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Anthophyllite Asbestos in Central Sierra Leone

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Abstract

The paper describes a petrologically complex area in Central Sierra Leone, containing a 8 km long and on the average ½ km wide zone of frequently fibrous anthophyllite rocks and discusses the origin of anthophyllite asbestos.

From the evidence in the field and under the microscope, the author infers, that the anthophyllite originated from antigorite in the tensional conditions of epidote amphibolite facies owing to the addition of silica and that the development of fibres took place not much later than the formation of anthophyllite.

Contents

Introduction

In Central Sierra Leone, the Sula Mountains and Kangari Hills form a geosynclinal schistbelt, approximately 130 km long and 15 to 20 km wide. Along the eastern flank of the southern part of the schistbelt of the Kangari Hills, a 20 km long and almost 3 km wide zone of serpentinites occurs (Fig. 1). In northern direction, the Kangari schist area suddenly narrows into a narrow "bridge", mainly consisting of quartzites and amphibolites, which connects the southern part of the schistbelt with the Sula Mountains in the north.

To the north-east of the serpentinite area of the Kangari Hills synkinematic gneisses occur, through which the NE continuation of ser-

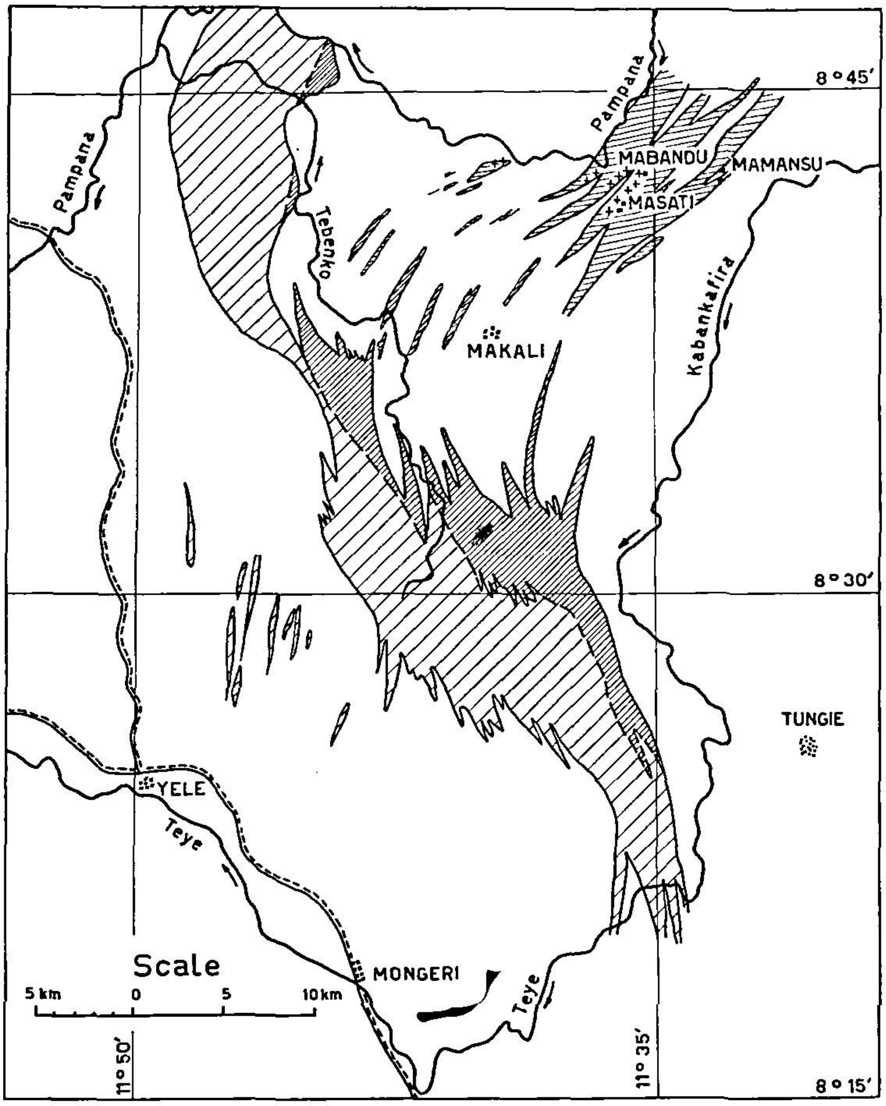

Fig. 1. The schistbelt of the Kangari Hills and the Masati area in Central Sierra Leone.

Hatched area = metasediments and amphibolites; densely hatched area = ultrabasic rocks; the rest of area = diorite-, granodiorite- and granite gneisses; the cross marks between Masati and Mabandu indicate the situation of anthophyllite asbestos zone.

pentinites can be traced by narrow serpentinite and tremolite schist strips, enclosed by the gneiss. These strips connect the Kangari serpentinites with similar rocks around Masati (Fig. 2), 15 km NE of the main serpentinite area of the Kangari. At Masati the serpentinite area measures approximately 10 by 5 km, but it is much less homogeneous than that of the Kangari Hills; the synkinematic rocks of granitic to dioritic composition split it in several strips.

Along the northwestern part of the Masati serpentinite area the rocks are often conspicuously talcose. There too anthophyllite rocks occur, and the latter are often developed into asbestose fibres.

The anthophyllite rock occurs as long and narrow lenses, and their geological position is distinct enough to allow a discussion regarding the origin of the anthophyllite asbestos.

Geology of the Masati Area

As one can see from Fig. 2, the geology of the Masati area is rather complicated. The area is composed of several strips of serpentinite, of tremolite schist and of anthophyllite rocks, etc., all stretching on average from SW to NE, and separated from each other by gneissose rocks. The composition of the latter varies from gabbroic to granitic. The broadest serpentinite strip is in the East, and its width averages 2 km. Other strips are considerably smaller. Eastwards their schistosity and talcosity increase, the central part of the largest strip being mainly composed of antigorite with a minor amount of olivine.

The main zone of anthophyllite rocks, which always contain varying amounts of asbestos as well, is that between Masuri and Mabandu. It is 8 km long and, on average, ½ km wide, except at Mabandu, where its width is about 1 km. In addition there are some other minor lenses, likewise containing fibrous anthophyllite.

The asbestos of the Masati area seems to be mostly hard and brittle, soft and flexible fibres occur comparatively seldom and are always accompanied by talc.

The gneissose rocks are exclusively synkinematic. In SE and in NE they are mainly biotite granodiorite gneisses, in NW they are mostly hornblende- and diorite gneisses (p. 37), and they often contain abundant portions of amphibolite. The abundance of the hornblende-bearing gneisses is remarkable because such rocks occur seldom within the gneisses embracing the Kangari Hills schistbelt (including serpentinites), the rocks being there predominantly biotite granodiorite and granite gneisses.

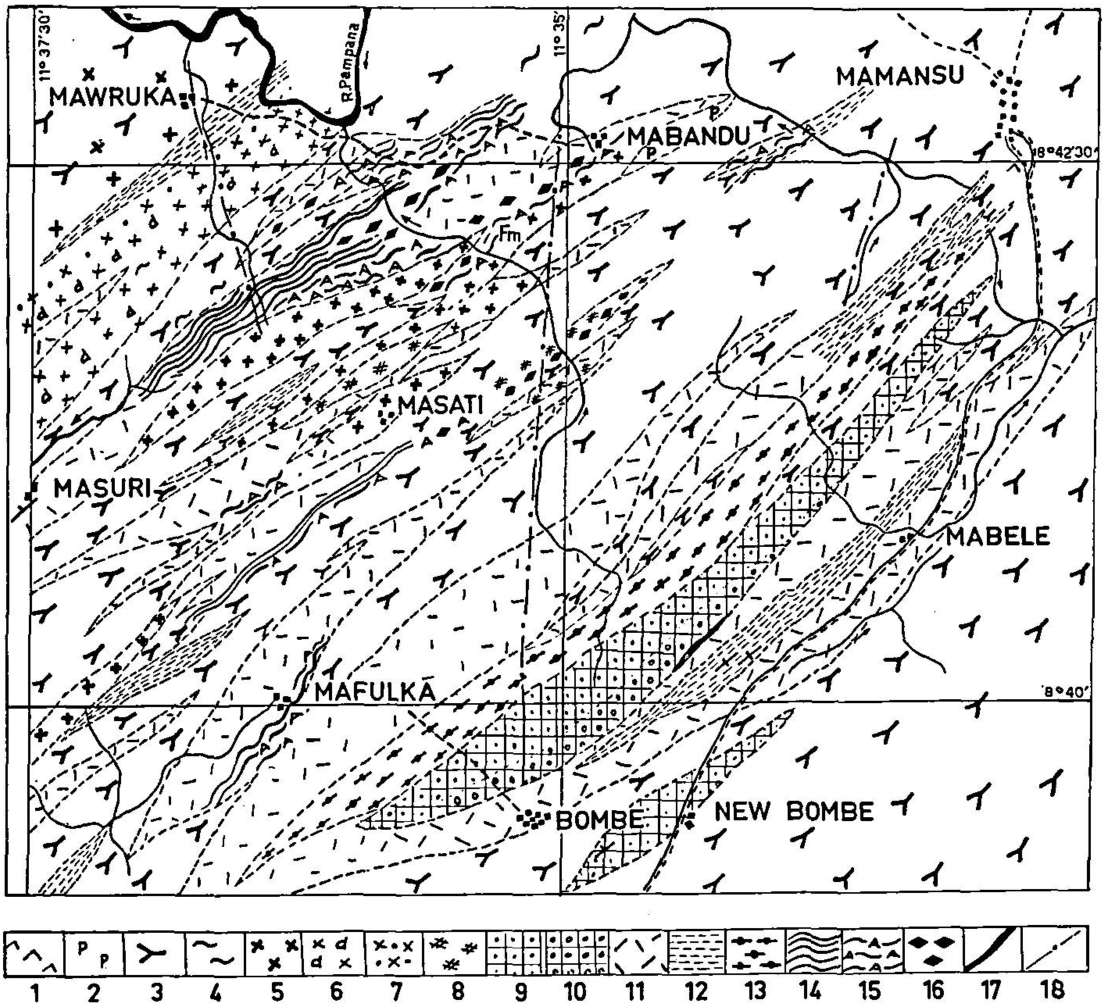

Fig. 2. Geological map of the Masati area.

1 = microcline granite; 2 = pegmatite; 3 = biotite gneiss and biotite granodiorite; 4 = migmatite; 5 = diorite gneiss; 6 = diopside diorite gneiss; 7 = epidote diorite gneiss and epidosite; 8 = amphibolite; 9 = olivine serpentinite; 10 = antigorite olivinite; 11 = tremolite serpentinite; 12 = tremolite schist; 13 = chlorite-tremolite schist; 14 = talc-anthophyllite rocks; 15 = asbestos; 16 = talc; 17 = seams consisting only of hornblende; 18 = observed shearing zones; Fm = farmhut.

At Mamansu microcline granite occurs in two places. It probably is latekinematic. In three places dolerite dykes have been found.

Description of the Rocks

Ultrabasic Rocks

Particularly in the south-east, in the large serpentinite lense between Bombe and Mabele, the rocks are conspicuously rich in olivine, and a narrow portion of these olivine serpentinites is composed of predominant olivine and lesser amounts of antigorite. The greater part of the mentioned lense, however, is built of much antigorite and only a small amount of olivine.

In these olivine-bearing rocks the olivine occurs as small rounded grains, which are always very fresh. Rarely any kind of alteration occurs within olivine, and if the olivine grains are "serpentinised", this alteration took place along the cracks, rarely along the margins, and the product of the "serpentinisation" is exclusively chrysotile. There are no signs of the formation of antigorite on the expense of olivine, and still even the antigorite is the only serpentine partaking in the formation of the main mass of the rock.

From the above described conditions between the serpentine and olivine of the serpentinites it has been concluded, that the olivine is there more or less contemporaneous with antigorite; consequently the latter is a primary constituent of the rock, and in hydrothermal conditions the olivine was formed due to a local loss of silica, which is in accordance with the experimental findings of YODER (1952), who has shown that in such conditions the contemporaneous formation of olivine and antigorite is to be expected and that the temperature of such crystallization is between 450° C (the lowest stability temperature of olivine if water vapour is present in excess) and 500° C (the upper limit of the stability of serpentine).

The lenses of the central part of the Masati area are mostly composed of tremolite serpentinite, consisting of tremolite and antigorite only. The relative abundance of both constituents is rather variable, and frequently the tremolite serpentinites gradually develop into tremolite schist. Along a narrow zone between the olivine serpentinites and the tremolite serpentinites, the latter are rich in chlorite.

In the small strips around Masati the tremolite serpentinite contains talc in addition and in northwestern direction they grade into talc-tremolite serpentinites or into talc-tremolite schists, and minor portions may contain anthophyllite in addition.

The main area of the anthophyllite-talc rocks, however, is in the northwestern part of the Masati region, and these strips always contain fibrous anthophyllite too. In addition they may be very rich in talc. In the strip at Mabandu and southwest of it, there are portions consisting entirely of talc. Exceptionally, talc-anthophyllite portions may contain magnetite octahedra as well.

The fibrous anthophyllite (asbestos) is present in different quantities in all strips consisting of anthophyllite alone or together with talc. There may be actinolite present sometimes as well, and especially in a small stream 1 ½ km NW of Masati, where the asbestos is particularly abundant, the rock contains clusters up to 1 cm across, consisting of dark yellowish green chlorite, which is causing the high alumina content of the rock (Anal. 1, Table I).

The asbestos occurs both as mass and as cross fibres. Actually the anthophyllite rock is slightly fibrous (mass fibres) everywhere, but the fibres are short (often less than ½ cm long) and brittle. In portions containing much talc the fibres seem to be better developed, and then they sometimes are flexible, but still less than 1 cm in length. Especially good mass fibres have been met with in the afore-mentioned small stream NW of Masati and on the farmhill 1 ½ km SSW of Mabandu, where they may be up to 2 cm long but still, and in most cases, remain brittle and hard. In the mentioned localities, however, veinlets occupied by cross fibres are abundant also, on the average such veins of cross fibre anthophyllite asbestos are 2 to 3 cm wide, yet exceptions up to 6 cm wide occur.

Following the main anthophyllite bearing strip of the area — it is the one between Masati and Mabandu — an interesting change in composition can be observed. At Mabandu and at the farmhill mentioned above the anthophyllite rock is conspicuously rich in talc, and the latter is usually massive or only slightly orientated. The talc decreases in quantity in the direction of Masuri, and in the small stream NW of Masuri (see above) chlorite clusters occur. Southwest of this stream, the rock gradually develops into tremolite serpentinite, and there no asbestos has been seen.

Synkinematic Rocks of Gabbroic to Dioritic Composition

All synkinematic rocks embracing or concordantly penetrating the strips of serpentinites are coarse and of gneissy appearance. Especially in the area west and north-west of the asbestos-bearing strip between Masati and Mabandu these gneissose rocks are hornblende-bearing, and they often contain none or little biotite. In the field they have been called "hornblende gneisses". But this name is misleading because the mentioned rocks usually contain only a small amount of quartz, and no potash feldspar. Plagioclase of these rocks is oligoclase to andesine. These gneisses frequently grade into amphibolites consisting of hornblende, plagioclase, and accessory sphene and apatite; the former accessory is drop-like. Pyrite too is often present in small quantities. In connexion with "hornblende gneisses" the serpentinite strips often contain narrow seams of amphibolite as well, and near Bombe there is a seam, 20 to 30 m wide, consisting solely of coarse hornblende.

A close connexion between amphibolite and "hornblende gneiss" is interpretable: by getting additional feldspar and quartz, amphibolite turns into "hornblende gneiss", the main texture remaining all the time the same, and particularly the manner of occurrence of sphene is in both rock types characteristically similar.

In narrow zones within the "hornblende gneiss", pyroxene (diopside with $c\varLambda\gamma = 38°$; occasionally augite with $c\varLambda\gamma = 52°$) may also be present, either instead or together with hornblende. Such "diopside gneisses" often also contain epidote, which obviously originated from the epidotisation of diopside and anorthite, and in two cases so far detected, on the margin of such a strip epidosite consisting of epidote and quartz only occurs; the width of those epidosite portions does not exceed 2 or 3 meters.

The rock name "hornblende gneiss" being misleading because the term "gneiss" should be preserved for the rocks of granitic to granodioritic composition, the author is of opinion that here a new definition is necessary. As revealed by the rock description, "hornblende gneiss" is much closer to amphibolite than to gneiss. As a matter of fact such rocks have not seldom been described as amphibolites, which, consequently, have included metamorphic rocks both of gabbroic and of dioritic composition. More frequently, however, the term "amphibolite" has been applied to quite different, usually more or less fine-grained and dark rocks, often referred to by the abandoned term "metabasites".

In order to distinguish clearly the rocks similar to the afore described "hornblende gneisses" from granodioritic or granitic gneiss and from typical amphibolites, the present author suggests that the term "diorite gneiss" be used for the former and that the diopside-bearing variety be given the name of "diopside diorite gneiss". Thus the term "hornblende gneiss" could be reserved for the hornblende-bearing gneisses of granodioritic to granitic composition and consequently to the rocks containing potash feldspar. The term "amphibolite" should be applied solely for the metamorphic, amphibole-bearing rocks of basaltic (gabbroic) composition.

Synkinematic Gneisses

In the eastern part of the Masati area, the gneissose synkinematic rocks are mostly of granodioritic composition, the granitic rocks being there exceptional. Virtually they are biotite gneisses and biotite granodiorites which contain much plagioclase (An_{20-30}), moderately to much quartz, and comparatively little dark biotite, which forms scales and clusters up to 5 mm across. They are pale and often penetrated by numerous quartz- and simple pegmatite veins, and often they attain a habit of migmatite with granodiorite paleosome and pegmatitic metasome.

Potash feldspar is always sparse and exclusively microcline, as has been shown to be typical of all synkinematic rocks of Central Sierra Leone (MARMO, 1955a and 1955b).

Microcline Granite

In two places near Mamansu large boulders and few outcrops of fine-grained, pinkish gray granite have been met with. It probably there forms a dyke not more than 50 m wide, and it is supposed to be late-kinematic. The granite consists of microcline, albitic plagioclase, and quartz. The micas are sparse, and muscovite clearly predominates over biotite.

Dolerite Dykes

N of Mamansu a 5 to 10 m wide dolerite dyke cuts the gneiss, roughly in N–S direction. In two places, 1½ km south of Masuri and 1½ km north of Masati, boulders of dolerite have been collected. Supposedly the dolerite dykes occur here too, in the former locality they cut the biotite gneiss and in the latter they do so to the migmatitic gneiss.

Petrogenetical Discussion

Petrochemical Aspects

The description of the rocks revealed that the anthophyllite asbestos is bound to the ultrabasic rocks. Within the Masati area, the principal mineral associations of these rocks are the following:

a) antigorite - olivine (- tremolite);
b) antigorite - tremolite (- chlorite);
c) (antigorite -) tremolite (- chlorite);
d) tremolite - talc;
e) anthophyllite - actinolite tremolite (- talc);
f) anthophyllite - talc (- tremolite) (- chlorite);

carbonates are very occasional within the entire area under discussion.

The fibrous varieties of anthophyllite are associated with the mineral associations (e) and (f).

The mineral assemblage (a) may be formed under hydrothermal conditions from a recrystallizing or crystallizing mass of appropriate composition and, as remarked on p. 35, the olivine is formed due to local deficiency in silica.

If such a mass contains calcium in addition, tremolite will also be formed. This will lead to the development of mineral combination (b), which likewise will be attained, if the necessary calcium is introduced from the outside, provided that silica is present in excess:

$$(1) \qquad \underset{\text{antigorite}}{2\,[3\,MgO\cdot 2\,SiO_2\cdot aq]} + 2\,CaCO_3 + 4\,SiO_2 \rightarrow \underset{\text{tremolite}}{5\,MgO\cdot 2\,CaO\cdot 8\,SiO_2\cdot aq} + MgCO_3 + CO_2 + aq.$$

The presence of chlorite indicates the initial alumina content of the crystallizing material, which, for convenience, will not yet be discussed in regard to its origin, but will only be considered as a mass of material yielding the mineral associations mentioned above as a result of crystallization (or recrystallization).

Talc may be considered as a silicaceous antigorite:

$$(2) \qquad \underset{\text{antigorite}}{3\,MgO\cdot 2\,SiO_2\cdot 2\,H_2O} + 2\,SiO_2 \rightarrow \underset{\text{talc}}{3\,MgO\cdot 4\,SiO_2\cdot H_2O} + H_2O.$$

If the formula of antigorite is written in the form according to its molecule structure: $(6\,MgO\cdot 8SiO_2)\cdot 6\,Mg(OH)_2\cdot 2\,H_2O$, the reaction may be easier to understand. According to it, the formation of talc means silification of the hydroxide component of the antigorite, and the expulsion of water means a release of the molecular water. The talcitisation

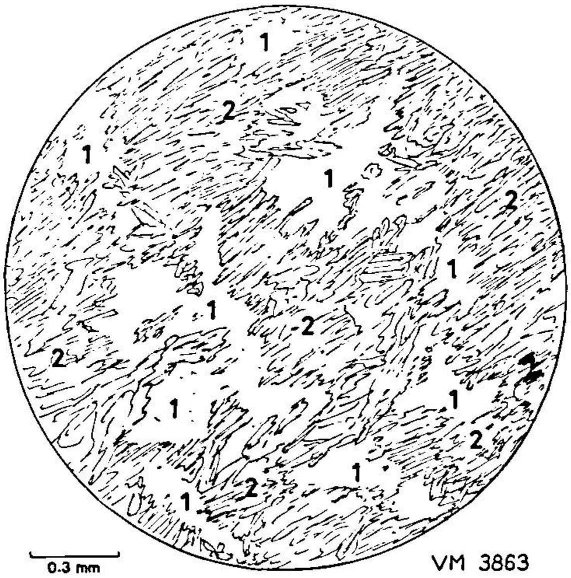

Fig. 3. Talc-antigorite schist. The Batfunke stream, 2 km W of Mawruka. Ragged remnants of the antigorite in a fine-grained talc mass. Talcitisation of antigorite. One Nicol. 1 = antigorite; 2 = talc.

of antigorite is well illustrated in Fig. 3, where the main mass consisting of fine-grained talc contains ragged remnants of the antigorite.

From the point of view of the formation of anthophyllite, the problem should be devided in two:

— the formation of anthophyllite;
— the development of anthophyllite into fibrous asbestos.

The anthophyllite has been produced in the laboratory by BOWEN and TUTTLE, and by YODER, but only metastably. YODER (1952, p. 609) concluded that anthophyllite is not stable if the water is present to excess.

Very recently, WEEKS (1955), on the basis of the experimentally obtained values of the heat of formation, concluded that the upper limit of the stability of anthophyllite is at 300° C.

According to its chemistry, it should be possible that by the presence of excess silica anthophyllite crystallizes from a mass exactly similar to that yielding antigorite + olivine,

$$(3)\quad \underset{\text{serpentine}}{4\,[3\,MgO\cdot 2\,SiO_2\cdot 2\,H_2O]} + \underset{\text{olivine}}{2\,MgO\cdot SiO_2} + 7\,SiO_2 \rightarrow \underset{\text{anthophyllite}}{2\,[7\,MgO\cdot 8\,SiO_2\cdot H_2O]} + 6\,H_2O.$$

The quartz veins are actually rather abundant in places where anthophyllite mainly occurs.

ESKOLA (1939) too considered the anthophyllite to have originated from serpentine by an addition of silica.

On the other hand the addition of silica to an antigorite mass may likewise yield talc, as a result of a slight silification of anthophyllite, which phenomenon has often been observed both in the Masati area and elsewhere in the occurrences of anthophyllite asbestos. The relationship between talc and anthophyllite can be expressed by the following equation:

$$(4)\quad 3\,[7\,MgO\cdot 8\,SiO_2\cdot H_2O] + 4\,SiO_2 + 4\,H_2O \rightarrow 7\,[3\,MgO\cdot 4\,SiO_2\cdot H_2O].$$

Anthophyllite asbestos and anthophyllite rocks in general are usually poor in alumina, often containing less than 1% Al_2O_3. Due to the presence of chlorite clusters (p. 36), the anthophyllite of the Masati area, however, is rich in alumina. A partial chemical analysis of the asbestos rock of Masati area is shown in Table I (Anal. 1), and its composition is close to that of the anthophyllite asbestos rock of Tiilikainen, Finland (HAAPALA, 1936), also shown in Table I.

The chemical composition of the anthophyllite rock of Masati is in good agreement with its modal composition, as obtained on the integration stage (Table II).

Table I: *Chemical composition of the anthophyllite rocks*

Constituents	1	2
SiO_2	52.15	57.56
Al_2O_3	4.09*)	3.34
Fe_2O_3	12.37**)	3.22
FeO		2.20
MnO		0.40
MgO	21.11	28.01
CaO	0.50	0.71
Na_2O		0.58
K_2O		0.10
H_2O+		2.88
H_2O-		0.68
Total	90.22	99.92

1 = Partial analysis of anthophyllite asbestos rock. Near Masati, Sierra Leone. Analyst J. Middleton.

2 = Anthophyllite rock. Tiilikainen louhos, Finland. Analyst E. Savolainen (Haapala 1936).

*) Includes TiO_2 and P_2O_5.
**) Taken as total iron.

Table II: *Modal composition of the anthophyllite rock of Masati*

Constituents	1 Measured on I-stage	1 Estimated from the partial chemical anal.	2 Measured on I-stage
Anthophyllite, $7(Mg, Fe)O \cdot 8SiO_2 \cdot H_2O$	50%	46.0%	60%
Chlorite, $5MgO \cdot Al_2O_3 \cdot 3SiO_2 \cdot aq.$	15%	20.0%	—
Actinolite, $5FeO \cdot 2CaO \cdot 8SiO_2 \cdot H_2O$	9%	9.0%	5%
Talc, $6MgO \cdot 8SiO_2 \cdot 2H_2O$	26%	16.0%	35%
SiO_2	—	9.0%*)	—
Total	100%	100%.0	100%

1 = Mass fibrous anthophyllite asbestos rock. Near Masati.
2 = Mass fibrous talc-anthophyllite asbestos rock. Near Mabandu.
*) Probably derived from quartz veinlets present in analysed sample.

The partial analysis of Table I can also be treated so, that it is calculated into actinolite, chlorite, antigorite and haematite, supposing that that was the rock composition before formation of talc and anthophyllite. Consequently assuming, that Ca, Fe and Al were primarily present in the rock:

tremolite actinolite	9.0%
chlorite	20.0%
antigorite	30.0%
hæmatite	10.5%
Total	69.5%

The remaining SiO_2 makes 16.5%, or approximately 57% of the amount of antigorite; and only 40% silica of the amount of antigorite is necessary to convert antigorite into anthophyllite, and 47% of the amount of antigorite to convert it into talc. These calculations support the idea, that the growth of anthophyllite is due to reaction between antigorite and incorporated silica.

In the Masati area silica has evidently always been present in excess and clearly in sufficient amount for the formation of talc as well. That, in spite of that, anthophyllite was formed, must depend on some particular conditions. The presence of iron may be the cause as the anthophyllite often contains Fe, while the talc is always conspicuously poor in this element. There are, however, numerous examples of talc schists containing ample octahedra of magnetite, and in Fig. 4 an instance is illustrated, where magnetite surrounds the talcose patches. One may

Fig. 4. Talc-magnetite schist. The Kangari Hills.
Fine-grained magnetite, deposited around the flakes of talc and along the planes of schistosity. One Nicol.

suppose, that if conditions are such that the oxidation of ferrous iron into ferric iron is hampered, thus preventing the formation of magnetite, it caused the formation of anthophyllite instead of talc. This explanation we cannot accept either because the anthophyllitic rocks often contain Fe_2O_3 in considerable quantity. Evidently special PT-conditions are here necessary, and from this point of view the question will be discussed again below.

The second question: the formation of the fibrous varieties, can hardly get an explanation from the petrochemical consideration, but it seems to be a purely physical phenomenon. In many instances, for example in Georgia, USA (BOWLES, 1934), and in Kaavi, Finland (AUROLA and VESASALO, 1954), the best qualities of asbestos occur near the surface and in the weathered parts of the rock, which underneath is fresh and brittle or consists of nonfibrous serpentine. Because of this manner of occurrence of asbestos, Frosterus supposed as early as in 1902, that the fibrous habit of the anthophyllite is a secondary quality, a result of the weathering processes. AUROLA and VESASALO (1954) suggest that in such conditions the water can have moved in a longitudinal direction through the anthophyllite and such cause its transformation into fibres. This explanation does not seem to be dependable, since there are no chemical datas indicating that the anthophyllite asbestos should be richer in water than the normal anthophyllite.

On the contrary, the softening of the anthophyllite fibres due to weathering is quite possible, and this view is particularly sustained by HOPKINS (in: LADOO and MYERS, 1951), who remarks, that the fresh anthophyllite, beneath the weathered, fibrous portion of the rock is splintery, although it has a good prismatic cleavage.

The softening of the serpentinites, of tremolite schists, and of anthophyllite rocks by weathering is an often observed phenomenon, and there are at least some instances of talc also appearing in the weathered portions, while it is entirely absent in the fresh ones. Evidently the processes of weathering may result in a talcitisation of serpentine, tremolite, and anthophyllite, if an addition of silica is introduced at the same time. Such phenomena, however, are hardly responsible for the formation of fibres; they may only "refine" the quality of the pre-existing fibres of anthophyllite.

Petrological Environs of the Fibrous Anthophyllite

The zone containing anthophyllite asbestos is narrow but long in the strike direction (Fig. 2). In all other places of the area anthophyllite is either absent — or only small, occasional anthophyllite patches occur.

Within the Masati area the diorite gneiss predominates over the biotite gneiss and granodiorite (p. 36). The latter rocks are always rich in quartz, and often they are migmatised by pegmatites (p. 38). Quartz veins are frequent also, and especially abundant they are in areas close to those containing asbestos, hence within diorite gneiss as well. Consequently, the strong introduction of quartz is typical for all parts of the Masati area. The potash feldspar, on the contrary, is conspicuously sparse there; in the biotite gneiss and granodiorite it is present in a subordinate amount and it always occurs in interstices of other minerals; in the diorite gneisses it is absent. The diorite gneiss is always rich in hornblende, and biotite too is often lacking there, thus also indicating the weakness of potassium metasomatism under which hornblende survived almost entirely.

While the diopside diorite gneiss occurs especially within the asbestos-bearing zones of the area, it does so quite occasionally in other parts of the area. The formation of diopside beside hornblende is obviously a result of a different initial composition, the diopside indicating portions richer in lime. Within the areas characterised by granodiorite and biotite gneiss, the lime appears in the ultrabasic rocks themselves, there partaking in the formation of tremolite. In the presence of diopside diorite gneiss, tremolite serpentinite may occur, but particularly typical for such areas is anthophyllite, the calcium content of which is very low (Anal. 1, Table I).

The mineral association diopside-hornblende-plagioclase has been discussed by Marmo (1955) in connection with a small nickeliferous basic rock in Finland and he explained this mineral combination to correspond to the average amphibolite facies. In the Masati area, however, the diopside diorite gneiss often contains epidote as well (p. 37), and there two alteration phenomena: epidotisation and uralitisation of pyroxene usually occur in the same rock.

Another interesting feature in these rocks is the occurrence of sphene. Fig. 5 illustrates two samples from the same strip of diopside diorite gneiss, only ten meters from each other. There seems to be no doubt, that sample VM 3329 is a product of epidotisation of a rock similar to that of VM 3326, as clearly revealed by inspection in the field and under the microscope; similar distribution of drop-like sphene in both slides favours the same assumption. Virtually, such distribution of sphene is typical of all diorite gneisses within the Masati area. Beside diopside plagioclase too is epidotised, and in VM 3329 the epidotisation proceeded to such an extent, that mainly quartz and epidote are present, and in addition a little tremolite — probably the remnant of uralitised pyroxene, which survived the epidotisation.

The purpose of the present paper is not to discuss the mechanics of epidotisation. Here the fact is of particular importance that the portions of the diorite gneiss which occur in close connection with the asbestos-bearing anthophyllite rocks bear clearly evidence of a strong epidotisation, which is much less pronounced in other parts of the diorite gneiss strips.

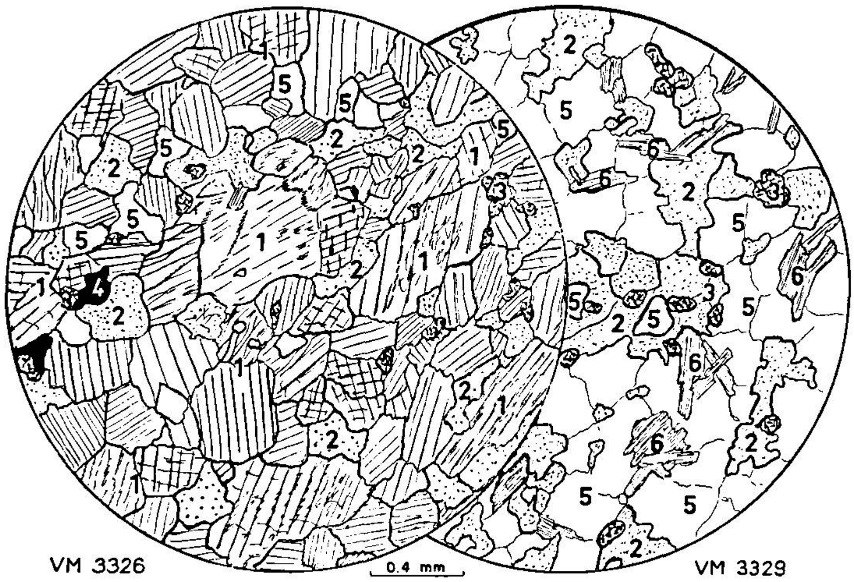

Fig. 5. Diopside diorite gneiss (VM 3326) and tremolite epidosite (VM 3329). Near Masuri.
1 = diopside; 2 = epidote; 3 = sphene; 4 = ore; 5 = quartz; 6 = tremolite. One Nicol.

In common opinion the conditions leading to an epidotisation are those of a temperature lower than that of the amphibolite facies, but higher than the greenschist facies.

The serpentinites of the Masati area (at least the olivine serpentinites) are probably formed at a temperature between 450 and 500° C (p. 35). The formation of anthophyllite took place at a much lower temperature than did the formation of antigorite (p. 40). In addition, the petrological facts indicate that in that region the potassium metasomatic processes were negligible but the introduction of silica considerable.

In similar conditions formation of talc is possible also.

Tectonics

A strong N-S fracturing and shearing is typical of all parts of the geosynclinal schistbelt of the Sula Mountains and Kangari Hills. This shearing is often accompanied by the formation of mylonites but more frequently by intrusion along the faults of latekinematic granites, usually rather rich in potassium (Marmo, 1955a), or of potassic pegmatites, which often are tourmaline-bearing. In points of axial culminations the latekinematic granite sometimes appears there forming domes.

Within the Masati area the same shear direction is well developed as well, but except for a small latekinematic dyke at Mamansu, the potassium does not play there any role in connection with these shear zones.

Fig. 1 illustrates the southern part of the schistbelt and also the relationship of the Masati area to it. The latter was clearly torn off from the schistbelt. Such tearing off may be dependably explained, if the mentioned shear direction, together with frequently present but less distinct E-W fracturing is taken as an indicator of the forces necessary for this tectonic event. The mentioned shear zones are comparatively young; they sometimes affect the latekinematic granites as well, but the porphyroblasts of the granites in the vicinity of the schistbelt often grow across the shear fractures. The movements responsible for the fracturing, however, may be much older than the visible shearing.

If from north to south a push directed against the eastern part of the schistbelt took place and then was resisted by the southernmost part of the geosyncline, some central parts of the geosynclinal formation may well be expected to be torn off. In such a case the area remaining between the main schistbelt and the torn off portion, must be characterised by an expansion of space. Into this "gap" the push caused materials to be introduced, including "juices", which within the area near Masati, evidently have mainly consisted of silica and water.

Within the Masati area, and especially close to the places of anthophyllite rocks, miniature folds have often been observed, the crests of such folds are strongly fissured and the fissures filled with quartz.

Consequently, the area characterised by the presence of mostly fibrous anthophyllite is on the verge of such an area, which during the last large movements obviously was expanded.

Because of the addition of silica, the conversion of antigorite into anthophyllite causes an increase of molecular volume of about 23%. The talcitisation of anthophyllite brings about an additional increase of volume of 20% (WIIK, 1953, p. 45). Consequently both reactions leading together to the formation of anthophyllite-talc rocks out of antigorite will be accompanied by an increase of volume.

WIIK (1953, p. 42) pays attention to the possibility of the formation of talc on account of anthophyllite, that is by addition of carbon dioxide:

(5) Anthophyllite + $3\,CO_2$ + Water $\rightarrow$ 0.67 Talc + 3 Magnesite + $2.64\,SiO_2$.

He expects that the silica released in the reaction will be removed. The talc-anthophyllite rocks of the Masati area are always penetrated by numerous quartz veins, but the carbonates are there negligible. Under conditions of weathering, however (p. 43), the role of carbon dioxide in the superficial talcitisation of serpentinites and of anthophyllite rocks may be rather important; in such cases also a complete removal of formed magnesite is not only possible but must even be expected.

The development of fibrous anthophyllite is another question, and there, probably, the minor tectonic features are of particular importance.

The anthophyllite fibres within the Masati area may be either unorientated mass fibres of the rock itself, or then they are parallel by arranged cross fibres filling the veinlets and growing subvertical to the walls of the veins. The formation of those parallel cross fibres is obvious and, regarding the mechanics of their formation, very much similar to that of the chrysotile cross fibres, much discussed in the geological literature.

TABER (1917) and later on KEITH and BAIN (1932), and others, have assumed that the fibres grow between the walls of original rock fractures; DRESSER (1913) believed that the fibres grew at the expense of the walls of the original rock fracture, a point of view which was later adopted by some geologists. RIORDON (1955) starts from peridotite, which serpentinized along the fractures; the chrysotile asbestos, according to him, would have derived from picrolite of the preformed composite veins as a result of recrystallisation of these veins. He holds important that the temperature should be adequate to induce sufficient contraction during the cooling period to produce stress conditions favourable for the recrystallisation of picrolite into asbestos.

The *anthophyllite rocks of the Masati area, containing abundant* veinlets of fibrous anthophyllite 0.5 to 60 mm in width (Fig. 6), are typically brecciated by the mentioned veinlets. In other words, the rock appears to have been crushed. On the other hand, fractures indicating shearing and containing mylonitic portions are there entirely absent. The portions richest in talc and anthophyllite are mostly unorientated (mass fibrous), and talc pseudomorphs after anthophyllite occur (Fig. 7); the occurrence of well orientated talc schists in the closest vicinity of the asbestos is inessential. Evidently the shearing of the anthophyllite rock areas is not responsible for the crushing of the rocks, but the veinlets filled by the cross fibres of anthophyllite seem to be tensional ones. Probably the main push from north to south (p. 46) caused this tension as well as the increase of volume by opening new space, which was occupied by introduced large quantities of silica.

In such conditions, the fracturing must have taken place at an early stage of the formation of anthophyllite, and at this stage, from the very beginning of the opening of the fractures, all elements required were present for the formation of asbestos filling the cracks.

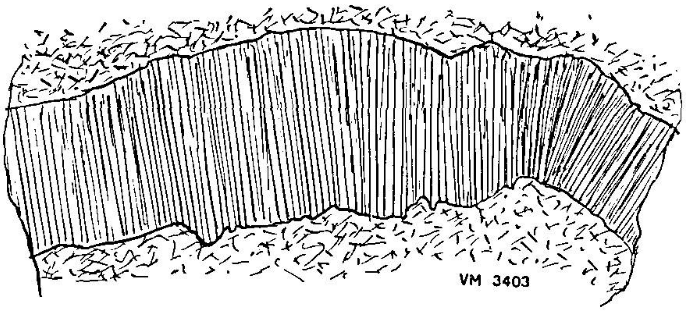

Fig. 6. 25 mm wide anthophyllite asbestos veinlet in unoriented talc-anthophyllite rock. W of Mawruka.

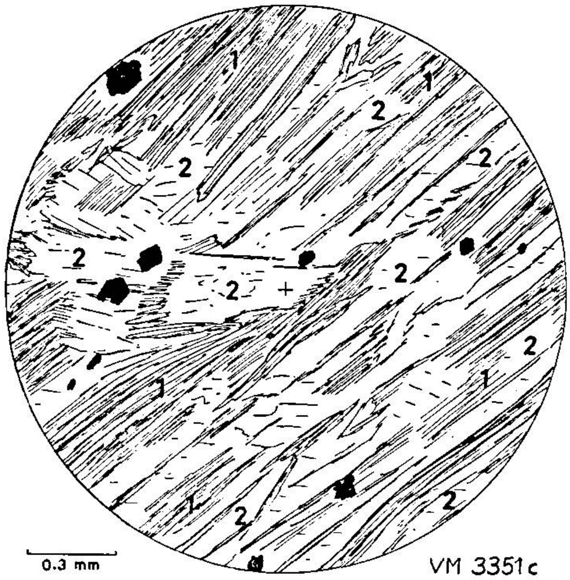

Fig. 7. Talc anthophyllite rock, 60 mm wide asbestos vein. Near Masati. Talcitisation of anthophyllite fibres. The talc lamellæ often cut the fibres. One Nicol.

The softening of the anthophyllite and the development of the fibres into true anthophyllite asbestos cannot be described from the evidence discussed above. The possibility that the weathering is the necessary factor for the softening of the fibres (p. 43) still remains.

Summary

The formation of anthophyllite within the Masati area has been described as to have taken place within an area, where during the regional metamorphism, adequate quantities of silica and water were present. At the same time, the potassium metasomatism was almost negligible. The PT conditions of the metamorphism are those of the epidote-amphibolite facies of ESKOLA (saussurite facies of ROSENQVIST).

The area where anthophyllite rocks occur is such, that during the large movements it represented an area characterised by an increase of volume and by one-sided pressure (push).

In such conditions the serpentine (antigorite) is believed to convert into anthophyllite owing to the introduction of silica.

The cross fibres of the anthophyllite which occur filling the cracks are supposed to have formed in the open fractures not much later than the mass fibre anthophyllite had crystallized.

The softening of the anthophyllite fibres into asbestos has not been discussed, but the earlier expressed views that the weathering may be the facilitating agent in such a softening has been considered possible.

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