

GEOLOGINEN TUTKIMUSLAITOS

**BULLETIN**  
DE LA  
**COMMISSION GÉOLOGIQUE**  
DE FINLANDE

N:o 165

COMPOSITION AND ORIGIN OF SOAPSTONE

BY  
H. B. WIIK

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WITH 11 FIGURES AND 6 TABLES IN TEXT

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HELSINKI  
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## PREFACE

The present paper deals with a series of conclusions based on chemical research work carried out by the author at the Chemical Department of the Geological Survey of Finland during the period of 1947—1952. Permission to use the facilities of the department was obtained from Professor Aarne Laitakari, Director of the Geological Survey, and Professor Lauri Lokka, formerly head of the Chemical Department.

The material for the new analyses to be presented in the following was partly collected by the author on excursions to the Finnish Karelides and the Scandinavian Mountain Range. In addition to this material, numerous specimens and other data were obtained from various institutions and individuals. On making a general inventory of the Finnish talc and soapstone occurrences, Dr. Erkki Aurola and Mr. A. Vesasalo, M. A., both of the Geological Survey of Finland, freely placed their material and data at the author's disposal. Professor Harold W. Fairbairn of the Massachusetts Institute of Technology, sent an excellent collection of Appalachian soapstones.

Professor Pentti Eskola of the University of Helsinki, made a number of very valuable suggestions that greatly facilitated the work. The manuscript was critically read by Professors Martti Saksela and Th. G. Sahama, both of the University of Helsinki, and by Dr. Ahti Simonen of the Geological Survey of Finland. The optical determinations were made by Mr. Kai Hytönen of the University of Helsinki. Some of the powder diffraction patterns needed for the work were prepared by Dr. Simo Kaitaro of the Geological Survey of Finland, and most of them by the author under the guidance of Professor Th. G. Sahama at the Institute of Geology, University of Helsinki. Some ore microscopic determinations were made by Dr. Oke Vaasjoki of the Geological Survey of Finland. Credit is due to Mrs. I. Björkstam, M. A., for her service as translator and to Mr. Paul Sjöblom, M. A., for correcting the manuscript.

To all the persons mentioned the author expresses his deep gratitude. To help carry out his work, the author has received grants from the Geographical Society of Finland and from the Nordenskiöld Society of Finland (Nordenskiöldsamfundet i Finland). The receipt of these grants is gratefully acknowledged.

*The Author*



## INTRODUCTION

Ultrabasic igneous and metamorphic rocks play a much more important part in any discussion on the general rock genesis than their quantitative share in the uppermost lithosphere would indicate. This circumstance is simply due to the fact that all current theories dealing with the principles of rock formation must also be able to deliver a reasonable idea of the processes leading to the ultrabasic rock types. Much and certainly most of the basic information for understanding the mode of occurrence and genesis of these rocks is obtained through observation in the field and under the microscope. However, the development of modern petrology has occurred, to a large extent, through studying in the laboratory the physical-chemical behavior of rock forming silicates and other compounds. The interpretation of the results of experimental work carried out in the laboratory is greatly hampered by the relative complexity of many phenomena connected with the formation of rocks in nature. For the ultrabasic rocks, falling essentially into the system  $\text{MgO—SiO}_2\text{—H}_2\text{O}$ , results of laboratory experiments are perhaps more readily applicable to nature than for most other rocks. The most important deviation of this system from corresponding natural conditions is the content of iron present in natural ultrabasic rocks.

For one group of ultrabasic rocks, the soapstones proper, there is another chemical feature of importance in this connection. In the system  $\text{MgO—SiO}_2\text{—H}_2\text{O}$  recently studied by Bowen and Tuttle (1949) the only mineralizing agent is water. In soapstones, however, carbon dioxide also plays an important role. The ternary system  $\text{MgO—SiO}_2\text{—CO}_2$  and the quaternary system  $\text{MgO—SiO}_2\text{—H}_2\text{O—CO}_2$  have not been worked out yet. Therefore, the phase relationships in these systems cannot be applied to the interpretation of the origin of soapstones. As was recently pointed out by Bowen and Tuttle (*op. cit.*), a study of rocks by ordinary petrographic means reveals only the characteristics of the end product of the corresponding rockforming process and may not, perhaps, give any unequivocal picture of the process itself. In any case, exact knowledge of the petrography of the rock, including its chemical and mineral composition, etc., is a necessary condition for obtaining an idea of its origin. In this respect, the data available for soapstone are not very satisfactory. The chemistry and also the quantitative mineral composition of soapstones of different kinds is still surprisingly inadequately known. The existing analyses in literature are few and insufficient to establish the range of variation of the chemical composition.



For this reason, the author has analyzed chemically a number of soapstones and the results are presented in this paper. The specimens studied both chemically and petrographically have been selected from Finnish and other localities with a known geological environment. On the basis of the data given in the following, the origin of soapstone will be discussed.

Some differences in terminology connected with soapstones occur. In European literature, steatite is often used as a designation for the mineral talc. On the other hand, Hess (1933 a), and other American authors mean by steatite a rock mainly consisting of talc. Hess' definition is as follows (op. cit., p. 635):

»Steatitization may be defined as that process of hydrothermal alteration of an ultrabasic which in its final stages results in the formation of talcose rock. It may be applied either to the process by which soapstones (steatites) are formed or to the process by which relatively pure concentrations of talc are formed.»

To avoid any confusion in the matter, the term soapstone is used in the following as a designation for the rock and the term steatite is not used at all. Accordingly, the following designations are adopted:

Talc: the mineral species with the idealized formula  $Mg_3Si_2O_{10}(OH)_2$ .

Soapstone: the rock consisting mainly of talc.

Steatitization: the process leading to the formation of talc or soapstone.

## COMPOSITION AND MODE OF OCCURRENCE OF SOAPSTONE

The purpose of this chapter is to give a brief review of the field data and of the mode of occurrence of soapstone and related ultrabasics. The

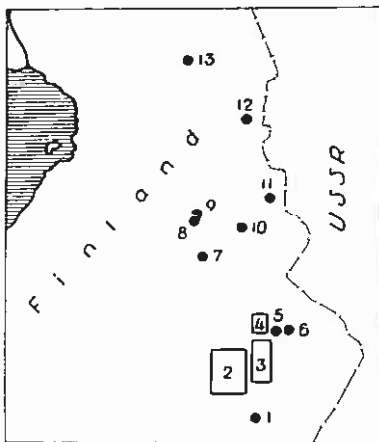


Fig. 1. Location of the Finnish soapstone occurrences mentioned in the text. 1. Turtianniemi. 2. The Paakkila field. 3. The Polvijärvi field. 4. The Nunnanlahti field. 5. Kelvänsaari island. 6. Siikalahti. 7. Jormaskylä. 8. Jormua. 9. Pitkänperä. 10. Vieksi. 11. Lentiira. 12. Saarijärvi. 13. Hoppula.

Finnish localities included in the following (Fig. 1) have been visited partly by Mr. A. Vesasalo and partly by the author. Observations made by previous investigators have also been taken into account. The localities of other countries have been referred to mainly on the basis of literature.

In addition to field data, also microscopic and other observations dealing with the petrology of the rocks will be given. Chemical analyses of the rocks, largely made by the author and partly taken from literature, will be given in connection with the descriptions of rocks. The chemical analyses and the mineral compositions calculated are compiled in Table I, at the end of this paper.

No systematic geological mapping of any of the localities mentioned in the following have been undertaken by the author. Local information considered of minor importance to the origin of soapstone has been omitted. The localities to be described have been arranged according to natural geological units.

#### THE KARELIDES AND ADJACENT AREAS OF EAST FINLAND

The rocks of the Karelidic zone of East Finland, which can be followed in a northwesterly direction from Lake Ladoga in the southeast up to Finnish Lapland in the northwest, contain in numerous localities ultrabasic rocks in schists and gneisses. These intrusions, belonging to the «alpine type» of Benson (1926), represent steeply dipping sheets or lenses concordant with the structure of the enclosing rocks. Although the horizons containing ultrabasics are probably not as uniform, in the Finnish Karelides as in the Appalachian mountain zone or in New Zealand, the mode of occurrence evidently is similar.

The ultrabasics of the Karelides have been studied by a number of authors. Frosterus (1902) and Frosterus and Wilkman (1916) have shown that these rocks follow certain horizons and are more steatitized and carbonatized in the east, where, according to the said authors, the schists belong to stratigraphically higher horizons. In the west, anthophyllite asbestos has been found at several places. Occasionally, the anthophyllite has been partly altered to talc schist with a very low content of carbonate. This alteration to talc has been explained as having taken place at a higher temperature and in a deeper horizon. According to Frosterus and Wilkman, the carbonate-bearing soapstones proper occurring in the east are metamorphic products of serpentinites almost always found in connection with the soapstones. Eskola (1933) has also shown that the Karelidic soapstones occur in contact with serpentinite. He regards it very probable that the soapstones as well as the abundant dolomites have been produced in connection with a metasomatic introduction of carbon dioxide that has partly or entirely driven out the silica from the serpentine. He thinks (Eskola, 1939) that the silica that has been driven out will be bound again and used in the formation of talc. Accordingly, varying amounts of carbon dioxide and water will be added to the serpentinite. In a paper dealing with the serpentine rocks of Karelia, Haapala (1936) has described a number of serpentinite localities of the Karelides and, in addition, some ultrabasics of different mineralogical composition. He also regards the carbonate-bearing soapstones as alteration products derived from serpentinite and, like Frosterus and Wilkman (op. cit.), he assumes that all ultrabasics of the area were originally dunites. Only in some few instances was the original rock

an enstatite-bearing peridotite. The alteration is thought to have taken place autometasomatically.

#### THE PAAKKILA FIELD

The occurrences of ultrabasics at Paakkila, Maljasalmi, Kinttumäki, and Tiilikainen, are here grouped together as the Paakkila field (Fig. 2). The north and northeast side of the area is occupied by the great Maarianvaara granite intrusion. Steatitization and carbonatization of the ultrabasics is weak. The only nonmetamorphic pyroxenite so far found in the Karelides of Karelia occurs in the area. No typical dunites have been found. However, scarce relictic olivine may occasionally be seen.

**P a a k k i l a.** The anthophyllite asbestos lenses at Paakkila, petrographically described by Haapala (1936), form rootless clumps concordant with the general strike. The enclosing rock is a biotite gneiss belonging to the gneissose Karelidic schists. The ultrabasic lenses have sharp contacts against the gneiss and are penetrated by pegmatite dykes. On the contacts, blackwalls may be observed that consist mainly of biotite and chlorite. The anthophyllite asbestos rock is mottled in appearance, owing to the fact that between the long asbestos fibres there frequently occur black aggregates of serpentine reaching the size of a fist. Olivine occurs as relicts inside the serpentine aggregates, which are frequently penetrated poiciloblastically by the anthophyllite. As has been found by Haapala, talc appears to have been formed without preceding serpentinization. Talc is often pseudomorphic after anthophyllite. Sometimes talc forms greater plates that closely resemble pseudomorphs after enstatite or bastite. The composition of the rock is shown by the analysis No. 1, Table I. Carbonatization has not been observed either by Haapala or the author.

**M a l j a s a l m i.** The anthophyllite asbestos lenses at Maljasalmi village are similar to those of Paakkila and are situated in a similar geological environment. Relicts of enstatite are relatively abundant. Olivine is more rare, however; black serpentine rich in olivine has been noticed by Haapala. The alteration of enstatite into asbestos may clearly be seen both in the specimen and in the thin section. The asbestos is partly altered into talc. The anthophyllite bundles have the same habit as the enstatite crystals and their c-axis is parallel to that of enstatite. These facts have led Haapala (op. cit., p. 70) to the conclusion that enstatite has formed a considerable portion of the premetamorphic minerals of the asbestos-bearing rocks of Maljasalmi. The same opinion has been expressed by Rimann (1936) in regard to the Paakkila ultrabasics. A chemical analysis of the enstatite-bearing asbestos is given in Table I, No. 2.

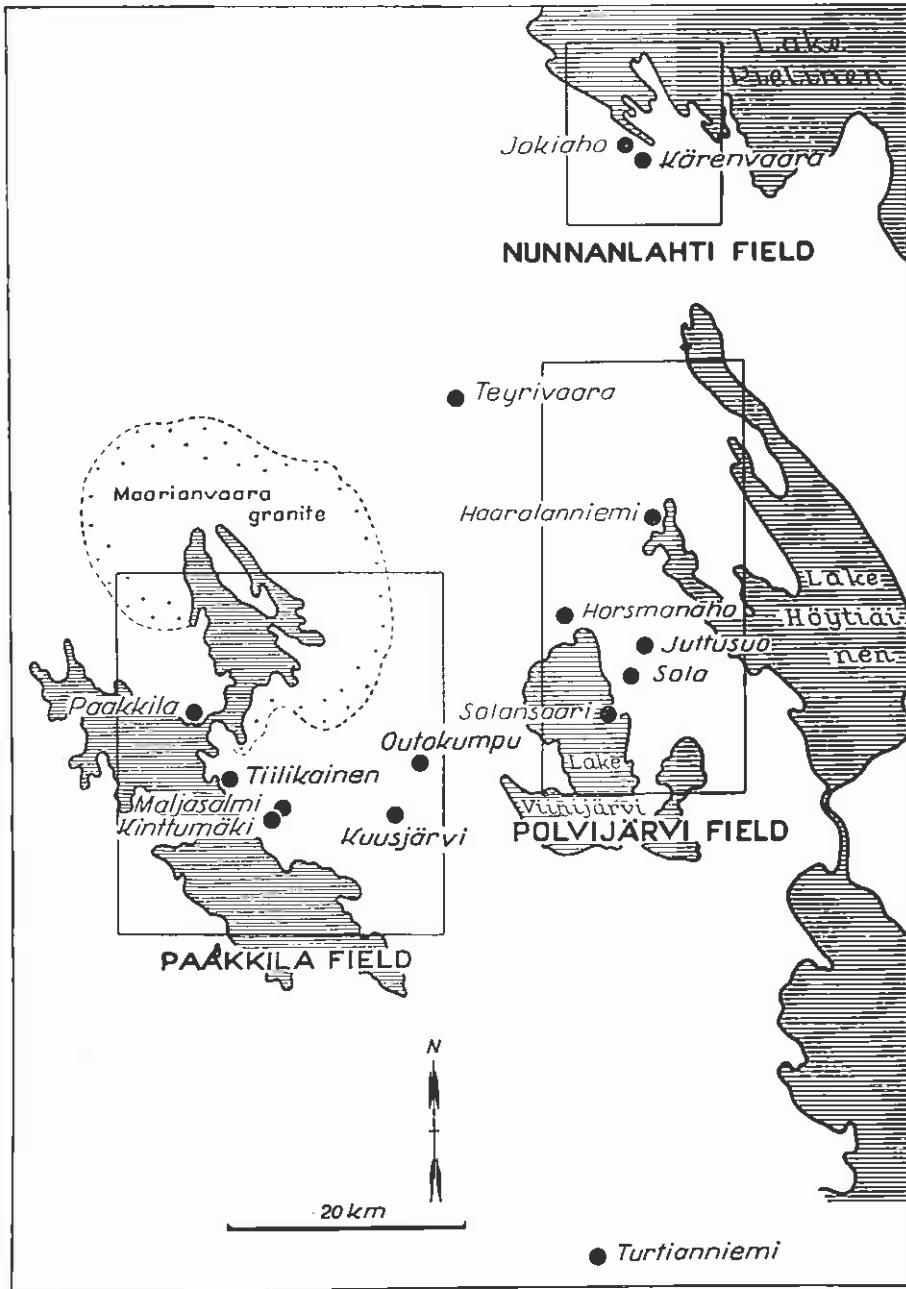


Fig. 2. Location of the ultrabasics of the Paakkila, Polvijärvi, and Nunnanlahti fields mentioned in the text.

**K i n t t u m ä k i.** About 800 meters south of the asbestos lenses mentioned, there are outcrops of completely steatitized and serpentized ultrabasics on the hill of Kinttumäki overlooking the little lake of Kinttulampi. The rock is here quarried for talc, which often contains considerable serpentine. Pockets of pure talc carbonate rock occur. From one of the large pure soapstone pockets, amounting to several tons, a specimen was taken for chemical analysis (No. 3, Table I). Carbonatization of the rock is weak.

About 500 meters southwest of Kinttumäki, by Lake Hilipanlampi, some other outcrops of ultrabasics are found. These rocks are least metamorphosed of the entire ultrabasic rock suite of the area. Haapala (op. cit., p. 53) has described an outcrop of pure pyroxenite. In addition, the author has found pyroxenite partly altered into talc rock with clumps of serpentine. Carbonatization is not observable. An analysis of unaltered pyroxenite is given in Table I, No. 4. Whether or not the outcrops along Lake Hilipanlampi and at Kinttumäki belong to the same occurrence cannot be decided. The country between these outcrops is covered by the lake and by quaternary deposits. The chemical compositions of the pyroxenite from lake Hilipanlampi, of the enstatite-bearing asbestos from Maljasalmi, and of the soapstone from Kinttumäki is very similar, despite the differing mineral composition. This similarity is characteristic also of the asbestos of Paakkila.

**T i i l i k a i n e n.** About six kilometers to the northwest from Maljasalmi, in the village of Varislahti, at the farmhouse of Tiilikainen, an outcrop of a very interesting ultrabasic rock consisting of anthophyllite is found. The rock is almost free of serpentine and shows a weak steatitization. In the anthophyllite rock, a dyke of pure anthophyllite, ca. 30 cm wide, is found. This dyke contains only little talc. The anthophyllite fibres are arranged perpendicularly to the dyke and are as long as the dyke is wide. An analysis of the anthophyllite rock and of the dyke has been given by Haapala (op. cit., pp. 64—65). The composition corresponds approximately to that of an anthophyllite very rich in magnesium (No. 5 and 6, Table I). According to the observation made by the author, chromite does occur in the enclosing anthophyllite rock, but not in the dyke.

Another outcrop of an ultrabasic rock similar to that at Tiilikainen is found at the farmhouse of Anttola in the same Varislahti village.

It is a remarkable fact that steatitization and carbonatization decrease to the west, *i. e.*, in the direction of the Maarianvaara granite massif. Pegmatite dykes, which are very common in that area, are not found any more in the east. Still farther to the east, in the Polvijärvi field, to be described in the following chapter, the ultrabasics are completely serpentized and steatitized. A strong carbonatization is visible. On the basis of its strong serpentization and steatitization, the Polvijärvi field has been treated as a different unit.

## THE POLVIJÄRVI FIELD

The soapstone occurrences included here in the Polvijärvi field are characterized by their situation within the Karelidic schist belt (Fig. 1). No amphibole or pyroxene rocks occur. Serpentinized and steatitized ultrabasics are abundant. Carbonatization has generally proceeded very far. Young acid intrusions do not occur.

**Horsmanaho.** About four or five kilometers southwest of the Polvijärvi church an occurrence of soapstone has been known a long time. The soapstone lens, ca. 10 meters thick, is situated in the schists, which are bent around it. Bodies of serpentine rock also occur in the neighbourhood but their contacts are covered by loose quaternary deposits. Dykes of completely steatitized anthophyllite rock cut across the soapstone. Sometimes these dykes reach a width of ca. 15 cm. Carbonatization is strong in the dykes as well as in the surrounding soapstone. No doubt, the dykes originally consisted of anthophyllite asbestos. Talc is beautifully pseudomorphic after anthophyllite and the tiny talc plates are arranged parallel to the c-axis of the previous anthophyllite. A chemical analysis of the dyke rock is given in Table I, No. 7. If, in this analysis, carbon dioxide and silica are added together, the composition corresponds to the ratio (Mg, Fe, Ca)<sub>7</sub>: (Si, C)<sub>8</sub>, in other words, that of an amphibole. The same ratio is also shown by the analysis of the surrounding soapstone (Table I, No. 8). Accordingly, the soapstone at Horsmanaho represents a completely steatitized and carbonatized analogue to the anthophyllite rock with its anthophyllite dykes at Tiilikainen more to the southwest. As at Tiilikainen, there is no chromite in the dyke, but it does occur in the main rock. Nickel could not be detected in the dyke either. Small crystals of pyrrhotite are to be seen in the dyke. This mineral is, however, more abundant in the surrounding main rock. It is interesting to note that calcium is more abundant in the dyke. Carbonatization is somewhat stronger in the main rock than in the dyke. As for carbonates, both dolomite and magnesite (breunnerite) are present<sup>1)</sup>. The refractive indices of magnesite were determined by the immersion method:

Magnesite from the	$\omega$			
dyke rock . . . . .	1 719	corresponding to ca. 9 mol. per cent	FeCO <sub>3</sub>	<sup>2)</sup>
Magnesite from the				
surrounding soapstone	1 722	»	ca. 11	» » »

<sup>1)</sup> The identification of the carbonate minerals was made by means of the X-ray powder diffraction method, using original rock powder. Further details of the method will be given in connection with Table I.

<sup>2)</sup> Throughout this paper, the estimation of the molecular content of FeCO<sub>3</sub> in magnesite is based on the diagram relating optical properties to composition in the MgCO<sub>3</sub>—FeCO<sub>3</sub> series published by Winchell and Winchell (1951).

As for the steatitized dyke, pieces of pure talc were picked out for chemical analysis. The purity of the analyzed material was tested under a binocular microscope. The analysis is given in Table I, No. 9. It shows a complete absence of calcium and manganese and a very low content of ferrous iron. Evidently, all the calcium and manganese and most of the iron are contained in the small carbonate lumps occurring interstitially between the steatitized amphibole bundles. The water content is very close to the theoretical value for talc. This feature is characteristic also of the two other talc analyses to be given below and is noteworthy because the water content of many minerals often corresponds to the least ideal composition of the mineral. The fact that the water content closely corresponds to the theoretical water content of talc may simply be due to the circumstance that the water determination is very simple in the case of a mineral like talc. The water content is accurately given by loss on ignition. As regards many other minerals, *e. g.*, the micas, the values for water tend to be very inaccurate. To obtain an idea of the chemical composition of the carbonate lumps contained in the steatitized anthophyllite dyke, a batch of the lumps was dissolved in hydrochloric acid diluted to 1 : 4. The insoluble silicate part amounted to 22.67 per cent. The composition of the soluble part of the carbonates is given in Table I, No. 10.

**H a a r a l a n n i e m i.** About seven kilometers north of the church of Polvijärvi, a few hundred meters north of the Huutokoski rapids, there is an outcrop of soapstone. This soapstone dyke has a width of about 30 meters and is concordant with the surrounding sulphide-bearing black schists and quartzite as well as with serpentinite. No granitic material is found in the neighbourhood. An analysis of the soapstone is given in Table I, No. 11. The rock is very poor in calcium and, accordingly, only magnesite has been found among the carbonates. The magnesite shows  $\omega = 1.721$ , corresponding to ca. 11 mol. per cent  $\text{FeCO}_3$ . To identify the opaque minerals of the rock, they were extracted by means of Clerici's solution. A polished section of the heavy concentrate was made and studied microscopically. The following minerals were detected: pyrrhotite, often containing exsolved pentlandite, pentlandite as separate grains, magnetite, and chromite. The presence of pyrrhotite and the absence of pyrite were further checked by a powder pattern prepared on the opaque mineral concentrate. Evidently, most of the nickel found in the rock is contained in pentlandite and most of the chromium is contained in chromite.

**S o l a n s a a r i.** About 11 kilometers south of the church of Polvijärvi, on the eastern shore of Lake Viinijärvi, a greater serpentine intrusion is found that rises about 10 meters above the flat terrain. On the western side of this serpentinite hill, named Nistinkallio, a soapstone horizon occurs the thickness of which cannot be determined because it continues under the lake in the west. The visible breadth of the soapstone occurrence is

about four or five meters and the length about 40 meters. In the soapstone rich in carbonate separate plates and dykes of pure talc occur. Carbonate lumps, the weathered surfaces of which are brown in color, are abundant. In the soapstone proper, carbonate occurs as well-rounded grains about one on three mm in size. They are easily identified under the microscope. Pyrrhotite is relatively common. The soapstone proper has been previously described by Frosterus and Wilkman (1916, p. 126). These authors also give an analysis of the rock. Unfortunately, in that analysis,  $\text{CO}_2$  and  $\text{H}_2\text{O}$  have not been determined separately but only together as loss on ignition. For that reason, a new analysis was made by the author (Table I, No. 12).

A chemical analysis was also made of talc extracted by hand from a pure talc dyke (Table I, No. 16) and, in addition, of carbonate derived from a pure carbonate lump (Table I, No. 17). The material for the carbonate analysis was extracted by dissolving the lump in diluted hydrochloric acid.

As is shown by the said new analysis of soapstone (No. 12 in Table I), the soapstone from Solansaari is virtually free from calcium. In agreement with this fact, the powder pattern prepared from the powdered rock revealed the presence of magnesite as the only carbonate mineral. For magnesite,  $\omega = 1.710$  corresponding to ca. 8 mol. per cent  $\text{FeCO}_3$ . On the other hand, chemical analysis (No. 17 on Table I) yields the following composition for the magnesite:

$\text{FeCO}_3$ .....	14.0 mol. per cent
$\text{MnCO}_3$ .....	2.1 » » »
$\text{MgCO}_3$ .....	85.8 » » »

The discrepancy between the content of  $\text{FeCO}_3$  in the mineral calculated from the analysis and, on the other hand, deduced on the basis of the refractive index ( $\omega$ ) is considered twofold. First, on dissolving the carbonate material for analysis, traces of iron not belonging to magnesite but originating from small amounts of magnetite and pyrrhotite may have gone into solution. Second, the diagram by Winchell and Winchell (1951) relating optical properties to composition for magnesite is relatively inaccurate.

Optical properties for talc are:  $\alpha = 1.545$ ,  $\gamma = 1.580$ ,  $2V\alpha = 15^\circ$ . The refractive indices are comparatively high for talc. Chemical analysis that agrees well with the formula for talc indicates a molecular ratio  $\text{Mg} : \text{Fe} = 97.5 : 2.5$ .

Chlorite shows a refractive index of  $\gamma = 1.592$ . Optically negative. Optic axial angle very small, almost uniaxial. According to Winchell and Winchell (1951), these optical properties correspond to a penninite relatively rich in iron.

The serpentinite of the locality has been described by Haapala (1936, p. 15). He also gives an analysis reproduced in Table I, No. 15. It is interesting that the content of chromium and nickel is virtually identical both



in the serpentinite and in the soapstone. These accessory elements are, accordingly, very evenly distributed throughout the ultrabasic body independently of the mineralogical composition.

**S o l a.** About 4 kilometers to the northeast from the locality described in the foregoing there is a greater ultrabasic occurrence. This locality is found on a special map of a part of the parish of Polvijärvi published by Frosterus and Wilkman (1916, p. 59). Another locality is found two kilometers from the main road between Joensuu and Polvijärvi, on the village road to Solansaari. This soapstone mass, called the Sola soapstone, shows a breadth of 20—30 meters in the direction of the road and is intercalated between two serpentinite bodies. An analysis of this soapstone from Sola is given in Table I, No. 13. The composition is virtually the same as that of the soapstone from Solansaari with somewhat stronger carbonatization. Neither here nor at Solansaari have any acid intrusives been observed.

Magnesite is the only carbonate mineral found in the Sola soapstone by means of powder pattern. It shows  $\omega = 1.723$ , indicating ca. 12 mol. per cent  $\text{FeCO}_3$ . Chlorite has  $\gamma = 1.575$  and is optically negative. These properties correspond to a penninite. The opaque minerals of the rock were extracted by means of Clerici's solution and a polished section of the heavy concentrate was studied microscopically in reflected light. The concentrate consists mainly of pyrrhotite, magnetite, chromite, and pentlandite. In addition, a considerable amount of niccolite was found in the material. The grains of this mineral are often surrounded by a thin rim of another mineral, probably belonging to the rammelsbergite series. Some separate grains of chalcopyrite were also detected.

**J u t t u s u o.** Approximately four kilometers further northeast from the previous locality, a lens of soapstone is to be found that is situated on the eastern side of the road from Joensuu to Polvijärvi. The soapstone occurs also here in connection with serpentinite. An analysis of the soapstone is given in Table I, No. 14. The carbonate contained in the rock is mostly magnesite with  $\omega = 1.722$  corresponding to ca. 11 mol. per cent  $\text{FeCO}_3$ . Dolomite is extremely scarce. Chlorite is also scarce.

#### THE NUNNANLAHTI FIELD

North of the Polvijärvi field, along the shore of Lake Pielinen, there is a markedly ultrabasic zone with lenses of serpentinite and soapstone. The zone, here called the Nunnanlahti field (Fig. 1 and 2), can be followed for a stretch of some 10 kilometers in a direction from southeast to northwest. The field has been carefully mapped by Frosterus and Wilkman (1916, pp. 70 and 125). Furthermore an excellent map (1 : 8 000) of the area was made by P. Eskola and A. Näätänen in 1923. This unpublished map is to be seen

in the archives of the Geological Survey, Helsinki. Of the soapstone occurrences belonging to this field, only that of Kärenvaara and Jokiahö have been investigated by the author.

**K ä r e n v a a r a.** Kärenvaara hill in the village of Nunnanlahti is probably the biggest occurrence of soapstone yet found in Finland (Fig. 3).



Fig. 3. Kärenvaara soapstone quarry, Nunnanlahti.

Soapstone has been quarried there during the whole of the twentieth century. Therefore, contacts and other geological details are easily discernible and have been carefully examined. Yet, a few of the author's own observations will be presented.

The rock of the soapstone lens, 30 meters broad and 100 meters long, is slightly schistose striking N 40° W and dipping 55° to the west. According to Frosterus and Wilkman (1916, p. 124), the soapstone body lies between lenses of serpentine, which in their turn are enclosed in metabasite (amphibolite). On visiting the locality, the author has found that the foot-wall of the soapstone body really consists of serpentinite, but the hanging wall is made of mica gneiss. On describing the Kärenvaara soapstone occurrence, Haapala (1936, p. 23) mentions that the contact between serpentinite and soapstone is not very clearly exposed but as far as is visible the transition is gradual. The author has not been able to find any transitional zone between these two rocks, but the contact appears to be quite sharp.

On the contact between soapstone and mica gneiss, a blackwall is found consisting of biotite, chlorite, and quartz. It is evident that the great ultrabasic intrusion has influenced remarkably little the enclosing rocks. The

contacts are quite »cold». This is the case also when serpentinite is in immediate contact with the enclosing rocks without any intercalating zone of talc. The said blackwall is at no point more than 10 centimeters broad. No chemical analysis of the Kärenvaara blackwall exists so far, but an analysis of a similar blackwall has been made from a contact between serpentinite and gneiss from Turtianniemi, parish of Savonranta, situated more to the south (No. 20, Table I). It consists chiefly of biotite and pyrrhotite. Tourmaline has not been observed by the author in any of the contact zones of the ultrabasic rock bodies of the Karelides. The presence of this mineral has been noticed by, *e. g.*, Du Rietz (1935) in the contact zones of ultrabasic rocks of some Swedish localities and by Koark (1950) in Austria. Chromium is absent and the content of nickel is very low in the Savonranta blackwall. On the other hand, the content of sulphur, iron, titanium, and potassium is high.

Chemical analysis was made of the serpentinite belonging to the foot-wall of the soapstone body (Table I, No. 18) and of the mica gneiss of the hanging wall (Table I, No. 19). The material of the serpentinite analyzed was collected only a few centimeters from the contact with soapstone. The composition of the bulk rock very closely approaches that of the mineral serpentine. The specimen of mica gneiss analyzed was collected ca. 10 centimeters away from the contact with the soapstone.

The soapstone itself is a talc carbonate rock with, on the whole, an approximately equimolecular amount of carbonate and talc. The ratio of the two minerals varies, quite considerably, however, within the same lens. Frosterus (1926, p. 17) has published an analysis of the rock reproduced in Table I, No. 23. In addition, two new analyses were made by the author. The one of the specimens analyzed was collected by the author himself from the Kärenvaara quarry (Table I, No. 21). The other specimen is from Nunnanlahti village, probably also from the Kärenvaara quarry (Table I, No. 22).

No traces of original pre-metamorphic minerals may be discovered. The carbonates form notched grains evenly dispersed in the ground mass of talc. In the two soapstone specimens of which new analyses have been made, both magnesite and dolomite occur. The following refractive indices were measured:

	Magnesite	Dolomite
Soapstone specimen for analysis No. 21 .....	$\omega$ 1.725	$\omega$ n. d.
Soapstone specimen for analysis No. 22 .....	1.738	1.695

The values given for of magnesite correspond to ca. 13 (soapstone No. 21) and 21 (soapstone No. 22) mol. per cent  $\text{FeCO}_3$ , respectively. Larger, aggre-

gates of pure carbonate may, however, also be found. They may reach the size of a fist and often contain a kernel consisting of an aggregate of magnetite, a few millimeters in diameter. These comparatively hard and welldefined lumps of carbonate probably have been the cause of the oral reports concerning lumps of quartz in the soapstone. In any case, such quartz lumps have not been found by the author.

Chlorite is always present as an accessory constituent of the soapstone of Kärenvaara quarry. The chlorite of specimen No. 22 shows  $\gamma = 1.594$  and is optically positive. Accordingly, it appears to be penninite (rumpfite) containing considerable iron and relatively rich in aluminum. Of the opaque minerals, magnetite dominates. In addition, pyrrhotite, pentlandite, chromite, and very small amounts of pyrite are detectable.

In the soapstone, concordantly with the schistosity, there are small protracted lenses of material in which chlorite is more abundant. These are well defined and, because of their green color, they stand out clearly against the almost white soapstone (Fig. 4).

*Jokiaho.* Some hundred meters to the north from the Kärenvaara soapstone quarry, in the direction of the schistosity, a smaller outcrop of soapstone is to be found. This occurrence, called Jokiaho, is also quarried at present. An analysis was made of a soapstone specimen collected from the Jokiaho quarry (No. 24, Table I). Also in this specimen, both magnesite and dolomite are found. For magnesite,  $\omega = 1.735$ , indicating a relatively high content of iron. Carbonatization in the Jokiaho occurrence is very strong; in fact, the soapstone of this locality is the richest in carbonate found in the Karelides so far.



Fig. 4. Lenticular pockets of soapstone rich in chlorite (dark) in the carbonate soapstone (white). Kärenvaara quarry, Nunnanlahti. Photo A. Vesasalo.

#### THE NORTHERN OCCURRENCES

In the extensions of the Karelides, northwest and north of Lake Pielinen, there are a number of soapstone occurrences. Scattered over a rather large area, these occurrences are marked on the general map of Fig. 1. Some of the localities will be described in the following.

**J o r m a s k y l ä.** Parish of Sotkamo, Hyllävä soapstone quarry on Talvijoki river. On the western side of the river, several narrow strips reaching two meters in width have been inserted in phyllitic schists. The concordance with the schists is not so marked as in the occurrences described earlier. Cross penetrations will be found. On the eastern side of the river, a bigger outcrop occurs that measures up to 25 meters in width. Here the soapstone is almost massif without any definite schistosity. This soapstone was chemically analyzed (Table I, No. 25). In this rock, the content of iron is lower than in the soapstones of the Nunnanlahti field. The content of calcium is comparatively high, as in the soapstones of Nunnanlahti. Both dolomite ( $\omega = 1.685$ ) and magnesite ( $\omega = 1.718$ ) are present in the rock of Jormaskylä. In agreement with the chemical analysis, the powder pattern prepared from the powdered rock indicates that dolomite strongly dominates over magnesite.

**P i t k ä n p e r ä.** Parish of Paltamo. Great lenses of serpentinite with soapstone horizons have been partly described by Wilkman (1931), who also made a map of the district. In 1949, Dr. E. Aurola and Mr. A. Vesasalo discovered a great new occurrence of soapstone in the Pitkänperä creek at the Mieslahti bay. The locality is situated on the northeastern shore of the bay and is about 50 meters wide. The rocks strike nearly from north to south and dip to the west. In the east, the foot-wall of the ultrabasic mass consists of phyllitic schists overlain successively by serpentinite, soapstone, and the hanging wall of amphibolite. The contact between serpentinite and soapstone is sharp. Within a couple of centimeters, the blackish-green, hard serpentinite passes over into the white soapstone. The soapstone itself is a somewhat schistose talc carbonate rock with comparatively abundant iron oxide minerals and insignificant traces of chlorite and sulfides. Chlorite shows  $\gamma = 1.583$ , optically negative. A chemical analysis of the soapstone is presented in Table I, No. 26. The analysis shows complete lack of calcium. Accordingly, the powder pattern prepared from the powdered rock shows the presence of magnesite carbonate as the only carbonate mineral. Magnesite has  $\omega = 1.710$ , corresponding to about 5 mol. per cent  $\text{FeCO}_3$ .

**J o r m u a,** rural commune of Kajaani. Here the soapstone is strongly schistous and contains inclusions of chloritized amphibolite. As regards its position, this occurrence belongs to the same ultrabasic horizon as Jormaskylä and Pitkänperä and the still more northerly Melalahti intrusion. A chemical analysis of the Jormua soapstone is presented in Table I, No. 27. Magnesite is the only carbonate present in the rock. It shows  $\omega = 1.723$ , corresponding to ca. 12 mol. per cent  $\text{FeCO}_3$ . The accessory chlorite has  $\gamma = 1.588$ .

**V i e k s i,** farmhouse Viitala, east of Lake Kellojärvi, parish of Kuhmo. The locality belongs to the separate zone of Karelidic schists that, ca. 40

kilometers east of the great western zone, passes through the parishes of Kuhmo and Suomussalmi. The soapstone is found in contact with serpentinite. A chemical analysis of the soapstone (Table I, No. 28) shows a relatively high content of iron, calcium, and aluminum. The only carbonate mineral present in the rock is dolomite with  $\omega = 1.088$ . Chlorite has  $\gamma = 1.603$ . Magnetite is abundant.

In the soapstone of this locality, veins of pure talc and, on the other hand, of pure carbonate occur. Chemical analyses were made of each (Table I, No 31 and 32, respectively). According to the analysis, talc shows Fe:Mg = 3.8:96.2. It has  $\alpha = 1.542$  and  $\gamma = 1.502$ . Dolomite has  $\omega = 1.683$ . The dolomite analysis indicates the following molecular composition:

FeCO <sub>3</sub> .....	2.6 mol. per cent
MnCO <sub>3</sub> .....	0.7 » » »
MgCO <sub>3</sub> .....	49.9 » » »
CaCO <sub>3</sub> .....	46.8 » » »

S a a r i j ä r v i, parish of Suomussalmi. A chemical analysis of the Saarijärvi soapstone is presented in Table I, No. 29. The only carbonate mineral of the rock is magnesite with  $\omega = 1.708$ , corresponding to ca. 7 mol. per cent FeCO<sub>3</sub>. The accessory chlorite has  $\gamma = 1.584$ .

H o p p u l a, village of Kynsiperä, parish of Posio. A chemical analysis of this soapstone is given in Table I, No. 30. The carbonatization is very weak and the content of calcium remarkably high. Calcite with  $\omega = 1.660$  is the only carbonate mineral of the rock. Chlorite with  $\gamma = 1.587$  is abundant.

#### OCCURRENCES IN THE GNEISSOSE GRANITE AREA EAST OF THE MAIN KARELIDIC ZONE

In the extensive area of gneissose granite east of the main Karelidic zone a number of smaller lenses of soapstone occur, three of which will be described in the following, *viz.*, those of Siikalahti, Kelvänsaari island, and Lentiira.

S i i k a l a h t i, village of Vuonisolahti, parish of Pielisjärvi. The occurrence has been mentioned by Frosterus and Wilkman (1916, p. 87). The soapstone forms lumps in amphibolite, about six by eight meters in size. In some cases, the wall rock is black hornblendite that nearer the contact becomes greenish. Material for chemical analysis (Table I, No. 33) was collected from a quarry on the shore of Lake Pielinen. Carbonatization is very slight. Talc is absolutely dominant. The carbonate is only calcite with  $\omega = 1.660$ . Chlorite has  $\gamma = 1.610$ .



Fig. 5. Tremolite soapstone from Lentiira, Kuhmo. Needles of tremolite in a groundmass of talc with a little magnesite. Mag. 20  $\times$ .

Kelvänsaari island, Lake Pielinen, about seven kilometers east of the Koli Hills. The soapstone of this locality is a talc tremolite rock with no carbonates. The rock is separated from the surrounding gneissous granite by a blackwall consisting of biotite and chlorite. The content of tremolite is variable. A specimen of a variety rich in tremolite was selected for chemical analysis (Table I, No. 34). The amphibole of the rock, amounting to ca. 32 per cent, is strongly zoned. Accordingly, the optical properties vary. The following data were obtained for the darkercolored portion:

$$\alpha = 1.616-1.625$$

$$\beta = 1.628-1.635$$

$$\gamma = 1.643$$

$$2V\alpha = 72^{\circ}-87^{\circ}$$

$$c \wedge \gamma = 14^{\circ}-22^{\circ}$$

Lentiira, parish of Kuhmo. On the south bank of the river between Lake Salmijärvi and Lake Änättijärvi, in the village of Lentiira, outcrops of tremolite soapstone without carbonate occur in amphibolite (Fig. 5). These soapstone lumps measure only five or six meters in diameter. The contacts against amphibolite are sharp. A specimen from one of the lumps was analyzed (Table I, No. 35). In addition to talc and tremolite, some magnetite and chlorite are found as accessory constituents. From the crushed rock, beautiful needles of tremolite were picked out by hand and analyzed (Table I, No. 36). The purity of the material analyzed was tested under a binocular microscope. According to the analysis, the molecular ratio  $(\text{Fe}^{\text{III}} + \text{Fe}^{\text{II}} + \text{Mn}) : \text{Mg} = 15.4 : 84.6$ . The refractive indices of the mineral are  $\alpha = 1.620$ ,  $\beta = 1.628$ ,  $\gamma = 1.640$ . These refractive indices are virtually identical with those of tremolite from Kelvänsaari island and closely correspond to the result of the chemical analysis of the Lentiira tremolite.

#### THE APPALACHIAN MOUNTAINS

A general geological map of the extended ultrabasic belt that stretches from the Saint Lawrence estuary to North Carolina in the Appalachians has been published by Pratt and Lewis (1905). Despite a number of good field examinations, the chemical aspects of the soapstones of that belt have

been very little investigated. Only one single complete analysis of soapstone is known to the author. This analysis of the soapstone from Schuyler, Virginia, has been published by Hess (1933 b, p. 398; Table I, No. 37). Further, some ten technical analyses have been given by Engel (1949 a, p. 347 and 1949 b, p. 1019). Hess' analysis shows a composition higher in calcium, iron, and aluminum than that of the Karelidic soapstones. In addition, the carbonatization of the Appalachian soapstones is slighter. In order to ascertain whether or not this is a general tendency, the author has made some analyses of the soapstones from the Appalachians.

Holden Quarry, Chester, Vermont. Hess (1933 a, p. 644) describes the deposit as consisting of a series of small lenses, each approximately 18 feet broad and 40 feet long. The soapstone consists of talc with some chlorite and carbonate and has a texture »made up of radiating clumps of acicular crystals pseudomorphic after actinolite«. According to Hess' interpretation, the original ultrabasic rock has probably been a serpentinite which already at an early stage had been transformed into actinolite rock and partly into hornblendite. Boulders of hornblendite were found by him in the quarry. These amphibole rocks are then supposed to have been metamorphosed into soapstone. In a later paper (Philips and Hess, 1936, p. 347) Hess has, however, revised his opinion to a certain extent. Having found pseudomorphs after enstatite, he assumes that his mineral was first formed as a product of metamorphism in serpentinite and that this enstatite later became steatitized. The silica required by the alteration process is supposed to have entered from the wall rock, a gneiss rich in silica. Jacobs (1916, p. 272) mentions enstatite rock as the original ultrabasic material. In this connection, he describes the Roxbury mine situated 50 kilometers to the north and thinks that there the dolomite component has been infiltrated into the rock. He found no relictic structures.

A chemical analysis of the Holden Quarry soapstone was made by the author. This new analysis is presented in Table I, No. 38. In this rock, the content of aluminum is very high. As a consequence, an ample amount of chlorite is found in thin section. Magnetite is also very abundant and shows in its arrangement the contours of an earlier, now completely steatitized and chloritized mineral. This mineral cannot have been olivine but must have been either an amphibole or pyroxene. Dolomite with  $\omega = 1.689$  is the only carbonate mineral of the rock. Chlorite shows  $\alpha = 1.593$ ,  $\gamma = 1.596$ ,  $2V\alpha = 20^\circ - 27^\circ$ .

Grafton, Vermont. An analysis made of the soapstone of this locality reveals a composition very much like that described in the foregoing. The analysis of the Grafton rock is given in Table I, No. 39. The carbonatization has, however, proceeded a little farther. Dolomite is also here the only carbonate present in the rock. The refractive indices of chlorite are relatively high, viz.,  $\alpha = 1.605$  and  $\gamma = 1.609$ . The rock is more strongly meta-



morphozed than that from Holden Quarry. No relicts of any kind can any longer be found in thin section. The iron oxide grains are scattered throughout the rock without any detectable regularity.

**FRANCES TOWN, N. H.** The specimen from this locality available to the author is significant in that it is the only one showing not steatitized relicts of hornblende. In thin section beautiful transitions from a typical pleochroitic amphibole to talc and chlorite are seen. The unaltered amphibole shows  $\alpha = 1.641$ ,  $\beta = 1.649$ ,  $\gamma = 1.659$ ,  $2V\alpha = 86^\circ$ . Chlorite has  $\alpha = 1.590$  and  $\gamma = 1.600$ . The chemical composition of the rock (Table I, No. 40) is very similar to that of the soapstones from Holden Quarry and Grafton with the exception that the Frances Town rock has not been carbonatized at all.

Table I, Nos. 37—40, shows that the analysis of the Schuyler rock published by Hess is by no means exceptional but represents very well the chemical characteristics of the Appalachian soapstones in general. This is the case at least as far as their content of calcium, aluminum, and total iron is concerned. Nevertheless, the degree of carbonatization varies the carbon dioxide content, which ranges from zero up to 9.50 per cent by weight. The chemical composition is on the whole very uniform in the Appalachian soapstones examined.

#### GODTHAAB, SOUTHWEST GREENLAND

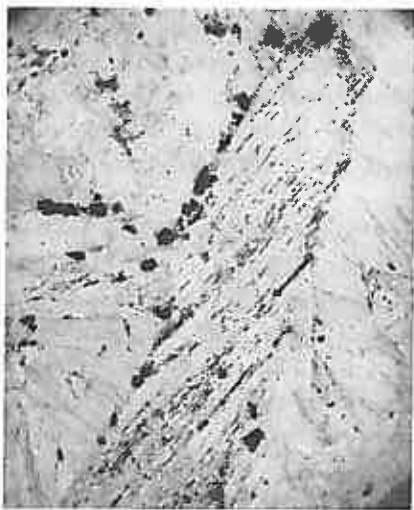


Fig. 6. Soapstone from Godthaab, Southwestern Greenland. In the groundmass consisting of talc, tiny grains of magnetite, arranged along straight lines, indicate that talc is pseudomorphous after anthophyllite (?). Mag. 20  $\times$ .

A specimen of soapstone derived from the collections of the University of Lund, Sweden, was examined. The rock is massif and consists of talc, oxide ore, and chlorite. It is remarkable that neither carbonate nor tremolite is to be found. This is the only specimen of a completely steatitized soapstone so far examined in which neither one of these minerals is present. The thin section reveals that tiny grains of magnetite are arranged along straight lines, indicating pseudomorphs of talc after a mineral, the microscopic identification of which is not possible (Fig. 6). An analysis made of the rock (Table I, No. 41) shows a composition very close to the pure anthophyllite asbestos rocks of the Karelides. The rock contains some apatite not found in other soapstone specimens investigated. Chlorite has  $\gamma = 1.590$ .

## SCANDINAVIAN MOUNTAIN RANGE

Ultrabasic rocks of all degrees of metamorphism have been found for a long time from the Caledonian Mountain range in Scandinavia. Larger continuous intrusions as well as narrower horizons where separate ultrabasic bodies are situated can be found here. Especially in Norway there are steatitized ultrabasics. In the following, some new soapstone analyses of the Scandinavian rocks will be presented. Existing analyses will also be collected from the literature.

L a l m, Ottadalen, Norway. The soapstone is situated in a strongly tectonized schist belt and is very schistose. The specimen analyzed was collected by the author. The rock is comparatively poor in carbonate (Table I, No. 42) and contains abundant chlorite and magnetite. Both dolomite and magnesite are present in the rock. Dolomite has  $\omega = 1.685$  and magnesite has  $\omega = 1.716$ . Chlorite shows  $\gamma = 1.590$ .

S t r ö m s å s, Tynset, Norway. This soapstone is slightly schistous. In comparison with the Karelidic soapstones, the content of carbon-dioxide (Table I, No. 43) is low. In thin section small grains of iron oxide are seen to have arranged themselves in such a way as to indicate a completely altered premetamorphic mineral, probably pyroxene. Magnesite, the only carbonate mineral, has  $\omega = 1.710$ . Chlorite shows  $\alpha = 1.599$ ,  $\gamma = 1.602$ ,  $2V\alpha = 16^\circ$ .

H a n d ö l, Jämtland, Sweden. This soapstone quarry, the largest in Sweden, has been examined in detail by Du Rietz (1935, p. 203). The peridotites are situated in a semi-circular zone on the south side of Lake Änn. Only in the western part of this zone have the ultrabasics been metamorphosed into soapstones. The wall rocks consist of amphibolite and different kinds of schists richer in silica. Du Rietz has also examined a great variety of ultrabasic rocks from northern Sweden. He arrives at the conclusion that the soapstones have originated from peridotite, saxonite or dunite. He stresses the importance of the intrusions rich in silica as a source of the solutions which are supposed to have altered the rock poor in water into serpentinite, soapstone, etc. Also at Handöl he has observed pegmatite dykes not far from the soapstone and quartz carbonate dykes in the quarry itself. A specimen of soapstone derived from the collections of the Geological Survey of Sweden was analyzed by the author (Table I, No. 44). The rock analyzed is a comparatively schistous green variety containing chlorite. Around the larger grains of magnetite, chlorite is especially plentiful, dark green in color and strongly pleochroitic (Fig. 7). It has  $\gamma = 1.606$ . The only carbonate mineral present is calcite with  $\omega = 1.664$ . Very small amounts of relictic amphibole occur. It shows  $\alpha = 1.623$ ,  $\beta = 1.638$ ,  $\gamma = 1.647$ .



Fig. 7. Soapstone from Handöl, Sweden. Chlorite (grey) arranged around the magnetite grains (black). The main mass of the rock (white) is talc. Mag. 20  $\times$ .

Muruhatten, North Jämtland, Sweden. The locality has been described by Du Rietz (op. cit., p. 164). Here the soapstone forms zones two to three meters broad between peridotite and tourmaline schist. An Analysis of the soapstone, published by Du Rietz, is presented in Table I, No. 45.

Laiholm, Tärna, Northern Sweden. Two analyses of soapstone from this locality have been published by Du Rietz (op. cit., p. 209 and 211) and are reproduced in Table I, Nos. 46 and 47, respectively. The surrounding rocks are mica schists, amphibolitic mica schists, and amphibolite. Serpentinities are found in connection with soapstone.

#### SWISS ALPS

In their compilation of the young igneous rocks of the Mediterranean published by Burri and Niggli (1945—1949), the data for steatitized rocks are but few. This is, perhaps, because of the very insignificant size of these rock bodies as compared with serpentinites and other ultrabasic rock types. The authors mentioned point to the orthaugitic chemical composition of the talcose rocks, which they suppose, however, to be the result of secondary processes. They state: »Bei metamorphen Gesteinen ist es naturgemäss immer fraglich, ob der heute feststellbare Bauschalchemismus primären Character besitzt oder bereits ein Abbild mehr oder weniger ausgedehnter Stoffwanderungen während der Umwandlung darstellt» (1945, p. 116). Burri and Niggli refer to a number of good analyses of soapstones. These analyses are reproduced in Table I, Nos. 48—49 and Nos. 51—55, and are taken from a collection of chemical analyses comprising Swiss rocks by Niggli, de Quervain, and Winterhalter (1930). A new analysis was made by the author and is added to Table I, No. 50.

#### MORAVIA

A chemical analysis of soapstone from Zöptau in Moravia, made and published by Kernhalter (1911, p. 153), is presented in Table I, No. 56.

## URALS AND MONGOLIA

A number of analyses of soapstone from the Urals and Mongolia has been published in a collection of chemical rock analyses by Alimarin and Romm (1935, pp. 59—61). These analyses have the merit that both nickel and chromium have been determined. The nine analyses are reproduced in Table I, Nos. 57—65.

## REVIEW OF THE MINERAL COMPOSITION OF SOAPSTONE

On the basis of the mineral composition, the soapstones proper may be divided into three different groups:

1. Carbonate soapstone: Talc + Carbonate + Chlorite + accessories
2. Tremolite soapstone: Talc + Tremolite + Chlorite + accessories
3. Godthaab-type soapstone: Talc + Chlorite + accessories

1. Carbonate soapstones are most common. The rock has been produced through metasomatic addition of water and substitution of  $\text{SiO}_2$  by carbon dioxide. Aluminum is contained in chlorite and the iron, not contained in carbonate or chlorite (talc is relatively devoid of iron), forms iron oxide or sulphide minerals. Calcium is contained in carbonate in toto. Among carbonate minerals, calcite, dolomite, and magnesite (breunnerite) have been observed. The relationship of the bulk composition of the rock and the carbonate minerals found is presented diagrammatically in Fig. 8. In the triangular diagram of Fig. 8, the datum points represent the molecular ratios of  $\text{CO}_2$ , CaO, and  $\text{MgO} + \text{FeO}$  for the 23 carbonate soapstone specimens of which new chemical analyses have been given in this paper. The numbers of these analyses in Table I are as follows:

No. 3.	No. 13.	No. 25.	No. 30.	No. 43.
7.	14.	26.	33.	44.
8.	21.	27.	38.	50.
11.	22.	28.	39.	
12.	24.	29.	42.	

For each specimen, the carbonate minerals, identified in the rock by X-ray and optical methods, are indicated in the figure.

As is seen from the figure, all rocks the datum points of which lie on the magnesite line, *i. e.*, on the line connecting the datum points for pure magnesite and talc (=  $\text{MgO} + \text{FeO}$ ), contain only magnesite (breunnerite) and no other carbonates. The rocks the datum points of which are situated between the magnesite and dolomite lines, contain a mixture of dolomite

and magnesite (breunnerite). The two datum points between dolomite and calcite lines happen to be very close to the dolomite line and, accordingly, these rocks contain only dolomite. The rocks the datum points of which lie above the calcite line show no carbonates but calcite.

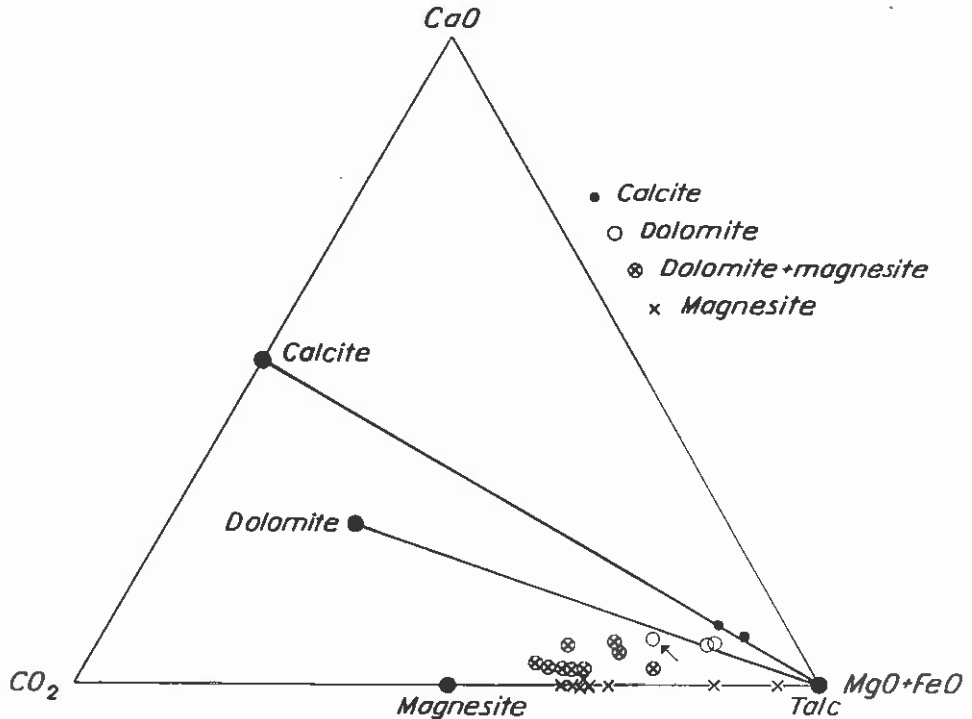


Fig. 8. The relationship between the composition of a number of soapstones and the carbonate minerals contained in the same rocks.

Among the soapstones investigated, there is one exception to the rule explained in the foregoing. The datum point of that particular rock, No. 39 in Table I, is marked with an arrow in the figure. According to its bulk composition, the rock should contain both dolomite and magnesite; yet only dolomite was found. The amount of magnesite that, according to the analysis, should be present in the rock is only about three per cent by weight. This relatively low content of magnesite is probably not readily detectable by the method used. Accordingly, in the mineral composition of the rock in Table I, all the carbonate was given as dolomite.

The close relationship between the bulk composition and carbonate mineral species of a soapstone strongly supports the idea that the formation of the carbonate minerals depends only on the chemical composition of the steatitizing material and not on the physical-chemical conditions of the steatitization process.

2. Tremolite soapstone has been produced through the metasomatic addition of water. It is not possible to decide whether carbon-dioxide was lacking in the hydrothermal solutions causing the metamorphism or, on the other hand, whether the temperature prevailing during the metasomatism was not suitable for the formation of carbonate. The second alternative seems perhaps to be more probable because these soapstones, free of carbon dioxide, mostly occur in areas where granites are abundant or where the soapstones are found in immediate contact with intrusive rocks.

All available calcium is here contained in tremolite. Carbonate and tremolite have never been observed together in soapstone.

3. Only one example of the Godthaab-type soapstone is known to the author (Table I, No. 41). The content of calcium is low and that of carbon-dioxide negligible. Therefore, tremolite and, virtually, carbonate are lacking.

In all three types of soapstone, magnetite, chromite, pyrrhotite, and pentlandite occur as accessories. In one case, niccolite was also observed.

#### REVIEW OF THE CHEMICAL COMPOSITION OF SOAPSTONE

In Table I, at the end of this paper, 49 chemical analyses of soapstone have been collected. Twenty-seven of them are new and 22 have been

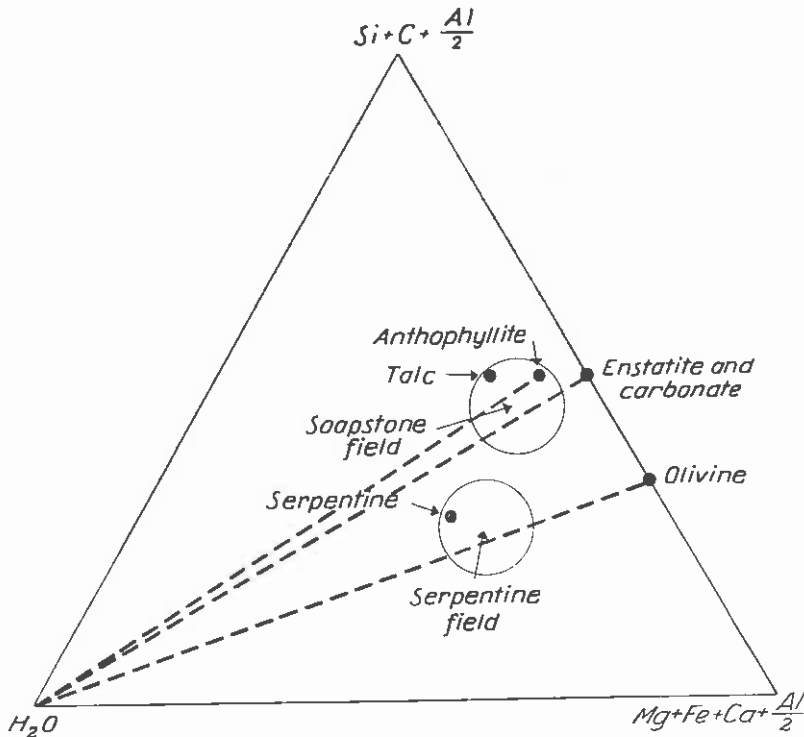


Fig. 9. Diagrammatic presentation of the chemical composition of soapstone and serpentinite.

taken from literature. The rocks analyzed represent mineralogically all three soapstone types defined in the previous chapter. The percentages found have been recalculated to indicate atomic percentages of the cations on a waterless basis. These figures, reduced to one hundred per cent, have been given for each analysis.

To obtain a general view of the range of variation of the chemical composition of soapstone, the analyses given in Table I have been plotted on a triangular scheme in Fig. 9. In this figure, the molecular percentage of  $H_2O$ ,  $Si + C + \frac{Al}{2}$ , and  $Mg + Fe + Ca + \frac{Al}{2}$  have been selected as coordinates. The small amount of aluminum present in the rocks has been divided equally between the two last-named coordinates. This was done because aluminum apparently occurs both in four-coordinated and in six-coordinated positions in the structures of the minerals in question. The datum points corresponding to the idealized composition of talc, anthophyllite, enstatite, serpentine, and olivine are shown in the diagram. For the sake of comparison, the area occupied by seven serpentinites of typical chemical composition is also indicated in the figure. The following serpentinites were selected:

- Serpentinite from Nunnanlahti. No. 18, Table I of this paper.  
 „ „ Solansaari. Haapala, 1936, Table I, p. 17.  
 „ „ Teyrivaara. Haapala, 1936, Table II, p. 27.  
 „ „ Outokumpu. Haapala, 1936, Table III, p. 34.  
 „ „ Kuusjärvi. Haapala, 1936, Table V, p. 52.  
 „ „ Lake Elijahärvi. Härme, 1949, Table II, No. 6, p. 28.  
 „ „ Western Ortoaivi. Lokka, 1934, No. 308, p. 61.

The idealized chemical composition of talc, tremolite, enstatite, magnesite, serpentine, and olivine are given in Table II.

Table II. Idealized Chemical Composition of Talc, Tremolite, Enstatite, Magnesite, Serpentine, and Olivine.

Mineral	Formula	Weight per cent					Atom per cent on water-free basis	
		SiO <sub>2</sub>	CO <sub>2</sub>	MgO	CaO	H <sub>2</sub> O	Si + C	Mg + Ca
Talc	Mg <sub>3</sub> Si <sub>4</sub> (OH) <sub>2</sub> O <sub>10</sub> . . . . .	63.35	—	31.90	—	4.75	57.14	42.86
Tremolite	Ca <sub>2</sub> Mg <sub>5</sub> Si <sub>8</sub> (OH) <sub>2</sub> O <sub>22</sub> . . . . .	59.15	—	24.82	13.91	2.22	53.33	46.67
Enstatite	MgSiO <sub>3</sub> . . . . .	59.83	—	40.17	—	—	50.00	50.00
Magnesite	MgCO <sub>3</sub> . . . . .	—	52.18	47.82	—	—	50.00	50.00
Serpentine	Mg <sub>3</sub> Si <sub>4</sub> (OH) <sub>8</sub> O <sub>10</sub> . . . . .	43.35	—	43.65	—	13.00	40.00	60.00
Olivine	Mg <sub>2</sub> SiO <sub>4</sub> . . . . .	42.69	—	57.31	—	—	33.33	66.66

According to Table II, the SiO<sub>2</sub> content by weight of pure talc is 63.35 %. As a natural rock it is a very great rarity. In the soapstone specimens analyzed so far the silica content by weight is less than 58 %. With an

increasing percentage of carbonate, the silica content by weight decreases and is as low as 29 % in the most carbonatized soapstones.

As is revealed by the analytical data compiled in Table I, the sum of Si and C, expressed in atomic percentages lies in the great majority of

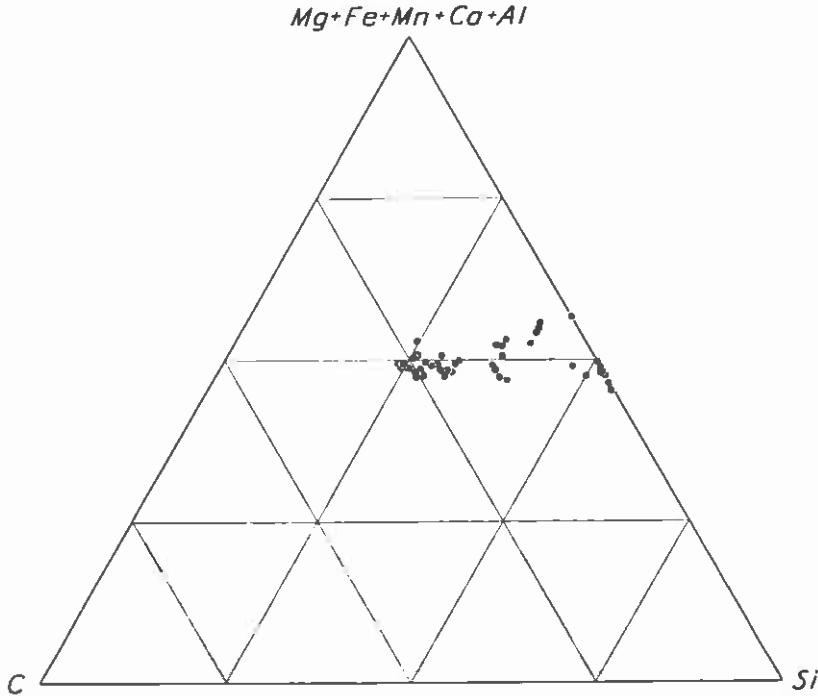


Fig. 10. Diagrammatic presentation of the chemical composition of soapstone showing the degree of carbonatization.

soapstones between 49 and 53 per cent. Taking into account the wider range of variation of the silica content of talc, tremolite, and serpentine as given in Table II, a somewhat greater variation in the silica content of soapstone could be anticipated.

To illustrate the degree of carbonatization of soapstone, all the analyses of soapstone proper contained in Table I were presented diagrammatically in Fig. 10. This figure gives the molecular ratio  $C : Si : (Mg + Fe + Mn + Ca + Al)$ . As the figure shows, the degree of carbonatization varies from zero up to a ratio of  $Si : C = 1 : 1$ . Only four examples of soapstones are known to date for which the molecular content of C is slightly higher than that of Si. These rocks are Nos. 24, 47, 61, and 63 (Table I). Among carbonate-bearing soapstones, types very poor in carbonate are comparatively rare.

In the contact zones of the soapstone lenses against the enclosing rocks and in the fissure fillings inside the soapstone lenses, pure concentrations



may be found of both talc and carbonate, respectively, as well as of chlorite, etc. These concentrations are relatively insignificant in mass as compared with the whole soapstone lens.

Except for the carbonate content, the chemistry of soapstone is quite constant. The amounts of calcium and iron vary slightly but these variations are not sufficient to allow any closer classification. The alkalis, titanium, and phosphorus are mostly almost lacking and the content of calcium, aluminum, and, usually, iron is remarkably low. Chromium and nickel are always present in small amounts. The nickel content constantly amounts to somewhat more than 0.20 % by weight NiO.

### CHEMICAL CHANGES INVOLVED IN THE FORMATION OF SOAPSTONE

The composition and the mode of occurrence of soapstones seems to indicate that these rocks cannot have been crystallized directly from a magmatic melt but are products of metamorphism derived from other kinds of rocks. Accurate data for the temperature and vapor pressure of carbon-dioxide and/or water vapor that characterize the stability field of all soapstone types is not yet available from experimental studies. The world-wide occurrence of soapstones of different mineral composition makes it apparent, however, that the mineral associations listed above (p. 27) are stable under definite physical and chemical conditions. If this last-named assumption is accepted, it will be evident that the mineral associations of the soapstones must, at least theoretically, be possible to establish from different rocks through metasomatic addition of certain components and through simultaneous removal of others.

Accordingly, two main kinds of alteration responsible for the formation of soapstone have been suggested in literature. First, a decarbonatization or silicification of sedimentary carbonate rocks that are mainly dolomitic in composition. Second, a carbonatization and steatitization of ultrabasic igneous rocks. In addition to these two opposite processes, carbonatization and steatitization of other more acid silicate rocks have been assumed to have produced soapstone. Field data and other information dealing with this third possibility for the formation of soapstone are very scanty. Consequently, they will be left out of consideration in the present connection.

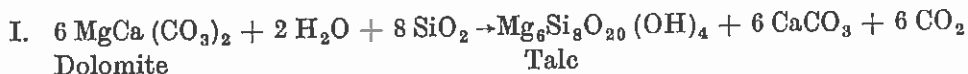
Examples of decarbonatization of sedimentary carbonate rocks leading to the formation of soapstone have been described from a number of American localities, as for example, from California by Wright (1950) and from New York by Engel (1949 a and 1949 b). A review of similar occurrences of the Canadian shield has been given by Bruce (1933).

According to Wright (op. cit.), the soapstones of the Californian deposits are mainly talc tremolite rocks, sometimes containing serpentine. The soapstones occur within or in contact with dolomitic carbonate rocks. These dolomitic carbonate rocks are often siliceous and have been produced through hydrothermal alteration of limestone. The talc tremolite bodies occur in immediate contact or proximate with quartz diorite, diabase, etc., and show mostly sharp contacts with the enclosing silicate rocks. The soapstones represent products of selective alteration of carbonate rocks and have been formed at the expense of dolomite. In some localities (Talc City Mine) quartzite-like silica rocks, obscure in their origin, have been extensively altered to soapstone. No chemical analyses or any detailed data dealing with the mineralogy of these Californian soapstones are known to the author.

In the Gouverneur district in the state of New York, soapstones occur in elongated zones interlayered within impure marble. According to chemical analyses and quantitative mineral compositions published by Engel (1949 a and b), these rocks vary within wide limits. The main constituents are tremolite, anthophyllite, serpentine, and talc. Other minerals include quartz, calcite, dolomite, chlorite, etc. Accordingly, only a part of the rocks, commercially called talcs and mined for various purposes, are to be classified among the soapstones proper. The rocks have been formed by reactions between quartzitic and dolomitic beds. The formation of soapstone has apparently been largely promoted by shear zones.

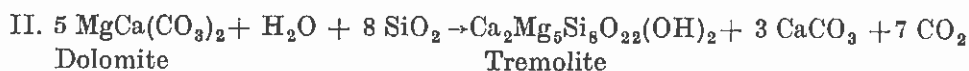
It is not the intention of the author to review here the rather extensive literature dealing with the individual occurrences of soapstone and related rocks, the origin of which may possibly be explained in a way essentially similar to that given for the soapstones from California and New York by Wright and Engel, respectively. The papers of these two authors have been cited only as examples of soapstones formed through decarbonatization of dolomitic carbonate rocks.

The formation of talc and tremolite through decarbonatization of dolomite by siliceous waters may taken place according to the following idealized reactions:



Assuming that all excess calcium carbonate and carbon dioxide is removed from the rock, the change in volume will be as follows:

	Dolomite	Talc
Grams participating in the reaction . . . .	842.46	758.43
Adopted sp. gr. . . . .	2.87	2.82
Volume in cc . . . . .	293.5	268.9
Decrease in volume 8.4 %.		



	Dolomite	Tremolite
Grams participating in the reaction . . . .	702.05	812.26
Adopted sp. gr. . . . .	2.87	2.98
Volume in cc . . . . .	244.6	272.6
Increase in volume 11.4 %.		

If talc and tremolite are formed simultaneously as products of the decarbonatization of dolomite, the volume change in the rock will be small. From the two reaction equations given it may easily be calculated that a decarbonatization of dolomite leading to a talc tremolite rock with a talc content of 56 % by weight and a tremolite content of 44 % by weight, both of ideal composition, will not affect the volume of the rock at all. This assumes, of course, that all excess calcium carbonate will disappear.

In this connection, it is of a certain importance to note that detailed chemical and mineralogical studies dealing with the transitional rock types between pure dolomitic carbonate rocks and talc tremolite rocks are lacking. These transitional rock types are of no commercial value and, probably for that reason, they have not received much petrographic attention. In addition, no examples among the Finnish soapstone occurrences are known to the author the origin of which has been explained through decarbonatization of a dolomitic carbonate rock. Because the Finnish soapstones and similar occurrences in other countries form the main interest of the present paper, the process of decarbonatization of dolomitic carbonate rock as a producer of soapstone will not be discussed here in detail. In his recent paper dealing with the mining field of Pitkäranta, now belonging to Russia, Eskola (1951) discusses at some length the decarbonatization of dolomite leading to a pure serpentine rock. The process of serpentinization of dolomite is very common in that mining field. The product is, however, only serpentine rock, not soapstone.

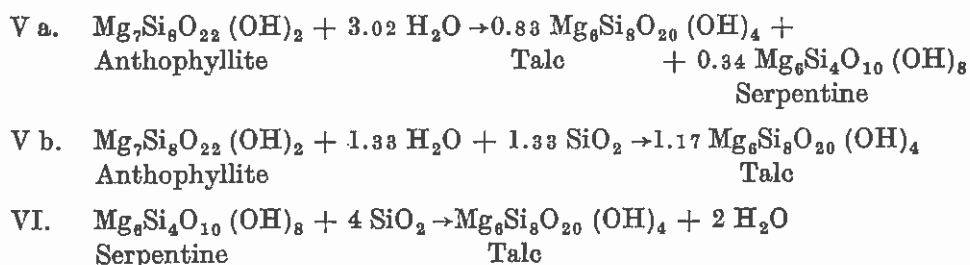
The second alternative for the formation of soapstone mentioned in the foregoing, *viz.*, the carbonatization of other ultrabasic igneous rocks, apparently is of much more importance in Finland. In a way, soapstones form an analogy to the serpentinites. As has been recently shown by Bowen and Tuttle (1949), both talc and serpentine crystallize only at relatively low temperatures and the vapor pressure of water vapor affects but little the temperature of formation of these minerals. Between the serpentinites and soapstones there is, however, a very important difference in this connection. In serpentinites, relict minerals and relict structures of many kinds are relatively frequent and often give a good clue as to the succession of the alteration processes leading to the formation of serpentine. In soapstones proper, those relict structures are much less common. The relative rarity

of relictic features in soapstones is apparently one reason why the problem of the origin of soapstone has not been discussed in literature as much as that of serpentinites. This is especially true as regards the mineral composition of the original rock from which the soapstones have been derived. Furthermore, the soapstones are much smaller in mass than the serpentinites in connection with which they usually occur. It is therefore quite understandable that interest has been mainly directed to the serpentinites, while the soapstones have been discussed to a lesser degree. Talc and soapstone are often regarded as a transition between the ultrabasic rocks with a low silica content and the enclosing rocks rich in silica. Silica has been metasomatically added to the premetamorphic ultrabasic rock or, on the other hand, the silica that has been liberated in the carbonatization has been bound anew, leading to the formation of a mixture of talc and carbonate instead of the original serpentine (Eskola, 1939, p. 392; Wellman, 1942, pp. 103 B—127 B).

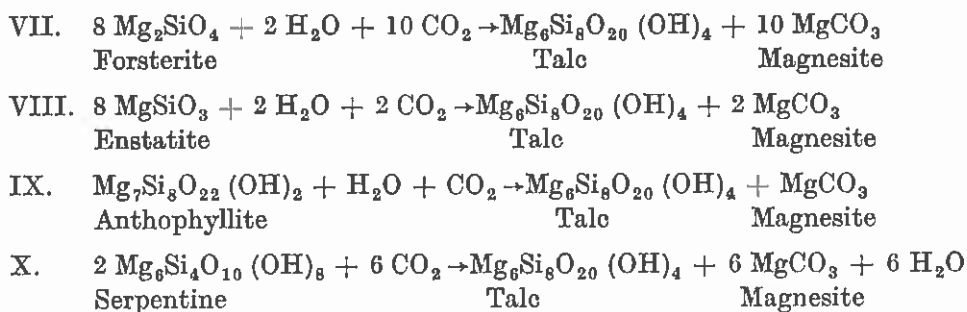
Upon studying both serpentinitization and steatitization in the field, Hess (1933, a and b) arrived at the conclusion that, if both these processes have taken place in the rock, the serpentinitization always is older and talc has been formed at the expense of serpentine. The same opinion has also been expressed by Haapala (1936, p. 68). Hess distinguishes two types of steatitization. In the first type, the entire ultrabasic mass undergoes steatitization with little or no change of chemical composition. The presence of solutions merely facilitates the recrystallization of the rock to minerals stable at the temperature prevailing. In the second type, the solutions attack the ultrabasic mass along the contacts and fractures, causing an intensive but local steatitization. A part of the material will turn into a solution and be redeposited in the neighbourhood. The system may be regarded as chemically open. Pure concentrations of talc may be formed in this way. Hess emphasizes that a characteristic succession of typical minerals leading to soapstone may be found as follows: Olivine + Pyroxene → Hornblende → Actinolite → Chlorite → Talc + Carbonate.

As the initial material for the steatitization process Hess often mentions serpentinite but also olivine + pyroxene (saxonite) and only pyroxene (pyroxenite). In other words, he assumes that a talc carbonate rock (soapstone) may be formed virtually from any ultrabasic rock type. He does not clearly state the origin of the necessary silica needed for these alterations. In a later paper, however, Phillips and Hess (1936) point out that, at least where the ultrabasics are surrounded by a zone consisting of talc, the silica has been metasomatically added from the enclosing rocks, causing an alteration of the original serpentine into talc or soapstone. In a paper dealing with the soapstone occurrences of Rochester, Vermont, Jacobs (1916) recalculated the chemical analyses of these rocks and arrived at the conclusion that the original pre-metamorphic material must have been





On other hand, starting with the same minerals and introducing water and/or carbon-dioxide, the reactions may be written as follows:



The change of volume, connected with the reactions III—X, is summarized in Table III. The specific gravities, adopted for the calculations, have been mainly taken from Winchell and Winchell (1951).

The reaction equations III—X listed above have been written for magnesium silicates of ideal composition. The content of iron, aluminum, calcium, etc. mostly shown by the corresponding natural minerals, have been neglected.

It is a well-known fact that forsterite, enstatite, anthophyllite, and serpentine found in ultrabasic rocks usually are richer in iron than talc is. As regards talc derived from soapstone or talc dykes and veins that cut the soapstone, three chemical analyses are included in Table I (Nos. 9, 16 and 31). These three analyses, very similar to each other, show a ratio of ferrous iron to magnesium of ca. 2.5 to 97.5. For talc, no appreciably higher content of iron in relation to magnesium is known to the author. It seems that talc represents a mineral in which a substitution of magnesium by ferrous iron is possible only to a very limited extent. This behavior for talc is even more pronounced than for the minerals of the humite group. The humite minerals are often regarded as the best examples of silicate minerals with limited diadochy between magnesium and ferrous iron. As a consequence, part of the ferrous iron originally contained in forsterite, enstatite, anthophyllite, serpentine, etc., can not enter into the talc structure in the steatitization process but will form iron oxide minerals, mainly magnetite. The content of ferrous iron in ultrabasic rocks to be steatitized is, however, usually comparatively low and will, apparently, not very radically change the main trend expressed in the reaction equations III—X.

Table III. Calculation of the Change

		Reaction			
		III a	III b	IV a	IV b
Forsterite Sp. gr. 3.21	Grams participating in the reaction . . . .	703.5	422.1	—	—
	Volume in cc . . . . .	219	131	—	—
Enstatite Sp. gr. 3.15	Grams participating in the reaction . . . .	—	—	1 003.8	602.3
	Volume in cc . . . . .	—	—	319	191
Anthophyllite Sp. gr. 2.98	Grams participating in the reaction . . . .	—	—	—	—
	Volume in cc . . . . .	—	—	—	—
Serpentine Sp. gr. 2.82	Grams participating in the reaction . . . .	460.0	—	460.0	—
	Volume in cc . . . . .	176	—	176	—
Talc Sp. gr. 2.82	Grams participating in the reaction . . . .	629.5	758.4	629.5	758.4
	Volume in cc . . . . .	223	269	223	269
Magnesite Sp. gr. 3.00	Grams participating in the reaction . . . .	—	—	—	—
	Volume in cc . . . . .	—	—	—	—
Increase (+) of volume in the reaction . . . . .		+82%	+105%	+25%	+41%

The only essential constituent of soapstones proper that may contain aluminum in considerable amounts is chlorite. No chemical analyses of chlorite found in soapstones have been made so far. The optical properties of chlorite that have been determined from several soapstone specimens and given in this paper agree mostly with the properties of penninite as given by Winchell and Winchell (1951). It is understood that the chemical composition can not be accurately decided solely on the basis of the optical properties in the rather complicated chlorite group. The refractive indices given in the previous chapter of this paper seem to indicate, however, that the mineral is not antigorite but, in addition to a certain iron content, it must also contain some aluminum. In penninites, the theoretical aluminum content may range as high as 10—15 per cent by weight  $Al_2O_3$ .

The actual content of chlorite in the soapstone specimens studied by the author ranges from zero up to 12 per cent. The only exception among the Finnish soapstones is that from Hoppula (Table I, No. 30) which contains 34 per cent chlorite. The three specimens of Appalachian soapstones studied by the author are exceptionally rich in this mineral.

There seems to be no special reason to assume that the amount of aluminum, now incorporated in the chlorite structure, has been introduced into the soapstone in the process of steatitization. The aluminum content found in soapstones is apparently more readily interpreted as belonging to the composition of the original rock that was subjected to alteration. Of course, this assumption can not be proved. The fact, however, that clino-

## of Volume for Reactions III a—X.

Number						
V a	V b	VI	VII	VIII	IX	X
—	—	—	1 125.6	—	—	—
—	—	—	351	—	—	—
—	—	—	—	803.0	—	—
—	—	—	—	255	—	—
780.7	780.7	—	—	—	780.7	—
262	262	—	—	—	262	—
188.4	—	554.2	—	—	—	1 108.4
72	—	212	—	—	—	423
629.5	887.4	758.4	758.4	758.4	758.4	758.4
223	315	269	269	269	269	269
—	—	—	843.3	168.7	84.3	506.0
—	—	—	281	56	28	169
+13 <sup>0</sup> / <sub>0</sub>	+20 <sup>0</sup> / <sub>0</sub>	+27 <sup>0</sup> / <sub>0</sub>	+57 <sup>0</sup> / <sub>0</sub>	+27 <sup>0</sup> / <sub>0</sub>	+13 <sup>0</sup> / <sub>0</sub>	+4 <sup>0</sup> / <sub>0</sub>

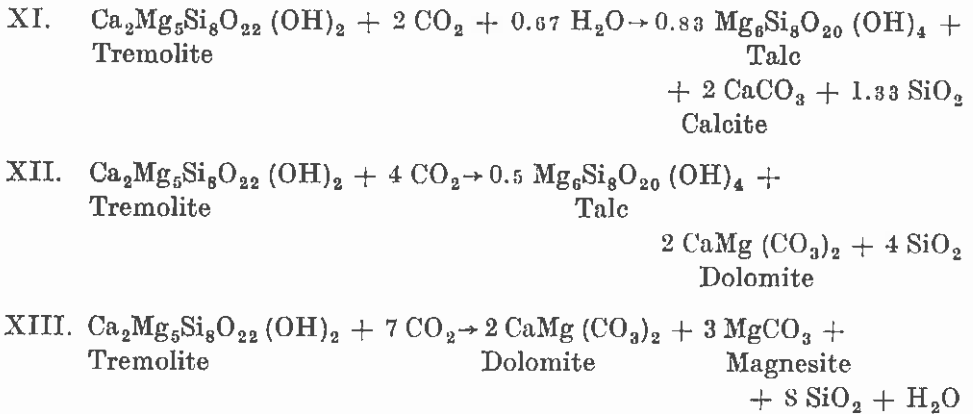
pyroxenes of ultrabasic rocks are generally not completely free of aluminum, makes it very probable that the occasional aluminum content of the soapstones represents a primary feature of the rock. If this is correct, then the steatitization process does not strictly follow the general trend of the reactions III—X listed in the foregoing. As long as the chemical composition of chlorite found in soapstones is not known, the formation of this mineral in the steatitization process can not be illustrated by accurate reaction equations.

The presence of calcium in ultrabasic rock subjected to steatitization is of particular interest. As is shown by the average calculations of the igneous rock compositions presented by Daly (1933), no ultrabasic rock types may be excepted to be entirely free of calcium. Even dunites proper contain 0.70 per cent CaO on the average. Of course, pyroxenites with clinopyroxene and hornblendites show a much higher calcium content. Now, if the rock, in the scheme presented by Hess (p. 35), has passed the stage characterized by hornblende, a calcium content will result in a crystallization of tremolite (actinolite). In fact, tremolite is the only silicate mineral of soapstones that may be regarded as an essential carrier of calcium. On the other hand, tremolite does not seem to occur in association with any of the carbonates (magnesite, dolomite, calcite) that are characteristic of many soapstones. Among the soapstone specimens that have been microscopically studied by the author, tremolite and carbonates were never found together. The author has not been able to find in literature any descrip-



tions of soapstone types in which tremolite and carbonate minerals would form essential constituents. If those tremolite carbonate rocks with or without talc exist, they apparently must be rare exceptions among the soapstones and, therefore, are not likely to affect the present discussion. Tremolite carbonate rocks are certainly not of any world-wide importance in connection with the problem of the origin of soapstone.

If the rock is subjected to carbonatization, tremolite may be altered according to reactions such as the following:



Assuming that all silica that is liberated in these reactions is removed in solution from the system, the change of volume is calculated in Table IV.

Table IV. Calculation of the Change of Volume in Reactions XI—XIII.

		Reaction Number		
		XI	XII	XIII
Tremolite Sp. gr. 2.98	Grams participating in the reaction .....	812.3	812.3	812.3
	Volume in cc .....	273	273	273
Talc Sp. gr. 2.82	Grams participating in the reaction .....	631.8	379.3	—
	Volume in cc .....	224	134	—
Calcite Sp. gr. 2.70	Grams participating in the reaction .....	200.2	—	—
	Volume in cc .....	74	—	—
Dolomite Sp. gr. 2.85	Grams participating in the reaction .....	—	368.8	368.8
	Volume in cc .....	—	129	129
Magnesite Sp. gr. 3.00	Grams participating in the reaction .....	—	—	253.0
	Volume in cc .....	—	—	84
Increase (+) or decrease (—) of volume in the reaction		+9%	—4%	—22%

The reactions XI—XIII have been arranged in order of increasing degree of carbonatization. As will be seen from the reaction equations, the cha-

racteristic succession of the carbonate minerals with an increasing degree of carbonatization is as follows:

Calcite — Dolomite — Magnesite

This succession is in agreement with the analytical data given in Table I and is well illustrated in Fig. 8. The data available to the author seem to indicate that calcite is formed in soapstones of low carbonatization. On increasing carbonatization, calcite is successively replaced by dolomite or dolomite + magnesite.

The carbonatization of tremolite will liberate some silica, the amount of which depends on the degree of carbonatization. This amount of silica may be used up in the formation of talc from forsterite, enstatite, anthophyllite, serpentine, etc.

The reaction equations III—XIII as given in the foregoing have been written only to illustrate the chemical changes connected with the formation of talc, serpentine, and carbonate minerals. Of course, the amounts of materials participating in the reactions that actually take place in natural ultrabasic rocks vary and do not necessarily agree with the proportions indicated by the equations.

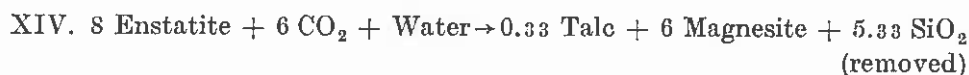
If, for the moment, the introduction of carbon-dioxide into the ultrabasic body is left out of consideration, reactions like III—VI are of importance. These reaction equations have been written so that nothing but water will be removed from the reacting system. If only talc is formed as a reaction product, a metasomatic addition of silica will be necessary. If talc and serpentine are formed simultaneously, only the alteration of forsterite (reaction III a) will require additional silica from the enclosing rock ground.

The alteration of forsterite, enstatite, anthophyllite, and serpentine into talc according to reactions III b, IV b, and VI, respectively, is accompanied by a considerable increase in volume of the reacting system. As is shown by the calculations summarized in Table III, this increase in volume is even more pronounced than if both talc and serpentine occur as reaction products.

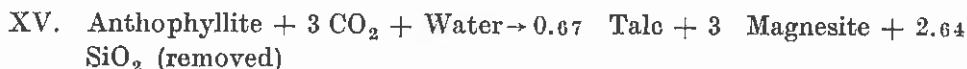
The change in volume accompanying the metasomatic alteration of ultrabasic rocks represents a serious problem. In principle, it is not easy to arrive at any decisive conclusion as to whether or not the volume of the ultrabasic rock body has remained approximately constant during the alteration process. The strongly schistous texture observable in some soapstones seems to indicate that these soapstone bodies have not been left unaffected by the tectonical events in the area. If the alteration process that resulted in the formation of soapstone was accompanied by more or less intense movements in the surrounding rock ground, than a certain »growth» of the relatively small soapstone bodies seems not to be completely impossible. Such a growth would result in a bending of the enclosing schists or gneisses

around the soapstone bodies. In fact, similar bending is a general rule in most soapstone occurrences where the rocks are sufficiently exposed to allow observations to be made. On the other hand, however, similar bending generally occurs around all kinds of small ultrabasic bodies independently, whether or not any secondary alteration is observable. The bending may simply be explained through the different mechanical properties of the ultrabasic rock and of the enclosing schists or gneisses.

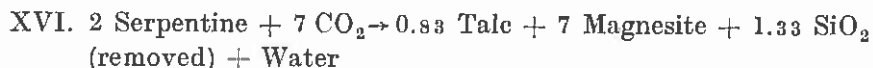
If the idea is accepted that the steatitization and carbonatization of the ultrabasic rock body must take place at approximately constant volume, the reaction equations VII—X are not applicable as such. As is seen from the data summarized in Table III, reactions VII—X are accompanied by a remarkable increase in volume. If only talc is formed, this increase in volume will be still more pronounced than if both talc and magnesite occur as reaction products. The volume of magnesite is smaller than that of an equivalent amount of enstatite, anthophyllite, or serpentine. The following reaction equations will approximately satisfy the requirement of the constancy of volume:



Reaction product: Talc ..... 33 per cent by weight  
Magnesite ..... 67 » » » »



Reaction product: Talc ..... 67 per cent by weight  
Magnesite ..... 33 » » » »



Reaction product: Talc ..... 52 per cent by weight  
Magnesite ..... 48 » » » »

Reaction X has been previously given by Turner (1948, p. 132) as an illustration of the chemical change upon converting serpentine to talc and magnesite at constant volume. The constancy of volume is for reaction XVI somewhat more accurate.

Now, simple calculations will show that, if carbon-dioxide is introduced into the rock in smaller amounts than indicated by the reaction equations XIV, XV, and XVI, the volume of the product will increase in inverse ratio to the amount of carbon dioxide participating in the reaction. This increase in volume requires that something must be removed from the reacting system. The silica that, according to the reaction equations, is liberated by the carbon-dioxide will disappear. Soapstones do not generally contain

quartz or other forms of silica. In some cases, however, clumps of chalcodony are formed in the soapstone. This has not been observed by the author but has been mentioned by Hess (1933 a). The removal of silica is not sufficient to neutralize the increase in volume. Therefore, it might be

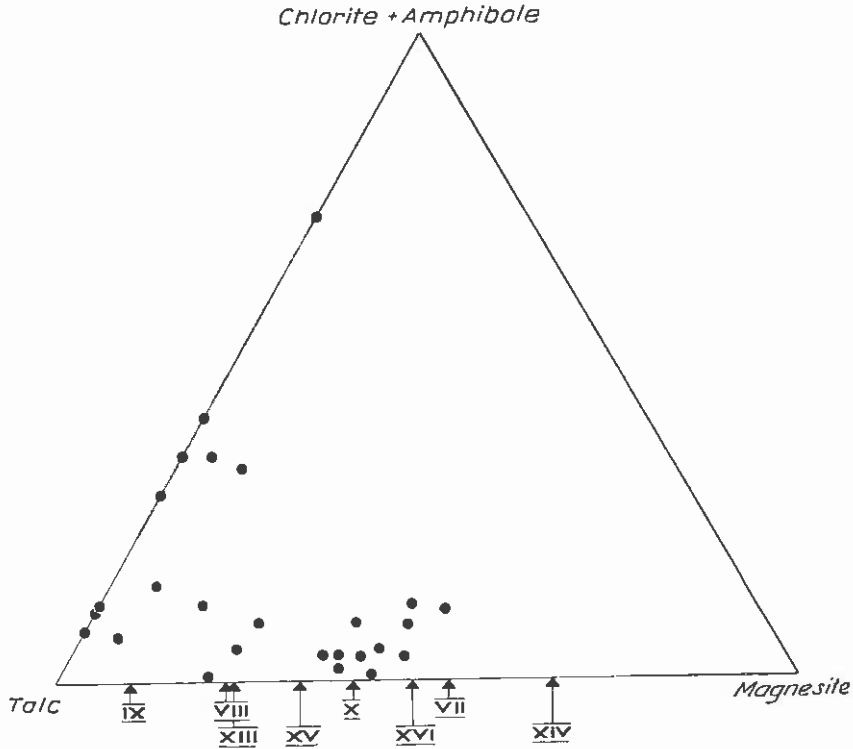


Fig. 11. The ratio of talc, magnesite, and chlorite in soapstone. Weight percentage.

appropriate to assume that, especially in weak carbonatization, also magnesium carbonate will be removed. Magnesium carbonate is by far more readily soluble than talc.

Further support for the assumption of the removal of magnesium carbonate is offered by the ratio of talc to magnesite found in soapstones. As mentioned (p. 31), the amount of carbonate minerals in soapstones so far studied ranges from zero up to about 50 per cent by weight. Fig. 11 illustrates the range of variation. This figure gives the weight ratios of talc, magnesite (including the amount of magnesium carbonate contained in dolomite), and chlorite + amphibole in the soapstone specimens analyzed by the author or by Mr. Tavela, *viz.* Nos. 3, 8, 11, 12, 13, 14, 21, 22, 24, 25, 26, 27, 28, 29, 30, 33, 34, 35, 38, 39, 40, 41, 42, 43, 44, and 50 (Table I). The ratios of talc to magnesite according to the reaction equations VII—X and XIII—XVI have also been indicated in the figure.

The amount of chlorite or amphibole (tremolite-actinolite) or both, virtually always present in soapstones proper, makes it apparent that the reaction equations given do not reflect the chemical changes connected with the formation of soapstone. The datum points in Fig. 11 are above the bottom line of the figure. If chlorite and amphibole were to be converted to talc, the datum points would be moved towards the left-hand corner of the figure.

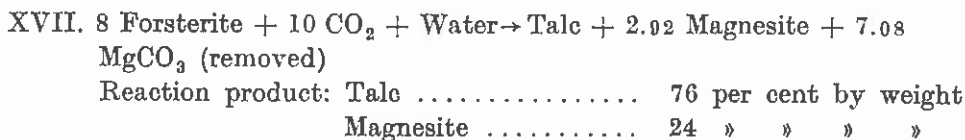
As is seen from Fig. 11, the amount of magnesite present in the soapstone specimens studied is always lower than required by the conversion of enstatite and serpentine to soapstone at constant volume (reactions XIV and XVI). In a considerable number of soapstones the amount of magnesite is even lower than that required by reaction XV. This fact, very remarkable indeed, is easily understood if a relatively weak carbonatization and subsequent partial removal of magnesium carbonate is assumed. In this way, the volume of the rock body will remain constant during the alteration process.

The conversion of forsterite into a mixture of talc and magnesite needs special discussion. In contrast to enstatite, anthophyllite, and serpentine, a conversion of forsterite to an equivalent amount of magnesite will result in an increase of volume. This fact is illustrated by the data summarized in Table VI.

*Table VI.* Molecular Volume of Forsterite, Enstatite, Anthophyllite, and Serpentine compared with the Volume of an Equivalent Amount of Magnesite.

Mineral	Formula	Volume	Equivalent Amount of Magnesite	Volume of Magnesite
Forsterite	Mg <sub>2</sub> SiO <sub>4</sub> .....	44 cc	2 MgCO <sub>3</sub>	56 cc
Enstatite	MgSiO <sub>3</sub> .....	32 »	1 »	28 »
Anthophyllite	Mg <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub> .....	262 »	7 »	197 »
Serpentine	Mg <sub>6</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub> .....	212 »	6 »	169 »

As will be evident from the data of Table VI, the steatitization and carbonatization of a rock consisting essentially of forsterite can not be effected without a considerable removal of magnesium. The following reaction equation will approximately satisfy the requirement of constancy in volume:





As a result of reactions XVIII and XIX, a rock is formed that consists of talc and varying amounts of tremolite and iron oxide minerals according to the calcium and iron content of the rock. Because the pyroxenes and amphiboles of the ultrabasic rocks almost always contain small amounts of aluminium, some chlorite is formed. As a result of reactions XX and XXI, a soapstone is formed that consists of talc, carbonate (dolomite and/or magnesite), iron oxide minerals and accessories. Calcium is here contained in the carbonate minerals.

The reactions XVIII—XXI given in the foregoing are, of course, quite schematical. The actual alteration process of a pyroxene or anthophyllite rock that results in a formation of soapstone may be considered as consisting of all these reactions simultaneously. Accordingly, the soapstones thus formed may contain smaller amounts of talc or carbonate, respectively, than indicated by the said reaction equations. Assuming that the silica that is liberated in carbonatization will be removed from the rock, the maximum and minimum amounts of silica and carbon-dioxide contained in the products of reactions XVIII—XXI will be as follows:

	Maximum	Minimum
SiO <sub>2</sub> .....	53.3 atomic per cent	26.7 atomic per cent
CO <sub>2</sub> .....	26.7 » » »	0 » » »

The silica and carbon-dioxide content of the individual soapstones analyzed so far lie well between these maximum and minimum figures.

## SUMMARY

In the present paper, the existing chemical analyses of soapstones from different parts of the world have been collected from literature and 39 new analyses presented. The mode of occurrence and the petrography of the soapstones under consideration have been briefly described.

According to their mineralogical composition, the soapstones have been classified into three groups:

1. Carbonate soapstones: Talc + Carbonate + Chlorite + accessories.
2. Tremolite soapstones: Talc + Tremolite + Chlorite + accessories.
3. Godthaab type soapstones: Talc + Chlorite + accessories.

Calcium has been bound to carbonate in carbonate soapstones and to tremolite in tremolite soapstones. Carbonate and tremolite have not been observed simultaneously in the same soapstone. If the content of calcium is very low and if carbonatization has not occurred, a Godthaab-type soapstone will be formed. This type is very rare.

Among carbonate minerals, calcite, dolomite, dolomite + magnesite, and magnesite have been found. The characteristic succession of these carbonate

minerals with an increasing degree of carbonatization is calcite-dolomite-magnesite. The carbonate minerals were identified in each specimen by means of powder diffraction patterns prepared from the powdered rock without any mechanical pre-enrichment.

The degree of carbonatization of soapstones proper varies from zero up to a ratio of Si : C = 1 : 1. Types containing very little carbonate are comparatively rare.

The chemical changes involved in the formation of soapstone are discussed. Soapstones formed through decarbonatization of sedimentary carbonate rocks, mainly dolomitic in composition, have not been found in Finland. Therefore, more attention is paid to the formation of soapstone through hydrothermal alteration of ultrabasic igneous rocks. The discussion is mainly based on the assumption that, in the steatitization and carbonatization process, the volume of the rock mass will remain approximately constant.

#### EXPLANATORY NOTE TO TABLE I.

At the top of the table, the composition of the analyzed specimens is given as found, in weight percentages. The middle part of the table contains the analyses calculated on a waterless basis and expressed in atomic percentages. At the bottom, the mineral composition (modes) is given in weight percentages.

The mineral composition was calculated from the analysis. The silicate, oxide, and sulphide minerals listed were identified microscopically. A microscopic distinction between the three carbonate minerals (calcite, dolomite, magnesite) not being possible, these minerals were identified by measuring the refractive index  $\omega$  by the immersion method and, in addition, by the powder diffraction pattern using a Philips Geiger counter X-ray spectrometer and CuK $\alpha$  radiation with nickel filter. The strongest lines of the three carbonate minerals ( $2\theta = \text{ca. } 29.5^\circ$  for calcite;  $2\theta = \text{ca. } 31.1^\circ$  for dolomite;  $2\theta = \text{ca. } 32.6^\circ$  for magnesite) are easily identified and sensitive enough to be found in powdered rock without mechanical pre-enrichment of carbonates.



Table I. Chemical Analyses and Calculated Mineral Compositions.

Number	1.	2.	3.	4.	5.	6.	7.	8.
Weight percentage								
SiO <sub>2</sub> .....	53.96	52.15	54.52	52.29	57.56	59.56	38.07	33.61
CO <sub>2</sub> .....	—	0.37	2.05	0.00	0.00	0.00	17.88	21.44
TiO <sub>2</sub> .....	—	0.06	—	0.04	—	—	0.02	0.04
Al <sub>2</sub> O <sub>3</sub> .....	0.86	1.25	2.49	1.85	3.34	0.66	0.48	0.50
Fe <sub>2</sub> O <sub>3</sub> .....	1.83	1.84	0.48	1.02	3.22	0.76	0.92	0.72
FeO .....	4.59	3.24	3.53	6.12	2.20	7.49	3.71	5.33
MnO .....	—	0.04	—	0.07	0.40	0.17	0.07	0.08
MgO .....	31.32	33.56	30.68	34.42	28.01	28.97	31.67	33.40
CaO .....	0.15	0.00	0.00	0.36	0.71	—	4.66	2.28
Na <sub>2</sub> O .....	—	0.27	—	0.20	0.58	—	0.19	0.16
K <sub>2</sub> O .....	—		—		0.10			
P <sub>2</sub> O <sub>5</sub> .....	—	0.00	—	—	—	—	—	—
H <sub>2</sub> O+ .....	5.14	6.42	5.62	2.84	2.88	2.38	2.61	2.00
H <sub>2</sub> O— .....		0.13	0.00	0.14	0.68	0.31	0.00	0.00
Cr <sub>2</sub> O <sub>3</sub> .....	0.24	0.25	0.30	0.41	—	—	0.00	0.13
NiO .....	0.25	0.17	—	0.21	—	—	0.00	0.19
S .....	1.08	0.63	—	1.30	0.24	—	0.43	0.62
—O = S .....	99.42	100.38	99.73	101.27	99.92	100.30	100.71	100.50
		0.31		0.65			0.22	0.31
		100.07		100.62			100.49	100.19

## Atomic percentage

Si .....	51.38	48.14	49.97	47.51	52.61	—	32.09	28.00
C .....	0.00	0.46	2.56	0.00	0.00	—	20.57	24.39
Al .....	0.96	1.36	2.60	1.99	3.60	—	0.47	0.49
Mg .....	44.42	46.15	41.88	46.58	38.14	—	39.76	41.46
Fe .....	2.89	3.19	2.90	2.98	3.49	—	2.52	3.15
Ca .....	0.15	0.00	0.00	0.35	0.70	—	4.21	2.04
Mn, Ni etc. ....	0.20	0.70	0.00	0.59	1.46	—	0.38	0.47
	100.00	100.00	100.00	100.00	100.00	—	100.00	100.00

## Mineral composition. Weight percentage

Talc .....	—	—	84	—	—	—	60	53
Dolomite .....	—	—	0	—	—	—	16	8
Magnesite .....	—	—	4	—	—	—	21	36
Chlorite .....	—	—	7	—	—	—	1	1
Magnetite .....	—	—	4	—	—	—	1.5	1
Chromite .....	—	—	0.5	—	—	—	0	0.2
Pyrrhotite .....	—	—	—	—	—	—	1	1.7
	—	—	99.5	—	—	—	100.5	100.9

1. Asbestos-bearing rock. Paakkilanniemi, Kuusjärvi, Finland. Analysis by Haapala (1936, p. 61).
2. Enstatite-bearing anthophyllite asbestos rock. Maljasalmi, Kuusjärvi, Finland. Analysis by the author.
3. Soapstone. Maljasalmi, Kuusjärvi, Finland. Analysis by M. Tavela.
4. Pyroxenite. Kinttumäki, Kuusjärvi, Finland. Analysis by the author.
5. Anthophyllite rock. Tiilikainen, Kuusjärvi, Finland. Analysis by E. Savolainen (Haapala, 1936, p. 64).
6. Anthophyllite from anthophyllite vein in anthophyllite rock. Tiilikainen, Kuusjärvi, Finland. Analysis by E. Savolainen (Haapala, 1936, p. 64).
7. Completely steatitized and carbonatized anthophyllite asbestos dyke in soapstone. Horsmanaho, Polvijärvi, Finland. Analysis by the author.
8. Soapstone. Horsmanaho, Polvijärvi, Finland. Analysis by the author.

Table I. (continued)

Number	9.	10.	11.	12.	13.	14.	15.	16.
Weight percentage								
SiO <sub>2</sub> .....	61.17	0.00	36.09	36.67	33.63	37.25	43.81	62.30
CO <sub>2</sub> .....	0.00	47.34	19.24	17.70	20.32	19.22	—	—
TiO <sub>2</sub> .....	0.00	0.00	0.05	0.05	0.05	0.07	tr.	0.00
Al <sub>2</sub> O <sub>3</sub> .....	0.52	0.42	1.42	1.36	0.98	0.85	1.46	0.19
Fe <sub>2</sub> O <sub>3</sub> .....	—	—	0.08	0.52	1.04	0.59	1.12	—
FeO .....	1.46	7.70	4.97	5.40	5.26	5.22	5.18	1.46
MnO .....	0.00	0.08	0.04	0.07	0.08	0.07	tr.	0.00
MgO .....	31.65	35.50	34.88	34.21	34.87	32.75	35.06	31.66
CaO .....	0.00	8.62	0.14	0.00	0.20	1.55	0.91	—
Na <sub>2</sub> O .....	—	—	0.16	0.19	0.13	0.08	0.35	—
K <sub>2</sub> O .....	—	—						
P <sub>2</sub> O <sub>5</sub> .....	—	—	—	—	—	—	—	—
H <sub>2</sub> O+ .....	4.93	—	3.22	2.85	3.02	1.59	10.94	4.75
H <sub>2</sub> O— .....	0.00	—	0.00	0.00	0.00	0.01	0.18	0.00
Cr <sub>2</sub> O <sub>3</sub> .....	—	—	0.25	0.30	0.23	0.27	0.32	—
NiO .....	—	—	0.27	0.22	0.21	0.26	0.26	—
S .....	—	—	—	1.39	0.51	—	—	—
—O=S .....	99.73	99.66	100.81	100.93	100.53	99.78	99.68	100.36
				0.69	0.25			
				100.24	100.28			

## Atomic percentage

Si .....	—	0.00	29.87	31.52	28.32	31.04	41.80	—
C .....	—	48.33	21.73	20.77	22.86	21.86	0.00	—
Al .....	—	0.36	1.38	1.37	0.97	0.83	1.65	—
Mg .....	—	39.55	43.00	43.80	43.75	40.66	49.84	—
Fe .....	—	4.81	3.40	1.98	3.48	3.83	4.82	—
Ca .....	—	6.90	0.12	0.00	0.18	1.38	0.91	—
Mn, Ni etc. ....	—	0.05	0.50	0.56	0.44	0.40	0.98	—
	—	100.00	100.00	100.00	100.00	100.00	100.00	—

## Mineral composition. Weight percentage

Talc .....	—	0	56	57	51	58	—	—
Dolomite .....	—	27	0	0	0	5	—	—
Magnesite .....	—	73	38	34	39	33	—	—
Chlorite .....	—	0	4	4	5	2	—	—
Magnetite .....	—	0.0	1.4	0.5	3.2	2.4	—	—
Chromite .....	—	0.0	0.4	0.4	0.3	0.4	—	—
Pyrrhotite .....	—	0.0	—	3.8	1.4	—	—	—
	—	100.0	99.8	99.7	99.9	100.8	—	—

9. Talc, pseudomorphic after anthophyllite. Horsmanaho, Polvijärvi, Finland. Analysis by the author.
10. Carbonate clumps contained in the steatitized and carbonatized anthophyllite dyke (No. 7 in this table). Horsmanaho, Polvijärvi, Finland. Analysis by the author.
11. Soapstone. Haaralanniemi, Polvijärvi, Finland. Analysis by the author.
12. Soapstone. Solansaari, Polvijärvi, Finland. Analysis by the author.
13. Soapstone. Sola, Polvijärvi, Finland. Analysis by the author.
14. Soapstone. Juttusuo, Polvijärvi, Finland. Analysis by the author.
15. Antigorite rock. Solansaari, Polvijärvi, Finland. Analysis by Elsa Ståhlberg (Haapala, 1936, p. 17).
16. Talc from a pure talc dyke in soapstone. Solansaari, Polvijärvi, Finland. Analysis by the author.

Table I. (continued)

Number	17.	18.	19.	20.	21.	22.	23.	24.
Weight percentage								
SiO <sub>2</sub> .....	—	40.23	69.47	18.93	30.10	39.47	32.74	28.62
CO <sub>2</sub> .....	<sup>1)</sup> 47.49	0.20	0.00	0.00	21.05	9.90	20.48	23.71
TiO <sub>2</sub> .....	—	0.08	0.40	1.43	0.05	0.53	0.03	0.04
Al <sub>2</sub> O <sub>3</sub> .....	—	2.56	12.60	10.95	1.47	2.85	1.65	0.75
Fe <sub>2</sub> O <sub>3</sub> .....	—	4.48	2.16	2.31	2.36	8.57	4.23	1.49
FeO .....	11.64	5.98	3.89	34.50	5.76	8.78	5.60	6.19
MnO .....	0.15	0.05	0.11	0.04	0.11	0.40	—	0.15
MgO .....	40.07	33.96	2.67	11.17	33.06	25.31	32.55	32.79
CaO .....	0.00	0.00	1.91	0.00	2.02	1.71	1.58	2.84
Na <sub>2</sub> O .....	—	0.22	2.64	1.20	0.17	0.19	—	—
K <sub>2</sub> O .....	—	0.11	3.23	3.32	0.10	0.26	—	0.05
P <sub>2</sub> O <sub>5</sub> .....	—	0.00	0.00	0.23	0.00	0.00	—	—
H <sub>2</sub> O <sup>+</sup> .....	—	12.22	1.09	2.77	3.35	2.26	—	3.15
H <sub>2</sub> O <sup>-</sup> .....	—	0.02	0.00	0.56	0.00	0.00	1.48	0.00
Cr <sub>2</sub> O <sub>3</sub> .....	—	0.17	—	0.00	0.21	0.02	0.28	0.41
NiO .....	—	0.17	—	0.07	0.18	0.14	—	0.11
S .....	—	0.05	—	17.28	0.14	—	—	0.12
—O=S .....	99.35	100.50	100.17	104.76	100.13	100.30	100.62	100.42
		0.02		4.31	0.07			0.03
		100.48		100.45	100.06			100.39

## Atomic percentage

Si .....	—	39.01	—	—	25.31	35.49	27.17	23.85
C .....	—	0.27	—	—	24.15	12.15	23.20	26.98
Al .....	—	2.92	—	—	1.45	3.02	1.61	0.74
Mg .....	—	49.06	—	—	41.39	33.90	40.24	40.71
Fe .....	—	7.96	—	—	5.26	12.39	6.35	4.93
Ca .....	—	0.00	—	—	1.82	1.65	1.40	2.54
Mn, Ni etc. ....	—	0.78	—	—	0.62	1.40	0.03	0.25
	—	100.00	—	—	100.00	100.00	100.00	100.00

## Mineral composition. Weight percentage.

Talc .....	—	—	—	—	42	59	—	39
Dolomite .....	—	—	—	—	7	6	—	10
Magnesite .....	—	—	—	—	36	17	—	39
Chlorite .....	—	—	—	—	11	8	—	10
Magnetite .....	—	—	—	—	3.6	10.5	—	1.5
Chromite .....	—	—	—	—	0.3	0.0	—	0.5
Pyrrhotite .....	—	—	—	—	0.4	—	—	0.3
	—	—	—	—	100.3	100.5	—	100.3

17. Magnesite (breunnerite) from soapstone. Sokusaari, Polvijärvi, Finland. Analysis by the author.
18. Serpentinite. Foot-wall of the soapstone from Kärenvaara, Nunnanlahti, Finland. Analysis by the author.
19. Mica gneiss. Hanging wall of the soapstone from Kärenvaara, Nunnanlahti, Finland. Analysis by the author.
20. Blackwall. Pyrrhotite and biotite-rich contact zone between serpentinite and gneiss from Turtianniemi, Savonranta, Finland. Analysis by the author.
21. Soapstone. Kärenvaara, Nunnanlahti, Finland. Analysis by the author.
22. Soapstone. Nunnanlahti, Finland.
23. Soapstone. Kärenvaara, Nunnanlahti, Finland. Analysis by A. Zilliacus (Frosterus, 1926, p. 17).
24. Soapstone. Jokiahö, Nunnanlahti, Finland. Analysis by the author.

<sup>1)</sup> CO<sub>2</sub> + H<sub>2</sub>O

Table I. (continued)

Number	25.	26.	27.	28.	29.	30.	31.	32.
Weight percentage								
SiO <sub>2</sub> .....	44.26	37.16	32.56	42.82	29.24	42.54	61.73	0.05
CO <sub>2</sub> .....	12.25	16.44	21.88	4.63	19.92	3.83	0.00	46.52
TiO <sub>2</sub> .....	—	0.05	—	0.23	0.14	0.35	—	0.00
Al <sub>2</sub> O <sub>3</sub> .....	0.00	0.91	1.49	4.31	2.47	4.79	0.28	0.00
Fe <sub>2</sub> O <sub>3</sub> .....	2.05	1.52	0.48	6.48	6.53	5.92	0.87	0.28
FeO .....	3.71	4.90	4.90	5.40	3.38	4.03	1.38	1.91
MnO .....	0.05	0.03	—	0.07	0.14	0.10	0.01	0.54
MgO .....	29.97	34.57	35.12	26.72	34.48	26.82	30.99	21.48
CaO .....	4.20	0.00	0.00	3.40	0.19	4.93	0.00	27.96
Na <sub>2</sub> O .....	} 0.20	0.20	—	} 0.03	} 0.13	} 0.10	—	—
K <sub>2</sub> O .....		0.19	—				—	—
P <sub>2</sub> O <sub>5</sub> .....	0.04	—	—	0.04	0.00	0.04	—	—
H <sub>2</sub> O+ .....	3.61	3.14	2.84	5.76	3.50	6.62	4.79	} 0.80
H <sub>2</sub> O— .....	0.00	0.00	—	0.02	0.02	0.02	0.00	
Cr <sub>2</sub> O <sub>3</sub> .....	0.25	0.25	0.29	0.41	0.31	0.28	—	—
NiO .....	0.29	0.22	0.11	—	0.19	0.26	—	—
S .....	—	0.13	—	0.11	—	—	—	—
—O=S .....	100.88	99.71	99.67	100.43	100.64	100.63	100.05	99.03
		0.06		0.05				
		99.65		100.38				

Atomic percentage

Si .....	38.38	31.51	26.92	40.07	24.54	39.72	—	—
C .....	14.50	19.03	24.70	5.91	22.82	4.88	—	—
Al .....	0.00	0.91	1.45	4.75	2.44	5.27	—	—
Mg .....	38.71	43.67	43.26	37.24	43.10	37.30	—	—
Fe .....	3.93	4.14	3.59	8.30	6.40	7.20	—	—
Ca .....	3.90	0.00	0.00	3.41	0.17	4.93	—	—
Mn, Ti, Ni etc. ....	0.58	0.74	0.08	0.32	0.53	0.70	—	—
	100.00	100.00	100.00	100.00	100.00	100.00	—	—

Mineral composition. Weight percentage

Talc .....	70	58	50	64	44	48	—	—
Calcite .....	0	0	0	0	0	9	—	—
Dolomite .....	14	0	0	11	0	0	—	—
Magnesite .....	11	32	44	0	39	0	—	—
Chlorite .....	1	3	4	12	8	34	—	—
Magnetite .....	4.1	4.7	1.0	11.4	7.5	8.3	—	—
Chromite .....	0.4	0.4	0.4	0.6	0.4	0.4	—	—
Pyrrhotite .....	—	0.4	—	0.3	—	—	—	—
	100.5	98.5	99.4	99.3	98.9	99.7	—	—

25. Soapstone. Quarry of Hyllävä, Jormaskylä, Sotkamo, Finland. Analysis by the author.  
 26. Soapstone. Pitkänperä, Paltamo, Finland. " " " "  
 27. Soapstone. Jormua, Kajaani, Finland. " " " "  
 28. Soapstone. Vieksi, Kuhmo, Finland. Analysis by M. Tavela.  
 29. Soapstone. Saarijärvi, Suomussalmi, Finland. Analysis by the author.  
 30. Soapstone. Hoppula, Kynsiperä, Posio, Finland. " " " "  
 31. Talc from vein in soapstone. Vieksi, Kuhmo, Finland. " " " "  
 32. Dolomite from vein in soapstone. Vieksi, Kuhmo, Finland. " " " "

Table I. (continued)

Number	33.	34.	35.	36.	37.	38.	39.	40.
Weight percentage								
SiO <sub>2</sub> .....	51.61	58.31	56.29	55.62	39.54	42.73	40.27	45.43
CO <sub>2</sub> .....	2.66	0.00	0.00	0.00	9.50	4.15	8.15	0.00
TiO <sub>2</sub> .....	0.14	0.11	0.11	0.12	0.27	0.37	0.34	0.36
Al <sub>2</sub> O <sub>3</sub> .....	4.12	0.83	2.34	1.92	3.72	8.25	7.12	7.71
Fe <sub>2</sub> O <sub>3</sub> .....	0.72	0.96	1.13	0.97	3.62	0.80	1.68	0.85
FeO .....	6.26	5.33	4.24	5.54	7.12	7.52	9.05	7.70
MnO .....	0.11	0.09	0.07	0.23	0.16	0.12	0.11	0.10
MgO .....	25.97	26.35	26.69	20.56	24.84	24.48	24.50	25.52
CaO .....	3.14	4.18	3.52	12.60	5.93	3.10	4.09	3.78
Na <sub>2</sub> O .....	} 0.15	} 0.10	0.14	—	0.08	0.13	0.04	0.29
K <sub>2</sub> O .....			0.08	—	0.00	1.00	0.13	0.25
P <sub>2</sub> O <sub>5</sub> .....			0.00	0.00	0.00	—	0.29	0.05
H <sub>2</sub> O+ .....	4.72	4.02	4.03	2.47	5.04	6.35	3.63	6.88
H <sub>2</sub> O— .....	0.07	0.00	0.11	0.00	0.02	0.00	0.00	0.00
Cr <sub>2</sub> O <sub>3</sub> .....	0.48	0.10	—	—	—	0.15	0.54	0.11
NiO .....	0.24	0.20	—	—	—	0.16	0.02	0.33
S .....	0.05	0.10	—	—	—	0.09	0.14	0.48
—O=S .....	100.44	100.68	99.65	100.03	100.13	99.45	99.83	99.84
	0.02	0.05				0.04	0.07	0.24
	100.42	100.63				99.41	99.76	99.60

## Atomic percentage

Si .....	47.72	53.77	52.36	—	36.12	40.09	36.72	43.59
C .....	3.37	0.00	0.00	—	11.85	5.31	10.18	0.00
Al .....	4.46	0.90	2.57	—	4.00	9.12	7.66	8.71
Mg .....	35.80	36.19	36.98	—	33.80	34.21	33.27	36.48
Fe .....	4.90	4.52	4.09	—	7.93	6.25	7.61	5.88
Ca .....	3.09	4.13	3.51	—	5.80	3.11	3.99	3.88
Mn, Ti, Ni etc. ....	0.60	0.49	0.49	—	0.50	1.01	0.57	1.46
	100.00	100.00	100.00	—	100.00	100.00	100.00	100.00

## Mineral composition. Weight percentage

Talc .....	77	63	68	—	—	56	51	27
Calcite .....	6	0	0	—	—	0	0	0
Dolomite .....	0	0	0	—	—	9	17	0
Amphibole .....	0	32	28	—	—	0	0	28
Chlorite .....	11	2	0	—	—	32	29	42
Magnetite .....	6.0	2.5	3.6	—	—	1.0	1.7	1.0
Chromite .....	0.7	0.2	—	—	—	0.2	0.5	0.2
Pyrrhotite .....	0.1	0.3	—	—	—	0.2	0.1	1.3
	100.8	100.0	99.6	—	—	98.4	99.3	99.5

33. Soapstone. Siikalahti, village of Vuonisahti, Pieltisjärvi, Finland. Analysis by the author.  
 34. Soapstone. Kelvänsaari island in Lake Pielenen, Finland. \* \* \* \*  
 35. Soapstone. Lentiira, Kuhmo, Finland. \* \* \* \*  
 36. Tremolite separated from the Lentiira soapstone (above). \* \* \* \*  
 37. Soapstone. Schuyler, Virginia, U. S. A. Analysis by R. B. Ellestad (Hess 1933 b, p. 398).  
 38. Soapstone. Holden Quarry, Chester, Vermont, U. S. A. Analysis by the author.  
 39. Soapstone. Grafton, Vermont, U. S. A. \* \* \* \*  
 40. Soapstone. Frances Town, New Hampshire, U. S. A. \* \* \* \*

Table I. (continued)

Number	41.	42.	43.	44.	45.	46.	47.	48.
Weight percentage								
SiO <sub>2</sub> .....	56.78	42.24	43.94	51.18	58.28	51.77	29.87	37.07
CO <sub>2</sub> .....	0.00	12.55	6.11	2.14	0.09	tr.	23.17	18.35
TiO <sub>2</sub> .....	0.04	0.05	0.21	0.19	—	—	0.00	—
Al <sub>2</sub> O <sub>3</sub> .....	2.65	2.12	3.99	3.18	0.83	1.93	0.76	2.40
Fe <sub>2</sub> O <sub>3</sub> .....	3.97	4.33	10.72	3.93	0.30	3.74	1.14	2.45
FeO .....	3.89	3.02	1.44	5.18	5.24	3.53	5.06	3.49
MnO .....	0.06	0.09	0.07	0.13	0.05	—	0.03	—
MgO .....	28.20	29.90	29.40	26.80	29.43	29.30	35.90	33.25
CaO .....	0.86	3.40	0.17	3.14	0.13	0.10	0.26	0.68
Na <sub>2</sub> O .....	0.04	0.00	0.00	0.07	—	tr.	0.00	—
K <sub>2</sub> O .....	0.11							
P <sub>2</sub> O <sub>5</sub> .....	0.16	0.00	0.00	0.10	—	—	—	—
H <sub>2</sub> O+ .....	3.20	2.29	3.39	3.85	5.03	5.92	3.63	2.81
H <sub>2</sub> O— .....	0.00	0.00	0.06	0.04	0.19	0.08	0.02	0.18
Cr <sub>2</sub> O <sub>3</sub> .....	0.11	0.32	0.63	0.49	0.25	0.40	0.10	—
NiO .....	0.27	0.20	0.19	0.26	—	—	—	—
S .....	—	0.03	0.04	0.06	0.55	—	—	—
—O=S .....	100.34	100.54	100.36	100.76	100.37	99.83	99.94	100.68
		0.01	0.02	0.03	0.28			
		100.53	100.34	100.73	100.09			

## Atomic percentage

Si .....	51.84	36.43	39.93	47.15	54.48	51.43	24.58	30.00
C .....	0.00	14.77	7.58	2.69	0.11	0.00	26.13	20.88
Al .....	2.85	2.16	4.27	3.45	0.91	2.13	0.73	2.35
Mg .....	38.35	38.42	39.79	36.78	41.15	41.21	44.18	41.29
Fe .....	5.63	4.83	7.90	6.25	3.18	5.13	4.13	3.97
Ca .....	0.84	3.14	0.16	3.10	0.13	0.10	0.23	0.61
Mn, Ti, Ni etc. ....	0.49	0.25	0.37	0.58	0.04	0.00	0.02	0.00
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

## Mineral composition. Weight percentage

Talc .....	87	64	65	78	—	—	—	—
Calcite .....	0	0	0	5	—	—	—	—
Dolomite .....	0	11	0	0	—	—	—	—
Magnesite .....	0	14	12	0	—	—	—	—
Chlorite .....	8	5	11	10	—	—	—	—
Magnetite .....	4.7	5.9	11.3	5.2	—	—	—	—
Chromite .....	0.2	0.5	0.9	0.7	—	—	—	—
Pyrrhotite .....	—	0.1	0.1	0.2	—	—	—	—
	99.9	100.5	100.4	98.9	—	—	—	—

41. Soapstone. Godthaab, SW-Greenland. Analysis by the author.  
 42. Soapstone. Lalm, Ottadalen, Norway. \* \* \* \* \*  
 43. Soapstone. Strömsås, Tynset, Norway. \* \* \* \* \*  
 44. Soapstone. Händöl, Jämtland, Sweden. \* \* \* \* \*  
 45. Soapstone. Muruhatten, Frostvikén, Jämtland, Sweden. Analysis by R. Blix (Du Rietz 1935, p. 182).  
 46. Soapstone. Laisholm, Tärna, Västerbotten, Sweden. Analysis by R. Blix (Du Rietz 1935, p. 211).  
 47. Soapstone. Laisholm, Tärna, Västerbotten, Sweden. Analysis by R. Blix (Du Rietz 1935, p. 209).  
 48. Talc magnesite schist. Bonatchesse, Val de Bagnes, Wallis, Switzerland. Analyst T. J. Woyno (Niggli etc., 1930, p. 175).



Table I. (continued)

Number	57.	58.	59.	60.	61.	62.	63.	64.	65.
Weight percentage									
SiO <sub>2</sub> .....	32.35	43.46	35.09	32.88	31.43	30.06	29.00	37.48	46.33
CO <sub>2</sub> .....	22.39	12.01	19.29	22.85	23.33	20.88	23.72	16.10	11.59
TiO <sub>2</sub> .....	0.00	tr.	0.01	tr.	tr.	0.04	0.00	0.00	tr.
Al <sub>2</sub> O <sub>3</sub> .....	0.81	1.19	1.16	0.72	2.02	1.98	0.91	0.95	2.07
Fe <sub>2</sub> O <sub>3</sub> .....	2.13	1.05	1.94	1.16	2.35	3.74	3.56	2.59	0.37
FeO .....	4.50	1.19	3.98	4.73	3.13	3.80	2.86	1.64	1.45
MnO .....	0.10	0.06	0.08	—	0.06	0.19	0.05	0.06	0.02
MgO .....	34.42	35.65	34.63	34.97	35.37	34.70	35.95	35.86	33.50
CaO .....	0.00	0.00	0.00	0.00	0.00	0.15	tr.	0.03	0.02
Na <sub>2</sub> O .....	} 0.10	} 0.10	0.00	—	0.10	0.02	0.08	0.06	} 0.16
K <sub>2</sub> O .....			0.00	—	0.04	0.08	0.07	0.09	
P <sub>2</sub> O <sub>5</sub> .....	0.00	0.00	0.00	—	0.00	0.00	—	0.00	0.00
H <sub>2</sub> O+ .....	2.95	5.28	3.11	} 2.59	1.79	3.20	2.26	4.69	4.83
H <sub>2</sub> O- .....	0.04	0.03	0.08		0.00	0.04	0.04	0.07	0.14
Cr <sub>2</sub> O <sub>3</sub> .....	0.24	—	0.35	n. d.	0.49	0.43	0.28	0.37	tr.
NiO .....	0.23	0.24	0.20	0.28	0.27	0.23	0.25	0.27	0.18
S .....	0.09	—	—	0.02	—	0.00	—	0.05	—
—O=S .....	100.35	100.56	99.92	100.20	100.38	100.44	99.93	100.31	100.66
	0.05			0.01				0.03	
	100.30			100.19				100.28	
Atomic percentage									
Si .....	26.82	37.20	29.02	26.95	25.58	25.85	24.46	31.90	39.80
C .....	25.34	14.03	21.77	25.56	25.92	23.80	26.49	18.70	13.59
Al .....	0.80	1.20	1.13	0.70	1.94	1.95	0.87	0.95	2.09
Mg .....	42.51	45.45	44.15	42.68	42.89	43.15	43.81	45.47	42.87
Fe .....	4.14	1.74	3.73	3.92	3.25	4.72	3.97	2.52	1.28
Ca .....	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.02	0.02
Mn, Ti, Ni .....	0.39	0.38	0.20	0.19	0.42	0.40	0.40	0.44	0.35
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

The analyses 57—65 are taken from the collection of analyses published by Alimarin and Romm. (1935, pp. 59—61).

57. Soapstone. Talowski Mountains, Miask, S-Ural.  
 58. Soapstone. Mramorskoje quarry, Ural.  
 59. Soapstone. Skitskaja Mountains, Nischnisetski, Ural.  
 60. Soapstone. Schabrovskoje quarry, Ural.  
 61. Soapstone. Schabrovskoje Mountains, 30 kilometers south from Sverdlovsk, Ural.  
 62. Soapstone. Sjrostanskoje quarry, S-Ural.  
 63. Soapstone. Mramorskaja, Central-Ural.  
 64. Soapstone. Lake Iltsehir, Sajanski Mountains, Burjato-Mongolian Republic.  
 65. Soapstone. " " " " " "



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