

# ON ANTIGORITE-SERPENTINES FROM OFOTEN WITH FIBROUS AND COLUMNAR VEIN MINERALS

BY  
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10 FIGURES IN THE TEXT AND 4 PLATES

**I**n the mountain wilds between Tysfjord and Ofotenfjord in northern Norway, where the rock is exceedingly well exposed, we frequently observe small, rounded knolls of a reddish-brown or yellowish-brown hue, visible at a great distance. Fig. 1.

They are lacking every trace of vegetation and their smooth surfaces retain the glacial striæ better than any other rock. They consist of more or less serpentized olivine rocks, and their generally massive structure is in a peculiar contrast with the foliation structure of the mica schists, amphibolites and other sedimentary and igneous crystalline schists of Palæozoic age, which constitute the region.

Notwithstanding their great number, these serpentine bosses — as we might call them — are quite subordinate in quantity, the individual bosses having diameters only from 10 to a couple of hundred meters.

They nearly look like drops, having an elongated to nearly circular outline, as well in vertical as in horizontal sections, and are not lenses, because the ends are always rounded. The major part of them occur within amphibolite bands (metamorphosed gabbros), and the general distribution leaves no doubt about their consanguinity to the other Caledonian intrusives of the region. They are also found over wide regions within the Caledonian mountain chain of northern Norway and Sweden.

Obviously very sensible to varying physical conditions they afford much of interest for the study of mineral facies, and may also contain minerals of economic value. Nevertheless they have not yet been much studied here from a petrological point of view.

The main work in this respect is that of F. Eichstädt<sup>1</sup>, nearly 50 years old. From norwegian side Carstens<sup>2</sup> has treated mainly the fresh peridotites, and Barth<sup>3</sup> the sagvandites.

The present paper will be limited to a couple of small bosses, lying 250 meters west and 2300 m east of Rauvatn (Red lake) in upper Melkedalen, Ofoten, 5—700 m above sea level, and with

dimensions  $33 \times 15$  and  $110 \times 25$  m. respectively. They may serve as a standard type for these rocks in the district, and moreover contain the very peculiar veins, which it is the main object to call attention to.

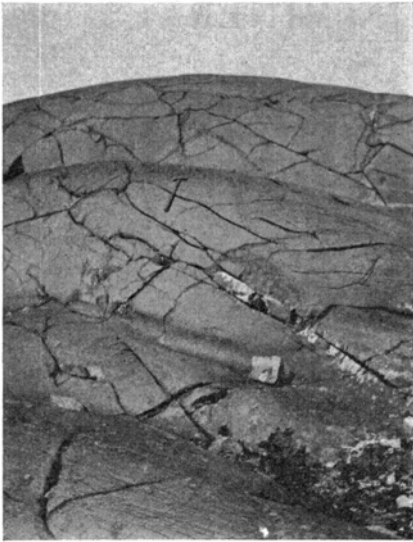


Fig. 1. Antigorite-serpentine. East of Rauvatn. Smooth and glaciated surface with open cracks, due to temperature fluctuations. (S. Foslie phot.).

structure, so characteristic of most serpentines, which have derived from olivine, is completely lacking. The serpentine mineral forms either leaves, growing in a more or less pronounced lattice texture along crystallographic lines in the olivine, or tufts, growing quite irregularly, and without traces of post-crystalline pressure. Pl. I, fig. 1.

### The antigorite-serpentines.

These serpentine bosses consist of a very tough rock of dark grey colour and an absolutely massive structure. Different from the more general type of serpentines, they are distinctly crystalline, fine-grained with numerous glistening scales. Fig. 8.

Under the microscope it is seen, that they contain more remains of the olivine, than expected from the water content of the analysis, and that the mesh

<sup>1</sup> F. Eichstädt: Olivinstenar och serpentiner från Norrland. Geol. Fören. Förh. VII, p. 333, Stockholm 1884.

<sup>2</sup> C. W. Carstens: Norske peridotiter I. Norsk Geol. Tidsskr. V, p. 1, Kristiania 1918.

<sup>3</sup> Tom Barth: Sagvandite, a magnesite bearing igneous rock. Norsk Geol. Tidsskr. IX, p. 271, Oslo 1926.

*Antigorite-serpentine rock. East of Rauvatn, Ofoten.*

Sp. gravity 2.786. Analyst: Emil Klüver.

	o/o	Mol. prop × 1000
SiO <sub>2</sub> .....	40.45	674
TiO <sub>2</sub> .....	none	
Al <sub>2</sub> O <sub>3</sub> .....	0.67	6.5
Fe <sub>2</sub> O <sub>3</sub> .....	3.34	21
Cr <sub>2</sub> O <sub>3</sub> .....	0.48	3
FeO .....	4.15	57
MnO .....	0.13	2
NiO .....	0.076	1
MgO .....	40.21	1005
CaO .....	none	
Na <sub>2</sub> O .....	0.11	2
K <sub>2</sub> O .....	0.05	0.5
CO <sub>2</sub> .....	1.41	32
P <sub>2</sub> O <sub>5</sub> .....	none	
S .....	0.08	2.5
H <sub>2</sub> O + 200° .....	8.51	473
— 100—200° .....	0.08	
— ÷ 110° .....	0.20	
	99.946	
÷ O for S .....	0.04	
	99.906	

*Mineral composition.*

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	FeO	MnO	NiO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	CO <sub>2</sub>	S	H <sub>2</sub> O	Sum weight <sup>o/o</sup>	Sp. gr.	Vol. o/o
Magnesite ...	-	-	-	-	0.15	-	-	1.21	-	-	1.41	-	-	2.77	3.1	2.50
Magnetite ...	-	-	3.34	-	1.53	-	-	-	-	-	-	-	-	4.87	5.1	2.66
Chromite ...	-	-	-	0.48	0.20	-	-	0.03	-	-	-	-	-	0.71	4.4	0.45
Pyrrhotite ...	-	-	-	-	0.18	-	-	-	-	-	-	0.08	-	0.22	4.6	0.13
Talc .....	0.95	-	-	-	-	-	-	0.48	-	-	-	-	0.07	1.50	2.7	1.55
Antigorite ...	15.12	0.46	-	-	-	-	0.06	15.35	0.09	0.05	-	-	4.67	35.80	2.5	40.00
Olivine ...	7.35	0.07	-	-	1.61	0.03	0.02	8.90	0.02	-	-	-	-	18.0	3.33	15.1
{ Olivine II ...	10.80	0.14	-	-	0.48	0.10	-	14.24	-	-	-	-	-	25.76	-	-
{ H <sub>4</sub> SiO <sub>4</sub> ...	6.23	-	-	-	-	-	-	-	-	-	-	-	3.74	9.97	2.7	37.2
	40.45	0.67	3.34	0.48	4.15	0.13	0.08	40.21	0.11	0.05	1.41	0.08	8.48	49.60	-	99.59

Eichstädt (loc. cit.) has already shown, that antigorite is a constituent of several serpentine rocks of Swedish Norrland, and that the lattice texture is not — as formerly believed — necessarily due to the serpentinization of pyroxene- and amphibole minerals. Later Becke<sup>1</sup> and others have proved the same from the Alps etc., and suppose that antigorite occurs only in folded chains.

From Norwegian serpentine rocks, antigorite apparently has not been mentioned at all. My investigations in the Ofoten district prove it to be quite dominant there.

The analysis (p. 221) is interesting in several respects. The absence of lime is so complete, that not the slightest trace could be found. This must obviously be a primary feature, when we see it in connection with the absence of  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  and the very low content of alumina. The rock must originally have been extremely dunitic.

#### *Microscopic examination.*

*Fresh Olivine* is the only primary mineral present, as pyroxenes, amphiboles and primary spinel minerals have not been found.

The olivine has a very good cleavage (010), better than usual for this mineral. The determination however is quite certain: Parallel extinction, axial plane  $\perp$  to the cleavage, with  $\alpha$  emerging on the cleavage plane, biaxial with axial angle near  $90^\circ$

$$\begin{aligned}\alpha &= 1.652 \pm 0.002 \\ \beta &= 1.6705 \pm \text{—} \\ \gamma &= 1.689 \pm \text{—}\end{aligned}$$

$\alpha$  and  $\beta$  were determined directly by the immersion method in daylight,  $\gamma$ - $\alpha$  by the aid of Berek's compensator. It was found to be 0.037, using  $\alpha$ -sections of the olivine for the thickness measurement, as  $\gamma$ - $\beta$  is nearly constant throughout the olivine series.

These constants suffice to establish the composition of the original olivine to 9.4 Mol-% fayalite<sup>2</sup>, corresponding to 9 $\frac{1}{4}$  weight-% (Fe, Mn, Ni)O.

*Olivine II.* It is only a part of the olivine present, which is still fresh, mainly in the central parts of the original grains. For the rest it has suffered a change, apparently of metasomatic nature, characterized by a small decline of the refraction and a very considerable decline of the birefringence, but retaining the original extinction, optical orientation and cleavage. There is a gradual change from the original olivine with  $\gamma$ - $\alpha$  0.037, down to about 0.012, and together they form grains with a high relief in contrast to, and with sharp borders against the anti-

<sup>1</sup> Becke: Olivinfels und Antigoritserpentin aus dem Stubachthal. T. M. P. M. 14, p. 271.

<sup>2</sup> E. Ernst: Ein Beitrag zur Kenntnis der Olivingruppe. Neues Jahrb. VII. Beil. Band A (1925). S. 144.

gorite, which crosses them both, with a much lower index of refraction. This change is not accompanied by any separation of magnetite. Its nature will be treated later on.

*Antigorite.* Optically it is characterized by the axial plane lying  $\perp$  to the cleavage and the elongation of the leaves.  $\alpha$  emerges on the cleavage flakes with a medium axial angle, the elongation is +, the optical character  $\div$ . No pleochroism.

$$\alpha = 1.562 \pm 0.003$$

$$\gamma = 1.569 \quad -$$

$$\gamma - \alpha = 0.007 \pm 0.001$$

The leaves, up to 1 mm long, have generally a random orientation. The iron content is obviously low.

*Talc* occurs very sparsely together with the antigorite, in parallel orientation with it, and without demonstrable difference of age.

$$\gamma - \alpha = 0.048$$

*Magnetite* is plentiful, but exclusively secondary, following only the antigorite, which nearly everywhere carries small jaggy grain aggregates of it.

*Pyrrhotite* is very scarce, following the magnetite, also secondary.

*Magnesite* (Breunnerite) occurs everywhere, but somewhat more unevenly distributed than the other minerals. It is certainly secondary, but obviously older than the antigorite, whose leaves penetrate it.

*Doubtful mineral.* It does not occur in the analyzed rock, but in the very similar rock west of Rauvatn. It is a leafy mineral, intimately associated with the antigorite, in parallel orientation with it and also with positive elongation. It is also probably optically negative, distinctly pleochroitic in a faint brownish tone. It has a little higher index of refraction than the antigorite, but the birefringence is much lower, approaching zero, with anomalous bluish interference colours, so that the axial figure is not visible. It might without hesitation have been classified as a *pennine*, except for the fact, that the absorption is quite opposite that, which is usual in the mica- and chlorite groups. It is the ray vibrating perpendicular to the cleavage, which is absorbed, in the other direction it is colourless. Realizing the close relationship between the chlorite- and serpentine molecules, one might perhaps presume the mineral to be an iron-bearing antigorite, of earlier date than the separation of the magnetite. Barely visible brownish remains are often seen in the antigorite.

### *The calculation of the mode*

(See table p. 221)

is much facilitated by the absence of lime, titanium and alkalies. A Rosiwal measurement of a big slide gives a quantity of opaque ore minerals of 3,80 vol.-%. This necessitates the calculation of all the ferric iron as magnetite and all the chrome as chromite (eventually secondary together with magnetite). Nevertheless we do not reach more than 3,25 vol.-% ore minerals, a difference that probably is due to the fact, that a good deal of the ore grains measured have a diameter, smaller than the thickness of the slide.

The talc quantity is estimated to 1,5 %. A slight deviation from this figure does not influence the calculation very much. The carbonic acid gives the quantity of magnesite.

Remaining are then only the olivines and the antigorite, of which the composition of the fresh olivine is already known.

If we for a moment consider the two olivine types as a unit, and on this assumption calculate the antigorite in 3 different ways: from the specific gravity of the rock, the water content of the rock, and the FeO remaining for the silicates, we get nearly corresponding values, namely 62—68 weight-% antigorite and 29—23 % olivine.

A Rosiwal measurement of the slides, however, gives the following result:

	Vol. %	Sp. gr.	Weight. %	
Olivines.....	52	3.33	53.8	(only about 15 % fresh)
Antigorite.....	40	2.5	35.8	

that means much more olivine, demanding a sp.gr. of the rock, considerably higher than observed.

This shows with certainty, that the mineral, named Olivine II must have undergone a very considerable change from its primary composition, and the calculation at least shows the tendency very plainly. It must be much hydrated, the silica content has increased, the iron content and the specific gravity have decreased considerably. All these changes point in the same direction as a serpentinization. That ordinary serpentine has not been formed at this stage was shown before by the fact, that the index of refraction remains much too high, and that it is not the question of recrystallization. The optical orientation has remained the same.

It is interesting to note, that Brauns<sup>1</sup> has supposed an intermediate state in the process of serpentinization, corresponding to the formula  $H_2Mg_3Si_2O_8$ , and here ranks the mineral Villarsite.

In our case, there can be no question of a fixed formula, because the birefringence proves the transition to be quite gradual.

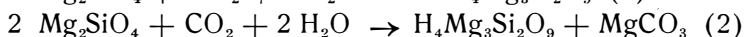
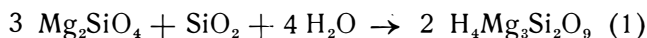
Very probably we therefore have the case of a simple hydration of the olivine,  $H_2$  gradually substituting its base metals, with preference to Fe'', and leading to the general formula  $[Mg, Fe, H_2]_2SiO_4$ .

<sup>1</sup> See Doelter: Handbuch der Mineralchemie. II 1, p. 409.

*The process of serpentinization.*

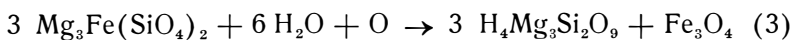
This process has been extensively studied, and there exists a vast literature on the subject. The general alternatives are clearly established, but there is still much difference of opinion concerning the progress of the process in the individual cases. We may summarize the principles, following f. i. Graham<sup>1</sup>:

The forsterite molecule of the olivine may change to serpentine in two ways. Besides hydration is needed either an addition of silica or a removal of magnesia, generally as carbonate.

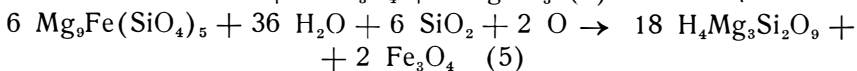
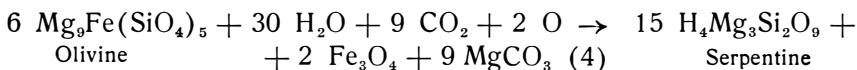


The fayalite molecule of the olivine can of course not take part in the serpentinization to any great extent, the serpentines generally being low in iron. It decomposes either under the formation of iron carbonate and free silica, or generally — when oxygen is available — under the formation of secondary magnetite. The liberated silica, of course, enters into reaction (1).

Between these two extremes there is an intermediate composition, permitting a direct change, namely when the olivine has the molecular ratio  $\text{Mg} : \text{Fe} = 3 : 1$



When the olivine, as is generally the case, contains less iron than this, addition of silica or loss of bases is absolutely necessary. In the present case, the ratio is  $\text{Mg} : \text{Fe} = 9,6 : 1$ , and we get the approximate formulas:



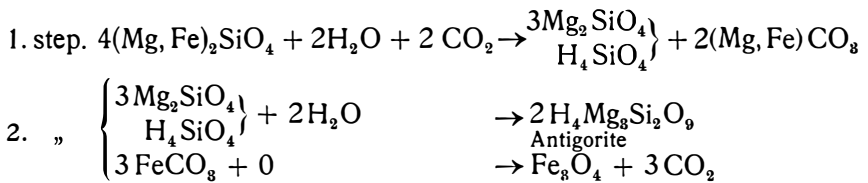
The quantity of magnetite, really found in the rock, corresponds nearly to that, demanded by these equations. They also show how insignificant a quantity of oxygen is necessary to perform the oxidation.

Magnesite is present in all the serpentine bosses of the district, although in varying amounts. There is therefore no reason to doubt

<sup>1</sup> R. P. D. Graham: Serpentine and chrysotile-asbestos. J. of Geol. XII, p. 164.

that the equation (4) has taken place, at least in part. In the analyzed rock, the quantity of magnesite is about  $\frac{1}{3}$  of that demanded by this equation. The rest has eventually been removed in solution, a process, that is more easily figured when we remember, that the very considerable expansion, demanded by the process, is thereby moderated considerably

It has been proved above, that the process of hydration here has taken place in two steps, and that the formation of magnesite obviously belongs to the first step. This may be figured qualitatively in the following equations:



It is remarkable that the separation of magnetite only follows the second step. We must therefore conclude, that the first part of the process had no oxygen available, and probably belonged to a deeper zone.

When we consider the much debated question concerning the origin of the serpentinizing solutions, two features are very remarkable.

We have in this very same district another group of olivine rocks, following more or less unmetamorphosed norites. They have completely escaped serpentinisation, or suffered from it only in a very slight degree.

Their horizon of intrusion is rather a little higher than that of the serpentines, and they are at any rate not older in the orogenic sequence. If therefore the serpentinizing solutions, as generally believed, derive from the peridotite magmas themselves, they ought to have been serpentinized as well. The same conclusion must be drawn from the rule, which Sir Thomas Holland has pointed out, that serpentinization mainly occurs within the orogenic regions of the world, and only occasionally within the continental massifs.

The other remarkable fact is, that these serpentine bosses, with a mineral association of typical epi-zone origin, occur in environments with a mineral facies of decidedly more high-temperated origin. So the gabbroidic rocks belong to the amphibolite facies and the mica schists to the garnet- or even the oligoclase facies. This is not — as



mentioned before — due to a late intrusion of the olivine rocks, and therefore probably must be due to the special sensibility of the magnesian silicates to changes of temperature and pressure, and their tendency to hydration. It might be compared with an extended retrogressive metamorphism (diaphtoresis). When diaphtoresis is not a universal phenomenon, the reason is that the velocities of the readjustment reactions decrease very rapidly with the temperature, and are generally induced only by the aid of violent tectonic movements. For the magnesian silicates we must suppose, that this velocity has not decreased so rapidly, but the readjustment could continue to lower temperatures than elsewhere.

The hydration is accompanied by a considerable expansion, producing an increased pressure in the interior of the bosses. This is responsible for the peculiar massive structure of these serpentine rocks in foliated surroundings, for the close folding of the bordering schists, which is often met with, and probably also for the common rounded form of the bosses. In those cases, where the massive structure has been maintained, we must suppose, that the period of hydration has outlasted the main period of orogenetic movements.

What the present district may show in the question of serpentinization is therefore, that it probably occurred in a late phase of the same orogenetic period, which introduced the olivine rocks, and that the serpentinizing solutions did *not* derive from the olivine magmas themselves. It must be ascribed to solutions of more regional distribution, viz. those percolating the rocks of the mountain chain during the greater part of the orogenetic period and partly emanating from the different magmas, partly set free during the crystallization of the sediments. They were still able to recrystallize these magnesian rocks after their action on the other rocks had ceased.

When we in the more central and deeper parts of the mountain chain, especially in the neighbourhood of the great granitic batholiths, often find the bosses of the olivine rocks more or less unchanged, a natural explanation is that the solutions had already left the surroundings, when these at last reached epi-zone conditions.

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The above mentioned process of antigorite formation is a regional one. It has changed the dunitic bosses in a uniform manner, without observable difference between periphery and center, and has not attacked it from fissures. On the contrary, during this period of

considerable expansion, the formation of fissures and veins has obviously been impossible.

It is generally supposed, that antigorite was formed under conditions of somewhat higher pressure (and temperature) than chrysotile, a supposition fully supported by my observations. The conditions have probably corresponded to the deeper parts of the epizone.<sup>1</sup>

Frequently we also encounter another form of transformation, namely to steatite rock, consisting of more or less pure talc with an extremely varying amount of carbonates. It is also to a certain extent areal, but generally limited to the border zones of the serpentine bosses and to irregular patches in their interior. Only the very smallest bosses may be transformed throughout. This process, which is obviously younger than the serpentinization, will not be further treated in this paper.

It must only be mentioned, however, that the earlier separated magnetite is preserved to a considerable extent, and that the carbonates are still exclusively magnesite (breunnerite).

### **Period of fissure- and vein formation.**

After the accomplishment of serpentinization with severe expansion, a period of readjustment set in, when fissures and veins might form. These are not common, however. Most frequently we meet veins of micaceous talc, sharp-cut in the antigorite-serpentine, more blurred in the steatitic parts of the rock.

On the other hand, seams of silky and flexible chrysotile-asbestos, so common in serpentine of many parts of the world, do not occur in these regions. Obviously the physical conditions for their formation have not been realized.

#### *Metaxite vein west of Rauvatn.*

It was therefore surprising to find, in one of these bosses, a couple of very large veins of cross-fibre asbestos belonging to the chrysotile group. The impressing looks of one of these veins is seen from fig. 2. It is different from ordinary chrysotile asbestos,

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<sup>1</sup> F. G. Wells: Hydrothermal alteration of serpentine. *Am. J. Sci.* 18, (1929), p. 52. It is here made probable, that serpentine does not form from olivine below 520° C. By silification of magnesite it is formed from 375° C.

being extremely harsh, of a wood-like appearance and with fibres stiff like needles and wounding the fingers. Pl. III, fig. 1.

These fibres are generally continuous over the whole width of the vein, amounting to  $\frac{1}{2}$  m. (20 inches). When the vein locally forms elbows, the direction of the fibre remains the same, and at such places they may nearly double this length. The vein forms a hair-line bor-



Fig. 2. Vein of cross-fibre metaxite W. of Rauvatn.  
(After photography).

der against the unchanged and massive antigorite-serpentine, as seen in the lower right part of Pl. III, fig. 1. The colour is light grey with a greenish tint, and on closer inspection the fibres are seen not to form rounded rods, like ordinary chrysotile, but are distinctly flattened.

That the asbestos really belongs to the chrysotile group is proved by the following properties:

Its loss on ignition is about 11 %, its loss of solution after boiling half an hour in 20 % HCl is 56 %<sup>1</sup>. Microscopically it shows

<sup>1</sup> Steinar Foslie: Litt om asbest, dens forekomst og anvendelse. Tidsskr. for Bergvæsen 1917, p. 53.

parallel extinction, positive elongation, axial plane parallel to the fibres, optically +, with a medium axial angle.

On account of the fibrous character, the optical constants are difficult to determine exactly. Following values are found:

$$\begin{aligned}\alpha &= \text{ca. } 1.548 \\ \gamma &= 1.560 \\ \gamma - \alpha &\text{ greater than } 0.010\end{aligned}$$

It is seen that the optical properties are distinctly different from those of the antigorite.

This harsh form of the chrysotile with approximately parallel fibres is called *metaxite*, in english sometimes also *picrolite*. Earlier investigations have shown, that there is no observable chemical or optical difference between chrysotile and metaxite, and the reason for the formation of the one or the other is not known. It is very probable, however, that pressure conditions are responsible, with metaxite as the more deep-seated form. Recently H. V. Anderson and G. L. Clark<sup>1</sup> by the aid of X-ray rotation patterns have shown, that a distinct difference between them is the more and less exact parallelism of the fibres.

Magnetite is completely absent on these veins, a feature that deserves close attention when we recall, that the antigorite, derived from olivine, always carries secondary magnetite up to the very border of the veins.

On the other hand some carbonates occur together with the asbestos, generally as very long, slender columns between the asbestos fibres, sometimes as shorter elongated grains. Like the asbestos they show a perfectly orientated growth, with their c-axis very nearly parallel to the fibres. On the broken mineral these carbonates are little visible, because their columns are covered with a film of asbestos. They are best shown by sawing off the end pieces.

At least in one place it is clearly seen, that the carbonates are most plentiful in the middle of the vein, gradually diminishing towards the borders. The appearance of this middle part is shown on Pl. III, fig. 2, consisting of dominant carbonates, with silky shining asbestos fibres among their columns. The main part of the carbonates has a greyish white colour, and is shown by determination

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<sup>1</sup> Application of X-rays in the classification of asbestos. Ind. Eng. Chemistry, 1929, p. 924.

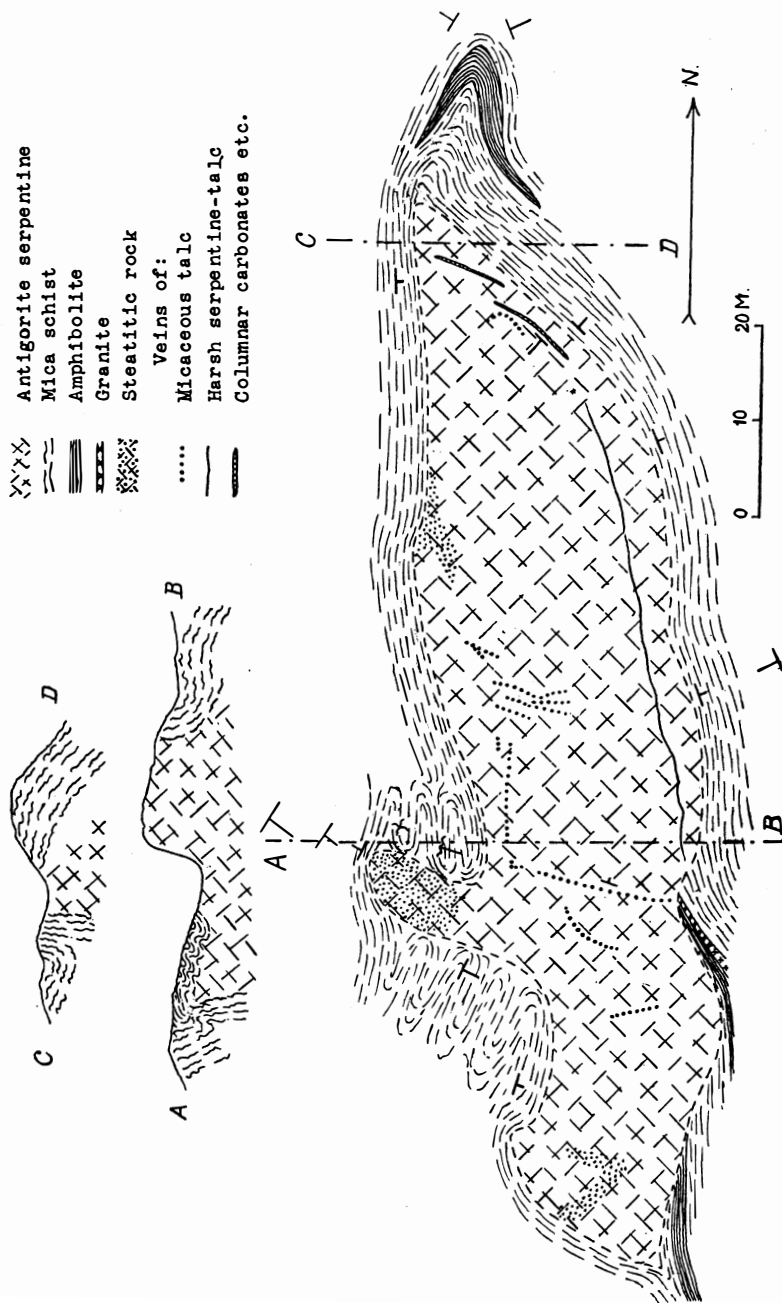


Fig. 3. Map of serpentinite boss E. of Rauvatn.

of the refraction to be *dolomite*. Some of the slender columns have a marked yellowish to brownish colour, and are shown to be *magnesite*.

Near the big veins we occasionally observe in the antigorite-serpentine small seams of a similar metaxite, accompanied by some orientated carbonate, here evidently only *magnesite*.

In the asbestos of the big veins is sometimes observed a scarcely visible ribbon-like banding, transverse to the fibres, suggestive of the annual rings in wood, Pl. III, fig. 1. They might be the traces of a gradual growth of the asbestos.

#### *Veins east of Rauvatn.*

A map and sections of the serpentine boss, containing these veins, is shown in fig. 3. It will be seen, that the serpentine rock appears to be younger than the foliated granitic sills and amphibolites occurring in the surrounding micaschists. As stated before we must be careful with such a conclusion, because the late expansion of the serpentine mass has deformed the border relations.

Among the veins occurring here, it is the two designated as columnar carbonate veins, which are of most interest, not only because they reveal a quite extraordinary appearance, but also because they supplement the earlier observations from the metaxite veins.

A cross section of one of them is shown in fig. 4.

These veins also contain metaxite fibres, but to a varying and much smaller extent. Their main mass consists of carbonates of an orientated growth, with their c-axis perpendicular to the vein walls.

Especially in places poor in metaxite, they are developed in well defined, coarse columns of a diameter up to 3 cm. The general appearance is that of a columnar basalt. Pl. IV, fig. 1. Moreover these columns are often of two distinctly different colours, one greyish white, which proves to be *dolomite*, and one wine-yellow to brownish, which proves to be *magnesite* (*breunnerite*). Pl. IV, fig. 2. They have sharply defined hair-line borders against each others, without any trace of mutual replacement, and it is quite obvious, that they have grown simultaneously.

It is only the direction of the c-axis, which is regular. In the other directions, the orientation may vary somewhat, and the best columnar development seems to be characterized by a slight diver-

gence of the cleavage planes in each column. When the cleavage planes are seen to reflect the light uniformly over a certain area, the columnar development is bad or none at all.

Where dolomite and magnesite occur together, the dolomite often seems to have a slight degree of idiomorphism towards the magnesite. Its columns have tendency to six-sided development, but always with rounded edges, and often quite round. The magnesite may then form a more irregular mesostasis with uniform cleavage. Pl. IV, fig 2. In some cases however the conduct may be opposite, and then the magnesite columns are always round like a log. Pl. III, fig. 3.

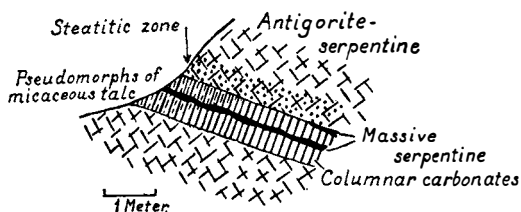


Fig. 4. Cross section of columnar carbonate vein. E. of Rauvatn.

Even when dolomite is the sole carbonate, its columnar development may be quite perfect. Pl. IV fig. 1. The columns have a strikingly dull surface, deriving from a thin film, which proves to be metaxite fibres, covering and separating them. In other places the metaxite within the carbonate mass may become more plentiful, and in connection with the previously described vein, we may find nearly all intermediate steps.

The deposit offered a rare opportunity of easy picking out of pure pieces of dolomite and magnesite, which had crystallized together under the same conditions. The total composition of these veins always remains on the magnesite side of dolomitic composition, and primary calcite, of course, does not occur. Carefully picked cleavage pieces of the two minerals were therefore analyzed, in order to contribute to the old question of the degree of mutual solid solubility of these carbonates.

The samples were dissolved in hot diluted hydrochloric acid. The small amounts of insoluble matter proved, on microscopic examination, to be fibres of asbestos, for the main part certainly deriving from the surface of the individual columns, which could not easily be avoided.

*Magnesite.*

Sp. gr. 3.100 (Pycnometre).

Analyst: E. Klüver.

	Mol. numbers	Pure carbonate
Insoluble . . . . . 0.14 %		
Fe <sub>2</sub> O <sub>3</sub> , Al <sub>2</sub> O <sub>3</sub> etc. . . . . 0.20 -		
FeO . . . . . 5.38 -	0.0748 } 1.1502	FeCO <sub>3</sub> 8.72 %
MgO . . . . . 43.04 -	1.0675 } 1.1502	MgCO <sub>3</sub> 90.49 -
CaO . . . . . 0.44 -	0.0079 } 1.1502	CaCO <sub>3</sub> 0.79 -
CO <sub>2</sub> . . . . . 50.61 -		<u>100.00</u> -
<u>99.81</u> -		

*Dolomite.*

Sp. gr. 2.898 (Pycnometre).

	Mol. numbers	Pure carbonate
Insoluble . . . . . 0.62 %		
Fe <sub>2</sub> O <sub>3</sub> , Al <sub>2</sub> O <sub>3</sub> etc. . . . . 0.05 -		
FeO . . . . . 1.74 -	0.0242 } 0.5341 } 1.0706	FeCO <sub>3</sub> 2.82 %
MgO . . . . . 20.56 -	0.5099 } 0.5365 } 1.0734	MgCO <sub>3</sub> 43.21 -
CaO . . . . . 30.08 -		CaCO <sub>3</sub> 53.97 -
CO <sub>2</sub> . . . . . 47.23 -		<u>100.00</u> -
<u>100.28</u> -		

Surplus of CaO over normal dolomite 0.13%.

Surplus of CO<sub>2</sub> over bases . . . . . 0.12 -

We see, that the minerals are very pure. The magnesite has under the present conditions only taken 0,79 % CaCO<sub>3</sub> or 1,45 % dolomite in solid solution. The dolomite, however, has not incorporated any magnesite at all, as might have been expected. On the contrary it seems to be on the calcite side of the stoichiometrical formula, which ought to be impossible in connection with magnesite. The excess of CaO is so small, however, that it is easily explained by a small inaccuracy in the separation of CaO and MgO, and the composition may be considered quite stoichiometrical.

The FeO-contents seem to be very nearly constant in the different parts of the vein, as shown by a control determination. The ferrous oxide present has therefore been divided between magnesite and dolomite in the molecular proportion 2,6 : 1.



As seen in the section, fig. 4 there is in the middle of the vein, and locally on the borders, a seam of massive serpentine, 5—10 cm thick. This serpentine is very different from the other two types of it, mentioned before. It is dark green, distinctly sub-translucent, hard and very brittle. It has a tendency to stratification and two sets of diaclasses, dividing it in rhomboedral pieces.

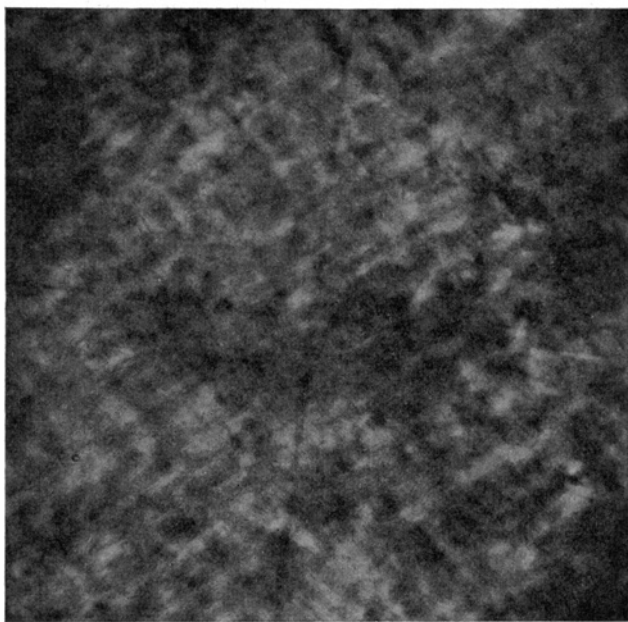


Fig. 5. Micro-photograph of massive, cryptocrystalline serpentine.  
Nic. + and gypsum plate inserted.  $\times 225$ .  
(Phot. by J. Stadheim.)

Thin sections in two different directions show under the microscope the same image of a uniform and nearly crypto-crystalline serpentine mass. With the highest magnification it is seen to consist of elongated grains (leaves ?) with positive elongation, regularly arranged in at least two directions in a sort of lattice texture. With the gypsum plate inserted, these directions are just visible on the photograph. Fig. 5. It seems evident, that the mineral has once been in the state of an amorphous serpentine gel.

The index of refraction is now between 1,560 and 1,570, the birefringence about the same as for antigorite.

Fig. 6 shows the border between this seam of massive serpentine, and the fibrous metaxite—carbonate. The former abruptly cuts off the fibres, partly penetrating in between them, and seems decidedly to be of later formation. It also contains some big rhombs of a carbonate, quite without orientation, which proves to be dolomite.

The age relation seems to be still more obvious in fig. 7. Here the dark serpentine (it is not a shadow!) has developed in a sharp



Fig. 6. Massive serpentine cutting fibrous metaxite—carbonate.  $\frac{2}{3}$ .  
Lower rim only due to weathering.  
(Phot. by J. Stadheim.)

bend of the fibrous minerals, and only in the bend, which must have opened the way for solutions.

For the microscopic investigation of the fibrous and columnar minerals, the thin sections must be made very carefully, because the carbonates easily drop out. With some care, however, very good longitudinal sections are obtained. Every effort to get transverse sections of the asbestos has been in vain, even in cases when the carbonate quantity is very great. Only when the asbestos is quite subordinate and the mineral is a little less fibrous, especially near the seam of massive serpentine, good transverse sections have been obtained.

The micro-photographs are taken from this last place, and are very interesting. The minerals present are only dolomite and metaxite.

Now, one might perhaps have expected, from the general appearance of the veins, that the carbonates were pseudomorphs after the metaxite-asbestos, and that the orientated growth of the carbonate stalks had been directed by the pre-existing asbestos. The microscope shows, that the opposite is the case.

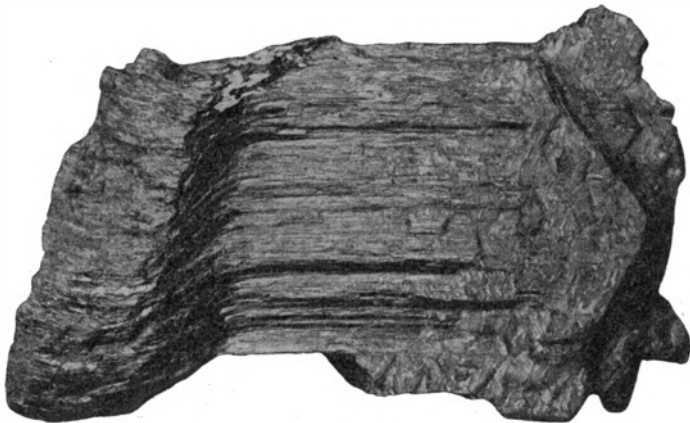


Fig. 7. Massive green serpentine developed in bend of the fibrous metaxite—carbonate.  $\frac{3}{5}$ . To the left are seen some white talc foils, to the right we see the cleavage of the dolomite.

(Phot. by J. Stadheim.)

Already a magnification of 11 in a longitudinal section Pl. II fig. 1 shows, how the metaxite (white) may deviate from its parallel growth, ramify into the dolomite, and totally enclose a number of small remaining dolomite grains. By a higher magnification, Pl. II fig. 2 it is furthermore seen, on the borders between the minerals, how the metaxite plainly replaces the dolomite. The extinction of both minerals is uniform and unaffected. Both minerals have their c-axis very nearly parallel to the fibres, and the plainly visible twinning lamellæ of the dolomite show, that the slightly varying orientation of the dolomite in the other direction, representing the different columns, is independent of the metaxite formation.

In the extinction position, when both the above named minerals are dark, there are, however, some carbonate grains, which are still

shining, and are quite unorientated. They occur only in connection with the metaxite, but not everywhere, and their borders are quite sharp, without replacement phenomena. See right side, Pl. II fig. 2. A direct determination of this carbonate has not been made, but as there is some effervescence with cold, diluted hydrochloric acid, it is very probable that it is calcite. It must have been formed secondarily, by a limited process of dedolomitization during the metaxite formation.

Pl. I fig. 2 shows a transverse section, which still better illustrates the age relations. The metaxite is seen as flaky seams around and through the dolomite columns. Replacement phenomena are seen on the borders and moreover we see a dendritic growth in the interior of the dolomite, representing the commencement of metaxite formation.

Quite deciding is the optical orientation of the metaxite. It shows uniformly the emergence of the positive bisectrix with a medium axial angle, but the other direction changes.  $\beta$  is everywhere parallel to the border line against dolomite,  $\alpha$  perpendicular to it.

While metaxite is thus proved to be somewhat younger, there is no reason to expect any considerable difference of age. Probably the whole vein formation belongs to the same period, with serpentinization in the later part of it. It is therefore difficult to explain it only by the action of siliceous waters, nor is the degree of dedolomitization sufficient for this. Probably the serpentine molecule itself has been transported in solution, first replacing the dolomite and crystallizing to metaxite, in a decidedly later period deposited as seams of massive serpentine.

This replacement process has its parallel in the formation of chrysotile asbestos in sedimentary magnesian limestones and dolomites<sup>1</sup>.

#### *Formation of talc.*

These processes are less uniform than those described before, and for a thorough understanding of them, a more extensive study must be made, than is the object of this paper.

In the present serpentine bosses, 3 types of talc occurrences may be distinguished. Before was mentioned the areal steatite for-

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<sup>1</sup> Alan Bateman: An Arizona asbestos deposit. *Econ. Geol.* 1923, p. 663.

mation, especially on the borders. It has been subjected to some foliation, but as the mineral very easily yields to pressure, this has not necessarily been very considerable.

In close connection with this, and also in the massive antigorite-serpentine and olivine-rich rocks, we meet narrow and irregular veins of pure talc. It is developed as foils, perpendicular to the vein walls, of a wonderfully pure, ice-green talc. Fig. 8. On the sharp borders against the massive serpentine, there is developed between them a seam of brown carbonates, exclusively magnesite.



Fig. 8. Micaceous talc as cross-bladed vein in antigorite-serpentine. 2/3.

(Phot. by J. Stadheim.)

Its grains are unorientated and occur also between the talc foils near the border. Together with the magnesite, the microscope reveals also on the border some grains of olivine, which seem to belong to the vein formation. Although closely bordering the serpentine rock with its olivine remains, it is distinctly different. It occurs in bigger and clearer grains, which show no signs of the ordinary antigorite formation. On the contrary, a beginning change of this olivine is to serpentine of the ordinary mesh-structure type. The occurrence of olivine at this place is at the present somewhat puzzling.

Although these talc veins occur in considerable number in both the serpentine bosses treated here, none of my observations have revealed their age relation to the columnar carbonate veins. These veins themselves may, however, contain talc in considerable quantity, and decidedly younger than their other minerals. This talc does

not belong to their regular mineral content, and does not occur everywhere in them.

Thus the metaxite vein west of Rauvatn has no traces of talc, and in the other two veins talc seems to occur only in their outer part near the surface. Fig. 4. Here we find it in big micaceous foils replacing the carbonates, and forming pseudomorphs after them. Fig. 9. It is partly accompanied by green serpentine. That this talc formation has been performed by siliceous solutions is rather certain, but where these solutions originated is uncertain.

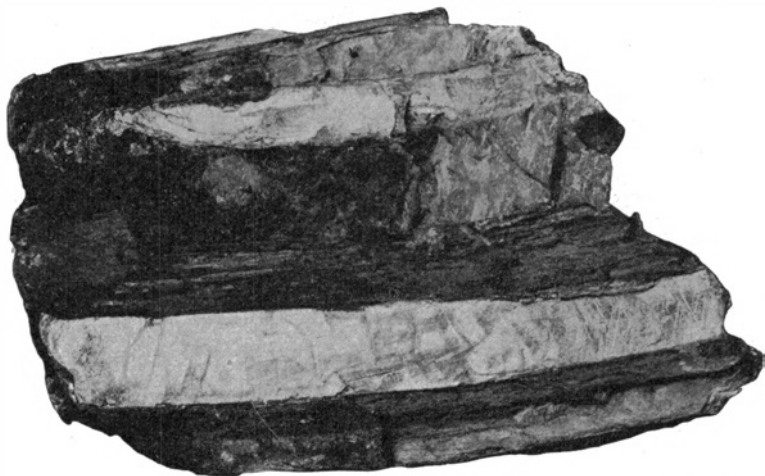


Fig. 9. Talc, pseudomorphous after columnar dolomite and magnesite.  $\frac{3}{4}$ .  
(Phot. by J. Stadheim.)

When we look at the section, fig. 4 and at the photograph, fig. 10, where coarse talc is formed at the outcropping face of a piece of columnar carbonates and green serpentine, one might suspect that it had something to do with the present surface. But such a formation of this coarse crystalline talc is less probable, and as long as the deeper part of the vein is not known, there is no proof of it. It might therefore be simultaneous with the formation of the massive serpentine.

#### Concluding remarks.

Apart from the talc veins, the mineral development during continuously decreasing temperature and pressure may here be recapitulated as follows:

1. Antigorite, magnetite, magnesite.
2. Chrysotile (metaxite), magnesite, dolomite.
3. Serpentine gel, (magnesite), dolomite, talc.

It has been shown before, that the whole process must have developed after the main period of orogenetic folding, and this is especially true for the vein formation. Indeed we may observe occasionally some bending of the asbestos, some diaclases in the carbonates and some kneading of the talc, but only inconsiderable, and the whole structure would certainly have been destroyed by more active movements.

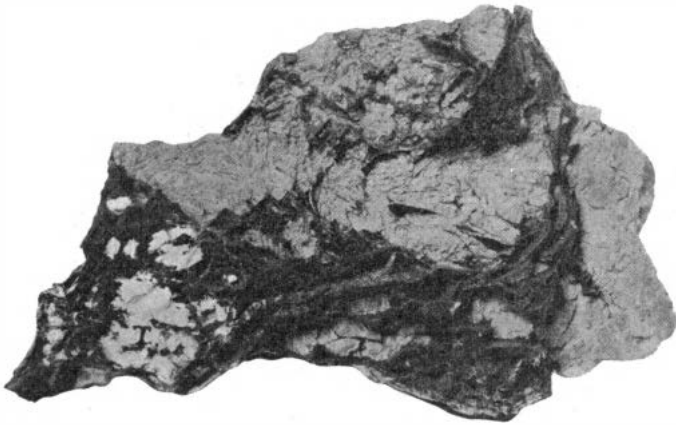


Fig. 10. Weathered end piece of carbonate columns with serpentine. To the left, some pure talc (T.) has developed in the cavity.  $\frac{2}{3}$ . (Phot. by J. Stadheim.)

It is not a matter-of-course, that conclusions from these veins may be directly transferred to the more general type of chrysotile asbestos deposits, because they are different in many respects. But one thing they have in common, — the arrangement of the minerals perpendicular to the vein walls, — and that is just the main problem with the asbestos deposits, which has not been solved.

A. L. Hall in a recent paper<sup>1</sup> has discussed the different possibilities for asbestos formation, and S. Taber<sup>2</sup> has classed the theories in 3 groups:

- <sup>1</sup> A. L. Hall: Asbestos in the Union of South Africa. S. A. Geol. Surv. Mem. nr. 12, p. 235—63.
- <sup>2</sup> Stephen Taber: The origin of veins of fibrous minerals. Econ. Geol. 1924, p. 475.

1. The asbestos was deposited in open fissures.
2. It was formed at the expense of the walls by recrystallization in situ or by replacement.
3. The veins, in growing, displaced the wall rock.

The number of vein minerals, which are known to occur in the crossfibre type, is very limited. Besides the ordinary asbestos-forming minerals it is mainly gypsum, graphite and calcite, in very rare and unimportant instances also magnetite and some others. The general experience concerning these minerals is stated by Taber (loc. cit.):

“Cross-fiber veins are composed essentially of a single mineral, which is also, usually, an important constituent and often the dominant mineral in the wall rock. In rare instances the vein mineral is not found in the wall rock, but in such cases it is a secondary mineral which has evidently been derived from minerals that are present in the wall rock.”

It is obvious that the present veins afford important new viewpoints.

The occurrence of dolomite and magnesite as cross-column minerals seems not to be mentioned in the literature, and in this respect the deposit is probably unique.

Moreover the substance of the dolomite must necessarily have been derived in part from some outside sources, because the wall rock does not contain traces of lime.

In general we may draw the conclusion, that the veins have not been formed by replacement in situ at the expense of the walls. As stated before, magnetite is completely absent on the veins, and it is not possible, that solutions similar to those, which precipitated the magnetite during the antigorite formation, should have dissolved it again at a lower temperature. Moreover the lime-bearing solutions of the veins have not caused any replacement of the lime-free wall rock.

The serpentines are the sole magnesium-rich rocks in the district, and there is no reason to doubt, that this base metal in the veins has been derived exclusively from the serpentines. The rocks in the environs contain considerable lime, and they are the only probable source of this element in the veins.

We may therefore conclude, that in the solutions, which percolated the massive rock and performed the antigoritization, only  $\text{CO}_2$  and  $\text{H}_2\text{O}$  were active. From the moment when fissures might open, also  $\text{CaCO}_3$  took part in the mineral formation.



Also Tabers conception is therefore difficult to apply. He believes that fibrous veins are developed only in those cases, where the material for growth was available from one direction only, namely from the vein walls. At least for the dolomite this has not been the case.

All the substances occurring here are often found as fillings in open veins, but of course without orientated growth. To perform such a growth, some directional force is necessary, and this has probably been a tensional one, which would be most in accordance with the conditions described above. But a tensional force has only an effect on solid material, and geological and laboratory experience shows, that fibrous growth is most generally met with during crystallization from the solid state. The only explanation that would be in accordance with all the observed facts is therefore, that the vein material was originally precipitated as a *gel*. This precipitation started the moment, when tensional fissures began to open and circulation commenced. The material in the present case came mainly from the serpentine rock, partly from outer sources.

Under continued stress the orientated crystallization of the gel in the direction of tension started soon afterwards. The carbonates with their considerable power of crystallization were first individualized. Whether some of the serpentine gel was present already at this stage or it was wholly introduced in a later part of the process is less important. At any rate it acted replacing on the carbonates and crystallized later as uniform and fibrous metaxite, with a texture that very much points to the formation from a gel. (See photographs.) Possibly the pre-existence of the carbonates is also in part responsible for the formation of metaxite instead of flexible chrysotile.

After the contraction and the unidirectional force had ceased, some serpentine was still precipitated as a gel. Consequently it has remained massive and has just been able to crystallize with a very fine-grained texture, on account of the lowered temperature.

The above conception of the formation of the fibrous and columnar minerals through the gel stage is not at all contradictory to former experience on gel formation, gel metasomatism and later crystallization, especially studied in connection with ore deposits<sup>1</sup>.

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<sup>1</sup> Wm. Lindgren: Metasomatism. Bull. Geol. Soc. Am. 1925, p. 247.

Moreover it is well known that the main type of magnesite veins in serpentine rocks throughout the world have not only precipitated in the gel state but have also remained amorphous.

The peculiar ribbon-like banding, transverse to the asbestos fibres, mentioned above and known from many other asbestos deposits, point in the same direction.

It is mainly the conduct of the carbonates, — especially characteristic of these veins —, which has been deciding for the conception of the process of formation, stated above.

I should be inclined, however, to extend this conception also to the chrysotile asbestos of the more ordinary type, and perhaps to most cross-fibre vein minerals in general. The transient passage of the gel stage should thus be one of the deciding factors for their formation.

In general terms, we may sum up the process as follows:

*In fissures, gradually opened on account of tensional forces, solutions continuously precipitated material as a gel, so that the fissures never remained really open. While tension was still active, the gel crystallized in fibrous and columnar minerals, growing in the direction of the least pressure.*

This conception seems to explain most of the observations, stated in the literature on cross-fibre minerals. Especially I want to draw the attention to some observations of C. L. Sagui<sup>1</sup> in the asbestos mines of Cyprus. He found, that the chrysotile veins gradually changed towards the depth into more harsh material, and finally into veins of solid serpentine of a greenish white colour, seen clearly against the brownish-green serpentine country rock.

The deposits at Rauvatn unfortunately do not seem to have much economic importance. The magnesite occurs in too small a quantity, the asbestos is harsh and useless, only the areal steatite formations might possibly be utilized. But from a scientific point of view they are very unique and interesting, and the magnificent material should be very well adapted for a thorough mineralogical study.

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<sup>1</sup> Cornelio L. Sagui: Asbestos deposits of Cyprus. Econ. Geol. 1925, p. 371.

Geological Survey of Norway, June 1931.

**Explanation of plates.**

- Plate I. Fig. 1. Antigorite-serpentine. Ordinary light.  $\times 18$ .  
White=antigorite. Black=magnetite. Grey=olivines and magnesite.
- Fig. 2. Dolomite-metaxite, perpendicular to fibres. Ordinary light.  $\times 36$ .
- Plate II. Fig. 1. Dolomite-metaxite, parallel to fibres. Ord. light.  $\times 11$ .  
White=metaxite.
- Fig. 2. Dolomite-metaxite, parallel to fibres. Ord. light.  $\times 36$ .  
Dolomite with uniform twin-lamellæ is replaced by metaxite. On one side, grain of unorientated carbonate with smooth borders, probably calcite.
- Plate III. Fig. 1. Metaxite-asbestos. In the upper piece are seen slender stalks of carbonates. In the lower piece is just visible the transversal banding. To the right hair-line border against wall-rock.
- Fig. 2. Columnar dolomite and magnesite, with silky-shining fibres of metaxite (white).  $\frac{4}{5}$ .
- Fig. 3. "Log" of magnesite in dolomite.  $\frac{1}{1}$ .
- Plate IV. Fig. 1. Columnar development of carbonate, looking like a basalt. Only dolomite.  $\frac{1}{3}$
- Fig. 2. Dolomite columns (D) partly idiomorphic against magnesite (Ms).  $\frac{3}{5}$ .

Printed, October 1931.



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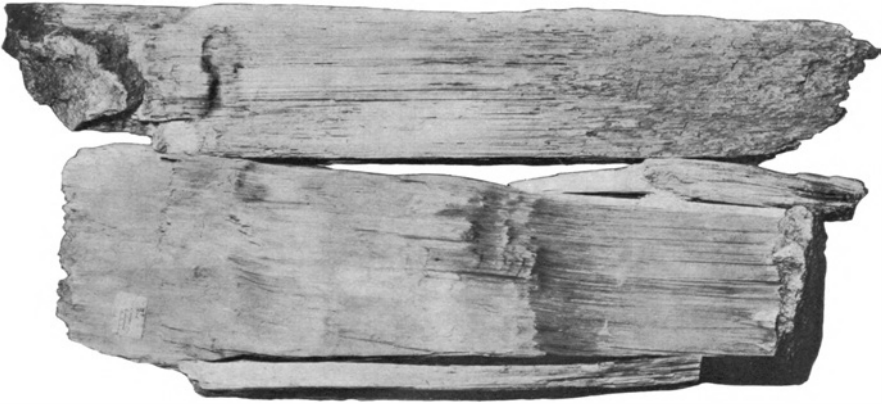
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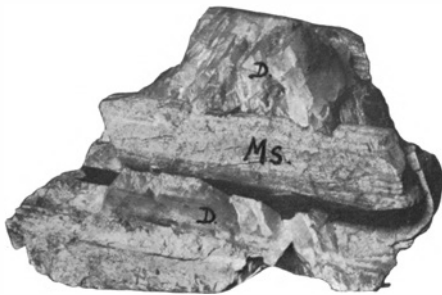
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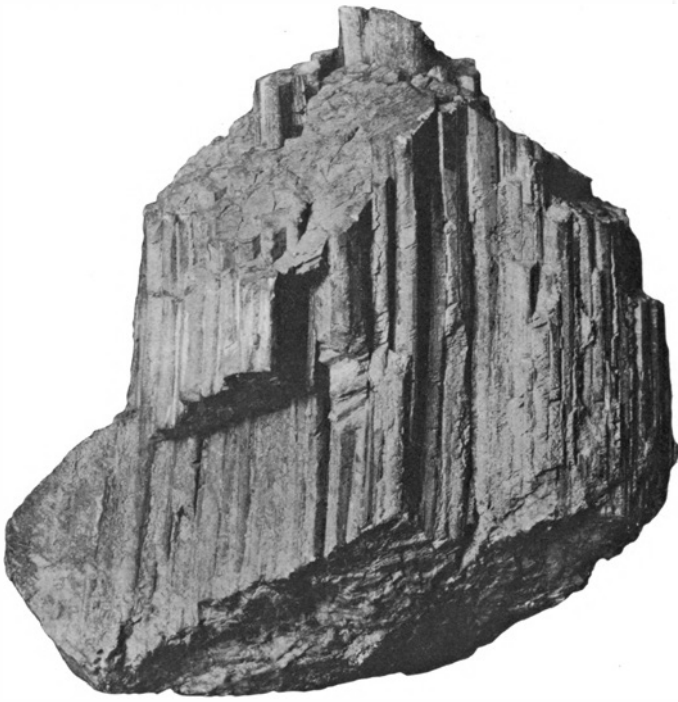
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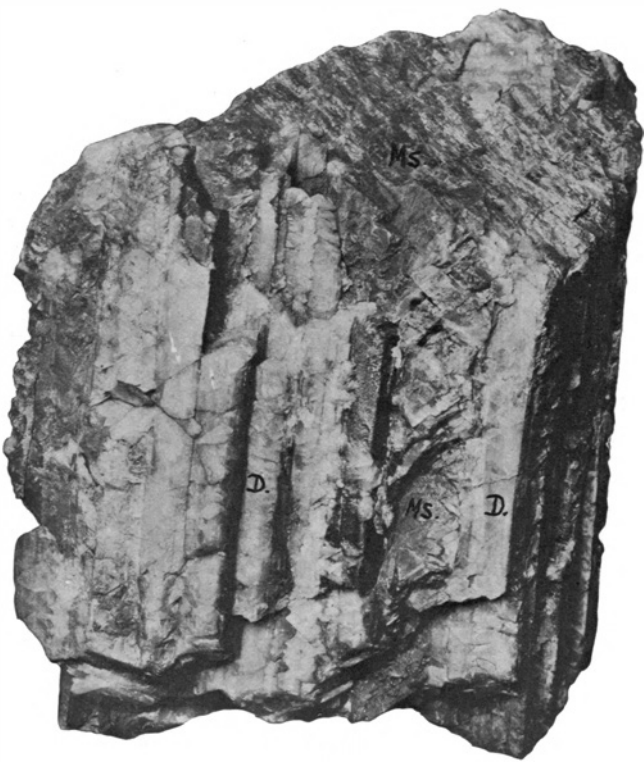
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