scanning Electron Microscopy (SEM), Photomicrography (high density) and for Transmission Electron Microscopy (TEM) with Energy Dispersive X-ray Spectrometry (EDXS) (low density).

Filters for SEM evaluation were cut and mounted with carbon dag mixed with polyvinyl acetate (PVA) on to standard Cambridge Instrument (Leica-Cambridge) 13mm aluminium sample stub. The samples were coated with gold and examined using a Cambridge Instrument S250 MkII SEM. Photomicrographs were taken at final magnifications of 1200X and 3000X.

Filters for TEM were coated with carbon and small (2.5mm square) sections were cut out and the carbon films were transferred to $100\mu\text{m}$ square mesh copper TEM grids using the Jaffe Wick method (Chatfield 1982). These were examined using a Hitachi H7000 TEM with SEM capability. 100 fibres in each reference asbestos and in other fibre types (50 for less important samples) were analysed with the microscope in scanning mode (STEM) for periods of ten seconds using a Link Analytical 860-200 X-ray detector, pulse processor and multi-channel analyser. The integrated X-ray peak intensities for the major elemental components of each fibre type in the energy range of 0-10KeV were recorded and mean X-ray peak counts and their standard deviations were evaluated from these. No attempt was made to calculate the chemical compositions more accurately by correction for fluorescence, micro absorption or detector effects.

3. RESULTS

3.1 Introduction

The fibres described below have been selected and prepared as suitable reference asbestos minerals in the quantities required. Their general and optical properties are fully described in the following section before comparisons are made with other reference materials and minerals in terms of optical and other physical properties as part of their validation. The optical properties of the Asbestos Reference Minerals are summarised in Table 1 below.

3.1.1 Chrysotiles

Two Reference Asbestos Chrysotile samples have been provided which have slightly different optical properties and are intended to show some of the variability.

The Cassiar chrysotile is from the McDame Mountain mine in British Columbia, Canada. This is a typical massive mountain-belt serpentinite formed tectonically from a slice of upper mantle rock (Ross, 1981).

The Zimbabwe Chrysotile is from the Shabani Mine.

Both Reference Chrysotiles were supplied by TBA Industrial Products Limited of Rochdale, UK.

The UICC asbestos minerals were produced from a variety of different sources for the Union Internationale Contre le Cancer (UICC) (Timbrell et al 1968). They were fully described by Rendall (1970) and Timbrell (1970) and have been recognised as an International Standard Reference Sample since that time. However, because the original intention had been to provide respirable dust-like materials for biological experimentation, all of the UICC minerals were heavily milled and as such they are not suitable reference materials for optical microscope analysis. The UICC Chrysotile "A" described here was also produced from the Shabani Mine in Zimbabwe (then Southern Rhodesia).

3.1.2 Amosites

The Reference Asbestos Amosite was produced from the Penge Mine in the Transvaal province of South Africa. This is in part of the main Banded Ironstone deposits in the Black Reef described by Hodgson (1969) and Ross (1981) and would be expected to be similar to the UICC varieties in all but fibre dimensions since the source localities are the same. The montasite and brown amosite were previously supplied by Mr Charles Hunt of the British Uralite Company and was presumably from the source described by Hodgson (1965) in Pietersburg, South Africa.

3.1.3 Crocidolites

The Reference Asbestos Crocidolite was produced from the Coretsi Mine at Kuruman in Griqualand, South Africa. This is part of the main Kuruman Iron Formation deposits in the Asbes Heuwel Subgroup described by Hodgson (1965) and Ross (1985) and the reference minerals would be expected to be similar to the UICC Crocidolite in view of this. The Reference Crocidolite and amosite were supplied by Dr P Heske of the South African Asbestos Producers Advisory Committee in Johannesburg. The Wittenoom Crocidolite was formed in a major geological deposit very similar

to the South African deposits in which the reference and the UICC Crocidolite were formed (Ross 1981). Indeed, it may be that the major rock formations of the two continents were originally contiguous and it is not surprising that the minerals were very similar. A fine lavender coloured crocidolite from Cochabamba in Bolivia was available as a few fibres and these have been compared where possible with the other examples.

3.1.4 Tremolites

The Reference Asbestos Tremolite comes from the Salt Works Mine in Death Valley, San Bernardino County, California. This is one of a large range of talc, and tremolite deposits described by Wright (1968) and Evans et al (1976) a few of which contain asbestos tremolite instead of the more normal prismatic tremolite. This material was generously provided to the authors by Mr Gordon Gill of Cyprus Minerals Inc of Denver, USA. The other tremolite from California comes from an unknown source at Jamestown in Tuolumne County in the North of the State. The mineral is among those described by Dorling and Zussman (1987) and was used by Addison and Davies (1985), and by Davis et al (1991). The Korean Tremolite is a commercially produced asbestos from the Korean Asbestos Mining Company Limited, Seoul, Korea. It was used in animal inhalation experiments as described by Davis et al (1978) and used in the experiments of Davis et al (1991). The tremolite from Ali di Stura comes from an unknown locality in the valley of the River Stura di Ala about 35 miles North-west of Turin. This also was used in the experiments of Davis et al (1991).

3.1.5 Actinolites

The Reference Asbestos Actinolite was collected from a small disused quarry at Ermington near Yealmpton in Devon. The authors are grateful to Mr S Day of Ermington for access to the site. The potential of the source was originally established by evaluation of various Memoirs of the Geological Survey of Great Britain, and in particular that of Ussher, (1912).

The Prieskaite Actinolite was provided by Ms Jean Prentice of McCrone Research Associates. It is a rare example of the material sporadically found in the Cape Asbestos asbestos deposits at Koegas, Griqualand West, South Africa. The mineral was previously described by Hodgson (1965). The Norwegian Actinolite was prismatic needle-like mineral specimen obtained from the Orkney Mineral Company in Thurso, Scotland.

3.1.6 Anthophyllites

The Reference Asbestos Anthophyllite was originally produced by the Oy Paraisten Kalkki Ab in Finland (now Oy Partek Ab) from an unknown exact source although in view of its similarities to the UICC variety this may be presumed to be Paakila in Karelia (Timbrell et al 1970 and Hodgson 1969).

3.2 The Asbestos Reference Minerals: Optical Properties

The optical properties of the Reference Minerals are summarised in Table 1.

3.2.1 Chrysotile, Cassiar

This Reference Asbestos Chrysotile is a soft, white, curly, silky fibre; it is a very flexible and inelastic long fibre. In PLM it is observed to be formed of curved fibres showing typical kinked morphology with easily split fibre bundles. It is colourless (non pleochroic), with low to moderate

birefringence, usually showing first order grey or white but sometimes blue and red interference colours. It has straight extinction and is optically length slow. In a liquid with RI of 1.550 it shows dispersion stain colours of blue-green/purple (PCOM) or deep blue/purple (McCrone objective). The Cassiar Chrysotile was analysed using the digestion techniques of Addison and Davies (1990) and found to be more than 99% pure. A small number of irregular shaped quartz (low birefringence RI \approx 1.550) and opaque iron oxide particles are also present.

3.2.2 Chrysotile, Shabani, Zimbabwe

This Reference Asbestos Chrysotile is a soft, white, curly, silky fibre; it is a very flexible and inelastic long fibre. In PLM it is observed to be formed of curved fibres showing typical kinked morphology with easily split fibre bundles. It is colourless (non pleochroic) with low first-order grey or white interference colours. It has straight extinction and is optically length slow. In a liquid with RI 1.550 it shows dispersion stain colours of blue-red/purple (PCOM) or deep blue/purple (McCrone objective). When examined by stereo-binocular microscopy this material can be seen to contain occasional dark grey, brown or black fibre bundles. In plane polarised light these fibres are intensely pleochroic from pale brown to dark brown but otherwise have all of the normal properties of chrysotile including the appropriate dispersion stain effects. These fibres have also been confirmed by electron microscopy as an unusual variety of chrysotile. This chrysotile was also analysed by the digestion techniques and found to be better than 98.5% pure. A small number of irregular shaped quartz and opaque iron oxide particles are also present.

3.2.3 Amosite

The Reference Asbestos Amosite is a colourless to grey straight needle-like fibre with a vitreous lustre. It is a long, tough and flexible fibre and deforms elastically. In PLM it is observed as straight needle-like fibres in bundles with typical "shaving-brush" ends. It is pale yellow-brown or colourless and when coloured it shows a faint pleochroism. It has a moderate birefringence and often displays high first order or second order interference colours. It shows straight extinction and is optically length slow. In a liquid with RI 1.670 it shows dispersion staining colours of blue-red/yellow (PCOM) and purple/yellow (McCrone objective). The fibre orientations in which these alternate colours are shown are reversed in a liquid with RI 1.700 (or 1.690). Some fibres are more strongly pleochroic, from brown to pale-brown and a few, probably closer to actinolite in composition, are green and pleochroic. There are also small quartz particles showing low birefringence and RI close to 1.550.

3.2.4 Crocidolite

The Reference Asbestos Crocidolite is a fine, soft, curly, blue fibre with vitreous, almost metallic lustre. It is a tough, long fibre which, as a free fibre is distinctly needle-like although because of its fine fibrous nature it appears to be inelastic and curly. In PLM it is observed to be fine needle-like or curved (open curves) easily split fibre with a strongly pleochroic blue-grey to deep blue colour. It has very low birefringence showing low first order interference colours combined with its strong absorption colours to produce a blue-grey or dull grey colour. It sometimes displays a russet brown colour referred to as anomalous low interference colours. It has straight extinction and is optically length fast. In a liquid with RI 1.700 it shows deep blue dispersion staining colours sometimes with red-purple fringes at the edges of the fibres. The normal fibre is occasionally intergrown with fine grains of opaque iron oxides (FeO or Fe₃O₄) and yellow-brown grains of iron hydroxides. There are also small irregularly shaped quartz particles present.

3.2.5 Tremolite

The Reference Asbestos Tremolite is a fine, soft, white fibre with vitreous, almost silky lustre. It is a long, elastically deforming needle-like fibre which appears to be soft, flexible and inelastic because of the fine nature of the fibres. In PLM it is seen to be fine and needle-like in bundles with typical "shaving-brush" ends. It is colourless and non-pleochroic. Between crossed polarising lenses it shows a moderate birefringence with interference colours frequently in higher first order or second order. The fibres are straight extinguishing and optically length slow although occasional prismatic cleavage fragment needles and stocky fibres show oblique extinction. In a liquid of RI 1.605 the fibres show blue-red/yellow (PCOM) or purple/yellow (McCrone objective). There are also rhombic shaped calcite crystals showing high birefringence and ribbon shaped talc fibres with high birefringence and RI's close to 1.590.

3.2.6 Actinolite

The Reference Asbestos Actinolite is a very fine, long, soft fibre with a greenish grey or bluish grey colour and a silky lustre. It is straight and needle-like when found as fine separate fibres but appears curly in bundles because of the fine nature of its fibres. In PLM it is observed as fine curved or needle-like fibres and fibre bundles with typical "shaving-brush" ends. It is pale green to bluish green or colourless and strongly pleochroic when coloured. Between crossed polarising lenses it shows low-moderate birefringence but, because of the fine nature of the fibres it mostly shows low first order interference colours. It has straight extinction and is optically length slow. Occasional prismatic cleavage fragments (not asbestos) fibres may display oblique extinction. ($10^\circ - 20^\circ$) In a liquid with RI 1.640 the fibre shows dispersion staining colours of blue-red/yellow (PCOM) or purple/yellow (McCrone objective). Some fibres are apparently altered to a brown colour and there are some natural organic fibres present also.

3.2.7 Anthophyllite

The Reference Asbestos Anthophyllite is a moderate length, soft, grey-white fibre with a silky lustre. It is needle-like when separated but appears flexible and inelastic in bundles because of the fine nature of the fibres. In PLM it is observed as needle-like fibres and fibre bundles with typical split or "shaving-brush" ends. It is colourless and non-pleochroic, although coarse fibres may be grey or grey-brown and faintly pleochroic. Between crossed polarising lenses it shows a low-moderate birefringence with first order or lower second order interference colours frequently displayed. It has straight extinction and is optically length slow. In a liquid with RI 1.605 it shows dispersion staining colours of blue-red/yellow (PCOM) or purple/gold (McCrone objective). The anthophyllite contains a proportion of fibrous talc which is recognised as ribbon-like fibres with many kinks, sharp curves, high birefringence and lower refractive indices (≈ 1.590). Platey talc is also present with similar RI's but lower birefringence.

3.3 Comparisons with Published Optical Properties

3.3.1 Chrysotiles

The optical properties of both Reference Asbestos Chrysotiles are fully consistent with all of the published optical properties data; the refractive indices shown by the dispersion stain colours in RI liquid 1.550 are in the middle of the range of the main sources of chrysotile described in ARC Technical Note 3 (1978), the range described by in the EPA interim test method (EPA 1982), Deer

et al (1963), McCrone and Stewart (1979), Monkman (1979) etc, as shown in Table 2a. The unusual brown pleochroic fibres in the Zimbabwe Chrysotile are recorded here for the first time and it should be noted that there are other coloured varieties of chrysotile which may then show pleochroism. The optical properties of UICC Chrysotile are very similar to the Reference Chrysotiles but the fibres of the UICC variety are very much finer and shorter.

3.3.2 Amosite

The optical properties of the Reference Asbestos Amosite are fully consistent with all of the published optical property data. The refractive indices are shown by the dispersion staining colours in RI liquid 1.670 to be within the ranges described by the references given above (3.3.1) as shown in Table 2b. The brown amosite varieties and those referred to as Montasite are generally similar to the Reference Amosite but have the appearance of having been altered, perhaps by superficial weathering. They contain brown iron oxide or hydroxide particles and only a few of the fibres show dispersion staining colours in liquids with RI of 1.670 or 1.700. These varieties are very rarely found and most amosite-containing products contain amosite identical to the Reference Mineral Type. The UICC Amosite is effectively identical to the Reference Mineral in all but fibre size which is very fine and comparatively short as a result of heavy milling.

Many amosite samples contain fibres which are green or green in parts and which are very similar to or actually identical to actinolite (qv).

3.3.3 Crocidolite

The optical properties of the Reference Asbestos Crocidolite are fully consistent with all of the published optical property data. The refractive indices are shown by the dispersion staining colours in RI liquid 1.700 to be within the ranges described by the references given above (3.3.1) as shown in Table 2c. The UICC Crocidolite is effectively identical to the Reference Crocidolite except that it has been heavily milled. Crocidolite from Wittenoom, Western Australia is also essentially the same although it has been found to contain some heavily oxidised (rust coloured) brittle fibres. The Bolivian Crocidolite (Cochabamba) is a very pale lavender coloured fibre with quite different optical properties to the Reference Crocidolite. This mineral might normally be better represented by a separate reference material but its rarity makes the provision of such a mineral unnecessary.

Heating of crocidolite to temperatures as low as 250°C can lead to a change in optic orientation from length fast to length slow with very little change in other properties.

3.3.4 Tremolite

The optical properties of the Reference Asbestos Tremolite are fully consistent with all the published optical property data. The refractive indices are shown by the dispersion staining colours in RI liquid 1.605 to be within the ranges described by the references given above (3.3.1) as shown in Table 2d. All of the true asbestos tremolites have optical properties effectively identical to the reference mineral ie. those with chemical compositions close to the pure calcium magnesium silicate and with fine flexible fibres in bundles such as the fine white asbestos from Jamestown, California and the asbestos from Korea. Tremolites like that from Ali di Stura and the coarser cleavage fragments in the Korean material differ from the asbestos tremolite in displaying oblique extinction.

The tremolite-ferro-actinolite mineral series forms a complete chemical sequence from the pure magnesium to the pure iron end-member compositions. There are a large number of occurrences of almost pure tremolites because of the common occurrence in metamorphic areas of dolomitic marbles and limestones which contain very little iron. Amphibole mineral occurrences with compositions close to tremolite-actinolite but with iron contents in the range of 0.5 to 2.5 atoms per formula unit are rare which is why the use of the term tremolite was so restricted in the first place and why it is still convenient to restrict the use of the term tremolite asbestos to a very narrow range of refractive indices. The published range of refractive indices from the US EPA represents the full range from tremolite to ferro-actinolite and is too broad to be useful for the identification of tremolite.

3.3.5 Actinolite

The optical properties of the Reference Asbestos Actinolite are fully compatible with the published optical property data. The refractive indices are shown by the dispersion staining colours in RI liquid 1.640 to be within the ranges described by the references given above (3.3.1) as shown in Table 2e.

Actinolite asbestos minerals such as the Prieskaite from South Africa have different compositions although they are in the same solid solution series and have different refractive indices when examined in detail. The range of refractive indices given by Monkman (1979) and by Deer et al (1963) and the US EPA represent the full variation that is mineralogically acceptable within the terms actinolite and ferro-actinolite (and tremolite in the EPA range) rather than the range of refractive indices that have been found for actual actinolite asbestos minerals.

Common hornblende, edenite and other amphibole minerals with significant substitution of aluminium for iron and silicon and addition of sodium to the crystal lattice may have almost identical optical properties to the non-asbestos actinolites but these amphiboles have not been found as asbestos varieties.

3.3.6 Anthophyllite

The optical properties of the Reference Asbestos Anthophyllite are fully compatible with the published optical property data. The refractive indices are shown by the dispersion staining colours in RI liquid 1.605 to be within the ranges described by the reference given above (3.3.1) and shown in Table 2f. The UICC Anthophyllite is identical to the reference mineral except that it has been more heavily milled and is a finer, shorter fibre. Materials identified as anthophyllite asbestos from Rajasthan have been shown by chemical analysis of individual fibres to be mixtures of anthophyllite and tremolite. This misidentification almost certainly stems from the mistaken expectation that the tremolite should not have straight extinction and indicates a general problem in differentiating between tremolite asbestos and anthophyllite asbestos using optical properties only. The optical properties are so similar that this differentiation will always be very difficult. The tremolite asbestos minerals are usually completely colourless or pale green while the anthophyllites are usually colourless or pale brown. Tremolite asbestos will be more likely to contain some obliquely extinguishing cleavage fragments although the absence of these would not mean that the asbestos was undoubtedly anthophyllite.

4. ELECTRON MICROSCOPY

4.1 Chrysotile

Reference Asbestos Chrysotile fibres are shown in the SEM photomicrographs in Plates 1a-d. They show typical curly fibrous morphologies with obvious kinking of the fibres. Fibre diameters down to $0.05\mu\text{m}$ were visible by SEM at magnifications of 10,000X. These fibrils were also clearly seen to exhibit the characteristic tubular morphology when examined by TEM.

The mean percentages and standard deviations of the ED X-ray counts for the principal elements - magnesium, silicon and iron, in the two Reference Chrysotiles and UICC Chrysotile A are given in Table 3a. The data on which these are based are shown graphically in Figure 1a-c. These show very similar composition ranges for the three minerals with X-ray counts for silicon between 68% and 76%, magnesium between 17% and 25% and iron between 2% and 13%. The Cassiar Chrysotile has much the most restricted range of composition while the Zimbabwean Chrysotile shows larger standard deviations for the iron and magnesium contents than either the Cassiar or the UICC. These may well reflect the presence of the optically unusual varieties in the Zimbabwe Chrysotile described in section 3.2.2. The mean compositions of the three minerals are all very close; the overall average X-ray counts for silicon were 72.2%, magnesium of 21.9% and iron of 5.9%.

4.2 Amosite

The Reference Asbestos Amosite fibres are shown in the SEM photomicrographs in Plates 2a&b. The typical needle-like form with gently curved fibres, fibre bundles and the tabular (rectangular cross section) shape are obvious.

The mean percentages and standard deviations of the ED X-ray counts for the principal elements - iron, silicon, magnesium and manganese of the amosites examined are given in Table 3b. The data upon which these are based are shown graphically in Figure 2a-c. These show almost identical narrow ranges for all elements in the Reference Amosite and in the UICC Amosite. Iron counts range between about 65-75%, silicon from 24-32% and magnesium around 1%. The brown amosite and montasite have lower manganese content which may be a result of the apparent weathering. The mean composition of the minerals are very close indeed with an overall X-ray count for silicon of 28.6%, iron of 67.1%, magnesium 0.8% and manganese 2.8%.

4.3 Crocidolite

The Reference Asbestos Crocidolite fibres are shown in the SEM photomicrographs in Plates 3a&b. The typical needle-like forms with gently curved fibres and fibre bundles are obvious and the fibres are distinctly finer than the amosites with diameters down to $<0.1\mu\text{m}$ visible by SEM at 10,000X magnification.

The mean percentages and standard deviations of the ED X-ray counts for the principal elements, silicon, iron, sodium and magnesium of the crocidolites examined are given in Table 3c. The data upon which these are based are shown graphically in Figure 3a-d. The chemical similarities between the Reference Crocidolite and the UICC Crocidolite are very clear. The silicon ranges from 30-40% and the iron from 58-70%. The Wittenoom Crocidolite is also very similar although both magnesium and sodium are slightly higher and the silicon lower in this variety. The mean compositions for these

three types are all very similar with overall averages silicon content of 35.1%, iron 63.8%, sodium 0.4% and magnesium 0.6%. The Bolivian Crocidolite is entirely different in its chemical composition and does not appear to be a true crocidolite. It has higher X-ray counts for magnesium, much higher counts for silicon and lower for iron than any of the other three crocidolites.

4.4 Tremolite

The Reference Asbestos Tremolite fibres are shown in the SEM photomicrographs in Plates 4a&b. The typical needle-like forms with gently curved fibres, fibre bundles and the tabular shapes to the fibres are obvious. The fibres are frequently very fine with diameters down to $<0.1\mu\text{m}$ visible by SEM at 10,000X magnification. The mean percentages and standard deviations of the ED X-ray counts for the principal elements, silicon, calcium, magnesium and iron of the tremolites examined are given in Table 3d. The data upon which these are based are shown graphically in Figures 4a-d. These show that the Reference Tremolite and the tremolite from Jamestown are very closely similar although the latter has slightly higher silicon, lower calcium and higher iron. The Korean Tremolite is also similar but with a somewhat greater variability for all elements. The Italian Tremolite has generally lower silicon, calcium and magnesium and higher iron contents. The silicon contents range from about 50% to about 58%, calcium from 30% to 40%, iron from 0% to 10% and magnesium from about 5% to 10%. The average elemental X-ray contents for the three true asbestos minerals (excluding the Italian tremolite) are silicon 54.5%, calcium 36.0%, magnesium 6.0% and iron 3.4%.

4.5 Actinolite

The Reference Asbestos Actinolite fibres are shown in the SEM photomicrographs in Plates 5a&b. The typical needle-like forms with gently curved fibres and fibre bundles with extremely fine fibres indeed are obvious. Many fibres can be seen by SEM with diameters less than $0.1\mu\text{m}$ at 10,000X magnification.

The mean percentages and standard deviations of the ED X-ray counts for the principal elements silicon, iron, magnesium and calcium of the three actinolites examined are given in Table 3e. The data upon which these are based are shown graphically in Figure 5a-c. The chemical compositions of the three actinolites are all different. The individual minerals all have narrow ranges of compositions but, as would be expected from the discussions in section 3.3.5, there are clear differences in the proportions of the main elements. The silicon content of the Reference Actinolite ranges between 34% to about 42% while that of the Prieska Actinolite is between 27% and about 35%. The iron contents range between 30-40% and 45-55% respectively and the calcium contents between 20-30% and 10-20% respectively. The increasing iron content and its effect on the micro-absorption of X-rays would explain most of the decreases in the silicon and calcium X-ray counts. The difference in the magnesium contents is certainly real since the magnesium content is inversely related to the iron content in the actinolites. The Norwegian Actinolite, a prismatic amphibole type, is included to show the lower iron, higher silicon and magnesium variations that are possible within the minerals classed as actinolites and ferro-actinolites. Both the Reference Asbestos Actinolite and the Prieskaite are more properly referred to as ferro-actinolite as in the classification system of the Mineralogical Association (Leake 1978) but actinolite is broadly accepted by common usage, it is probably less confusing to retain the simpler name.

4.6 Anthophyllite

The Reference Asbestos Anthophyllite fibres are shown in the SEM photomicrographs in Plates 6a&b. The typical needle-like fibres with gently curved fibres and tabular shapes and fibre bundles are obvious. Also obvious are the large thin flexed plates and ribbons of talc or chlorite. These may be identified by the clear kinks in the shapes of deformed fibres and plates since the lack of elasticity is very characteristic of these minerals.

The mean percentages and standard deviations of the ED X-ray counts for the principal elements, silicon, magnesium and iron in the anthophyllite examined are given in Table 3f. The data upon which these are based are shown in Figures 6a&b. The chemical properties of the Reference Anthophyllite and UICC Anthophyllite are clearly almost identical but the chemistries are very unusual in comparison to the other asbestos minerals described earlier. The mean compositions of 100 fibre analyses are very close but the ranges of composition are very much wider than the tightly clustered compositions of the chrysotiles for example. Silicon contents vary between 55% and 75%, magnesium contents between 3% and 13% and iron contents between 5% and 37%. This variability in composition for both the Reference Asbestos Anthophyllite and the UICC Anthophyllite probably indicates a common source for both minerals but we have been unable to establish this exactly. The variability in colour described in earlier sections may reflect this variation in composition; the more strongly coloured fibres being richer in iron. It is not known at this time how typical this variability might be of other anthophyllite sources.

5. INFRARED SPECTROPHOTOMETRY (IR) AND X-RAY DIFFRACTOMETRY (XRD)

5.1 Chrysotile

Parts of the IR spectra for the two Reference Asbestos Chrysotiles and UICC Chrysotile are shown in Figure 7a-c. All three spectra are effectively identical and very similar to that published by Van Olphen & Fripiat (1979). The strong absorbance bands at 3690 and 3648cm⁻¹ have been omitted from the figures but they also are identical. There are slight variations in the relative intensities of the absorption bands and there may be two small additional absorbances in the Cassiar Chrysotile but these can not be ascribed to any particular mineral.

The X-ray diffraction patterns in Figures 8a-c are also essentially identical although the UICC shows more minor diffraction peaks probably as a result of being more finely divided and therefore more closely packed in the sampler holder. The data from Van Olphen and Fripiat (1979) indicate that some of the low angle ($<12.5^{\circ}2\theta$) diffraction peaks at least may be from other mineral impurities (eg chlorite).

Chemical digestion (Addison & Davies, 1990) of the three chrysotiles indicate that they contain very few impurities, $<2\%$ in total, but that these include quartz and magnetite.

5.2 Amosite

Parts of the IR spectra for the Reference Asbestos Amosite, UICC Amosite and the brown amosite, montasite are shown in Figures 9a-c. The three spectra are very similar, and similar absorbances around 3660-3670cm⁻¹ wavenumbers have been omitted from the figures for simplicity. The most obvious parts of the spectra are the increasing triplets from 1200cm⁻¹ to 1000cm⁻¹ usually associated with 5:-0 stretching but these are common to all of the amphiboles and many other silicates. The three small absorbance peaks between 800cm⁻¹ and 600cm⁻¹ appear to be related to the divalent metal proportions Fe, Mg and Ca and are very characteristic of amosite (grunerite) in their positions and intensities. The additional absorbance peak at 800cm⁻¹ and the increased absorption at 780cm⁻¹ in the spectrum of the brown amosite probably result from the presence of quartz.

The X-ray diffraction patterns of the Reference Amosite and the UICC Amosite are identical in most peak positions and differ only slightly in relative peak intensities (Figures 10a&b). As with the chrysotiles this may be the result of differences in sample packing for the coarse Reference Amosite and the fine UICC variety. The main diffraction peaks at $10.8^{\circ}2\theta$ ($\sim 9.2^{\circ}A$) about $29^{\circ}2\theta$ ($\sim 3.0^{\circ}A$) are very characteristic of the amphiboles.

5.3 Crocidolite

Parts of the IR spectra for the Reference Asbestos Crocidolite, Wittenoom Crocidolite and UICC Crocidolite are shown in Figures 11a-c. The three spectra are very similar in all but the relative intensities of the main absorbance bands at 1000cm⁻¹ and 470cm⁻¹ wavenumbers. The absorbance bands at 3650cm⁻¹ omitted from the figures are also identical. As with the other amphiboles the strong triplet absorption between 1200cm⁻¹ and 1000cm⁻¹ is generally characteristic and again the triplets between 800cm⁻¹ and 600cm⁻¹ are very characteristic and different from the other asbestos amphiboles as described earlier.

The X-ray diffraction patterns of the Reference, Wittenoom and UICC Crocidolites are shown in Figure 12a-c to be very similar. The strong diffraction peaks characteristic of amphiboles at 10.8° and $29^\circ 2\theta$ are common to all three as are most of the other lesser diffraction peaks. The Wittenoom Crocidolite appears to have additional peaks around 27° , $21^\circ 2\theta$ and others which may result from the presence of small amounts of quartz.

5.4 Tremolite

Parts of the absorption spectra of the Reference Asbestos Tremolite and tremolites from Jamestown, Korea and Italy are shown in Figures 13a-d. The spectra of the first three of these are very strikingly similar, even in the smallest absorption bands and shoulders. The complexity of the absorption bands from $1200\text{-}900\text{cm}^{-1}$ is characteristically different from that of the other amphibole asbestos minerals other than the actinolite. It is also clear that the divalent metal (Mg, Fe and Ca) differences between the tremolites and the amosites and crocidolites appear to have produced different absorption bands between 800cm^{-1} and 600cm^{-1} wavenumbers. Absorption bands around 3650cm^{-1} wavenumbers omitted from the figures are also very similar for all of the amphiboles. The resolution in absorption spectrum of the Italian Tremolite is less clear although the main bands are all present and the absorbance bands at 950cm^{-1} and 1000cm^{-1} are unusually strong. These may be a result of the comparatively coarse particle size of the ground prismatic crystalline tremolite.

The X-ray diffraction patterns of all four minerals are virtually identical, all with the strongest diffraction peaks at 10.8° and $29^\circ 2\theta$ which are characteristic of the amphiboles. The diffraction pattern of the Korean Tremolite has minor peaks at around 12.5° and $25^\circ 2\theta$ which are characteristic of serpentine minerals (chrysotile).

5.5 Actinolite

Parts of the absorption spectra of the Reference Asbestos Actinolite, and actinolites from Prieska and Norway are shown in Figures 15a-c. As would be expected from the compositional differences there are a number of differences in detail between the three spectra although all three are distinctly similar to each other and to a lesser extent to the tremolites. Indeed the Norwegian Actinolite which is chemically closest to tremolite has a spectrum which is closer to that of the tremolites than it is to the actinolites (despite having actinolite optical properties). Once again the absorption peaks in the region of $800\text{-}600\text{cm}^{-1}$ wavenumbers appear to be characteristic of the amphibole type. Absorption bands at around 3650cm^{-1} have been omitted from the figures.

The X-ray diffraction patterns of the Reference Asbestos Actinolite and the Norwegian Actinolite (Figure 16a&b) are very similar and show the typical diffraction peak patterns of the amphiboles with strong peaks at 10.8° and $29^\circ 2\theta$.

5.6 Anthophyllite

Parts of the absorption spectra of the Reference Asbestos Anthophyllite and the UICC Anthophyllite are shown in Figure 17a&b. The spectra are almost identical although the UICC Anthophyllite spectrum has peaks with slightly better resolution which might be a particle size effect since it is a more finely divided mineral. This variety also has a few small additional absorption bands. Absorption bands at around 3650cm^{-1} similar to all of the other amphiboles have been omitted from the diagram. The main absorption bands between 1200cm^{-1} and 1000cm^{-1} and the minor bands between 800cm^{-1} and 600cm^{-1} are all much simpler than with the other amphiboles described above which may be a result of the relatively simpler composition and orthorhombic crystal symmetry of the anthophyllite.

Both X-ray diffraction patterns (Figures 18a&b) are identical. They differ from the other amphiboles in the position of the strong diffraction peak at $10^{\circ}2\theta$ (instead of $10.8^{\circ}2\theta$) although the general form of the patterns are similar to the other amphiboles. The presence of talc and chlorite are indicated by the diffraction peaks at about 6.5° , 11° and $19^{\circ}2\theta$.

6. CONCLUSIONS

Sources of good quality asbestos reference minerals for each of the six named asbestos varieties in the Control of Asbestos at Work Regulations have been successfully identified, and around 5Kg of each have been obtained and prepared in forms suitable for supply to analytical laboratories for purposes of asbestos identification by optical microscope methods. The reference asbestos minerals are fully compatible with other established reference materials and other well known mineral types and with published mineralogical data. The asbestos reference minerals have been packaged securely and are now available to any bona-fide analytical laboratory for the stated purposes from the authors at the Institute of Occupational Medicine.

7. ACKNOWLEDGEMENTS

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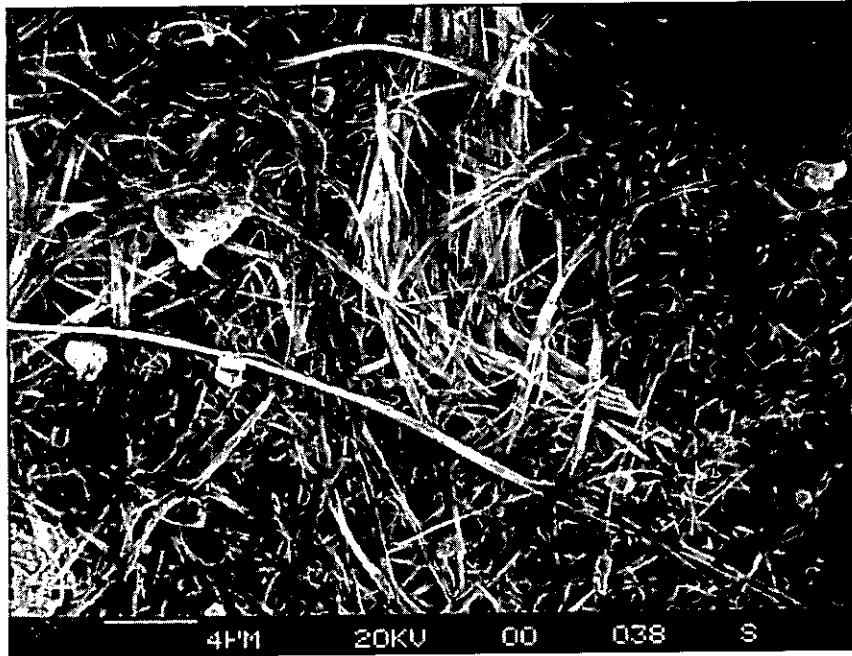


Plate 1a

Reference Chrysotile Asbestos 1 Cassiar - Mag. 3000X

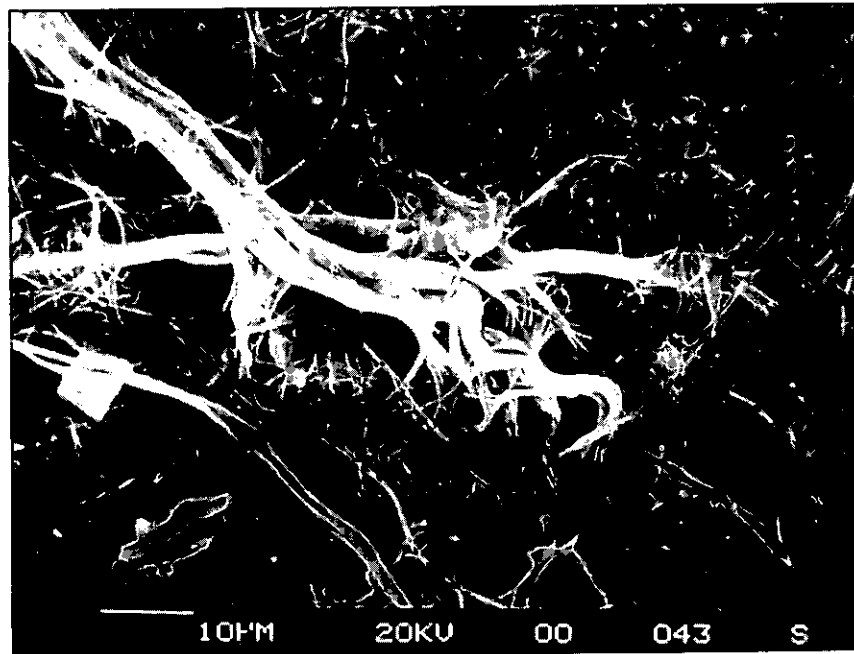


Plate 1b

Reference Chrysotile Asbestos 1 Cassiar - Mag. 1200X

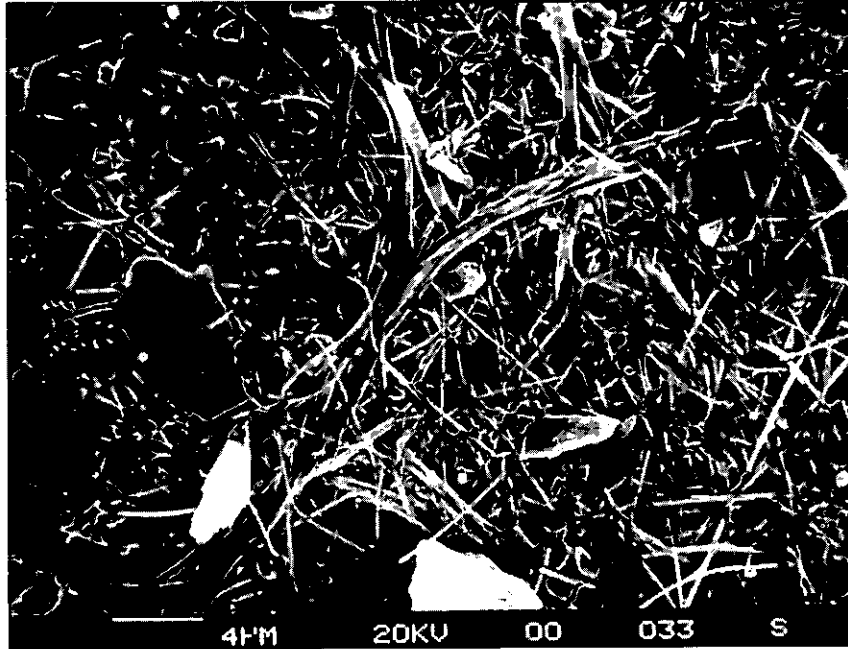


Plate 1c

Reference Chrysotile Asbestos 2 Zimbabwe - Mag. 3000X

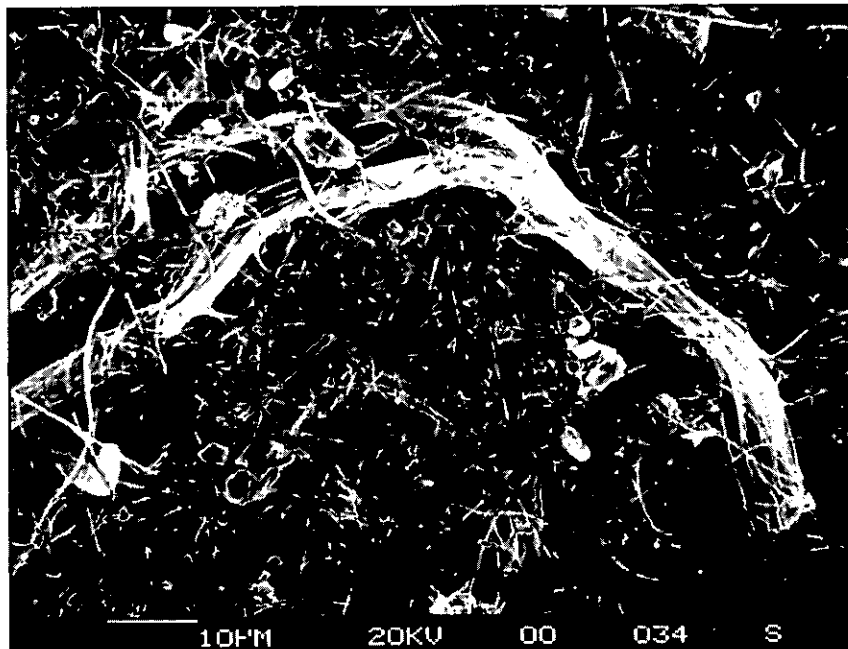


Plate 1d

Reference Chrysotile Asbestos 2 Zimbabwe - Mag. 1200X

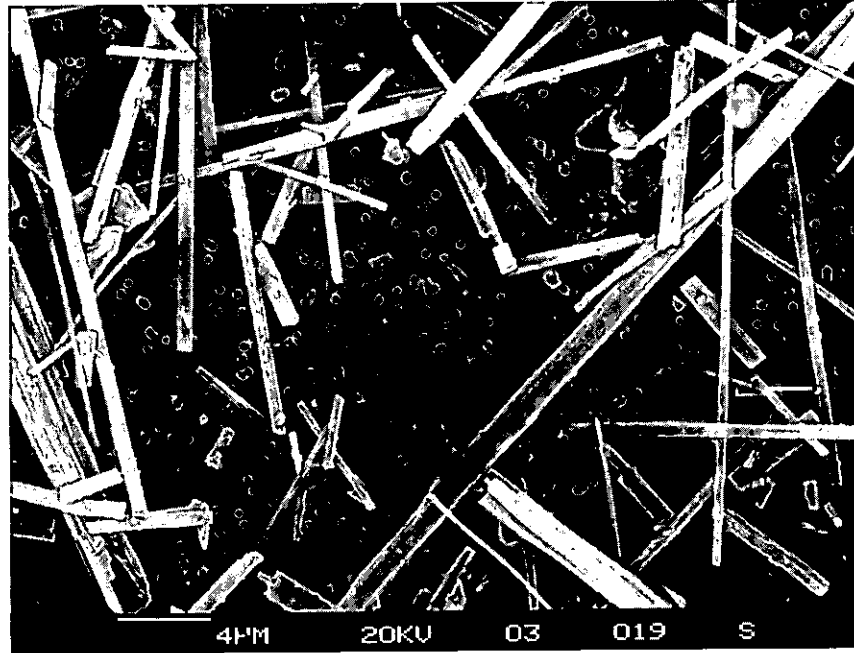


Plate 2a

Reference Amosite Asbestos - Mag. 3000X

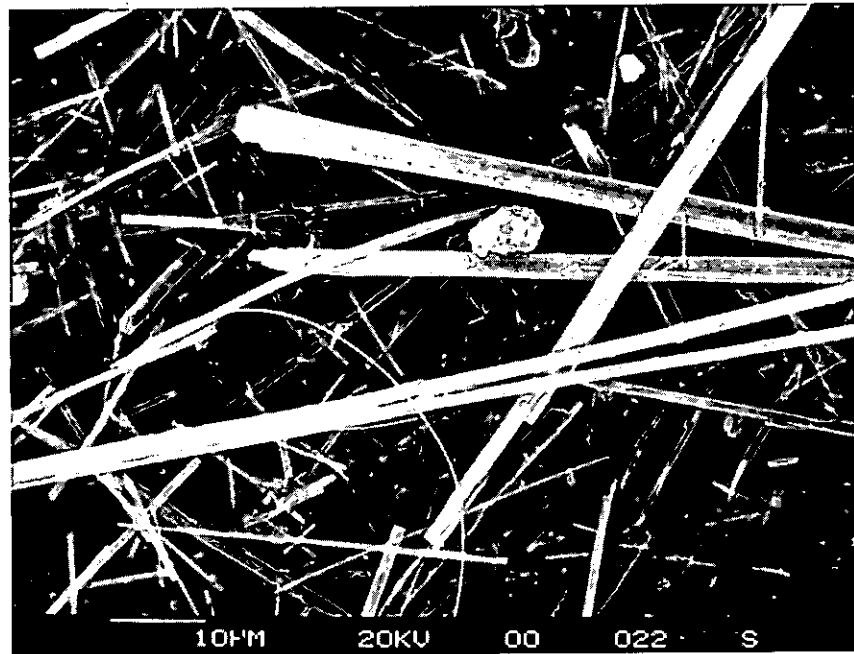


Plate 2b

Reference Amosite Asbestos - Mag. 1200X

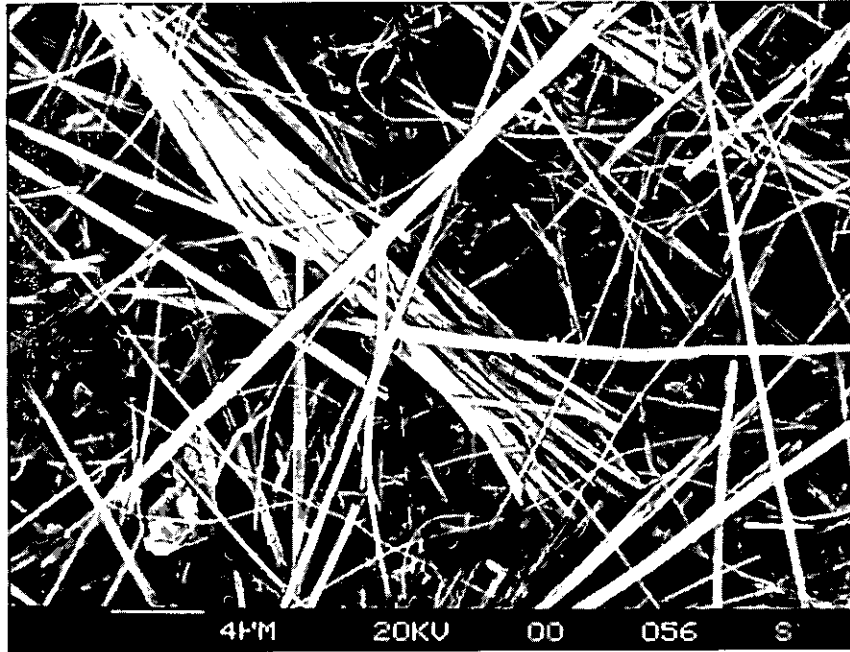


Plate 3a

Reference Crocidolite Asbestos - Mag. 3000X

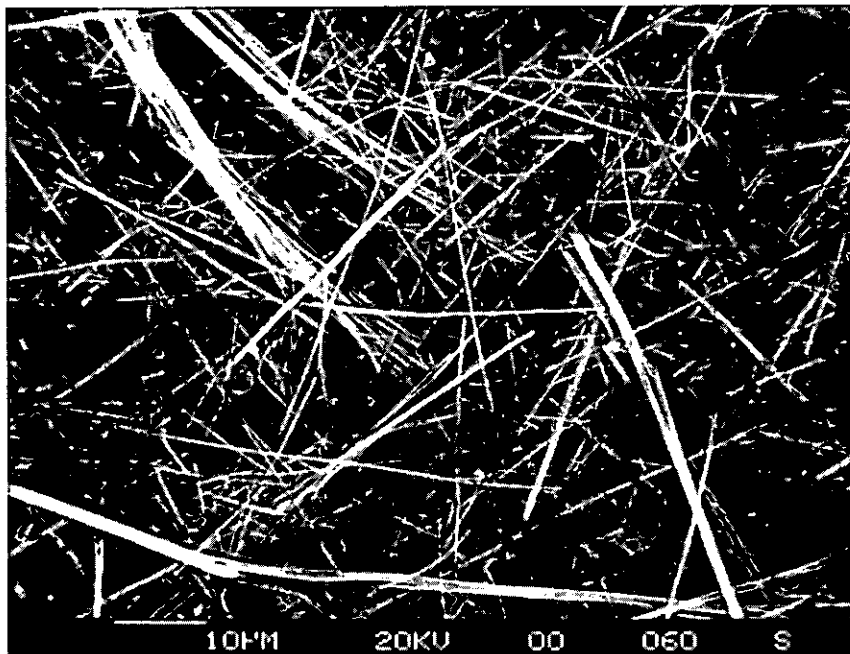


Plate 3b

Reference Crocidolite Asbestos - Mag. 1200X

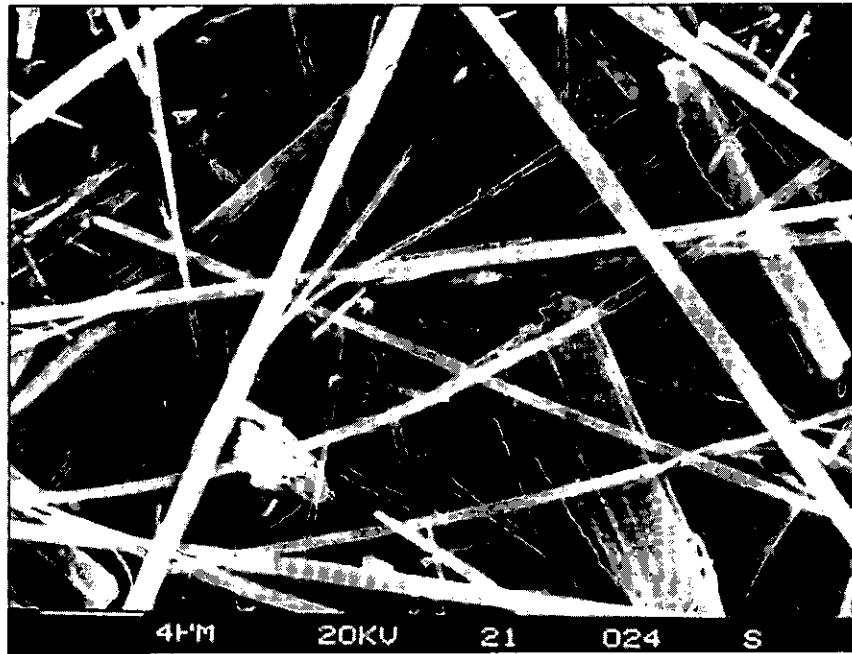


Plate 4a

Reference Tremolite Asbestos - Mag. 3000X

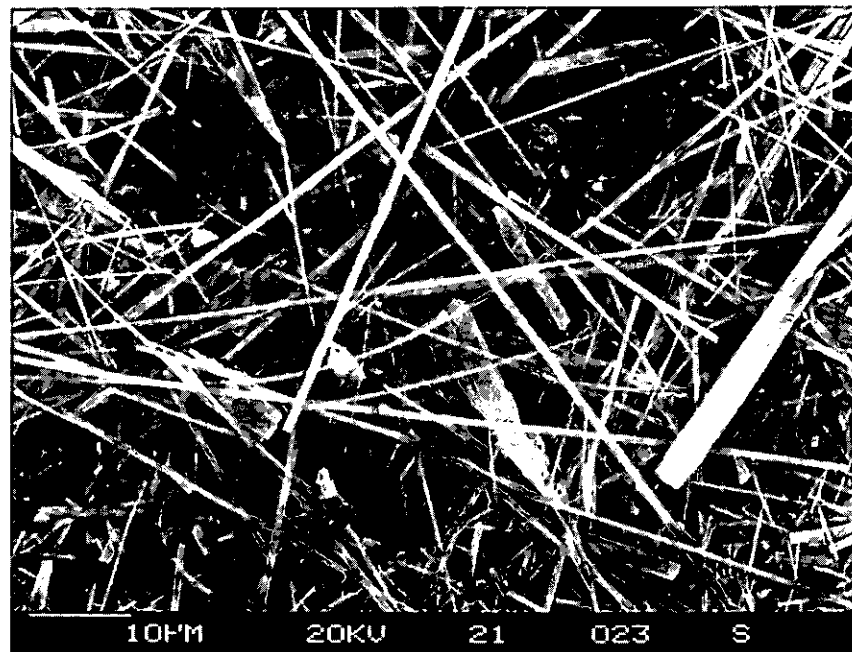


Plate 4b

Reference Tremolite Asbestos - Mag. 1200X

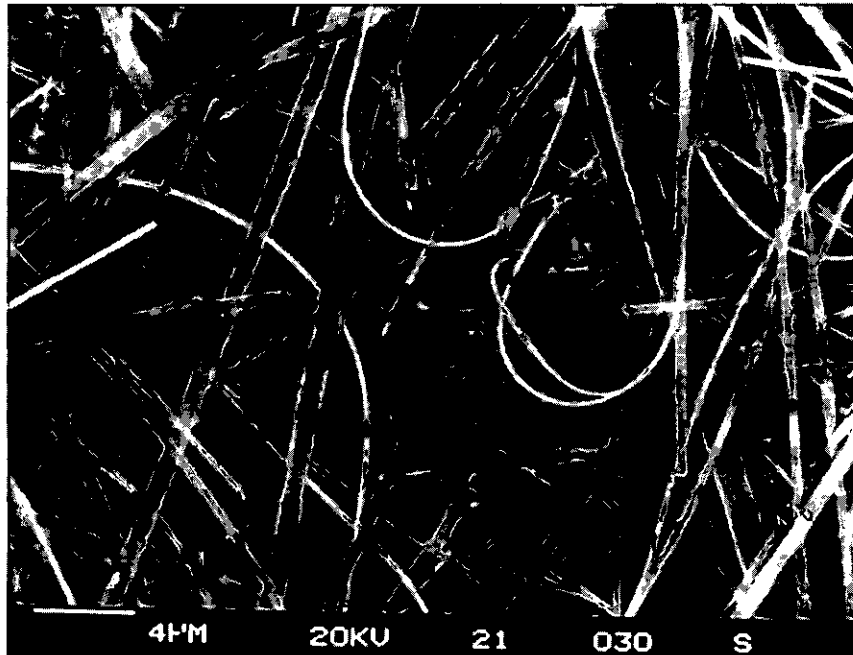


Plate 5a

Reference Actinolite Asbestos - Mag. 3000X

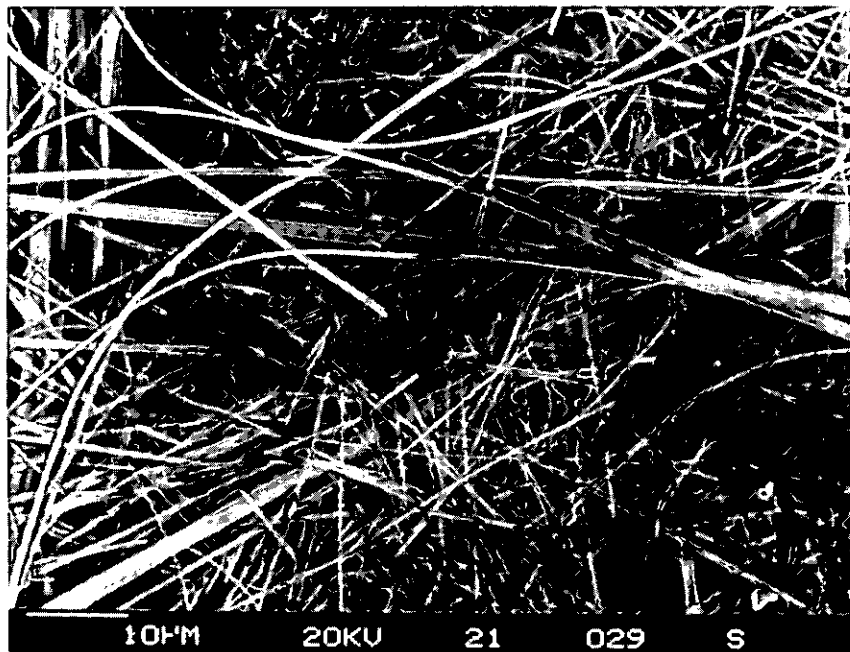


Plate 5b

Reference Actinolite Asbestos - Mag. 1200X

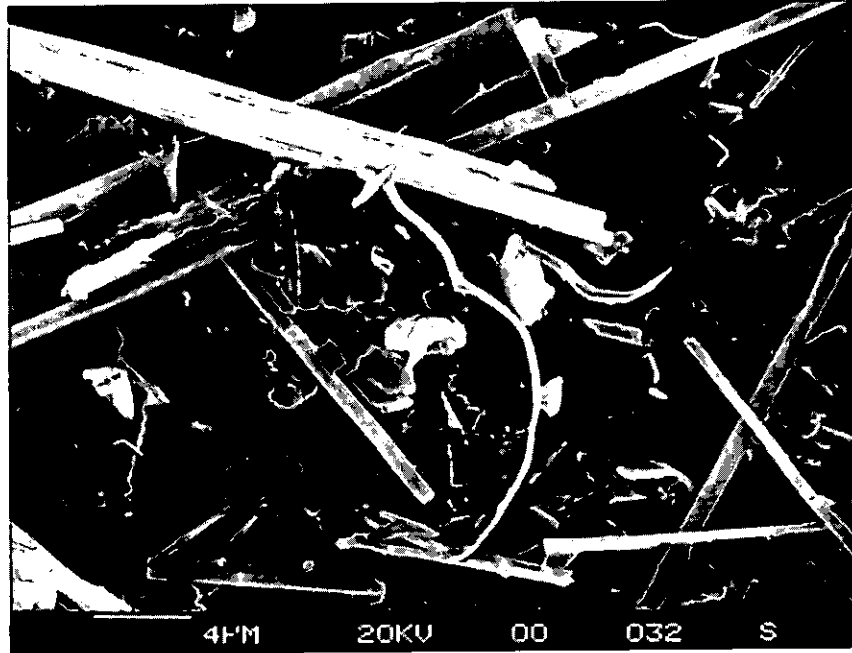


Plate 6a

Reference Anthophyllite Asbestos - Mag. 3000X

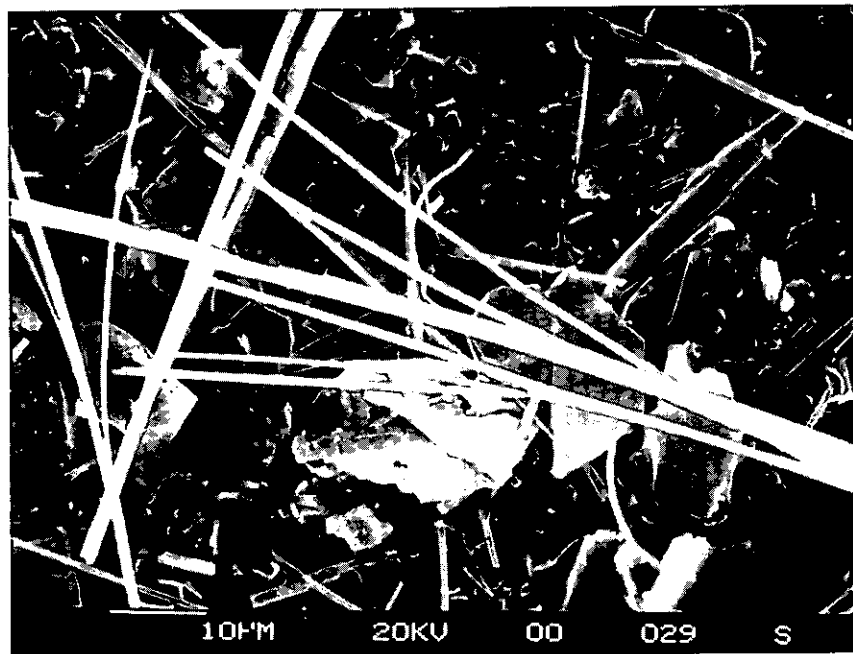
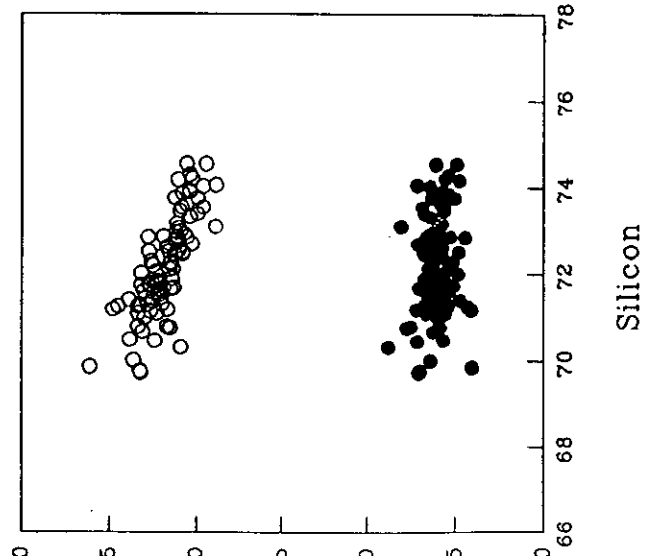


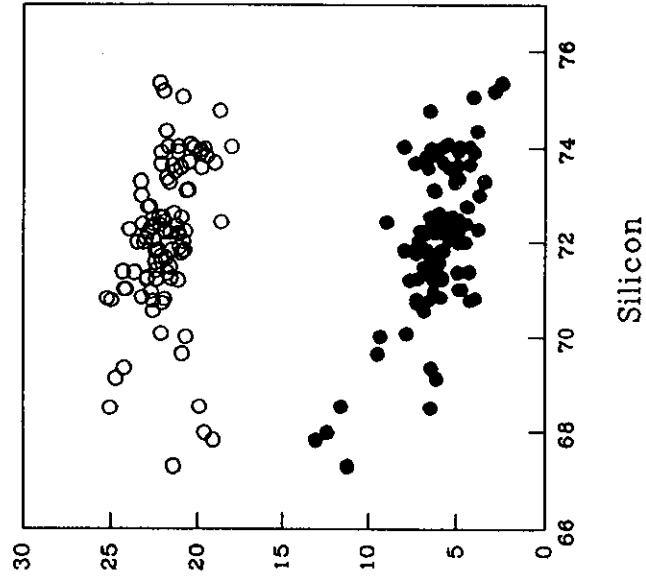
Plate 6b

Reference Anthophyllite Asbestos - Mag. 1200X

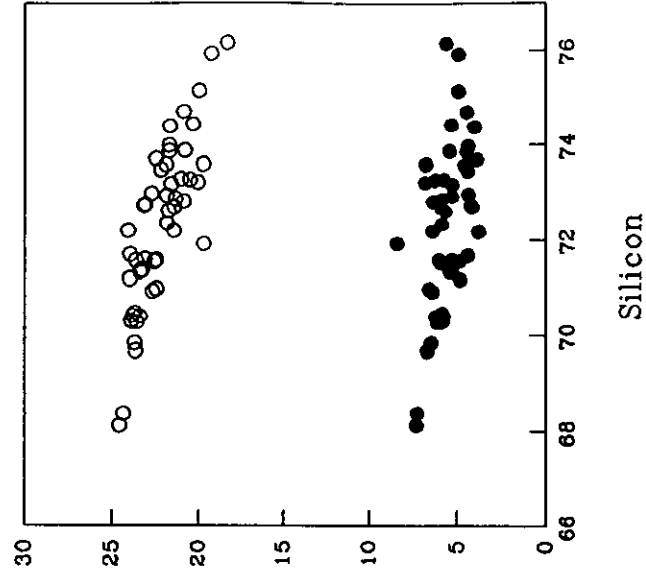
REFERENCE ASBESTOS CHRYSOTILE
Cassiar, British Columbia, Canada



REFERENCE ASBESTOS CHRYSOTILE
Shabani, Zimbabwe



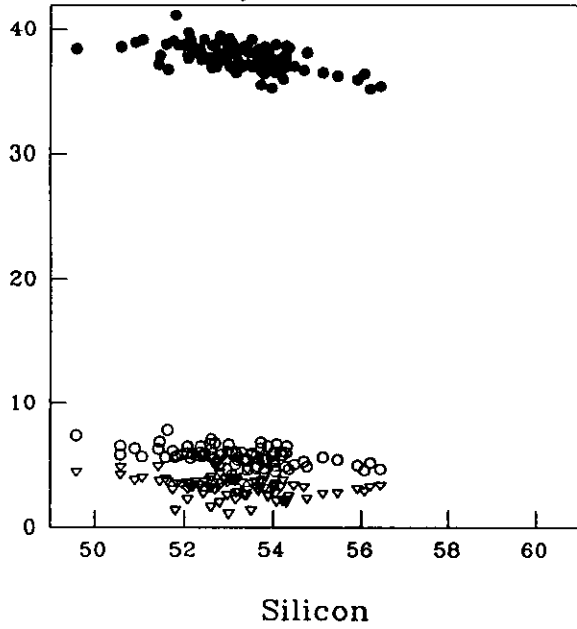
Chrysotile, UICC. A



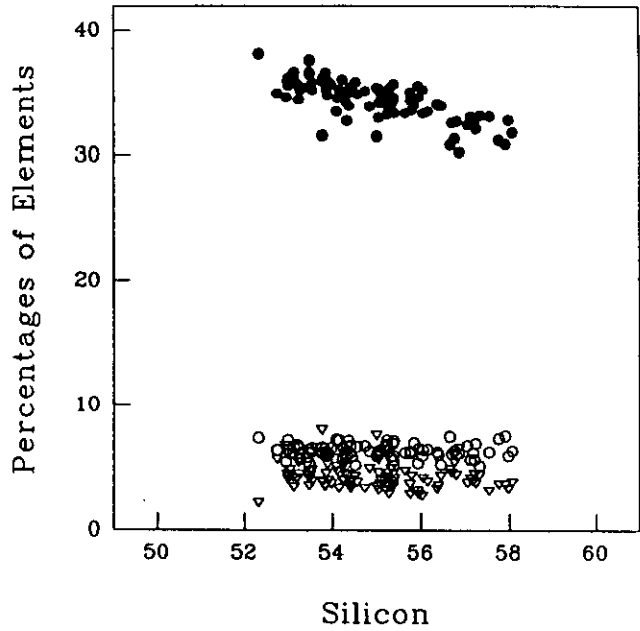
○ = Magnesium, ● = Iron

Figure 1a - c Chemical variability in STEM/EDX analyses of individual fibres of the Reference Asbestos Chrysotiles and UICC Chrysotile

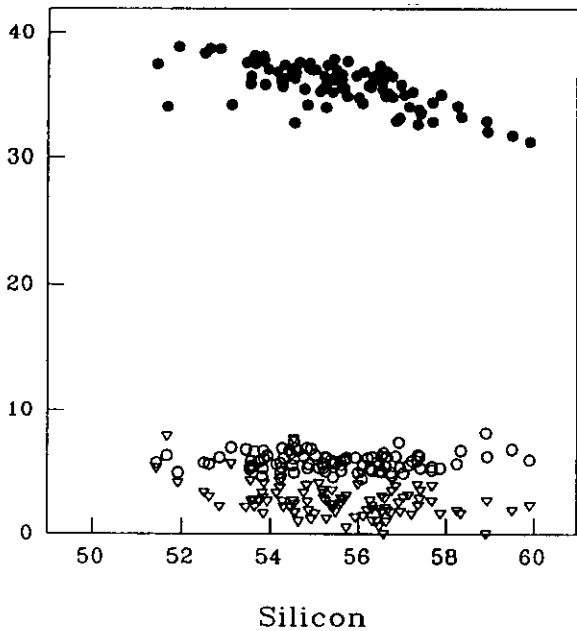
REFERENCE ASBESTOS TREMOLITE
Death Valley, California



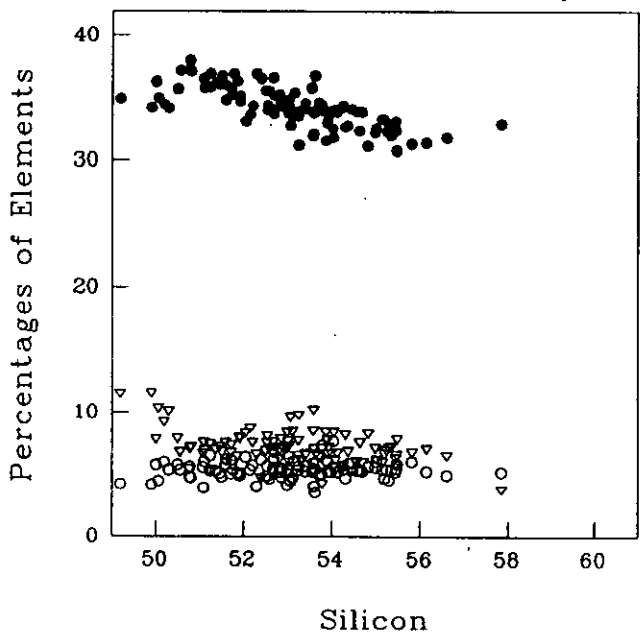
Tremolite, Jamestown, California



Tremolite, Korea



Tremolite, Ala di Stura, Italy

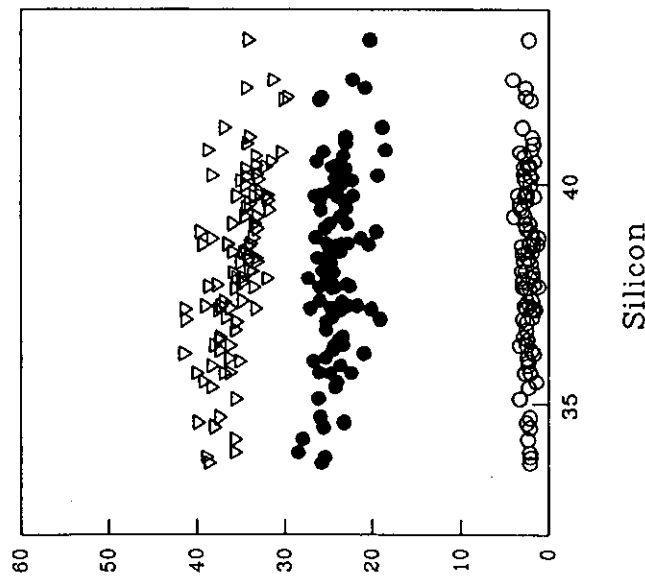


○ = Magnesium, ▽ = Iron, • = Calcium

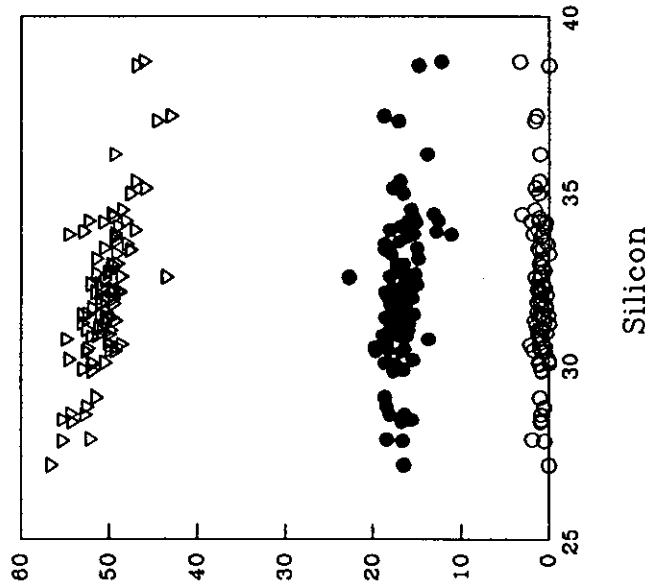
Figures 4a - d

Chemical variability in STEM/EDX analyses of individual fibres of the Reference Asbestos Tremolite and other tremolite types.

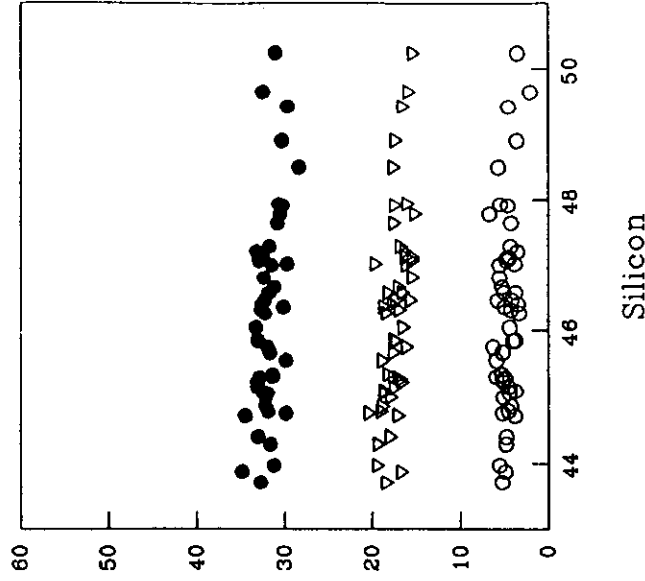
REFERENCE ASBESTOS ACTINOLITE
Ermington, Devon



Actinolite Asbestos
Prieska, South Africa

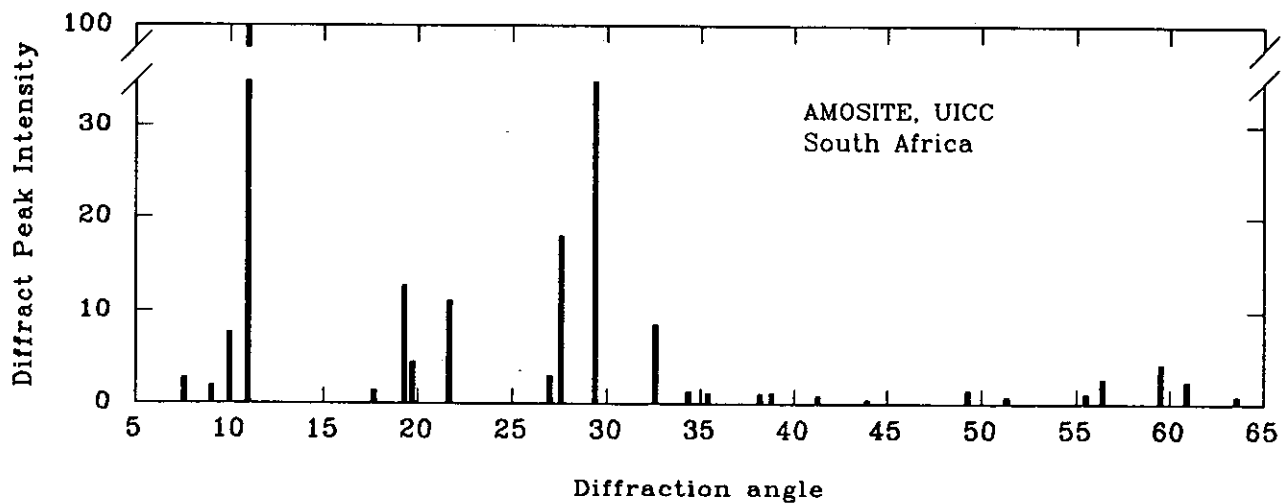
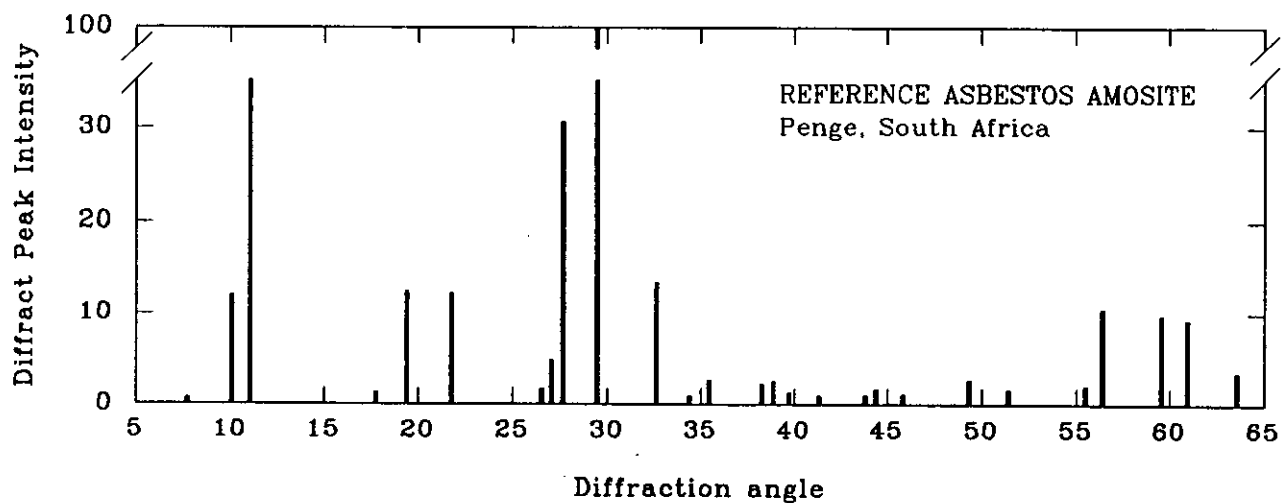


Actinolite
Norway



○ = Magnesium. ▽ = Iron, ● = Calcium.

Figure 5a - c Chemical variability in STEM/EDX analyses of individual fibres of Reference Asbestos Actinolite and other actinolite types.



Figures 10a & b X-ray diffraction patterns from 5° to $65^\circ 2\theta$ of the Reference Asbestos Amosite compared to that of UICC Amosite.

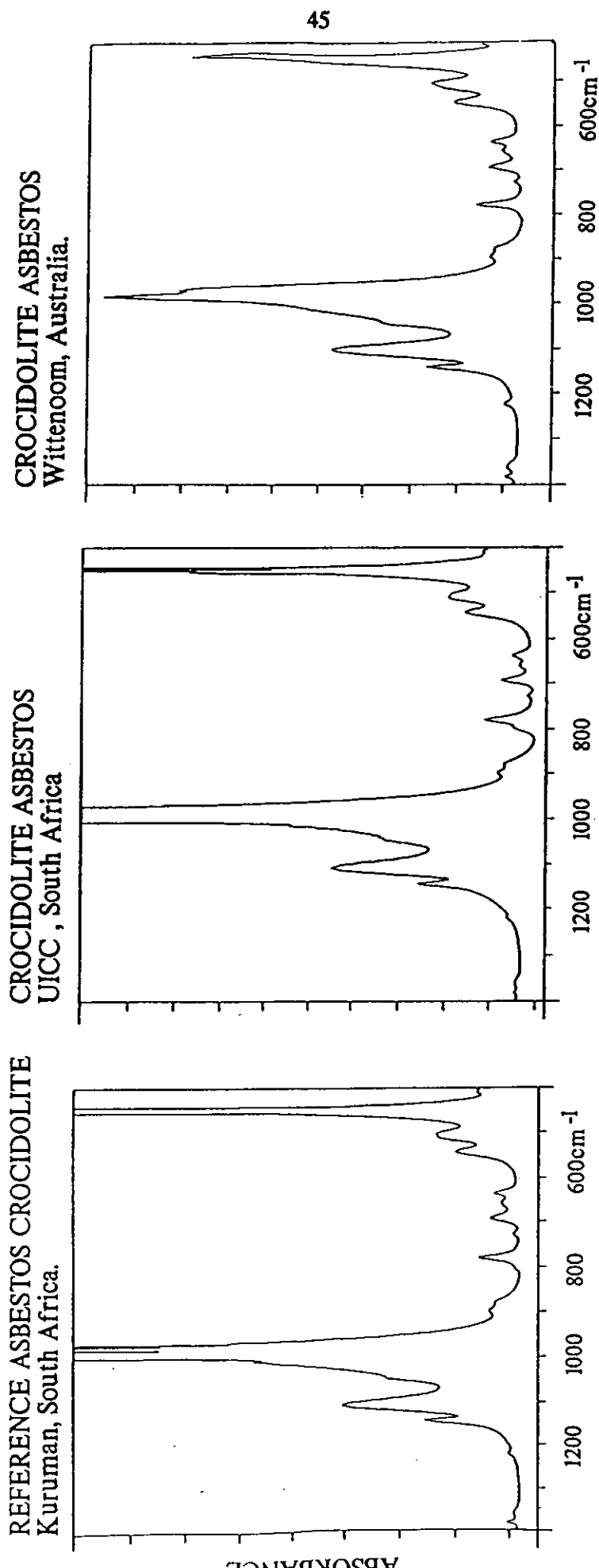
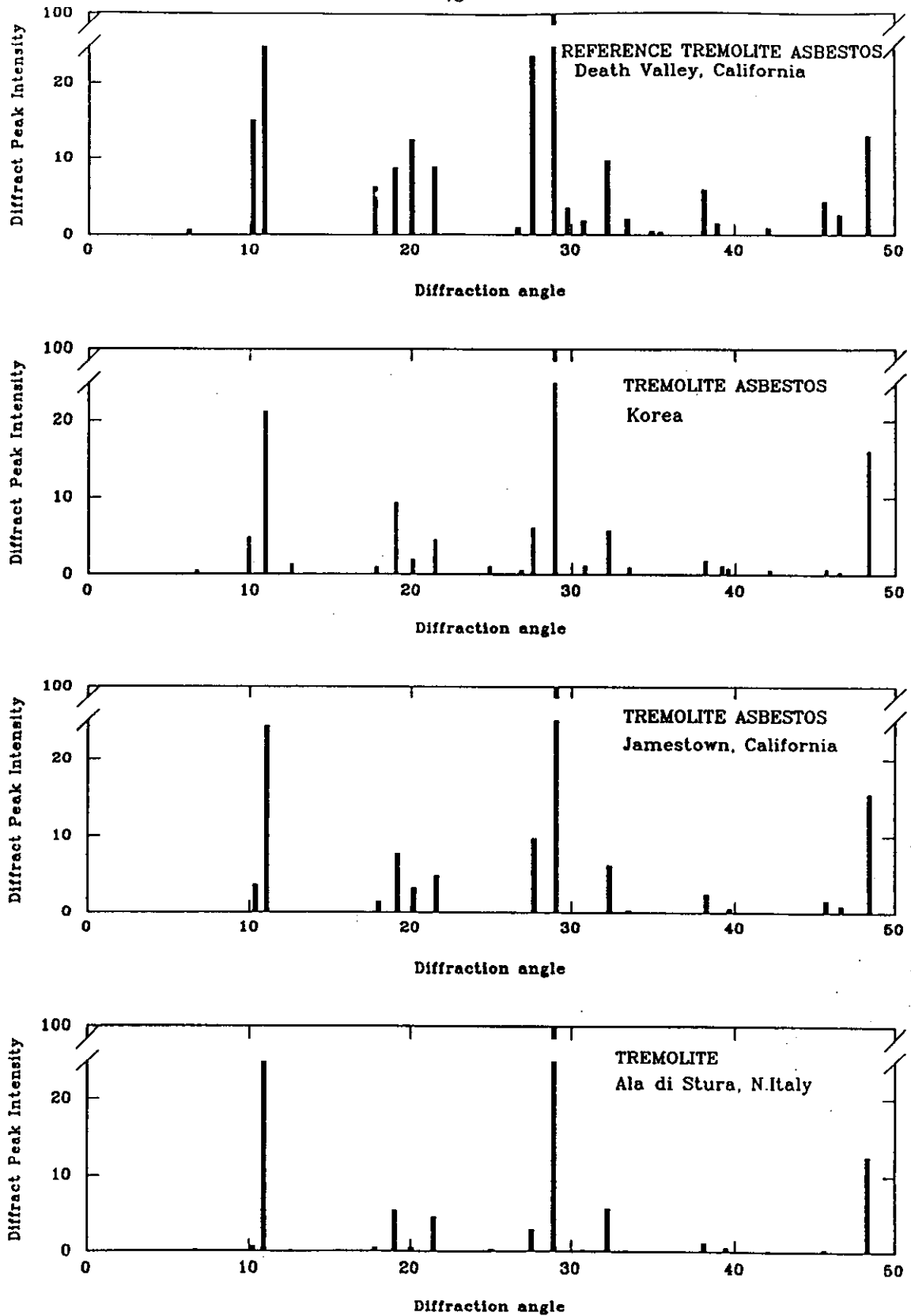


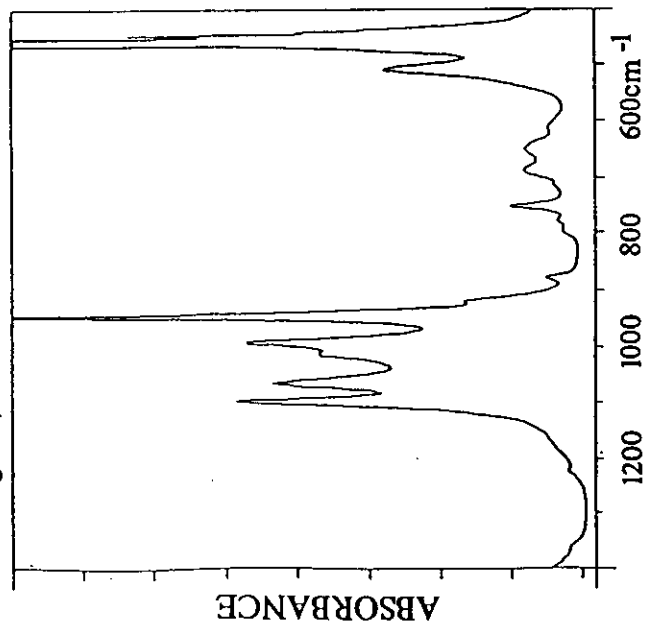
Figure 11a - c Infrared absorption spectrum from the Reference Asbestos Crocidolite compared to other crocidolites from South Africa and Wittenoom, Australia. Wavenumbers from 1400-400cm⁻¹ only are shown.



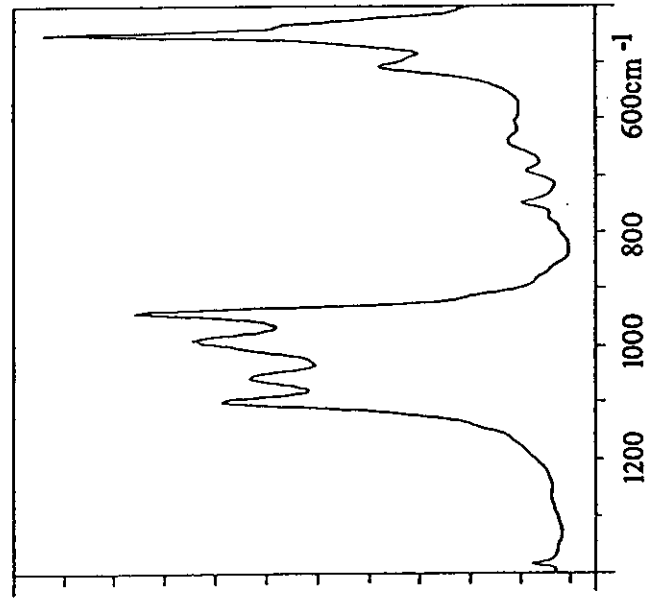
Figures 14a - d

X-ray diffraction patterns from 5° to $65^{\circ}2\theta$ for the Reference Asbestos Tremolite compared to various other asbestos and prismatic tremolite.

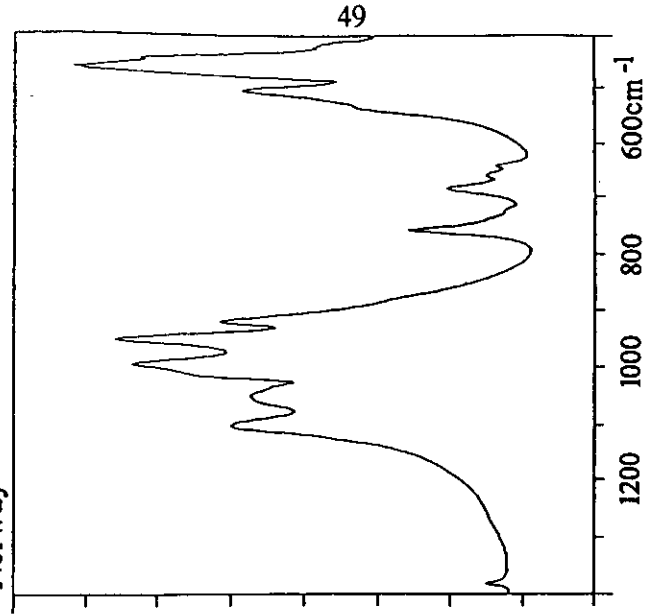
REFERENCE ASBESTOS ACTINOLITE
Ermington, Devon.



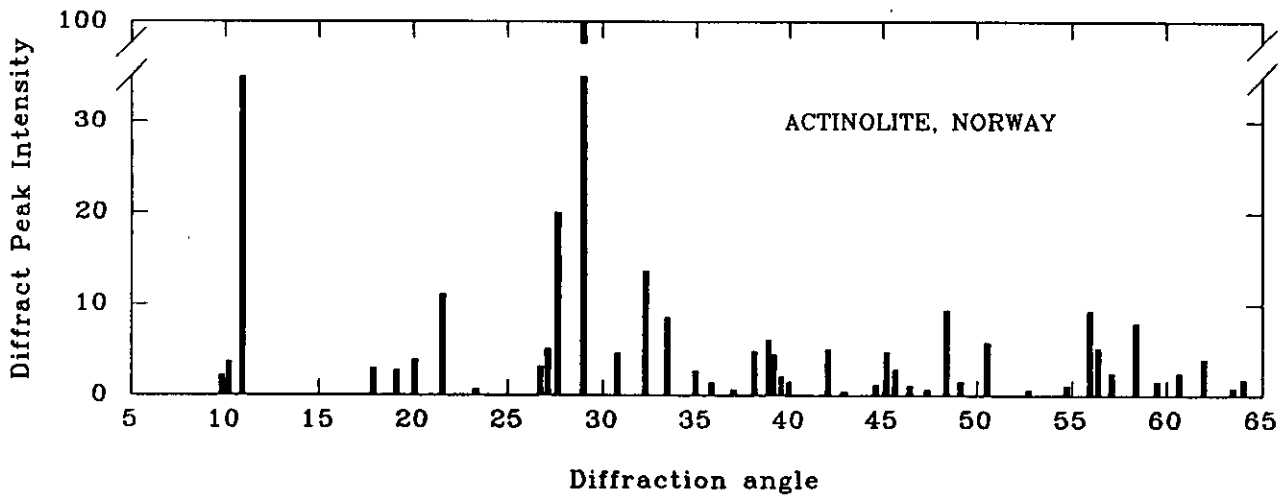
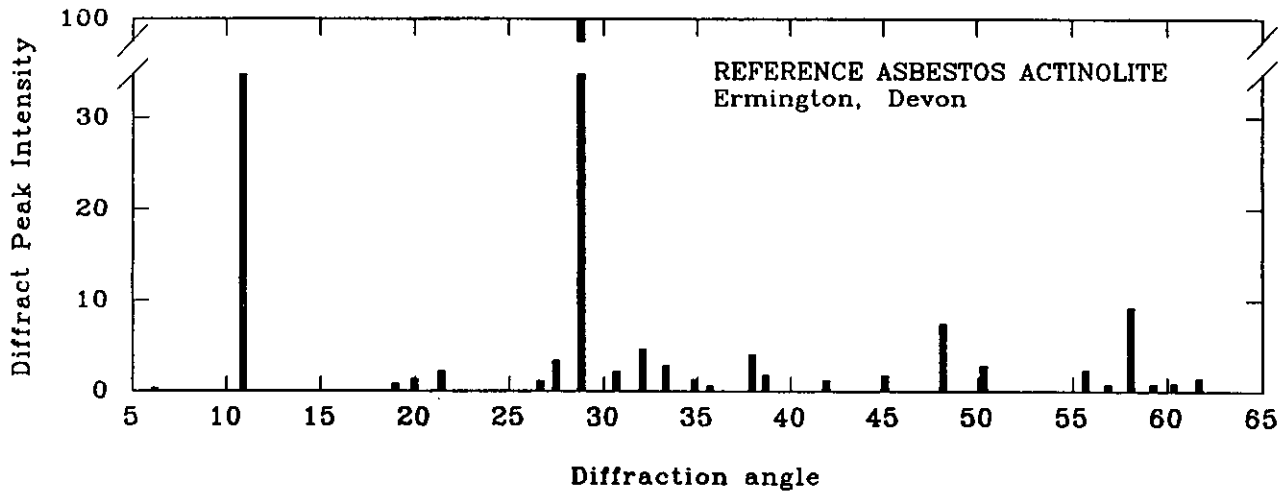
ACTINOLITE ASBESTOS (PRIESKAITE)
South Africa



ACTINOLITE
Norway



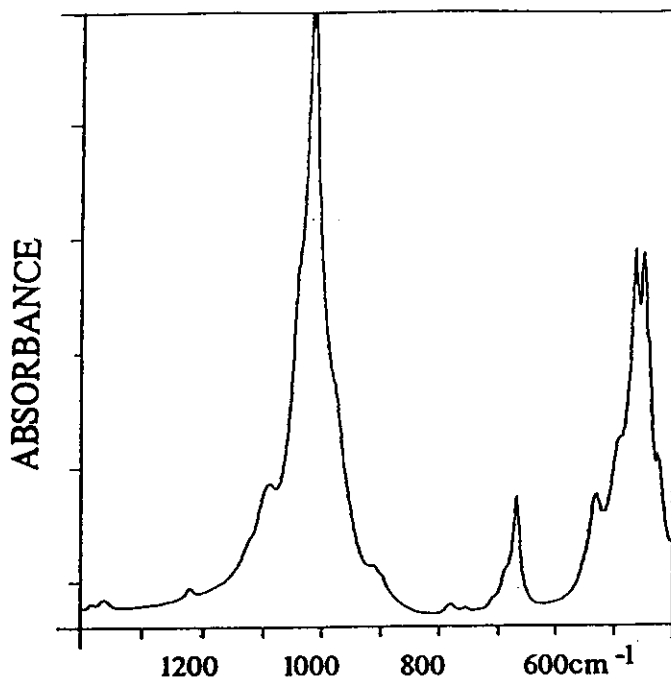
Figures 15a - c Infrared absorption spectrum from the Reference Asbestos Actinolite compared to other actinolites from South Africa and Norway. Wavenumbers from 1400-400cm⁻¹ only are shown.



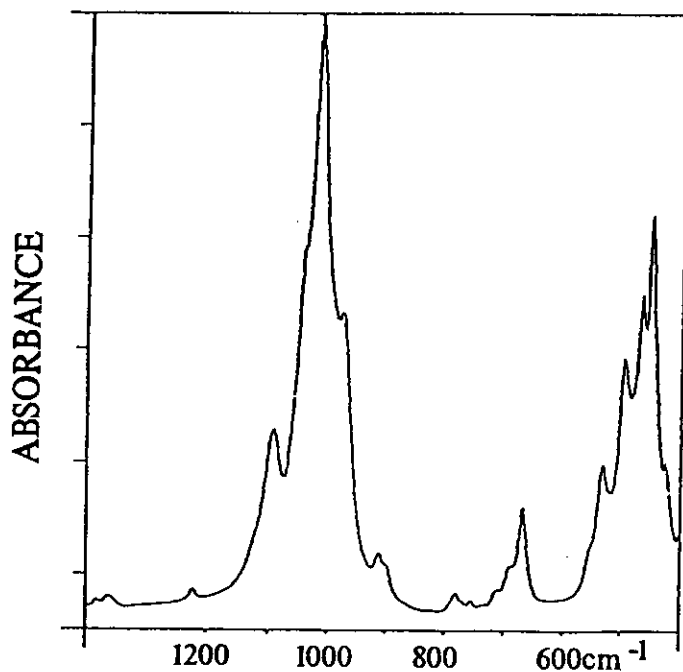
Figures 16a & b

X-ray diffraction patterns from 5° to $65^\circ 2\theta$ (Cu $K\alpha$ radiation) of the Reference Asbestos Actinolite compared to that of the Norwegian Actinolite.

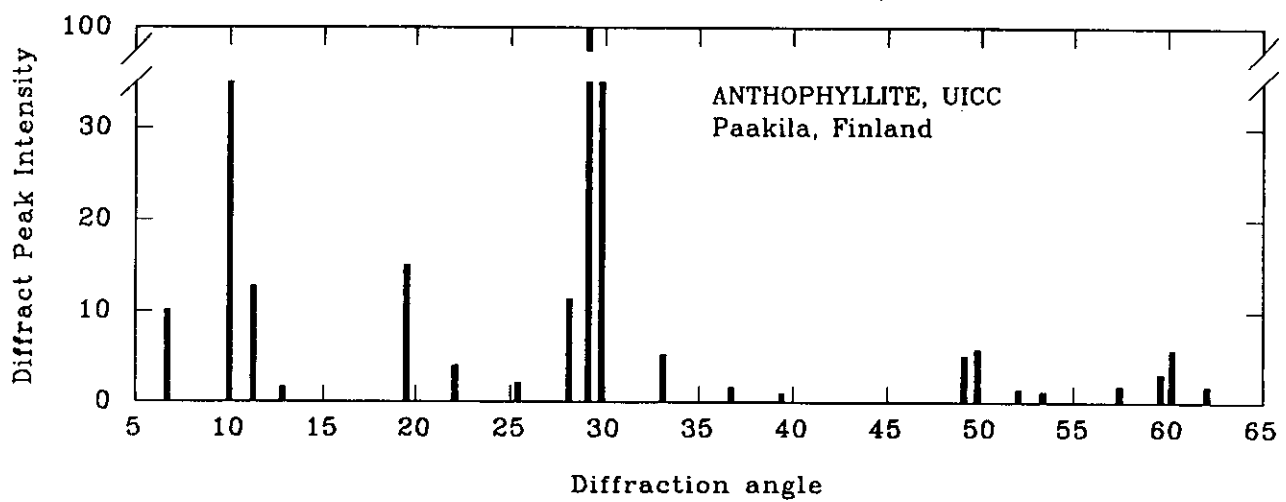
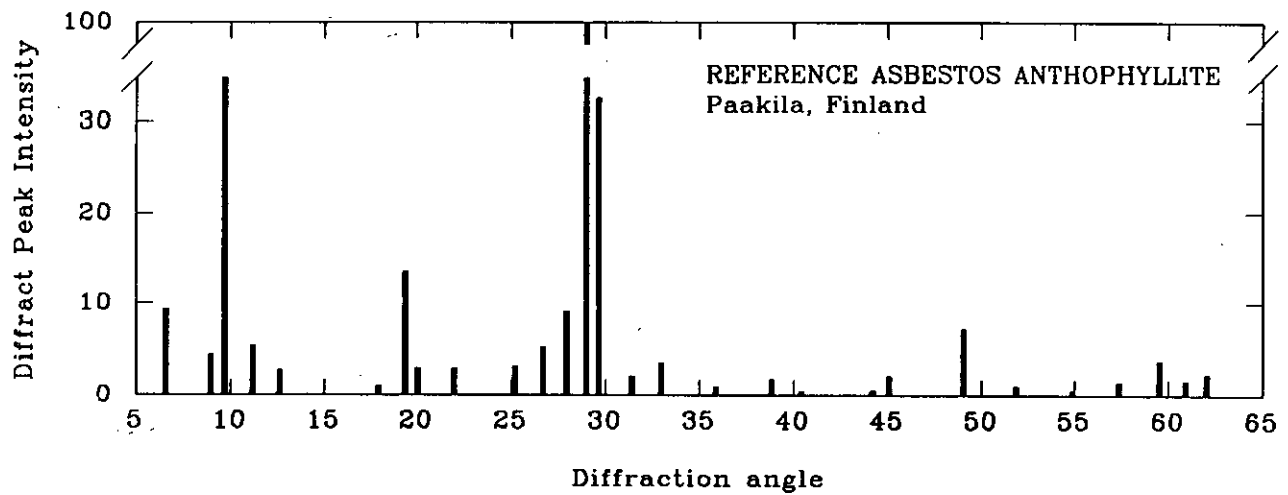
REFERENCE ASBESTOS ANTHOPHYLLITE
Finland



ANTHOPHYLLITE ASBESTOS
UICC, Finland



Figures 17a & b Infrared absorption spectrum of the Reference Asbestos Anthophyllite compared to that of the UICC Anthophyllite. Wavenumbers from 1400-400cm⁻¹ only are shown.



Figures 18a & b

X-ray diffraction patterns from 5° to $65^\circ 2\theta$ ($\text{Cu K}\alpha$ radiation) of the Reference Asbestos Anthophyllite compared to that of the UICC Anthophyllite.

Table 1. Summary of Optical Properties of Asbestos Reference Minerals

1. Phase 1 (x 100)
2. McCrone

ASBESTOS TYPE	MORPHOLOGY	COLOUR	PLEOCHROISM	BIREFRINGENCE	ORIENTATION	DISPERSION STAINING	R.I. LIQUID
CHRYSOPILE CASSAIR CANADA	CURLY-KINKED FIBRES	COLOURLESS	NIL	LOW MOD IN BUNDLES	L-SLOW STRAIGHT EXT	BLUE-GREEN/PURPLE BLUE/PURPLE	1. 1.550 2.
CHRYSOPILE ZIMBABWE	CURLY-KINKED FIBRES	COLOURLESS	NIL	LOW	L-SLOW STRAIGHT EXT	BLUE-RED/PURPLE BLUE/PURPLE	1. 1.550 2.
AMOSITE S. AFRICA	STRAIGHT NEEDLE	PALE YELLOW	FAINT	MODERATE	L-SLOW STRAIGHT EXT	BLUE-RED/YELLOW PURPLE/YELLOW	1. 1.670 2.
CROCIDOLITE S. AFRICA	STRAIGHT NEEDLES	PALE BLUE/GREY DARK BLUE	STRONG	LOW	L-FAST STRAIGHT EXT	BLUE/BLUE BLUE/BLUE	1. 1.700 2.
TREMOLITE DEATH VALLEY	STRAIGHT & CURLY FINE FIBRES SHAVING BRUSH ENDS	COLOURLESS	NIL	LOW MOD FOR THICK FIBRES	L-SLOW STRAIGHT EXT OBLIQUE FOR FRAGMENTS	BLUE-RED/YELLOW PURPLE/YELLOW	1. 1.605 2.
ACTINOLITE ERMINGTON	STRAIGHT & CURLY FINE FIBRES OBVIOUS SPLITTING	PALE GREEN	FAINT	LOW	L-SLOW STRAIGHT EXT	BLUE-RED/YELLOW PURPLE/YELLOW	1. 1.640 2.
ANTHOPHYLITE FINLAND	STRAIGHT NEEDLES OBVIOUS SPLITTING	COLOURLESS GREY IN COARSE FIBRES	NIL	LOW MOD FOR THICK FIBRES	L-SLOW STRAIGHT EXT	BLUE-RED/YELLOW PURPLE/GOLD	1. 1.605 2.



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