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Morphology and alteration of asbestiform grunerite and anthophyllite

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ABSTRACT. Sections perpendicular to [001] of ion-thinned specimens of amosite (fibrous grunerite) from Penge, Transvaal and anthophyllite from Paakila, Finland and Söndeled, Norway, have been examined by high-resolution transmission electron microscopy. Observations on the nature of grain boundaries and alteration are compared with those of other workers on other fibrous amphiboles. Fibrous crystals grow with their fibre (*c*) axes approximately parallel to one another but they have considerable rotational disorder about that axis. Grain boundaries are generally irregular in shape and only follow low-index planes for short sections. In all specimens the amphibole has undergone some alteration to sheet silicates along grain boundaries, fractures, cleavages, and multiple-chain lamellae. Anthophyllite alteration products are talc, serpentine and chlorite, and amosite alteration products approximate to iron analogues of talc and serpentine. Talc layers are generally planar and their orientation is strongly controlled by the amphibole structure, whereas serpentine and chlorite layers often curve and their orientations are less frequently related to that of the amphibole. Comparison of specimens which appear finely fibrous in hand specimen with those which appear coarser, acicular or massive suggests that the nature of fibres produced by crushing is mainly controlled by the grain boundaries in the former type, but other factors such as fractures, cleavages, and defects are more important for the latter types.

PREVIOUS electron microscopic studies of fibrous amphiboles (e.g. Hutchison *et al.*, 1975) have been mainly restricted to sections parallel to fibre axes because of the difficulty in preparing the necessarily ultra-thin sections perpendicular to the fibre axes. However, Alario Franco *et al.* (1977) have succeeded in observing lattice images and grain boundaries in ion-thinned cross-sections of crocidolite (fibrous riebeckite). Because of their brittle nature, sufficiently thin cross-sections of amphibole asbestos have generally been prepared by ion-thinning, although very successful studies of fibrous riebeckite (crocidolite asbestos) have been made by Crawford (1980). There are in any case reasons for thinking ion-thinning to be generally more satisfactory because the technique is less likely to cause much mechanical deformation of the specimen, though it is possible that during cutting or polishing the fibres embedded in resin could be subjected to some shear stress. The method used to prepare specimens for this study has been described more fully elsewhere (Whittaker *et al.*, 1981). The electron microscope used to obtain high-resolution images was a JEOL JEM 100B with double tilt stage which enabled the fibre axes to be aligned exactly parallel to the beam.

Concurrently with this study, Veblen and Buseck have been investigating anthophyllite from Cascades, Washington (Veblen and Buseck, 1979*a*), Chester, Vermont (Veblen *et al.*, 1977; Veblen and Buseck, 1979*b*, 1980), and Pelham, Massachusetts (Veblen, 1980), using similar techniques and observing similar features to those we have found in the specimens we have studied. However, our observations have mainly been on amosite (fibrous grunerite), a different type of asbestos from a different geological environment. In addition we have examined specimens of anthophyllite from two different localities. The purpose of this paper is to describe our findings and compare them with those of other workers.

As the various asbestiform amphiboles become more fully characterized, it is hoped that we shall be able to understand more clearly the mechanism or mechanisms responsible for producing the fibrous habit in some amphiboles while other specimens of apparently identical chemistry and crystal structure are brittle, and acicular or massive in habit.

We have studied two specimens of grunerite

asbestos from Penge, Transvaal. In both specimens the asbestiform habit is well developed, but under the optical microscope one consists predominantly of coarser fibres (several hundred microns in diameter) which appear optically uniform whereas the other contains mainly finer fibres (optically indistinguishable from one another so that on rotation under crossed polars no extinction position can be seen). We have also examined fibrous anthophyllite from Paakila, Finland which is similar in appearance to the amosite, and also anthophyllite from Söndeled, Norway which appears massive or splintery in hand specimen and acicular in thin section. Most of the features described here were found to be common to both acicular and fibrous habits, and perhaps more surprisingly, common to both amosite and anthophyllite.

Chain-width disorder

All the above-mentioned studies of amphiboles by high-resolution electron microscopy have revealed extensive defects involving multiple chains wider than the double silicate chains of amphibole itself. In all of the samples examined in this study we have observed many multiple-chain lamellae, as reported previously (Cressey *et al.*, 1980; Whittaker *et al.*, 1981), varying in width from triple to 24-tuple. A substantial proportion of these lamellae have been observed to terminate within the structure, as has also been observed by Veblen and Buseck (1980). In such terminations the multiple-chain lamellae give place either to double-chain lamellae of normal amphibole type or to multiple ones of smaller width. Terminations may be either coherent or incoherent, the latter involving disturbance of the structure akin to dislocations. With coherent terminations the structure is undisturbed except along a line (parallel to *c*) at the termination of a single multiple lamella, or along a plane or planes (parallel to *c*) joining the terminations of two (or more) multiple lamellae. For coherent termination, certain criteria must be satisfied regarding the widths and numbers of lamellae before and after the termination. These rules for coherent terminations have been formulated and discussed by Veblen and Buseck (1980) based on their observations on anthophyllite from Chester, Vermont and by ourselves (Whittaker *et al.*, 1981) from our study of the amosite described in this paper. Whereas Veblen and Buseck only observed two examples of incoherent terminations, we found incoherent terminations to be very common in the amosite we examined and therefore discussed them in more detail.

The frequency of multiple-chain lamellae in the coarser grained specimen of amosite appears to be very similar to that in the finer grained specimen. In our anthophyllite specimens we have also observed multiple-chain lamellae, many of which can be seen to terminate coherently but a substantial proportion also terminate incoherently. In the massive or acicular specimen the frequency of multiple-chain lamellae is considerably lower than in the amosite, but in the fibrous anthophyllite it is much greater than in the amosite. Various other published reports (Chisholm, 1973, 1975; Veblen *et al.*, 1977; Alario Franco *et al.*, 1977; Veblen and Buseck, 1980) have suggested that amphibole asbestos specimens contain a higher concentration of multiple-chain lamellae than their massive counterparts. Bands of regularly alternating double and triple chains, a structure which has been named chesterite (Veblen and Burnham, 1976), occur in the fibrous anthophyllite. These do not appear to be uncommon but are not very extensive; the maximum width of such a band that we have observed is 25 unit cells, but they are mostly less than 10 unit cells in width. We have not yet observed the termination of this structure within the amphibole, but according to the termination rules, such a band can only terminate coherently if the band width is a multiple of four chesterite unit cells.

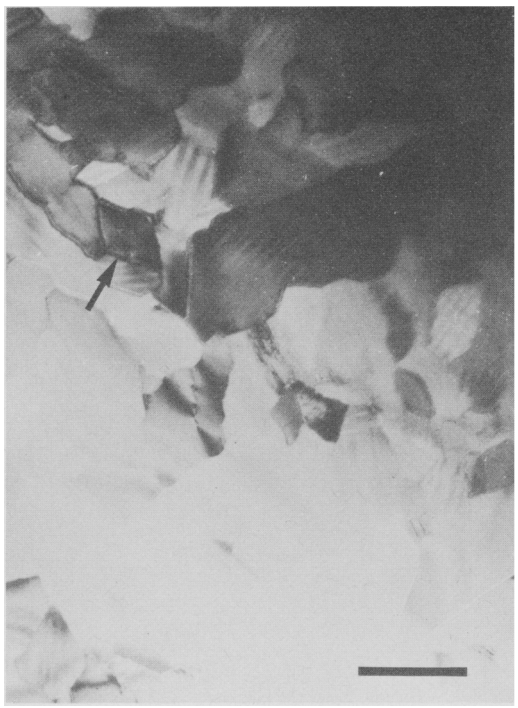
The relationship between multiple-chain lamellae and alteration of the amphiboles is discussed in a later section.

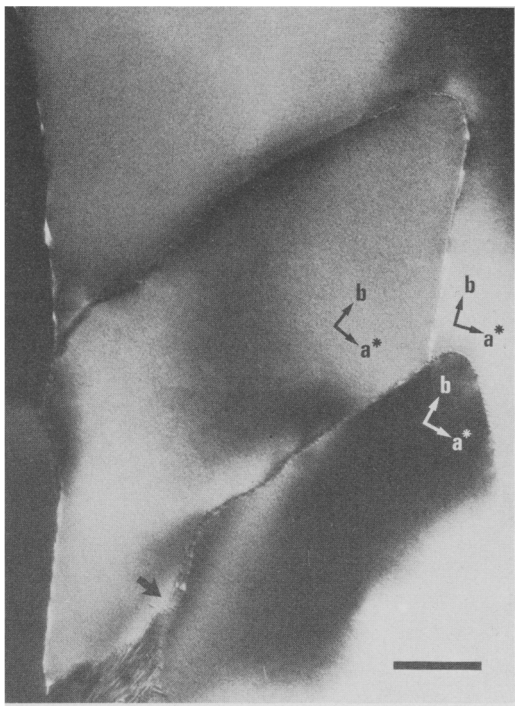
Grain boundaries

Alario Franco *et al.* (1977) found that crocidolite fibril boundaries are generally irregular in shape with fibrillar faces only occasionally having crystallographic indices coinciding with the low-index faces (010) and (110). We have reported similar observations from amosite (Cressey *et al.*, 1980). Micrographs published by Veblen (1980) also show boundaries which are irregular in shape, though some boundaries do follow the expected low-index planes, often for only short sections but occasionally running straight for at least several hundred angstroms. Our observations, on all the specimens we have studied, are similar.

In all our fibrous specimens adjacent crystallites have their *c* axes moderately well aligned parallel to one another and are rotated with respect to each other around that axis. This was also found to be the case in the Pelham anthophyllite (Veblen, 1980), crocidolite (Alario Franco *et al.*, 1977) and a South African amosite which was the subject of X-ray studies by Zoltai (1979).

Fig. 1 is a transmission electron micrograph of a typical area of the more finely fibrous specimen of amosite, taken with the electron beam parallel

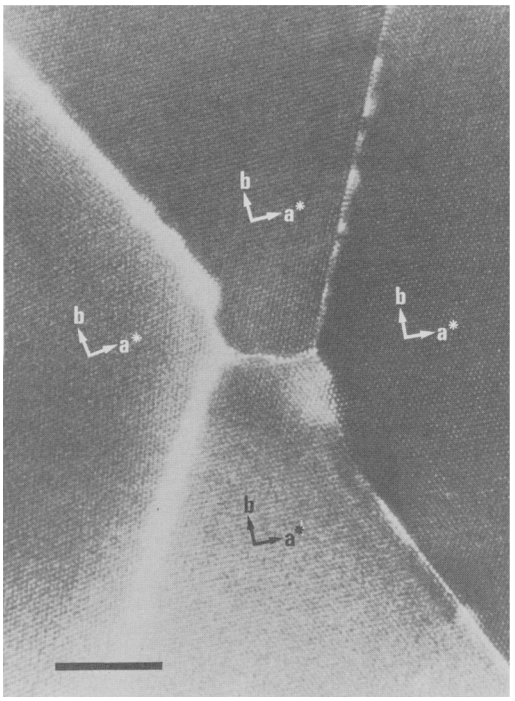


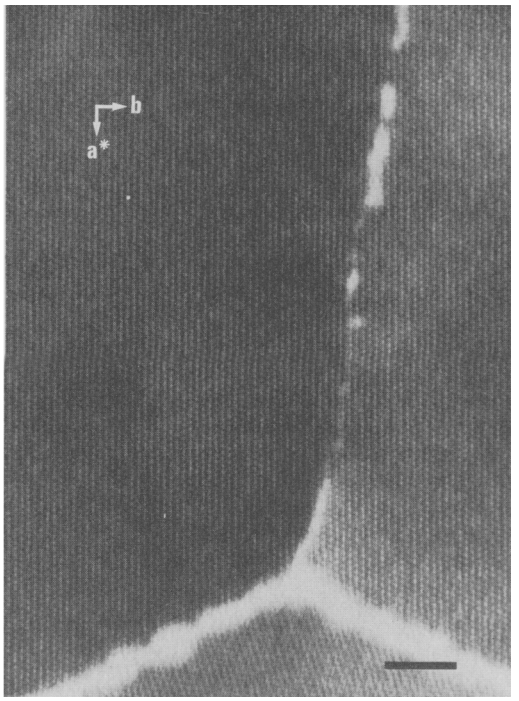


FIGS. 1 and 2. FIG. 1 (*left*). Amosite: the arrowed grain bounded mainly by (110) segments, others irregular. Bar: 2000Å. FIG. 2 (*right*). Orientation relationships between adjacent grains. The arrowed boundary is not sharply defined. Bar: 500Å.

to *c*. One grain (arrowed) appears to be bounded approximately by (110) faces, but others do not and are quite irregular in shape. Several grains contain sets of fine, parallel bands which it is tempting to interpret as polysynthetic twinning, as observed by Hutchison *et al.* (1975). However, we have reservations about accepting this interpretation in the light of certain fine details which are visible on the original micrograph, and of theoretical considerations. This feature needs further investigation.

Fig. 2 shows a similar area from the same specimen at higher magnification. The area contains several irregularly shaped grain boundaries. There is appreciable rotation between the grains, as there is also in the previous figure, but in places the lattice fringes bend at the boundary and seem to imply coherence or semi-coherence between adjacent crystals, as at the arrowed point. The pointed ends of the grain in the centre and the one to the lower right of it are rounded rather than sharp. The difference in orientations of the crystals in figs. 1 and 2 suggests that many grains were nucleated with the physical conditions dictating the orientations of only their *c* axes. Growth was clearly fastest in the direction of this common axis, producing fibres, and we assume that the cross-sectional shape is likely to be uniform along their length. If this is so, then the way in which the fibres abut on one another in any section provides information about the sequence of events in their initial growth to meet one another, perpendicular to *c*. The shape of the boundaries in fig. 2 suggests that growth of these grains in directions perpendicular to the fibre axes was not absolutely contemporaneous since some grains are clearly imposing their shapes on others. In the area shown in fig. 3, however, from the same sample, the shapes of the boundaries suggest almost contemporaneous growth of the grains. In this figure four grains meet. Two of them have one straight face, parallel to the expected (110) cleavage plane. At these two boundaries there is little difference between orientations of the adjacent grains and the simple low-angle grain boundaries are mostly coherent with partial dislocations absorbing the structural mismatch. One of these two boundaries has a smaller difference in orientation between the adjacent grains, and therefore fewer dislocations than the other. The other two boundaries involve larger angular differences and so have no structural coherence. In fig. 4 from the same sample as figs.





FIGS. 3 and 4. FIG. 3 (*left*). Amosite: straight low-angle boundaries equivalent to a series of dislocations, and larger angle boundaries with no structural coherence. Bar: 200Å. FIG. 4 (*right*). Two grains in parallel orientation separated by a triple lamella which sidesteps and terminates in a series of holes. Bar: 100Å.

2 and 3, there are what appear to be three grains but two are parallel to one another. The boundary between these contains a triple lamella which sidesteps several times and then terminates in a series of large holes with bridges of coherent amphibole structure.

The grain boundaries described above are clearly growth features, but the type of boundary shown in fig. 5, from the same sample as the previous figures, has clearly been formed subsequent to crystal growth. This is a crack which cuts two multiple-chain lamellae within the area of this micrograph. It displaces one of them laterally but does not displace the other, thereby showing that the shearing occurred at a time between the formation of the two lamellae. The crack has then opened further as a result of a rotation of one side relative to the other. This indicates that not all boundaries between fibrils are produced by growth of many nuclei but that they can also be produced later in response to shear stresses imposed on the fibrils. This photograph also indicates that at least some multiple-chain defects are produced after the growth of the crystal.

The observations described above are all from the more finely fibrous amosite, but grain boundaries in the coarse amosite and in the fibrous anthophyllite show very similar features. However, many more of the boundaries in the anthophyllite contain alteration products than those observed in amosite, and are therefore described in the next section.

In the acicular anthophyllite we did not observe any boundaries in which one amphibole crystal is in contact with another. What look like boundaries between grains in exactly the same orientations as one another are probably fractures and tend to follow (210) planes. All other boundaries observed in this specimen have an alteration product in direct contact with the amphibole.

Alteration

All the samples examined show evidence of some degree of alteration to more hydrated, sheet silicates that are related to chlorite and serpentine.

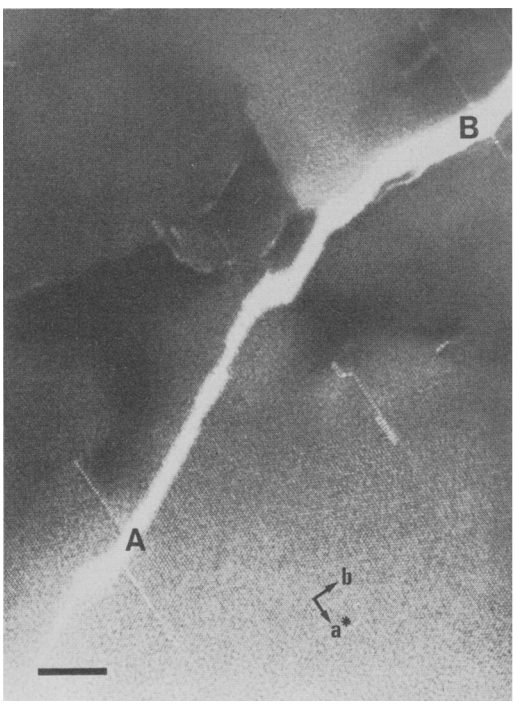
Veblen (1980) has described alteration in a fibrous anthophyllite. His observations suggest that at anthophyllite grain boundaries which contain sheet silicates, the interface between the sheet mineral and one of the amphibole grains is usually

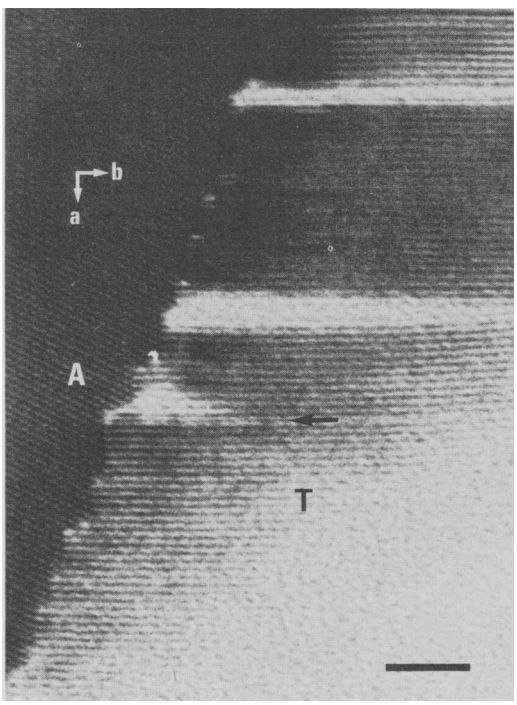
planar and controlled by the structure of the amphibole, typically parallel to (010), (210) or (100) of the anthophyllite. At such a controlled interface the orientation of the sheet silicate is usually related to that of the amphibole, so that (1): $a_{talc} \parallel c_{anthophyllite}$, $b_{talc} \parallel b_{anthophyllite}$ and $c_{talc} \parallel a_{anthophyllite}$ or less commonly (2): $(001)_{talc} \parallel (210)_{anthophyllite}$. Where the sheet silicate is chlorite or serpentine, (001) of the sheet silicate is commonly parallel to (210) of one adjoining anthophyllite grain.

The interface between the sheet silicate and other adjoining amphibole grains is usually irregular or ragged. Less commonly Veblen observed orientation relationships as in (1) across a ragged boundary, while the talc boundary with another anthophyllite grain in an unrelated orientation was planar and parallel to $(210)_{anthophyllite}$. Veblen suggests that the fact that one of the anthophyllite boundaries is nearly always planar and has a rational crystallographic orientation of low index suggests that the interface energy is minimized by having one planar boundary and one ragged boundary, rather than two ragged boundaries with the sheet silicate.

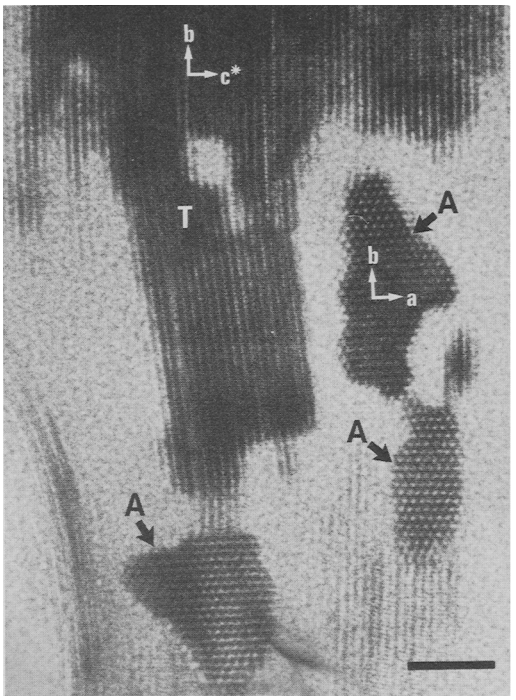
We have also observed the above relationships between amphibole and sheet silicate alteration products. However, whereas Veblen found that these relationships nearly always occur, we have found that the orientations of sheet silicates are commonly not closely related to those of the amphibole, or else are related for only short sections and the sheets curve. This is particularly so with chlorite and serpentine, whereas talc orientation is more often related to that of amphibole. This is perhaps to be expected, since $d\,(001)_{talc}$ (9.3Å) is equal to $d\,(001)_{amosite}$ and $d\,(200)_{anthophyllite}$, whereas serpentine ($d\,(001) = 7.3$Å) and chlorite ($d\,(001) = 14.3$Å) are more poorly matched. Similarly it is not surprising that the relationship $(001)_{talc} \parallel (210)_{anthophyllite}$ is less common than relationship (1) above as the mismatch is greater ($d\,(210)_{anthophyllite} = 8.3$Å).

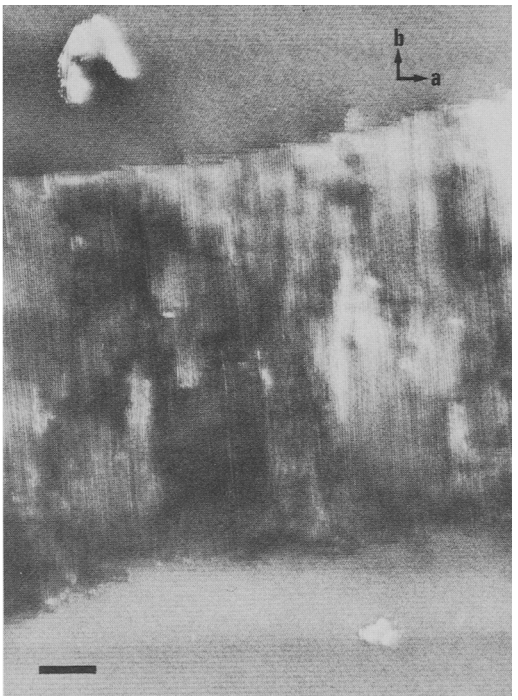
Anthophyllite alteration. The fibrous anthophyllite specimen was found to be more extensively altered than the massive anthophyllite and the amosite. Because of the difficulty in preparing ion-thinned cross-sections of fibres compared with non-fibrous specimens, we have been able to study more samples of the acicular anthophyllite than of the fibrous one. However, there appear to be no





FIGS. 5 and 6. FIG. 5 (*left*). Amosite: boundary formed by lateral NW displacement and anticlockwise rotation of the upper portion. Note displacement of the predeformation lamella at A and lack of displacement at B. Bar: 200Å. FIG. 6 (*right*). Acicular anthophyllite (A) altered to talc (T) with a single intercalated serpentine layer (arrowed). $c^*_{talc} \parallel a_{anth}$. Bar: 100Å.





FIGS. 7 and 8. FIG. 7 (*left*). Acicular anthophyllite: islands of residual amphibole (A) surrounded by fairly well aligned, but slightly curved talc layers. Bar: 100Å. FIG. 8 (*right*). A wide talc-filled crack with the interface generally along (010). Talc is extending by incorporating lamellae of amphibole I-beams two at a time. Bar: 200Å.

significant differences in the nature of the alteration in these two specimens.

Fig. 6 shows a typical anthophyllite boundary with talc. The boundary is irregular and stepped, though it has short sections (up to 6 unit cells† in length) which are straight and parallel to *a* of the anthophyllite. In the area shown in this micrograph the talc is well aligned with $c^*_{talc} \parallel a_{anthophyllite}$. It also contains a single intercalated serpentine layer. The talc, in common with all the alteration products we have observed, is very beam-sensitive and much of it has become amorphous during the time taken to align the specimen and record the image. Fig. 7 is from another part of the same specimen and shows similar alteration, though in this area the talc sheets are slightly bent. In this micrograph another set of fringes can be seen running perpendicular to the more obvious 9.3Å fringes. This second set have a spacing equal to $\frac{1}{2}b$ and confirm the orientation of talc layers as $c^*_{talc} \parallel a_{anthophyllite}$ and $b_{talc} \parallel b_{anthophyllite}$, as observed by Veblen. There are several islands of residual amphibole surrounded by and aligned with the talc.

† The unit cells referred to here are unit cells of the projection down (001) which are half the length of true anthophyllite unit cells.

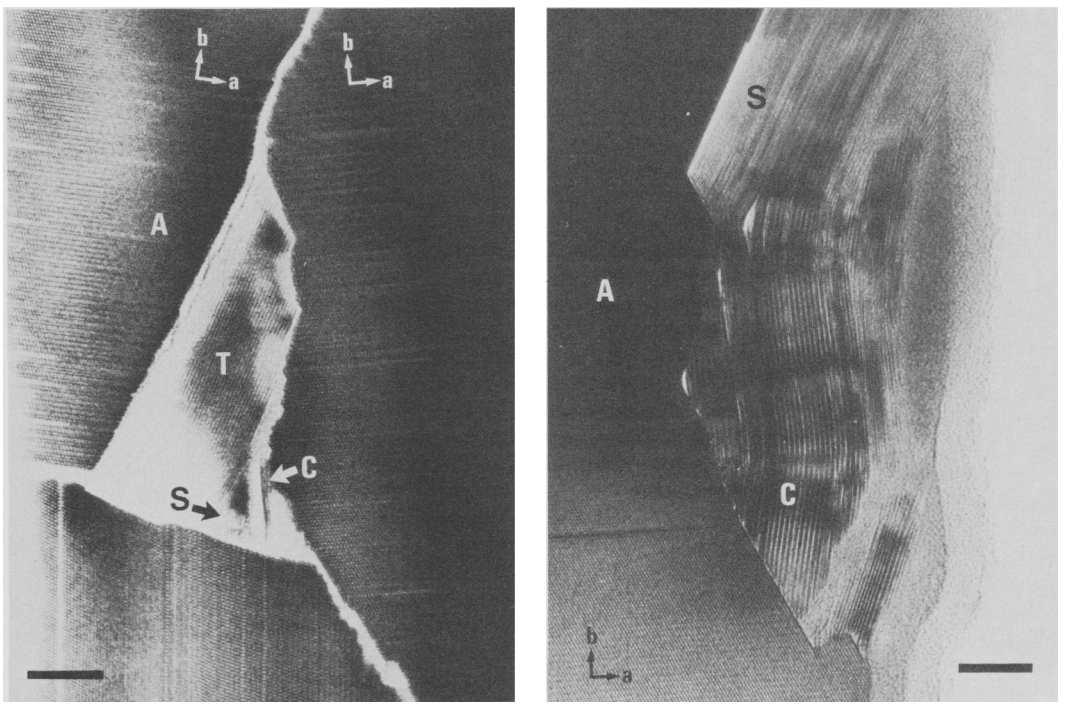
Talc is also the alteration product shown in fig. 8 which is part of a crack about 1400Å wide. As in fig. 9, the talc orientation is controlled by the amphibole near to the interface, but further away from it the talc sheets deviate from this orientation in this area by up to 15°. The interface is mainly along (010) of the amphibole and generally sidesteps along (210). The talc band appears to be extending its width by incorporating lamellae of amphibole *I*-beams two at a time. Other examples have been seen in which alteration extends into the amphibole along multiple-chain lamellae, widening them by incorporating lamellae of amphibole *I*-beams two at a time. This is consistent with the observation that talc most commonly occurs in the above-mentioned orientation relationship, which corresponds to its structure being that of extended amphibole *I*-beams. Widening of *I*-beams in this manner provides a simple step-wise mechanism, as has been previously discussed (Whittaker *et al.*, 1981), for the formation of lamellae of *n*-tuple *I*-beams where *n* is of the form $4N+2$, or for the broadening of lamellae of triple, quadruple, or quintuple *I*-beams. It does not, however, provide so easy a mechanism for the formation of lamellae of these latter three types,

which are in fact among the commonest. Coherent terminations of lamellae of these types can only occur cooperatively, and in the case of odd *I*-beams must involve a displacement of a substantial volume of the structure by $c/2$ as in fig. 5 of Whittaker *et al.* (1981). It therefore seems that these lamellae are more likely to be growth features whereas other lamellae can easily be produced by alteration.

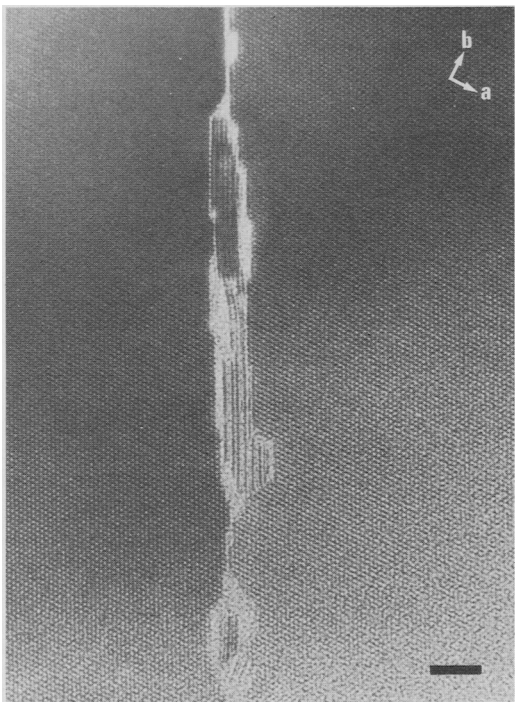
The amphibole in fig. 8 also contains what appear to be holes or negative crystals which are similarly filled with talc, the orientation of which is controlled by that of the amphibole.

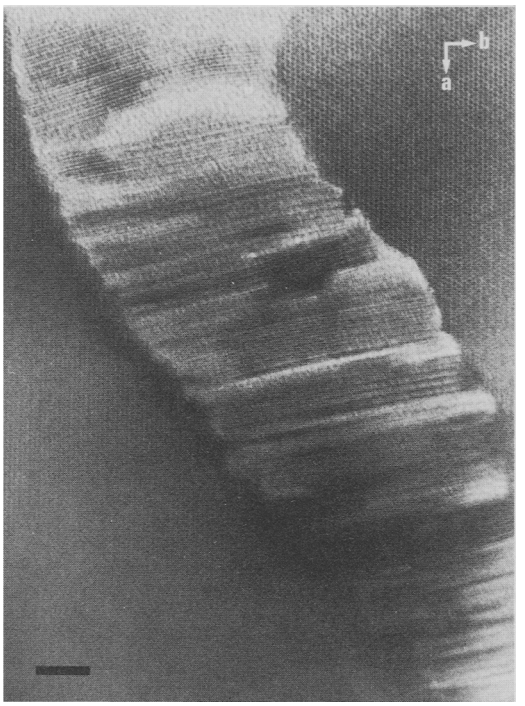
Only once have we observed the relationship $(001)_{talc} \| (210)_{anthophyllite}$. This is shown in fig. 9, which is from the fibrous specimen (all other micrographs of anthophyllite described in this section are from the acicular specimen). The observation of this orientation relationship implies that talc is not always formed as extended amphibole *I*-beams. One boundary is approximately straight and parallel to $(210)_{anthophyllite}$. However, the amphibole grain with this boundary is not the one controlling the talc orientation. Although the sheets appear at first sight to be parallel to this boundary, in fact they are not, but are parallel to (210) of the anthophyllite grain at the right of the picture, which has a ragged boundary. At one end of this area of alteration is a smaller area of serpentine. The serpentine layers are fairly straight and parallel to those of the talc for some distance, but curve away towards the (*a*) direction of the adjacent amphibole grain. There is also a narrow band of chlorite in an orientation not related to the other alteration products.

Orientations of chlorite and serpentine tend to be more poorly related, or unrelated, to the amphibole. Fig. 10 shows an anthophyllite grain boundary with alteration to serpentine and chlorite. In some areas the sheet silicates tend to be mainly parallel to the (210) cleavage planes but as shown here they may show a marked curvature away from this direction. Between the well defined 14Å fringes of the chlorite lie weaker, off-centre fringes. This is consistent with the composite layer structure of chlorite, which consists of regularly alternating talc-like and brucite-like sheets. It appears that the resolution of the instrument used



FIGS. 9 and 10. FIG. 9 (*left*). Fibrous anthophyllite: one anthophyllite (A) grain boundary is approximately parallel to (210). Talc (T) sheets are not parallel to this, but to (210) of the anthophyllite grain with a ragged boundary at the right. Alteration also contains serpentine (S) and chlorite (C). FIG. 10 (*right*). Acicular anthophyllite (A) with alteration to serpentine (S) and chlorite (C) and fine-scale irregular intercalations of the two. Sheet silicates lie parallel to (210) cleavage planes at the top of the picture, but elsewhere they are curved. Bars: 200Å.





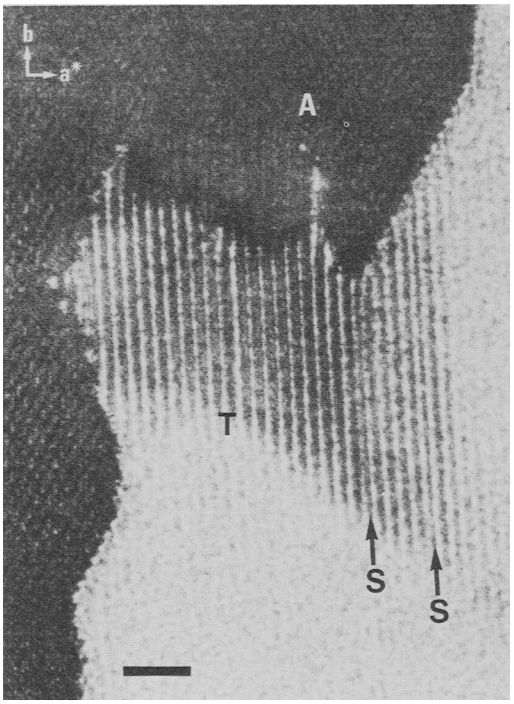
FIGS. 11 and 12. FIG. 11 (*left*). Acicular anthophyllite with a narrow crack containing chlorite (wider) and serpentine (narrower) sheets roughly parallel to the crack walls, i.e. approximately $(210)_{anth}$. FIG. 12 (*right*). A wider crack filled with chlorite sheets running across the crack but not aligned with the anthophyllite. Bars: 100Å.

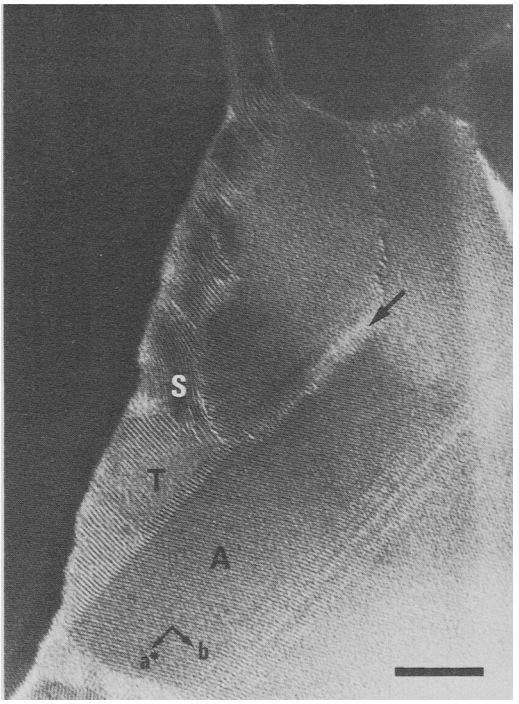
in this study is insufficient to resolve the two components (a layer of linked SiO_4 tetrahedra and a brucite-like layer) of the serpentine sheets, but also serpentine is extremely beam-sensitive and so fine detail in the image is lost very rapidly. We have also observed small areas of serpentine in which the layers curl more tightly, as though tending towards the chrysotile-type structure. These are difficult to record because they damage so rapidly in the electron beam, although Veblen (1980) has recorded excellent micrographs illustrating this feature.

Many cracks within grains contain serpentine and chlorite. In narrow cracks, such as that in fig. 11, the layers of the alteration products usually tend to run parallel to the crack walls, which are generally parallel to (210). Any irregularities in the walls appear to be filled with amorphous material, but it is not possible to determine how much of this is due to beam damage. Wider, irregular cracks such as that shown in fig. 12, which is about 500Å wide, are usually filled by chlorite (and/or serpentine) layers which run across the crack but are not aligned with any particular direction in the amphibole.

Amosite alteration. Although much less alteration was observed in the amosite specimens than in the anthophyllite specimens, the general appearance of the alteration products in the two types of amphibole is similar. Talc-like layers are usually straight and have c^* roughly parallel to a^* of the amosite, and serpentine-like layers tend to follow edges of grains roughly rather than being strictly controlled by the amphibole lattice orientation. No chlorite was found. Fewer grain boundaries and less alteration were observed in the coarser specimen, and the following micrographs were all taken from the finer specimen.

Close inspection of areas such as that shown in fig. 13 reveals some slight but important differences between the presumed talc-like alteration product of amosite and talc produced by alteration of anthophyllite. The former has a fringe spacing of 9.8Å, which is larger even than that (9.55Å) reported by Gruner (1944) for minnesotaite, so it must depart substantially from being a direct Fe-containing analogue of talc. A description of the locality from which these specimens were taken (Hall, 1930) reports the presence of nontronite, a smectite, $(\frac{1}{2}Ca,Na)_{0.66}Fe_4^{3+}(Si_{7.34}Al_{0.66}O_{20})(OH)_4 \cdot n(H_2O)$, in the banded ironstones which contain the amosite veins. The layer spacing of





FIGS. 13 and 14. FIG. 13 (*left*). Amosite (A) altered to a talc-like sheet silicate (T) with layers 3° off parallel to (100) amphibole planes. Many fringes are coherent, some bending at the interface, but other fringes terminate at the boundary. The alteration also contains two serpentine-like layers (S). Bar: 50Å. FIG. 14 (*right*). Amosite (A) altered to talc-like sheets (T) which are mostly coherent with, but 3° off parallel to (100) amphibole fringes of the grain to the right. (110) amphibole fringes are the most obvious and observation of (100) planes requires more careful inspection. Alteration may have started where the sidestepping multiple chain lamella (arrowed) met the grain boundary, and progressed by extending the lamella width. The alteration also contains curved serpentine-like sheets (S). Bar: 200Å.

nontronite is variable from 9.2Å at 575 °C to 15.8Å when moist. Nontronite has a similar structure to that of talc, but is dioctahedral like pyrophyllite rather than trioctahedral like talc. It is possible that the talc-like alteration product of amosite is more closely related to nontronite than to talc. Many of the talc-like fringes are coherent with the amphibole, some achieving this, in spite of the mismatch in spacing, by bending immediately next to the boundary.

Other amphibole fringes appear to terminate at the boundary, though the amphibole is not clearly resolved in this region.† The talc-like fringes are not exactly parallel to the (100) planes of the amphibole, but are 3° off this orientation. This angle would only partially compensate for the mismatch between spacings of the amphibole and alteration product; a tilt of 18° would be required to do so completely with no distortion or termination of any fringes at the boundary. The area of alteration in this figure also contains two separate intercalated serpentine or serpentine-like layers. The amosite does contain 4–6% MgO, so serpentine could be derived from this. Also the field observations (Hall, 1930) indicate the presence of thin veins of magnesite within the banded ironstones which contain the amosite veins. However, since there is much more Fe than Mg in the amphibole it would seem more likely that greenalite, the iron analogue of serpentine would be produced by alteration of amosite, and its layer spacing is indistinguishable from that of serpentine.

Another similar talc-like alteration is shown in fig. 14. Many of the sheets again appear to be continuous with the (100) amphibole fringes though part of the boundary is not clearly resolved and some of the amphibole fringes again appear to terminate without passing into the talc-like

† It should be noted that in this micrograph the most obvious amphibole fringes are (110). Determination of the relationship between (100) amphibole planes and (001) talc fringes requires more careful inspection.

material. The latter is not coherent with the amphibole grain at the other side of the area of alteration. As in fig. 13, the talc-like layers are straight and parallel and are about 3° off parallel to (100) of the amphibole.

The amosite contains several multiple-chain lamellae. One of these meets the area of talc-like alteration and forms one side of it. It appears that the talc-like material may have started growing where this wide lamella met the grain boundary. There is also a substantial amount of serpentine-like alteration product, whose layers bend and are not coherent with the amphibole. Other grains with irregular margins have undergone alteration to produce mainly serpentine-like layers which are not straight but tend to lie roughly parallel to the general trend of the grain boundary. The margins of some such grains are embayed with talc-like layers filling the embayments, giving the appearance that the alteration is starting to 'eat into' the amphibole along *a*.

Chemical analyses

The massive anthophyllite from Norway, fibrous anthophyllite from Finland, and fibrous grunerite (amosite) from Transvaal have been analysed by electron microprobe. The results are shown in Table I, and have been converted to numbers of ions on the basis of 23O in the anhydrous state. Calculated water contents have been inserted into the analyses (in parenthesis) on the assumption of $(OH)_2$ per mole.

The analysis of the Norwegian anthophyllite is satisfactory as to total on this basis; the water content must indeed be very marginally higher in view of the talc and wide chain material present, which would improve the total. It clearly contains a significant amount (~ 25%) of the gedrite component.

The Finnish anthophyllite and grunerite analyses have substantially deficient totals. The ratios of octahedral to tetrahedral cations are low, which is compatible with the presence of appreciable wide-chain and talc-like alteration products, which would also increase the water contents above those calculated for amphibole and so marginally improve the analysis totals. The water content would be more sensitive to the presence of serpentine phases, but they would increase the ratio of octahedral to tetrahedral cations, so that no quantitative conclusions can be drawn.

Growth habits and mechanisms of fibre formation

From our observations and those of other workers on amphiboles that are fibrous in hand specimen, it would seem likely that the main mechanism by which fibres are produced by crushing is separation of crystallites along grain boundaries. These are obvious zones of weakness. Grain boundaries both of crystallites which are so small as to be only visible in the transmission electron microscope and of larger crystals which can be seen in the optical microscope, are all generally irregular in shape.

In addition we have observed cracks within both fine and coarse crystals which are also likely sites for disaggregation on crushing. Fine cracks, which often tend to follow $(110)_{amosite}$ or $(210)_{anthophyllite}$ cleavage planes, could have been formed by mechanical damage during specimen preparation, but cracks which contain alteration products, as many do, cannot have been produced in this way. Larger cracks, which tend not to follow regular planes extensively, are nearly always filled with alteration products. Material which is more coarsely fibrous or acicular in hand specimen can also disaggregate into fine fibres when crushed and grain boundary separation alone cannot explain this. Breaking of crystals along cracks is probably

TABLE I. *Electron microprobe analyses of amphiboles examined in this study*

	1 (%)		2 (%)		3 (%)	
SiO_2	55.50		58.85		50.33	
Al_2O_3	6.43		0.34		0.13	
TiO_2	0.17		0.03		0.02	
FeO	4.18		4.47		36.04	
MgO	29.33		29.78		6.03	
MnO	0.05		0.19		3.92	
Na_2O	0.57		0.03		0.04	
CaO	0.67		0.19		0.23	
K_2O	0.01		0.03		0.03	
H_2O(calc)	(2.30)		(2.32)		(1.94)	
Total	99.21		96.23		98.71	
Si	7.46	8.00	8.11		8.06	
Al^{IV}	0.54		—		—	
Al^{VI}	0.48	7.10	0.06	6.76	0.02	6.88
Ti	0.02		—		—	
Fe	0.47		0.52		4.83	
Mg	5.87		6.12		1.44	
Mn	0.01		0.01		0.53	
Na	0.15		0.01		0.01	
Ca	0.10		0.03		0.04	
K	—		—		0.01	
OH	(2.00)		(2.00)		(2.00)	

1. Massive anthophyllite, Norway.
2. Fibrous anthophyllite, Finland.
3. Fibrous grunerite (amosite), Transvaal.

more important in this type of material than in the asbestos which grows as finer fibres, and the degree and nature of alteration may also be a significant factor.

Some kind of parting of anthophyllite and of some other amphiboles on (010) and (100) seems to be well documented (Veblen *et al.*, 1977; Veblen and Burnham, 1978; and Veblen and Buseck, 1980), but the mechanism of such partings is less well established and the existence of such a parting on wide-chain lamellae in crocidolite has been denied (Crawford, 1980). It is perhaps desirable to point out that the high-resolution electron micrographs and interpretative drawings and models showing wide-chain lamellae can rather easily be misinterpreted as indicating planes of weakness on (010), because they contain evident large holes aligned on such planes. The falsity of such an interpretation is demonstrated by fig. 15 which represents a portion of amphibole structure containing a multiple-chain lamella, modelled with cardboard cut-outs as described by Whittaker *et al.* (1981). A crack has propagated along a (110) cleavage plane (arrowed) until it has reached the multiple-chain lamella. It is clear that the cleavage will be expected to cross the lamella (path A) rather than run parallel to it (path B). Indeed, path A actually involves breaking fewer bonds per unit length as it crosses the lamella than it would within the normal regions of the amphibole, whereas path B involves more. Whatever the cause of partings on (010) it is not the presence of the row of large holes associated with wide-chain lamellae. If (010) partings are localized on wide-chain lamellae it must presumably be because of the relative instability of the wide chains, as suggested by Veblen (1980). On the other hand partings on (100) may be promoted by the presence of co-operative terminations of wide-chain lamellae which can cause a complete absence of bonding on a segment of such a plane (see Whittaker *et al.*, 1981, fig. 4).

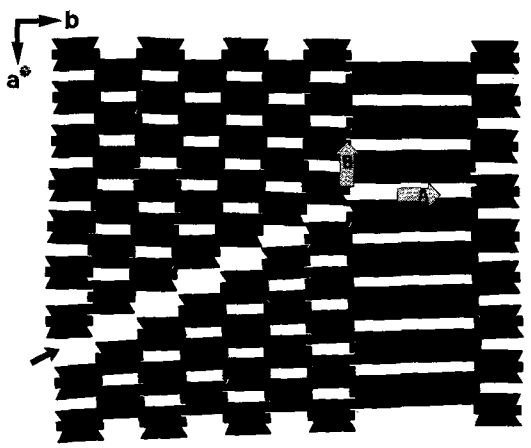


FIG. 15. *I*-beam model of a multiple chain lamella in amphibole . A (110) cleavage plane (arrowed) reaching the wide lamella probably continues perpendicular to the lamella (path A) rather than parallel to it (path B).

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