

PETROLOGY OF THE NORTHERN ADULA REGION, SWITZERLAND (WITH PARTICULAR REFERENCE TO THE GLAUCOPHANE-BEARING ROCKS)

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PREFACE

In 1954 Professor Dr E. Niggli offered me the opportunity of doing fieldwork in the northern Adula region in Switzerland, the country that may well be called the cradle of Alpine geology. From then on his keen interest in my work and his constant support have been an important stimulant.

On the completion of this work I wish to express my gratitude to all those who so kindly gave their advice, support and help.

This work, originally taken up with the invaluable assistance of Professor Dr E. Niggli, found its completion under the guidance of Professor Dr W. P. de Roever. Hence it bears the traces of a felicitous combination of two different ways of approach and investigation.

Fieldwork was carried out under the supervision of Professor Dr E. Niggli. In preparatory work on the geological maps and the chapters I and II he offered valuable advice, he gave the manuscript in question a thorough reading and was so kind also to comment on the other chapters.

The "Kraftwerk Zervreila A.G." and the "Ingenieurbüro Kälin" gave all possible assistance during the mapping of fresh outcrops on their building sites. For this help I am particularly indebted to Mr A. Capaul, C. E.

The inhabitants of Vals did their utmost to make the stay of our team quite unforgettable. In this respect I wish to remember particularly the Burgomaster of Vals, Mr O. Schmid, the Schnyder family of the Alpina hotel and Mr Jos. Schmid and his family. Mr P. Floor, Mr W. F. H. Pilaar, Mr J. P. Engels and Mr I. B. H. M. Rubbens, students of the Leiden State University, Geological Department, were pleasant company during the days in the field.

The laboratory investigations were mainly carried out at the Leiden Geological and Mineralogical Institute under the supervision of Professor Dr W. P. de Roever. I benefited greatly from his experience in dealing with glaucophane-bearing rocks and from the methods of investigation he developed in this special field. Moreover he very kindly put at my disposal the unpublished material of his exhaustive studies of the literature on glaucophane- and lawsonite-bearing rocks, as well as the results of his own investigations on glaucophane- and lawsonite-bearing rock-specimens from various localities. The results could only partly be inserted in chapters VI and VII.

The University of Bern enabled me to study the crystallography of the mineral chloritoid and also gave me an opportunity to get acquainted with the geology of Switzerland, by offering me twice a scholarship, during which time I worked at the Mineralogical and Petrographical Institute of this University.

Professor Dr W. K. Nabholz, with his vast knowledge of the geology of

the northern Adula and its Mesozoic cover, critically examined the blue-prints for the geological maps, and gave valuable advice during the fieldwork.

I am indebted to Professor Dr Th. Hügi who made three chemical analyses of minerals and some partial analyses of manganese contents of garnets. He moreover advised in dressing problems.

Professor Dr J. Cadisch was so kind as to put at my disposal a collection of rock samples, taken from the waterdrift Zervreila-Ampervreila-Peil.

Professor Dr A. J. Pannekoek, Professor Dr L. U. de Sitter, Professor Dr E. den Tex and Professor Dr I. M. van der Vlerk were so kind as to read parts of the manuscript.

Mr A. R. Bloemena M. E., of the Statistics Department of the Mathematical Centre, Amsterdam, kindly assisted me in handling the numerical data incorporated in chapter V. His Department controlled the calculations. I am indebted to him for guiding my first steps in the interesting field of statistics.

Dr E. Kündig kindly supplied supplementary data on the distribution of glaucophane.

The material incorporated in this work has been partly taken from the fieldwork done by my friends and colleagues Dr R. O. Müller of Bern University and T. H. Tan, geol. drs. Our close cooperation during the field campaigns and in the laboratory and the numerous vivid discussions led to results and conclusions of which it is hard to tell the parentage.

Miss Dr E. Jaeger of Bern University expertly carried out a T. G. A. and a D. T. A. analysis of the mineral chloritoid.

Mrs Dr C. M. de Sitter—Koomans and Miss H. M. I. Bik prepared a number of chemical analyses of rocks and minerals.

I am most grateful for the warm interest and help of friends and colleagues of the Institutes of Bern and Leiden. They were of the greatest value for the preparation of this paper.

The "Sikkens Lakfabrieken N. V.", Sassenheim, Holland, put their International Business Machines Equipment at my disposal for preliminary investigations, the results of which are given in chapter VI. I am indebted to Mr C. A. Rol and Mr A. M. A. Eggen for their assistance while using these sorting and tabulating machines.

Mr M. Snoep skilfully assisted in preparing the English text, he spent hours correcting and reformulating. Mr R. Cope kindly read the chapters I, II and VII.

Finally I wish to thank the personnel of both the Bern and the Leiden Institutes for large and small services. Mr J. Bult has expertly illustrated the text. He also drew the maps. Mr J. Hogendoorn carefully prepared the microphotographs. Mr A. Verhoorn of Leiden University and Mr H. Huber of Bern University made numerous X-ray photographs. Thin sections were prepared by Mr M. Deijn, Mr H. Huber and Mr C. J. van Leeuwen.

CHAPTER I

INTRODUCTION

The northern part of the Adula region, which will be the subject of discussion in this paper, is a part of the canton of Graubünden in the south-east of Switzerland. This northern Adula region comprises the Valsertal. The main village in this valley is Vals (about 1000 inhabitants), a rather old settlement of Walliser colonists. The Valsertal is one of those forgotten areas, isolated by their geographical position, which are not affected by main roads. The upper end of the valley as well as its slopes are barred by high mountains (about 3000 m).

In the 15th century the Walliser colonists entered the Valsertal from Hinterrhein, along a track leading over the pass of the Valserberg and farther along the sites where now the settlements of Valatsch Alp and Auf der Matte are situated (see geological map). It is highly probable that this track was for centuries the most important link with the outer world, because Hinterrhein, the last stage on the northern side of the pass of San Bernardino, was a good market to sell butter and cheese. Corn, salt and wine formed the main exchange products. The Valser dairy farmers and herdsmen preferred to travel by this difficult track rather than to follow the Valserrhein to the north, having to pass through Rhaeto-Roman territory, to the town of Ilanz, the first town on the river Rhine. Between the years 1920 and 1930 the motor road from Vals to Ilanz was constructed and this road considerably improved the accessibility of the Valsertal. The presence of a warm spring in Vals ($\pm 300,000$ l/day at 25°C) led to the building of a small "Kurhotel". The water is rich in iron and calcium sulphates.

One of the most important watersheds in Europe, viz the one between the drainage areas of the river Rhine and of the river Po, cuts through the central part of the northern Adula region. The pass of San Bernardino, already mentioned, and the Rheinwaldhorn or Adulahorn, from which springs the Valserrhein, form parts of this watershed.

The "Raeten", an unruly clan inhabiting these regions, caused the Roman emperor Augustus so much trouble, that they were subjugated in 15 B. C. To maintain their supremacy in these parts the Romans constructed roads and strongholds in this rough country. From that time on, the road crossing the pass of San Bernardino became one of the main roads in Europe. Another part of this vital north—south road is the well-known Via Mala. Along this road the transport of goods, consisting mainly of military equipment, textiles, wine, dairy products and corn, was carried out by "Säumer" over those sections that could not be used by carts. The construction of tunnels and roads in the 19th and 20th centuries, greatly detracted from the importance of this road.

For centuries, however, this road was one of the main European highways and consequently the Adula region has been a closely concerned

party to the development of European economy and has been involved in many a war.

For a more extensive survey of the history of this region and especially that of the Bernardin pass, the reader is referred to the booklet *San Bernardino-Strasse*, edited by the Swiss Post Office, Bern.

Switzerland is covered by a number of excellent maps, 1:50.000, edited by the "Landeskarte der Schweiz". The region of our geological mapping is to be found on sheets No 513, 514, 533, 534. For our purpose the edition 1947 and 1949 were used, but a later edition 1955 has already been issued of No 257, the sheet covering No 513 and No 514.

The grid of these maps will be used throughout this paper in order to denote localities and is consequently to be found on the geological map. As topographical basis for the simplified structural and geological map of the surroundings of the mapped area, another issue of the same Office, mentioned above, was used, viz the "Reduzierte Generalkarte der Schweiz, 1:300.000; Provisorische Ausgabe 1956". This map is also of outstanding quality. Availability of such reliable maps made mapping of this region quite easy. As a result the localities of outcrops could be given within an accuracy of about 10 m.

GEOLOGICAL SETTING

The Adula region is for the greater part occupied by a large structural unit, the so-called Adula Nappe. The Adula Nappe is one of the Pennine Nappes. According to Staub (1951) the Penninides, see map I, form a belt running from the north-east of the isle of Corsica — the region around Bastia — alongside Genoa in Italy, W of Turin, E of the Mont Blanc Massif, where it curves to the E and runs through the south of Switzerland as far as Chur. Near Chur the deepest parts of this zone are exposed. In the region of the eastern Swiss border the Penninides are covered by higher tectonic units, but they turn up once more in this region in a tectonical window, the "Engadin Window". Farther on, the upper parts of the zone reappear in the Tauern region in Austria and finally it may be found between Vienna and Graz, cf. Staub (1951).

The structure of the Penninides has a.o., been described in English by Bailey (1935) and by Collet (1927) and has recently received brief treatment by de Sitter (1956). A recent description is to be found in the "Geologie der Schweizer Alpen" by Cadisch (1952). The belt can roughly be divided into the Upper, Middle and Lower Penninides. The Adula shows partly the characteristics of the Lower Pennine units, viz of the Lepontinic region, cf. Wenk (1956, p. 252), partly those of the Middle ones.

The Adula Nappe crops out between Vals (Platz) — 30 km south of Ilanz — and an imaginary line between Bellinzona and the Lago di Mezola, the northern extension of the Lago di Como in Italy.

The area of detailed field investigations comprises the north-eastern part of this unit, between the arêtes of the Frunthorn and the Schwarzhorn on one side and the Peilerbach and the Fanellahorn on the other. The river Valserrhein intersects this area in a SW—NE direction.

As an illustration of the immediate surroundings of the Adula Nappe, the author has ventured to draw a map of these surroundings in black and red shading (map II); black to denote a highly simplified lithological differ-

entiation, red showing the outlines of the larger structural units (N.B. the notation Mesozoic sediments should read Mesozoic sediments and Permian and Carboniferous sediments of the Helvetian zone). From this map it appears that our area, south of Vals Platz, is part of a large structural unit, viz the Lower Penninides. A subdivision of the Lower Penninides has not been given. A useful subdivision may, a.o., be found in a paper written by Staub (1958). Provisionally the author prefers to consider this region as a whole, in accordance with Wenk (1956a, p. 93, fig. 3 and 1956b). Moreover, this map illustrates that the southern part of the Lower Penninides is mainly built up by metamorphic rocks, viz gneisses, mica-schists, amphibolites and calcareous rocks and schists, assumed to be partly of pre-Alpine, partly of Alpine age, cf. Wenk (1956). Wenk assumes that through the action of Alpine mobilization and granitization the mineralogical composition of the greater part of these rocks came into being during the Alpine period. Therefore it is hardly possible to consider these rocks to be of pre-Alpine age. Among them granodiorites are found that are assumed to be the products of late kinematic Alpine intrusion and of granitization, e.g., the Cocco granodiorite, cf. Kündig (1934, 1936). The northern extension of the Lower Penninides is formed by Mesozoic sediments, mainly "Bündnerschiefer". North of the Lower Penninides are drawn the outlines of the Gotthard Massif and of the Aar Massif (N of the Gotthard Massif), together with the "Tavetscher Zwischenmassiv". These massifs are mainly built by metamorphic and intrusive rocks, presumably of Hercynian origin. On the map they are not shaded in red. The Gotthard and Aar Massifs are surrounded and partly covered by Mesozoic rocks of the Helvetides. These Helvetides consist of autochthonous and parautochthonous sediments and real nappes of Mesozoic sediments.

East of the Lower Penninides the Middle and Upper Penninides are represented. They comprise the Tambo and the Suretta Nappe. The northern part of the Tambo Nappe, cf. Gansser (1937), is lithologically more or less comparable to the northern Adula region. Further to the east and to the south the metamorphic rocks as well as the Mesozoic sediments usually show different characteristics. Within these Middle and Upper Penninides is situated the late Alpine Bergell intrusive-mass, consisting of granites and allied rocks, mainly porphyritic biotite granites and tonalites. The Melirola Tonalite of Val Morobbia, east of Bellinzona, is thought to be connected with this Bergell Massif, cf. Cadisch (1952, p. 71).

The Highest Penninides* and the Lower Austrides** cover the units mentioned before. The eastern parts of the Upper Penninides and the Highest Penninides are rich in ophiolites and greenschists. Among these mafic rocks serpentinites are occasionally found, representing former peridotites; this holds true for the rather large greenschist masses of the Platta Nappe and the rather large greenschist and serpentinite masses of Malenco, north of Sondrio.

The higher structural units, the Middle and the Upper Austrides, are roughly sketched on the right-hand side of the map, together with the outlines of a part of the Engadin Window. East of Davos, the metamorphic

* The name Highest Penninides in this description is used as a translation of the German name "Hochpenninikum".

** The name Austrides in this description is used as a translation of the German name "Ostalpin", so Lower Austrides stands for "Unterostalpin".

rocks of the Silvretta unit as well as those of the Oetzal unit, in the immediate surroundings of St. Maria, are visible, mainly consisting of mica-schists, paragneisses, orthogneisses and amphibolites, presumably of pre-Alpine age. Within the Engadin Window the pre-Alpine Tasna granite is situated. In the same area large regions are covered with metamorphic Palaeozoic sediments. Such rocks are not denoted elsewhere on the map, because of rather complicated alternations, that made it difficult to introduce a lithological differentiation on this scale. The mica-schists of the Adula Nappe for instance may be assumed to represent Palaeozoic sediments.

South of the units described, an important compressive zone, viz the Insubric line is found. For a brief discussion of the theories concerning this line, the reader is referred to Cadisch (1952, a. o., p. 428) or for a description in English to de Sitter (1956, p. 177—179). It is not only a zone of compression, but also one of dislocation, separating two larger structural units within one mountain system. This Insubric line has been roughly drawn as a red line. The rocks south of this line have not been shaded in red, because they do not concern us in the present paper.

In addition the map shows locations of the minerals glaucophane, crossite and other sodium-amphiboles, the presence of which will be discussed in chapter VII.

For further information on structural and lithological features of these regions, the reader is referred to the papers of Cadisch (1952), Hess (1953), Nabholz (1954), Staub (1949, 1951, 1958) and Wenk (1948, 1953, 1955, 1956 a & b).

The greater part of this simplified map is covered by the sheets 7 and 4 of the "Geologische Generalkarte der Schweiz" 1:200.000. The author is indebted to Professor Dr W. K. Nabholz for permission to use the still unedited structural maps 1:750.000 and cross-sections 1:250.000, that will be published later as parts of the explanatory booklets accompanying each sheet, edited by the "Schweizerische Geologische Kommission".

HISTORICAL REVIEW

Kopp (1923), Nabholz (1945) and Müller (1958) have written excellent surveys of the work done by former investigators. Therefore it suffices to give a review of only the most important papers. The development of the views held by different authors concerning the northern part of the Adula Nappe, is closely connected with the advancement of the theories concerning the origin of the Alpine structures.

Albert Heim (1891) regarded the Adula as a remarkably regular vault of sedimentogenic origin, because of the concordant structures of the metamorphic rocks. The marbles and dolomites between the gneisses, mica-schists and amphibolites are according to him normal stratigraphical intercalations and for all these rocks he assumed a Palaeozoic age. Some structural phenomena, however, needed a different explication and he had already spoken about "in folding" of the Triassic dolomites to explain the folds of a dolomitic rock on the pass of Sorreda. With this paper the first phase of the reconnaissance of this part of the Alps comes to an end.

With the "Nappe theory" a new period started. Bertrand (1884) was the first who tried to explain the well-known double fold of the "Glarner Alps" by a process of overthrusting. This theory was worked out by

P. Termier, M. Lugeon and others and as early as 1906, Heim applies this hypothesis to the Adula, while drawing a new set of sections through the Alps. From this moment on the Adula was considered to represent a nappe. Wilckens (1907) argued that the dolomitic rocks in the Adula are of Triassic age and Schardt (1906) drew a section through the northern part of the region, on which for the first time the so-called "Rückfaltung" (backfolding) of the northern part of the Adula Nappe could be seen. From then on a number of papers dealt with the intensive folding of this area. In the field of mineralogy the first paper came out in 1917 and in it Königsberger gave a list of the minerals found in the neighbourhood of Vals, a village well-known for the fine mineral specimens collected by the local "rockhounds", called "Strahler".

The first important papers dealing with the petrography came from Schmidt (1891) and Roothaan (1919). The latter author abandoned the idea of a sedimentogenic origin for all the rock types by explaining some phenomena as a consequence of injection of aplitic or granitic material in a formation of mica-schists. Later, according to Roothaan, the mass of rocks was folded and divided into several units thrust over each other. At this time a main subject of the Alpine literature was the possible correlation of the different nappes in the Alpine chain. Leaders in this field were E. Argand, M. Lugeon, R. Staub and H. Preiswerk. At the same time an extensive paper concerning the region around Vals appeared (Kopp 1923). In this dissertation a detailed description of the field-data was given for the first time. Furthermore the paper dealt exhaustively with the structural problems and ventured a petrographical description of the rocks. It supplied the first detailed map of the northern Adula and this map is, apart from a few minor details, still up to date. The subdivision of the Adula Nappe, defined by Kopp, is still in use today. He was the first to acknowledge the importance of the body of gneisses in the neighbourhood of Zervreila, which he considered as a laccolite of granitic to granodioritic composition. The age of intrusion was assumed to be Upper Carboniferous. The mica-schists were assumed to represent sediments of Carboniferous origin. The origin of the amphibolites was not solved and he closes his chapter on the amphibolites with the words:

"Wir haben also in der Aduladecke wahrscheinlich vier Arten von Amphiboliten:

paläozoisch-eruptive,
paläozoisch-sedimentogene,
mesozoisch-eruptive,
mesozoisch-sedimentogene."

For a long time afterwards it was thought that no more problems were hidden in the Adula, although from a study of Kopp's paper it could easily be seen that the difficulties only had just begun. In 1945 Nabholz tried to solve one of these problems. In an extensive paper he discussed the Mesozoic cover of the metamorphic rocks of the Adula. He succeeded in bringing order into the chaotic "Bündnerschiefer" formations that are heaped on the metamorphic basement. The Liassic nature of some of these schists is confirmed by fossil data and he unravels the tectonical and stratigraphical structure of this part of the area. Besides he is the first to mention the occurrence of real glaucophane in this region (the glaucophane of Schmidt, 1891, probably being a blue-green amphibole). He corrects a misunderstanding

ing of Kopp as to the nature of the plagioclase and his arguments make plausible the intrusive character of the greater part of the ophiolites. This thesis could be said to mark the end of the second phase of the study of the Adula Nappe.

The third phase is introduced by the papers of Bearth, Wenk and others. Although the contents of these papers have no direct bearing on our region, they are valuable for the light they throw on the petrographical and structural nature of the area under discussion. Both authors emphasize the importance of the Alpine metamorphism as well as the influence of Alpine processes on the structural behaviour of the rocks. Bearth (1945) discusses the influence of albitization and recrystallization on the older rocks and the possible existence of intrusive rocks of post-Hercynian age in the metamorphic formations of the Monte Rosa. It should be mentioned, however, that he discarded this revolutionary view in 1952. French geologists, e.g. Michel (1953), stress the influence of Alpine metamorphism in dealing with the genesis of the crystalline schists of the Gran Paradiso and the Sesia-Lanzo Massifs.

Continuing the work of Wegmann, Wenk recognizes infrastructural phenomena in the southern Tessin region. He ventures the conclusion that in these Tessin gneisses, the deepest parts of the Penninides, the role of Alpine processes may be far more important than was formerly thought. Moreover, he discusses the possibility of recognising structures and mineral assemblages of pre-Mesozoic age, because tectonic movement as well as metamorphic and metasomatic activity during the Alpine period practically obliterated evidence of an older origin. Furthermore the pre-Mesozoic granitoid rocks might have undergone Alpine mobilization causing a renewed intrusion afterwards.

Müller's thesis (1958) points in the same direction as the works of these authors, when he claims the possibility of a post-Hercynian origin for the gneisses. The present paper should be judged in the light of these developments.

INVESTIGATIONS OF THE PRESENT AUTHOR AND DELIMITATION OF SOME PROBLEMS IN THE NORTHERN ADULA

As a result of our mapping some field observations lead to interpretations that are different from those of Kopp (1923). These results of a structural and geological nature are included in chapter II.

Vals is rather famous for being rich in beautiful specimens of Alpine fissure minerals and of rare rock-making minerals. An investigation of the region around this hospitable Alpine village would be incomplete without a description of some fine mineral specimens collected there, a. o., chloromelanite, chloritoid and ferrian phengite.

In the previous section, the development of the ideas concerning the age and origin of the rocks in the northern Adula region and concerning the structure of this area, was briefly described. From this historical review it will be clear that a great number of questions still remain unanswered. The author mainly investigated the characteristics and the age of the metamorphism in this region. Further, the genesis and the age of the original material of the phengite-gneisses and of the amphibolites will be discussed. For a better understanding of these questions we had to investigate:

- a. the physical and chemical properties of the rock-making minerals;
- b. the frequency of the occurrence of these rock-making minerals in the region and in different groups of rocks;
- c. the quantitative mineralogical composition of the different groups of rocks;
- d. the quantitative chemical composition of the different groups of rocks;
- e. the variability of both mineralogical and chemical composition within one group;
- f. the distribution of several minerals, especially of glaucophane s.l., in other parts of the Alps.

To obtain information about the various points listed above, the following methods were used, apart from the current ones:

1. Point counter analysis
2. Statistical analysis
3. Sorting and tabulating methods with the aid of an International Business Machines equipment.

Our material could not be subjected to point counter analysis without having solved the question about the minimum number of points that have to be counted under the given circumstances (structure, grain size, number of components, occurrence of periodic trends, etc.) in order to reach a reasonably accurate result to which elementary statistical formulae can be applied. For this reason some properties of point counter analysis were investigated, and are reported in chapter V.

Concerning the characteristics and the age of the metamorphism, a microscopical investigation of the rocks in this region directly revealed two striking points. First the mica-schists, the Mesozoic sediments and the amphibolites may hold sometimes more than 12 different minerals in one section. Secondly the mineral glaucophane was found in ophiolites, amphibolites, mica-schists and Mesozoic sediments, whereas many samples of these rocks show a blue-green amphibole. Consequently the question arose whether these rocks underwent the influence of polymetamorphism comprising different phases, and whether they were influenced by sodium metasomatism. Moreover, the metamorphism in these regions is mainly of Alpine age, but may partly also be of Hercynian age. These questions will be discussed in chapters VI and VII.

The question concerning the origin and the age of the original material of the phengite-gneisses is connected with the occurrence of a kind of laccolithic mass consisting of more or less homogeneous rocks, with a granitic to granodioritic composition. Müller (1958) showed that this body is practically surrounded by amphibolites, see geological map. The age and origin of these gneisses, however, is still a matter of doubt. According to former authors, a.o., Kopp (1923), these gneisses are metamorphosed intrusive granites, the intrusion having taken place in the late Carboniferous. The ideas of Müller run more or less parallel to those held by Kopp and he reaches an ultimate conclusion when he writes (Müller 1958, p. 467):

"In den Phengitgneisen der nördlichen Adula scheinen granitoide Gesteine vorzuliegen, die schon voralpin vorhanden waren und welche durch die alpine Metamorphose vollständig umgeprägt wurden, so stark, dass es während der alpinen Orogenese lokal schon zu selbständigen Bewegungen der granitoiden Massen gegenüber ihrem starrerem Rahmen aus Paragneisen kam".

The same summary, however, contains also the following statement (p. 466):

“Im Laufe dieser Untersuchungen stellte sich aber auch die Frage, ob die heutigen Phengitgneise nicht erst alpin entstandene granitoide Gesteine sein könnten”.

Thus age and origin of these northern Adula gneisses were still a matter of doubt. They will therefore again be discussed in the following chapters, however, without reaching a definite conclusion.

The question concerning the origin and the age of the original material of the amphibolites has also been discussed by Kopp (1923) and by Müller (1958). The solution suggested by Kopp is more or less arbitrary. Müller's suggestion is based mainly on a large amount of field evidence and an additional investigation of a number of thin sections. He points to the fact that the amphibolites are always associated with phengite-gneisses, and may represent a basic border of these rocks. In his summarizing conclusions (Müller 1958, p. 467, last paragraph) he states that the origin of this basic border of amphibolites seems to be related to that of the phengite-gneisses, while the rocks of this basic border, i. e., the amphibolites, represent transformed mica-schists. There are, however, a few points — partly also mentioned by Müller — that are at variance with this hypothesis, which will be discussed in chapters V and VI, where a different origin is suggested.

It will be evident that the data now available are still insufficient to bring the problems outlined in the opening of this section to an ultimate solution. With reference to these regions Staub's words have lost nothing of their significance (Staub 1919):

“Hier an der Grenze von Bünden und Tessin harrt ein grossartiges Problem noch immer seiner Lösung”.

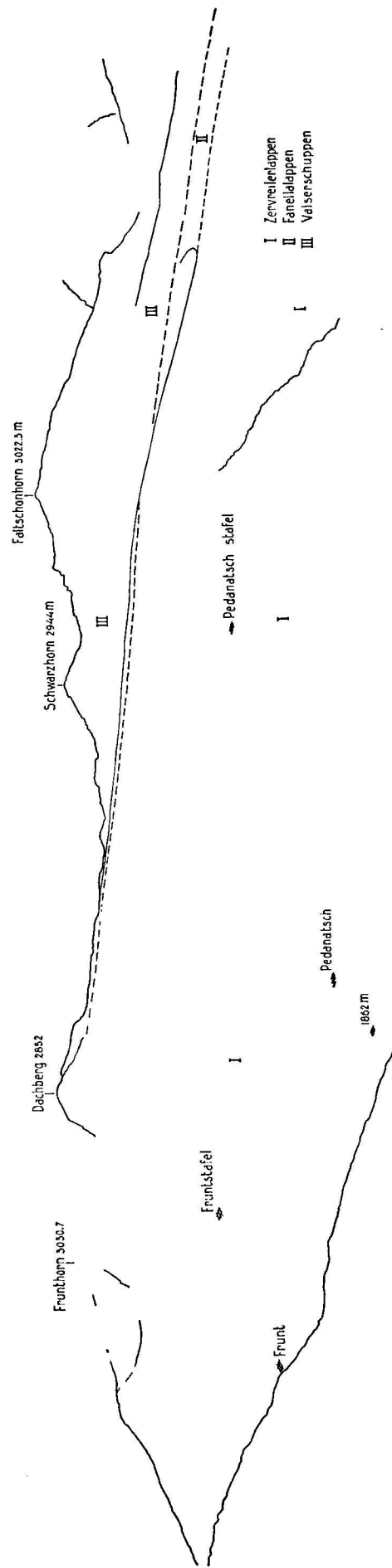


Fig. 1. The north-western slope of the Valserrhein valley, as seen from Ampervreila.

CHAPTER II

MORPHOLOGICAL, STRATIGRAPHICAL AND STRUCTURAL OUTLINES

The region mapped in detail by T. H. Tan, R. O. Müller and the present author measures about 70 km². In order to obtain a general view of this region, the reader is referred to the panorama-photographs of fig. 1 and 2, the little map on page 440 and the schematic block-diagram of fig. 3. Extensive descriptions of the geology of this region have been given by Roothaan (1918, 1919), Kopp (1923, 1933) and Nabholz (1945). From a stratigraphical and geological point of view, our mapping did not contribute substantially to the knowledge of the region. The main objective of our mapping was to throw some more light on petrographical and structural features.

The outlines of the mapped area are more or less morphologically determined; to reach neighbouring regions, high mountain passes have to be crossed and if one travels by road, journeys of over 50 km have to be made. It will be evident that the structure of this region is reflected by its present surface.

A splendid survey of the morphology of the drainage area of the river Rhine in this part of Switzerland has recently been given by Jäckli (1957). He deals intensively with the causes as well as with the results of mechanical, chemical and biogenic degradation. Such phenomena as "Auflockerung", "Hakenwurf" and other processes related with gravity and transport are analyzed. Part of his work is devoted to the morphology and the "Gegenwartsgeologie" (recent geological processes) of the northern Adula region. In view of Jäckli's work it seems adequate in a thesis dealing with the petrography of this region, to mark but a few outstanding features of the activity of gravity in cooperation with glaciers and water.

The scenery in this part of Switzerland is dominated by dissected and fretted arêtes, rugged peaks, both steep and gently undulating slopes, narrow cols and deep gorges. Some valleys still preserve the U-shaped profile of a glacial trough. The valley of the Peilerbach is a hanging valley, connected with the Valserrhein by way of a subsequently excavated gorge. The torrent at the western slope near Pedanatsch ends in a kind of hanging-valley-waterfall. Glacial cirques, barred by a rock-step and filled by a lake are found at the alps Ampervreila and Guralätsch. Below these cirques, terminal moraines and lateral moraines mark the different stages of the former glaciers. Roches moutonnées are everywhere to be found. After the glaciers had disappeared, the steep slopes and sharp ridges lost their support and gravity regained its full influence on these rocks. The consequences came suddenly and unexpectedly as rockfall; in other cases they came slowly but yet destructively in the form of creep of a large area, more aptly described by the German word "Sackung". The glacial cover of such "Sackung" regions often comes

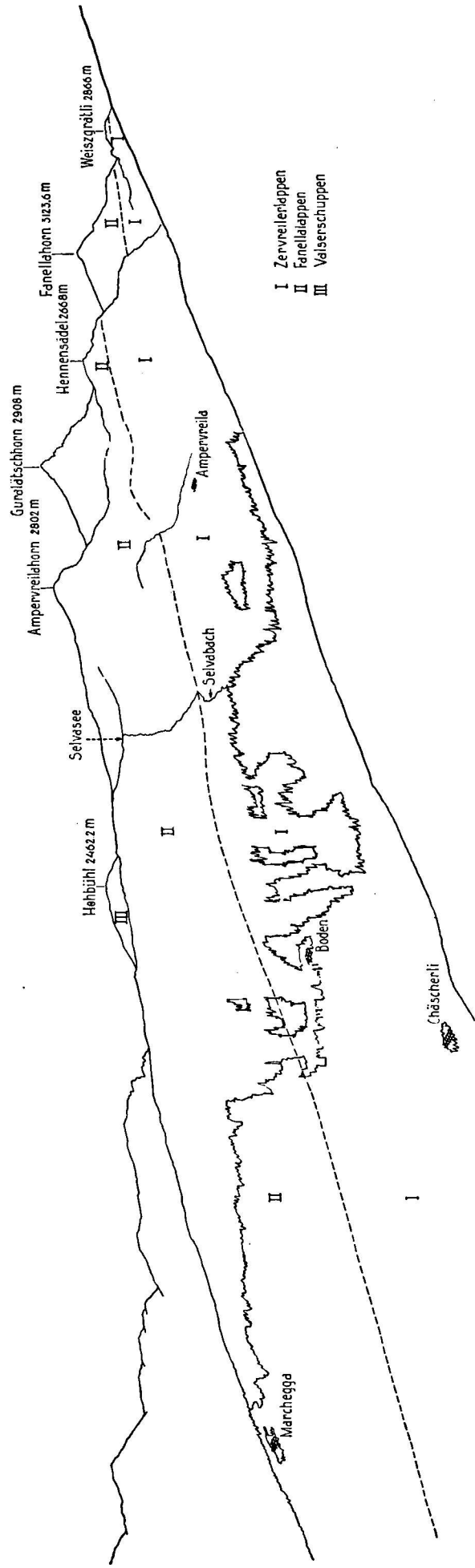
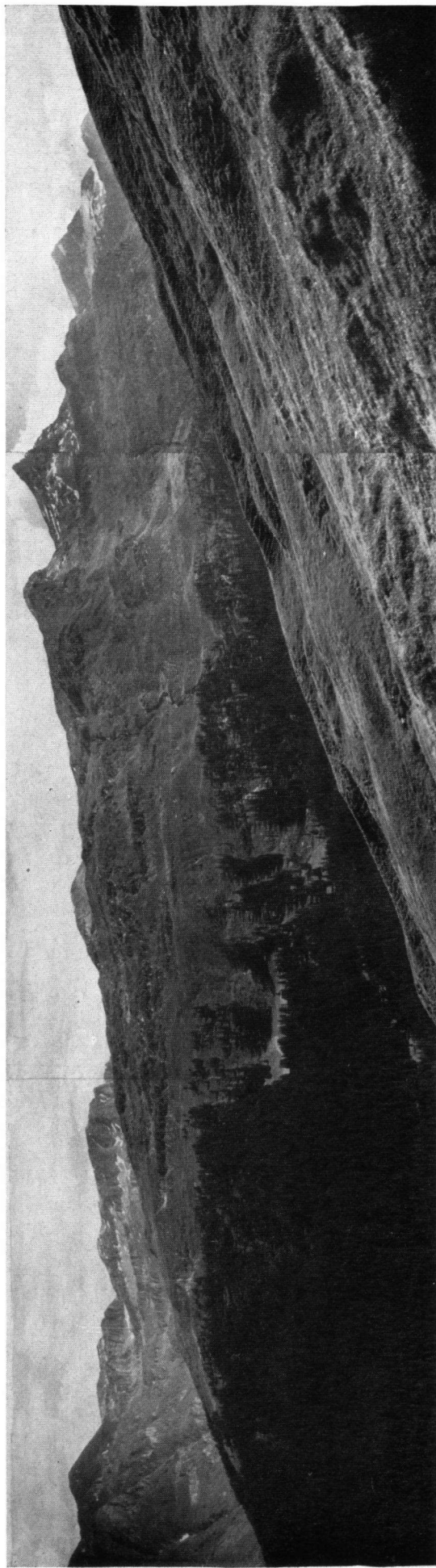


Fig. 2. The south-eastern slope of the Valserrhein valley, as seen from Stafelvi, coord. 7315—1614, alt. 1942 m. Note the dashed line on the sketch, indicating the zone of Mesozoic sedimentary rocks between the Fanella- and the Zervveilerlappen, holding chloritoid at the Weissgräbli and the Hennensadel.

down as landslides. Whenever these "Sackung" regions are below the timberline, pines, curved at the lower part of the trunk, are one of their typical features. This type of growth is called "Säbelwuchs" in German, a term that might be translated as scimitar growth.

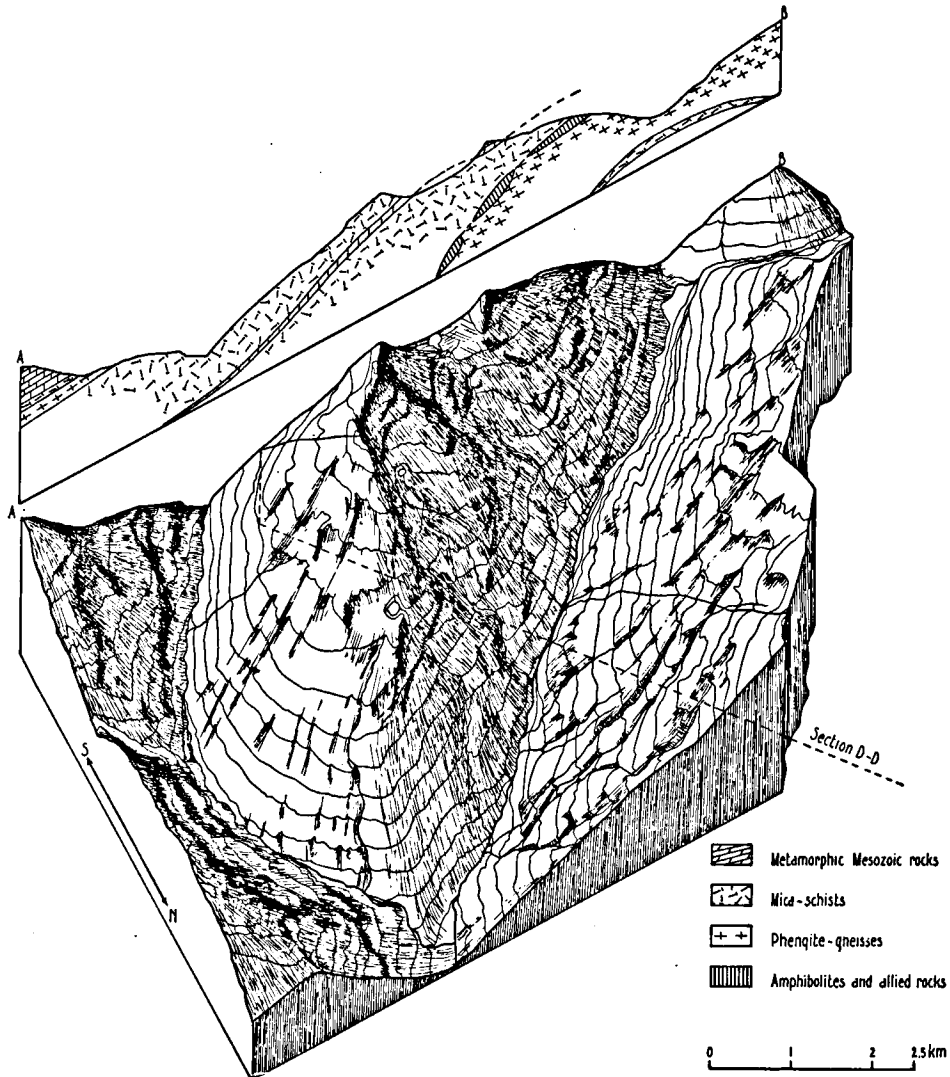


Fig. 3. Schematic block-diagram of the mapped region, seen from the NNE.
Section DD corresponds to fig. IV.

The mapped region is the drainage area of the Valserrhein, one of the head-waters of the Rhine. The river has its source at the Lenta glacier, on the northern slope of the Rheinwaldhorn. Its main tributaries are the Peilerbach and the Kanalbach, both coming from smaller glaciers, viz the Fanella

glacier and the remnants of the Kanal glacier, respectively. The glaciers show evidence of glacial retreat. At the tongue of these glaciers a ruin of large blocks, embedded in a thin sheet of ice is visible, covered with slope debris and a chaotic mass of lateral moraine. Glacier tables and debris cones are numerous on the tongues of these glaciers. The mouth of the Lenta glacier, from which spouts the milky torrent, is collapsed over a length of some 90 metres.

The valleys of the main rivers in this region, viz the Valserrhein and the Peilerbach conform almost perfectly to ideal valley types of geomorphologists. The Peilerbach is a subsequent stream with down-dip lateral migration, while the Valserrhein is a consequent river following the old glacier trough. The pre-glacial Valserrhein, carving a valley for this glacier to follow, was subsequent to the main joint-direction in the region. The following data illustrate the relief intensity of the region. The horizontal distance from Vals, alt. 1200 m, to the Frunthorn, alt. 3030 m, is about 8 km, resulting in a total declivity of 1830 m over a distance of 8 km. Another interesting example is found in the difference in altitude between the source of the Valserrhein at the Lenta glacier, alt. 2200 m and the place where it joins the Vorderrhein at Ilanz, alt. 700 m, showing a difference of 1500 m over a distance of 37 km.

Looking from Vals in a south-western direction, the region appears as a large dome, overlain by Mesozoic rocks, the remnants of which are still to be found, a.o. the Hohbühl. To the north-west and the east the surface of this dome dips under a formation of Mesozoic rocks. The dome itself is built by mica-schists, gneisses and amphibolites, whereas the covering rocks are dolomites, marbles and calcareous schists.

At first sight it seems as if the region consists of a practically undisturbed sequence of rock formations, gently dipping to the east and forming a regular vault; the older rocks, viz the schists and gneisses being overlain by younger calciferous sediments. Closer study reveals that appearances are deceptive and that a structural accumulation of different sheets, thrust over each other, builds up the region. The limiting surfaces of these sheets are more or less parallel to the bedding and to the schistosity. An intensive isoclinal folding is seen in some gneisses with EW or NS axes. The Mesozoic rocks generally do not show isoclinal folding, but the axes observed in the folds in these rocks have the same directions. Structural unconformities are occasionally seen between two sheets. The transition zone from one sheet to another is marked by a band of Mesozoic rocks, a zone of mylonitization, or both.

Kopp (1923) was the first to suggest a useful division in different sheets, for the purpose of structural description. This scheme — completed by Nabholz (1945) — of splitting up the region in several units, called "Lappen" or "Schuppen", was adopted by the author and follows here in order of occurrence from top to bottom.

- 1 Tomüllappen
- 2 Gravaserie
- 3 Aullappen
- 4 Obere Valserschuppen
- 5 Untere Valserschuppen

- 6 Fanellalappen
- 7 Zervreilerlappen
- 8 Mittlere Lappen der Aduladecke

As the units 1, 2 and 8 do not occur in the region under review, they are of minor importance for our purpose.

A few words about the characterization of the units. The Gravaserie and the Tomüllappen are built by Mesozoic sedimentary rocks and intercalated ophiolites. The Aullappen is mainly composed of marbles with a few ophiolite bands. The Upper and Lower Valserschuppen comprise, apart from Mesozoic rocks, some schists and gneisses, similar to those found in the lower units. The Fanellalappen, Zervreilerlappen and the lowest units (see 8), consist mainly of mica-schists, gneisses and amphibolites with an occasional dolomite or marble. From this description it is clear that the total amount of Mesozoic rocks of a unit decreases with increasing depth, while rocks occurring essentially in the lower units, viz non-calciferous mica-schists and gneisses, are seldom found in the three uppermost sheets. This does not imply that metamorphic rocks of presumably pre-Mesozoic origin are not found in tectonical units at a higher position than the above-mentioned Tomüllappen, Gravaserie and Aullappen. Non-calciferous mica-schists and gneisses, not belonging to the Adula Nappe, but to nappes at a higher structural position, are frequent in other parts of the Alps.

For a better understanding of the following, it is necessary to give a short description of the various types of rocks to be found in this region; an extensive description is given in chapter IV.

Rocks of presumed Mesozoic origin. — According to their genesis two types of rock have to be distinguished, viz rocks of sedimentary origin and rocks of igneous origin. The following *rocks of sedimentary origin* are found: dolomites, dolomitic marbles, rauhwackes (see also p. 519), marbles, calcareous and argillaceous schists, quartzites, calcareous quartzites and gypsiferous and anhydritic rocks. The calcareous and argillaceous schists just mentioned are called "Bündnerschiefer" by German and Swiss authors, after "Bünden" or "Graubünden", a canton in Switzerland in which these rocks are frequently found and in which the mapped area is situated. These sedimentary rocks underwent the influence of regional metamorphism. They occasionally bear garnet, glaucophane, microcline, chloritoid, kyanite, phlogopite and phengite as characteristic minerals.

The *ophiolites* (which are sometimes called "prasinites" or greenschists) are rocks of igneous derivation and are of intrusive origin, cf. Nabholz (1945). Some authors, however, favour an extrusive origin. The ophiolites are metamorphic rocks with a greenish grey colour, an arenaceous fracture plane and a small grain size (0.02 mm), occasionally showing the original ophitic or gabbroid structure. They occur within the Mesozoic rocks.

Gneisses. — The gneisses are thickly-bedded rocks, with a light greyish colour. The colour of the schistosity plane is greyish green, due to a green mica, viz phengite. They may have developed as augen gneisses, ribbon gneisses or equigranular gneisses. They are fairly solid and show block-jointing. The joint pattern is regular with WSW and SSE directions. Because of the occurrence of phengite, these gneisses will be called *phengite-gneisses*.

Mica-schists. — For convenience sake the rocks of this unit will be denoted as mica-schists in the following, although calciferous mica-schists are also found among the Mesozoic rocks. These foliated rocks, with a brownish grey colour are often strongly weathered. Occasionally eyelets of albite are seen. For this reason, Müller (1958), speaks of muscovite-albite-gneisses or muscovite-chlorite-gneisses. Formerly these rocks were called mica-schists and paragneisses. Since the rocks under review are *not* coarse-grained and irregularly banded, while the schistosity is *not* rather poorly defined because of the preponderance of quartz and feldspar over micaceous minerals, the rocks of the unit under discussion have not been denoted as gneisses. Moreover, a confusion with the phengite-bearing gneisses is avoided in this way.

Amphibolites and allied rocks. — The amphibolites are fine- or medium-grained tenacious rocks with a black to dark-greenish colour, in accordance with the amount of albite and quartz. They are resistant to weathering and seldom show jointing. The allied rocks comprise sodium-pyroxene rocks, with or without garnets and rocks rich in epidote, garnet or albite. In the amphibolitic lenses, white veins and bands may occasionally be found, giving the rock a migmatitic appearance. These white bands consist mainly of albite, some quartz and an occasional garnet or amphibole. In accordance with Müller, these leucocratic rocks are called "Metatekts". To avoid complexity the group of amphibolites and allied rocks will occasionally be described as the group of the amphibolites. If special types are meant, they will be called explicitly by their proper names.

STRATIGRAPHY

Being now acquainted with the general morphological outlines and the various types of rocks, the first question that may be asked, might deal with the age and origin of these rocks. This question, however, is hard to answer. Fossiliferous rocks are not found in the region under review, whereas the only fossiliferous type of rock in the immediate surroundings of the mapped area is found a few kilometres north of Vals on the Alp Grava. Here a ferruginous sandstone shows marble lenses, containing remnants of Gryphaeae. Therefore a stratigraphy of the rocks in this region can only be the result of a complex of lithological, structural and petrographical considerations.

The age of the Mesozoic sedimentary rocks

The stratigraphy of the post-Palaeozoic rocks has been treated in detail by Nabholz (1945). The stratigraphy of the Mesozoic rocks is based on comparative lithology and on the occurrence of *Gryphaea arcuata* LAM. (determined by Professor A. Jeannet, Zürich)*.

Heim (1891) observed the similarity between certain dolomites in the region under consideration and the Röthi dolomites. Wilckens (1907) goes far in convincing his readers of the Triassic age of the dolomites of the Valser-schuppen and the Fanellalappen on lithological grounds.

The ultimate proof of a Mesozoic age of all these sedimentary rocks

* Cf. note on page 436.

has not yet been given and theoretically it may well be possible that Palaeozoic rocks are hidden among the calciferous schists and dolomites of the lower tectonical units, in which ophiolites are seldom found.

According to Nabholz (1945) the following stratigraphical units may be distinguished in the uppermost structural units of the Adula Nappe, viz the Tomüllappen, the Gravaserie, the Aullappen and the Valserschuppen.

Dogger

Lithology. — Dark-coloured quartzites and argillaceous schists with a varying amount of lime.

Stratigraphical considerations. — The rocks under discussion show a striking similarity to Nolla-schists, which, according to R. Staub, are for the larger part deposited in the Aalenian.

Upper Liassic

Lithology. — Calcareous phyllites and marbles, locally called "Bärenhorn-schiefer", are the main types of rock.

Stratigraphical considerations. — The position between the alleged Dogger and Middle Liassic points to an Upper Liassic age.

Middle Liassic

Lithology. — Gneiss-quartzites, calcareous to argillaceous, occasionally arenaceous schists, brecciated in the lower parts, are frequently found.

Stratigraphical considerations. — There is a striking similarity with schists of Middle Liassic age occurring in the region of the Gotthard Massif.

Lower Liassic

Lithology. — Calcareous and argillaceous schists, ferruginous sandstones and sandy limestones occur, the latter showing remnants of *Gryphaea arcuata* LAM. and fragments of belemnites and crinoids. The lowest beds are brecciae with dolomitic components in a matrix of lime. Occasionally albitic quartzites, ribbon limestones and pebble-string limestones are intercalated among the calcareous mica-schists.

Thick marble beds, the so-called Aul-marbles, a conspicuous type of rock in the immediate surrounding of the region under review, may belong partly to the Lower Liassic, partly, however, they may be of another age. The lithology of the formations that may be of Lower Liassic age, differs from one unit to another, as is clearly shown by plate IV of the paper of Nabholz (1945).

Stratigraphical considerations. — According to Charles (1949) *Liogryphaea arcuata* LMK, being the same as *Gryphaea arcuata* LAM., is restricted to the Sinemurian s.s. and the lower part of the Lotharingian, both belonging to the Liassic. Thus the fossiliferous rocks definitely belong to the Lower Liassic.

Triassic

Lithology. — Massive dolomites, gypsiferous dolomites and dolomitic brecciae mark these formations. In the region mapped by the author anhydrite beds and gypsiferous lenses have recently been found in a waterdrift from Ampervreila to Peil.

Stratigraphical considerations. — The Triassic in the Alps is nearly always built by dolomites, gypsiferous and anhydritic rocks with quartzites at the base of these formations.

R. Trümpy (1957, 1958) is of a different opinion concerning the age of the younger sedimentary rocks; in this respect the following may be quoted (1957, p. 449):

Dans une zone plus interne de la même fosse à Bündnerschiefer, W. Nabholz (1945) a pu prouver l'existence du Lias inférieur par des trouvailles de Gryphées². Ces fossiles ont été trouvées peu au-dessus du Trias. Des grès et des calcschistes gréseux sus-jacents sont rangés dans le Lias moyen et supérieur par Nabholz; enfin, un niveau de schistes argileux à pyrite, les Nolla-Tonschiefer (Jäckli, 1941), représenteraient l'Aalénien. Or, Jäckli (1944) a pu suivre ce dernier niveau schisteux pas à pas jusqu'au Praetigau, où il recouvre la série de la Klus. Ce serait donc, de toute vraisemblance, du Crétacé; les calcschistes gréseux entre les Schistes de la Nolla et le Lias fossilifère pourraient être parallélisés avec la série de la Klus. W. Nabholz (1951) a fait l'observation très importante qu'une discordance sépare ces calcschistes gréseux de leur substratum. Cette discordance serait non pas l'effet d'une phase "embryonnaire" liasique, mais l'expression d'une lacune très importante, où manqueraient le Jurassique supérieur et moyen. En effet, les calcaires du Malm qui se trouvent de part et d'autre du géosynclinal pennique externe, semblent absents de celui-ci³.

As to the age of the "série de la Klus" he remarks in a section on a larger unit comprising Liassic to Eocene rocks (ibid.):

Les termes les plus récents se trouvent dans le Praetigau (grès de Ruchberg à Nummulites yprésiennes). Au-dessous, se trouve une puissante série à faciès flysch, où P. Nänny (1948) a pu dater le Maestrichtien, l'Emschérien et le Turonien à l'aide des *Globotruncana*. Les galets des niveaux bréchiques proviennent de N. Sous le Turonien, la série se poursuit jusqu'à une épaisse formation de calcaires siliceux lités avec quelques lentilles de microbrèches, dite série de la Klus (D. Trümpy, 1916). Puisque toutes les unités lithostratigraphiques distinguées au sein des schistes du Praetigau passent de façon tout à fait graduelle les unes aux autres, Nänny arrive à l'hypothèse très vraisemblable d'un âge méso- et infracrétacique de cette division inférieure; la série de la Klus pourrait être comparée aux calcaires siliceux de l'Hauterivien helvétique. Les terrains pré-turonien possèdent un faciès intermédiaire entre celui du Flysch typique et celui des Schistes lustrés banaux; les lits de brèches sont répandus, mais moins épais, moins polygéniques et à matériel plus fin que ceux du Néocrétacé et du Tertiaire. La sédimentation reste assez homogène sur de grands ensembles. C'est en somme un faciès "pré-flysch", qui paraît être assez caractéristique de ce géosynclinal infracrétacique.

As stratigraphy is not the main theme of this paper, the author will refrain from giving comments on this controversy. To some stratigraphers this account may seem to be a *testimonium paupertatis*, but in this region a more substantiated stratigraphy could hardly be expected. The lack of fossils may be due to two different causes. First these rocks underwent intensive metamorphism and mechanical disturbance. Secondly it may well be possible that they were originally poor in remnants of organisms. Correlation of formations over large distances is difficult in Alpine regions, because of rapid changes of the sedimentary facies.

² Probablement du groupe de la *Gryphaea obliqua* GDF.; Nabholz les attribue à *G. arcuata* LMK, mais sur les échantillons que nous avons eu sous les yeux on ne voit pas de sillon postérieur.

³ A moins qu'ils ne soient représentés par les marbres du Piz Aul. Les calcaires dits de Safien, attribués à cet âge par Jäckli, Nabholz et Staub, se situent au-dessus des schistes de la Nolla et seraient plutôt des calcaires urgoniens, à comparer aux Tristelkalke du Falknis et aux couches de l'Aroley de la zone de Ferret.

The age of the ophiolites

The age of all ophiolites is clear from their position within Mesozoic sedimentary rocks, which are fossiliferous in some parts of the Alps. The ophiolites in our region form no exception. They may be partly of Liassic, partly of post-Liassic age. It is still an unsolved problem whether they originated as intrusive or as extrusive rocks, but the investigations of Nabholz (1945) make it very plausible indeed that an intrusive origin of the larger part of these rocks is the most appropriate explanation so far given, pointing at least to a post-Liassic age.

Having dealt with the stratigraphy of the Mesozoic rocks, the age of the gneisses, schists and amphibolites of the lower structural units has to be discussed. For a treatment of their age and origin, one needs the help of specialized petrography.

The age of the mica-schists

Age of the original material. — According to former authors, the mica-schists are similar to the Casanna-schists of the Bernhard Nappe, cf. Kopp (1923) and Gansser (1937). This nappe, however, is found at a relatively great distance from the region under review and discussions about parallelization of the Adula Nappe with the unit just mentioned are highly hypothetical. Heim (1891) suggested that some rocks among these schists might be similar to Verrucano. Both Casanna-schists and Verrucano represent Permocarboniferous sediments. According to R. Staub (Main address, Annual meeting of the Schweizerische Naturforschende Gesellschaft at Sills 1944) it may well be possible that the rocks under discussion are of pre-Palaeozoic, viz of Jotnian age. Gansser (1937) adduces a better argument for a Carboniferous age. He describes the occurrence of hardcoal in schists of the Misoxerzone, a structural unit separating the Adula Nappe from the higher Tambo Nappe. These schists may be similar to some of the rocks found in our region, but this argument has to be used with caution.

Age of the metamorphism. — In chapter V, p. 562, it will be shown, that there are reasons to assume that the mica-schists of the northern Adula region have been influenced not only by Alpine metamorphism, but also by metamorphism of Hercynian age (this would also point to a pre-Alpine age of the original material).

The age of the phengite-gneisses

Age of the original material. — As early as 1908 the phengite-gneisses were thought to be Triassic intrusives, because of a questionable primary contact with dolomites, cf. Freudenberg (1908). Freudenberg's conclusion, however, was disputed by Wilekens (1910) on good grounds. Roothaan (1919), Kopp (1923), Nabholz (1945 a. o.) and Staub (loc. cit.) assume these gneisses to be transformed granites or injection gneisses of pre-Permian age, comparable with the Maloja-, Corvatsch- and Arolla-gneisses. The arguments of these authors are mainly based on the assumption that the Adula region is a nappe in the classical sense of the word. Recent investigations of E. Wenk and others, however, make it clear, that the massive granitoid rocks of the central

Tessin regions are to be considered as products of Alpine processes, rather than as relics of pre-Triassic rocks. Mobilization, metasomatism and metamorphism radically transformed the original material, giving rise to late Alpine intrusions. The deepest parts of the Alps would no longer preserve Hercynian structures. Consequently the origin and age of these rocks has to be thoroughly proved anew. An attempt to solve this problem by means of structural and petrographical research has recently been made by Müller (1958). Both age and origin of these gneisses were discussed, but a definite conclusion could not be drawn. He considered first the possibilities of granitization versus intrusion, without reaching a definite conclusion.

Petrographical investigations, to be described in chapters IV and VI, provides scanty evidence in favour of a Hercynian igneous origin of these rocks.

Age of the metamorphism. — There is vague evidence that these rocks did not suffer the same Hercynian metamorphism as the mica-schists, and therefore have only been influenced by regional metamorphism of Alpine age.

The age of the amphibolites and allied rocks

Age of the original material. — Our attempt to determine the age and origin of the amphibolites and allied rocks involved a complexity of problems not easily solved. For a discussion of these problems the reader is referred to chapters IV, V and VI. The only reasonable conclusion so far seems to be that the amphibolites and allied rocks are Hercynian or older igneous rocks of a dioritic composition.

Age of the metamorphism. — Apart from the influences of Alpine metamorphism, these rocks show some traces of a presumed Hercynian metamorphism (see p. 562).

STRUCTURAL OUTLINES

The mountains of south-eastern Switzerland have been the focus of interest for generations of geologists. As far back as the beginning of the nineteenth century A. Escher von der Linth, B. Studer and L. von Buch were puzzled by the complicated structures they observed in these regions. These early investigators paid attention mainly to the structures observed in Mesozoic sedimentary rocks. The greater part of the Adula region and of the mountains in Tessin, more to the south-west, were considered to be a regular, hardly disturbed crystalline massif built by mica-schists and gneisses. This view was favoured until the beginning of the twentieth century, when by the Nappe Theory an impulse was given to new structural investigations in these regions. Between 1900 and 1925 many papers were published dealing with structural and stratigraphical problems of the Adula region and its surroundings.

Meanwhile, the seeds for new ideas and a new approach were sown. Freudenberg (1908) assumed the gneisses of the Adula to represent intrusives of Triassic age. Staub (1920) suggested that the zone of Alpine anatexis and mobilization had to be sought in the Tessin regions. Kündig (1934, 1936) pointed out the relatively late origin of the Cocco granodiorite. The classical

Nappe Theory, however, had gained so much well-deserved authority, that these attempts at unconventional explanation of the phenomena observed were rather slow in making themselves felt. Tentatively Wenk (1948) adduced a large number of observations diverging in some respect from the classical Nappe Theory. His structural map of 1955 and his paper of 1956 can be considered as an introduction to a new line of thought. Consequently a period of renewed investigations and new interpretations is to be expected, in which a number of well-established ideas will be critically re-examined.

The data included in this chapter resulted a. o., from a number of detailed sections, mapped in cooperation with R. O. Müller and T. H. Tan, along the Finstererbach, the Guralätschbach, the Ampervreilerbach, the Selvabach, the nameless torrents on the western slope of the Valserrhein valley, along the road Vals-Zervreila, in the bed of the Valserrhein and along an imaginary line drawn through the top of the Ampervreilerhorn and the chapel of Calvari-berg, called section DD (after the Dutch for Dead Pine, viz Dode Den, because a conspicuously shaped dead pine visible from nearly every spot along the section was used as an orientation mark). Further, a section was made on the north-western slope of the Valserrhein from the Dachberg down to the chapel of Frunt and one at right angles to the main direction of the folding axes, starting from Pedanatsch. In order to avoid prolixity only one section is given in full, viz the section DD (fig. IV). The results of the survey of the other sections are incorporated in the map.

The different structural units of the mapped region will first be described separately and special reference will be made to those observations that may lead to interpretations and conclusions, that are at variance with the ideas of former authors. For a detailed description of the geology of the mapped area the reader is referred to the papers of Kopp (1923), Nabholz (1945, 1948) and Müller (1958).

On page 432 the following units were distinguished: the Valserschuppen, the Fanellalappen and the Zervreilerlappen. Other units do not occur in our region.

Valserschuppen

The outlines of this unit are given in fig. 4. Comparison with the geological map shows that this unit is mainly built of Mesozoic rocks, with some wedges of phengite-gneisses and non-calcareous mica-schists. Since a subdivision of the Valserschuppen entails severe problems in the region N of the Valserrhein, Tan (1957), in contrast with former authors, prefers to take the Upper and Lower Valserschuppen together. The units are wedging out here and are strongly disturbed by tectonic activity. A division into two units may be more appropriate for the formations E of the Peilerbach and those still more to the south-east, where the Valserschuppen cover not only the deeper units of the Adula Nappe, but are also linked with the Mesozoic rocks covering the Tambo Nappe. According to Nabholz (1945) the Valserschuppen comprise the lowest parts of the Mesozoic formation thrust over the metamorphic basement and consequently they have taken along with them wedges of basement rock. The rock sequence in the Valserschuppen, as found NW of the Valserrhein, from top to bottom is given below:

- 1 Albitic quartzites
- 2 Phengitic augen gneisses, the so-called "Riesenaugengneis"

- 3 Sandy limestones and calcareous schists
- 4 Sandy calcareous phyllites, mica-schists and calcareous phyllites
- 5 Phengite-gneisses without microcline (according to Tan 1957 these rocks may represent altered arkoses, because of their clastic appearance)
- 6 Calcareous phyllites with intercalated white quartzites
- 7 Mica-schists
- 8 Glaucophane-bearing ophiolites
- 9 Dolomites

Fanellalappen

The outlines of this unit are given in fig. 4. Comparison with the geological map shows that this unit is essentially built of mica-schists, phengite-

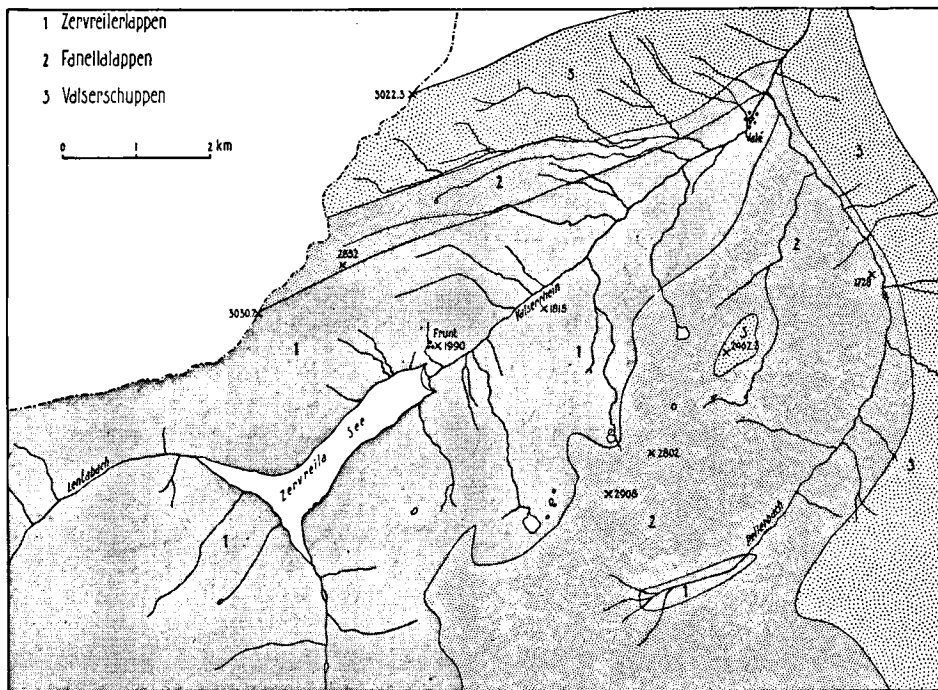


Fig. 4. Distribution of the different tectonic units in the investigated area.

gneisses and amphibolites. The outlines of this unit, as suggested by the author, are slightly different from those given by Kopp (1923). Therefore it is necessary to give a more detailed description of this unit. The difference concerns the rocks found on the slope NW of the Valserrhein.

The Fanellalappen south-east of the Valserrhein. — The uppermost part of this unit is built of dolomites, sometimes associated with ophiolites, e.g. SW of point 2248. Parts of the Hobbühl dolomites also belong to the Fanellalappen. East of the Peilerbach the limiting surface with the Valserschuppen occurs as a continuous band of Mesozoic rocks. The most complete section of

this unit can be observed in the area SE of Boden. This section follows here from top to bottom.

alt. 2280 m	Mesozoic rocks
alt. 2280—2260 m	Stromatitic amphibolites with glaucophane
alt. 2260—2230 m	Chlorite-mica-schists
alt. 2230—2220 m	Amphibole-bearing chlorite-mica-schists
alt. 2220—2215 m	Amphibole-bearing mica-schists
alt. 2215—2210 m	Chlorite-mica-schists
alt. 2210—2190 m	Equigranular phengite-gneisses
alt. 2190—2100 m	Mica-schists with some albite
alt. 2100—2090 m	Phengitic augen gneisses
alt. 2090—2020 m	Mica-schists with some albite
alt. 2020—2010 m	Mesozoic rocks overlying the Zervreilerlappen

Two things will be clear from this section.

First the section illustrates the general characteristics of a "Lappen", viz a formation of metamorphic rocks between two incompetent beds. The usual core of granitoid rocks is better developed in and near the Ampervreilerhorn.

Secondly it shows the important role mica-schists play in this part of the Fanellalappen.

If this section is compared with the geological map, it follows that the two bands of phengite-gneisses are due to the splitting up of a much thicker formation, building the summits of the Ampervreilerhorn, the Guralätschhorn and part of the Plattenberg. Here we touch upon a characteristic of the phengite-gneisses, viz their tendency to build mountain peaks. The statement can easily be checked with the help of the map. This zone of phengite-gneisses occurs as a continuous band underneath the stables and houses of Kartütseha, Auf der Matte, Balmadachli and Valatsch Alp E of the Peilerbach. The band of Mesozoic rocks at the base of the Fanellalappen, mentioned above, can be followed from the Weissgrätli, through the Fanellagrätli (pt 2731), N slope of the Hennensädel, along the small lake of Ampervreila (pt 2377), E of the dwellings of Alp Ampervreila, E of Boden, to the Peilerschlucht E of Valé.

The general trend of the rock-formations left and right of the Valserrhein is V-shaped, due to a dip to the NE. With this trend in mind we may try to find this zone of Mesozoic rocks at the western side of the Valserrhein. Here a discontinuous band of dolomites is found in a mylonitic zone between phengite-gneisses (a. o., passing through Moos). The map and section DD indicate that in all probability this discontinuous band of dolomites is the same as that of the Mesozoic rocks found at the base of the Fanellalappen SE of the Valserrhein, which gives an opportunity to trace the Fanellalappen NW of the Valserrhein.

The Fanellalappen north-west of the Valserrhein. — The Mesozoic rocks at the base of this unit can be traced until they disappear in a mylonitic zone passing through the Frunthorn. The map shows the Fanellalappen not to be so completely developed in this part of the region as in the section of Boden. The predominance of phengite-gneisses is its main feature and underlying mica-schists are not exposed. Some small wedges of mica-schists may be found in the region of the Fuorela de Puzas, as parts of an im-



Fig. 5. Mullion gneisses near the Dachberg in the mylonitic zone between the Fanellalappen and the Zervreilerlappen. The debris reminds of a pile of timber. Photo T. H. Tan.

brication with the lower parts of the Valserschuppen. This explanation of the field evidence is different from the ideas held by Kopp (1923, p. 114), who assumed the Zervreilerlappen to appear again between the Fanellalappen and the Valserschuppen in the region of the Dachberg, through a form of back-folding. As mentioned in the preceding paragraph the Valserschuppen wedge out in this region; the same seems to be the case in the Fanellalappen.

On the southern slope of the Dachberg a beautiful fold is seen. This fold, in combination with others in the neighbourhood of Olivone, led Kopp to assume back-folding of the Zervreilerlappen in this part of the region. In the opinion of the author there is no need to assume such a back-folding, but this does not mean that in regions more to the west, such a phenomenon may not be observed. This hypothetical back-folding will again be discussed

after dealing with the Zervreilerlappen. The reader will then be in possession of the available field evidence.

Along the boundary with the Zervreilerlappen the phengite-gneisses of the Dachberg and the Frunthorn are highly mylonitized through severe thrusting and show rod and mullion structures. Moreover, they show intensive isoclinal folding, causing a thickening of the formation. Mullion gneisses are not exceptional in the rest of the region, but are best studied in the Dachberg region, see fig. 5. The slope debris is strongly reminiscent of a huge pile of timber and roof tiles. The eyes of microcline are often of a foggy blue and whenever the surface of the outcrop is roughly parallel to the schistosity they stand out like giant warts.

Zervreilerlappen

The outlines of the Zervreilerlappen are also drawn in fig. 4. Comparison of the small structural map with the geological map clearly shows the main characteristics of this unit. First two rather large bodies of phengite-gneisses are apparent, viz that in the neighbourhood of the Alp Ampervreila and the large gneiss body now holding the Zervreilasee. A second feature is the large number of amphibolite bodies, which are associated with the phengite-gneisses. Between the two gneiss masses, just mentioned, a zone is found showing marked signs of tectonic activity. This zone comprises a number of dolomitic bands alternating with narrow bands of mica-schists and gneisses. Moreover, blastomylonites are found here that are rich in biotite.

Works connected with the construction of the Zervreila dam provided a large number of fresh outcrops. These works comprised a.o., a widening of the road Vals-Zervreila, necessary for transport of cement, machinery and tools for the building of the dam. For distribution of surplus water over a number of hydroelectrical plants, the waterdrift Zervreila-Wanna, of which the waterdrift Zervreila-Ampervreila-Peil is the first part, was constructed. To lay the foundations for the dam, a trough of about 40 m wide and averaging 20 m in depth was made in the slopes on both sides of the Valserrhein. The dam reaches a height of 152 m. The mapping of the trough provided Müller (1958) with a substantial amount of data for his thesis.

The new outcrops along the Vals-Zervreila road made it possible to obtain a detailed section through the Zervreilerlappen. The waterdrift Zervreila-Peil had just been completed before we entered the field. Unfortunately we have no detailed geological information about this tunnel. However, a set of samples taken by one of the working foreman at the request of Professor Dr J. Cadisch of Bern, could be studied. Furthermore, we are greatly indebted to the employees of the contracting companies, who did their utmost to give as much information as possible. The result of a reconstruction based on these data is given in the section waterdrift Ampervreila-Peil (fig. 6). This section does not show the dip and strike of the formations in the tunnel, because they were not accessible.

Having briefly sketched the general outlines of the Zervreilerlappen and the methods followed while mapping this part of the region, some special subjects may now be discussed in detail, viz the Mesozoic rocks covering the Zervreilerlappen, the base of the Zervreilerlappen, the occurrence of amphi-

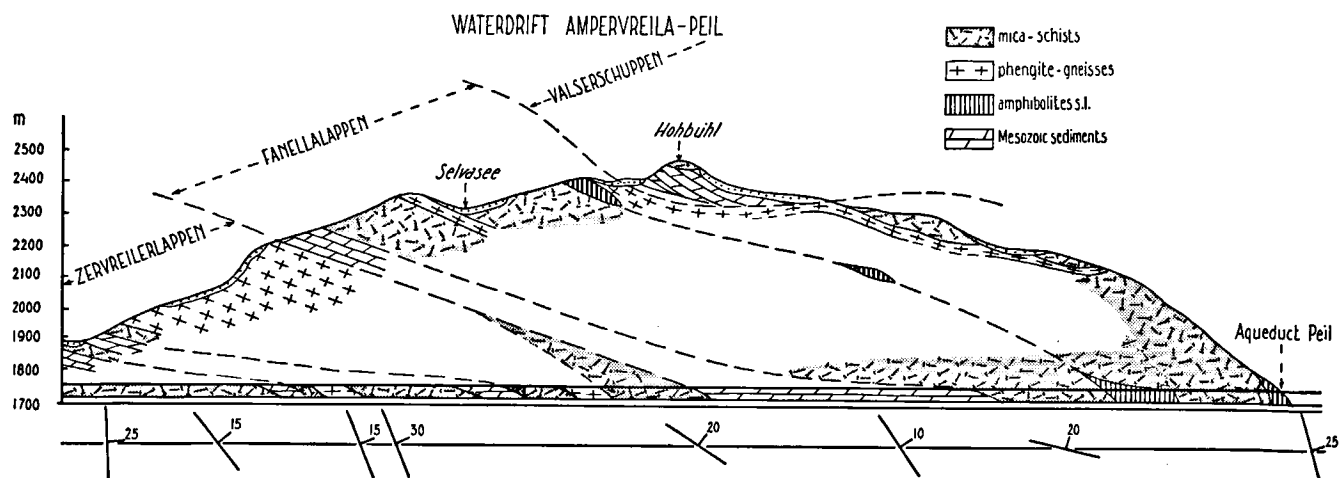


Fig. 6. Section waterdrift Ampervreila-Peil; the tunnel section is a reconstruction based on the available data, the surface was mapped by the author. The dip and strike symbols at the bottom of the section were measured at the surface.

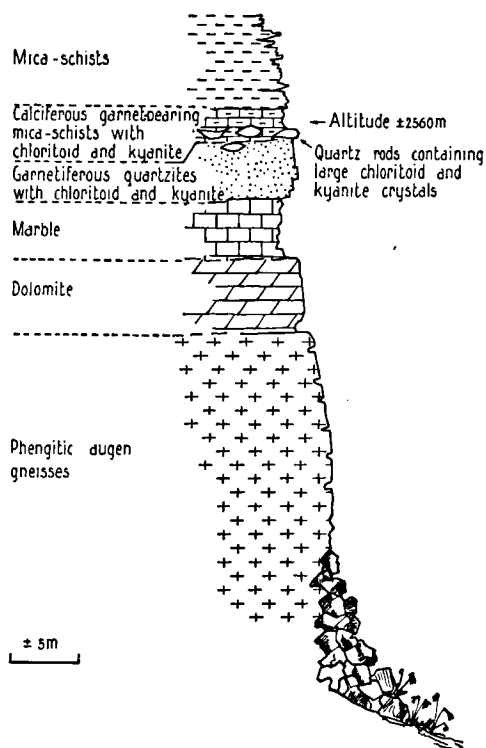


Fig. 7. Section Hennensädel north slope.

bolites associated with the phengite-gneisses, the zone of springs near Boden, and the blastomylonites underneath Calvariberg.

The Mesozoic rocks overlying the Zervreilerlappen. — Covering the Zervreilerlappen a band of Mesozoic rocks is found. Starting from the summit of the Weissgrätli (alt. 2866 m) this zone may be traced along the SE slope of the glacial cirque of the Guralätschsee; it crops out at the Hennensädel (point CK on the geological map); continues along the slopes of the cirque enclosing the small lake, east of the Hennensädel, appearing as two small outcrops amidst morainal deposits and slope debris; a few hundred metres SE of Ampervreila Alp this band is found again; from here it strikes NNE, crosses the Selvabach and can be traced down as far as Valé, where it crops out in a small quarry in the Peilerschlucht. On the other side of the Valserrhein, this zone is found again below Leis in the Leiserbach. Here the surface of the zone runs more or less parallel to the slope, causing a number of outcrops in this torrent. At one point, however, the dip and strike change and the surface of the zone again makes an appreciable angle with the slope surface. To the south-west, this zone is seen almost continuously over a long distance, up to a point NE of Pedanatschstafel. The construction of the waterdrift Ampervreila-Peil, revealed the occurrence of this Mesozoic formation in the tunnel, underneath the top of the Hohbühl, at an altitude of about 1700 m. Rock specimens taken from this site are extremely rich in gypsum and anhydrite, and monomineralic rocks consisting of these minerals are found. The outcrops at the Weissgrätli and the Hennensädel are characterized by the occurrence of a bed of quartzite with chloritoid and kyanite, covered by calciferous garnet-bearing schists with large flakes of chloritoid (2 cm) and quartz rods with chloritoid and kyanite. The most complete section through these Mesozoic rocks is to be made either on the Weissgrätli or on the Hennensädel. The section through the Hennensädel is given in fig. 7. Traces of gypsum at the surface were only found on the Weissgrätli and in the outcrop of the Selvabach. In the latter gypsum was not found, but a *rauhwacke* crops out that may have contained gypsum.

The base of the Zervreilerlappen. — The basal part of this formation lies outside the mapped region and for details the reader is referred to the descriptions given by Jenny, Frischknecht and Kopp (1923). A few outcrops of Mesozoic rocks are found in the Lentatal, the Kanaltal and the Hinterrheintal. The exact localities are:

1. Lentalücke;
2. SE of point 2168, alt. 2330 m, Lentatal;
3. SW of the cabins of the Kanaltal, alt. 2400 m, Kanaltal;
4. a few outcrops in the Hinterrheintal, W of Hinterrhein;
5. outcrops in the region of the pass of San Bernardino.

The authors just mentioned assumed that either these Mesozoic rocks or amphibolites formed the base of the Zervreilerlappen. They based their assumption on the theory that the amphibolites occasionally derived from Mesozoic marls. This implies that in their view amphibolites and Mesozoic sediments, from a structural point of view functioned in the same way. Chapter V will show that the amphibolites are presumably igneous rocks of

older than Mesozoic age. Therefore a re-examination of the base of the Zervreilerlappen seems appropriate.

The association phengite-gneisses - amphibolites. — Field evidence undoubtedly points to a close relation between the amphibolites and the phengite-gneisses. This fact was ascertained by Müller (1958) and is clearly illustrated on the map by the outcrops bordering the Zervreila gneiss and by those near Ampervreila. These amphibolites are always found between phengite-gneisses and mica-schists. Müller (1958) in his description of the field data (p. 412) states: "Die Amphibolite. Sie umkränzen im grossen gesehen den homogenen Phengitgneiskörper, wo dieser mit den Paragesteinen zusammentrifft". This phenomenon is not restricted to the mapped region, but was also observed in the region of the pass of San Bernardino. Observations of the fresh outcrops in the trench for the Zervreila dam, fig. 8, first led Müller and the author to the conclusion that these amphibolites originated by interaction between the mica-schists and the gneisses. Occasionally these mafic rocks are found together with veins and lenses of leucocratic albite-quartz-rocks, giving the outcrops a migmatitic appearance. Two splendid photographs of these "migmatites" underneath the Zervreila dam are given in Müller's thesis on plate II. It should be noted, however, that such rocks are relatively rare and occur in certain quantities only in the area of the Zervreila dam and in the immediate surroundings of the aqueduct at Peil, where the waterdrift makes a curve to the north, to Valatschalp. Two other outcrops of this type of rock are amidst the amphibolites SW of Heinisch Stafel and those near Fanellastafel; at these two sites, however, the role of "migmatites" is less important.

A look at Müller's sections (plate VII) and at his map, gives a clear illustration of the appearance of these rocks in connection with the phengite-gneisses and the enveloping mica-schists. These sections give rise to some doubt as to the correctness of the hypothesis that the amphibolites were formed by interaction of the phengite-gneisses and the mica-schists, irrespective of the nature of this interaction. Putting aside for a moment the results of detailed mapping and petrographical investigation, the sections drawn by Müller might well represent a structural imbrication of three unconnected types of rock.

It is indeed not unlikely that local interaction between schists and gneisses gave rise to a small zone of mafic rocks, afterwards disrupted into boudins and lenses through subsequent mechanical disturbance along the limiting surface. This interaction could have been something like metamorphic differentiation. Metamorphic differentiation, however, does not seem powerful enough to account for the large bodies of amphibolites. In Müller's thesis the mechanism of granitization is regarded as a possible cause of the formation of most of the amphibolites, but it will be shown in chapter V and VI that the occurrence of such a process is not supported by chemical and petrographical evidence. Therefore structural imbrication seems for the moment the most satisfactory mechanism to explain the relation between the gneisses, amphibolites and mica-schists; their constant succession in many sections is probably due to an older structure of a simpler character, showing the same succession. In chapter VI evidence will be given, suggesting that the amphibolites and allied rocks represent neither a contact aureole, nor a basic border, nor a basic front of the gneiss body. Hence the succession in the above



Fig. 8. Northern part of the trough of the Zervreila dam, as exposed in august 1956.
P = phengite-gneisses; M = mica-schists.

mentioned older structure may have been a succession of three independent units (see also p. 551). The author is inclined to assume that the succession in this older structure was of tectonic origin as well.

The zone of springs near Boden. — In the phengite-gneisses SW of Boden (coord. 7322—1617), a zone of springs occurs along the 1800 m contour line. The water of these springs runs down the slope and is received by the Selvabach. An investigation into the source of this water yielded the following results. The Selvabach was followed from the Selvasee, in the direction of Chäserli and its water-content was measured (surface of a section through the bed, combined with stream-velocity). At the overflow of the lake the quantity of water is about 20 l/sec in summertime. Below the band of Mesozoic rocks at an altitude of about 2040 m, the river bed is dry! The bed remains dry until it curves to the NE, following the contact between the phengite-gneisses and the large amphibolitic body near Boden. Here it has a water-content of about 100 l/sec, owing to the springs mentioned before. The construction of the waterdrift Ampervreila-Peil supplied the answer to the question of the origin and large quantity of the water of the springs, as well as the difference in water-content in the upper parts of the Selvabach. The dolomite band, described above, was found in the tunnel and proved to be a water-bearing bed. The amount of water that rushed into the tunnel was about 200 l/sec. If the course of this Mesozoic formation is constructed, assuming that folds do not change its trend, the rocks strike into the tunnel exactly at the same place where they were actually found. A rough survey of the amount of water that flowed into the Selvasee made it evident that far more water went into this lake than was measured at the overflow. Consequently a large amount must have seeped away through joints in the bottom, finding its way down until the water-bearing bed of Mesozoic rocks was reached, where it joins the smaller quantity of water directly derived from the Selvabach. This bed might have functioned as a reservoir overflowing in the springs of Boden. Still one question remains. The water pouring into the tunnel was extremely rich in sulfate ions, due to the solution of gypsum and anhydrite, whereas the water of the springs has a normal composition. Apparently the upper part of the water-bearing bed had already lost all its sulfate.

The blastomylonites of Calvariberg. — Along the road from Vals to Zervreila, below Calvariberg, a conspicuous type of rock crops out. The rock can be described as a nebulitic (cf. Huber 1943) augengneiss-like blastomylonite and shows bluish white streaks of extremely fine-grained quartz. Within these rocks leucocratic rocks appear, standing out because of less intensive weathering, as well as shear zones, consisting of large flakes of colourless mica with an occasional deformed cube of pyrite. Mylonites with such a structure were only found here. The other mylonites of the region under review are recrystallized, but formation of new biotite after mylonitization is rare, especially the formation of brown biotite, which has been formed in the Calvariberg rocks. The rocks in this area are accompanied by several small bands of Mesozoic rocks, wedging out in both directions. Mapping here is time-consuming, because of the wood that covers these slopes and the "Sackung" that brought about steep slopes. From the results of this mapping, the assumption seems justified that this band represents a large thrust zone within the Zervreilerlappen.

Thrusting and folding

Having concluded a separate treatment of the different sheets, the structure of the region as a whole will now be considered. From the work of Kopp (1923) it follows that this part of the Adula region is considered as the crown of a nappe. According to Kopp, the Zervreilerlappen was folded upwards and backwards along an ENE—WSW axis passing through the region of the Dachberg. Evidence for this structure is taken from a kind of back-folding zone of Mesozoic rocks outside the region under review, on the Piz Casinel, and from a recumbent fold observed in the Dachberg when looking from the small lake just south of it. The author did not find any conclusive evidence for Kopp's assumption within the investigated area and therefore did not incorporate this backfolding in his section DD.

Another difference of opinion concerns the Mesozoic rocks in the area of the Weissgrätli, of which Kopp (1923) assumes that they have been brought to a lower level by zigzag folding. Further the dolomites of Calvariberg and E of Ampervreila are assumed to represent the same formations as found in the region of the Weissgrätli. This assumption is at variance with field evidence and with the observations during the construction of the waterdrift Ampervreila-Peil. First it could be proved that the rocks of the Weissgrätli can be traced down into this tunnel. Moreover, combination of field data at the surface and in the tunnel makes it clear that isoclinal folding in this region does not bring the beds to a lower level, but only leads to a thickening of the beds in certain parts. The section of waterdrift Ampervreila-Peil clearly shows that this part of the mountains is built up by a large number of sheets and wedges, whereas folding is a phenomenon of only secondary importance. The fact that the minerals chloritoid, kyanite and gypsum are restricted to one zone of outcrops, whereas these minerals in the same habit and association do not occur in other Mesozoic formations in this region, strongly corroborates the above statement.

A number of formations of Mesozoic rocks, viz those near Calvariberg, show lenses and sheets, wedging out in all directions, as if through the action of thrusting a wedge of the Mesozoic cover is smeared out and broken up into smaller units.

In connection with the work done by Wenk (1955) in regions to the south-west, a large number of measurements were carried out on b-axes (the axes of folds and lineations). These axes generally show two directions, approximately NS (more exactly NNW—SSE) and approximately EW (more exactly NE—SW). Müller (1958, p. 419) states that on the Hohberghorn an outcrop is found which clearly shows the EW axes here to be younger than the NS axes. In the region mapped by Müller and the author, the pattern observed by Wenk (*loc.cit.*) is changing (see also Müller, 1958, p. 419). The general NS trend observed in southern regions comes to an end in the Zervreila gneiss-body and its direct environment and dips under higher units in our region, units that show generally an EW trend. The dipping down of formations with a NS trend could easily be mapped and the last outcrop showing NS direction is found in the bed of the Valserrhein in a V-shaped outcrop of amphibolites, just S of Pedanatsch. Measurements of b-axes were continued along the road from Vals to Ilanz, as far as Ilanz and it was found that the EW direction appears continuously from the Mesozoic cover of the Adula region into the Mesozoic rocks covering the Gotthard Massif. Along this road, however, in some places an occasional NS axis is measured.

Faults and joints

Most thrust faults in the northern Adula region are parallel to the bedding and schistosity. They form the boundaries between the various tectonic units and their numerous subdivisions.

Other faults, transverse to the bedding and to the schistosity seldom show a throw large enough to be visible on the map. It was sometimes even difficult to find any throw in the field. The faults, indicated on the map, have all more or less the same characteristics. In the field a system of narrow gullies is observed. These gullies may reach a depth of 10 m and a width of about 30 m. An outstanding example is found just south of the Zervreila dam. During the construction of the dam it was thought that these gullies might have some connection with faults and one was excavated. It appeared to be filled with morainal material and at the very bottom a small mylonitic zone was found (Professor Dr J. Cadisch, personal communication, 1957). The largest fault of this type is the fault of Frunt, clearly indicated by the topography. On this fault too a system of gullies is observed, partly filled with small marshes.

Many rocks show more or less well-developed joints. In the region of the water-intake of the waterdrift near Ampervreila, these joints lead to large and small crevices, one of which came into being by the continuous passing of heavy trains carrying debris of the tunnel on their way to the dump, that is situated amidst the amphibolites more to the NE. These crevices form a rather large system in this part of the region with a NE—SW direction. One of these deep fissures is named "Warme Krache" by the local people, because it seems to send forth a continuous stream of warm air. The author descended into this fissure on a cold day and it was obvious why it was given that name, as it really was nice and warm inside. This "Warme Krache" is found along the old road from Vals to Zervreila, somewhere near the chapel of Calvariberg. The fissure can be seen over a distance of more than 300 m.

Another type are the quartz-filled joints on the Plattenberg, the largest of which is drawn on the map. The whole Plattenberg is dissected by a system of such quartz-filled joints, all tending to a NW—SE direction. The mapped joint is filled with a kind of milky white quartz and is about 10 to 20 m wide.

CHAPTER III

MINERALOGY

Introduction

In this chapter the minerals found by the author in the northern Adula region are described. These minerals comprise important rock-making minerals, e. g., amphiboles (a. o. glaucophane), sodium-pyroxenes, garnets and micas (a. o. ferrian phengite) as well as Alpine fissure minerals such as adularia.

The region around Vals is rather famous for being rich in beautiful specimens of Alpine fissure minerals and of rare rock-making minerals. A splendid survey of the minerals found in these regions is given by Parker (1954).

The minerals are treated in alphabetical order; different members of a group of minerals, e. g., the group of the amphiboles, are described in one paragraph.

For the location of samples mentioned in the text, the reader is referred to the table on p. 596.

Alphabetical list of the minerals described in this chapter

Actinolite, see amphiboles	Hematite
Adularia	Ilmenite, see rutile, sphene and ilmenite
Albite	Kyanite
Amphiboles	Magnetite
Anhydrite	Malachite, see fahlore
Antigorite, see chlorites	Microcline
Apatite	Muscovite
Azurite, see fahlore	Orthoclase, see microcline and orthoclase
Biotite	Phengite, see muscovite
Blue-green amphibole, see amphiboles	Phlogopite, see biotite
Calcite, see carbonates	Pistacite, see epidote
Carbonates	Prochlorite, see chlorites
Chalcopyrite	Pyrite
Chlorites	Pyroxene, see sodium-pyroxenes
Chloritoid	Quartz
Chloromelanite, see sodium-pyroxenes	Ripidolite, see chlorites
Clinocllore, see chlorites	Rumpfite, see chlorites
Clinzoisite, see epidote	Rutile
Cobalt-bearing calcite, see carbonates	Siderite, see carbonates
Crossite, see amphiboles	Sodium-pyroxenes
Delessite, see chlorites	Sphene, see rutile, sphene and ilmenite
Diabantite, see chlorites	Stilpnomelane (?), see biotite
Dolomite, see carbonates	Tourmaline
Epidote	Zircon
Fahlore	Zoisite, see epidote and zoisite
Ferrian phengite, see muscovite	
Ferrohastingsite, see amphiboles	
Galena	
Garnets	
Glaucophane, see amphiboles	
Gray-copper, see fahlore	
Gypsum	

1 ADULARIA

The mineral named after the Adula mountains can be found in tension joints and mineral pockets. No special study was made of its properties. It usually is milky-white and shows several types of twinning. The average size of the crystals is a few centimetres. Fig. 9 shows a sample with adularia and quartz from a tension joint in phengite-gneisses, coord. 7322—

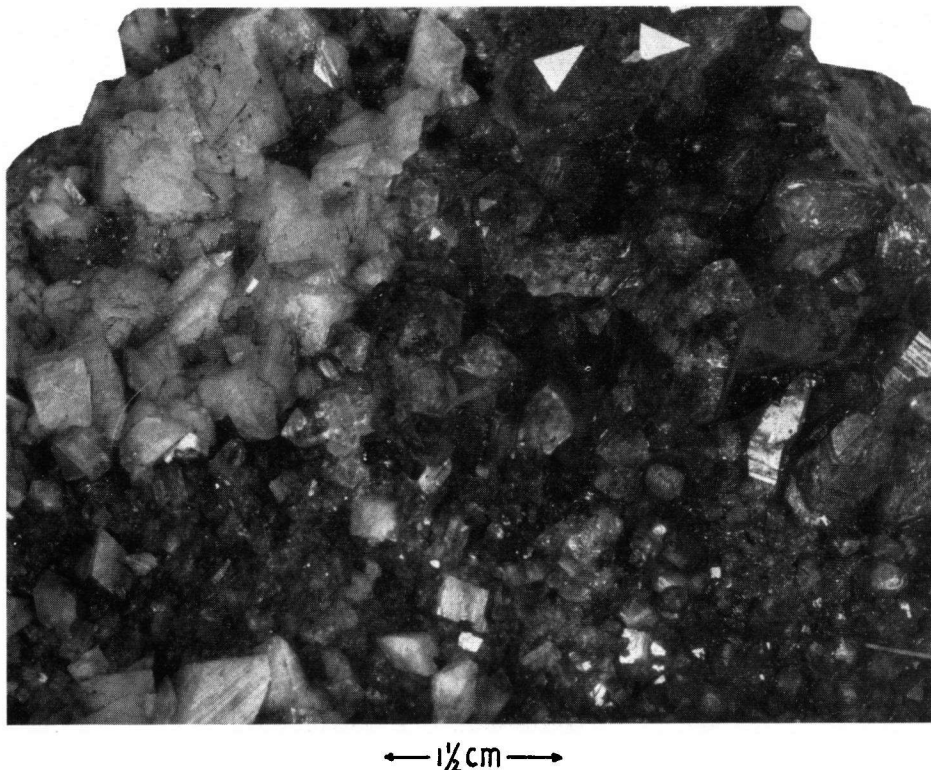


Fig. 9. A specimen taken from a tension joint in phengite-gneisses showing adularia (left side of the photograph) and quartz, coord. 7322—1625.

1625. Adularia is associated with quartz, epidote, chlorite and sphene, a. o. in joints in the following rocks:

- a. The amphibolite at the southern end of the largest tunnel, road Vals-Zervreila, coord. 7315—1624, alt. 1550 m.
- b. The phengite-gneiss in the wood N of Boden, along the track from Vals to Boden, near the huts called Chäserli, coord. 7322—1625, alt. 1600 m.
- c. The dolomites at the northern end of the Boden sward-land, about 100 m into the wood, coord. 7326—1623, alt. 1800 m.

2 ALBITE

Albite is of wide-spread occurrence. It is found as a rock-making mineral and also occurs in veins and mineral pockets. The pellucid euhedral albite crystals of Alp Rischuna are famous and found their way to mineral col-

lections all over the world. Recently Weibel (1958) reported on the albites of mineral pockets in Switzerland. He came to the conclusion that these albites are generally almost pure $\text{NaAlSi}_3\text{O}_8$. A chemical analysis of albite from Vals, presumably from Alp Rischuna (analyst Max Weibel) is quoted here:

Na_2O	K_2O	CaO	SrO	Al_2O_3	SiO_2	Sum
11.6	0.10	0.07	0.003	19.6	68.6	100.—

Albite is always present in the gneisses and mica-schists and absent from some pyroxene rocks, belonging to the group of the amphibolites and allied rocks. The grain size in the gneisses is about 0.5 mm, in the schists it does not exceed 1 cm, in amphibolites it ranges from 0.1—0.5 mm.

The anorthite percentage in the gneisses varies from 2—6, in the schists it varies from 3—8 and in the amphibolites from 5—10 (this region) and 5—20 (Val Calanca). The determination of the anorthite percentage was carried out with the aid of a universal stage, by measuring the angle between 010 and the nearest extinction in a section normal to the a-axis. Albite porphyroblasts and poeciloblasts so common in the schists and in the amphibolites are rare in the phengite-gneisses. In these gneisses the albite generally has a granoblastic structure. Twinning of the albites is found in every type of rock, but it is more frequent in the phengite-gneisses.

Simple twins of albite are more frequent in the schists and the amphibolites. The composition face is mostly 010. The twins found in the phengite-gneisses have been the subject of a special investigation. The different kinds of twinning observed are listed below:

twinning axis	composition face	name	remarks
normal twinning			
\perp 010	010	albite	multiple & simple
parallel twinning			
c	010	Carlsbad A	simple
b	001	acline A	simple
b	rhombic section	pericline	multiple & simple
complex twinning			
c & \perp 010	010	albite-Carlsbad A	simple

In some sections the number of the various twins was counted in order to arrive at a clear picture of their distribution. The result is given in table 1. The determination was carried out with the aid of a universal stage. The simple pericline twins, also observed in the other types of rock, are characteristic of these gneisses and provide valuable information about the origin of the albite. The composition face of these pericline twins makes an angle of about 29° with the face 001. According to Laves and Schneider (1956), this angle points to a primary origin of the albite, i. e., this mineral has not been formed by albitization of plagioclase with a higher percentage of anorthite. Only once an albite-Carlsbad A twin was observed in the schists. The albite poeciloblasts and granoblasts in the gneisses never give rise to

"Augen" structures, as in the other rock types. They contain quartz drops and some minute amphibole needles as inclusions. In the other rocks, however, the poeciloblasts are studded with all kinds of inclusions, but they have a clear rim. The enclosed minerals may be either remnants, or normal

Table 1

Distribution of twins in the albite of the phengite-gneisses

Sample number LP	42	47	58	105	105*)	125	152	335	460	502	531	534	900**)	A 1
Polysynthetic albite	24	15	9	9	3	11	14	20	12	x	x	x	x	13
Simple albite	6	10	2	6	2	3	13	2	4	—	x	—	—	2
Polysynthetic pericline	2	—	1	3	1	1	3	—	—	—	x	—	—	1
Simple pericline	1	6	1	1	—	4	—	2	4	—	x	—	x	3
Albite-Carlsbad A	1	2	1	4	2	3	1	—	3	—	—	x	—	2
Carlsbad	1	2	2	3	4	1	2	—	1	—	—	—	—	2
Accline	—	—	—	—	—	—	1	—	—	—	—	—	x	—
Sum	35	35	16	26	12	23	34	24	24					23
Angle 001/pericline composition face						27°	29°	29°	34°					

*) Albite crystals enclosed in a large microcline poeciloblast.

**) Number should be: St 3/900.

constituents of the sample. Inclusions in the albite are generally arranged parallel to the schistosity, whether wavy or not. A random orientation is less common. In a few cases they are parallel to the crystal face 010.

3 AMPHIBOLES

Introduction

The types of amphiboles, that are found in the different types of rock in this region, are manifold.

Special investigations were made to improve our knowledge of the petrographical significance of these minerals. The amphiboles were grouped in the following categories:

Actinolite;

Blue-green amphibole with a large axial angle, described as blue-green amphibole;

Blue-green amphibole with a small axial angle, described as ferrohastingsite; Sodium-amphibole with the axial plane parallel to the c-axis, and positive elongation, described as glaucophane;

Sodium-amphibole with the axial plane transverse to the c-axis, described as crossite.

Actinolite

In the region under discussion the actinolites are more or less colourless to weak bluish green. Pleochroism is hardly to be observed. The axial angle is about 80°. The birefringence is generally larger than that of the

blue-green amphiboles, viz .02—.03. The extinction angle varies from 15°—25°. Extinction dispersion or axial dispersion has not been observed.

Blue-green amphibole (with a large axial angle)

Optical properties. — The following list of characteristics gives a general impression of the variability of this mineral:

c/nZ	from 10° to 25°	over a hundred measurements in thin sections, 15 measurements with the universal stage.
nZ—nX	from .012 to .025	over a hundred measurements with the Berek-compensator.
2V _x	from 48° to 80°	over a hundred estimates, 15 measurements with the universal stage.
nX	from 1.644 to 1.655	about ten measurements with an accuracy of 0.01, two measurements with an accuracy of 0.002.
nZ	from 1.66 to 1.67	(see nX).
Pleochroism:		
nX	yellowish, yellowish green.	
nY	green, olive-green, green with a tinge of violet.	
nZ	greenish blue, bluish green, blue-green.	

The blue-green amphiboles are always zonal, with the more pronounced colours either in the cores or in the rims. In a number of samples the cores of some prisms are built by glaucophane or ferrohastingsite. The blue-green amphiboles show a weak to marked extinction dispersion. The dispersion of the optical angle may be large or small, $r > v$ and $r < v$ were both observed. The optical properties of a number of blue-green amphiboles are listed in the following table 2. The localities of the samples are given in table 37 on page 596.

Table 2
Optical properties of some blue-green amphiboles

Sample		c/nZ	2V _x	nZ—nX	dispersion
LP	1	14°—20°	core 72° rim 80°	ca. .025	$r < v$
LP	4	ca. 14°	core 54° rim 61°	ca. .020	$r < v$
LP	4a	18°—19°	68°—72°	ca. .018	$r < v$
LP	5	19°—20°	ca. 64°	n.d.	$r > v$
LP	12	ca. 17°	ca. 78°	n.d.	nil
LP	14	18°—21°	58°—60°	ca. .016	nil
LP	15	18°—21°	ca. 65°	n.d.	$r < v$
LP	18	19°—21°	core 48°—56° rim 64°—72°	ca. .016	$r > v$
LP	24	18°—23°	65°—73°	ca. .021	$r < v$
LP	28	14°—17°	core 50° rim 55°	ca. .015	nil
LP	39	14°—15°	74°—75°	ca. .018	$r < v$
LP	112	12°—22°	58°—62°	.012—.024	$r < v$
LP	278	ca. 15°	71°—75°	ca. .018	$r < v$

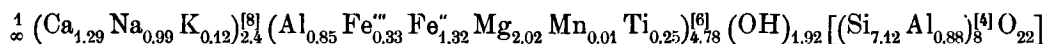
The results of a qualitative investigation of these amphiboles by means of ultraviolet light suggested a possible interrelation between the intensity of the red-luminescence and the sodium content. Actinolite for instance, hardly showed this typical red colour, blue-green amphiboles on the other hand showed a marked, but varying red-luminescence, while glaucophane showed the strongest intensity observed. This may link up with the observations of Melancholin (1956), who stated that the absorption spectrum of sodium-amphibole — which is mainly due to their content in Fe'' and Fe''' — shows a shifting from the infra-red to the visible red, due to the amount of sodium present.

Chemical composition. — Sample LP 112 provided the material for a chemical analysis carried out by Professor Dr Th. Hügi in the Petrochemical Institute of the University of Bern, Switzerland. As the amphiboles in our region are always zonal, it was impossible to find a sample with homogeneous amphibole crystals. Sample LP 112 forms no exception; furthermore the amphibole crystals occasionally show a core of glaucophane. It was selected because it contained about 60 % of a zonal blue-green amphibole with garnet and rutile as other main constituents, so that the amphibole could be easily extracted. The analysis should not be regarded as representing the chemical composition of one homogeneous member of the amphibole group. This analysis is given together with two other analyses of blue-green amphiboles with roughly similar optical properties. Of these two other analyses one (viz No 2) was used for the calculation of the chemical compositions of different types of rock in chapter V, because an analysis of the proper amphibole (No 3) was not available until just before the end of the preparation of the manuscript. The analyses No 2 and No 3 do not differ largely and the calculations were carried out with the assumption that actinolitic amphibole and blue-green amphibole have more or less the same composition.

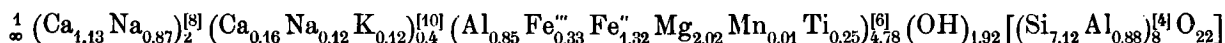
Table 3 illustrates that it is not easy to distinguish between blue-green actinolite, bluish common hornblende and blue-green amphibole with a higher sodium content. It seems that actinolite has a smaller refringence and a higher birefringence.

The chemical analysis of No 3 leads to the following formulae

following Machatschki (1953)



following Heritsch (1955)



The sum of Ca, Na and K is more than 2, as with barroisite, cf. Heritsch, Paulitsch and Eva M. Walitzi (1957). According to the formulae given above, the number of kations in the group with 6-coordination would be less than 5. The admixture of other minerals (garnet, rutile and albite) being less than 0.5 %, this deficiency might be due to inaccuracy of the analysis. According to Fumiko Shidô (1958), however, it is also possible to assume a slight admixture of $\text{Ca}_2\text{Ca}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$. Assuming such an admixture, the composition of the blue-green amphibole from Vals corresponds to a mixture of:

Table 3
Chemical analyses of some blue-green amphiboles

	No 1	No 2	No 3;	Kation aeq.	Kations/23 O.
SiO ₂	58.72	46.68	49.49	Si 8240	7.12
Al ₂ O ₃	2.02	14.37	10.08	Al 1998	1.73
Fe ₂ O ₃	1.76	4.00	3.01	Fe''' 378	0.33
FeO	9.68	8.29	11.00	Fe'' 1531	1.32
MnO	1.63	—	0.10	Mn 14	0.01
MgO	13.25	11.71	9.43	Mg 2339	2.02
CaO	10.30	10.32	8.40	Ca 1498	1.29
Na ₂ O	0.23	2.41	3.55	Na 1146	0.99
K ₂ O	0.02	1.06	0.63	K 134	0.12
H ₂ O ⁺		0.54	2.00	H 2220	1.92
H ₂ O ⁻	1.74	0.23	0.03		
TiO ₂	0.28	0.35	2.34	Ti 586	0.25
Sum	99.63	99.96	100.06		

No. 1. Blue-green actinolite, Iron Mt., Missouri; Allen & Fahey (1956)

No. 2. Blue-green amphibole, Umhausen, Austria; Hezner (1903)

No. 3. Blue-green amphibole, sample LP 112, Vals, tunnel section road Vals-Zervreila; analyst Th. Hügi.

No. 1. Optical prop.: 2V_x 80°; c/nZ 16°;

nX 1.631 colourless
nY 1.650 yellow-green
nZ 1.660 blue-green

No. 2. Optical prop.: 2V_x ?; c/nZ 21°;

nX greenish yellow
nY green
nZ blue-green

No. 3. Optical prop.: 2V_x 58°—62°; c/nZ 12°—22°;

nX 1.644—1.649 yellowish
nY 1.66 green
nZ 1.663—1.668 blue-green

46½%	$\text{Na}_2(\text{Mg, Fe, Mn})_3(\text{Al, Fe})_2\text{Si}_8\text{O}_{22}(\text{OH})_2$	glaucophane
18%	$(\text{Na, K})\text{Ca}_2(\text{Mg, Fe, Mn})_4(\text{Al, Fe})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$	hastingsite
1%	$\text{Ca}_2(\text{Mg, Fe, Mn})_3(\text{Al, Fe})_2\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$	tschermakite
25%	$\text{Ca}_2(\text{Mg, Fe, Mn})_4\text{TiSi}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$	titaniferous amphibole
41⅛%	$\text{Ca}_2(\text{Mg, Fe, Mn})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	actinolite
43⅞%	$\text{Ca}_2\text{Ca}_3\text{Si}_8\text{O}_{22}(\text{OH})_2$	
1%	rest	

Only part of the high content of glaucophane may be ascribed to the occasional presence of glaucophane cores within the analyzed crystals.

X-ray investigations. — X-ray powder data of the blue-green amphibole of sample LP 112, are given in table 4. There is only one reflection between $56\bar{1}$ and 600. This feature constitutes a difference with the group of the real sodium-amphiboles, cf. Zwaan et al. (1958). The unit-cell moreover is large in comparison with that of actinolites and sodium-amphiboles.

Table 4

X-ray powder data of a blue-green amphibole, Sample LP 112, Reg. No 1702, Fe K_α camera \varnothing 9 cm

d in Å	C^2h hkl	l	d in Å	C^2h hkl	l	d in Å	C^2h hkl	l
8.54	110	VS	2.72		VS	1.643	561	W
4.94		M	2.59		M	1.607		VW
4.50		M	2.54		M	1.582	600	W
3.89		W	2.33		MW	1.552		VW
3.40		S	2.28		MW	1.514		W
3.25		S	2.17		MW	1.495		VW
3.11		S	2.05		W	1.429		VW d.
2.95		M	2.01		W	1.338		W d.

Ferrohastingsite

Amphiboles with a pronounced blue colour, strong absorption, a small axial angle and positive or varying elongation were named ferrohastingsite, a name that may be given to these amphiboles if similarity of optical properties is assumed to indicate similarity of chemical composition. The optical properties of these amphiboles in the northern Adula region are generally:

$2V_x$	0° — 48°	axial plane normal to 010, $Z=b$.
$2V_x$	0° — 20°	axial plane parallel to 010, $Y=b$.
c/nY	20° — 30°	
c/nZ	12° — 20°	
nX	1.668	(one measurement only)
nZ	1.680	(one measurement only)

The above measurements were all carried out in Na light. Values for other wave-lengths may differ largely from these data. The extinction dispersion in day-light is large and comparable to that of imerinite from Madagascar.

The colour parallel to the c-axis is of a pronounced blue, the colours normal to the c-axis are olive-green ($=b$) and yellowish. The absorption is not so strong as in riebeckites. The dispersion of the optical axes is ex-

treme. In one case the difference between measurements made in Li light and those made in Na light was about 7° , viz $2V_{xLi} = 41^\circ$, $2V_{xNa} = 48^\circ$. Crossed dispersion may be present, but this was no further investigated.

The optical properties of ferrohastingsite, compiled by Billings (1928), are:

$2V_x$ 16° — 47° or small, $Z=b$ or $Y=b$, $r > v$ or $r < v$.
 c/nY 9° — 20°
 c/nZ 9° — 20°
 nX 1.693—1.705 yellow
 nY 1.710—1.731 deep bluish green or olive-green
 nZ 1.713—1.732 olive-green or deep bluish green.

The properties described by Sahama (1947) fit in with those given by Billings, he also emphasizes the high fluorine and chlorine content of these amphiboles. Recently Quensel (1958) reported again on these amphiboles, a. o. compiling optical data given by Rosenbusch and Sundius.

From these data it follows that the refringence of the ferrohastingsite of our region is rather low. The values of other properties conform with those found in literature on the subject. The optical properties of other members of the hastingsite group show less conformity with our measurements. The axial angle of femaghastingsite and magnesiohastingsite is always larger than 50° , Z of these minerals is brownish green and $Y=b$.

The minerals described by Billings, Sahama and Quensel as well as that, which was taken from the type locality (in a nepheline syenite of Hastings County, Ontario, Canada), are taken from igneous rocks. Ferrohastingsite from metamorphic rocks has been described by De Roever (1940) and Foslie (1945); chemical analyses are not available.

As ferrohastingsite has not yet been reported from Switzerland, it seemed worth while to carry out a chemical analysis. This analysis will be made in the Petrochemical Institute of Bern University, by Professor Dr Th. Hügi, and will be published later. The sample that provided the material to be examined is an albite rock, cutting through glaucophane-epidote-magnetite-ferrohastingsite-rocks. The albite has about 5 % of anorthite. The zonal amphibole prisms are about 2 cm long and 0.5 mm thick. The cores of these prisms have varying elongation, the rims a positive elongation.

The refractive indices given in the opening of this paragraph are measured on the cores of this material. The refringence of the rims seems to be higher.

Glaucophane and other sodium-amphiboles

The amphiboles with a violet colour parallel to the b -axis were called sodium-amphiboles. The name alkali-amphibole was not adopted, because the role of potassium in these amphiboles is the same as in other amphiboles. As the name soda-amphibole is a misnomer, cf. Howell (Glossary of geology and related sciences, 1957, p. 272, see soda) this name was discarded.

The sodium-amphiboles found in our region fall into group I of Miyashiro (1957), the riebeckite-glaucophane group.

The sodium-amphiboles of the northern Adula region are glaucophane in a wider sense and crossite.

Glaucophane, optical properties:

$2V_x$ 0° — 45° ; $r < v$; $Y=b$.
 c/nZ 4° — 21°

nX 1.620 (one measurement only)
 nZ 1.638 (one measurement only)
 nZ-nX .012—.020.

As these amphiboles are always zonal, the above values only fix the range of variation.

Crossite, optical properties:

$2V_x$ 0° — 13° ; $r > v$; $Z = b$.
 c/nY small
 nZ-nX .012—.015.

A description of the optical properties of an amphibole prism of sample T 116 illustrates why more detailed measurements cannot be given. This amphibole prism is built by a core of crossite and a rim of glaucophane. The orientation of the core is $Z = b$. The largest value of $2V_x$ in the core is about 12° . The axial angle decreases in an outward direction. A narrow nearly opaque zone between core and rim has an axial angle of 0° . The orientation changes to $Y = b$. The axial angle increases afterwards to about 30° . The absorption of the core is higher than that of the rim.

The chemical composition of these amphiboles has to be guessed from the optical properties. Enough homogeneous material for a chemical analysis could not be separated.

Occurrence

The blue-green amphiboles occur in every type of rock in the northern Adula region. In the phengite-gneisses they were found in about 10 thin sections of samples taken from various outcrops. The amphibole crystals in these rocks are rather small, about 0.06 mm, and are always enclosed in albite. The optical properties can easily be determined by using a high power immersion objective (100 \times).

In the schists and amphibolites the crystals of blue-green amphibole are occasionally enclosed in albite porphyroblasts; blue-green amphibole in porphyroblasts or even poeciloblasts is a normal or main constituent. Occasionally the blue-green amphibole shows a purplish green core, also glaucophane cores appear. In the amphibolites it sometimes builds large poeciloblasts (0.5 cm) studded with euhedral garnets and epidotes. Patches of pyroxene having the same extinction position throughout the amphibole crystals in which they are enclosed, point to an amphibole pseudomorphous after pyroxene. In the ophiolites blue-green amphibole associates with rather weak-coloured amphibole and is often found building the cores of this actinolite-like amphibole.

Actinolite is a main constituent of some actinolite rocks from the Val Calanca and frequently occurs in the ophiolites. In some of the amphibolites it forms rims around the other amphiboles and occasionally the blue-green amphiboles show irregular patches of a colourless amphibole.

Glaucophane is a minor constituent of some mica-schists and can also be observed within the amphibolites, e.g., as armoured relics in epidote or garnet. In the mica-schists it is partially transformed into a blue-green amphibole. In some ophiolites or in rocks that presumably derived from ophiolites, glaucophane is common, having rims of blue-green amphibole or actinolite as in the case of the ophiolite found near Nufenen, cf. Nabholz (1945). Cores of crossite can be seen in some rocks that show well-developed glaucophane.

Ferrohastingsite with strong colours and a small axial angle was found in rims around glaucophane near the Hobbühl and as a minor constituent of some amphibolites on the pass of San Bernardino, where it occurs as cores amidst blue-green amphibole or as armoured relics in garnet.

4 ANHYDRITE

Anhydrite was discovered in the waterdrift Ampervreila-Peil. It is still to be found on the dumps at both ends of the tunnel. It appears either in coarse-grained monomineralic samples or as large crystals in a kind of mica-schist. These large crystals form boudins together with gypsum, quartz, chlorite and muscovite. The crystals show the faces 001, 010 and 100. They are pellucid and have a violet colour, reaching dimensions of over 2 cm. Fig. 10 shows such a boudin with a well-shaped anhydrite crystal in the right corner.

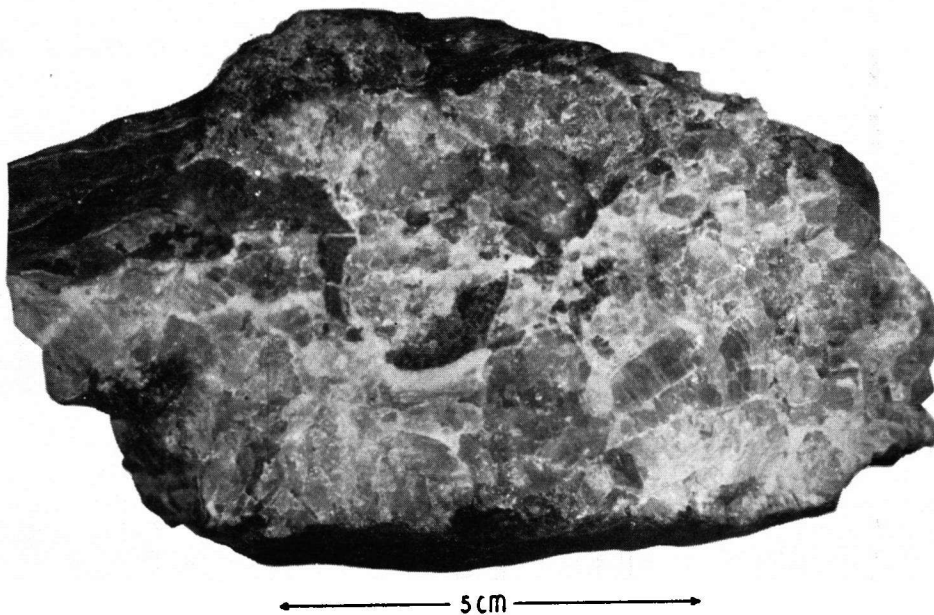


Fig. 10. Anhydrite in a specimen holding quartz, chlorite and gypsum. The sugar-grained gypsum fills the cracks in the euhedral anhydrite crystals.

5 APATITE

A normal accessory of the rocks is apatite. The crystals are nearly always rounded. At one time rounded saucer-shaped crystals as large as 1 cm were found in the "pseudodiorite" of Peil. The optical properties of this apatite are: n between 1.635 and 1.647, uniaxial negative, birefringence low.

6 BIOTITES

For our purpose it was sufficient to distinguish between the different kinds of biotite on the basis of their colour. According to Hall (1941) the

colour of biotites is essentially due to their chemical composition, whereas it is impossible to determine the chemical composition from the refringence. On the other hand it may well be that the chemical composition of biotites largely depends on the physical circumstances that caused their formation, for red-brown biotites (rich in Ti, cf. Hall) are nearly always found in granites and high-grade metamorphic rocks, whereas green biotites are frequently found in low-grade metamorphic rocks.

The biotites encountered in the northern Adula can be placed in four groups:

- Red-brown biotites
- Olive-green to greenish brown biotites
- Green biotites
- Colourless to weak-coloured biotites, viz phlogopites

So far it has been impossible to distinguish between ferrostilpnomelane and green biotite by optical methods. It may, however, be assumed that some of the green biotites, especially when the mottled effect (birds-eye structure) is absent, are ferrostilpnomelane. This is still to be proved by X-ray powder photographs. Of late, E. Niggli has reported stilpnomelane from various localities in the Swiss Alps. These localities are found in a zone north of the chloritoid zone first described by E. Niggli (see van der Plas et al. 1958). Therefore it seems unlikely that stilpnomelane can be found in the region under review. On the other hand Streckeisen and E. Niggli (1958) reported the occurrence of stilpnomelane in a phengite-gneiss from Wallis. Up till now the association chloritoid-ferrostilpnomelane has not been reported. One of the characteristics of the greenish biotites is their small axial angle, a feature that may also be found in stilpnomelane (a. o., Netelbeek 1951). Glaucophane schists of the Valserschuppen occasionally contain a conspicuous brownish flaky mineral with strong pleochroism. It could be argued that this mineral is ferristilpnomelane.

The red-brown biotite is found in the mica-schists, seldom in the amphibolites and rarely in the phengite-gneisses. The brown to olive-green specimens are the common biotites in the amphibolites and schists; the green biotites occur in every type of rock; the phlogopites occur in some metamorphic dolomites. The brown and sometimes reddish brown biotites of the rocks occurring in the Val Calanca build fringes around muscovite and have grown in veinlets that cut, a. o., blue-green amphibole. The green biotites form fringes and rims along the minerals amphibole, muscovite, phengite, garnet and biotites of the other types.

7 CARBONATES

Calcite

Calcite is a common constituent of the rocks in this region. Well-developed crystals are rarely to be found in veins. Calcite is generally of secondary origin in the gneisses, schists and amphibolites but is a main constituent of many Mesozoic rocks.

Cobalt-bearing calcite

In the neighbourhood of Soladüra, a small group of huts just north of Vals (the locality lies outside the mapped region), a pink vein-filling mineral

was found in a rock that may be described as a mixture between "Bündnerschiefer" and ophiolites (ophiolites of mixed origin, cf. Nabholz 1945). The mineral is soluble in cold dilute hydrochloric acid and shows rhombohedral outlines. The X-ray powder pattern and the optical properties are identical with those of calcite. Microchemical analysis showed a relatively high content of cobalt and a trace of zinc. This type of calcite is not unknown in the south-east of Switzerland and has a.o. been described by Günthert (1954) from Gheiba in Val Peccia.

Dolomite

Dolomite is a common constituent of the Mesozoic dolomites. Only once a small (1 cm) rhombohedron with curved faces was found in a kind of tension joint.

Siderite

Siderite, found in some Mesozoic quartzites, very often associates with chloritoid in these rocks. It was determined by its refringence.

8 CHALCOPYRITE

Chalcopyrite is locally found in the amphibolites and the ophiolites. Weathering occasionally produces a greenish cover on these rocks whenever aggregates of chalcopyrite are near. The aggregates of chalcopyrite never reach dimensions of more than 1 cm.

9 CHLORITES

Chlorites are to be found in nearly every sample taken from the region under discussion. The interference colours are normal grey, abnormal blue or abnormal brown. The pleochroism is from yellow to green and may be strong, moderate or weak. A large number of birefringences were measured with a Berek-compensator and the rapid graphical method suggested by Tobi (1954). They range from .002 to .008. The axial angle varies from 0° to 40° . Grouping these measurements the following 5 groups are distinguished:

- | | | | | | | |
|----|------------|------------------|-----------|--------------|-------------|-----------------|
| 1) | $2V_x$ | small; | $nZ - nX$ | .002 — .007; | pleochroism | yellow to green |
| 2) | $2V_z$ | small; | $nZ - nX$ | .002 — .005; | „ | yellow to green |
| 3) | $2V_z$ | ca. 20° ; | $nZ - nX$ | .002 — .006; | „ | yellow to green |
| 4) | $2V_z$ | ca. 40° ; | $nZ - nX$ | .002 — .006; | „ | yellow to green |
| 5) | $2V_{x/z}$ | small; | $nZ - nX$ | .002 — .006; | colourless | |

Measurements of refractive indices were only made for 13 samples, cf. table 5.

Miyashiro (1957) calls attention to the fact, that Winchell's diagrams for the optical determination of chlorites are constructed as if all chlorites are orthochlorites. We may leave his objection for what it is, as there is no better diagram available. It seems likely that most chlorites of the northern Adula region belong to the ripidolite, diabantite, prochlorite, rumpfite, brunsvigite and jenkinsite groups of Winchell's classification (1951).

Müller (1958) assumes the prochlorites to be rich in magnesium because of their n_Y being about 1.62.

TABLE 5
Optical properties of a number of chlorites

Sample	axial angle	n _Y	n _Z —n _X	colour	name	rock type
LP 18	2V _Z ca. 10°	1.61—1.62	.007, normal grey	yellow to green	PROCHLORITE	epidote-chlorite-rock with euhedral albite
LP 32	2V _X ?	1.63	.003, abnormal violet	yellow to green	DIABANTITE	amphibole-bearing mica-schist
LP 95	2V _Z 10°—20°	1.59—1.61	.002, abnormal brown	yellow to green	RUMPHITE	glaucophanes-bearing mica-schist
LP 164	2V _X ca. 4°	1.60	.007, normal grey	weak green	JENKINSITE	amphibolite
LP 168	2V _Z 0°—10°	1.61—1.63	.003, abnormal brown	yellow to green	RIPIDOLITE	albite-bearing mica-schist
LP 170	2V _Z 0°	1.62	.003, abnormal brown	weak green	RIPIDOLITE	amphibolite
LP 204	2V _Z 0°	1.61	.007, normal grey	weak in green	PROCHLORITE	albite-chlorite-schist
LP 276	2V _X ca. 10°	1.63	.008, normal grey	yellow-brown	BRUNSVIGITE	chloritoid-bearing mica-schist
LP 380	2V _Z 30°—40°	1.61—1.63	.006, abnormal brown	yellow to green	PROCHLORITE	glaucophanes-bearing amphibolite
LP 555	2V _Z small	1.61—1.63	.004, normal grey	green	RIPIDOLITE	ophiolite
A 15	2V _Z 0°	1.61—1.63	.006, normal grey	yellow to green	PROCHLORITE	chlorite-mica-schist
T 10	2V _X 0°	1.61—1.63	.002, abnormal blue	yellow to green	DIABANTITE	greenschist
T 207	2V _Z 30°—40°	1.61	.003, abnormal brown	yellow to green	RUMPHITE	amphibolite
Id.	2V _X 0°—10°	1.61—1.63	.006, normal grey	yellow-brown		

Chlorite is generally found as an alteration product of the biotites, garnets, amphiboles, muscovites and phengites. Some boulders of serpentinite found in the Valserrhein are exclusively built of antigorite.

10 CHLORITOID

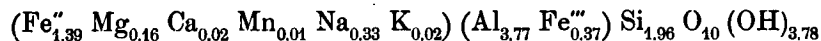
Chloritoid is found enclosed in garnets of the mica-schists, amphibolites and Mesozoic sedimentary rocks. In Mesozoic quartzites and calcareous schists it is found in composite poeciloblasts together with kyanite and garnet. The mineral was also found in separate crystals in a mica-schist. Descriptions dealing with these aspects of chloritoid are found in chapter IV.

Large chloritoid crystals (up to more than 2 cm) occur in some samples. Such crystals from the Hennensädel (coord. 7306—1592) were the subject of a thorough investigation, in which members of the staff of the Petrographical and Mineralogical Institute of the University of Bern participated (van der Plas, Hügi, Mladeck and E. Niggli, 1958). A summary of the results of this investigation follows here for completeness' sake.

Table 6
Chemical analysis of chloritoid from Hennensädel

SiO ₂	23.92	Analyst: Th. Hügi, Bern
Al ₂ O ₃	39.13	S. G. 3.57
Fe ₂ O ₃	6.01	The value of Fe ₂ O ₃ and the value of H ₂ O ⁺ were checked by thermogravimetric analysis. The loss of weight at 1050° C is 4.70%.
FeO	20.38	
MgO	1.35	This figure is also found by the subtraction: 6.92—2.27 (the amount of H ₂ O ⁺ and the amount of oxygen necessary to oxidize 20.38% FeO).
CaO	0.20	
Na ₂ O	2.08	
K ₂ O	0.15	
TiO ₂	tr.	
H ₂ O ⁺	6.92	
Sum	100.28	

The chemical analysis leads to the following formula:



D. T. A. and thermogravimetric analysis. — Miss Dr E. Jäger made two D. T. A. analyses and one thermogravimetric analysis. D. T. A. showed an endothermic reaction at 770°C, due to loss of H₂O. Thermogravimetric analysis showed a rapid loss of weight, starting at about 650°C. The mineral did not melt at 1050°C and an X-ray powder photograph of the powder after heating showed the structure being partly disturbed. The same was reported by Bachmann (1956).

Optical properties. — Anna Hietanen (1951) and Snelling (1956) have reported optically monoclinic and optically triclinic chloritoid. Halferdahl (1957) proved the existence of both triclinic and monoclinic chloritoid by X-ray methods. Optical investigation of the chloritoid from Hennensädel shows the presence of both polymorphs. Both the monoclinic and the triclinic crystals show polysynthetic twins, with 001 as composition face. It

could not be established optically whether a structural law determines the way triclinic and monoclinic crystals are intergrown. Both polymorphs show the following optical properties:

nX 1.720 $2V_z$ ranges from 54° to 69° .
 nY 1.723
 nZ 1.727

Pleochroism:

nX light yellowish green
 nY slaty blue
 nZ light greyish brown

In the monoclinic crystals $X=b$, the triclinic polymorph shows $X \wedge 001 = 3^\circ\text{--}12^\circ$.

Snelling (1956) observed that the refringence of chloritoid decreases with an increasing amount of Mg. It might, however, be suggested that the Al—(Fe + Mg) ratio also contributes to this trend, because ranking of the known chemical analyses of chloritoid in order of increasing refringence, does not indicate a simple relation between the amount of Mg and the refringence.

X-ray investigations. — Mounting minute chloritoid flakes with an average diameter of 0.1 mm in a "Waldmann" sphere (Waldmann 1947), it was possible to isolate crystals that were either optically monoclinic or triclinic. Afterwards these flakes were mounted on a goniometer head, in such a way that nY was parallel to the glass specimen holder of the goniometer. The triclinic flakes had to be readjusted, in order to give a useful Weissenberg photograph. The Weissenberg and tilted-crystal photographs were made by Mr M. H. Mladeck. His results are similar to those of Halferdahl (1957), see below.

X-ray powder photographs of a mixture of both polymorphs from Vals and of triclinic and monoclinic chloritoid, kindly put at our disposal by Dr L. B. Halferdahl, were compared. The chloritoid of Vals shows characteristics of both triclinic and monoclinic patterns. Many reflections are broad and diffuse, as a result of the mixing of both polymorphs.

X-ray data for the reciprocal cell of chloritoid from Hennensädel

Monoclinic: ($X=b$)	Triclinic: ($Y \approx a$; $X \wedge 001 = 3^\circ\text{--}12^\circ$)
b^* 0.181	b^* 0.183
c^* 0.056	c^* 0.112
α^* $90^\circ 0'$	α^* ca. 83°

In the X-ray diagram the monoclinic polymorph furnished by Dr Halferdahl shows an intensive double reflection at 2.35 Å and 2.29 Å, whereas the triclinic polymorph shows four weak reflections at about 2.35 Å and 2.29 Å, due to splitting up. These samples came from:

Monoclinic: Üstüağıksarınç, Turkey;

Triclinic: Chibougamau, Quebec (optically negative).

11 EPIDOTE AND ZOISITE

Members of the epidote group are normal constituents of the rocks in the region under consideration. Zoisite is not common.

Epidote is occasionally found in more or less monomineralic rocks, embedded in amphibolite masses, or as well-developed prisms of more than 4 cm in veins with clear quartz (near Peil and underneath the top of the Weissgrätli). In some cases pleochroic epidotes are found, having Z yellow and Y colourless or violet with a brownish tinge. In the phengite-gneisses the cores of the epidotes are occasionally built by a brownish orthitic variety, at times surrounded by a pleochroic halo.

Table 7

X-ray Powder data of chloritoid from the Hennensädel, Vals, FeK α radiation, camera \varnothing 9 cm

		Heated to 1050° (Reg. No 2410)	
d in Å	I	d in Å	I
4.90	VW	5.43	M
4.69	VW		
4.43	VS	3.41	VS d
3.08	MW		
2.96	M	2.89	W
2.69	M d*	2.70	W
2.60	W d	2.56	W d
2.45	M d	2.51	W
2.35	M	2.45	S d
2.29	M	2.22	W
2.11	W	2.08	VW
1.872	W	1.53	W
1.742	VW d	1.44	W
1.578	S		
1.553	M d		
1.502	VW d		
1.479	W d		
1.469	W		
1.402	W d		
1.381	VW d		
1.363	S d		

*) d means diffuse

Clinozoisite can be found in thin sections of all rock types and is frequently encountered in the ophiolites. Specimens of ophiolites occasionally show aggregates of clinozoisite as large as one foot. The colour of this mineral in these aggregates is like that of brown sugar.

Some schists and amphibolites contain iron-free *zoisite* as well as zoisite with some Fe₂O₃. Zoisite is of common occurrence in some Mesozoic rocks and is relatively rare in the other types. Green to grass-green prisms of zoisite can be found on the eastern slope of the Hennensädel in a small outcrop of amphibolites underneath a band of calciferous mica-schist. These prisms contain two-phase inclusions that can be seen with a handlens.

12 FAHLORE

Some fahlore was found in a large quartz vein on the Ampervreila Alp. The dolomites in which this vein occurs show small aggregates of malachite and azurite in the parts bordering the vein.

13 GALENA

Occasionally the mica-schists hold small cubes of galena. A study of a few thin sections showed them to be commonly associated with tourmaline. The mineral is of late origin in these schists. Galena can also be found in large quartz veins.

14 GARNETS

As the chemical composition of a garnet can only roughly be determined from its physical properties, a chemical analysis was made of the most frequent type of garnet. The composition of the other garnets was roughly determined using the following physical properties:

Density
Index of refraction
Unit-cell size

To determine the index of refraction the Cargille set of index liquids was used together with a Leitz-Jelley refractometer. The determinations were carried out in Na light. The density was approximately determined with the balance of Westphal and dilute Clerici solution. The unit-cell size was measured from X-ray powder photographs (FeK_α radiation, Bradley camera). To determine the unit-cell size starting from the distances between the reflections 4100; 2410; 880 a graphical method, suggested by Mr. P. Floor (personal communication 1958), was used with good results.

An approximate determination of the chemical composition was made with the aid of the graphs of Frietsch (1957), as well as the graphs of Winchell (1951). As the manganese content still remained uncertain, a few quantitative manganese analyses were made by Professor Dr Th. Hügi and by the author. The data thus obtained are grouped in table 8.

In all specimens of which the Mn content was determined, the amount of the spessartite molecule appears to be low. The garnet of sample L 5, is particularly poor in Mn. According to its paragenesis this garnet, in contrast to the others might be of pre-Alpine age. It is not impossible, that future investigations will prove that the Alpine and pre-Alpine garnets of the investigated region can be distinguished with the aid of their Mn content.

The unit-cell size is largest in the garnets found in the phengite-gneisses (11.65—11.73 Å), smaller and rather constant in those of the amphibolites (11.58—11.63 Å) and it reaches a minimum in some garnets of the mica-schists (11.52, 11.55 and 11.56 Å), while some other garnets of these rocks show unit-cell sizes of up to 11.60 Å.

The garnets in the phengite-gneisses, especially those in the specimens M 114 and LP 299, with $a_0 = 11.73$ Å and 11.72 Å respectively, must be rather rich in grossularite.

The refringence is commonly between 1.785 and 1.81, but is distinctly smaller in the grossularite-rich garnets of the phengite-gneisses M 114 and LP 299, viz 1.775—1.79, and in the garnets of two specimens of the group of the amphibolites and allied rocks, viz LP 243 and LP 523. The first sample, an amphibolite of the Weissgrätli, is assumed to be a transformed ophiolite, the second one is a sodium-pyroxene rock in which the pyroxene and the garnet are of contemporary origin.

Chemical composition. — Sample LP 295 was selected to provide the material for a chemical analysis. From this sample euhedral crystals of garnet, embedded in a loose fabric of muscovite and some amphibole prisms, were easy to separate. Sodium-pyroxene (p. 479) is also found in this sample, in lenticular aggregates. This pyroxene, however, was never found in direct contact with the garnetiferous parts of the sample. The transparent euhedral garnet has a grain size of about 0.8 mm. It is seldom intergrown with amphibole or muscovite. The sample was crushed, the still euhedral garnets were separated from the rest by using heavy liquids. The remainder was purified with an isodynamic separator. The concentrate of euhedral garnets — all

Table 8
Physical data of a number of garnets

Reg. No. *)	Sample **)	S.G.	n	α_c	MnO in weight %
Mica-schists					
2253	LP 96	< 3.79	1.79 — 1.80	11.56	n.d.
2264	LP 550	n. d.	1.80 — 1.81	11.58	n.d.
2262	L 5	3.90	1.795 — 1.805	11.60	0.02
2263	LP 2	4.02	1.80 — 1.81	11.52	1.33
2270	LP 134	4.00	1.795 — 1.81	11.55	n.d.
2370	M 373	n. d.	1.795 — 1.805	11.60	n.d.
Amphibolites and allied rocks					
2252	LP 112	3.93	1.79 — 1.80	11.63	1.21
2254	LP 116b	3.93	1.785 — 1.795	11.62	n.d.
2259	LP 295	3.95	1.79 — 1.80	11.62	1.30
2260	LP 497	3.95	1.795 — 1.805	11.60	n.d.
2267	LP 247	4.02	1.795 — 1.805	11.58	n.d.
2268	LP 434	3.93	1.785 — 1.795	11.59	2.62
2269	LP 227	3.86	1.785 — 1.795	11.59	n.d.
2369	M 395	n. d.	1.79 — 1.80	11.60	n.d.
2255	LP 523	4.03	1.76 — 1.77	11.58	n.d.
2265	LP 243	3.80	1.775 — 1.785	11.61	n.d.
Phengite-gneisses					
2368	M 114	n. d.	1.78 — 1.79	11.73	n.d.
2378	LP 84	n. d.	1.795 — 1.805	11.65	n.d.
2379	LP 299	n. d.	1.775 — 1.785	11.72	n.d.

*) Registration number of X-ray photographs, collection Leiden Institute.

**) For the location of the samples see table 37, page 596.

about the same size — was examined with a binocular microscope and those crystals that still showed inclusions or other impurities were removed by hand-picking. The result was a sample of about 12 grams. Part of this sample was ground into extremely fine powder and analyzed. The values for MnO, MgO, CaO, Na₂O, TiO₂ and P₂O₅ were determined three times in different parts of the sample.

Total iron as Fe₂O₃ was determined three times in different samples of purified garnet material. The results were:

Colorimetric analysis	30.68 wght %	}	Mean: 31.28 wght %
Gravimetric analysis	32.11 wght %		
Titrimetric analysis	31.05 wght %		

The FeO content found with the aid of current methods appeared to be too low to fit in with a garnet formula. As various authors think it impossible (a. o. Jakob 1952, p. 160) to obtain by these methods a fair estimate of the ratio FeO—Fe₂O₃, a special procedure was followed. Part of the sample was pulverized in a CO₂ atmosphere. The water content was determined twice with great care. After this some of this extremely fine powder was put in a crucible of SiO₂ glass and weighed carefully, whereupon the powder was heated to about 1100° C. Then it was weighed again and the loss of weight, due to dehydration and the oxidation of FeO, was used to calculate the amount of FeO.

During experiments, carried out in the chemical laboratory of the Geological Institute of the Leiden University (leader Mrs. C. M. de Sitter—Koomans) we found that this garnet did not increase in weight during pulverization: Even heating up to 110°C for more than one hour in a normal atmosphere, did not have a measurable effect. Only after five days of heating the sample up to about 1100°C, did the weight of the sample remain constant. In table 9 the chemical analysis is given together with the analysis of an almost similar garnet, published by Iris Y. Borg (1956). This garnet was analyzed according to current methods (Miss I. Y. Borg, personal communication, 1959), the FeO—Fe₂O₃ ratio may thus be slightly wrong, as calculation of the formula confirms, see Borg (1956, p. 1571).

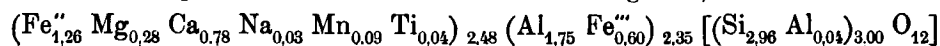
Table 9
Chemical analysis of some garnets

	No 1	No 2		Kation aeq.	Kations/ 12 O
SiO ₂	37.26	37.46	Si	0.6237	2.96
Al ₂ O ₃	20.12	19.24	Al	0.3774	1.79
Fe ₂ O ₃	2.60	10.14	Fe'''	0.1270	0.60
FeO	25.18	19.02	Fe''	0.2648	1.26
MnO	0.92	1.30	Mn	0.0183	0.09
MgO	2.96	2.40	Mg	0.0595	0.28
CaO	9.83	9.22	Ca	0.1644	0.78
Na ₂ O	n.d.	0.20	Na	0.0064	0.03
K ₂ O	n.d.	tr.			
H ₂ O ⁺	0.09	0.08			
H ₂ O ⁻	0.04	0.05			
TiO ₂	0.54	0.67	Ti	0.0084	0.04
P ₂ O ₅	n.d.	0.08			
Sum	99.54	99.86			7.83

No 1. Garnet from eclogite, Healdsburg, Cal., U.S.A. Analyst: W. Herdsman. Lit. Iris Y. Borg (1956).

No 2. Garnet of sample LP 295, Ampervreila, Vals, Graubünden. Analyst: Mrs C. M. de Sitter-Koomans.

In spite of precautions taken in analyzing the FeO—Fe₂O₃ ratio, the formula does not correspond to the structural formula of a garnet, viz:



If, however, the highest figure of total iron, viz 32.11 wght %, is taken and if the surplus in the sum of the analysis, viz 2.81 % is assumed to represent the increase of weight through oxidation, we arrive at the following values:

FeO	25.23 wght %
Fe ₂ O ₃	4.07 wght %

With these figures the formula corresponds approximately to theoretical demands. From the values thus obtained, the following proportions of participating molecules of end-members were calculated. The values of analysis No 1 are also listed.

Mole per cent of end-members:

	No 2	No 1
Pyrope	10	12
Almandite	59	57
Spessartite	3	2
Andradite	12	10
Grossularite	16	19

The physical properties of both garnets mentioned above are listed below:

No	n	a ₀	S.G. measured	S.G. calculated
1	1.795	11.62	4.08 ± 0.02	4.044
2	1.794	11.62	3.95 ± 0.05	4.070

The theoretical density was calculated from Skinner's values for end-members of the garnet group, cf. Skinner (1956).

Occurrence. — The grossularite garnets in the phengite-gneisses are small and have corroded outlines. The garnets in the schists and in the amphibolites belong to at least two generations. The first generation is cataclastic. Clastic crystals with sizes up to 1 cm show rims of biotite, occasionally chloritized. The garnets within these haloes of phyllosilicates and their alteration products have cracks transverse to the schistosity plane. In other cases the crystals are broken up and smeared out in patches consisting of fragments of garnet, quartz, chlorite and epidote, with small crystals of sphene. Pseudomorphs composed of chlorite, epidote, sphene and ore are visible whenever chloritization is strong. Occasionally the clastic fragments show new growth with idioblastic outlines (LP 4). The rims of this newly built garnet, however, are pink whereas the old fragment is reddish.

There are also small euhedral garnets within albite porphyroblasts, often showing a dusty core. A special type is the atoll garnet (cf. Forster 1947) found in some pyroxene rocks. Its cavity is filled up with muscovite and quartz. The atoll garnets are often enclosed in amphibole pseudomorphs after pyroxene.

The inclusions in the garnets give ample information as to the course of metamorphism. The following enclosed minerals can be found: glaucophane, chloritoid, blue-green amphibole, epidote, biotite, muscovite, tourmaline, rutile, quartz and apatite. In some cases these minerals are not to be found in the rest of the sample, this pointing to a relation in time,

15 GYPSUM

Fresh outcrops of some dolomites occasionally show small caverns in which water-clear gypsum crystals are visible. If the rock is only slightly weathered these crystals have generally disappeared. The waterdrift Ampervreila-Peil yielded hand-specimens of sugar-grained white gypsum with clear euhedral quartz crystals. Water pouring out of this tunnel has an extremely high content of SO_4 ions, due to solution of gypsum and anhydrite. Also Müller found this mineral on the Weissgrätli.

16 HEMATITE

Hematite is a normal accessory of the amphibolites, mica-schists and ophiolites. It can also be found in other rocks. Joints are often lined with hematite.

17 KYANITE

Kyanite is found in association with chloritoid. It can be found as distorted prisms (length up to 5 cm) in spools and rods exclusively built of quartz, chloritoid and kyanite, and as small prisms in quartzites. It is occasionally sericitized. The optical properties are:

$2V_x$ about 80°	Twining on 001 may frequently be
n_X 1.71	observed, the crystals are nearly
n_Z 1.73	always bent.

18 MAGNETITE

Small octahedrons of magnetite appear on joint planes in different types of rock. Mica-schists on the western slope of the Valserrhein valley locally contain nodules of magnetite. Magnetite is a minor constituent of some mafic rocks.

19 MICROCLINE AND ORTHOCLASE

Microcline was only encountered in the phengite-gneisses and in a few samples of Mesozoic quartzites and dolomites.

The average microcline content of the gneisses is about 10 %. The highest values of about 20 % can be measured in the Zervreila gneiss as well as in some ribbon gneisses. Near the contact with the adjoining rocks (mainly mica-schists) the microcline content of the gneisses decreases rapidly and this value reaches zero in the nearest vicinity of the contact. This holds true for the Zervreila gneiss-body as well as for the gneiss bands in the higher structural units. In these bands and in some narrow parts of the "apophyses" described by Müller (1958), microcline was never found. The microcline crystals are clear and there is no trace of alteration. The well-developed quadrille structure is sometimes distorted and wavy owing to mechanical disturbance.

With a high power objective it is possible to distinguish negative crystals, filled with liquid and a small gaseous bubble. The bubbles are movable and occasionally show Brownian motion. The size of the negative crystals ranges from 0.001–0.003 mm. Other liquid inclusions appearing as feathers and droplets are found in some samples. Both liquid and gas seem to be H_2O . These low temperature inclusions may be of secondary origin. When the

microcline shows the influence of subsequent mechanical disturbance, the cavities are mostly empty and appear as dark spots.

The following minerals are enclosed in the microcline crystals of the gneisses: quartz, albite, phengite, green biotite, garnet, apatite and sodium-pyroxene. Some of the enclosed albite is in granoblasts, twinned according to the same laws as described in paragraph 2. In some samples two generations of potassium-feldspar can be observed. The somewhat dusty orthoclase porphyroclasts of the "Augen", occasionally showing microclinization, perhaps due to mechanical disturbance, belong to an older generation. The small granoblasts with splendid twins seem to be of more recent date. Perthitic albite is not common in the microcline. The grain size of the potassium-feldspar ranges from 0.2 mm in the matrix up to 2 cm in the large porphyroclasts.

In the Mesozoic sediments, microcline is occasionally found. In sample LP 234, a phengite-bearing dolomite, anhedral microcline crystals appear, having the same size as the dolomite crystals, viz about 0.3 mm. From their outlines it is evident, that these microcline crystals are not detrital. For comparison slightly metamorphic calciferous sediments, with detritic potassium-feldspar, from the zone of Lunchania - Piz Terri (cf. Nabholz 1945) were studied. These sediments occasionally hold a crystal of microcline. This microcline, however, is dusty, highly sericitized and partly transformed into chess-board albite. The quartzites found near the waterintake of the waterdrift Ampervreila - Peil, coord. 7309—1611, and the quartzite in the section DD below the dolomites near point 1991 show an occasional microcline porphyroblast. These porphyroblasts are studded with small quartz crystals, still arranged according to a more or less stratified pattern similar to that found outside the porphyroblasts.

Orthoclase may be found as large porphyroclasts in those phengite-gneisses that form a continuous band from the Dachberg to Leis. These gneisses are highly mylonitized, as was shown in chapter IV, p. 487. The orthoclase was determined with the aid of the universal stage, by means of its monoclinic optics.

20 MUSCOVITE

Introduction

Muscovite proper is nearly always present in the rocks of the region under consideration. Paragonite was not found. Even the mica of some sodium-pyroxene rocks proved to be muscovite. Phengite gives the gneisses their characteristic green colour. A mica with a conspicuous red colour was found at one locality; its chemical composition points to a ferrian *) phengite.

The colourless mica of some schists and amphibolites is the end-product of a process that is often described as the bleaching of biotite. In that case the mica has a small axial angle.

In some cases the mica shows a fan-like extinction due to late mechanical influence. The presence of green or brown biotite building fringes around the mica flakes is a striking feature. The grain size of the mica varies from 0.1 mm to more than 2 cm. The mica content of the gneisses is about 20 %, ranging at least from 3 to 25 %; of the mica-schists about 40 %; of the amphibolites about 12 %.

*) Dana, System of Mineralogy, Vol. I, 1944, p. 43—44.

Muscovite proper

The optical properties of a number of colourless micas were measured, and four samples were subjected to X-ray investigation by Professor Dr E. Niggli. In the case of these minerals, special care was taken, because the colourless micas in comparable regions, after optical and/or X-ray examination, proved in a number of cases to be either margarite or paragonite. The optical properties of the colourless mica are:
 $2V_x$ 35° — 40° ; $n_Y \leq 1.63$; $n_Z - n_X$ about .035—.045 and occasionally even slightly higher.

X-ray powder data show the normal muscovite pattern, differing notably from the paragonite pattern.

Occasionally the muscovites in our region have a weak greenish or yellowish pleochroism. In a few cases they are chloritized. A chemical analysis of muscovite proper from this region is not available. An analysis of muscovite from the neighbouring Val Calanca is given as No 3 in table 23.

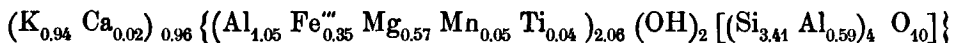
Ferrian phengite

In the Ebene Runse, coord. 7302—1588, alt. 2225 m, a ribbon marble crops out, showing greenish bands alternating with pink bands. The colour of these bands is due to red and green mica. The green mica has optical properties more or less similar to those of normal phengite. The red mica was studied in detail. Its optical properties are:
 n_Z and n_Y between 1.60 and 1.63; $n_Z - n_X$ about .05;
 $2V_x$ varies from 32° — 43° , $r \gg v$; n_X is colourless; n_Y and n_Z are yellowish pink and pink, respectively. The mineral is slightly zonal. These optical properties differ from those of ferrimuscovite (cf. Winchell 1951), viz n_Y ca. 1.66; $2V_x$ 38° ; $n_Z - n_X$ ca. .06.

An X-ray powder diagram of this red mica is given in table 11. Comparison with the powder diagram of a synthetic 2M polymorph of muscovite (Yoder and Eugster 1955), proves that the unit-cell of this red mica is somewhat smaller than that of the synthetic muscovite. The red mica may be assumed to represent also a 2M polymorph.

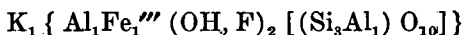
A chemical analysis of this mica was made by Mrs. C. M. de Sitter—Koomans. The results are given in table 10.

The analysis, calculated on the anhydrous basis of 11 O, leads to the following structural formula:

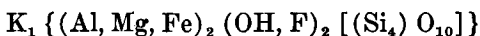


N.B. $H = 1.24$, which may account for the low total of the analysis. From the formula it follows that this mica consists roughly of one part of ferri-muscovite and two parts of phengite, if the following formulae are used:

Ferrimuscovite (Winchell, 1951):



Phengite (Machatschki, 1953):



Phengite proper

Phengite proper is a main constituent of the phengite-gneisses and of some Mesozoic rocks. The identification of phengite is rather difficult, since the refringence and birefringence are similar to those of muscovite. The phengite is greenish in thin section, with a faint pleochroism. One of the main characteristics is the rather small axial angle of this mineral in a number of cases. Still this small axial angle is by no means a characteristic of all the phengites. Müller (1958, p. 427) illustrates clearly that phengite

Table 10
Chemical analysis of ferrian phengite, from Heinisch Stafel

			Kation aeq.	Kations/ 11 O
SiO ₂	50.50	Si	0.8408	3.41
Al ₂ O ₃	20.57	Al	0.4036	1.64
Fe ₂ O ₃	6.95	Fe ⁺⁺⁺	0.0870	0.35
FeO	nil			
MnO	0.82	Mn	0.0116	0.05
MgO	5.68	Mg	0.1409	0.57
CaO	0.26	Ca	0.0046	0.02
Na ₂ O	tr.	Na	tr.	
K ₂ O	10.95	K	0.2324	0.94
H ₂ O ⁺	2.74	H	(0.3042)	(1.24)
TiO ₂	0.76	Ti	0.0095	0.04
P ₂ O ₅	0.03	P	tr.	
Sum	99.26		1.7304	7.02

Sample LP 99, coord. 7302—1588, alt. 2225m;
analyst Mrs. C. M. de Sitter-Koomans.

with a small axial angle is relatively rare. He demonstrates that of 600 flakes, only 40 had an axial angle of 0°, whereas the rest showed an axial angle of $36^\circ \pm 4^\circ$.

Roothaan (1919, p. 15) is also of opinion that phengite with a rather large axial angle is more frequent.

Gansser (1937, p. 378) calls these micas "phengitic muscovite" whenever they show a small axial angle because so far phengite has not yet been satisfactorily defined.

Nabholz (1945, p. 24) states that phengitic muscovite tends to be altered into chlorite.

Measurements carried out on phengites of the phengite-gneisses showed axial angles of about 0° to 12° beside others of about 30° to 40°. Phengite with an axial angle of about 15° to 25° was not encountered.

Axelrod and Grimaldi (1949) report the occurrence of a muscovite with a small axial angle from Sultan Basin, Wash., U. S. A. This muscovite is weakly pleochroic with greenish colours. The investigations of Yoder and Eugster (1955) revealed that this muscovite is a 3T polymorph. The variation of the axial angle, according to Axelrod and Grimaldi, may be due to superposition or penetration of twins. According to these authors X-ray powder patterns of this mica did not show reflections at 2.99, 3.20, 3.49 and 4.12 Å

TABLE 11

X-ray powder diagrams of ferrian phengite and phengite from the northern Adula region, compared with those of 2M muscovite and a 3T muscovite reported by Yoder and Eugster (1955)

Ferrian phengite Reg. No. 2440 & 2441			Synthetic 2M Muscovite			Natural 3T Muscovite			Phengite Reg. No 1884	
d in Å	I		d in Å	I	hkl	d in Å	I	hkl	d in Å	I
10.48	M		10.01	100	002	9.97	100	0003	10.23	M
9.73	S		5.02	55	004	4.99	53	0006	5.03	W
4.89	W		4.48	55	110	4.49	19	10 $\bar{1}$ 0	4.50	M
			4.46	65	11 $\bar{1}$	4.46	19	10 $\bar{1}$ 1		
4.45	M		4.39	14	021					
			4.30	21	111				4.29	WM
			4.11	14	022					
			3.97	12	112					
			3.89	37	11 $\bar{3}$	3.87	10	10 $\bar{1}$ 4	3.90	W
3.84	W		3.74	32	023					
3.71	W									
						3.60	8	10 $\bar{1}$ 5	3.63	VW
3.47	W		3.50	44	114					
3.28	S		3.35	100	006 024	3.33	100	0009	3.36	S
3.18	M		3.21	47	114					
						3.11	10	10 $\bar{1}$ 7	3.11	W
2.97	M		3.00	47	025					
2.85	W		2.87	35	115	2.88	16	10 $\bar{1}$ 8	2.88	W
2.77	W		2.80	22	11 $\bar{6}$					
			2.59	50	13 $\bar{1}$	2.59	15	11 $\bar{2}$ 1	2.59	M
			2.58	45	116					
2.56	VWd		2.56	90	20 $\bar{2}$	2.56	27	11 $\bar{2}$ 2		
			2.51	20	008	2.50	11	00012		
			2.46	19	13 $\bar{3}$	2.46	7	11 $\bar{2}$ 4	2.47	W
			2.45	12	20 $\bar{2}$					
			2.40	10	204					
2.38	VWd		2.38	24	133	2.38	8	11 $\bar{2}$ 5	2.39	MW
			2.25	12	22 $\bar{1}$ 040	2.25	5	20 $\bar{2}$ 0		
			2.24	5	041					
						2.22	4	11 $\bar{2}$ 7		
			2.20	5	22 $\bar{1}$	2.20	4	20 $\bar{2}$ 3		
			2.18	7	22 $\bar{3}$					
			2.15	10	222					
2.13	VWd		2.13	23	043 135	2.14	12	11 $\bar{2}$ 8	2.13	MW
			2.05	6	044	2.06	3	20 $\bar{2}$ 6		
1.980	W		2.01	75	0010	1.999	47	00015	1.982	W
			1.975	14	13 $\bar{7}$	1.966	7	11 $\bar{2}$ 10		
						1.885	2	11 $\bar{2}$ 11		
									1.812	MW
			1.736	6	139					
					150					
			1.699	6	24 $\bar{1}$					
			1.670	12	20 $\bar{1}$ 0					
1.637	W		1.653	17	314	1.654	10	11 $\bar{2}$ 14	1.652	VW
						1.638	3	21 $\bar{3}$ 5		
						1.614	3	21 $\bar{3}$ 6	1.613	VW
						1.551	2	21 $\bar{3}$ 8	1.536	W
						1.521	6	11 $\bar{2}$ 16		
1.508	Wd		1.499	40	33 $\bar{1}$ 060	1.502	11	30 $\bar{3}$ 0	1.506	WM

Reg. No 2440, sample of ferrian phengite, K α Fe, Sibor sample holder, camera \varnothing 9 cm

Reg. No 2441, sample of ferrian phengite, K α Fe, Sibor sample holder, camera \varnothing 9 cm

Reg. No 1884, sample of phengite, K α Fe, Lindeman sample holder, camera \varnothing 9 cm

2 M Muscovite, Yoder and Eugster (1955), p. 247

3 T Muscovite, Yoder and Eugster (1955), p. 248; Axelrod and Grimaldi (1949):

sample of muscovite with small axial angle, Sultan Basin, Wash.; U.S.A.

and the mineral showed a stronger reflection at 3.10 Å. Similar characteristics are shown by the pattern of phengite with $2V_x$ 0° in sample LP 79 (Reg. No. 1884), which therefore might also be a 3T polymorph. The X-ray powder data of this mica are also given in table 11, together with the data given by Yoder and Eugster (1955) for the mica of Sultan Basin.

The first chemical analysis ever made of phengite was published by Schmidt (1891), see table 12. Roothaan thought it impossible to select enough material with a small axial angle and therefore believed that this analysis was made on a mechanical mixture of muscovite and phengite. Calculation of the structural formula from this analysis proves that this mica is a phengite according to Winchell's formula (1951); if the formula of Machatschki (1953) is used this mica contains about 50 % of phengite. The greenish mica of the phengite-gneisses may well be chemically homogeneous but showing two polymorphs, if the difference in the characteristic properties is due to a difference in the stacking. Further, an analysis of phengite from Vals, made by J. Jakob is given in table 12. The sums of $Al + Fe'''$ and $Mg + Fe''$ do not differ much from those of the analysis given by Schmidt.

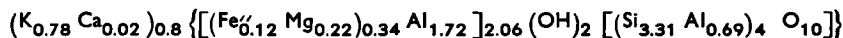
Table 12

Phengite

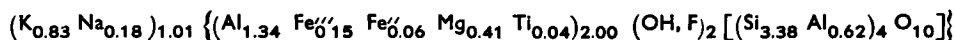
	Chemical analyses			Physical properties
	No 1	No 2	No 3	
SiO ₂	49.57	50.64	47.69	No 1 $2V_x$ ca. 3° , or about 20° , $X < Y \& Z$. n_X 1.55 n_Z 1.59
Al ₂ O ₃	30.69	25.25	28.30	
Fe ₂ O ₃	0.12	2.97	1.02	
FeO	2.09	1.01	3.88	
MnO	0.06	0.02	n.d.	
MgO	2.19	4.15	2.72	No 2 $2V_x$ 0° — 3° , or $30^\circ \pm 4^\circ$, $X < Y \& Z$ n_Z 1.60
CaO	0.30	0.00	n.d.	
Na ₂ O	0.00	1.41	1.87	
K ₂ O	9.04	9.80	9.06	
TiO ₂	0.00	0.72	0.11	
P ₂ O ₅	0.00	n.d.	n.d.	No 3 $2V_x$ 0° , the axial angle changes on heating
F	n.d.	n.d.	n.d.	
H ₂ O ⁺	5.10	3.88	4.07	
H ₂ O ⁻	0.95	0.00	n.d.	
Sum	100.11	99.85	98.72	

These analyses calculated on an anhydrous basis of 11 O lead to the following formulae:

No 1. Phengite, Vallée de Ribordone, analyst C. Rouger (Michel 1953, p. 173). N.B. in the paper of Michel, the formula is given for O₂₂ and (OH)_{4.2}



No 2. Phengite, Vals, analyst J. Jakob (P. Niggli et al. 1930).
Formula calculated by the author (OH = 1.77).



No 3. Phengite, Vals, analyst E. Wülfing (Schmidt 1891).
Formula calculated by the author (OH = 1.85).



In table 12 the composition and the properties of the analyzed phenigites from Vals are listed, providing a comparison with a phengite from Vallée de Ribordone, Italian-French Alps (Michel 1953, p. 173).

21 PYRITE

Pyrite is of common occurrence. In quartz veins it is locally well-developed, building cubes with edges up to 2 cm.

22 QUARTZ

A main constituent of the rocks under discussion is quartz. This mineral is only absent in about one out of every five samples of amphibolites. On microscopical observation it shows strain shadows and other influence of mechanical disturbance. Traces of recrystallization are also found. In the gneisses and schists a conspicuous lattice orientation can be observed in some cases. The grain size ranges from 0.02—0.5 cm and is slightly higher in the schists. The average quartz content of a gneiss is about 32 %, varying at least from 5 % to 75 %; of a schist about 35 %, varying at least from 16 % to 63 %. The average quartz content of the amphibolites is low, being about 8—9 %. The variation of the quartz content in amphibolites cannot be given, because of the many transitional types of albite-rich schists that surround the amphibolites in some places.

Veins and crystal pockets contain well-developed quartz crystals. The crystals from mineral pockets and tension joints in the dolomites and marbles are usually clear, those from veins and pockets in the gneisses and schists are nearly always milky white. In veins in dolomites the quartz crystals may reach a length of 4 cm. A milky white crystal with a length of 17 cm was found in the Dachberg region, presumably deriving from a tension joint in the phengite-gneisses. The prismatic faces of this crystal show tablets of albite, twinned according to the albite law. Crystals taken from veins in dolomites occasionally show both terminations or twins in the shape of a cross with four terminations. Large quartz veins, about 1 km long and 20 m wide, can be found on the Plattenberg. These veins are parallel to each other in a direction more or less normal to the b-axes of the NE—SW folds. Occasionally these veins contain sulphide ores, such as pyrite and fahlore. The parts of the vein that hold these ores also show inclusions of liquid and gas under high pressure. This can easily be demonstrated by crushing the quartz in glycerol, cf. Deicha (1955).

23 RUTILE, SPHENE AND ILMENITE

The metamorphic rocks of the south-eastern part of Switzerland are rich in titaniferous minerals.

The region about Vals provided beautiful specimens of sphene, rutile, brookite and anatase. These specimens are a.o. to be seen as part of a collection of minerals taken from the region around Vals, shown at the Museum of Natural History, Bern, Switzerland. The author's collection only holds sphene and rutile. *Rutile* may be found as golden yellow needles in clear quartz crystals, that derive from the large quartz-lined joints of the east slope of the Piz Ault. The amphibolites may contain large rutile prisms. Deep-red, slightly bent prisms of 2 cm length and 1 cm diameter form no exception. These prisms can easily be found in the horse-shoe shaped outcrop

of amphibolites SW of the Hohbühl, coord. 7325—1599, alt. 2480 m. This rutile when seen through a microscope is normally yellow-brown and translucent. Amphibolites of the tunnel section along the road Vals-Zervreila, however, contain deep violet crystals of rutile. The crystals show a well-developed cleavage parallel to the prism faces. The X-ray powder pattern confirms that this mineral is rutile.

Sphene crystals of about 1 cm are found in the Lentatal in the amphibolite, just outside the mapped region, at coord. 7245—1591 and alt. 2300 m.

Rutile and sphene are regular accessories of the rocks of our region. Their interrelation is complicated. Rims of sphene or *ilmenite* around rutile are frequently observed in the whole region. Ilmenite is moreover a normal accessory of the rocks in the region investigated.

24 SODIUM-PYROXENES

The first to describe the optical properties of the sodium-pyroxenes, that may be found in this region and its immediate surroundings, was Gansser (1937).

The optical properties of a number of these sodium-pyroxenes were measured. A study of X-ray powder data was made and the sodium-pyroxene of one sample was chemically analyzed by Professor Dr Th. Hügi in the Petrochemical Institute of the University of Bern.

Chemical composition. — The sodium-pyroxene of sample LP 295 was chosen for chemical analysis, because it is not as zonal as the others, and fairly easy to separate from the rock, thanks to its large grain size and the fact that more than 95 % of the sample consists of this mineral. The other minerals in this sample are muscovite (not paragonite, X-ray analysis), blue-green amphibole and garnet (see table 9). The sample was crushed and the muscovite, garnet and amphibole were removed by using heavy liquids. The remainder, consisting of pyroxene grains and grains of intergrown pyroxene and amphibole, was purified with the aid of an isodynamic separator. As a result practically pure pyroxene was obtained. In table 13 the analysis of this pyroxene and analyses of more or less similar minerals are given. The structural formulae obtained from these analyses are listed too. As to the composition of these pyroxenes in terms of pure end-members, a number of suggestions exists regarding the procedure of calculation. The reason for this is the fact that no analysis available could bear only one construction. This may a.o. be due to errors in the analysis e.g., in the ratio $Fe''-Fe'''$, in the content of Al and in the content of Na + K. The procedure followed here, starts from the assumption that the diopside and hedenbergite present show some substitution Al Al instead of (Mg, Fe) Si, and are therefore of a slightly augitic character. Further Ti is combined with an equal amount of Mg to substitute part of the above mentioned Al in 6-coordination. Having thus accounted for the amount of Al in 4-coordination and the amount of Ti present, the problem arises in which order Al and Fe''' have to be assigned to Na, since in practically all analyses available the amount of Na does not equal the sum of Fe'' and the remaining Al in 6-coordination. According to Mügge (1927), who found a similar deficiency in aegyrte-augites, the quantity of Fe''' does not seem to be matched by an equal quantity of Na. In this respect Mügge refers to Zambonini (1919) who observed that Fe_2O_3

TABLE 13

Chemical analyses of some sodium-pyroxenes

	No 1	No 2	No 3;		Kation aeq.	Kations/6 O
SiO ₂	54.03	53.31	54.87	Si	0.9136	1.99
Al ₂ O ₃	11.54	10.52	9.18	Al	0.1802	0.39
Fe ₂ O ₃	5.62	4.11	5.07	Fe'''	0.0636	0.14
FeO	4.09	2.84	4.56	Fe''	0.0635	0.14
MnO	0.05	0.05	0.07	Mn	0.0010	—
MgO	5.13	8.42	7.20	Mg	0.1786	0.39
CaO	11.82	14.50	11.96	Ca	0.2133	0.46
Na ₂ O	6.81	5.90	6.43	Na	0.2074	0.45
K ₂ O	0.20	0.05	0.23	K	0.0048	0.01
H ₂ O ⁺	0.29	0.16	0.35	—	—	—
H ₂ O ⁻	—	—	0.15	—	—	—
TiO ₂	0.54	0.26	0.12	Ti	0.0015	—
P ₂ O ₅	—	—	—	—	—	—
Sum	100.12	100.12	100.19			3.97

Structural formulae:

No 1 (Ca_{0.46} Na_{0.48} K_{0.01})_{0.95} (Al_{0.44} Mg_{0.28} Fe_{0.15}''' Fe_{0.12}'' Ti_{0.02})_{1.01} [(Si_{1.95} Al_{0.05})_{2.00} O₆]No 2 (Ca_{0.56} Na_{0.41})_{0.97} (Al_{0.37} Mg_{0.45} Fe_{0.11}''' Fe_{0.09}'' Ti_{0.01})_{1.03} [(Si_{1.92} Al_{0.08})_{2.00} O₆]No 3 (Ca_{0.46} Na_{0.45} K_{0.01})_{0.92} (Al_{0.38} Mg_{0.39} Fe_{0.14}''' Fe_{0.14}'' Ti_{0.01})_{1.05} [(Si_{1.99} Al_{0.01})_{2.00} O₆]

No 1 Chloromelanite, Sjønmøre, Norway; analyst L. Thomassen (Eskola 1921, p. 32, 33)

No 2 Acmitic diopside-jadeite, Healdsburg, Cal. U.S.A.; analyst F. Gonyer (Birch 1943, p. 272).

No 3 Chloromelanite, Amperveila, Vals, Switzerland; analyst Th. Hügi.

can partly be extracted from aegyrite-augite with the aid of warm HCl, without damaging the crystal structure by this treatment. The crystals only lose their green colour and become brownish. For these reasons it seems appropriate to assign the remaining Al to jadeite first, and afterwards to assign the rest of Na to acmite. In calculating the content of diopside, hedenbergite and clinoenstatite or clinoferrrosilite (see analysis No 2 & No 3) again a dilemma arises since either Mg or Fe'' can first be assigned to Ca. These constituents taken together are combined with the components containing Ti and Al in 4-coordination to form subcalcic augite. The results of the calculations are listed in table 14.

Table 14

	Jad.	Acm.	Subcalcic Augite	Rest
No 1	43	6	43; with Di ₂₆ Hed ₁₂	8
No 2	31	10	58½; with either Di ₄₄ Hed ₄ ClFs ₅ or Di ₃₉ Hed ₉ ClEn ₅	½
No 3	37	9	50; with either Di ₃₉ Hed ₆ ClFs ₄ or Di ₃₁ Hed ₁₄ ClEn ₄	4

Comparison of the analyses in table 13 shows that the pyroxene of Ampervreila, viz No 3 is rather similar to the chloromelanite described by Eskola. As to the nomenclature to be adopted it is worth noting that Damour (1893) and Eskola (1921), see analysis No 1, table 13, described greenish pyroxenes with a similar acmite content as chloromelanite. Iris Y. Borg (1956), see analysis No 2, table 13, used the name acmitic diopside-jadeite for a comparable pyroxene. Washington (1922) gave the name diopside-jadeite to a pyroxene with a much lower content of acmite. Hence it seems appropriate to retain the name diopside-jadeite for acmite-poor members only, e. g., for members with an acmite content of less than 5 % arrived at by the above described calculation method. The pyroxene from Ampervreila as well as those described by Damour (1893), Franchi (1900), Eskola (1921) and Borg (1956) then are to be designated as chloromelanite.

Pyroxenes similar to those just described are often erroneously called omphacite by many authors. Omphacite, in the original sense of Werner (1812, p. 302) — who gave this name to green pyroxene occurring in association with pyrope-rich garnet in rocks later named eclogites, from the vicinity of Bayreuth, Germany (11°30' E, 50° N) — is according to Riess (1878) poor in sodium (Na_2O 0.87—1.73 %). Recent analyses of pyroxenes from the type locality show a maximum of 3.64 % Na_2O (von Wolff, 1942). They have much lower values for Fe_2O_3 and much higher ones for CaO than were ever found in chloromelanite. The analysis published by Tilley (1937) has a Na_2O content of 2.88 %, the sample also derived from the type locality.

Optical properties. — The optical properties of the chloromelanite of sample LP 295 are:

n_X 1.686—1.690

n_Y 1.690—1.694

n_Z 1.700—1.704

$2V_x$ 72° (rim)—86° (core); $r > v$ moderate; c/n_Z 44° (rim) to 76° (core);

$n_Z - n_X$.012 (rim)—.017 (core)

Colour green with a weak pleochroism.

The optical properties of a number of other pyroxenes are listed in table 15.

From these optical data it is evident that the pyroxenes in this region are optically more or less similar sodium-pyroxenes.

X-ray powder data. — X-ray powder photographs of a number of these pyroxenes show patterns, corresponding to the B 3 pattern of Zwaan (1954). Zwaan pointed out that sodium-pyroxenes can be distinguished from other pyroxenes by means of X-ray powder data. According to Zwaan the intensities of, and the distances between, the reflections 221, 310—311, 131 and $2\bar{2}\bar{1}$ are characteristic. In the following table 17 the d in Å units of these reflections is given for two pyroxenes from the region under review, together with the corresponding values for aegyrte and jadeite adopted from Zwaan (1954). The calculated d_{hkl} values for acmite given by Schüller (1958) are listed as well.

From these data the conclusion seems justified that the pyroxenes occurring in the northern Adula region are sodium-pyroxenes, showing both jadeite and acmite properties from a structural point of view, whereas diopside-hedenbergite properties are less well developed in these powder patterns. For completeness' sake the entire powder pattern of the analyzed chloromelanite from Ampervreila is given in table 16.

Table 15

Optical properties of a number of sodium-pyroxenes

Sample	Colour	2V _z	c/nZ	nZ—nX	r > v	nX	nY	nZ
M 248	weak	rim 72° core 78°	ca. 50°	rim .016 core .018	weak	n.d.	n.d.	n.d.
B 6	weak	ca. 85°	ca. 52°	n.d.	n.d.	n.d.	n.d.	n.d.
LP 325	colourless	ca. 70°	ca. 45°	rim .019 core .020	str.	n.d.	n.d.	n.d.
LP 116 ^a	yellow to green	rim 88° core 80°	rim 49° core 64°	ca. .022	weak	n.d.	n.d.	n.d.
M 431	yellow to green	ca. 80°	ca. 59°	ca. .020	weak	1.682	1.694(?)	1.704
LP 522	weak	ca. 80°	ca. 45°	ca. .020	mod.	1.669	n.d.	1.689
LP 284	yellow to green	ca. 80°	ca. 45°	ca. .018	mod.	1.668	n.d.	1.688

- M 248 Sodium-pyroxene bearing amphibolite from the Zervreila dam-site.
 B 6 Minute sodium-pyroxene prism enclosed in microcline, phengite-gneiss from the Zervreila dam-site.
 LP 325 Pyroxene garnet rock, from the arête between the Guralätschhorn and the Fanellahorn.
 LP 116^a Sodium-pyroxene rock with garnet and blue-green amphibole, "Pseudodiorite" of Peil.
 M 431 Sodium-pyroxene rock with garnet and glaucophane, Alp Ampervreila.
 LP 522 Sodium-pyroxene rock with garnet, Pian d'Asc, Val Calanca.
 LP 284 Sodium-pyroxene bearing amphibolite from Peil.

Table 16

X-ray powder data of a chloromelanite from Ampervreila, Vals, sample No 295, Reg. No 2409, Fe K_α, camera Ø 9 cm.

d in Å	I	d in Å	I	d in Å	I	d in Å	I
8.30	VW	2.71	VW	2.01	M	1.493	M
6.31	VW	2.54	S	1.820	VW	1.458	VW
4.37	VW	2.50	M	1.792	VW	1.392	M
4.00	W	2.47	VW	1.718	VW	1.370	VW
3.65	W	2.25	VW	1.657	VW	1.312	VW
3.33	VW	2.19	W	1.619	W	1.264	VW
3.18	M	2.11	W	1.597	VW	1.227	VW
2.95	VS	2.07	VW	1.583	VW	1.147	VW
2.87	M			1.519	VW		

Occurrence. — Sodium-pyroxene is rare in the phengite-gneisses and common in the amphibolites.

In the phengite-gneisses sodium-pyroxene was found in seven samples as minute prisms enclosed in microcline. With a high power immersion objective it can be distinguished from amphiboles by its large extinction angle. In one case, viz B 6, it was even possible to determine the axial angle with the aid of the universal stage and the Leitz U.M. 4 objective. The samples were taken from the Zervreila dam-site, the tunnel section of the road Vals-Zervreila and from the new road into the Kanaltal.

In the amphibolites about one out of every six samples contains sodium-

TABLE 17

X-ray powder data of some sodium-pyroxenes

Chloromelanite Vals, LP 295 Reg. No 2409		Pyroxene Vals, M 431 Reg. No 2411		Aegyrine Ditro, Zwaan '54 Reg. No 1521		Jadeite Burma, Zwaan '54			Acmite Schüller '58	
d in Å	l	d in Å	l	d in Å	l	d in Å	l	hkl	d in Å	hkl
3.18	M	3.18	W	3.22	W	3.09	MW	220	3.182	220
2.95	VS	2.94	VS	3.01	VS	2.91	VS	221	2.978	221
2.87	M	2.86	S	2.92	S	2.82	VS	310	2.902	310
2.54	S	2.51	S	2.53	S	2.48	S	131	2.890	311
									2.546	202
									2.539	131
2.50	M	2.46	SM	2.48	SM	2.42	S	221	2.468	221
1.62	W	1.62	W	1.64	MW	1.61	W	312	1.615	441
1.60	VW	1.60	W	1.62	MW	1.57	SM	531	1.610	531
1.58	VW	1.58	VW	1.60	W	1.55	MW	223	1.591	440

pyroxene. The mineral is not easy to identify because of its resemblance to epidote.

Cross-sections are of great help to arrive at clear and unambiguous determination, because they show the cleavage angle of about 90° and have a rather small birefringence. From the samples examined it is evident that the pyroxenes were unstable during one or more phases of metamorphism subsequent to their formation. Blue-green amphibole pseudomorphs after pyroxene are abundant. They occur either as large poeciloblasts with patches of relic pyroxene or as fibrous aggregates. Apart from glaucophane and garnet, no inclusions of any mineral were ever found in the pyroxene crystals. The sections betray their zonal habit by a varying birefringence from core to rim.

25 TOURMALINE

Tourmaline is frequently observed in all the rock types. Once radiated aggregates of tourmaline were found on the schistosity plane of a phengite-gneiss. Some mica-schists show numerous small black tourmaline prisms scattered all through the rock.

26 ZIRCON

Zircon is a normal accessory of all the rock types. It is rather exceptional in the phengite-gneisses, but it can be seen in almost every slide of the mica-schists. As a constituent of Mesozoic rocks it was rarely observed. All the crystals are rounded.

CHAPTER IV

PETROGRAPHY

or the description of rocks

Introduction. — In this chapter a macroscopical and a microscopical description of the various types of rocks occurring in the northern Adula region will be given. Successively the following groups of rocks (see also p. 433) will be described:

Phengite-gneisses

Mica-schists

Amphibolites and allied rocks

Mesozoic rocks of sedimentary origin

Mesozoic rocks of igneous origin

N.B. As mentioned in chapter II, some calciferous mica-schists are described under the heading "Mesozoic rocks of sedimentary origin". The other mica-schists belong to a different formation.

The mineralogical composition of the different groups of rocks is given in table 18. This table shows that some minerals, like glaucophane, sodium-pyroxene and microcline, have not been found in all rock groups distinguished. The wide-spread occurrence of the other minerals indicates that rocks of different age, origin and chemical composition going through the same metamorphic cycle, bear similar traces afterwards.

For the location of samples mentioned in the text, the reader is referred to the table on p. 596.

PHENGITE-GNEISSES

Occurrence

The phengite-gneisses are among the common rock types in the northern Adula region. They occur in the area around the Zervreilasee and on the Ampervreila Alp, in the neighbourhood of Leis and on the Selva Alp. The gneisses may build bands with a thickness of 2 to 20 m, that are intercalated between mica-schists and amphibolites, but they are also found in larger sheet-like bodies. The latter may reach a thickness of more than 700 m, viz in the region of the Zervreilasee. In the region of Pedanatsch the bands have a thickness of about 80 m.

Macroscopical description

In the field this type of rock is easy to distinguish. It has a light greyish colour, tending to a greyish green. The gneisses show a strong preferred orientation of the micas and as a rule are thickly banded. The micas are of a higher concentration in certain zones, which are therefore more apt to weathering, a characteristic that gives the appearance of a washboard to

Table 18
Qualitative mineralogical composition of the various types of rocks

	Quartz	Albite	Microcline	Muscovite	Phengite	Phlogopite	Biotite (brown)	Biotite (green)	Chlorite	Actinolite	Blue-green amphibole	Ferrohastingsite	Glaucophane s.l.	Sodium-pyroxene	Epidote s.l.	Zoisite	Garnet	Apatite	Sphene	Rutile	Calcite	Dolomite	Siderite	Anhydrite	Gypsum	Tourmaline	Chloritoid	Kyanite	Zircon	Opaque minerals
Phengite-gneisses	x	x	x	x	x	x	tr	x	x	x	x	x		x	x	x	x	x	x	x	x					x		x	x	x
Mica-schists	x	x	x	x	tr		x	x	x	x	x	x	x		x	x	x	x	x	x	x					x	x	x	x	x
Amphibolites and allied rocks	x	x	x	x	tr		tr	x	x	x	x	x	x	x	x	x	x	x	x	x	x					x	x	x	x	x
Mesozoic rocks of sedimentary origin	x	x	x	x	x	x		x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Mesozoic rocks of igneous origin	x	x		x				x	x	x	x	x	x		x	x	x	x	x	x	x					x			x	x

those surfaces of an outcrop which are transverse to the schistosity plane. In some outcrops fine examples of isoclinal folding of the gneisses can be seen, fig. 11.

The fresh fracture plane of a hand-specimen shows white quartz and feldspar and an apple-green mica, viz phengite. Closer examination reveals the presence of the minerals epidote, chlorite, biotite and garnet in some cases, as well as of ore minerals, mostly pyrite. In a few samples radiating

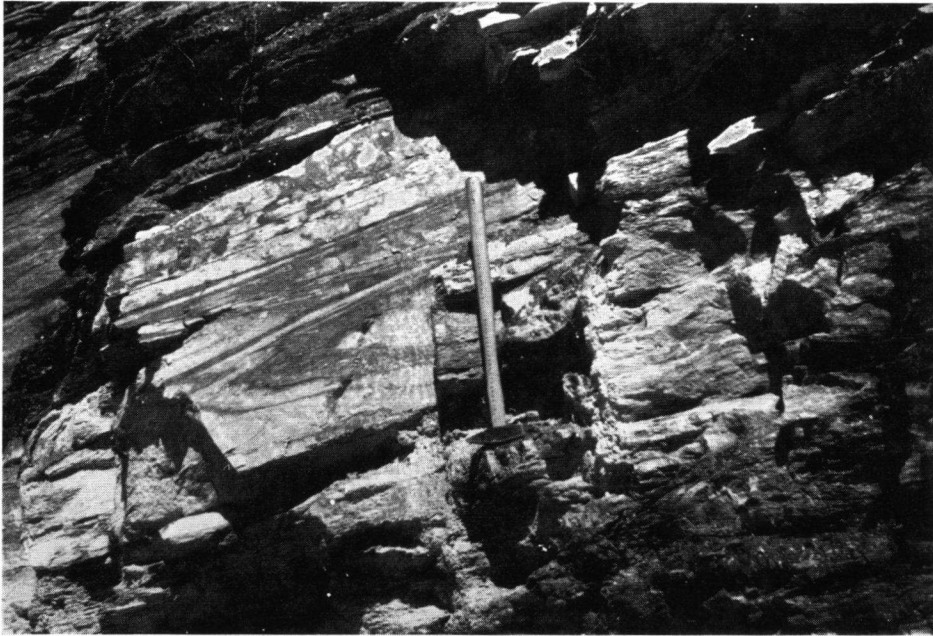


Fig. 11. Isoclinal folds in phengite-gneisses, exposed along the road Vals-Zervreila, coord. 7296—1604.

needles of tourmaline were observed on the schistosity plane. Both even-grained types and augen gneisses occur. The eyes, with an average size of 2 cm, are for the greater part built of microcline, sometimes showing Carlsbad twins. A specimen taken along the road from Vals to Zervreila has eyes up to 5 cm, of a fine blue colour. The rims of these eyes and the cracks within them are built by sugar-grained white quartz and albite.

Having given a general macroscopical description of the phengite-gneisses, some special types still need to be mentioned. The so-called orthogneisses "Typus Zervreila" described by former authors, have a slightly different appearance. Along the old road to Zervreila-Oberboden, now at the bottom of the lake, one could observe a few outcrops where a phengite rock was to be seen that did not show any preferred orientation. The upper part of the Zervreila gneiss-body, at one time beautifully exposed during the construction of the dam, is characterized by leucocratic augen gneisses and ribbon gneisses. Generally speaking the Zervreila gneisses have a more or less "granitic" fabric and are brighter than the other phengite-gneisses,

The conspicuously banded ribbon gneisses occurring in the quarry near the village of Vals in the Peilerschlucht (fig. 12) are still used as roof-coverings, because of their well-developed schistosity. They can be split up in large slabs, a few centimetres thick. These rocks are the so-called "injection gneisses" of former authors. They are fine-grained with grain sizes of about 0.5 mm. The cleavage planes in the direction of the schistosity



Fig. 12. Ribbon gneisses similar to those near the Peilerschlucht. The outcrop is situated in the torrent coming down from Valatschalp.

are thickly covered with green phengite, whereas this mineral is of sparse occurrence between them.

A third type of rock that needs description is the "Riesenaugengneis" of the Valserschuppen. This rock demonstrates the influence of mylonitization, whereas parts of the large orthoclase crystals have resisted the tectonical forces that ground the other components. Fig. 13 shows a polished section

of this gneiss. The large orthoclase eye in the centre still preserves a Carlsbad twin. It is clear how the other constituents are rolled out in long seams, indicated by dark bands, that connect the resisting feldspars like a string of beads. Microscopically these dark strings consist of phyllosilicates and small crystals of ore.

Mylonitization phenomena are very common within the phengite-gneisses. Megascopically they can be studied in the region of Pedanatsch and in the outcrops along the Selvabach at an altitude of 2000 m, cf. chapter II, p. 443.

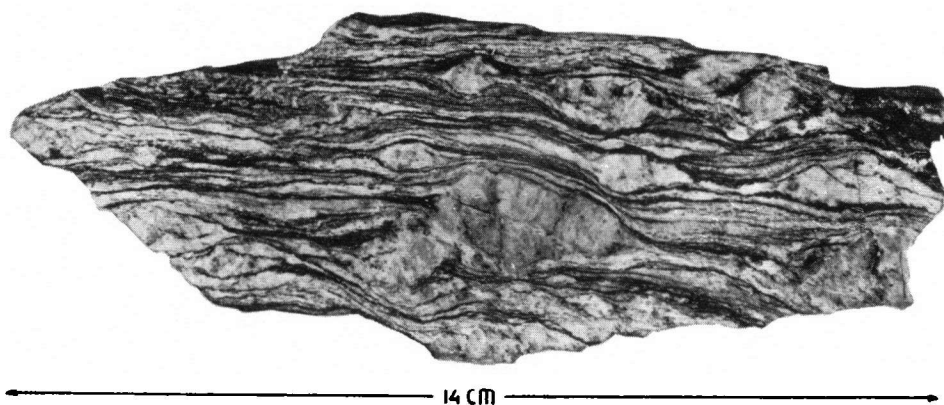


Fig. 13. Polished section of the "Riesenaugengneis" coord. 7291—1635. Note the mylonitic character of this rock and the orthoclase porphyroblast in the centre still preserving a Carlsbad twin.

Relation with the adjoining rocks

The phengite-gneisses are in contact with different rock types and thanks to excellent exposures the relations can be studied in detail. First the contacts with Mesozoic rocks will be dealt with. These are not manifold and wherever they could be studied, they were clearly of tectonic origin. The contact surface shows traces of mylonitization, the Mesozoic rock is crushed and large patches of a fine-grained dark-coloured micaceous film have been formed. Moreover the phengite-gneiss near the contact is fine-grained and secondary calcite makes the rock react with dilute HCl. A primary contact with the Mesozoic rocks has not been found.

The contact relations with the mica-schists are very complicated and have been the subject of a thorough discussion in the paper of Müller (1958). The occurrence of amphibolitic bodies along the contact surface between the phengite-gneisses and the mica-schists is a striking feature (see map). There are outcrops where the phenomenon is apparently lacking, but these are rare and it may well be that here too small amphibolitic lenses are present, because weathering makes it difficult to study this particular characteristic of the gneiss-schist contact. In cases where fresh exposures were found, these lenses were always present, e. g., along the road Vals-Zervreila, in the exposures of the foundation trench of the Zervreila dam and along the main road on the pass of San Bernardino.

The following description of the contact relations covers largely the

phenomena that may be encountered. When we start from a point well within the phengite-gneiss-body and proceed in an outward direction, towards the contact surface, after having left the normal phengite-gneiss, a zone is first encountered where microcline gradually becomes obsolete. This zone starts about 10 m from the contact surface. Proceeding further in the outlined direction, the potassium-rich feldspars disappear at a distance of 1—3 m from the contact. The contact itself is sharp, sometimes marked by a narrow zone rich in phyllosilicates. In other cases a zone of ribbon gneisses, a few metres thick, is seen. Samples from this zone usually contain calcite. The adjoining rocks consist of amphibolitic lenses separated by thin layers of stromatitic amphibole-bearing or biotite-bearing mica-schists. These schists may be rich in small albite eyelets. The lenses, with a dimension ranging from a few centimetres up to more than five metres, fit into each other, building larger bodies. These composite bodies may reach dimensions of over a hundred metres. The lenses in these bodies have a shell in shell structure of zones composed of different minerals. Having passed this amphibolite zone, the embedding material of the lenses, i. e., the amphibole-bearing albite-rich mica-schist, gradually changes into a normal type of mica-schist.

Microscopical description

Microscopically these phengite-gneisses show flaser- and augen structures or an even-grained gneissic structure with micas and an occasional epidote in parallel arrangement. First an average gneiss will be described.

Sample St 3/900, taken from the waterdrift Ampervreila-Peil.

Macroscopical description: An even-grained phengite-gneiss, with a tendency to augen structure.

Microscopical description: The section shows a crystalloblastic structure. The crystals have a parallel arrangement, while the micas are concentrated in zones. A more or less equigranular mosaic of anhedral quartz (ca. 0.8 mm) builds the bulk of the rock. In this mass albite porphyroblasts of a somewhat larger size (ca. 2.0 mm) can be seen, having all kinds of inclusions, viz quartz droplets, calcite patches and flakes of phengite. The albites are twinned according to 010 and rarely on 001. Almost hidden in this quartz-albite fabric, small microcline granoblasts with a pronounced quadrille structure, occur. The micas, arranged parallel to the schistosity, make up about one fifth of the volume of the sample. These slightly pleochroic phengites (length about 1.0 mm) are occasionally bent around the albites and have a fan-like extinction. Tiny flakes of green biotite are seen within the phengite aggregates and at times build fringes at the frayed ends of the phengites. These mica zones moreover hold epidote prisms, with a brownish core, due to some admixture of orthite. Only seldom are the prisms surrounded by pleochroic haloes. Accessory minerals are apatite, calcite and ore minerals. The ore minerals may have a flaky appearance, in other cases they form opaque equant grains with an occasional pleochroic halo. According to a rough estimate the quantities of the main constituents are: Q ca. 50 %; Ab ca. 25 %; Mica ca. 20 %.

This sample gives a fair picture of a normal phengite-gneiss, but there is a great number of variations on this general theme. The highly mylonitized "Riesenaugengneis" that crops out on the western slope of the Valserrhein, situated amidst the "Bündnerschiefer", is a special type that needs to be described.

Sample T 432, "Riesenaugengneis", coord. 7291—1635, alt. 2570 m.

Macroscopical description: A coarse-grained augen gneiss with augen of potassium-feldspar (up to 5 cm) and a groundmass of quartz, albite and phengite, see further page 487.

Microscopical description: The matrix of this rock consists of a linear fabric of quartz, albite and phengite. The mica is concentrated in zones. The grain size of the matrix is about 0.3 mm. The large porphyroclasts appear to consist of orthoclase, partially transformed into microcline. The large crystals show the influence of a mechanical grinding process. The rims of the orthoclase crystals have a mortar structure and the cracks are filled up with albite. Within the orthoclase inclusions of albite are seen, showing repeated twinning on 010. The crystals of albite are generally studded with inclusions of green biotite, phengite and epidote. Accessory minerals are apatite, epidote and zircon.

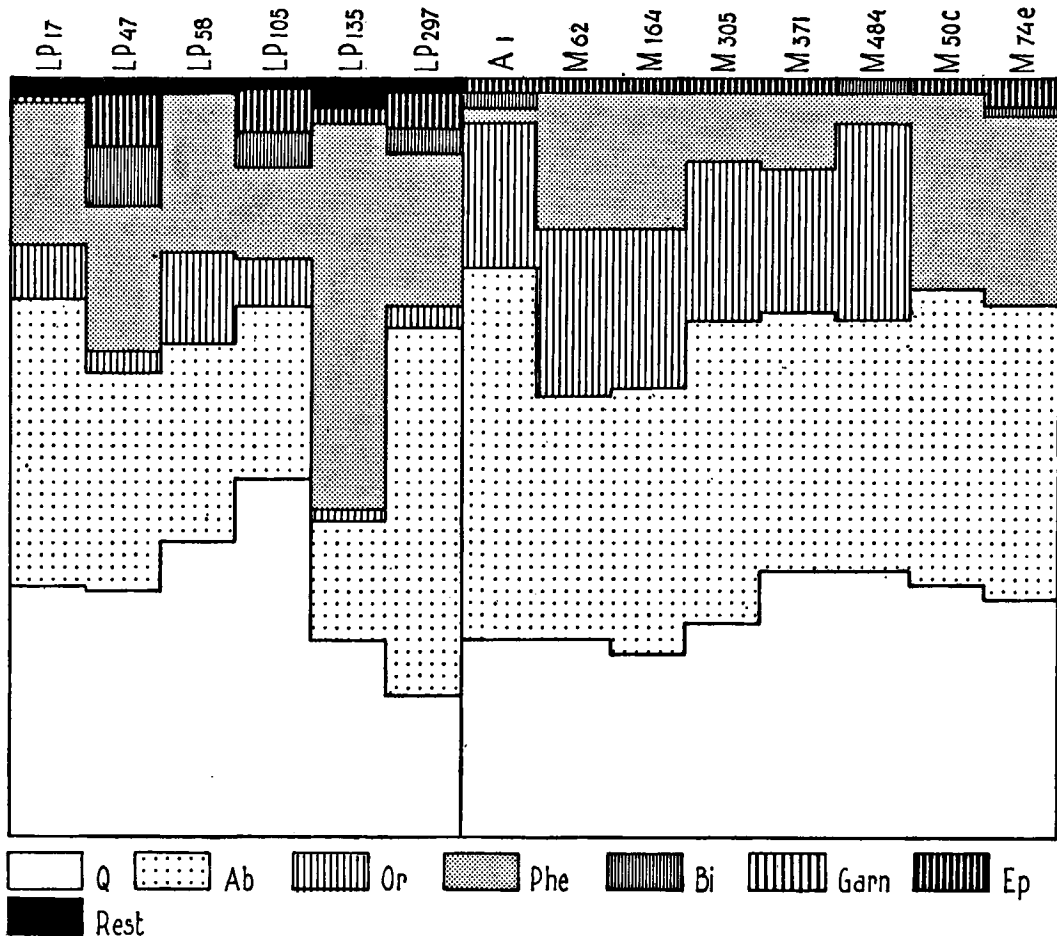


Fig. 14. The mode of 14 thin sections of phengite-gneisses graphically represented. Samples of the Zervreila gneiss are shown to the right of the vertical line; the modes of these rocks are for the greater part adopted from Müller (1958). Or is microcline and orthoclase.

Ribbon gneisses are still another type. These rocks consist of two types of bands, one that shows a leucocratic fine-grained fabric of quartz and feldspar with an occasional mica-flake and another that is rich in mica with epidote, feldspar and quartz as other main constituents. A sample taken from the Peilerschlucht will be described next.

Sample LP 297, coord. 7334—1637, alt. 1300 m.

Macroscopical description: A thinly banded ribbon gneiss with a perfect schistosity and consisting of light and dark bands of about 4 cm thick. The sample is even-grained with a grain size not exceeding one millimetre.

Microscopical description: The leucocratic bands consist of an equigranular mosaic of granoblastic quartz and albite with some microcline crystals, showing a perfect quadrille structure. Phengite is subordinate. The bands rich in phyllosilicates consist of albite, quartz and mica, roughly in the proportion 1:1:2. In some zones calcite appears in irregular patches parallel to the schistosity. The accessories are the same in both parts. The phengite flakes have a marked pleochroism and are occasionally slightly bent. Greenish brown biotite builds much smaller crystals. Yellow epidote prisms with a greenish tinge are arranged parallel to the schistosity. The albite granoblasts have inclusions of both mica and epidote and small quartz droplets. The accessory minerals are apatite, sphene, rutile and a rare opaque grain.

These three samples, describing both the extreme and the normal varieties, are more or less representative of what one can expect to find when studying the thin sections and hand-specimens of the phengite-gneisses. The minerals pertinent to this description were treated systematically in chapter III. For clearness sake these minerals are enumerated here again in order of importance. Quartz, albite, phengite, microcline, biotite, epidotes and apatite nearly always occur, the rest, viz blue-green amphibole, orthoclase, sodium-pyroxene, clinozoisite, zoisite, brown biotite, garnet, apatite, sphene, rutile, tourmaline, zircon and ore minerals are occasionally found.

The phengite-gneisses in the immediate vicinity of the contact differ from the normal types in their content of microcline and albite. Approaching the contact, the microcline content gradually diminishes to zero. On the other hand these rocks are slightly richer in albite. Their structure is similar to that of the rocks at a greater distance from contacts.

In samples from the Zervreila dam-site, the tunnel section of the Vals-Zervreila road and the new road into the Kanaltal, minute prisms of sodium-pyroxene were sometimes found as inclusions in microcline, cf. p. 482. Glaucophane was never encountered.

Summary

Summarizing, the mineralogical composition of these phengite-gneisses is simple if compared with the mica-schists and the amphibolites, as will be shown in the next paragraphs. The average number of minerals in 30 samples is 8½. Six samples have more than 10 minerals, while one of these samples contains 12 different mineral phases.

The blastic structure of nearly all the rocks points to a total recrystallization of the original material, whatever this might have been. The only structural relics are the large porphyroclasts of orthoclase.

In thin sections the phengite-gneisses appear as remarkably clean rocks, traces of alteration of the feldspars are seldom found. The only "secondary" minerals are calcite and chlorites. Calcite is mostly present in rocks that bear traces of mylonitization. Chlorites, if present, are pseudomorphous after biotites, garnets and sometimes even after phengite.

The quantitative mineralogical composition of the phengite-gneisses is not constant as can be seen from fig. 14, where the results of a number of modal analyses are given graphically. Some of these analyses are quoted from Müller (1958, p. 437). The quantitative mineralogical composition of the Zervreila gneiss clearly differs from that of the other phengite-gneisses.

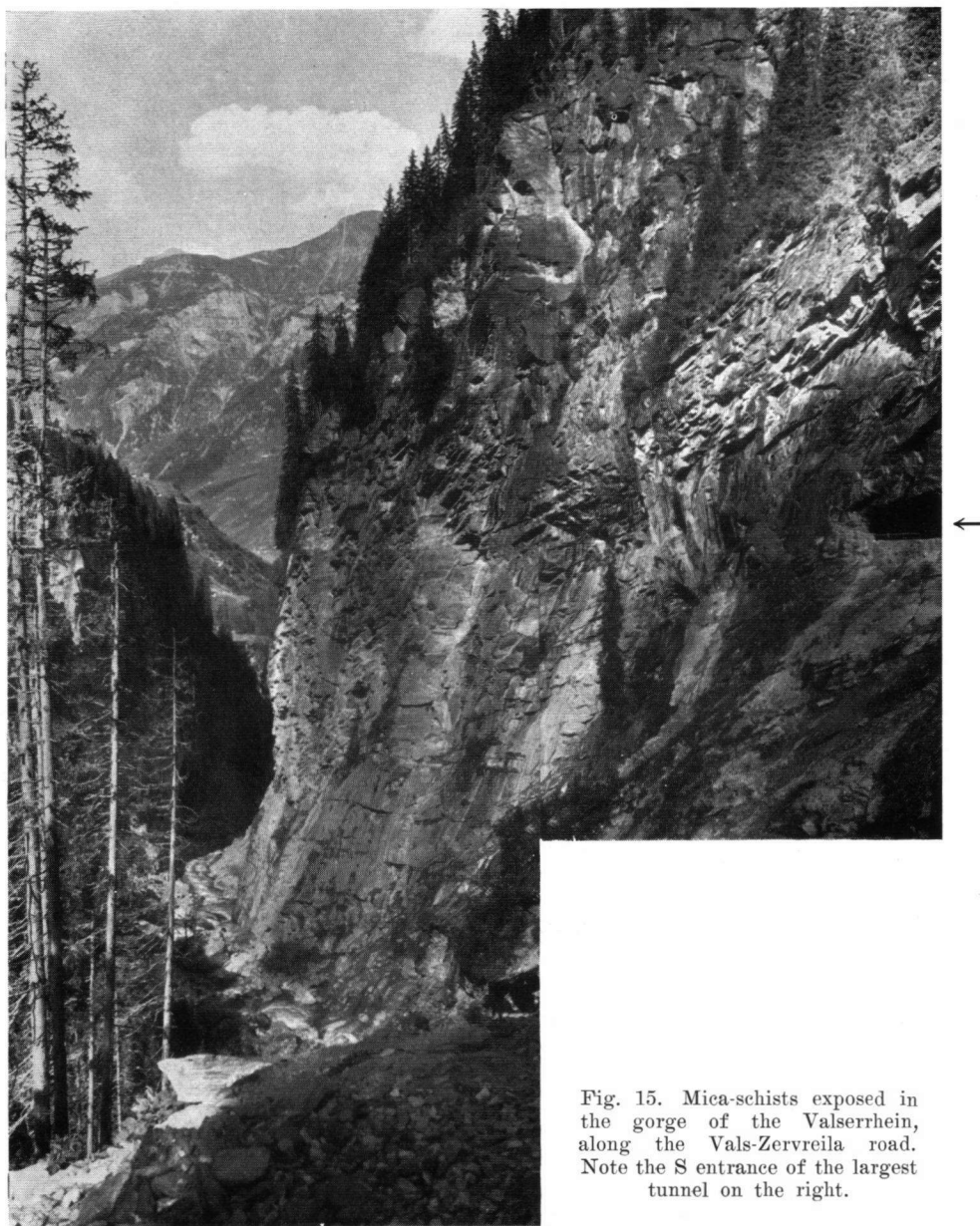


Fig. 15. Mica-schists exposed in the gorge of the Valserrhein, along the Vals-Zervreila road. Note the S entrance of the largest tunnel on the right.

MICA-SCHISTS

Occurrence

This group of rocks that are presumably of pre-Mesozoic origin comprises different types, with a variable mineralogical composition.

Up till now it has not been possible to find a clue to unravel the history

of the formation of these mica-schists and to introduce a kind of stratigraphy. They may all belong to one period of sedimentation, but it seems impossible to prove this. It is also credible that rocks of Mesozoic age are concealed within these masses.

Mica-schists are mainly found on the Plattenberg and the Lenta Alp, in the neighbourhood of the village of Vals and along the road leading to Zervreila, fig. 15.

Macroscopical description

The mica-schists build highly schistose masses and sheets. A high amount of mica (ca. 50 %) gives the rocks their characteristic appearance. In the field they have a brownish colour, due to weathering. The greater part of these schists shows small lenticular eyes of albite, that can sometimes be so numerous as to give the rock a conspicuous appearance. For this reason these rocks were called "pea-gneisses". Other types show green patches of chlorite as large as 0.5 cm on the schistosity plane, as well as prisms of black tourmaline.

In general the rocks are plain mica-schists with a crystalloblastic structure and a well-developed schistosity. They are rich in quartz and mica and usually contain albite. Garnets are often found. Types rich in chlorite alternate with garnetiferous mica-schists, types rich in biotite are not common, others contain exclusively quartz and coarse-flaky muscovite.

The quartz content is about 15 to 20 %, while the grains are small. Within these schists veins and rods of quartz can be observed, mostly parallel to the schistosity.

The minerals that can macroscopically be recognized are:

Quartz	Garnet	Ore minerals
Albite	Epidote	pyrite
Muscovite	Amphibole	galena
Biotite	Tourmaline	hematite
Chlorite	Rutile	magnetite

Near the amphibolitic bodies, which are always associated with phengite-gneisses, albite-rich mica-schists are of local importance. Müller (1958), who made a special study of the transition zone between the mica-schists and the amphibolites describes these albite-rich rocks separately as albite-rich muscovite-gneisses. He argues that the mica-schists near the Zervreila gneiss have a higher content of albite. Similar albite-rich rocks, however, can also be found far from the phengite-gneisses and amphibolites, e.g., on the Plattenberg. Besides, normal mica-schists also appear near the contact with the Zervreila gneiss, a fact illustrated by the modal composition of some samples taken from outcrops a few metres from the contact (see fig. 16 and page 541). Therefore it is the author's opinion that the quantitative mineralogical composition of the mica-schists near the contact of the Zervreila gneiss does not show any appreciable difference from the mica-schists found in other outcrops (see also p. 541).

Isoclinal folds generally could not be found because of the flaky character of the rocks. In one outcrop, near the amphibolite body NE of the Selvasee, mica-schists were found which show a sharp accordion folding, the flanks being about one centimetre in width. The b-axes of the folds are parallel to the other b-axes measured in this area.

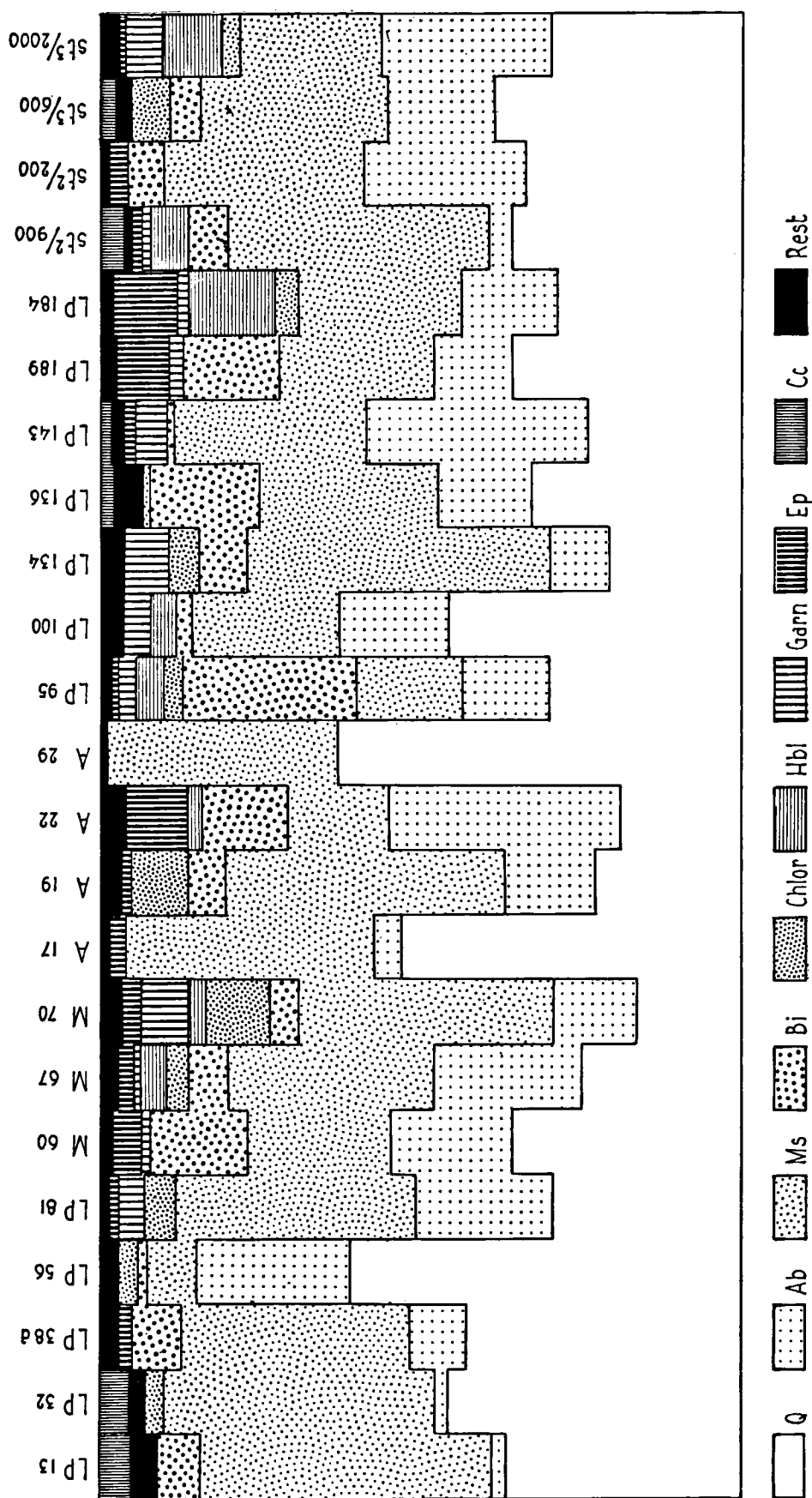


Fig. 16. The mode of 23 thin sections of mica-schists graphically represented; Hbl = blue-green amphibole as well as sodium-amphibole or actinolite.

Relation with the adjoining rocks

The contact relations with the phengite-gneisses have just been treated. Contacts with the Mesozoic rocks can be observed on the Hennensädel and the Weissgrätli, on top of the Hohbühl and at some other places (see map). In all these outcrops it is impossible to determine the character of the contact. Structural unconformities on a small scale do not occur and the contact surface is always parallel to the schistosity. Unconformities that are revealed

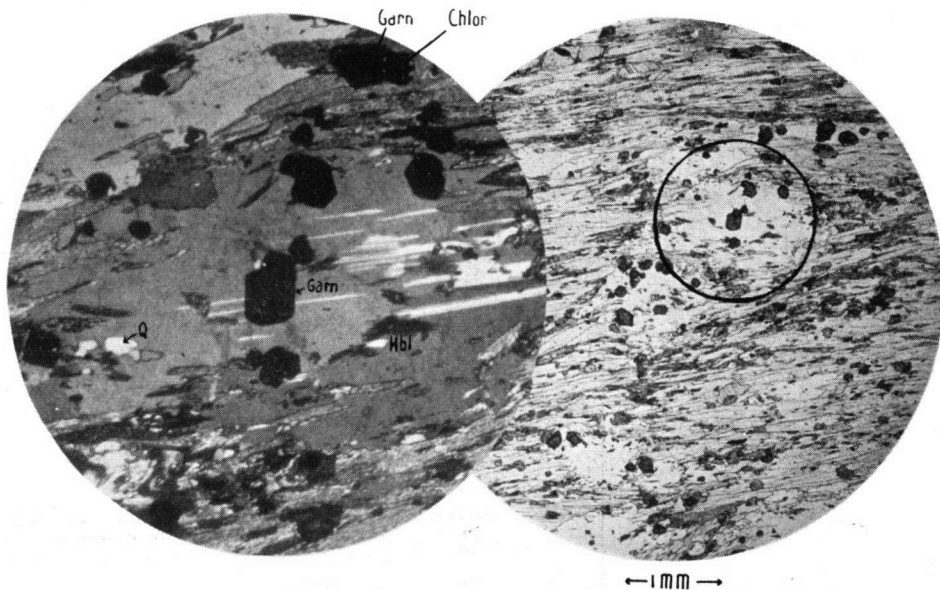


Fig. 17. Right: A representative section of a mica-schist (LP 168) showing a few albite poeciloblasts with enclosed fresh euhedral garnets. Left: The encircled part enlarged, crossed nicols. Note the fissured and partly chloritized garnet outside the albite and the occurrence of small blue-green amphibole crystals as well as quartz within the albite.

by the geological mapping point to tectonic contact relations. Apparently there are no primary contacts between the Mesozoic rocks and the metamorphic rocks of older origin.

Microscopical description

First it is useful to give a description of a representative sample of the mica-schists, in order to illustrate their general characteristics. Sample LP 168 was selected because it contains 15 of the 19 minerals that can be found in rocks of this type, cf. fig. 17.

Sample LP 168, coord. 7319—1627, alt. 1490 m, Road Vals-Zervreila, about 180 m N of the entrance to the large tunnel.

Macroscopical description: A compact greenish grey rock, with a wavy schistosity plane and the following conspicuous minerals; albite, building pellets of 1.5 mm, muscovite, giving the surface a silky lustre, and dark green patches of chlorite.

Microscopical description: Bands rich in phyllosilicates alternate with quartz-rich bands. The thickness of these quartz-rich bands does not exceed 1.5 mm. Main constituents are recrystallized equigranular quartz and parallel-arranged muscovite. The grain size is about 0.6 mm. Albite poeciloblasts with more or less lenticular outlines parallel to the schistosity show all kinds of inclusions, among them brown biotite, garnet,

blue-green amphibole, muscovite, chlorite, epidote and rutile. Sometimes simple or repeated twinning on 010 occurs, but in general the albite is untwinned. The crystals of garnet in the zones rich in micas are fissured and partly chloritized (grain size ca. 0.3 mm). When enclosed in albite they are usually fresh and euhedral. Their cores may be filled with minute needles of rutile. Occasionally the muscovite shows fringes of green or brown biotite.

The chlorite is a ripidolite. Small prisms of fresh golden yellow rutile may occur as inclusions of the albite, they may have a rim of sphene when not enclosed in albite. Other accessories are apatite, calcite, hematite, limonite and pyrite.

The most important feature of sample LP 168 is the occurrence of fresh minerals enclosed in the albite poeciloblasts. Outside the armour of albite the alteration of these minerals is either partial or complete.

In the other mica-schists this feature of armoured relics in albite as well as in the other minerals is of common occurrence. Another characteristic is the absence of microcline in the sections studied. Former authors have described orthoclase as a mineral of the mica-schists in this region, due to false determination of untwinned albite. The mica-schists studied by the present author were never found to contain microcline or orthoclase. Neither were clinopyroxenes ever found. In most of the samples the albite porphyroblasts must have grown in a rather coarse-grained surrounding as can be deduced from the occurrence of fairly large quartz inclusions. There are samples in which the quartz shows the same mosaic structure within the albite porphyroblasts as outside them. On the other hand albite porphyroblasts are to be found, in which the quartz appears as droplets, whereas outside the quartz has an entirely different appearance.

The modal composition of the mica-schists is as variable as the mineralogical composition. An average modal composition cannot be given. In general the mode differs from that of the phengite-gneisses and that of the amphibolites, the content of phyllosilicates being higher than in the other rocks. In fig. 16 a graph of the results of point counter analyses of 23 thin sections is given.

Some samples need a special description. The samples LP 188 and LP 189 (taken from the road Vals-Zervreila; coord. 1610—7301, alt. 1690 m) belong to a nebulitic augengneiss-like rock (a blastomylonite), rich in biotite, with bluish eyes not consisting of feldspar but of fine-grained quartz.

Samples LP 188 & LP 189, a nebulitic augengneiss-like blastomylonite.

On microscopical observation the rock appears to consist of several different parts, viz the quartz masses, wavy zones with rather coarse mica flakes and between these masses and zones very fine-grained aggregates mainly consisting of either albite and muscovite, or of a larger number of minerals. The minerals occurring in this rock are: quartz, muscovite, brown biotite, albite, epidote, garnet, sphene, apatite, ore, zircon and traces of amphibole and of brownish green as well as of red-brown biotite. The quartz crystals of the eyes are much coarser than the minerals in the other parts. Apart from an occasional mica flake no other minerals are found in these masses. Their grain size is about 0.5 mm. The coarser mica zones consist mainly of brown biotite (0.2 mm) and are slightly mechanically disturbed. In these zones garnet fragments with a dusty core and rims showing birefringence occur together with epidotes and patches of calcite and ore. An occasional large apatite (0.3 mm) is seen. Smaller crystals of muscovite with a random orientation are enclosed within these larger biotite crystals and show opaque grains in linear arrangement parallel to the basal faces of the biotites in which they occur.

The patchy appearance of the main body of the rock is due to the local concentration of different groups of minerals. Patches consisting of angular albites (0.06 mm) between tiny muscovites in random arrangement alternate with patches that are also rich in brown biotite, minerals of the epidote group and minute euhedral non-isotropic garnets (0.02 mm). In both types of patches there are groups of a large number

of albite crystals showing a roughly similar optic orientation, but adjoining groups of albite often show an entirely different orientation. The albite shows enclosed mica and small quartz droplets.

Both the macroscopical and the microscopical structural features of this rock point to the fact that we are dealing here with a blastomylonite, i. e., with a rock affected by mylonitization, which was followed by recrystallization.

The samples T 10, T 413 and LP 223 taken from garnetiferous mica-schists contain chloritoid. They derive from the following outcrops:

T 10, coord. 7300—1618, alt. 1990 m, Pedanatsch.

T 413, coord. 7289—1605, alt. 1990 m, Frunt.

LP 223, coord. 7290—1601, alt. 1740 m, Zervreila plant.

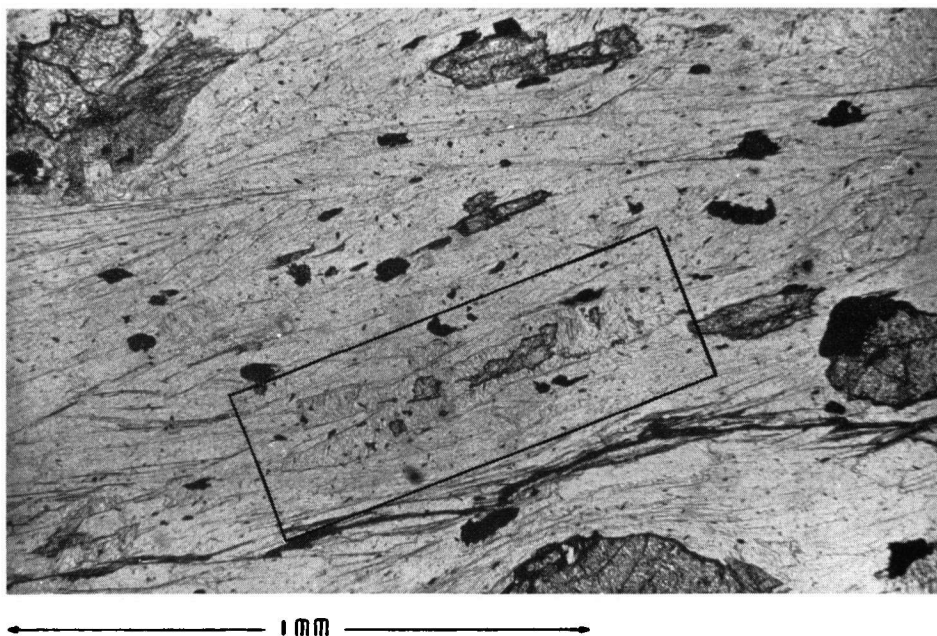


Fig. 18. Remnants of chloritoid in transverse muscovite. Sample T 10, a garnetiferous mica-schist with chloritoid from Pedanatsch.

A description of sample T 10 is given below.

Macroscopical description: A brownish schistose rock with a high amount of coarse mica. The other minerals that can be distinguished are sandy quartz and minute garnets.

Microscopical description: The section shows a fabric of mechanically disturbed quartz (0.5 mm) and parallel flakes of muscovite, with less chlorite, garnet and chloritoid. The inclusions in the garnet porphyroblasts (0.3—1.5 mm) are mainly quartz and rutile. Chlorite (diabantite) may be found throughout the sample, partly parallel to the schistosity, partly replacing the garnet porphyroblasts. Sparse rather small crystals of muscovite are seen transverse to the schistosity ("Querglimmer"). Flakes of chloritoid are parallel to the schistosity. Several remnants of one chloritoid crystal may be found within the transverse muscovite crystals (fig. 18), clearly indicating that the transverse muscovite is younger than the chloritoid. The rims of most of the chloritoid crystals consist of transverse muscovite.

Epidote, rutile and apatite are accessories, whereas tourmaline was not found in the section examined.

The fissured garnet poeciloblasts of sample T 413 enclose quartz, chlorite (ripidolite), tourmaline, chloritoid, muscovite, biotite and epidote. The mineral chloritoid was not found in the enveloping rock. Sample LP 223 shows the same feature.

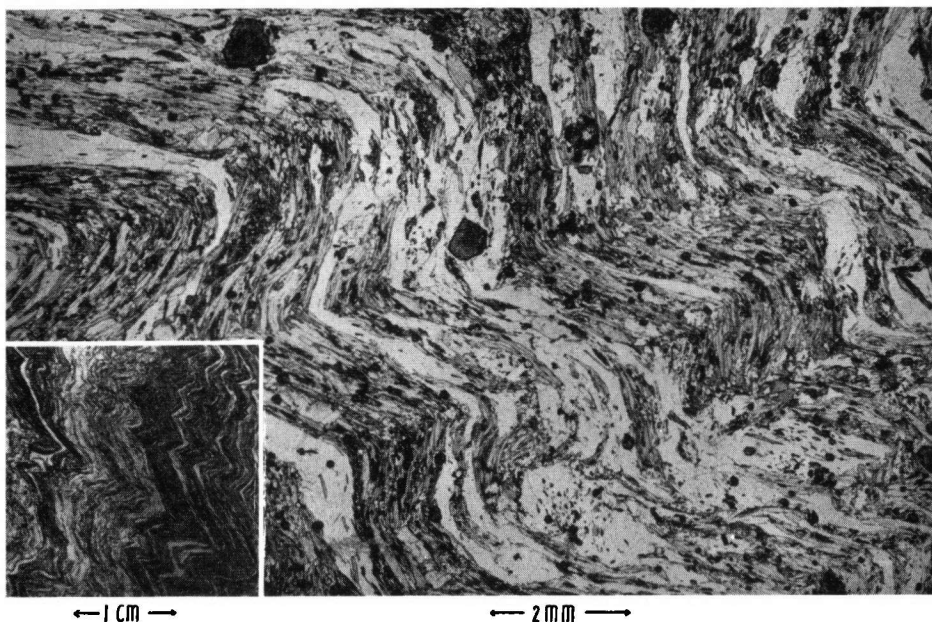


Fig. 19. A glaucophane-bearing garnetiferous mica-schist with occasional albite poeciloblasts (LP 95). The inset shows the thin section. Note the distinct accordion folding, the micas in tangential arrangement and the occasional albite poeciloblast. On this scale of enlargement the glaucophane is not to be distinguished.

Whenever glaucophane can be determined in the mica-schists, as in sample No LP 65, LP 95, LP 375, LP 85, T 28, this mineral always has rims of blue-green amphibole. The samples are derived from:

LP 65, coord. 7300—1588, alt. 2160 m, Guralätschbach.

LP 95, coord. 7330—1615, alt. 2210 m, N of the Selvasee.

LP 375, coord. 7314—1622, alt. 1560 m, Vals-Zervreila road.

LP 85, coord. 7348—1602, alt. 1700 m, Peil.

T 28, coord. 7299—1613, alt. 1870 m, Pedanatsch.

Sample LP 95, a glaucophane-bearing garnetiferous mica-schist is characterized by a sharp accordion folding (with NE—SW axes, cf. fig. 19). In the crowns of the folds the muscovite may build straight or slightly bent flakes in tangential arrangement ("Polygonalbogen"). This illustrates their post-kinematic age with regard to the main phase of folding. The bending of the micas is apparently due to slight movements of a younger age, with the same axes. The glaucophane is in prisms with obscure blue-green rims. It is mainly preserved within the albite poeciloblasts, but is also found in the main body of the rock. The small euhedral crystals of garnet show minute dusty inclusions in zonal arrangement.

Two samples contain ferrohastingsite, viz LP 72, old road Vals-Zervreila (coord. 7300—1607) and T 37, Frunt (coord. 7288—1604). Sample LP 72

moreover shows much zonal tourmaline and well-developed fringes of green biotite around the muscovite. In some cases the ferrohastingsite is seen to be surrounded by blue-green amphibole with a larger axial angle.

Some samples contain a fair amount of red-brown biotite, e. g., sample L 5.

Sample L 5, a garnetiferous albite-bearing mica-schist. Entrance to the Lental, Aetzmäder.

The sample shows undulating zones, mainly consisting of muscovite, wrapping around albite poeciloblasts and rather large fissured and partially altered garnet crystals (0.5 cm). There are also smaller crystals of garnet, set in these mica-zones. These crystals show fringes and patches of a red-brown biotite that is partially chloritized. The biotite builds a kind of halo around these crystals of garnet, but the haloes are never seen to surround the garnet entirely. Within the mica-zones large flakes of red-brown biotite are seen, occasionally altered into chlorite. In other cases the biotite is bleached giving rise to a colourless mica with a rather small axial angle. In some cases it could not be determined whether bleached biotite still preserves some coloured parts, or whether young red-brown biotite builds rather poor-shaped fringes and patches at the expense of muscovite. Transverse muscovite is seen to grow through biotite flakes surrounding a crystal of garnet. Enclosed in albite, smaller subhedral and euhedral crystals of garnet are seen, occasionally accompanied by some surrounding biotite.

Summary

Summarizing, the mica-schists show a number of indications that these rocks have been affected by several different phases of metamorphism, e. g., the chloritization of the garnets, the replacement of chloritoid by transverse muscovite ("Quermuscovit"), the occurrence of several successive generations of amphibole, the occurrence of fringes of biotite around the crystals of muscovite, and the occurrence, within the albite poeciloblasts, of armoured relics of minerals that outside the albite armour, have been more strongly or entirely transformed.

The clue to unravel the complicated history of these rocks has to be sought in the Mesozoic rocks and the amphibolites and allied rocks.

The average number of mineral phases in 66 samples is 11, 15 samples having more than 12 minerals.

AMPHIBOLITES AND ALLIED ROCKS

Occurrence

The amphibolites of the investigated region are closely associated with rocks containing varying amounts of sodium-pyroxene, which in the field are difficult to recognize. Since there is obviously a genetic connection between these two rock types, they are treated together in one paragraph. The associated metatectic *) quartz-albite rocks are also described here.

Amphibolitic and allied rocks are to be found throughout the region under consideration and are also widely distributed in the other parts of the Adula Nappe. Their origin has been the subject of much discussion and speculation, but in the opinion of the author a satisfactory solution to this problem has not yet been given.

The larger outcrops of these rocks are found in the area of the Zervreilasee, near the chapel of Frunt, on the Alp Ampervreila, below the dwellings of

*) see note on page 501.

Boden, along the road Vals-Zervreila in the tunnel area, in the environment of the Selvasee, at Peil and on the Fanella Alp. The typés found in these outcrops are more or less similar but small differences may be observed.

The amphibolites and allied rocks are found in lenticular masses as well as in stromatitic bands between them. The lenses are mostly contorted, the axes being more or less parallel to the schistosity, but often oblique to the b-axes of the adjoining rock.

Relation with the adjoining rocks

Field experience points to the remarkable fact, that the amphibolites nearly always occur between the mica-schists and the phengite-gneisses (Müller 1958). This phenomenon could not only be observed in the region under review, but also on the pass of San Bernardino and in the higher parts of the Val Calanca. The map by Kopp, Jenny and Frischknecht (1923) reveals a great number of other localities. From the papers by Gansser (1937) and Buchmann (1953) it is clear that this phenomenon is not restricted to the Adula Nappe, but is also present in the northern part of the Tambo Nappe and the higher Maggial, respectively. A hypothesis about the origin of the amphibolites has to account for this structural or primary relation.

Amphibolites in contact with Mesozoic rocks are rare and are exposed on the Weissgräti, on the Selva Alp and in the region of Fuorela de Puozas near point 2495. In these cases it can be argued that the amphibolites have derived from Alpine ophiolites, in contrast with the amphibolites mentioned above. The arguments are of a structural and petrographical nature and will be dealt with in their proper place.

Macroscopical description

The macroscopical features of the amphibolites are not easily described because there are as many different types as specimens can be collected. It is rather useless to subdivide them into groups with special macroscopical properties, for in case of subdivision, rocks that are microscopically similar land in different groups. Apart from this the groups are not confined to special localities or areas and do not seem to have a petrographical significance. Therefore the amphibolites will be treated much as they occur in the field.

The amphibolites of the region near the Zervreilasee. — Fresh outcrops of these rocks can be studied along the road leading to the hydroelectrical plant, the "low" road, and along the road leading to the crown of the dam, the "high" road. Let us take the low road first. Approaching the power station and passing mica-schists with folded leucocratic bands of phengite-gneisses a large amphibolitic body appears at a slight curve in the road. The adjoining gneissic *) schists are massive and show some amphibole crystals. The amphibolite itself is built by strongly contorted bands and lenses of different mineralogical composition. The lenses have a shell in shell structure and are apt to exfoliation. The wavy concentric bands within the lenses are different in composition and vary in thickness from a few millimetres to some tens of centimetres. The alternating bands have a high content of yellow

*) The "albitreiche Muskovitgneise" of Müller (1958, p. 430).

epidote and grass-green pyroxene or dark amphibole. Occasionally they are rich in crystals of garnet of about one centimetre or they are built exclusively by small garnet crystals. Other bands are rich in albite poeciloblasts showing a pink colour due to the presence of macroscopically invisible garnet.

In between these mafic rocks *), contorted veins occur, consisting almost exclusively of albite and quartz, the so-called "Metatekts" **). Below the waterdrift entrance, a migmatitic amphibolite is seen, rich in "Metatekts". An excellent photograph of this very outcrop has been given by Müller (1958, plate II).

Along the high road on the left hand side an outcrop of the same amphibolitic body, described above, is visible. Here again amphibolitic lenses of varying size alternate with white "Metatekts". A pyroxene-rich lens, formerly covered by morainal deposits, shows canon-ball weathering. Above the level of the dam a beautiful lenticular body of amphibolites is exposed, on top of phengitic ribbon gneisses. Other amphibolitic masses not so well exposed, appear on the slope S of the Zervreilasee, showing the same features as the one described.

The amphibolites of the Ampervreila Alp. — The amphibolites mapped in the area of Ampervreila and the Schwarz Fluh, do not show so many lenticular



Fig. 20. Sketch of an outcrop of amphibolites and allied rocks near the large tunnel of the road Vals-Zervreila, showing the lenticular structure of these rocks, coord. 7316—1624.

masses as those of Zervreila, and have more quartz, albite and muscovite. Lenses of beautiful green chloromelanite appear in more or less stratified

*) The "Restgewebe der Migmatite" of Müller (1958, p. 433).

"Restgewebe" means remaining tissue.

**) Metatekt is a term defined by Scheumann (1937) and Mehnert (1949). Metatexis is a process during which mobile constituents of a rock are concentrated in veins or in irregular masses, which can easily be distinguished from the comparatively immobile parts ("Restgewebe"). It is of no importance from where the mobile part has come or how it originated.

rocks. This pyroxene forms spool-shaped bodies of 5–30 cm in size, embedded in a loose matrix consisting of euhedral red garnet, amphibole prisms and an abundance of muscovite (crystal size ca. 1 mm). Other lenticular bodies have a massive fabric of yellow epidote and show vugs filled with sandy dark green chlorite (prochlorite) and euhedral twinned albite crystals, measuring up to 1 cm. The joints in these amphibolites are often lined with quartz crystals, magnetite octahedrons and adularia.

The amphibolites of the tunnel section, road Vals - Zervreila. — North of the tunnel entrance on the left hand side, mica-schists appear that have a conspicuous yellow colour, due to alteration. Approaching the tunnel, the mica-schists show a gradual transition into a more solid kind of albite-rich rock indicating the proximity of amphibolite by its ever increasing content of hornblende. The contact between the two types of rock lies in the tunnel. Splendid amphibolitic lenses embedded in a mica-rich matrix are exposed on the left hand side of a road section, nowadays closed for cars, where garnetiferous amphibolites are the most important type of rock (coord. 7316–1624). Fig. 20 schematically illustrates the textures. South of the southern entrance of the new tunnel-section the rock wall on the left hand side (coord. 7316–1624) is composed of a tenacious black hornblende-rich rock holding red garnets of ca. 0.5 cm. The hand-specimen shows conspicuous dark violet patches of rutile and occasional crystals of chalcopyrite. Vugs and tension cracks are lined with idiomorphic quartz, adularia and epidote needles and are filled with fluean ("Kluftlette"). Further on along the road the amphibolite becomes stratified and is bordered by a band of phengite-gneiss of about 1 m, not shown on the map.

The "Pseudodiorite" of Peil, coord. 7347–1599, alt. 1710 m. — At the site where the waterdrift Ampervreila - Peil comes to the surface near the Peilerbach, a coarse-grained stromatitic rock with bands alternately rich or poor in amphibole, garnet, sodium-pyroxene or albite (fig. 21) was exposed during the construction of the tunnel. Samples taken from this outcrop can still be found on the dump in the immediate surroundings of the aqueduct. At first sight the rock seems to be a banded diorite, the main constituents being feldspar and amphibole. A study of the artificial exposure made it clear that it is a rare type of amphibolite. Fig. 21 can only give an imperfect impression of the variation of the beautifully coloured rocks. Fine-grained tenacious green rocks consisting of sodium-pyroxene might have provided our palaeolithic ancestors with material for their polished axes, cf. Hügi (1948). Sometimes these green rocks show patches rich in garnet, making them look like eclogites.

The amphibolites of the Selvasee region and Heinisch Stafel. — The amphibolites treated so far belong to the rocks of the Zervreilerlappen. The next group comprising rocks taken from the Fanellalappen, has slightly different characteristics. In general these rocks are more schistose and have a lighter colour, while rocks that might have originated from ophiolites are found in between. The mafic rocks of this region can be found in two small areas; first on a ridge running from the Selvasee to Heinisch Stafel, secondly, around the Hohbühl, where a group of small outcrops is found. The ridge consists of a stromatitic amphibolite alternating with accordion-folded mica-schists. A few pyroxene-rich lenses occur.

Microscopically these rocks are conspicuous because of their relatively high

content of glaucophane. The outcrops grouped around the Hohbühl supply the same kind of samples as the Heinisch Stafel ridge, but other types can also be found.

In the gully W of the Hohbühl, coord. 7326—1604, a solid bluish black rock crops out. Macroscopically epidote veins and magnetite octahedrons are distinguishable. A vein of pellucid feldspar about 10 cm thick breaks through it and long needles of a shiny black amphibole (ferrohastingsite) are seen in

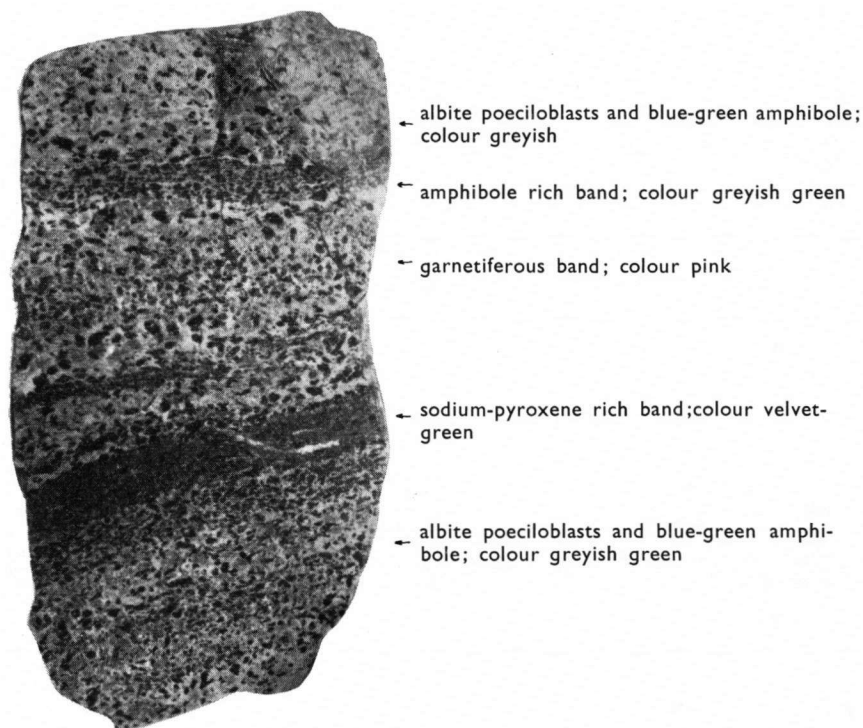


Fig. 21. "Pseudodiorite" of Peil, a coarse-grained stromatitic rock with bands composed of different mineral assemblages, natural size.

the feldspar mass. The whole aspect of the rock points to a type of rock not comparable with the amphibolites and the hypothesis seems justified that this might be a metamorphosed mafic igneous rock of Mesozoic age, i. e., an ophiolite. Microscopically the bulk of this rock appears to consist of epidote, ferrohastingsite and relics of glaucophane.

Other outcrops near the Hohbühl, especially in the SW are normal amphibolites and can be linked with the outcrops at the Ampervreilahorn, the Guralätschhorn and the arête limiting the basin of the Guralätschsee to the east. The rocks in the outcrop near point 2248, E of the Hohbühl, are of a different appearance and may well be transformed ophiolites. Here the rocks are of a light colour and they are rich in chlorite. They are in contact with dolomitic rocks, in which no trace of thermal metamorphism could be found. Fragments of dolomitic rocks with irregular outlines occur within the

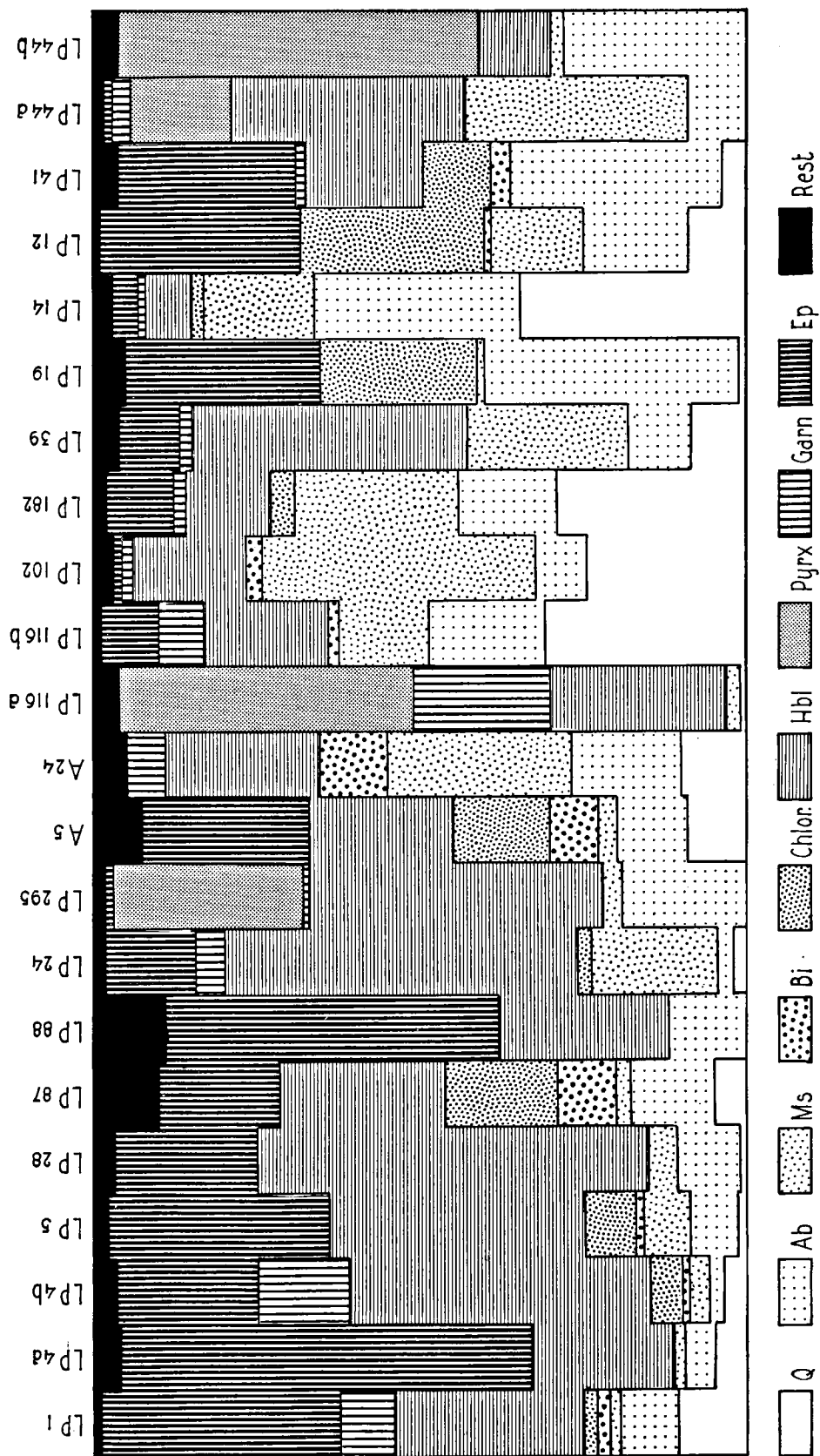


Fig. 22. The mode of 22 thin sections of amphibolites and allied rocks graphically represented.
Hbl = blue-green amphibole as well as sodium-amphibole or actinolite.

amphibolites, without any trace of rolling out or other structural phenomena, this pointing to the former existence of a primary contact. The contact area in the dolomite is rich in quartz and contains a conspicuous green mica. The colour is due to traces of nickel.

The amphibolites of the region of Fuorcla de Puozas, coord. 7277—1620. — The ridges running from the mountain gap Fuorcla de Puozas in north-eastern direction, are built by many rock types, a.o., mica-schists, phengite-gneisses, dolomites, amphibolites and glaucophane-schists. These rocks are intensely folded and rolled out. Amphibolites and other mafic rocks, structurally intercalated between other rock types, are locally highly mylonitized. Therefore it is hard to distinguish amphibolites from ophiolites, the latter, no doubt, being more common.

Microscopical description

The mode of a number of sections is given in fig. 22, indicating that the variation in these rocks is not only of a qualitative but also of a quantitative character. These point counter analyses emphasize the importance of epidote in most of the amphibolites.

In the following a description of a number of thin sections will be given, mostly cut from samples of the regions described in the former paragraphs.

Sample LP 522, a garnetiferous sodium-pyroxene rock from Pian d'Asc, Val Calanca.

Macroscopical description: A fine-grained tenacious rock, showing a linear and also a less well-developed parallel structure. It has a green colour and contains numerous small garnets. Two parallel sets of veins oblique to both types of schistosity and to each other intersect the sample. Apparently the veins are filled tension cracks. Samples of this type may be found as boulders in the river Calancasca.

Microscopical description:

A fine-grained (0.3 mm) mass of subhedral to anhedral sodium-pyroxene and minute euhedral garnets holds larger zonal poeciloblasts of amphibole and occasional crystals of muscovite, with golden-yellow rutile as a frequent accessory.

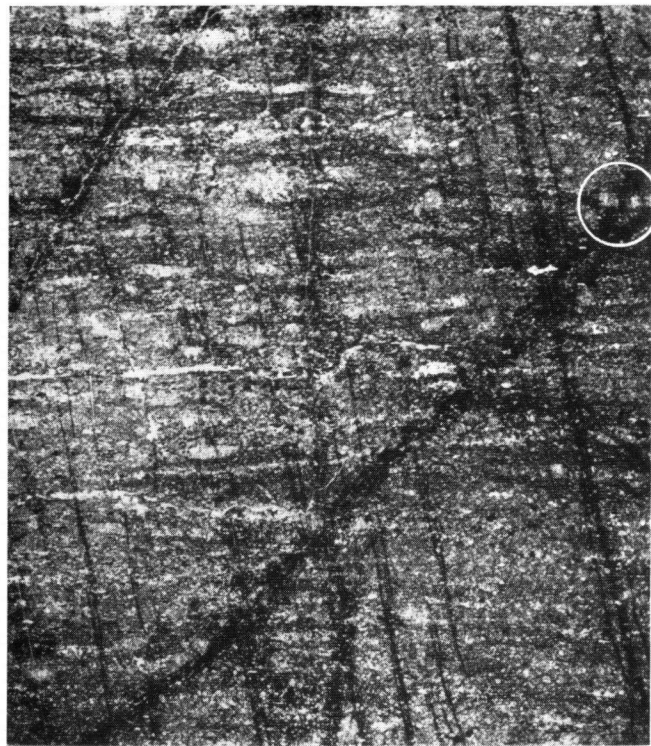
The sodium-pyroxene is light greenish. Its crystals show a parallel arrangement causing the linear structure of the rock. The garnets have a pink colour. In a number of cases a cavity is seen in the centre that is commonly filled up by muscovite and/or quartz. Such garnets are often called *atoll garnets*. The cavity is euhedral as well and occasionally contains a small euhedral garnet in its centre (fig. 23b). In their centre the zonal amphibole poeciloblasts show a pleochroism with faint blue and violet colours parallel to the c- and b-axes (glaucophane). Narrow rims are built by blue-green amphibole with a more pronounced colour.

Enclosed within these poeciloblasts are garnets, sometimes with an *atoll* structure (fig. 23c), irregular crystals of sodium-pyroxene or quartz, flakes of muscovite and prisms of rutile.

The two sets of veins mentioned above are filled with calcite, green amphibole, chlorite, epidote, quartz, albite and sphene.

The solutions that circulated through the veins penetrated the walls and caused a metasomatic alteration of the older minerals of the rock, mainly a production of blue-green amphibole at the expense of sodium-pyroxene and of the light coloured amphibole, resulting in a dark colour of the section along the veins (fig. 23a, a 1, a 2). Moreover epidotization of garnet was locally observed. In a number of instances the veins, when intersecting a crystal of amphibole, are filled with amphibole showing a similar crystallographic orientation as the intersected crystal. Here the amphibole crystals of the walls of the veins apparently functioned as cores of crystallization for the vein-filling minerals.

The epidote is mainly confined to those parts of the veins that are bordered by crystals of garnet. In some instances sphene was found at the intersection of rutile crystals.



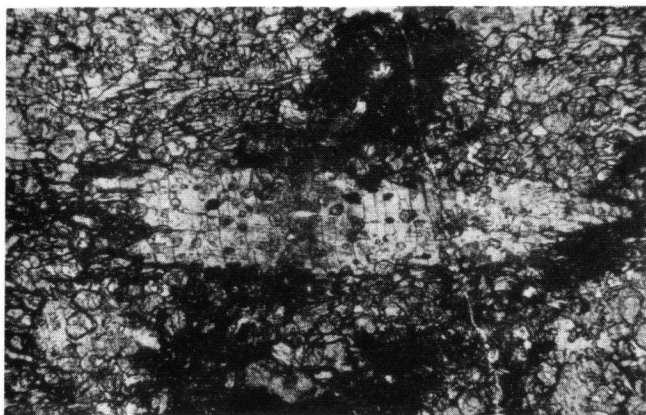
← 1 cm →

d

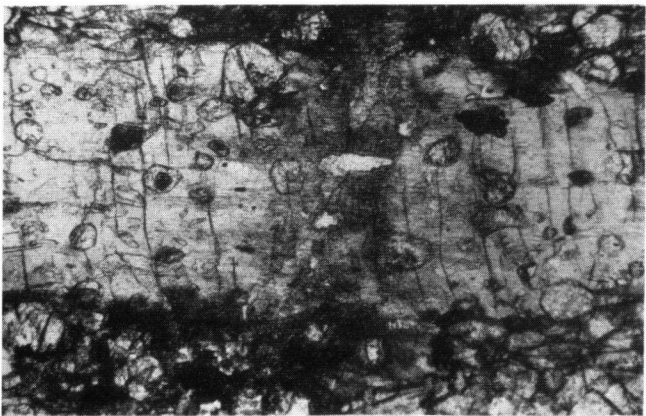


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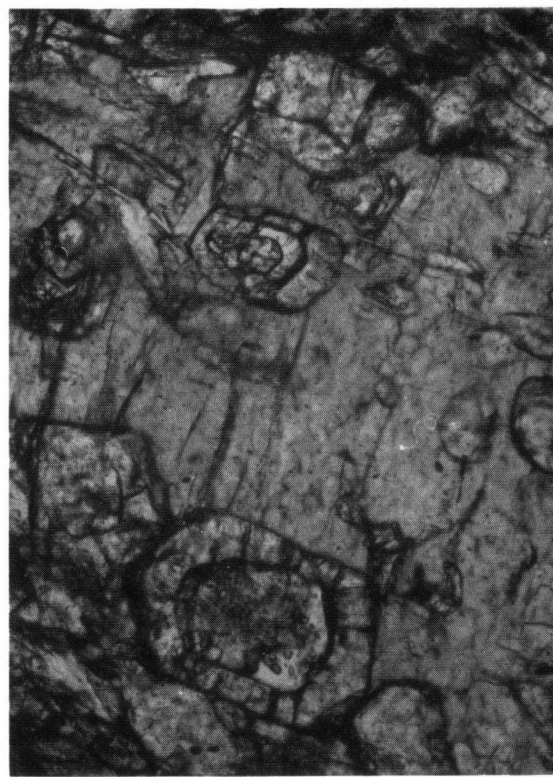
b



d1



d2



← 0.4 mm →

c

Fig. 23. Sample LP 522, a garnetiferous sodium-pyroxene rock from the Val Calanca. The photo (a) shows two sets of dilatation veins with metasomatically altered walls, as well as parallel glaucophane poeciloblasts in a fine-grained matrix. One of the glaucophane poeciloblasts that is intersected by dilatation veins, is shown enlarged in fig. (a1) and (a2). These glaucophane poeciloblasts show enclosed euhedral atoll garnets, filled with quartz and muscovite (c). One of the atoll garnets of fig. (c) shows a rather euhedral garnet in its cavity (b).

The mineral assemblage of the veins is different from that in the main body of the rock. The same mineral association is frequently observed in amphibolites without garnet, sodium-pyroxene and sodium-amphibole.

Sample M 431. Garnetiferous sodium-pyroxene rock from Ampervreila, Collection R. O. Müller.

Microscopically parts of the rock that are very rich in green sodium-pyroxene contrast sharply with garnet and amphibole-rich schlieren containing much accessory rutile. The pyroxene-rich parts, in which the pyroxene does not show any trace of alteration, contain zonal crystals of glaucophane with rims of blue-green amphibole, and also local concentrations of quartz. The amphibole in the garnet-rich schlieren, in contrast to the amphibole of the pyroxene-rich parts consists of blue-green amphibole with an occasional core of glaucophane.

Sample LP 112. Garnetiferous amphibole rock from the tunnel section, road Vals - Zervreila, coord. 7316—1624, alt. 1550 m.

This sample contains the following minerals: amphiboles, garnet, albite, epidote, chlorite, green biotite, rutile, sphene, apatite, calcite, zoisite, quartz, muscovite, tourmaline, chalcopyrite, ilmenite and pyrite.

The amphiboles, that build about 60 % of the sample, are short prismatic (ca. 2 mm). They are zonal with rims built of blue-green amphibole, while the core occasionally has a violet colour parallel to the b-axis. Fibrous amphibole pseudomorphs after pyroxene show relic patches of this latter mineral. Within the garnets numerous inclusions of amphibole are found, usually of the blue-green variety, rarely of a blue-violet sodium-amphibole without blue-green rims.

The garnets may reach a size of ca. 2 mm and show a pink colour. In several garnet crystals a well-developed zonal structure is visible, with large dusty cores and narrow clear rims of a lighter colour. Cracks within the garnets are filled up with chlorite, epidote and blue-green amphibole. Occasionally the younger light coloured garnet variety of the rims is also found in sharply bounded veins within the dusty cores. These veins are seen to cut several crystals of blue-green amphibole that are enclosed within the older dusty garnet, but themselves may also contain blue-green amphibole, thus illustrating the contemporaneity of both minerals. Calcite and epidote are also enclosed within these veins.

Albite poeciloblasts (0.2—0.6 mm) are studded with inclusions of the other minerals occurring in the sample. Rutile is a conspicuous mineral, occurring in grains measuring up to 2 mm. The colour of the rutile is dark violet and brownish yellow, occasionally rims of sphene are apparent. Anhedral apatite (1 mm) is a frequent accessory. The blue-green amphibole of this sample is coarse if compared with the same mineral in the other samples, and easy to separate. This property made it possible to prepare a sample of blue-green amphibole for chemical analysis, see p. 457.

Samples LP 82; LP 83; LP 121; LP 278; LP 280; LP 281; LP 282; LP 283; LP 284. "Pseudodiorite" of Peil, coord. 7347—1599, alt. 1710 m.

Macroscopical description of these samples, see p. 502.

These samples are: albite amphibolites (LP 278, 283)

sodium-pyroxene amphibolites (LP 82, 83, 281)

sodium-pyroxene rocks (LP 121, 280, 282, 284)

Sample LP 278, is a stromatitic garnetiferous albite amphibolite. Fig. 24 shows the hand-specimen, fig. 25 the thin section taken from the place marked with a circle. The hand-specimen is taken from a banded rock.

The rock is medium-grained. The light coloured bands are built by oval albite crystals, some colourless mica and tiny garnets. Amphibole prisms are sparsely scattered throughout the light coloured bands and may be as large as 0.5 cm.

The mafic bands are built by the same minerals as the leucocratic ones, but now amphiboles are in the majority.

Occasionally these mafic bands are separated from the felsic ones by a small quartz seam. This for instance, applies to the part of the specimen marked by a circle. The section described below was made from this part of the sample.

Microscopical description:

The most conspicuous feature of both the light and dark coloured bands is the presence of an old schistose fabric of a grain size of some tenths of a mm, that

is preserved within the large poeciloblasts building the main body of these bands and attaining sizes of about 1 mm in the dark and about 3 mm in the light coloured bands.

The quartz seam separating both parts of the rock is devoid of this older fabric and consists of coarse recrystallized quartz, with a occasional flake of muscovite and cubes of pyrite.

The leucocratic part of the section consists of an aggregate of albite poeciloblasts

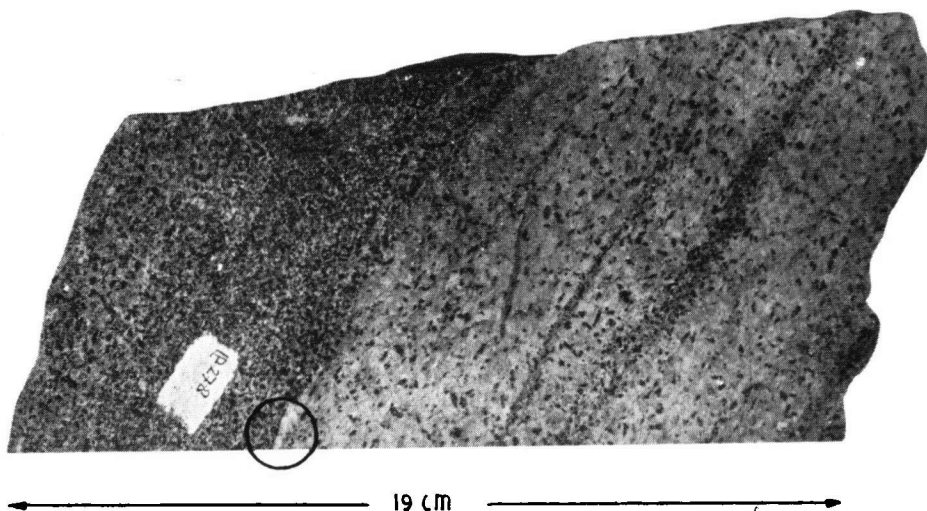


Fig. 24. Sample LP 278, a stromatitic garnetiferous albite-amphibolite from Peil. The thin section is cut from the place marked with a circle; photographs of this section are given in the following figure. "Pseudodiorite" of Peil.

of about 3 mm. These poeciloblasts are studded with euhedral garnets, epidote prisms, small amphibole needles, rutile and muscovite. The slightly zonal blue-green amphibole poeciloblasts are in the minority. Minerals enclosed in these amphibole poeciloblasts are garnet, epidote, muscovite, rutile and quartz.

The mafic part shows the same minerals in different quantities. Amphibole and epidote are the main dark constituents, accompanied by some garnet. Albite porphyroblasts are not so numerous.

Sample LP 82 and LP 83, stromatitic epidote-amphibolites with sodium-pyroxene rich bands.

These samples contain bands showing more or less the same features as the foregoing sample, as well as strongly schistose bands of a finer grain and bands rich in relic sodium-pyroxene. The albite poeciloblasts enclose small euhedral garnets as well as larger garnet fragments and the minerals biotite, blue-green amphibole, epidote, muscovite and rutile. Biotite occurs among others enclosed in blue-green amphibole. Zonal epidote (Δ rim $<$ Δ core) is occasionally enclosed in the blue-green amphibole. In some bands a distinct zoning of the garnet can be observed with pink cores and colourless rims. Here, the garnets enclosed in amphibole show both core and rim, whereas an occasional garnet enclosed in sodium-pyroxene is pink and has no rim. The amphiboles are slightly zonal being mainly built of a blue-green variety and occasionally having bluish cores with a very faint tinge of violet parallel to the b-axis. The large amphibole poeciloblasts enclose garnet, muscovite, epidote, relic sodium-pyroxene, biotite and rutile. The sodium-pyroxenes are zonal (Δ rim $<$ Δ core) and have a weak pleochroism. The average grain size is 1.0 mm.

Sample LP 121, a garnetiferous sodium-pyroxene rock.

The section consists mainly of granular, zonal, greenish sodium-pyroxene (0.2 mm) with subordinate blue-green amphibole, garnet and rutile. Some of the amphibole crystals show cores with a more or less purplish tinge parallel to the b-axis. Garnets

may show inclusions of pyroxene and blue-green amphibole. Dilatation veins are filled with a mineral assemblage of another composition, viz quartz, green biotite, epidote, chlorite, calcite and actinolite. Next to these veins the sodium-pyroxene is transformed into a dark blue-green amphibole. Muscovite, a minor constituent of the rock, has fringes of brownish green biotite near the veins. Vein sections joined by rutile are filled with sphene. Other accessories are apatite, hematite and limonitic ore.

The samples LP 280, 281, 282, 283 and 284 are interesting on account of the occurrence of sodium-pyroxene in different ways of appearance, and on account

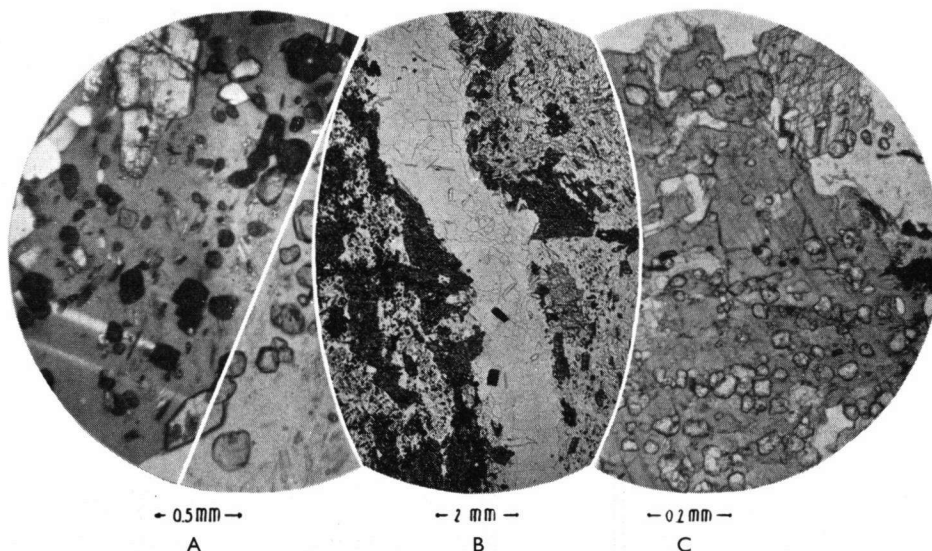


Fig. 25. Sample LP 278. A stromatitic albite-amphibolite, "Pseudodiorite" of Peil.
 A. An albite poeciloblast, the minerals shown are epidote, garnet and amphibole needles. Note the well-shaped rutile prism at the top (crossed nicols and plane polarized light).
 B. A pyrite-bearing quartz vein separating the mafic and the felsic parts of the section. The minerals shown are poeciloblastic blue-green amphibole and albite, with additional epidote and muscovite.
 C. A blue-green amphibole poeciloblast studded with small crystals of garnet. Other minerals are muscovite, ore and rutile and a horse-shoe shaped patch of calcite.

of the presence of dilatation veins, filled with a mineral assemblage that is different from that of the main body of the rock.

LP 280, a fine-grained (0.3 mm) garnetiferous muscovite-bearing sodium-pyroxene rock, with subordinate quartz, blue-green amphibole poeciloblasts (up to 2 mm) and accessory rutile, apatite and calcite. The sample is stromatitic with alternating bands consisting either of muscovite with an occasional rim of brown biotite, quartz, garnet and sodium-pyroxene, or of extremely fine-grained pyroxene and occasional small euhedral garnets, or of sodium-pyroxene and euhedral garnets with some amphibole poeciloblasts. Among the euhedral garnets a few show inclusions of a dark blue-green amphibole with a rather small axial angle. Some of the others are real atoll garnets filled with muscovite and quartz.

The sodium-pyroxenes are usually fresh but in the immediate surrounding of small dilatation veins, metasomatic transformations caused alteration into a fibrous blue-green amphibole. In these fibrous masses adjoining the veins, brownish green biotite and chlorite were observed. The vein-filling minerals are quartz, albite, fibrous amphibole, sphene and epidote. In one case a vein intersects a large amphibole poeciloblast. Here the trace of the vein stands out through a more greenish colour of the amphibole and by inclusions of epidote.

LP 281, a stromatitic garnetiferous epidote-amphibolite with some sodium-pyroxene.

The sample shows bands, either rich in quartz and epidote, with minor amounts of garnet, calcite and blue-green amphibole, or mainly consisting of epidote, blue-green amphibole and garnet, with subordinate quartz, albite, calcite and pyroxene. The average structure is granoblastic to poeciloblastic with grain sizes of about 0.3—0.5 mm. This sample is mainly interesting because it shows how pyroxene changes into amphibole, either of the fibrous kind or in large poeciloblasts enclosing both patches of relic pyroxene and euhedral garnet, together with quartz, epidote and rutile. The sodium-pyroxene when enclosed in albite, has narrow fibrous rims. Albite, moreover, shows inclusions of blue-green amphibole, epidote, calcite and garnet.

LP 282, garnetiferous sodium-pyroxene rock with amphibole poeciloblasts and muscovite.

Minor constituents are: albite, brown biotite, chlorite, epidote, rutile, sphene, apatite and ore minerals.

Large blue-green amphibole poeciloblasts and albite poeciloblasts within an irregular, more or less granular mass of smaller pyroxene and euhedral garnet give some information as to the course of metamorphism. The amphibole crystals are zonal and show in their cores at times a purplish hue parallel to the b-axis. The extinction position of different enclosed pyroxene patches being similar, it may well be argued that these amphiboles have partly grown at the expense of sodium-pyroxene.

The large albite poeciloblasts, being of rather sparse occurrence, are crowded with inclusions of the following minerals: sodium-pyroxene with narrow fibrous rims, blue-green amphibole, garnet, rutile (with an occasional rim of sphene), muscovite, an occasional epidote and apatite.

Small dilatation veins filled with albite, green biotite, sphene, fibrous amphibole, blue-green amphibole, epidote and chlorite, intersect the sample and cause a metasomatic change of the wall-minerals, comparable to that in sample LP 522 (p. 505). There are certain relations between the minerals observed in the vein and the minerals forming the walls that give some information about the stability relations during the formation of the vein. The associations enumerated below, however, are not always encountered and some of them are even exceptional.

Minerals building the wall.

Minerals in the vein.

Sodium-pyroxene	Green biotite
Sodium-pyroxene with rims	Albite in which blue-green
of fibrous amphibole	amphibole fibres
Muscovite	Aggregates of green biotite and chlorite
Garnet	Green biotite or epidote
Rutile	Sphene
Albite	Albite

The vein is not easily distinguished if a large amphibole poeciloblast or an albite poeciloblast is intersected. But the trace of the vein stands out through a different colour and birefringence in the amphibole and through a special arrangement of the inclusions within the albite.

LP 283, stromatitic albite-amphibolite.

Large crystals of albite and blue-green amphibole together make a poeciloblastic aggregate, with a more or less subparallel trend. The rather large albite poeciloblasts (0.5 cm) are crowded with fibrous pyroxene relics, blue-green amphibole laths, rather large muscovite, rutile, sphene and epidote.

The blue-green amphibole poeciloblasts show inclusions of rutile, sphene, calcite, muscovite, green biotite, and a rather exceptional sodium-pyroxene relic. The following other minerals were found in this sample: quartz, apatite (up to 0.8 mm) and ore minerals.

LP 284, a rather solid garnetiferous sodium-pyroxene rock with an occasional blue-green amphibole crystal and subordinate muscovite, quartz, apatite and rutile.

A rather fine-grained sodium-pyroxene and larger euhedral garnets are chief constituents. The garnets occur mainly as fissured crystals with inclusions of minute needles of rutile and occasionally of dark blue-green amphibole and quartz. They are also found in rare clusters around aggregates of sodium-pyroxene.

The crystals of blue-green amphibole are usually euhedral and may also build larger poeciloblasts enclosing garnet, rutile and patches of sodium-pyroxene.

Two veins traverse the section, intersecting each other. The first vein, a dilatation vein, is filled with twinned albite, blue-green amphibole, garnet fragments of the wall, greenish brown biotite, quartz, calcite, epidote, muscovite and sphene. The wall consists partly of minerals that are the product of a metasomatal influence on the original material of the rock. Here epidote, fibrous blue-green amphibole, brownish green biotite, muscovite, garnet and sodium-pyroxene are present. Minerals of this wall functioned as cores of crystallization for some of the vein-filling minerals, a.o., amphibole for amphibole and rutile for sphene. Garnet seems to be relatively stable in this vein, because epidote as a vein-filling mineral at the intersection of garnets was not observed. On the other hand garnet fragments of the wall are now found in the centre of the vein.

The second vein has a patchy appearance and is mainly filled with calcite. The rims are partly formed by an extremely fine-grained aggregate of green biotite. Within this vein, sodium-pyroxene skeletons and chloritized garnet fragments are present, demonstrating its metasomatic character. Other vein-filling minerals are actinolite and green biotite (both surrounding sodium-pyroxene in some places), quartz, muscovite with fringes of green biotite and apatite.

At the place where the second vein cuts off the first, the dilatation vein is practically obliterated and its trace can only be found in some relic fragments of sodium-pyroxene with a crack filled with biotite amidst the calcite mass of the second vein. The influence of the second vein can also be found in one branch of the dilatation vein, that has been filled with calcite over a distance of 1 mm.

It seems appropriate to give the above recorded phenomena in a schematical diagram.

Minerals composing the rock.	Minerals in vein A.	Minerals in vein B.
Zonal sodium-pyroxene	Blue-green amphibole sometimes fibrous	Actinolite and calcite
Blue-green amphibole	Blue-green amphibole	
Garnet	(Garnet fragments)	
Rutile	Sphene	Sphene
	Albite	
	Brown to green biotite	
	Calcite	Calcite
	Epidote	
Muscovite	Muscovite	Green biotite
Quartz	Quartz	Quartz

In this diagram minerals under different headings are listed behind each other if some relation between these minerals was observed. N.B. this should not be thus interpreted that wherever such a mineral is observed the other minerals of the row need to be present.

Samples LP 88; LP 88a and LP 452. West of the Hohbühl; coord. 7326—1604, alt. 2400 m.

Macroscopical description see p. 503.

Microscopically this rock shows patches of an epidote fabric and patches built by parallel amphibole prisms with magnetite octahedrons. The size of these patches is about 2 to 3 cm, their shape is irregular.

The epidote patches chiefly consist of granular or fan-like yellowish epidote with an occasional prism of glaucophane (0.2 mm).

The patches built by parallel prisms of a weakly coloured amphibole with magnetite hold several crystals of amphibole with dark greenish blue cores and light-coloured rims. The transitional type of fabric between these extremes consists of many dark greenish blue amphiboles with light-coloured rims, set in a matrix of albite and epidote, together with separate crystals of more colourless amphibole. The glaucophanes within the epidote mass in many but not all cases have fringes of this dark greenish blue amphibole, while the dark greenish blue amphibole in the transition zone may show an occasional glaucophane core. It may be emphasized that glaucophane without rims of other amphiboles in numerous cases occurs in direct contact with epidote. The dark greenish blue amphibole, having a small axial angle and a negative elongation

in some sections, is beautifully developed in an albite vein cutting through these rocks. The amphibole prisms here may reach a length of 4 cm and were determined as ferrohastingsite. It shows slightly fibrous rims, due to alteration. The optical properties are to be found on p. 458.

Samples LP 380—389, LP 397 and LP 435. Ridge between the Selvasee and Heinisch Stafel.

These samples were taken from a formation of stromatitic amphibolites and banded amphibole-bearing mica-schists with associated leucocratic bands.

Sample LP 384 is a specimen of such a leucocratic band. Irregular large and small interlocking albite porphyroblasts make the rock, the rest is of muscovite, epidote and chlorite. These latter minerals are arranged in such a way as to form a wavy almost parallel pattern. A few fissured and partly shattered garnets with rims of phyllosilicates were observed. The albite shows inclusions of smaller albite, quartz and mica and it is seldom twinned.

The other samples are more or less albite-rich or amphibole-rich rocks. They show a well-developed schistosity. The zonal amphibole prisms are always more or less parallel to the b-axes of the rocks, the average grain size varies but is about 0.3 mm. Albite porphyroblasts, if present, show inclusions, a. o. of remnant glaucophane, garnet, rutile, blue-green amphibole, mica and other minerals. As the microfolds in sample LP 386 go unhindered through the albite porphyroblasts, it may be assumed that the albite is at least partly subsequent to the main folding phase, responsible for the formation of the well-developed b-axes in these samples. Part of the other minerals are older than these folds, e. g., at least part of the epidote and glaucophane.

The samples LP 387 and LP 388 contain a rather fair amount of glaucophane.

Sample LP 435 contains sodium-pyroxene, glaucophane and haloes of epidote around the crystals of garnet.

Sample LP 397 shows glaucophane and tourmaline in one sample. The glaucophane usually shows rims of blue-green amphibole. The cores of the glaucophane crystals hold at times epidote and calcite inclusions (LP 387, 388) or patches of a dusty green amphibole with a similar crystallographic orientation (LP 388). This dusty amphibole shows a slight difference in colour with the blue-green rims. It shows veins of glaucophane as well, and therefore is apparently older than the glaucophane. The glaucophane itself is again cut by veins of the blue-green amphibole variety of the rims. The rims of the blue-green amphibole that, consequently, are younger than the glaucophane may occur around the same crystals that show the cores of older dusty amphibole. The same sample contains zonal garnet with a more intense colour in the cores. The garnet occasionally shows inclusions of glaucophane, without rims of blue-green amphibole. The sodium-pyroxenes are sometimes zonal and may show narrow or broad rims of a fibrous blue-green amphibole. Rutile in these rocks often shows rims of sphene. The chlorite, a common constituent of these rocks, in some instances was determined as prochlorite, see p. 464.

Glaucophane-rich sections are poor in albite. Garnet is found in the majority of samples deriving from this ridge.

Samples T 207, LP 479. Deriving from the region of Fuorcla de Puezas, coord. 7270, 7280—1620, alt. 2744—2495 m.

Sample T 207, albite-epidote-biotite-schist with a fair amount of amphibole.

The section consists of a fabric of fine-grained minerals, with an almost parallel arrangement. The average grain size is about 0.3 mm. The following minerals, ranked more or less in order of importance, were observed: albite, brown to olive-green biotite, chlorite (a. o., rumpfite), epidote, blue-green amphibole, ferrohastingsite, sphene, apatite, quartz and ore minerals. The amphiboles show cores of ferrohastingsite and rims of blue-green amphibole with a large axial angle. The amphiboles and biotites are usually intergrown. Sphene may a. o., form rims around opaque grains.

Sample LP 479, epidote-glaucophane-crossite-schist.

Irregular bands and zones consisting either of varying portions of fine-grained epidote and glaucophane and boudin-shaped aggregates, mainly of coarser calcite, quartz and mica with some epidote, make this sample. As minor constituents the minerals chlorite,

green biotite, blue-green amphibole, crossite, ferrohastingsite and ore minerals are to be reported.

The amphibole crystals consist mainly of glaucophane. Cores with a more pronounced violet colour an occasional negative elongation consist of crossite. Occasionally the glaucophane has narrow rims of a blue-green amphibole with an occasional negative elongation, pointing to the presence of ferrohastingsite. The rutile crystals in this sample are sometimes rather large (2 mm).

The samples of this region are generally fine-grained and rich in chlorite. Marks of mylonitization are to be seen everywhere. Microscopical evidence of this mechanical disturbance is the cataclasis of quartz and epidotes, as well as the stromatitic structure of the samples, some bands being ground to an anhedral fine aggregate of different minerals. It may well be possible that the samples T 207 and LP 479, just described, are original ophiolites or mixed types between ophiolites and Mesozoic sediments.

Along the road to Peil, an outcrop is found that shows contorted amphibolites overlain by greyish garnetiferous marbles, calciferous mica-schists and phengite-gneisses. The marbles and calciferous mica-schists may belong to the formation of Mesozoic rocks that appear on the summit of the Weissgrätli and on the Hennensädel. These amphibolites are mainly important because they show fresh glaucophane in contact with garnet; a sample will be described next.

Sample LP 4, a garnetiferous amphibolite, coord. 7330—1631, alt. 1420 m, road to Peil.

The sample consists mainly of blue-green amphibole and garnet, both concentrated in zones and patches. The crystals of reddish garnet (up to 1 mm) are cracked and fissured and show newly built rims of a pink coloured garnet. Garnet fragments with a reddish colour show pink rims that tend to grow euhedral outlines. The cores of these garnets are locally studded with glaucophane prisms, not showing a rim of blue-green amphibole.

Blue-green amphibole, building the greater part of the sample (ca. 30 %), shows an occasional core of glaucophane. Another main constituent is epidote, while quartz, albite, muscovite, biotite, chlorite, apatite, rutile and calcite are subordinate constituents.

Summary

Summarizing, the metamorphic history of the amphibolites and allied rocks, just as that of the mica-schists, is rather complicated, as indicated by many observations.

Among the relations between the members of one mineral group the occurrence of zonal amphiboles and zonal garnets may be mentioned in this connection, as well as the occurrence of veins of another type of amphibole or garnet. The most wide-spread type of zoning of the amphiboles shows cores of glaucophane and rims of blue-green amphibole, the former mineral in some instances being veined by the latter. Other amphiboles are less frequent, but also appear according to general rules. So ferrohastingsite, if present, may show cores of glaucophane and rims of blue-green amphibole (with a larger axial angle) or of light-coloured actinolite-like amphibole. Again this light-coloured amphibole, if present in zonal crystals, always appears in the outermost zone. Crossite occurs as cores in glaucophane, in crystals showing rims of ferrohastingsite.

In one case, the glaucophane is associated with two slightly different types of *blue-green* amphibole, one occurring in the cores, another in the rims of

the composite crystals. Since the cores of dusty blue-green amphibole are cut by veins of glaucophane, this dusty blue-green amphibole must be older than the glaucophane. On the other hand the blue-green amphibole variety of the rims also occurs in veins within the glaucophane.

The above observations are schematically summarized in the following list of amphibole types, drawn in such a way, that an arbitrary amphibole of this list only shows cores of one of the types mentioned below it, or rims of one of the types mentioned above it.

N.B. the most wide-spread types are denoted in capitals, those observed only once are put in parenthesis.

Actinolite-like amphibole
 BLUE-GREEN AMPHIBOLE
 Ferrohastingsite
 GLAUCOPHANE
 Crossite
 (Dusty blue-green amphibole)

The garnet occasionally shows pink cores and lighter coloured rims, or veins of lighter coloured garnet in pink garnet.

Among the relations between members of different mineral groups the occurrence of inclusions of one mineral in another mineral is of importance, as well as the occurrence of very narrow dilatation veins filled with other minerals than those of the surrounding rock. A complete enumeration of the inclusions in the different minerals need not be given here. For instance the following minerals belonging to other groups were found as inclusions within glaucophane: garnets (sometimes atoll-shaped), sodium-pyroxene, muscovite, rutile, quartz, epidote and calcite.

Among the very narrow dilatation veins mentioned above only those are of special interest, which were apparently formed during a phase of metamorphism subsequent to the main phase shown by the rock. The assemblage of each of these veins is assumed to have originated in a relatively short stretch of time and to represent an association of minerals, stable under the circumstances during its formation. It would lead too far to enumerate all the vein-filling associations observed, the more so since they are listed on p. 505, 510 and 511. The most interesting of these associations (p. 511) consists of albite, blue-green amphibole, greenish brown biotite, calcite, epidote, muscovite, quartz and sphene in a rock composed of sodium-pyroxene, garnet, younger blue-green amphibole poeciloblasts, muscovite, quartz, apatite and rutile. Garnet fragments of the wall are also found within the vein, without showing any trace of alteration.

The mutual age relations of the different minerals occurring in the amphiboles and allied rocks will be discussed in chapter VI.

The average number of mineral phases in 126 samples is 10, 25 samples having more than 12 minerals, cf. sample LP 121, p. 508.

MESOZOIC ROCKS

Occurrence

The Mesozoic rocks may be subdivided into two groups. The first group comprises metamorphosed carbonate-bearing sedimentary rocks, the second one consists of metamorphosed mafic igneous rocks. Both groups have been thoroughly dealt with by Nabholz (1945). The occurrence of these rocks in our limited region has been described in chapter II. The following types can be distinguished:

- a) Mesozoic rocks of sedimentary origin:
 - Simple calcite-marbles and simple dolomite-marbles
 - Sandy limestones
 - Sugar-grained dolomites
 - Ribbon marbles and ribbon dolomites
 - Rauhwaackes
 - Brecciae
 - Calcareous schists and calcite-bearing arenaceous schists
 - Impure calcite-bearing quartzites, with some phengite
 - Phlogopite-bearing or phengite-bearing dolomites
 - Garnetiferous chloritoid- and kyanite-bearing schists and quartzites
 - Monomineralic rocks containing either gypsum or anhydrite
- b) Mesozoic mafic rocks of igneous origin:
 - Ophiolites
 - Greenschists, occasionally with glaucophane
 - Stromatitic rocks consisting of ophiolitic parts and sedimentary parts causing ribbon ophiolites, and sedimentary rocks with small bands and streaks of ophiolitic material

On the Hennensädel and on the Weissgrätli a group of metamorphic rocks comprises, a. o., dark brown massive quartzites with green patches (chloritoid poeciloblasts) of 0.5 cm, and lime-rich garnetiferous schists with quartz lenses and rods in which sometimes large chloritoid crystals can be found as well as spools of kyanite and quartz. The crystals of chloritoid and kyanite in these lenses may reach dimensions of more than 2 cm. A description of the outcrop at the Weissgrätli is given by Müller (1958). The outcrop at the Hennensädel has already been described before (van der Plas et al. 1958). A section through this outcrop is given in fig. 7.

Rocks deriving from the waterdrift Ampervreila-Peil can be found at the dumps on both sides of the tunnel. Among them anhydrite- and gypsum-bearing specimens appear, that have been described in chapter III, paragraph 4 and 15. The tectonic position of these rocks, of the rocks found at the Hennensädel and of those found at the Weissgrätli is described in chapter II.

In a torrent coming down from the Selvasee and running along Heinisch Stafel, a coarse ribbon marble was found at coord. 7335—1619, alt. 2010 m. The beautifully folded bands form a formation of about 10 m thick. The bands are green or red due to their content of phengite or ferrian phengite, see p. 474.

Phengite-marbles, dolomites and phlogopite-dolomites are common rocks of the Mesozoic formations. A phengite-dolomite collected near the Finstererbach, contains some albite and an occasional crystal of microcline, see p. 473. Outcrops below the meadow of Boden, showing fine-grained yellow dolomites

with well-developed mineral-lined tension joints, yielded clear quartz crystals, distorted rhombohedral dolomite crystals and milky adularia.

Near the entrance to the waterdrift below Ampervreila a dolomite covers a quartzitic band (not indicated as such on the map). These quartzites show an equigranular quartz mosaic with some phengite flakes. On microscopic observation this rock (sample LP 76) appears to contain a few microcline porphyroblasts with some enclosed quartz crystals. There is a distinct interlocking of the microcline crystals and their surroundings, pointing to a subsequent formation of this microcline.

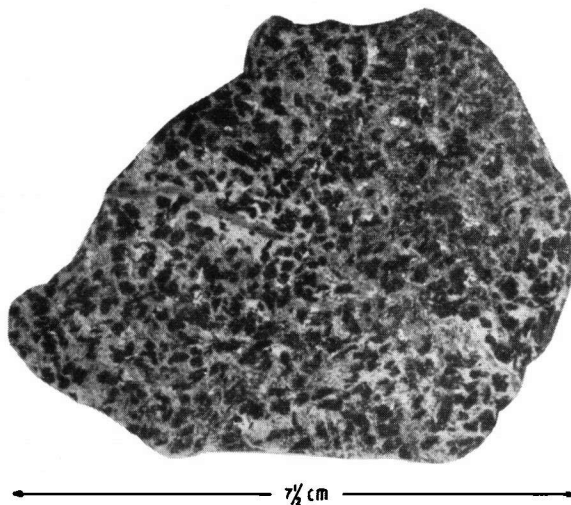


Fig. 26. Polished section of an ophiolite from the Tomülbach. The sample still shows a kind of gabbroid structure, the dark patches, however, consist exclusively of a fine-grained aggregate of chlorite, actinolite and epidote.

Mafic rocks are not abundant in our limited region and occur mainly in the uppermost parts of the slopes west of the Valserrhein. Metamorphism changed these rocks, but the old ophitic structure can still be observed in those cases where mylonitization did not grind the rock to a fine-grained greenschist. Fig. 26 shows the fabric of such a rock from the Tomülbach. The original minerals are completely transformed into albite, epidote, chlorite and calcite with some additional sphene. In some types glaucophane can macroscopically be seen.

Relation with the adjoining rocks

The contacts of the Mesozoic sedimentary rocks with the other types already described are always of tectonical origin. Structural unconformities on a large scale can directly be seen on the map.

The mafic igneous rocks occasionally show primary contacts with sedimentary Mesozoic rocks, a. o., at the Weissgrätli and near the Hohbühl. The dolomites in the vicinity of these contacts locally show large amounts of garnet.

According to Nabholz (1945) the greater part of the ophiolites are of intrusive origin.

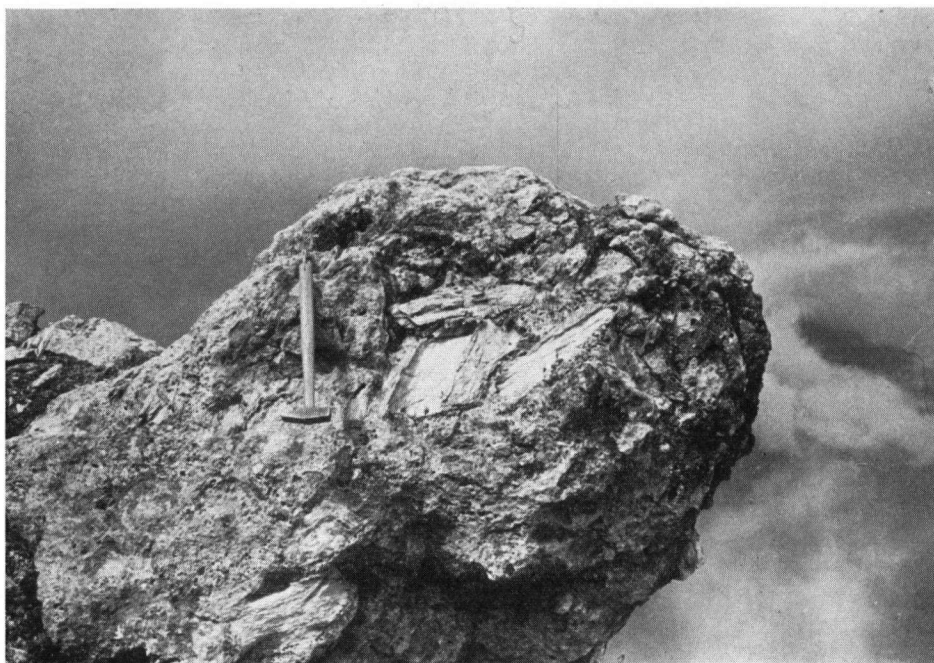


Fig. 27. Breccia of dolomitic components in a matrix rich in calcite.
Summit of the Weissgrätli, pt. 2866 m.

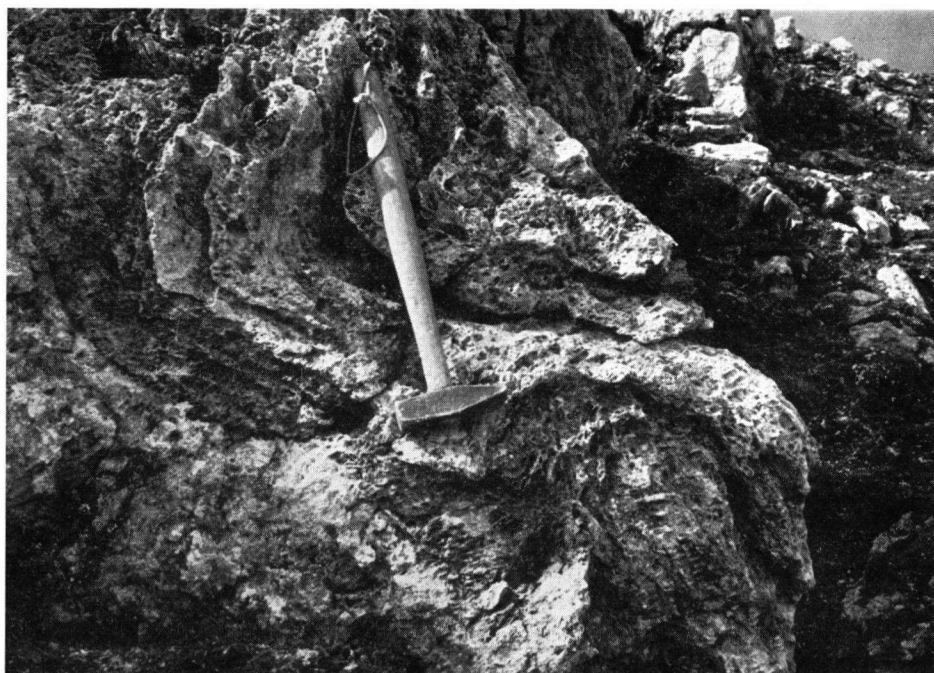


Fig. 28. Rauhwackes on top of the Weissgrätli, showing a NW—SE folding axis.

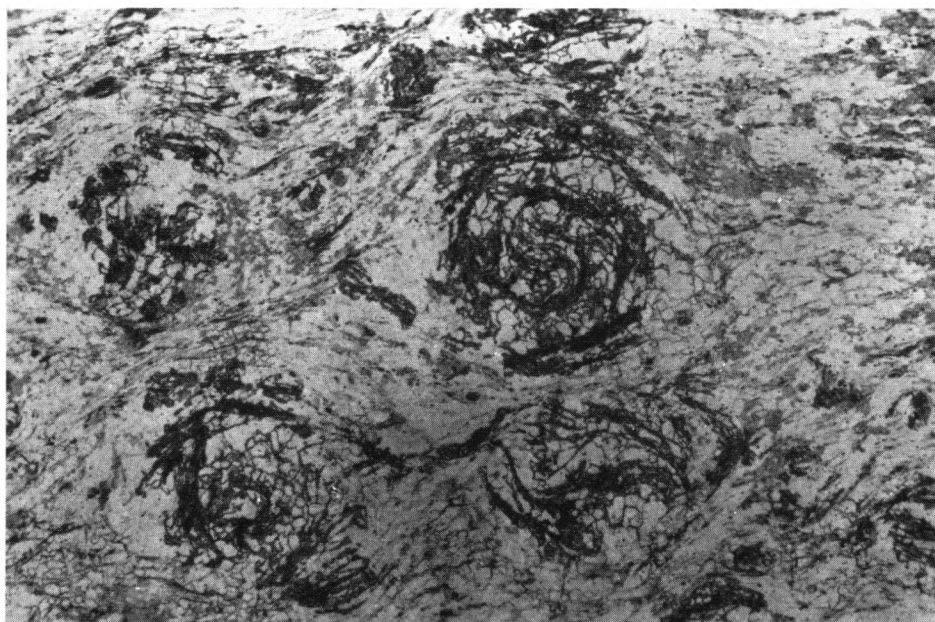


Fig. 29. Sigmoidal poeciloblastic aggregates in a calciferous mica-schist, sample LP 276a. The aggregates consist of garnet, chloritoid, kyanite and chlorite with enclosed quartz. Enlargement about 10 \times .

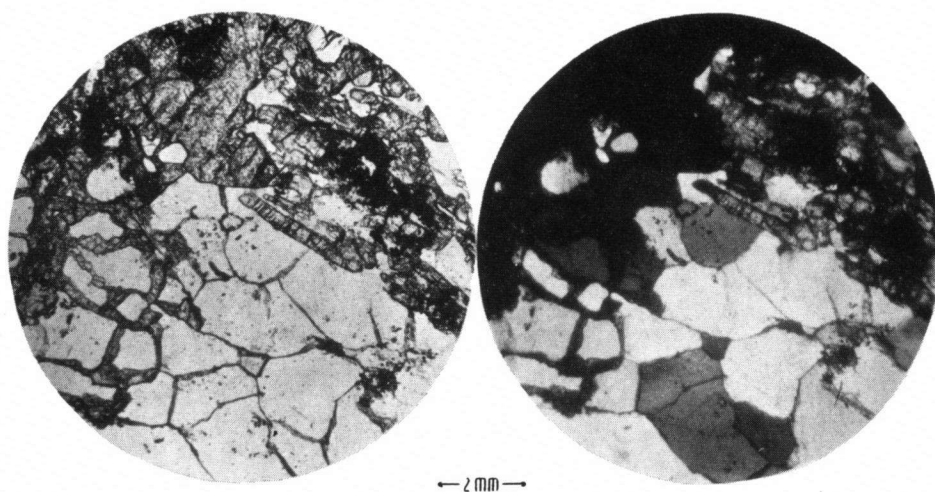


Fig. 30. Part of a composite poeciloblastic aggregate consisting of garnet, quartz and chloritoid, sample LP 276a. An extremity of a chloritoid flake is seen to have been changed into garnet (left upper part of the rod-shaped crystal just right of the centre of the photograph). Note the fine garnet lace between the quartz crystals. Plane polarized light and crossed nicols.

Description of some rock types

Samples derived from the Weissgrätli and the Hennensädel are, a. o., yellow dolomites, yellow mica-bearing dolomites, rauhwackes (being mostly brecciated dolomite-calcite rocks, sometimes containing weathered gypsum, fig. 27 and 28), marbles, calciferous schists and quartzites. Dull-brown quartzites and lime-bearing garnetiferous schists contain the minerals chloritoid and kyanite. Specimens of these last mentioned rocks will be described next.

Sample LP 276a, coord. 7306—1592, alt. 2560 m, Hennensädel.

Mode: Q 60 %, Ms 15 %, Garn 5 %, Ce 12 %, Chloritoid 5 %, Rest: Ru, Kyanite, Ep, Chlor, Zr, Tourmaline, Ore.

The sample is a fine-grained garnet-bearing calciferous mica-schist. The main constituent quartz builds an equigranular mosaic (0.2 mm) and shows traces of subsequent mechanical disturbance and recrystallization.

Strangely shaped poeciloblastic aggregates (up to 4 mm), consisting of garnet, chloritoid, kyanite and chlorite with enclosed quartz, are of frequent occurrence. As can be seen from fig. 29 the appearance of these composite poeciloblasts suggests rotation during their growth. The main constituent of these poeciloblasts is garnet appearing both as flaky bodies in a sigmoidal arrangement and as an irregular lace surrounding almost all the quartz crystals within these poeciloblasts, fig. 30. Some flakes of chloritoid, occasionally in a similar sigmoidal arrangement, are also seen. Sometimes one extremity of a chloritoid flake is seen to be changed into garnet, explaining the flaky habit of some garnet masses, fig. 30. Apparently garnet is formed pseudomorphous after chloritoid. Both garnet and chloritoid are partly transformed into chlorite. The inferred age relations are:

Chloritoid (old) — Garnet — Chlorite (young).

Kyanite is a rather subordinate constituent of the composite poeciloblasts. The composite poeciloblasts are to be compared with irregular honeycombs where the wax structure is represented by garnet and the honey by quartz. Perhaps this explains why the outlines of the poeciloblasts are lenticular, because mechanically they have to be considered as more or less rigid bodies, that remained stiff during subsequent mechanical disturbance.

The kyanite also builds many small crystals outside the composite poeciloblasts and this mineral is partly altered into muscovite.

Calcite with patches of hydrous iron oxide is common. Siderite may be observed in direct contact with chloritoid. It may even be possible, that part of the siderite is pseudomorphous after chloritoid. The association chloritoid-tourmaline, so frequent in chloritoid-bearing rocks, can also be observed here. The muscovite flakes, that are arranged subparallel to the schistosity, have a dusty appearance and are slightly bent.

Sample LP 276, coord. 7306—1592, alt. 2560 m, Hennensädel.

Mode: Q 80—85 %, Garn 5 %, Ce 8 %, Chloritoid 3 %, Ore 1 %, Rest: Tourmaline, Ru, Ms, Chlor, Ap, Zr, Tit, Ep, Zof, Bif.

The sample is a fine-grained quartzite with dark patches of poeciloblastic chloritoid and garnet. The chief constituent quartz builds an equigranular mosaic.

Within this matrix we observed, apart from these poeciloblasts: calcite with rims and patches of brown iron oxide; tourmaline crystals, concentrated in clusters or just as single crystals; an occasional minute kyanite fragment, partially transformed into muscovite; and some muscovite.

The poeciloblasts consist either of garnet, or of chloritoid, or of both. Other minerals in these poeciloblasts playing a subordinate role are calcite, chlorite (brunsvigite), kyanite, rutile, muscovite and an occasional tourmaline. The quartz enclosed in these poeciloblasts has a smaller grain size than the quartz of the matrix. Moreover the quartz of the matrix shows a conspicuous lattice orientation, whereas lattice orientation of the enclosed smaller quartz is not obvious. Quantitative measurements of this lattice orientation and of the difference in the orientation patterns of the quartz of the matrix and the enclosed quartz were not made. The chloritoid and the garnet form aggregates of a few crystals, see fig. 31. The poeciloblasts, whether composed of chloritoid or of garnet, are similar in shape, the garnet poeciloblasts having more inclusions of quartz. The chloritoid generally occupies the central part of a composite

poeciloblast, whereas the garnet is concentrated in the rims, tending to grow euhedral outlines.

Both chloritoid and garnet are partly chloritized.

These minerals show the same age relations as in sample LP 276a.

Mesozoic igneous rocks are more important in the region mapped by T. H. Tan. Ophiolites in the region W of the Valserrhein occasionally contain some glaucophane. Sample T 116 is such an ophiolite.

Sample T 116, coord. 7318—1637, alt. about 1700 m.

Macroscopical description: The hand-specimen shows a dark coloured rock, with a tinge of blue. The schistosity is well-developed, and closer examination reveals the presence of small parallel yellowish green bands (1 mm).

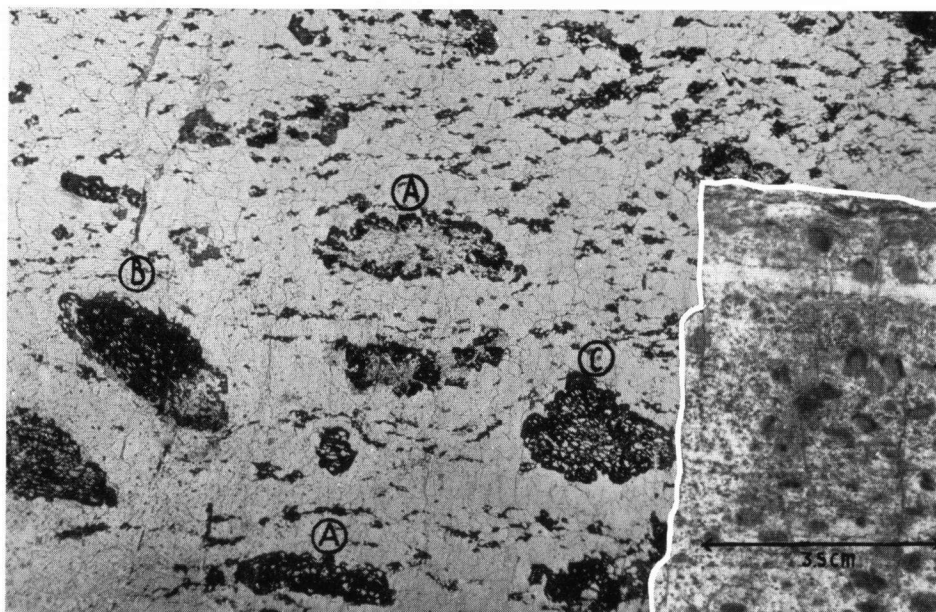


Fig. 31. Sample LP 276, a fine-grained quartzite showing patches of chloritoid and garnet (see inset). The thin section shows poeciloblasts consisting either of garnet (A), or of chloritoid (B) or of both (C). Note the difference in grain size between the enclosed quartz and the quartz outside the poeciloblasts.

Microscopical description: The thin section shows the sample to be mainly built of epidote and glaucophane, both concentrated in zones, or in irregular patches. As minor constituents calcite, chlorite, rutile and dark blue-green amphibole were observed. They usually show glaucophane with a core and/or rim of more intensely coloured crossite (see also page 460). The sodium-amphibole shows fringes and rims of a dark blue-green amphibole, while this amphibole is also present in fibrous aggregates with small cubes of ore. It shows an occasional negative elongation, a small birefringence and a strong absorption, pointing to ferrohastingsite.

In the sections an occasional garnet was seen.

A marked characteristic of some greenschists and ophiolites is the high content of large sphene crystals, which can even develop into poeciloblasts. The mineralogical composition of these rocks is rather simple. The chief con-

stituents are epidote, chlorite, albite, blue-green amphibole and actinolite. The blue-green amphibole usually shows rims of actinolite. In some samples sodium-amphiboles as well as ferrohastingsite are present.

The microscopical structure of the ophiolites and greenschists is strikingly different from that of the amphibolites. In some cases the old ophitic structure still persists, but the minerals originally present, are transformed into chlorite, epidote, actinolite and albite. Other samples bear traces of mylonitization, but in some spots the old structure can still be seen. Again, mechanical disturbance may have obliterated all original structures, giving rise to fine-grained aggregates of partly recrystallized actinolite, chlorite, epidote and calcite, blue-green amphibole being of rare occurrence.

Summary

Summarizing, the Mesozoic rocks may provide us with information about the age of a large number of metamorphic minerals, since these minerals can only have been produced during metamorphism of Alpine age.

The most interesting of these minerals are:

microcline	phlogopite	actinolite
muscovite	crossite	garnet
phengite	glaucophane	chloritoid
olive-green biotite	ferrohastingsite	kyanite
green biotite	blue-green amphibole	

The occurrence of microcline, biotite and kyanite of Alpine age deserves special emphasis. As in the case of the mica-schists and the amphibolites and allied rocks, the Mesozoic rocks were affected by more than one phase of metamorphism, producing a number of complicated mineral assemblages.

However, the metamorphism shown by the Mesozoic rocks, in contrast with that of the mica-schists and the amphibolites and allied rocks, is exclusively of Alpine age. Therefore the conclusion is warranted that the Alpine metamorphic history of the Adula comprises more than one phase of metamorphism.

The occurrence of composite spiral poeciloblasts of, a.o., garnet and chloritoid, in one of the samples studied, points to the existence of a phase of synkinematic metamorphism of Alpine age. A conspicuous lattice orientation of the quartz was produced in another rock following the growth of garnet and chloritoid. These rocks show the age relation:

chloritoid (old) — garnet — chlorite (young).

In the same rocks kyanite has been altered into muscovite.

In one of the ophiolites zonal crystals of amphibole show the following succession:

crossite (core) — glaucophane — crossite — ferrohastingsite (rim).

In general, however, these rocks contain actinolite accompanied by epidote, chlorite, albite and calcite, with occasional relics of blue-green amphibole.

CHAPTER V

CHEMICAL COMPOSITION OF THE VARIOUS ROCK TYPES

The chemical composition of some of the metamorphic rock types is of great importance for a petrological discussion of their original character. One single analysis of each type of rock does not supply the necessary information. Thus means must be found to obtain a number of analyses without having to apply the cumbersome chemical method. A solution to this problem has been given a.o. by Eskola (1921): the chemical composition of a rock sample is calculated from the results of a modal analysis and the chemical composition of the constituent minerals. It will be made clear that this method can be successfully applied in the present case.

MODAL ANALYSIS

As the metamorphic rocks under discussion are more or less even-grained and have a grain size of about 0.5 mm, it is possible to make a modal analysis with the aid of a point counter. For metamorphic rocks this method is especially recommended by Harrison & Shaw (1955). A description of inherent shortcomings of point counter methods in general is given by Chayes (1956). This author deals especially with the quantitative modal composition of rocks, the reproducibility of the analysis and the numerical characterization of the analytical error.

It has to be emphasized that in the present case the modal analyses were not made in order to determine the accurate mode of the different rock types, but in order to arrive at an insight in their chemical composition. The accuracy of a point counter analysis is not linear proportionate to the number of points counted, but the increase in accuracy decreases rapidly after a certain number of points and there is no appreciable increase after this number. Thus, since the composition of the minerals used in the calculation is only roughly known, it is useful to know the minimum number of points that have to be counted under the given circumstances (structure, grain size, number of components, ect.), in order to reach a final result with reasonable accuracy, to which elementary statistical formulae can be applied. Such formulae are valid in the case of random sampling, whereas point counter analysis is a systematic sampling technique.

If in one-dimensional systematic sampling the relation between the distance of the points and the average grain size is such that successive points lead to correlated measurement — in which the amount of correlation decreases faster than, or as fast as, linearly whenever a greater distance between the points is chosen — it has been proved by Cochran (1953) that the accuracy of this systematic sampling is superior to that of random sampling. As for sampling in two dimensions, however, it has been proved that systematic sampling is not necessarily superior to random sampling (cf. Quenouille 1949, p. 371). Further, the actual standard deviation of a mean, obtained by systematic sampling, can only be calculated with a fairly complete knowledge of the sampled population — which may either be obtained by sampling or by some other means — and by applying more cumbersome mathematics.

If, however, in point counter practice we proceed in such a way, that successive points do not give rise to correlated measurements, the statistical formulae, based on random sampling may be applied even in cases where systematic sampling techniques are used.

In this respect two characteristics of the material used in our investigations are of importance, viz the grain size and the occurrence of banding and schistosity ("periodic trends"). In taking the distances between the points smaller than the average grain size, one cannot hope to obtain uncorrelated measurements. Thus it seems advisable to choose as the distance between the points, the diameter of the largest grains that occur in appreciable quantities, or any larger distance.

In previous literature it has often been argued that in modal analysis the distance between the points is irrelevant. As has been explained above, this statement does not hold true in general. Only in the case where an estimate of the mode of one single thin section is wanted — without reference to any statistical argument — the distance between successive points is irrelevant. But if the concept of accuracy enters into the argument, a distance between successive points, which is small compared to the size of the largest grains, leads to an inefficient counting procedure and to results, the accuracy of which cannot be judged by elementary statistical formulae.

As to the second characteristic of the material studied, viz the periodic trends, we note that if these trends occur in the sampled area, systematic sampling may cause highly inaccurate results, mainly if the distance between the sampled points roughly coincides with the amplitude of the periodic trends. To avoid this, the starting points of each run should be given a small random translation (see also Chayes 1956, p. 29).

Another question concerning the efficiency of the measurement is the orientation of the measurement area. According to Chayes (1956), the measurement area should be at a high angle to the plane of the banding and preferably normal to it, because normal orientation is more efficient.

The orientation of the runs in such a measurement area must also be given due consideration. In this respect a small experiment has been performed, with the aim of examining the correlation in two different ways of counting, viz normal and parallel to the banding. A description of this experiment is given on page 528. From the results it was clear that in counting parallel to the banding it is more difficult to obtain uncorrelated measurements.

To find out the number of points to be counted in order to arrive at some degree of accuracy, a thin section of sample LP 58 was used to provide the numerical data. This sample was chosen because it showed several structural phenomena, that would be expected to cause serious problems during modal analysis and therefore could provide a good test-case. It is a normal phengite-gneiss, containing the minerals quartz, albite, phengite and microcline, with epidote, apatite and a little ore as accessories. The structure is granoblastic with a tendency to "Augen" structure. The "Augen" are built by an aggregate of granoblasts of albite and microcline. The mesostasis consists of albite, microcline, quartz and mica. The mica content of the "Augen" is not as high as in the other parts of the section. The average grain size is 0.2 mm, the largest crystal has a length of 0.8 mm.

In determining the mode a Swift Automatic point counter with 14 keys was used. The distance between the points is about 0.4 mm. The distance

between the runs can be chosen at random and was in this case 1.25 mm. The observations in different runs are considered as independent observations.

The standard deviation of one single observed fraction, e. g., a fraction quartz, depends on the total number of points on which it is based. Denoting by:

- p the true fraction;
- n the total number of runs;
- m_i the number of points in the i -th run;
- k_i the number of points in the i -th run at which quartz has been observed;

the true fraction in the i -th run can be estimated by

$$\hat{p}_i = \frac{k_i}{m_i}, \text{ where } \hat{p}_i \text{ is an estimate of } p. \quad (1)$$

Its standard deviation is

$$\sigma_i = \sqrt{\frac{p(1-p)}{m_i}}. \quad (2)$$

As the square root of m_i is more or less the same for all runs, the difference of the value of σ_i for the different runs is negligible. If the product mp is not too small, e. g., > 5 , an estimate s of the standard deviation σ of a single observed fraction Q (quartz) can be obtained in this case by the well-known formula

$$s = \sqrt{\frac{\sum \hat{p}_i^2 - \frac{(\sum \hat{p}_i)^2}{n}}{n-1}} \quad (3)$$

where s has $n-1$ degrees of freedom (here the term degrees of freedom has a mathematical implication of the number of independent variables involved; for our purpose the term will be used only to tell where to look for tabled numbers in statistical tables). The standard deviation of the average observed fraction, i. e., of the mean of n independent observed fractions is $\frac{\sigma}{\sqrt{n}}$.

An estimate S of this standard deviation is

$$S = \frac{s}{\sqrt{n}}. \quad (4)$$

Given the average observed fraction $\frac{\sum \hat{p}_i}{n}$, and an estimate of its standard deviation S , we can indicate a 95 % confidence interval for the true fraction p — which should be thus interpreted that on the average 95 out of 100 intervals obtained in this way, will include the true value p — by

$$\frac{\sum \hat{p}_i}{n} - t_\alpha S \leq p \leq \frac{\sum \hat{p}_i}{n} + t_\alpha S \quad (5)$$

where t_α is (in this case) the 97.5 % fractile of a Student's t -distribution, based on $n-1$ degrees of freedom. The values of t_α can be found in all

TABLE 19

Sample LP 58, phengite-gneiss, coord. 7333—1604 alt. 2300 m, E of the Hohbühl. Point counter analysis of a section roughly normal to the schistosity; direction of runs, approximately parallel to the schistosity. The section was not refixed after each run.

Run	k_i = number of points in the i -th run at which the mineral has been observed				m_i = number of points in the i -th run		Observed fractions $\hat{p}_i = \frac{k_i}{m_i}$				Total number of runs $n = 10$
	Q	Ab	Or	Ms	Σ		Q/ Σ	Ab/ Σ	Or/ Σ	Ms/ Σ	
1	26	16	8	17	67		0.39	0.24	0.12	0.25	Average observed fractions $\frac{\Sigma \hat{p}_i}{n}$: Q 0.438 Ab 0.187 Or 0.171 Ms 0.199 N.B. Since the number of points is different in different runs, these figures differ slightly from those obtained in dividing the total number of points at which a mineral was observed by the total number of points counted. (Q 0.438 Ab 0.189 Or 0.170 Ms 0.201) Estimates of the standard deviations of the single observed fractions: Q : s 0.087 Ab: s 0.050 Or: s 0.052 Ms: s 0.079 Estimates of the standard deviations of the average observed fractions: Q : S 0.028 Ab: S 0.016 Or: S 0.016 Ms: S 0.025
2	24	17	16	10	67		0.36	0.25	0.24	0.15	
3*	22	11	9	25	68		0.32	0.16	0.13	0.37	
4	31	15	13	10	69		0.45	0.22	0.19	0.14	
5	30	16	8	13	67		0.45	0.24	0.12	0.19	
6	24	10	10	17	61		0.39	0.16	0.16	0.28	
7	22	7	10	6	45		0.49	0.16	0.22	0.13	
8	30	15	15	14	74		0.41	0.20	0.20	0.19	
9	44	10	7	9	70		0.63	0.14	0.10	0.13	
10*	34	7	16	11	69		0.49	0.10	0.23	0.16	
Sum	287	124	112	132	657		4.38	1.87	1.71	1.99	

* In the runs marked with an asterisk some other minerals were counted leading to a higher Σ .

statistical tables, e. g., Dixon and Massey (1951), Introduction to statistical analysis, table 5, p. 307. *)

Using the above formulae for sample LP 58, see table 19, the following values were found.

LP 58 Q(uartz). Runs approximately parallel to the schistosity in a section roughly normal to the schistosity. Number of runs 10, average number of points per run 66.

$$\begin{aligned}\frac{\sum \hat{p}_i}{n} &= 0.438 \\ s &= 0.087 \\ S &= 0.028 \\ t_{\alpha} &= 2.3\end{aligned}$$

The 95 % confidence interval for p (being the true fraction quartz occurring in the slide) according to (5) is:

$$0.438 - 0.064 \leq p \leq 0.438 + 0.064, \text{ so } 0.374 \leq p \leq 0.502.$$

The standard deviation of an average observed fraction was seen to be $\frac{\sigma}{\sqrt{n}}$.

This helps to estimate the value of n in order to obtain a given accuracy. Such a value of n will be denoted by N. We note that the length of the confidence interval is approximately

$$2 t_{\alpha} \frac{\sigma}{\sqrt{n}}. \quad (6)$$

The question about the number of runs to be counted in order to obtain a 95 % confidence interval shorter than 2 times 0.02 (0.02 being about 5 % of the average observed fraction Q) can now be answered.

$$4.6 \frac{\sigma}{\sqrt{N}} = 0.04.$$

An estimate of σ , viz $s = 0.087$, i. e., about 0.09

$$\sqrt{N} = 4.6 \frac{0.09}{0.04} \approx 10.$$

Thus N is at least 100. That is to say if we count 100 runs of about 66 points, we expect to arrive at an estimate of the fraction Q with an accuracy of at least 0.05 times the observed fraction Q in on the average 95 of every 100 of such total countings. This is only correct if the fraction Q is not smaller than 0.35. It pertains to counting parallel to the schistosity as in our example, under the assumption that successive points are not correlated. If a 90 % confidence interval, which is shorter than 2 times 0.04 is wanted, $t_{\alpha} = 1.8$ and the number of runs may be calculated as follows:

$$\sqrt{N} = 3.6 \frac{0.09}{0.08} \approx 4; N \approx 16; \text{ number of points is about } 1050.$$

*) These tables give one-sided values.

TABLE 20

Sample LP 58, phengite-gneiss, coord. 7333—1604, alt. 2300 m, E of the Hohbühl. Point counter analysis approximately normal to the schistosity; the section was refixed after each run.

Run	k_i = number of points in the i -th run at which the mineral has been observed				m_i = number of points in the i -th run		Observed fractions $\hat{p}_i = \frac{k_i}{m_i}$				Total number of runs $n = 19$			
	Q	Ab	Or	Ms	Σ		Q/ Σ	Ab/ Σ	Or/ Σ	Ms/ Σ	Average observed fractions $\frac{\Sigma \hat{p}_i}{n}$:			
1	11	14	6	11	42		0.26	0.33	0.14	0.26	Q	0.384	Ab	0.291
2	21	9	4	11	45		0.47	0.20	0.09	0.24	Or	0.116	Ms	0.207
3	16	13	1	9	39		0.41	0.33	0.03	0.23	N.B. Since the number of points is different in different runs, these figures differ slightly from those obtained in dividing the total number of points at which a mineral was observed by the total number of points counted.			
4	16	14	2	11	43		0.37	0.33	0.05	0.26	(Q 0.382 Ab 0.292 Or 0.112 Ms 0.210)			
5	14	13	4	7	38		0.37	0.34	0.11	0.18	Estimates of the standard deviations of the single observed fractions:			
6	19	11	2	8	40		0.48	0.28	0.05	0.20	Q : s	0.061		
7	15	13	3	8	39		0.38	0.33	0.08	0.21	Ab: s	0.055		
8	15	12	4	10	41		0.37	0.29	0.10	0.24	Or: s	0.050		
9	13	9	4	9	35		0.37	0.26	0.11	0.26	Ms: s	0.056		
10	14	12	4	8	38		0.37	0.32	0.11	0.21	Estimates of the standard deviations of the average observed fractions:			
11	14	13	4	7	38		0.37	0.34	0.11	0.18	Q : S	0.014		
12	17	11	6	4	38		0.45	0.29	0.16	0.11	Ab: S	0.013		
13	16	9	5	7	37		0.43	0.24	0.14	0.19	Or: S	0.011		
14*	15	6	6	9	37		0.41	0.16	0.16	0.24	Ms: S	0.013		
15	15	9	9	3	36		0.42	0.25	0.25	0.08				
16	10	14	3	12	39		0.26	0.36	0.08	0.31				
17	12	13	5	9	39		0.31	0.33	0.13	0.23				
18*	12	11	5	5	34		0.35	0.32	0.15	0.15				
19*	12	6	4	4	27		0.44	0.22	0.15	0.15				
Sum	277	212	81	152	725		7.29	5.52	2.20	3.93				

* In the runs marked with an asterisk some other minerals were counted leading to a higher Σ .

If the same is applied to runs that are counted more or less normal to the schistosity, the results are far better, as the following calculation illustrates. The numerical data are listed in table 20.

LP 58 Q(uartz). Runs normal to the schistosity. Number of runs 19, average number of points per run 38.

$$\begin{aligned}\frac{\sum \hat{p}_i}{n} &= 0.384 \\ s &= 0.061 \\ S &= 0.014 \\ t_{\alpha} &= \begin{array}{l} 1.7 \text{ for a 90 \% confidence interval} \\ 2.1 \text{ for a 95 \% confidence interval} \end{array}\end{aligned}$$

The number of runs, to be counted in order to obtain a 95 % confidence interval which is shorter than 2 times 0.02 may be calculated according to formula (6).

$$\sqrt{N} = 4.2 \frac{0.06}{0.04} \approx 6.3; N \approx 40; \text{ the number of points is about 1500.}$$

For a 90 % confidence interval, which is shorter than 2 times 0.04, N is about 7 and the number of points 270. In both cases counting normal to the schistosity compares favourably with counting parallel to the schistosity, again under the assumption that successive points are not correlated.

In view of the purpose of our calculations and the accuracy of the assumed chemical composition and specific density of the minerals, a 90 % confidence interval which is shorter than 2 times 0.04 seems to be sufficient. This means that on the average about 9 out of every 10 intervals obtained in this way will include the true value p . In table 21 the number of points that have to be counted is given for LP 58 and for two other samples. The results are more or less the same, being up to about 600 points, when counting normal to the schistosity. It should be borne in mind that the results thus obtained are only valid if the assumption, that every point may be treated as an independent observation, holds true.

The question whether or not the observations at successive points of a run are correlated, has been examined in the following way. Consider two successive points on a run, say point 1 and 2. Successive observations are not correlated, if the probability of finding quartz at point 2, given that quartz had also been found at point 1, is equal to the probability of finding quartz at point 2, given that muscovite had been found at point 1. If both probabilities are not equal it means that successive observations are *correlated*.

In order to test this a small experiment has been performed. For this experiment a section of sample LP 58, roughly normal to the schistosity, was used. The largest grains observed in this sample have a diameter of 0.8 mm. A number of points has been counted at successive distances of approximately 0.4 mm, about two times the average grain size. The distance between the runs is 2.0 mm, ten times the average grain size, in order to avoid a correlation of points in different runs. The observations are classified in tables 22 A and 22 B, according to the following criteria:

- A the mineral found at the observed point;
- B the mineral found at the preceding point.

TABLE 21

		pnts	$\frac{\Sigma \hat{p}_i}{n}$	s	$\frac{s}{\sqrt{n}} = S$	N	number of points to be counted
Sample LP 58, phengite-gneiss							
Normal to the schistosity	Q	277	0.384	0.061	0.014	7	270
19 runs	Ab	212	0.291	0.055	0.013	5	190
725 points	Or	81	0.116	0.050	0.011	5	190
38 points/run	Ms	152	0.207	0.056	0.013	6	230
Parallel to the schistosity	Q	287	0.438	0.087	0.028	16	1050
10 runs	Ab	124	0.187	0.050	0.016	5	330
657 points	Or	112	0.171	0.052	0.016	5	330
66 points/run	Ms	132	0.199	0.079	0.025	13	860
Sample S 2/1400, mica-schist							
Normal to the schistosity							
27 runs	Q	858	0.677	0.080	0.015	12	560
1260 points	Ms	328	0.263	0.071	0.014	<12	
47 points/run	rest	74					
Parallel to the schistosity							
13 runs	Q	601	0.722	0.098	0.027	19	1220
834 points	Ms	188	0.223	0.096	0.027	19	1220
64 points/run	rest	45					
Sample LP 56, mica-schist							
Normal to the schistosity	Q	391	0.588	0.077	0.017	11	360
20 runs	Ab	132	0.199	0.074	0.016	<11	
665 points	Mica	126	0.191	0.065	0.015	<11	
33 points/run	rest	16					
Parallel to the schistosity	Q	206	0.599	0.081	0.029	15	650
8 runs	Ab	80	0.226	0.056	0.020	<15	
346 points	Mica	52	0.150	0.051	0.018	<15	
43 points/run	rest	8					

Point counter analyses of 3 samples, counted normal and parallel to the schistosity in sections. roughly normal to the schistosity; with the number of runs N, to obtain a 90 % confidence interval which is shorter than 2 times 0.04, under the assumption that successive points are not correlated. The highest N in one column determines the accuracy of the total count

As N is determined by s, the highest s needs to be taken into consideration.

Table 22 A gives the observations in runs parallel to the schistosity, table 22 B those in runs normal to the schistosity.

The distribution of Q, F and Ms may or may not depend on the occurrence of quartz and muscovite at the preceding point. This can be tested by the methods applied to such so-called contingency-tables*) (Dixon and Massey, 1951, p. 187). The figures in table 22 A strongly indicate that the

Table 22A, LP 58 //

Mineral at the observed point		Mineral at the preceding point		Sum
		Quartz	Muscovite	
Quartz	Q	70	50	120
Feldspar	F	46	42	88
Muscovite	Ms	20	45	65
Sum		136	137	273

Table 22B, LP 58 ⊥

Mineral at the observed point		Mineral at the preceding point		Sum
		Quartz	Muscovite	
Quartz	Q	91	105	196
Feldspar	F	93	84	177
Muscovite	Ms	44	64	108
Sum		228	253	481

observations at successive points are correlated. As to the observations in table 22 B, correlation is much less than in the case of counting parallel to the schistosity and statistical evidence for the existence of such a correlation could even not be ascertained.

Conclusions:

1. It is commonly more efficient to count normal instead of parallel to the schistosity.
An experiment has been described in which counting parallel to the schistosity in a section roughly normal to the schistosity led to correlated measurements, whereas counting normal to the schistosity led to measurements in which no correlation was evident.
2. For the purpose envisaged in this chapter, fractions can be estimated with sufficient accuracy by counting about 600 points. In this case "sufficient accuracy" is meant to imply that the 90 % confidence interval for the true fraction is on the average shorter than twice 0.04 (of

*) For the observations in table 22 A, the value of the test-statistic χ^2 (with two degrees of freedom) is calculated to be 13.2. For the observations in table 22 B the value of the test-statistic is 3.9. Entering the tables for the χ^2 -distribution (cf. Dixon and Massey, 1951, p. 308, table 6a) the hypothesis of independence is rejected at the 0.5 % level in the case of the observations in table 22 A. The value of χ^2 in the case of the observations in table 22 B, viz 3.9, is too small to reject the hypothesis of independence. The fluctuations in table 22 B between the two figures in a row, may reasonably be attributed to chance fluctuations.

the total sample volume). This means that the interval between the average observed fraction (expressed "per unum")* minus 0.04 and the average observed fraction plus 0.04 includes the true value of the fraction in on the average about 90 out of a 100 cases.

3. In order to avoid correlation between the observations in different runs normal to the schistosity, it might be useful to refix the thin section after each run, in order to add a small random translation with a component in the direction of the runs.
4. In order to avoid correlation it seems advisable to choose as the distance between the points, the diameter of the largest grains that occur in appreciable quantities, or any larger distance. The theory that the grain size is irrelevant in modal analysis, is disproved.

CALCULATION OF THE CHEMICAL COMPOSITION OF A ROCK SAMPLE

Provided the chemical composition of the constituent minerals is known, the calculation of the chemical composition of a sample from its modal composition is only a matter of simple arithmetics. The fact, however, that the composition of some minerals is not sufficiently known and cannot be measured from the optical or other physical properties of these minerals, leads to inaccuracies. An account of the minerals occurring in the rocks of the northern Adula gives an insight into these problems. These minerals are listed below, together with some information about their composition and their quantitative importance. At the time the calculations of the different samples were made a chemical analysis of some of the minerals of the investigated region was not yet available**. Therefore we had to take minerals of comparable Alpine regions, with similar physical properties, as a substitute. Most mineral analyses, however, were made on material from the region under review.

Rock-making minerals of the northern Adula region:

Albite	Chemical composition known through chemical analysis, see table 23, No 1.
Amphiboles	
actinolite	Always less than 5 vol.%, calculated as blue-green amphibole.
blue-green amphibole	For the calculations the chemical composition of a more or less similar amphibole was used, table 23, No 8.
glaucoophane	Always less than 5 vol.%, calculated as glaucoophane from Val de Bagnes, table 23, No 11.
Apatite	Chemical composition more or less constant.
Biotite	Chemical composition not sufficiently known. From the colours of this mineral it was clear that Mg-rich varieties and Fe-rich varieties might appear. As representatives, two analyses were chosen, one of a sample from Loderio, the other from Alp Ajone, table 23, No 5 & 6.
Chlorite	As a result of optical investigations, the existence of several different chlorites was ascertained. As a representative, the penninite of Zermatt was chosen, see table 23, No 7. Afterwards, measurements of the refringence indicated the chlorites to contain more iron.

*) This means that the sample is denoted by 1, a fraction by a part of 1.

**) After completion of the calculations, chemical analyses of a blue-green amphibole and of a common type of garnet were made. Since the deviations of these analyses from those used in this paragraph do not lead to essential differences in the results of the calculations, no corrections were made.

TABLE 23

Chemical composition of minerals used in calculating the chemical composition of the various rock types

	Albite	1	Microcline	3	Muscovite	4	Phengite	5	Biotite rich in MgO	6	Biotite rich in iron	7	Chlorite, Penninite	8	Blue-green amphibole	9	Blue-green amphibole	10	Chloromelanite	11	Glaucophane-crossite	12	Epidote	13	Garnet	14	Garnet
SiO ₂	68.14	65.00	50.79	50.64	39.70	36.33	33.26	46.68	49.49	54.87	52.76	38.21	37.97	37.46													
Al ₂ O ₃	20.14	19.21	26.53	25.25	16.33	17.45	11.69	14.37	10.08	9.18	6.80	28.61	19.18	19.24													
Fe ₂ O ₃	0.15	0.20	2.94	2.97	1.95	3.32	—	4.00	3.01	5.07	10.38	7.30	2.61	10.44													
FeO	—	—	1.34	1.01	8.70	16.81	7.20	8.29	11.00	4.56	8.45	0.17	26.35	19.02													
MnO	—	—	0.05	0.02	0.08	0.37	—	—	0.10	0.07	—	0.13	0.18	1.30													
MgO	0.22	0.03	2.80	4.15	20.04	9.81	35.18	11.71	9.43	7.20	9.38	0.23	3.80	2.40													
CaO	0.09	0.35	—	—	—	—	—	10.32	8.40	11.96	2.25	23.37	9.47	9.22													
Na ₂ O	10.82	2.20	1.01	1.41	0.48	0.71	—	2.41	3.55	6.43	7.20	—	—	0.20													
K ₂ O	0.32	13.62	9.71	9.80	7.81	9.44	—	1.06	0.63	0.23	1.11	—	—	—													
H ₂ O +	0.12	0.12	3.90	3.88	2.67	3.04	12.18	0.54	2.00	0.35	0.52	2.05	—	—													
CO ₂	—	—	—	—	—	—	—	0.23	0.03	0.15	—	—	—	—													
TiO ₂	—	—	1.10	0.72	2.23	2.79	—	0.35	2.34	0.12	1.00	0.19	0.02	0.67													
P ₂ O ₅	—	—	—	—	—	—	—	—	—	—	—	—	—	0.08													
Sum	99.67	100.73	100.17	99.85	99.99	100.10	99.51	99.96	100.06	100.19	99.85	100.26	99.98	100.16													
	Vals, Alp Rischuna *)	Pikes Peak *)	Val Calanca *)	Vals *)	Loderio *)	Alp of Ajone *)	Zermatt *)	Umhausen (1903)	Vals, analyst Th. Hügl	Vals, Ampervreila, analyst Th. Hügl	Val de Bagnes *)	Maigelschal *)	Umhausen, see Hezner (1903)	Vals, Ampervreila, anal. C. M. de Sitter-Koomans													

*) The analyses marked with an asterisk are found in P. Niggli et al. (1930).

**) Dashes indicate that the values were either not determined, or are equal to zero.

Epidote	From optical investigations it was clear that an epidote between pure pistacite and clinozoisite was appropriate for our purpose. An analysis of an epidote from Maigelstal was chosen, table 23, No 12.
Garnet	For the calculations the analysis of a similar garnet was used, table 23, No 13.
Microcline	Chemical composition unknown, but constant within certain limits. As a representative an analysis of microcline from Pikes Peak was chosen. It has to be noted that this analysis is the only one not taken from Alpine regions, table 23, No 2.
Muscovite & phengite	Chemical composition known through chemical analysis, table 23, No 3 & 4.
Quartz	Chemical composition constant.
Sodium-pyroxene	Chemical composition known through chemical analysis, see table 23, No 10.
Ore minerals	Always less than 5 vol.%, calculated as hematite.

It might be evident that there are only five groups of minerals giving rise to notable inaccuracies viz the micas, chlorites, amphiboles, pyroxenes and garnets.

The calculation can be subdivided into several steps as is shown below, marked a, b and c (see also table 24).

- a. The volume percentages of the minerals composing the sample under discussion are transformed into weight percentages. In addition the theoretical density of the sample is found and can easily be checked. In measuring the specific gravity of a sample the method described by Perdok (1955) was followed.
- b. Using the chemical analyses of minerals listed in table 23, the contribution of each mineral to each of the twelve oxides is calculated in proportion to its weight percentage. To speed up calculations part of the work was done graphically. The graphs used — showing the contribution of each mineral, to each of the oxides — show along their ordinates the weight percentages of the twelve oxides (recalculated in order to obtain a sum of 100 % for all oxides), along the abscisses the percentages of the mineral in a mode.
- c. Adding up the columns under the symbols of the oxides the chemical composition is found in weight percentages.

In the example of table 24, sample LP 58 was chosen again. Comparison with a quantitative chemical analysis of this sample shows a fair amount of agreement for most of the oxides.

The only important difference is seen in the values of the alkalis. The alkali content was checked by a duplicate analysis in the Laboratory of Analytical Chemistry of the University of Amsterdam, which gave similar values for both alkalis. Therefore, during the counting the proportion of microcline may have been underestimated in favour of albite. Similar results were obtained, however, during all countings performed on different thin sections of the sample. Assuming that the micas do not contain Na_2O and the microcline is a pure potassium-feldspar, does not account for the difference observed.

These considerations show it to be possible to obtain a rather reliable estimate of the chemical composition of a phengite-gneiss from the modal analysis and the chemical composition of the constituent minerals. To prove this for every type of rock is beyond the scope of this paper.

TABLE 24
Example of the calculation of the chemical composition of a rock-sample

	Number of points	Vol %	S.G.	Wght %										
Quartz	Q	484	39.2	2.65	38.9	Sample LP 58, phengite-gneiss, coord. 7333—1604, alt. 2300 m, E of the Hobbühl. Total number of points counted 1235 (normal to the schistosity). S.G. measured: 2.70 after the method of Perdok (1955). S.G. calculated: 2.67.								
Albite	Ab	330	26.7	2.60	25.9									
Microcline	Or	151	12.2	2.60	12.0									
Phengite	Phe	261	21.1	2.80	22.2									
Green Biotite	Bigr	2	0.2	3.00	0.2									
Epidote	Ep	2	0.2	3.50	0.3									
Apatite	Ap	5	0.4	3.20	0.5									
Sum		1235	100.0		100.0									
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O	Wght %		
Quartz	Q	38.90	—	—	—	—	—	—	—	—	—	38.9		
Albite	Ab	17.65	5.21	0.04	—	0.06	0.02	2.80	0.09	—	0.03	25.9		
Microcline	Or	7.70	2.32	0.02	—	—	0.04	0.26	1.65	—	0.01	12.0		
Phengite	Phe	11.30	5.70	0.67	0.22	0.93	—	0.31	2.21	—	0.86	22.2		
Green Biotite	Bigr	0.08	0.03	0.01	0.03	0.02	—	—	0.02	—	0.01	0.2		
Epidote	Ep	0.11	0.08	0.02	—	—	0.07	—	—	—	0.01	0.3		
Apatite	Ap	—	—	—	—	—	0.30	—	—	0.20	—	0.5		
Sum		75.74	13.34	0.76	0.25	1.01	0.43	3.37	3.97	0.20	0.92	100.0		
Chemical analysis		73.45	14.05	1.37	0.53	0.83	0.30	2.38	6.25	0.17	0.66	100.27*		

* TiO₂ = 0.28 wght %.

CHEMICAL COMPOSITION OF THE PHENGITE-GNEISSES

The chemical composition of these rocks played an important part in the development of the ideas concerning their genesis. This chemical composition is comparable to that of some granites. For this reason they were called orthogneisses. Roothaan (1919) thinks the phengite-gneisses to be injection gneisses. Kopp (1923) holds the view that these rocks comprise larger

Table 25

Chemical analyses of phengite-gneisses

	RH 3	RH 4	RH 5	RH 6	LP 58
SiO ₂	75.95	71.46	74.98	72.77	73.45
Al ₂ O ₃	12.49	15.88	11.57	14.08	14.05
Fe ₂ O ₃	0.56	0.82	1.75	2.04	1.37
FeO	0.16	1.03	0.87	0.78	0.53
MgO	0.36	0.14	0.46	0.08	0.83
CaO	0.63	1.76	1.04	0.87	0.30
Na ₂ O	3.07	3.59	3.48	2.35	2.38
K ₂ O	6.90	4.18	4.56	6.03	6.25
TiO ₂	tr.	0.40	0.45	0.30	0.28
P ₂ O ₅	n.d.	n.d.	n.d.	n.d.	0.17
H ₂ O—	—	0.06	0.02	0.09	n.d.
H ₂ O+	0.17	0.89	0.48	0.89	0.66
CO ₂	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	—	tr.	0.06	0.02	tr.
Sum	100.29	100.21	99.72	100.30	100.27

RH 3 "Granulit", an aplitic band in the Peilerschlucht; analyst H. Ph. Roothaan (1919).
 RH 4 "Phengit-Injektionsgneis", a normal phengite-gneiss from Valé, near Vals; analyst H. Ph. Roothaan (1919).
 RH 5 "Phengit-Biotit-Injektionsgneis", a normal phengite-gneiss from the gneiss-body at Zervreila, Zervreilahorn; analyst H. Ph. Roothaan (1919).
 RH 6 "Phengit-Augengneis (Typus Horn)", a phengitic augen gneiss of the Valserschuppen; analyst H. Ph. Roothaan (1919).
 LP 58 Phengite-gneiss, N of the Hohbühl, coord. 7333—1604, alt. 2300 m; analyst Mrs. C. M. de Sitter-Koomans.

intrusive masses as well as injection gneisses. Müller (1958) discusses two possibilities, viz:

- The phengite-gneisses are products of granitization of Alpine age.
- They are Hercynian or older granitoid rocks, transformed into gneisses by metamorphism of Alpine age.

It seems useful to take the chemical composition of these rocks as a starting-point for our considerations. The chemical analyses available are listed in table 25. Their kation percentages are given in table 26, together with those of a number of calculated analyses. Before taking the latter into account, it seems appropriate to examine, whether there are significant differences between the group of calculated analyses and the group of chemical analyses. In order to test this a statistical method is used that is based on ranking, viz Wilcoxon's two sample test. This is a distribution-free test in contrast with the famous test of Student. In an appendix on page 599, a short description of this test is given. A specification of the assumptions,

TABLE 26
Chemical analyses and calculated analyses of phengite-gneisses in kation percentages

	Chemical analyses					Calculated analyses									
	RH 3	RH 4	RH 5*	RH 6	LP 58	LP 17	LP 47	LP 58	LP 62	LP 105	LP 135	LP 297	A 1*	M 164b*	
Si	70.8	67.2	71.1	69.5	69.3	68.5	62.4	71.5	72.0	72.3	61.4	60.8	67.7	65.7	
Al	13.8	17.6	12.9	15.8	15.6	15.7	19.6	14.8	14.5	13.2	19.5	19.2	16.2	18.1	
Fe ⁱⁱⁱ	0.4	0.6	1.3	1.4	0.9	0.5	1.0	0.6	0.5	0.8	1.8	0.8	0.3	0.6	
Fe ⁱⁱ	0.1	0.8	0.7	0.6	0.4	0.6	1.2	0.2	0.2	0.6	0.4	0.4	0.2	0.2	
Mn	—	—	0.1	—	—	—	—	—	—	—	—	—	—	—	
Mg	0.5	0.2	0.6	0.1	1.1	1.4	2.8	1.4	1.0	2.5	3.2	2.9	1.0	1.2	
Ca	0.6	1.8	1.0	0.8	0.3	1.0	2.6	0.4	0.8	2.4	1.9	2.5	0.7	0.7	
Na	5.6	6.5	6.5	4.3	4.4	8.1	5.9	6.1	8.2	5.0	4.6	9.6	10.0	7.9	
K	8.2	5.0	5.5	7.3	7.6	3.7	3.8	4.8	2.7	3.1	6.5	3.5	3.8	5.5	
Ti	—	0.3	0.3	0.2	0.2	0.1	0.7	—	0.1	0.1	0.3	0.3	0.1	0.1	
P	—	—	—	—	0.2	0.4	—	0.2	—	—	0.4	—	—	—	
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
Q	56.3	55.4	57.4	57.0	56.9	56.0	49.4	60.8	60.8	62.4	49.0	45.9	53.1	52.0	
L	41.3	39.9	37.4	36.4	35.8	36.7	37.0	32.4	35.0	31.4	37.0	46.7	43.9	42.3	
M	2.4	4.7	5.2	6.6	7.3	7.3	13.6	6.8	4.2	6.2	14.0	7.4	3.0	5.7	

Q	56.3	55.4	57.4	57.0	56.9	56.0	49.4	60.8	60.8	62.4	49.0	45.9	53.1	52.0
L	41.3	39.9	37.4	36.4	35.8	36.7	37.0	32.4	35.0	31.4	37.0	46.7	43.9	42.3
M	2.4	4.7	5.2	6.6	7.3	7.3	13.6	6.8	4.2	6.2	14.0	7.4	3.0	5.7

* Samples of the Zervreila gneiss.

For the analyses and locations of the samples of the first group, see table 25; for the modal analyses of the calculated samples see fig. 14.

	M	s ²	s	$S = \frac{s}{\sqrt{n}}$
Si	67.59	15.56	3.94	1.09
Al	16.28	5.52	2.35	0.65
Fe'''	0.84	0.19	0.44	0.12
Fe''	0.49	0.09	0.30	0.08
Mg	1.42	1.14	1.07	0.30
Ca	1.32	0.65	0.81	0.22
Na	6.66	3.77	1.94	0.54
K	5.09	3.39	1.84	0.51

that have to be satisfied, is briefly given too. In further application of this test, a level of significance of 5 % has been chosen.

Application of Wilcoxon's two-sample test to the groups of calculated and chemical analyses revealed the presence of significant differences for Mg and K. For the other kations no such differences could be established. This means either that the calculation method is not entirely adequate or that both groups of samples were not taken from the same population, i. e., from the same groups of rocks.

It is apparent that the Mg values of the calculated analyses are systematically higher and that the values of K are systematically lower than in the chemical analyses. If the method to obtain calculated analyses is not sufficiently reliable, the Mg values could be systematically higher because the Mg content of the phengite in reality is lower than in the analysis of this mineral used as a base for our calculations. It is also possible that the light-coloured mica of these phengite-gneisses comprises both phengite and ordinary muscovite. The difference in K could be due to underestimation of the microcline content during the counting.

If, on the other hand, the possibility is considered that both groups of samples were not taken from the same group of rocks, one might expect the differences between the groups to be based on differences in their content of phengite, muscovite and microcline, similar to those between the central part of the Zervreila gneiss and other phengite-gneisses (see page 491 and fig. 14).

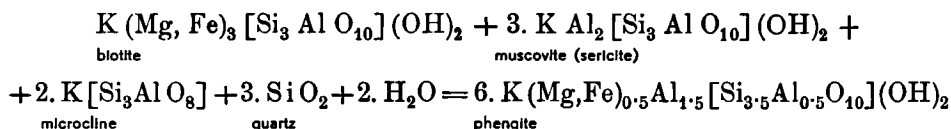
Table 27
Niggli values of a number of phengite-gneisses

	RH 3	RH 4	RH 5	RH 6	LP 58
si	461	346	440	413	419
al	44.5	49.5	40	47	47
fm	7	8.5	16.5	13.5	15.5
c	4	9.5	6.5	5	2
alk	44.5	32.5	37	34.5	35.5
k	0.60	0.44	0.47	0.63	0.63
mg	0.47	0.11	0.24	0.05	0.45
	LP 17	LP 47	LP 105	LP 135	LP 297
si	397	278	445	272	266
al	45.5	43.5	39.5	43	42
fm	14.5	22.5	22.5	24	18
c	6	12	14	8.5	11
alk	34	22	24	24.5	29
k	0.31	0.39	0.37	0.58	0.27
mg	0.57	0.56	0.64	0.59	0.70

Surveying the analyses it is obvious that the phengite-gneisses, as a group, are more or less of a granitic composition, as mentioned above. Their chemical composition does not show a greater variation than can be found in a group of samples from any granitic body, as is clearly shown by the QLM diagram, fig. 32. This chemical homogeneity, as contrasted with the variation in mineralogical composition — from microcline-rich to phengite-rich rocks — is due to the chemical similarity of microcline and phengite.

The Niggli values of the analyses are listed in table 27. As done by Müller (1958, p. 461), we may compare the phengite-gneisses with the pre-Alpine granitic rocks of Fibbia, Scai, Medelser, etc. The chemical analyses

of the latter rocks (P. Niggli et al. 1930) seem to show a rather close resemblance with those of the phengite-gneisses. Therefore, the chemical composition of the phengite-gneisses does not contribute an argument against the supposition that these rocks represent granitic rocks of pre-Alpine age. Müller (loc. cit.), however, stressed the difference in appearance and mineralogical composition between both groups of rocks, pointing to the fact that they are found in the same mineral zone in the sense of E. Niggli. In the opinion of the author, however, the differences in appearance and mineralogical composition between both groups of rocks, can be very well ascribed to a difference in degree of metamorphic rearrangement ("Umkristallisation") between rocks showing the same grade of metamorphism (cf. Egeler 1956, p. 118). One of the main mineralogical characteristics of the pre-Alpine granitic rocks, mentioned above, is their appreciable content of biotite, whereas this mineral is rather rare in the phengite-gneisses. In a following chapter the conclusion will be reached, that the phengite was produced by metamorphism of Alpine age. The Mg and Fe content of this mineral could be very well derived from original biotite, e. g., according to the following reaction:



Such a reaction could account for the rarity of original biotite in the phengite-gneisses. From the appearance of the phengite-gneisses it is clear that the formation of phengite was accompanied (or followed) by metamorphic differentiation, which locally resulted in the production of conspicuously banded rocks.

A possible granitization origin of the phengite-gneisses can only be discussed from a chemical point of view after having dealt with the chemical composition of their alleged original material and basic front, viz the mica-schists and amphibolites (see p. 541 and 544).

CHEMICAL COMPOSITION OF THE MICA-SCHISTS

In agreement with former authors the present author assumes the mica-schists to be of sedimentary origin. This is evident from their mineralogical as well as from their chemical composition. The rocks are rich in quartz and mica and show high aluminium and silica contents. Four analyses have been made in course of time, the results of which are given in table 28. The chemical analyses show great intrinsic variations, essentially caused by differences in the composition of the original sediments. According to Müller the mica-schists (called by him chlorite-muscovite-gneisses) near the Zervreila gneiss-body are richer in albite than the other ones, as a consequence of sodium metasomatism. Therefore, the samples of which the chemical composition is calculated were divided into two groups. The first group (table 29) deals exclusively with samples taken in the immediate surroundings of the Zervreila gneiss-body, the second group of samples (table 30) is randomly taken from the remainder of the mapped region. The latter group includes four calculated analyses of samples from the waterdrift Ampervreila-Peil.

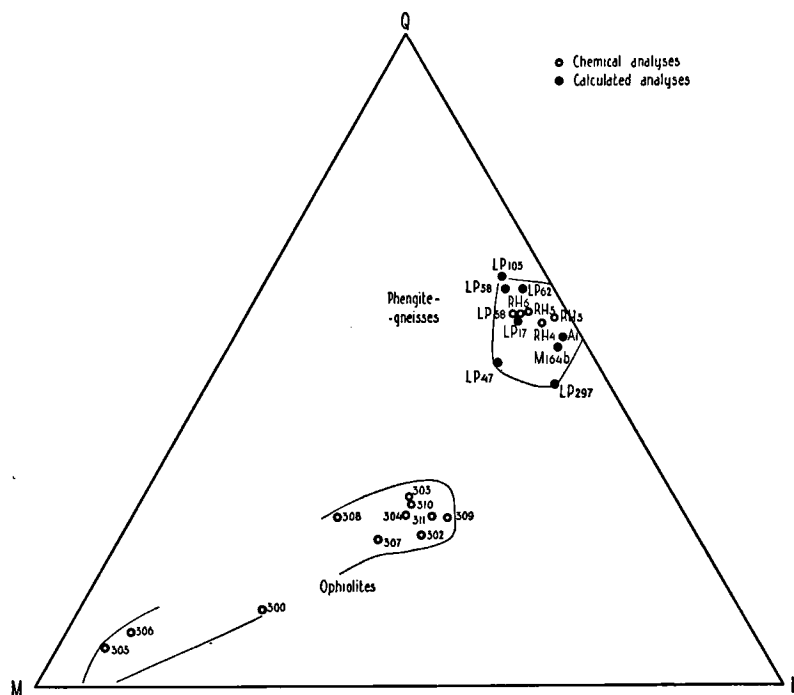


Fig. 32. QLM diagram of the phengite-gneisses and the ophiolites.

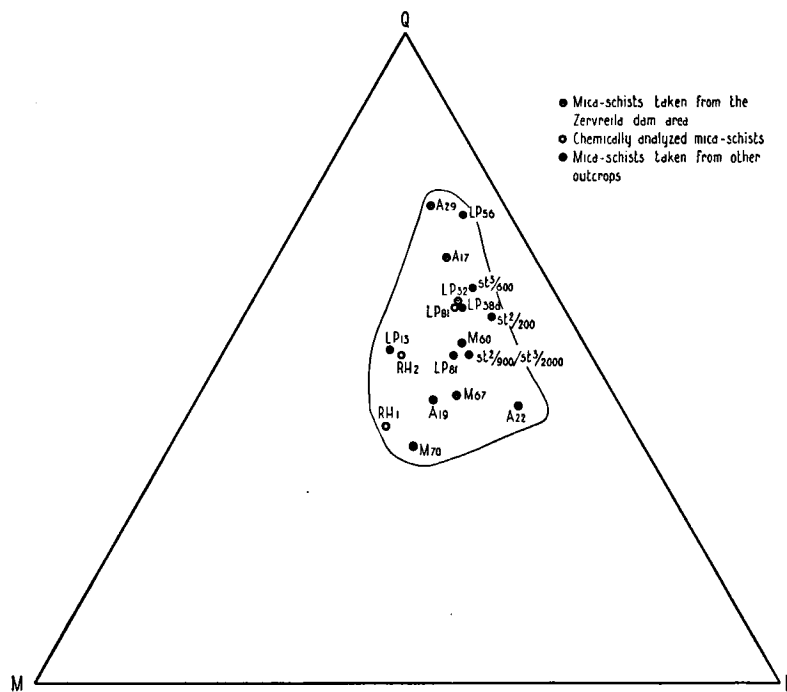


Fig. 33. QLM diagram of the mica-schists.

Table 28
Chemical analyses of mica-schists
weight percentages

	RH 1	RH 2	LP 81	M 60
SiO ₂	54.53	57.15	69.80	65.77
Al ₂ O ₃	26.08	20.28	15.50	14.92
Fe ₂ O ₃	2.86	3.54	2.03	1.38
FeO	3.78	2.18	2.68	4.59
MnO	0.11	tr.	tr.	0.04
MgO	3.03	2.78	1.02	2.67
CaO	0.97	1.70	1.29	1.50
Na ₂ O	0.97	1.87	2.38	2.30
K ₂ O	5.37	6.58	2.90	4.04
TiO ₂	0.82	0.68	0.58	0.79
P ₂ O ₅	n.d.	n.d.	0.15	0.45
H ₂ O—	0.06	0.12	—	0.07
H ₂ O+	1.07	2.88	1.53	1.14
CO ₂	—	0.87	—	0.40
Sum	99.65	100.63	99.86	100.06

	RH 1	RH 2	LP 81	M 60
Si	51.6	55.0	67.3	63.1
Al	29.2	23.0	17.6	16.8
Fe ^{III}	2.0	2.7	1.5	—
Fe ^{II}	3.0	1.5	2.1	4.6
Mn	—	—	—	—
Mg	4.3	4.0	1.5	3.8
Ca	1.0	1.7	1.4	1.6
Na	1.8	3.5	4.5	4.3
K	6.5	8.1	3.6	4.9
Ti	0.6	0.5	0.4	0.6
P	—	—	0.1	0.3
	100.0	100.0	100.0	100.0

RH 1 Garnetiferous mica-schist, Wenglispitze; analyst H. Ph. Roothaan (1919).

RH 2 Chlorite-bearing mica-schist, Weissgrätli; analyst H. Ph. Roothaan (1919).

LP 81 Garnetiferous mica-schist, coord. 7346-1598, alt. 1725 m, Peil; analyst Mrs. C. M. de Sitter-Koomans.

M 60 Feldspar-rich mica-schist, alt. 1860 m, N part Zervreila dam; analyst Th. Hügi (Müller 1958).

As the number of chemically analyzed samples is small, a systematic error in the calculated analyses can only be found, if this would be an appreciable error. To detect small systematic deviations a larger number of chemical analyses will be required. If, however, such a deviation occurs, it must have influenced both groups of calculated analyses in a roughly similar way, because the results are obtained by the same procedure of modal analysis and calculation. So if there are differences between the two groups they should be ascribed to differences in the chemical composition of the samples.

First the variance in the two groups of calculated analyses is tested with the variance ratio test. For a clear and simple explanation of this test we refer to Moroney (1957). For judging the variance ratio we used table 7 of Dixon and Massey (1951, p. 311; N.B. These tables give one-sided ex-

ceedance probabilities, which in this case had to be multiplied by 2, in order to give the two-sided ones). As a result of this test, slight indications of a difference between the two groups, with regard to the variability of the observations, were only found in the case of Mg and K. Applying Wilcoxon's two-sample test to both groups of calculated analyses, the test-result does not give any indication of a difference between both groups, i.e., neither in sodium content nor in the content of other elements. Taking into account that Wilcoxon's test is not powerful in regard of the situation where the populations, from which the two groups of samples were taken, differ only in the variance, this result does not necessarily contradict the above mentioned result of the variance ratio test.

Statistics cannot give a straight answer to our questions. A hypothesis can never be proved by means of statistics. They only provide indications whether a hypothesis should be rejected or not. Rejection of a hypothesis always implies the risk of rejecting the true hypothesis. This risk can be fixed beforehand by choosing the level of confidence. When there is no reason to reject the hypothesis, it does not necessarily follow that the hypothesis is true, it can also mean that the observational evidence is insufficient to detect a small though practically significant deviation. In the case of the mica-schists no significant difference has been established between both groups. If this argument is translated into a petrological conclusion it has to be formulated as follows: From the available data it is impossible to conclude whether the rocks in the neighbourhood of the Zervreila gneiss-body are richer in *sodium* or not.

If the quantitative mineralogical composition of Müller's mica-schists (Müller 1958, p. 428 and p. 430) is subjected to the same test, we find an indication that the *albite* content is higher in his group of albite-bearing mica-schists than in his group of ordinary mica-schists. This group of albite-bearing mica-schists only contains samples taken from the narrow contact zone of the Zervreila gneiss-body. The groups of Müller show a more convincing indication for significant differences in the mica content. If the same test is applied to the albite content of the two groups of mica-schists of the author (see fig. 16), no indication whatsoever is found of the slightest difference, though the groups of the author comprise 22 samples and the groups of Müller 15 samples. If all samples are taken together, the differences in albite content become less pronounced. The *sodium* content of Müller's mica-schists was calculated in the same way as done for the samples described in this paper, in order to make a comparison with that of the mica-schists described by the author. It has to be born in mind that sodium is not only found in albite, but also — in minor quantities — in mica. So mica-schists poor in albite, still may have a considerable sodium content, if they are rich in mica. If Wilcoxon's test is applied to the available groups, no differences were found, if groups of samples of the same area are compared. Comparing all the samples from the vicinity of the Zervreila gneiss-body with all the other samples also gives a negative result. A slight indication of a difference in sodium content is found if both groups of Müller are compared.

In conclusion it may be stressed that Müller's conclusions as to the enrichment in albite and sodium near the Zervreila gneiss-body, were based on a comparison of groups of 7 and 8 samples. These conclusions are not supported by the results of our measurements on a larger number of samples. So from the data now available there is no reason to assume the mica-schists to be influenced by contact with the Zervreila gneiss. It must be noted, however, that owing to the limited number of observations this does not necessarily imply that such an influence does not exist. A small, yet interesting difference might remain undetected by the side of large random errors.

In fig. 33 the QLM values of the mica-schists are given. The field of this type of rock partly overlaps the field of the phengite-gneisses. The estimates of the variance s^2 for the different variations in the case of the

TABLE 29

Calculated analyses of mica-schists from the immediate surroundings of the Zervreila gneiss-body, in kation percentages

	LP 32	M 60	M 67	M 70	A 17	A 19	A 22	A 29
Si	68.4	64.2	58.7	51.5	73.8	57.3	57.2	79.3
Al	14.6	16.2	18.0	20.3	14.1	19.0	18.7	11.7
Fe'''	3.0	0.9	1.1	1.4	0.9	1.1	1.3	0.8
Fe''	0.8	3.0	4.7	6.4	0.4	2.0	2.5	0.4
Mn	—	—	0.1	—	—	—	—	—
Mg	3.5	4.1	5.1	8.2	1.6	8.6	3.4	1.6
Ca	2.9	2.1	1.8	2.9	1.7	1.4	4.7	0.5
Na	1.0	3.9	5.1	3.2	1.6	3.5	7.1	0.7
K	5.4	4.7	4.6	5.2	4.8	6.0	3.4	4.5
Ti	0.3	0.7	0.6	0.7	0.8	0.9	1.4	0.3
P	0.1	0.2	0.2	0.2	0.3	0.2	0.3	0.2
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Q	58.8	52.6	44.5	36.8	65.4	43.7	42.9	73.4
L	27.3	31.2	34.2	32.6	22.7	31.8	43.7	16.4
M	13.9	16.2	21.3	30.6	11.9	24.5	13.4	10.2

	M	s ²	s	$S = \frac{s}{\sqrt{n}}$
Si	63.80	89.24	9.45	3.34
Al	16.58	8.60	2.93	1.04
Fe'''	1.31	0.51	0.71	0.25
Fe''	2.53	4.61	2.15	0.76
Mg	4.51	7.15	2.67	0.94
Ca	2.25	1.59	1.26	0.45
Na	3.26	4.72	2.17	0.77
K	4.83	0.58	0.76	0.27

TABLE 30

Calculated analyses of mica-schists, taken at some distance from the Zervreila gneiss-body, in kation percentages

	LP 13	LP 38a	LP 56	LP 81	St 2/200	St 2/900	St 3/600	St 3/2000
Si	62.6	67.7	79.7	62.2	66.6	62.8	69.4	62.4
Al	16.7	15.7	8.9	18.5	18.3	18.9	16.5	17.3
Fe'''	1.2	1.4	0.2	2.7	0.8	0.7	—	0.6
Fe''	3.1	1.5	0.3	1.9	0.8	2.4	1.0	4.1
Mn	—	—	—	—	—	—	—	—
Mg	4.1	3.2	2.5	4.2	1.2	3.1	3.1	2.2
Ca	3.8	2.0	1.2	1.2	2.1	3.6	2.0	2.4
Na	1.2	2.4	4.9	4.7	5.1	1.6	3.6	6.4
K	6.4	5.3	1.2	4.5	4.4	5.8	4.2	2.6
Ti	0.8	0.6	1.0	0.1	0.3	1.0	—	1.6
P	0.1	0.2	0.1	—	0.4	0.1	0.2	0.4
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Q	51.2	58.0	72.0	50.5	56.5	50.6	60.8	50.8
L	22.5	28.5	21.8	31.1	33.0	33.0	28.4	33.1
M	26.3	13.5	6.2	18.4	10.5	16.4	10.8	16.1

	M	s ²	s	$S = \frac{s}{\sqrt{n}}$
Si	66.68	35.44	5.95	2.10
Al	16.35	10.27	3.20	1.13
Fe'''	0.95	0.71	0.84	0.30
Fe''	1.89	1.61	1.27	0.45
Mg	2.95	0.97	0.98	0.35
Ca	2.29	0.94	0.97	0.34
Na	3.74	3.43	1.85	0.65
K	4.30	2.89	1.70	0.60

phengite-gneisses are generally smaller than in the case of the mica-schists. This leads to the conclusion that, if granitization really took place, this process could obliterate part of the variance in the chemical composition of the mica-schists.

CHEMICAL COMPOSITION OF THE GROUP OF AMPHIBOLITES AND ALLIED ROCKS

As the origin of these rocks up till now has been a matter of dispute, their chemical composition may throw some light on their probable genesis.

At present 5 chemical analyses are available (table 31), while 11 calculated analyses were made (table 32). Two of the latter pertain to chemically analyzed samples and show a satisfactory agreement with the corresponding chemical analyses. Using Wilcoxon's two-sample test, significant differences between the chemically analyzed and the calculated group could not be established.

TABLE 31

Chemical analyses of amphibolites and allied rocks

	RH 7	RH 8	M 56	M 246	M 57
SiO ₂	48.61	54.03	49.11	51.09	71.03
Al ₂ O ₃	18.93	20.01	17.41	16.91	14.63
Fe ₂ O ₃	1.50	2.03	3.78	3.33	0.82
FeO	6.94	3.68	6.18	7.27	2.73
MnO	0.21	0.08	0.13	0.07	0.01
MgO	6.51	3.02	5.53	5.46	1.30
CaO	9.62	6.21	9.09	7.93	2.27
Na ₂ O	3.48	7.19	3.48	2.92	5.98
K ₂ O	1.17	0.77	2.31	1.60	0.42
H ₂ O+	0.73	0.91	1.26	1.17	0.26
H ₂ O-	—	0.10	0.06	0.10	0.03
CO ₂	0.36	1.01	0.78	0.77	0.17
TiO ₂	1.73	1.08	0.86	1.13	0.28
P ₂ O ₅	n. d.	n. d.	0.06	0.22	0.07
Sum	98.79	100.12	100.04	99.97	100.00

RH 7 Garnetiferous amphibolite, Guralätschsee; analyst H. Ph. Roothaan (Roothaan 1919).

RH 8 Amphibolite, Fanella pass; analyst H. Ph. Roothaan (Roothaan 1919).

M 56 Amphibolite, Zervreila dam; analyst Th. Hügi (Müller 1958).

M 246 Amphibolite, Zervreila hydroelectric plant; analyst Th. Hügi (Müller 1958).

M 57 Leucocratic band in amphibolitic migmatites of the Zervreila dam, so-called "Metatekt"; analyst Th. Hügi (Müller 1958).

According to the Niggli values of the arithmetic mean the average chemical composition of these rocks is comparable to that of a diorite. Chemically this average type belongs to the orbic magma-type of P. Niggli (1936). From the QLM diagram, fig. 34, it is clear that these rocks form a close group. The chemical analyses of the minerals blue-green amphibole, chloromelanite and glaucophane (table 23) are plotted to show that their projection points are close to the field of the amphibolites and allied rocks. These three minerals can be formed in quantities, provided that the physical circumstances

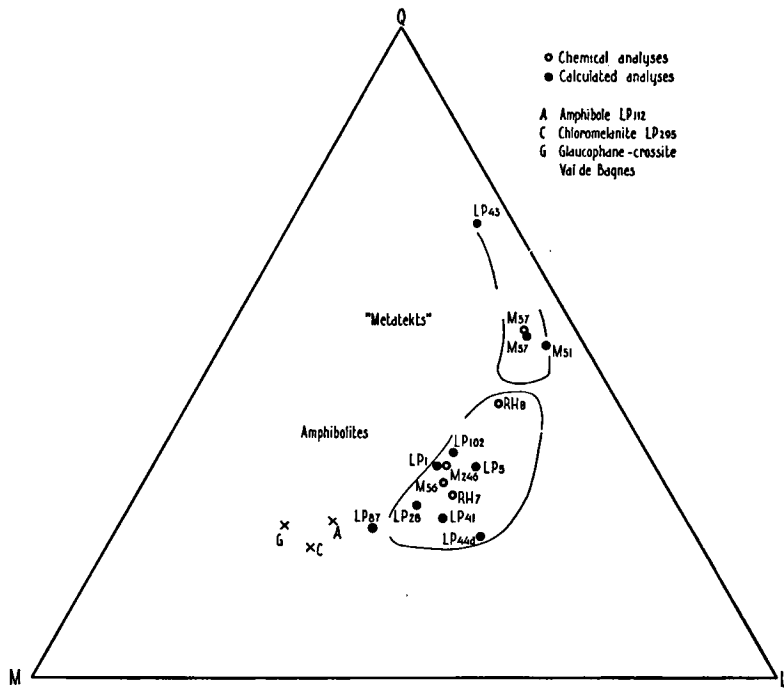


Fig. 34. QLM diagram of the amphibolites and allied rocks, and of the "Metatekts".

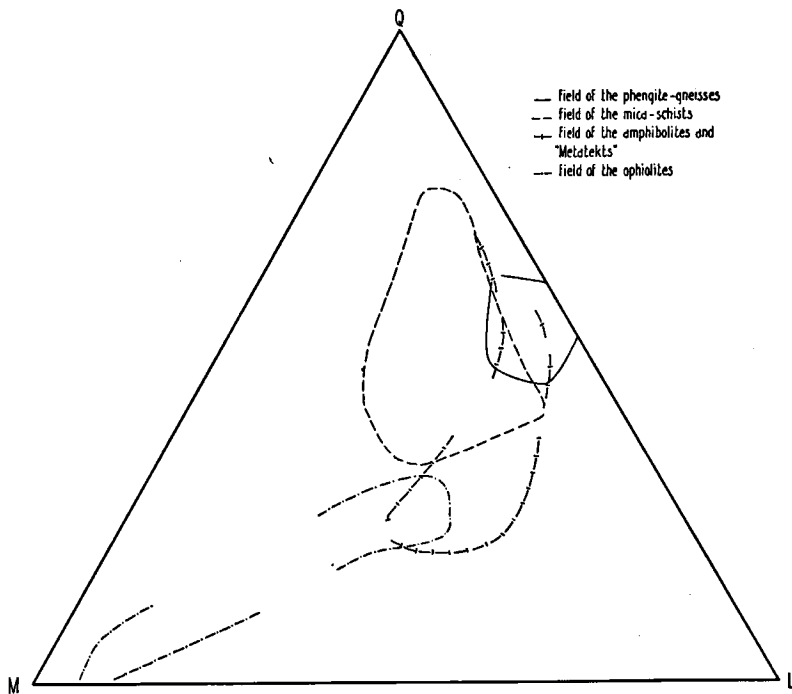


Fig. 35. QLM diagram showing the fields of the various types of rock, viz phengite-gneisses, mica-schists, ophiolites, "Metatekts" and amphibolites and allied rocks.

are favourable. The field of the "Metatekts" coincides with that of the phengite-gneisses, but the values of potassium differ considerably.

Müller (1958) considers the possibility that the phengite-gneisses are the products of granitization of mica-schists and that the amphibolites and allied rocks have been formed as a consequence of accumulation, in a basic front formed within the mica-schists, of those kations that could not find a place in the phengite-gneisses.

In order to check this possibility from a chemical point of view the three groups of rocks were compared by means of Wilcoxon's two-sample test. As a result it appeared that the K content is considerably lower in the amphibolites, the contents of the other ions being more or less appropriate. In this procedure, however, the influence of the addition of Fe, Mg and Ca on the K percentage was not yet accounted for. According to the hypothesis given above the amphibolites — from a chemical point of view — would have to be considered as mica-schists with additional kations. A considerable addition of Fe, Mg and Ca disturbs the $(\text{Si} + \text{Al})$ — $(\text{Fe} + \text{Mg} + \text{Ca})$ — alkali ratio in such a way that although the $(\text{Si} + \text{Al})$ — alkali ratio remains similar, the analysis shows a lower percentage of Si, Al and alkalis. Therefore, if the analyses of the different groups of rocks are compared, this shifting has to be taken into account. In order to make a correction for this shifting we had to set the addition of caferic material at a certain value. This value being unknown and undeterminable we started from the assumption that all the caferic material was added, i.e., that the amphibolites derived from rocks without Fe, Mg and Ca, thus allowing for a maximum lowering of the K percentage by the addition of caferic elements (this assumption slightly favours the possibility to accept the granitization hypothesis). The K values of the amphibolites were recalculated on this base. In table 33, the K values of the phengite-gneisses, the mica-schists and the amphibolites are listed together with these recalculated K values of the amphibolites. The "Metatekts" are not included.

If the amphibolites were formed as a basic front at the expense of mica-schists, the recalculated K values of the amphibolites may by no means be lower than the K values of the phengite-gneisses and the mica-schists, because the K values of these latter rocks are more or less similar. A statistical test for the hypothesis that the three groups do not differ as to their K values is e.g., a comparison of the recalculated K values of the amphibolites and those of the mica-schists and phengite-gneisses taken together by means of Wilcoxon's two-sample test. It can be proved, cf. Doornbos and Prins (1958), that the exceedance probability of this test should be multiplied by 3×7 , being the number of possible ways in which one type of rock can be chosen from the three types multiplied by the number of ways in which one type of kation can be chosen from the 7 important kations.

On testing the values of table 33 in such a way, the test gave an exceedance probability < 0.05 . This indicates that the tested hypothesis can be rejected in favour of the alternative hypothesis that the recalculated K values of the amphibolites are lower than those of the other rocks. So the hypothesis that the amphibolites and allied rocks are a basic front produced during granitization, is highly improbable in view of the low K content of these rocks.

A brief survey of the suggestions of former authors as to the nature of

TABLE 32

Chemical and calculated analyses of amphibolites and allied rocks, a.o. "Metatekts", in kation percentages

Amphibolites and allied rocks, "Metatekts" not included

"Metatekts"

Statistical values of the
amphibolites and allied
rocks, "Metatekts"
not included

Chemical analyses				Calculated analyses										Chemical analysis	Calculated analyses			
RH 7	RH 8	M 246	M 56	M 56	LP 1	LP 5	LP 28	LP 41	LP 44a	LP 87	LP 102	M	s ²	s	M 57	M 57	LP 43	M 51
Si	45.2	53.3	48.8	46.3	44.5	45.5	42.4	43.6	42.3	41.1	57.7	46.27	23.55	4.85	65.9	66.5	77.7	66.3
Al	20.8	23.3	18.9	19.3	21.2	22.3	24.8	20.4	19.5	21.2	18.4	20.69	4.08	2.02	16.0	15.4	11.4	16.4
Fe ^{III}	1.0	1.4	2.3	2.9	3.0	3.0	2.8	2.4	1.0	4.8	1.7	2.44	1.15	1.07	0.6	1.1	0.3	0.1
Fe ^{II}	5.4	3.0	5.8	4.6	3.0	4.3	4.7	4.3	8.6	7.2	3.7	4.91	2.72	1.65	2.1	0.7	0.5	1.6
Mn	0.2	—	0.1	0.1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Mg	9.0	4.3	7.7	7.8	9.8	6.6	5.3	10.2	5.2	6.0	13.9	7.60	7.60	2.76	1.8	2.0	1.0	1.2
Ca	9.5	6.5	8.1	9.2	8.9	13.7	9.9	12.4	10.2	8.7	11.5	9.31	7.57	2.75	2.2	2.0	0.5	0.3
Na	6.4	6.9	5.4	6.4	4.6	2.8	5.0	4.2	8.3	8.6	3.3	5.41	3.82	1.96	10.6	11.7	6.7	13.7
K	1.4	0.5	1.9	2.8	3.0	0.7	1.3	1.1	0.3	3.5	1.4	1.94	2.21	1.49	0.5	0.3	1.6	0.4
Ti	1.1	0.8	0.8	0.6	2.0	1.1	0.9	1.8	1.8	1.1	2.0	1.0	—	—	0.2	0.3	0.1	—
P	n.d.	n.d.	0.2	—	—	—	0.8	0.2	0.1	0.4	0.1	—	—	—	0.1	—	0.2	—
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Q	28.1	42.2	32.5	29.7	27.9	32.6	32.3	26.1	24.4	21.4	44.5	30.0	—	—	53.4	52.7	69.3	51.2
L	42.8	41.8	39.4	40.5	43.2	38.8	43.5	38.6	43.0	49.9	34.3	41.6	—	—	39.3	41.3	25.2	43.2
M	29.1	16.0	28.1	29.8	28.9	28.6	24.2	35.3	32.6	28.7	21.1	28.4	—	—	7.3	6.0	5.5	5.6

Niggli values of the mean: si 121 al 27.0 fm 39.2 c 24.3 alk 9.5 k 0.26 mg 0.51 ti 3.2

the amphibolites and allied rocks will now be given, in order to show that these suggestions are for the greater part not in accordance with the facts.

According to Roothaan (1919) they partly derive from gabbroid igneous rocks, partly even from peridotites. Their average chemical composition, however, is dioritic.

Königsberger (1917) describes them as assimilated sediments, a suggestion that hardly can be defended in view of their chemical composition.

Table 33

K values of the amphibolites, mica-schists and phengite-gneisses in kation percentages, together with the K values of the amphibolites on a base without Fe, Mg and Ca

Amphibolites Calculated analyses		Mica-schists Calculated analyses		Phengite-gneisses Calculated analyses	
normal values	recalculated values				
3.0	3.9	6.4	5.3	3.7	3.8
0.7	1.0	1.2	4.5	2.7	3.1
1.3	1.7	4.4	5.8	6.5	3.5
1.1	1.6	4.2	2.6	3.8	5.5
0.3	0.4	5.4	4.7	4.8	
3.5	4.5	4.6	5.2		
1.4	2.1	4.8	6.0		
5.4	6.3	3.4	4.5		
Chemical analyses		Chemical analyses		Chemical analyses	
1.4	1.9	6.5	4.9	8.2	5.0
0.5	0.6	8.1	3.6	5.5	7.3
1.9	2.5			7.6	
2.8	3.7				

N.B. the original values were taken from tables 26, 29, 30 and 32.

The three authors of "Geologie der Adula", Jenny, Kopp and Frischknecht (1923) concluded that these amphibolites derive partly from Triassic marls, partly from Mesozoic eruptive rocks, while mafic rocks of pre-Mesozoic age may well be hidden among them. The assumption that the amphibolites could have derived from marls is not likely, since the Ca content of the amphibolites is low for a marl, marls with such a low content of Ca always showing a higher value for silica, cf. P. Niggli et al. (1930, 1942). The same silica value as in these amphibolites is only to be found in marls that are very rich in lime, or perhaps in dolomitic marls. The sparse "dolomitic marls" of the region under consideration (being the impure dolomitic rocks, rich in phlogopite, colourless mica and chlorite), however, do not contain amphiboles.

The suggestion that the amphibolites might have been ophiolites changed by metamorphism has to be tested. The chemical composition of the ophiolites will be given in table 34. It can be shown, that the chemical compositions of both rock types differ in several points. Applying Wilcoxon's two-sample test to these two groups it is clear that the amounts of Si, Al, Ca and Na in both groups are approximately the same. Moreover we find that:

Fe is systematically lower in the amphibolites;

Mg is systematically lower in the amphibolites;

K is systematically higher in the amphibolites.

In view of the fact that the amphibolites and the ophiolites consist of the same minerals — viz amphibole, albite, epidote and chlorite — and that both were influenced by Alpine metamorphism, it may be clear from these

substantial data that the tested hypothesis has to be definitely rejected, or in other words the amphibolites and allied rocks did not derive from ophiolites.

Summarizing, the amphibolites and allied rocks have not derived from marls or ophiolites. The hypothesis that they represent a basic front at the boundary of the phengite-gneisses is highly improbable in view of their low K content. The chemical composition of these amphibolites strongly points to an igneous origin of their original material.

CHEMICAL COMPOSITION OF THE MESOZOIC ROCKS

As these rocks are of minor importance to the main theme of this paper, their chemical composition will be only briefly discussed. The sedimentary rocks in this group viz dolomites, calcareous dolomites, calcareous and arenaceous schists, marbles and rauhwackes have a chemical composition conformable with logical expectations. Analyses given by Roothaan (1919) can also be found in "Chemismus schweizerischer Gesteine" by P. Niggli et al. (1930).

The greenschists or ophiolites are of greater importance for our discussion and will form the subject of a brief description. As a result of their small grain size and the intensive transformation of their original minerals, modal analysis is impossible. Twelve chemical analyses of ophiolitic rocks from the region around Vals are available. These analyses are given in kation percentages, together with their average composition, in table 34. Together with other ophiolites of the Alpine mountain-chain they are thoroughly dealt with by Burri and Niggli (1945). From the chemical analyses it may be clear that the ophiolites of the Adula region have a much lower K content than the amphibolites; moreover, the Fe content is higher and the Mg content much higher (see p. 548). In the QLM diagram (fig. 32) the amphibolite field and the ophiolite field coincide in part, but another part of the field of the ophiolites corresponds to an ultrabasic composition, which was never found for the amphibolites (fig. 35).

From a chemical point of view the ophiolites could have derived from lavas or basic intrusions, according to some authors even from tuffaceous deposits. Nabholz (1945) assumes them to have intruded. The interaction between these mafic igneous rocks and the adjoining Mesozoic sediments can locally be very important, resulting in mixed rocks.

CONCLUDING REMARKS

A theoretical discussion of point counter analysis was given, the results of which are summarized on page 530. In order to avoid correlation it seems advisable to choose as the distance between the points the diameter of the largest grains that occur in appreciable quantities, or any larger distance.

The chemical composition of a sample may be calculated from the quantitative mineralogical composition. The chemical composition of the rocks, partly obtained by chemical analysis and partly by calculation, was the subject discussed.

There is — not only in petrology — a tendency to draw important conclusions from scanty data, without any consideration of the aspects of variability arising from, and the errors inherent in, sampling techniques. To give average compositions of rocks, without mentioning the variance of these compositions is not only a waste of information, but also a procedure that is not recommendable.

TABLE 34
Chemical analyses of ophiolites in kation percentages

	299	300	302	303	304	305	306	307	308	309	310	311
Si	26.6	33.3	42.4	50.2	45.5	25.9	25.7	43.2	42.5	49.2	48.0	44.8
Al	10.6	16.4	19.2	14.0	17.3	24.1	25.2	16.2	23.2	11.8	15.5	18.7
Fe ^{III}	9.3	3.2	5.7	2.3	4.0	3.6	2.2	3.3	4.2	6.0	3.0	2.1
Fe ^{II}	8.4	7.6	5.9	3.8	4.7	7.2	12.8	4.7	4.5	3.9	5.5	6.9
Mn	—	—	—	—	—	—	—	—	—	—	—	—
Mg	40.5	30.2	6.8	15.2	9.8	36.6	29.1	9.4	7.7	10.2	9.9	9.7
Ca	2.0	6.8	11.3	4.5	11.0	1.3	2.7	15.1	8.9	8.4	7.7	8.3
Na	0.7	1.2	7.0	9.1	6.7	—	0.3	6.2	6.0	9.4	7.9	7.4
K	0.3	0.2	0.5	0.6	0.5	1.2	0.2	0.8	1.9	0.3	1.1	0.6
Ti	0.8	1.1	1.2	0.3	0.5	0.1	1.6	1.1	1.1	0.8	1.4	1.5
P	0.8	—	—	—	—	—	0.2	—	—	—	—	—
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Q	0.0	11.8	22.9	28.7	26.1	6.1	8.2	22.3	25.8	25.7	28.1	26.0
L	7.5	24.6	40.1	35.5	36.7	7.5	8.7	34.8	46.7	32.2	36.8	40.1
M	92.5	63.6	37.0	35.8	37.2	86.4	83.1	42.9	27.5	42.1	35.1	33.9
299 Magnetite-chlorite-schist, Olivone, Cima Giux, analyst Staub 300 Amphibole-chlorite-schist, Hochberghorn, Zapport, analyst Roothaan 302 Greenschist, Valsenberg, Vals, analyst Scheide 303 Albite-actinolite-schist, Leisalp, Vals, analyst Roothaan 304 Greenschist, Leisalp, Vals, analyst Roothaan 305 Magnetite-chlorite-schist, Alp Rischuna, Vals, analyst Roothaan 306 Magnetite-chlorite-schist, Alp Rischuna, Vals, analyst Roothaan 307 Albite-epidote-chlorite-schist, Horn, Vals, analyst Roothaan 308 Albite-epidote-chlorite-schist, Fuorcla de Patnaul, Vals, analyst Roothaan 309 Diabase, Piz Tomül, Vals, analyst Roothaan 310 Chlorite-epidote-albite-schist, Piz Tomül, Vals, analyst Roothaan 311 Greenschist, S slope Piz Tomül, Vals, analyst Roothaan												
								Si	M	s ²	s	$S = \sqrt{\frac{s}{n}}$
								Al	39.78	86.85	9.32	2.69
								Fe ^{III}	17.68	21.69	4.66	1.35
								Fe ^{II}	4.08	4.27	2.07	0.60
								Mg	6.33	6.43	2.54	0.73
								Ca	17.93	154.55	12.43	3.59
								Na	7.33	17.16	4.14	1.20
								K	5.16	12.67	3.56	1.03
									0.75	0.25	0.50	0.14

Analyses taken from P. Niggli et al. (1930).

Statistical methods have been used to test hypotheses regarding the chemical composition of the different types of rock. In this way it was possible to obtain some information as to the origin of the amphibolites and allied rocks of the northern Adula region. It was established that the chemical compositions of the amphibolites and the ophiolites differ in several points, which strongly suggest that these amphibolites did not derive from ophiolites. According to their chemical composition, these amphibolites are also different from marls. The concept of granitization has also been discussed in relation to the origin of the amphibolites and allied rocks. These rocks are regarded by some authors as a basic front at the boundaries of the phengite-gneisses and the mica-schists, in the sense of Doris Reynolds (1947). This possibility is highly improbable since their potassium content is low in comparison with that of the phengite-gneisses and the mica-schists. The present author is of opinion that the amphibolites have no genetical relation whatsoever with the mica-schists or with the phengite-gneisses.

A sodium-metasomatism of the mica-schists around the Zervreila gneiss-body, as assumed by Müller (1958), could not be found by means of applying statistics on 37 samples.

The chemical composition of the various types of rocks is shown in a comprehensive QLM diagram (fig. 35), that is composed of the QLM diagrams given before.

CHAPTER VI

PHASES OF METAMORPHISM IN THE NORTHERN ADULA REGION

Introduction

In the following paragraphs it will be shown that certain metamorphic minerals in the northern Adula region show a distinct succession in time, as witnessed by the occurrence of armoured relics and of veins containing deviating mineral assemblages formed during a later phase of metamorphism. The same succession is indicated by the occurrence of zoned crystals.

Especially the mutual relations of the different types of amphibole will appear to be of great help in unravelling the metamorphic history. Therefore the age relations of the different members of the amphibole group will first be established. Since some of these are of local occurrence, this procedure mainly reveals the succession in time of three different types of amphibole, viz:

GLAUCOPHANE — BLUE-GREEN AMPHIBOLE — ACTINOLITE

Next the age relations between the other minerals and each of these types of amphibole will be established. As a result it will appear that *the metamorphic rocks of the northern Adula region are mainly characterized by the succession in time of three different mineral assemblages.*

It will be shown that these main assemblages are of Alpine age, an obscure older assemblage probably being of Hercynian age.

Finally some suggestions as to the age of the original material of the amphibolites and the phengite-gneisses will be made.

It may be emphasized that the conclusions to be drawn in the following paragraphs are based on the detailed investigation of about 500 thin sections, selected as representative specimens from a larger collection of thin sections, covering about 1000 rock samples.

The minerals occurring in the northern Adula region are listed on page 451, the distribution of the rock-making minerals over the different rock types is given in table 18 on page 485.

AGE RELATIONS OF THE DIFFERENT TYPES OF AMPHIBOLE

A first indication of the age relations between the different types of amphibole is given by the occurrence of *armoured relics*. Sample LP 4, cf. p. 513, e. g., shows numerous crystals of glaucophane without rims of blue-green amphibole enclosed in zonal garnet, while outside this garnet the rock consists mainly of blue-green amphibole with an occasional core of glaucophane. This sample illustrates that, at least in this case, the glaucophane is definitely older than the blue-green amphibole. Sample LP 88, cf. p. 511, holds glaucophane and ferrohastingsite enclosed by epidote. Other parts of the rock show either ferrohastingsite with glaucophane cores and actinolite rims or actinolite with ferrohastingsite cores next to well-developed separate

crystals of actinolite. From these phenomena it may be concluded that in this case, the glaucophane is older than the actinolite.

Amphiboles occurring in very narrow *dilatation veins* with a deviating mineral assemblage formed during a later phase of metamorphism, differ from at least some of the amphiboles found in the intersected sample, thus giving information about the sequence of these amphiboles. In sample LP 522, cf. p. 505, glaucophane with narrow rims of blue-green amphibole is rather frequent in the main body of the rock, while blue-green amphibole is found wherever this glaucophane is intersected by dilatation veins.

In sample LP 121, cf. p. 508, blue-green amphibole crystals with purplish cores are found, whereas veins are filled with actinolite. These examples indicate that in these cases the glaucophane is older than the blue-green amphibole and the blue-green amphibole is older than the actinolite.

From armoured relics and dilatation veins we arrive at the following time-sequence:

GLAUCOPHANE — BLUE-GREEN AMPHIBOLE
 BLUE-GREEN AMPHIBOLE — ACTINOLITE
 GLAUCOPHANE ————— ACTINOLITE

This sequence is established on a rather small amount of evidence, and therefore we have to look for phenomena that can bear out the correctness of this succession and that are at the same time of rather frequent occurrence.

The amphiboles of the northern Adula region, just as those of the northern Tambo region, are nearly always zonal. These amphiboles have been repeatedly described in chapter IV. Numbering the types of amphibole as follows (types occurring in more than one zone are indicated with two different numbers):

actinolite	7
blue-green amphibole	6
ferrohastingsite	5
crossite	4
glaucoophane	3
crossite	2
dusty blue-green amphibole	1

the following successions from core to rim were observed:

1 — 3 — 6	sample LP 388
2 — 3 — 4 — 5	sample T 116
2 — 3 — 5	sample LP 479
3 — 5	sample LP 88 & LP 452
3 — 5 — 7	sample LP 88 & LP 452
3 — 6	nearly all glaucophane-bearing samples
5 — 6	a. o., sample T 207
5 — 7	a. o., sample LP 88 & LP 452
6 — 7	all ophiolites with blue-green amphibole.

An investigation into the frequency of occurrence of these types of amphibole yielded the following results for 186 amphibole-bearing samples (11 phengite-gneisses, 51 mica-schists, 114 amphibolites, 10 ophiolites):

7. actinolite	17 %
6. blue-green amphibole	92 %
5. ferrohastingsite	4 %
4. crossite	1 %
3. glaucophane	27 %
2. crossite	3 %
1. dusty blue-green amphibole	1 %

It follows that the most frequent types are actinolite, blue-green amphibole and glaucophane. According to the observations earlier mentioned these most frequent amphiboles show the following succession from core to rim in zoned crystals:

GLAUCOPHANE — BLUE-GREEN AMPHIBOLE
BLUE-GREEN AMPHIBOLE — ACTINOLITE

The resulting ideal scheme

GLAUCOPHANE — BLUE-GREEN AMPHIBOLE — ACTINOLITE

corresponds entirely to the age sequence established above, which is based on the evidence provided by *armoured relics* and younger *vein-filling assemblages* formed under the influence of metamorphism.

The only exception to this general scheme was found in one sample, viz LP 388, which shows zoned crystals with cores of dusty blue-green amphibole (no 1 of the above list), an intermediate zone of glaucophane and rims of a blue-green amphibole of slightly different colour. The dusty blue-green cores are intersected by dilatation veins, filled with glaucophane, while the glaucophane itself is again cut by veins of the blue-green amphibole variety of the rims. Therefore the age sequence

dusty blue-green amphibole — glaucophane — blue-green amphibole is definitely established. The dusty blue-green variety apparently represents a rare older generation of blue-green amphibole. The epidote and calcite enclosed within the same crystals of glaucophane may be of similar age. It is not impossible that the dark blue-green amphibole found as inclusions in some crystals of garnet (occurring in two glaucophane-bearing samples that only contain younger blue-green amphibole of a lighter colour), may also belong to this generation. This older generation of blue-green amphibole, being the oldest amphibole generation observed, was apparently almost entirely obliterated during the younger phases of amphibole growth. As this mineral is always accompanied by younger blue-green amphibole, its occurrence is not inconsistent with the general age scheme of the most frequent types of amphibole given above.

The rare crossite may be regarded as a local variation of the glaucophane, while the same may hold true for the ferrohastingsite with regard to the younger blue-green amphibole, see also p. 558.

Minerals and zonal structures that are of frequent occurrence in different types of rock must have originated in consequence of rather important processes that functioned more or less independently from local circumstances. The age sequence

GLAUCOPHANE — BLUE-GREEN AMPHIBOLE — ACTINOLITE

is therefore an important clue to the unravelling of the metamorphic history of the northern Adula region.

Comparison with adjoining regions. — With regard to the ophiolites of Nufenen (Nabholz 1945, p. 64; Roothaan 1919, p. 57; Gansser 1937, p. 479) and Neu Wahli (Gansser 1937, p. 461—479), Gansser makes it clear that the cores of the amphibole crystals in these rocks are in most cases built of crossite, set in an inner rim of glaucophane and an outer rim of "bluish actinolite", probably corresponding with our younger blue-green amphibole. Another type of amphibole has a small axial angle as well as pronounced blue and green colours pointing to ferrohastingsite (the barroisite or karinthine of Gansser). These scanty data suggest that similar age-relations of the amphiboles may also be valid for adjoining regions.

In conclusion, it follows from the observations discussed in this paragraph, that a fixed age sequence of the main types of amphibole may be adopted and that the suggested scheme is not at variance with any observation made so far.

SUCCESSION OF METAMORPHIC ASSEMBLAGES CHARACTERIZED BY DIFFERENT TYPES OF AMPHIBOLE; METAMORPHIC PHASES

The structure of a number of samples provides us with some information about the age relations between the different types of amphibole and the other minerals. Some striking examples will be mentioned in the following.

As to the age relations between poeciloblasts and enclosed minerals the mere occurrence of inclusions was not taken to indicate a significant difference in age. Only the core of an enclosed zonal mineral was assumed to be significantly older than the poeciloblast and the rim of a zonal poeciloblast was assumed to be significantly younger than a mineral enclosed in the core.

For example the atoll garnets of sample LP 522, cf. p. 505, along with remnant pyroxene, quartz, muscovite and rutile are enclosed in glaucophane with narrow rims of blue-green amphibole. In this sample the blue-green amphibole is of significantly younger age than the other minerals mentioned. The "pseudodiorite" of Peil (LP 82 & 83) contains a.o., garnets with pink cores and colourless rims enclosed within blue-green amphibole, indicating that the pink garnet is significantly older than the blue-green amphibole.

Additional information is supplied by observations on very narrow veins with a mineral assemblages corresponding to groups of common metamorphic minerals. The assemblage of such a vein is assumed to have originated over a relatively short stretch of time, under metamorphic conditions, and is considered to represent a stable association of approximately contemporaneous minerals. Often the same does not hold true for the main body of the rock.

In sample LP 112, cf. p. 507, such veins contain light coloured garnet, blue-green amphibole, epidote and calcite. They cut through pink garnet and blue-green amphibole. Sample LP 284 (p. 510) contains two sets of veins, one being of metasomatic origin. The main body of the rock contains a.o., sodium-pyroxene, garnet and rutile. The older veins show the assemblage blue-green amphibole, epidote, albite, biotite, muscovite, calcite, quartz and sphene, while garnet fragments of the wall do not show any alteration. The younger, metasomatic veins contain actinolite, calcite, biotite, quartz and sphene.

An actinolite-bearing vein in sample LP 121 (p. 508) shows epidote and chlorite in addition to the assemblage of the younger vein in the above sample.

These observations point to the succession in time of the following mineral groups:

	blue-green amphibole	actinolite
sodium-pyroxene	garnet	epidote
garnet	epidote	biotite (green)
muscovite	albite	chlorite
quartz	biotite	quartz
rutile	muscovite	calcite
	quartz	sphene
	calcite	
	sphene	

So far only the younger two groups have been argued to represent mineral associations. With reference to the first group it should be emphasized that it has not yet been demonstrated whether we are dealing here with minerals of about the same age as the glaucophane, or with older minerals, e. g., minerals grown in eclogites.

Further information on the composition of the mineral assemblages associated with each of our main types of amphibole (viz glaucophane, blue-green amphibole and actinolite) was obtained from an investigation of the mineralogical composition of 299 samples. The data taken from the descriptions of the corresponding thin sections were feeded into an International Business Machines equipment. This method was adopted, because it rapidly provided accurate answers to the numerous questions raised during our preliminary investigations.

The following data were coded and punched into punch-cards:

Type of rock
 Locality
 Sample number
 Minerals occurring in the sample, irrespective of their structures,
 quantities or mutual relations.

The group of samples was composed in this way:

11 samples taken from ophiolites
 130 samples taken from amphibolites and allied rocks
 86 samples taken from mica-schists
 24 samples taken from Mesozoic sediments
 48 samples taken from phengite-gneisses.

The frequency of occurrence of the rock-making minerals in this group is given in percentages in fig. 36. This figure illustrates that quartz, albite, muscovite and epidote are to be found in at least 80 % of the samples. Garnet, chlorite, blue-green amphibole, apatite, sphene and rutile are found in at least 50 % of the samples.

The pile of cards was afterwards sorted by the machine according to several demands. It will be clear that the best information about the composition of, e. g., the assemblage with blue-green amphibole, is furnished by a study of the mineralogical composition of those rocks which contain blue-green amphibole, but none of the other main types of amphibole, viz actinolite and glaucophane. Mutatis mutandis the same holds true for the

actinolite-bearing assemblage. All glaucophane-bearing samples of the studied group, however, contain blue-green amphibole as well, so that 1) while studying the actinolite assemblage we could restrict ourselves to samples without blue-green amphibole and 2) it is not possible to select a similar representative group of rocks for the study of the glaucophane-bearing assemblage.

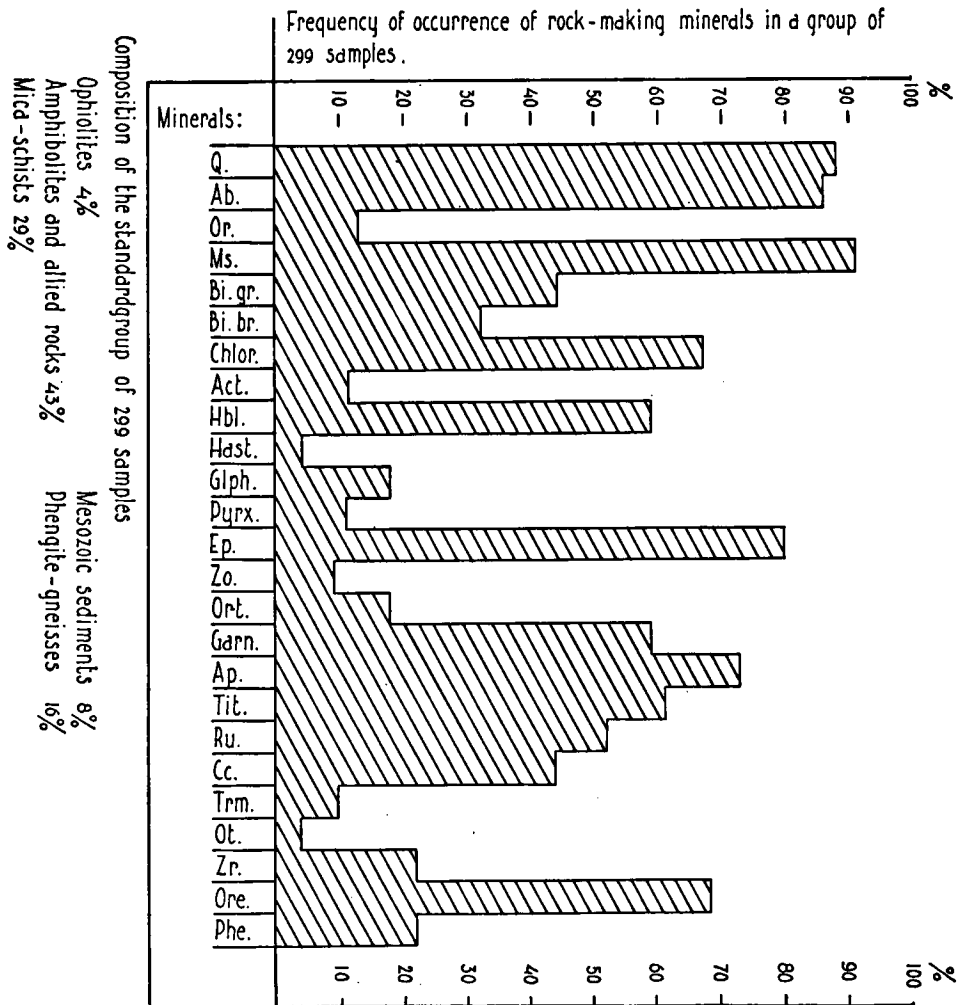


Fig. 36. Frequency of occurrence of rock-making minerals in a group of 299 samples, for explanation see page 556; Or = microcline or orthoclase; Hast = ferrohastingsite; Ot = chloritoid.

Consequently the following groups of rocks were sorted out:

- (1) Glaucophane-bearing rocks without actinolite, 49 samples
- (2) Blue-green amphibole bearing rocks without glaucophane and actinolite, 112 samples
- (3) Actinolite-bearing rocks without blue-green amphibole, 16 samples.

The frequency of occurrence of each of the different rock-making minerals in these groups is given in table 35.

The value 84 for quartz in column 1, for instance, means that quartz is present in 84 % of the total number of glaucophane-bearing samples that do not contain actinolite.

It will be clear that the second and third columns provide much more information about the composition of the mineral assemblages with blue-green amphibole and actinolite, respectively, than the first column gives about the glaucophane-bearing assemblage. The samples of the first column are strongly contaminated by minerals of the assemblage with blue-green amphibole. Of course, such a contamination with minerals of another assemblage also occurs to a minor extent in the other columns.

Table 35

Frequency in percentages of the occurrence of the rock-making minerals in:

- ① 49 samples with glaucophane not showing actinolite,
- ② 112 samples with blue-green amphibole not showing glaucophane or actinolite,
- ③ 16 samples with actinolite not showing blue-green amphibole.

	①	②	③
Quartz	84	89	63
Albite	86	95	81
Microcline	0	8	0
Muscovite	92	94	81
Phengite	0	15	0
Biotite (green and brown)	76	79	13*
Chlorite	78	69	88
Actinolite	0	0	100
Blue-green amphibole	100	100	0
Ferrohastingsite	0	7	0
Glaucophane	100	0	0
Crossite	8	0	0
Sodium-pyroxene	23	14	0
Epidote	86	86	69
Clinozoisite	14	22	6
Zoisite	10	5	38
Garnet	84	70	38
Sphene	63	73	94
Rutile	86	59	19
Calcite	35	42	43
Chloritoid	2	1	0

The bold percentages are either larger than 60% (in columns ② and ③) or considerably outnumber the percentages listed in the same row.

* This figure pertains exclusively to green biotite.

As a first result of these investigations it appears that crossite is confined to the glaucophane-bearing assemblage and ferrohastingsite to the assemblage with blue-green amphibole. This corroborates our earlier statement, that crossite may be regarded as a local variation of the glaucophane, while the same applies to the ferrohastingsite with regard to the blue-green amphibole.

Furthermore, some information concerning the composition of the assemblages with either blue-green amphibole or actinolite may be obtained by a selection of those minerals which are either of frequent occurrence (e.g. more than 60 %) in the corresponding groups of samples or show considerably

higher values than in the other columns. In the table the percentages in question are printed bold.

For the actinolite-column (3) the selection yields the following list of minerals: actinolite, quartz, albite, muscovite, chlorite, epidote, zoisite and sphene. The selection corresponds to the mineral assemblage in actinolite-bearing veins but for the presence of albite, muscovite and zoisite and the absence of calcite and green biotite (cf. p. 556). Since albite and muscovite may logically be expected as members of the actinolite-bearing assemblage, only the predominance of zoisite in the third column is a striking phenomenon. From evidence provided by the corresponding thin sections it follows that zoisite also belongs to this assemblage.

A similar selection for the blue-green amphibole assemblage yields, apart from ferrohastingsite, the following minerals not yet listed as vein-filling associates of the blue-green amphibole: microcline, phengite, chlorite and clinozoisite. Chlorite and clinozoisite apparently belong to the assemblage investigated. The predominance of microcline and phengite in this column is mainly due to the fact that the phengite-gneisses do not contain any other amphibole than the blue-green variety, and therefore their appearance in this column has no real significance (cf. p. 491).

As to the composition of the glaucophane-bearing assemblage again the difficulty arises that, apart from the crossite already discussed, the minerals that show a conspicuous predominance in the first column, viz sodium-pyroxene and rutile, may either belong to the glaucophane-bearing assemblage or to an older eclogitic one (cf. p. 556). Now the sodium-pyroxene does not show any alteration into glaucophane whereas alteration of this pyroxene into blue-green amphibole is a wide-spread phenomenon. Further the sodium-pyroxene in sample M 431 (p. 507) occurs together with amphibole crystals of equal size with large cores of glaucophane. Finally Gansser (1937, p. 461-479) describes glaucophane-bearing ophiolites of Alpine age, containing sodium-pyroxene together with pink garnets, that are mainly concentrated in the pyroxene-rich parts of these ophiolites, while in several other regions (e.g., Celebes, cf. de Roever 1947) glaucophane is closely associated with contemporaneous sodium-pyroxene. All this evidence strongly suggests that the sodium-pyroxene indeed belongs to the glaucophane assemblage.

In sample LP 284, cf. p. 510, clusters of garnet surround masses of sodium-pyroxene, whereas the sodium-pyroxene occasionally encloses a crystal of garnet. Further, the glaucophane is perfectly fresh when in contact with the enclosing garnet of sample LP 4, cf. p. 513. Finally the garnet is not a pyrope-rich variety, cf. p. 471, and does not show celyphitic borders. These observations together with the association of sodium-pyroxene and garnet in Alpine ophiolites described by Gansser (loc. cit.) indicate that at least a large part of the older garnet belongs to the glaucophane-bearing assemblage, along with the numerous rutile crystals of the glaucophane-bearing rocks.

In view of contacts between perfectly fresh glaucophane and epidote (LP 88, p. 511) the same may hold true for the latter mineral. This conclusion is strongly supported by the composition of many glaucophane-bearing rocks in other parts of the world (e.g., Val de Bagnes, Switzerland; Ile de Groix, France).

In addition, these rocks contain quartz, albite, muscovite, chlorite and calcite. In our samples quartz and muscovite show contacts with fresh sodium-pyroxene and garnet, so quartz and muscovite are also held to be members of the glaucophane-bearing assemblage. There is no positive proof that albite, chlorite and calcite belong to this mineral-assemblage (see also p. 554).

Garnet pseudomorphs after chloritoid were found in sample LP 276a, p. 519, both minerals showing alteration into chlorite. The age-sequence inferred is: *chloritoid* — *garnet* — *chlorite*. This evidence in combination with the fact that in the glaucophane-bearing rocks of Val de Bagnes and of Ile de Groix, chloritoid is a well-developed mineral, with all characteristics pointing to a contemporaneous origin with glaucophane, strongly suggests that the chloritoid also belongs to the glaucophane-bearing assemblage. In that case the younger garnet and the chlorite belong to the blue-green amphibole and the actinolite assemblages, respectively.

Biotite is not assumed to belong to the glaucophane assemblage because the simultaneous growth of these two minerals is not reported from other glaucophane-bearing regions. The same holds true for microcline, which in some phengite-gneisses encloses sodium-pyroxene. This microcline as well as that produced in the Mesozoic sediments, is therefore assumed to belong to the blue-green amphibole assemblage. Part of the microcline of the phengite-gneisses, however, but most probably the orthoclase of these rocks may be of older age than the glaucophane-bearing assemblage.

The mineral phengite is a main constituent of the phengite-gneisses and the Mesozoic sediments. It is a rare constituent of some mica-schists and amphibolites. In the region under consideration the following relations were observed: some phengite has rims of olive-green or greenish biotite; phengite together with sodium-pyroxene is enclosed by microcline. It follows that the phengite might or might not be significantly older than the microcline and olive-green biotite. Michel (1953, p. 183), describing the "gneiss albitiques de Pont-Canavese à amphibole", mentions amphiboles with cores of glaucophane in a rock containing, a.o., quartz and epidote. The glaucophane encloses quartz, phengite and chlorite. This would place phengite in the glaucophane-bearing assemblage.

The age of the kyanite found in some chloritoid-bearing rocks is not known, except that the mineral is of Alpine age and that it has been altered into muscovite, most probably during, or before, the production of the actinolite-bearing assemblage.

In conclusion, the following metamorphic assemblages were argued to have been produced in association with the three main types of amphibole in the region under discussion:

Glaucophane	Blue-green amphibole	Actinolite
Crossite	Ferrohastingsite	Quartz
Sodium-pyroxene	Quartz	Albite
Garnet	Albite	Muscovite
Epidote	Microcline	Biotite
Rutile	Muscovite	Chlorite
Quartz	Biotite	Epidote
Muscovite	Chlorite	Zoisite
Chloritoid	Epidote	Sphene
Phengite (?)	Clinozoisite	Calcite
	Garnet	
	Sphene	
	Calcite	

The occurrence of the three mineral assemblages, given above, forms one of the main characteristics of the rocks of the northern Adula Nappe. Minerals of the first group are older than minerals of the second and the second group is older than the third. The period of time during which the physical circumstances favoured the production of such an assemblage will be called a *metamorphic phase* for the rest of this paper. Such a metamorphic phase should not be confused with a metamorphic facies. A metamorphic phase is a more or less definite stretch of time characterized by particular physical circumstances, giving rise to a special type of mineral assemblage, whereas a metamorphic facies comprises a group of rocks that have originated under more or less similar physical circumstances.

The period during which the glaucophane-bearing assemblage was produced, will thus be called *phase I*; that of the blue-green amphibole assemblage, *phase II* and that of the actinolite-bearing assemblage, *phase III*. Minerals not classed in these phases are: the orthoclase porphyroclasts and the grossularite garnets of some phengite-gneisses; the dusty blue-green amphibole surrounded and veined by glaucophane; and large flakes of red-brown biotite rarely surrounding the garnet of some mica-schists, large crystals of such biotite being absent in the Mesozoic rocks. There are reasons to assume these minerals to be older than phase I. This group of minerals probably also comprises a large number of minerals occurring in metamorphosed pre-Alpine rocks, minerals that as yet could not be distinguished from their counterparts belonging to the phases I, II or III.

METAMORPHISM AND GEOLOGICAL HISTORY

In this paragraph tentative comments will be made on the relation between the metamorphic phases and the geological history of the region.

In the Adula Nappe rocks of different age can be found. The Mesozoic rocks certainly originated after the Hercynian period. The original material of the mica-schists may be of Hercynian or older age; that of two groups of rocks, the amphibolites and the phengite-gneisses, could be conceived to belong either to the Mesozoic or to some older period.

The arguments of Kopp (1923), Gansser (1937) and Nabholz (1945) for a Carboniferous age of the mica-schists were discussed in chapter II. These arguments are based on a lithological comparison and on theoretical considerations. As yet, the age of the mica-schists has not been established by fossils or by the existence of primary contacts with Mesozoic rocks. The Hercynian period certainly was accompanied by metamorphism and if Mesozoic rocks are compared with rocks that have a pre-Hercynian origin, it may well be possible to find specific Hercynian relics (cf. the biotite and the non-fibrous green hornblende of metamorphic origin found in Corsica, Egeler 1956, p. 115). Large crystals of red-brown biotite are absent from the Mesozoic sediments, but present in some mica-schists; this fact suggests a pre-Permian age for the mica-schists.

The Alpine period is characterized a. o., by intensive metamorphism as witnessed by the production of, a. o., kyanite and garnet in Mesozoic sediments of the region under review. It needs no arguing that apart from some rare clastic grains in sediments, Hercynian or older metamorphic minerals cannot be found in Mesozoic rocks, whether sedimentary or igneous. Therefore, *the metamorphic minerals occurring in the Mesozoic sediments must be of Alpine age*. These minerals are listed in Chapter IV, table 18 under the heading

Mesozoic sediments. They comprise characteristic minerals of the three metamorphic phases distinguished before. The metamorphic minerals of the ophiolites are also of Alpine age, but it might be difficult to distinguish in certain cases between metamorphic minerals and minerals of igneous origin. These metamorphic minerals are also listed in Chapter IV, table 18, under the heading ophiolites, and comprise the three main types of metamorphic amphibole, viz glaucophane, blue-green amphibole and actinolite.

The Mesozoic origin of all these rocks is evident among others from the paper of Nabholz (1945). His argument is briefly described in Chapter II. All main phases of metamorphism are therefore of Alpine age, the only possible Hercynian minerals being the older minerals listed on page 565.

HERCYNIAN metamorphism

The mica-schists might partly have been the products of Hercynian metamorphism. A special characteristic of some of these rocks is the occurrence of large flakes of red-brown biotite. Such crystals were not found in the Mesozoic rocks, while there is no reason to assume that the chemical composition of these rocks should be incompatible with the occurrence of red-brown biotite. On the contrary, samples from more southern regions, e. g., from the Val Calanca, are, irrespective of their period of origin, rich in young red-brown biotite. This observation emphasizes the fact that red-brown biotite may have formed during Alpine metamorphism under favourable conditions. The absence of large crystals of red-brown biotite in the Mesozoic rocks of the northern Adula region therefore points to an older, Hercynian age of the red-brown biotite found in the mica-schists. Older garnet, which is set in haloes of this red-brown biotite, is also to be considered as a product of the Hercynian metamorphism.

Some of the phengite-gneisses contain large orthoclase crystals, partly microclinized and having a dusty appearance under the microscope. These orthoclase crystals often show Carlsbad twins. If these gneisses are products of metamorphism and mechanical disturbance of a former granite — a possibility already hinted at by Kopp (1923), Nabholz (1945, 1948, 1954 & 1956) and Müller (1958) — these orthoclase crystals may be of Hercynian igneous origin.

The occurrence of grossularite-rich garnets in a number of phengite-gneisses is still an unsolved problem, the more so because the present mineral assemblage of these gneisses is generally accepted to be of a low-temperature genesis. Grossularite on the other hand is a mineral of a rather high temperature association. These garnets may also represent relics of a former, pre-Alpine stage of these rocks, of which up till now only little is known.

One sample of an amphibolite holds dusty blue-green amphibole that — probably together with epidote and calcite — is older than the associated glaucophane. On the other hand there are numerous indications that glaucophane and crossite were among the first metamorphic minerals produced in the Mesozoic rocks. This older blue-green amphibole generation consequently may be of pre-Alpine age. Now blue-green hornblende as a mineral of an igneous mineral association seems to be rather rare. The local presence of this older blue-green amphibole therefore might indicate that the amphibolites existed already as such before the Alpine period and that the original rocks consequently were transformed into amphibolites by Hercynian or older meta-

morphism. Furthermore, a number of common metamorphic minerals, such as quartz and muscovite, may logically be assumed to have belonged to the Hercynian mineral assemblage. Again it should be emphasized here, that discussions on Hercynian relics are based on scanty data and are still highly hypothetical.

ALPINE metamorphism

As shown above, the three main phases of metamorphism that were distinguished are of Alpine age. Therefore, they can be entitled Alpine phase I, Alpine phase II and Alpine phase III. These phases will be separately discussed in the following. As to the quantitative importance of the different phases it may be remarked that a phase covering only a relatively short stretch of time, could not press its marks so intensively on the rocks in its realm as a phase that lasted longer. Moreover, if temperatures during certain phases are relatively low, the transformation velocity is slow. So a long-lasting phase with comparatively high temperatures had the best chance to cause the most important transformation. Metamorphism of a younger phase, however, can have obliterated part of the products of an older phase, especially if this younger phase was long-lasting and characterized by comparatively high temperatures.

Alpine phase I

As argued before, glaucophane, crossite, sodium-pyroxene, garnet, epidote, chloritoid, quartz, muscovite and rutile were formed during this phase. It is self-evident that the recrystallization of the Mesozoic limestones also produced calcite during this phase. The same mineral assemblage, with additional albite and chlorite, is found in the glaucophane-bearing rock-associations of the Val de Bagnes, Switzerland (a. o., Tschopp 1923) and Ile de Groix, France (Prof. Dr W. P. de Roever, personal communication, and our own observations on thin sections of samples in the collection of the Leiden Institute).

Concerning the fact that we could not prove albite to belong to phase I, an observation of Professor Dr P. Misch is enlightening. He writes: "A large portion and probably the great majority of the rocks with glaucophane minerals show an inverse proportion between the amount of sodic amphibole and the amount of albite present" (personal communication 1955). This statement is supported by the observations of many authors who have written on glaucophane-bearing rocks (a. o., Brothers, 1954, and Bloxam, 1959).

Further some observations mentioned on p. 560 would place phengite in the glaucophane-bearing assemblage, while some samples from the Hennen-sädel and the Weissgrätli contain both chloritoid and kyanite, the kyanite being partly altered into muscovite. This association is not so rare as is usually assumed, see e. g., Cornelius and Clar, according to Frasl (1958, p. 368 and 415), Bachmann (1956), Naha (1956) and van der Kaaden (1959). As for the hypothetical possibility that the chloritoid- and kyanite-bearing quartzites and calciferous mica-schists from the Hennensädel and the Weissgrätli, though being intercalated between Mesozoic dolomites, etc., might be of Hercynian origin, it may be pointed out that chloritoid- and kyanite-bearing quartzites in a glaucophane-bearing region in Turkey, cf. van der Kaaden (loc. cit.), are intercalated between fossiliferous Lower Permian limestones, suggesting an Alpine rather than a Hercynian age of the minerals in question.

Alpine phase II

This phase, which is essentially characterized by the occurrence of blue-green amphibole, is taken to be the main phase of metamorphism in our region (cf. p. 556). This is suggested by the fact that the greater part of the samples of our test-group of 299 samples shows the occurrence of blue-green amphibole, see fig. 36.

Some indications were given that at least part of the microcline of the phengite-gneisses as well as the microcline found in the Mesozoic sediments was produced during this phase. Other minerals are garnet, biotite, ferrohastingsite, quartz, albite, muscovite, chlorite, epidote, clinozoisite, sphene and calcite. It needs no arguing that the assemblage of phase II is a common metamorphic mineral assemblage.

As this phase is characterized by the abundant production of biotite, it may be assumed that the phlogopite of some dolomites may have originated during this phase as well.

There are numerous indications that a large amount of albite in the mica-schists, the amphibolites and the phengite-gneisses is the product of Alpine phase II.

Alpine phase III

The most recent products of metamorphism are the actinolite, quartz, albite, muscovite, green biotite, chlorite, epidote, zoisite, sphene and calcite of phase III.

Most of the highly mylonitized rocks of the region of Fuorela de Puozas, coord. 7277—1620, among others amphibolites and ophiolites, consist mainly of actinolite, chlorite and epidote, with remnants of blue-green amphibole or glaucophane. This illustrates the relation of this phase with tectonic movements. This third phase represents a well-developed retrogressive metamorphism (in the sense of Turner, 1951), its mineral assemblage corresponding to that of many greenschists.

Summarizing, the composition of the mineral assemblages of the different metamorphic phases is schematically given in table 36.

THE AGE OF THE ORIGINAL MATERIAL OF THE AMPHIBOLITES

One of the amphibolite samples holds a dusty blue-green amphibole, which was assumed to be of Hercynian metamorphic origin. Furthermore a number of samples of amphibolites contain red-brown biotite, in various stages of alteration. Some of this red-brown biotite may be of Alpine age, but another part may be older.

Structural phenomena observed in the amphibolites and allied rocks illustrate that these rocks were subjected to Alpine deformation. The N—S b-axes of the contorted folds in the region of the Zervreila dam illustrate that the amphibolites were present before the phase producing these axes made itself felt; this tectonic phase is of Alpine age, but is older than that producing the E—W axes, cf. Müller (1958, p. 448—449).

The amphibolites occur in bodies that are strikingly concentrated along the boundaries between the phengite-gneisses and the mica-schists. As to their original material or origin, a number of theoretical possibilities can be envisaged. They might represent:

1. Mafic igneous rocks of Alpine origin
2. Mafic igneous rocks of pre-Alpine origin
3. Triassic marls
4. The contact aureole of an intrusive granite of pre-Alpine origin
5. The basic border of an igneous body
6. A basic front of pre-Alpine origin
7. A basic front of Alpine origin

Ad point 1. In chapter V it was pointed out that the chemical composition of the amphibolites has little relation with that of the ophiolites.

Ad point 2. As the chemical composition of the amphibolites is more or less dioritic, this assumption seems probable. A tectonical emplacement might explain why the amphibolites always appear as lenses and spools between mica-schists and phengite-gneisses (see p. 500). In fact the structural phenomena along the boundaries of the mica-schists and the phengite-gneisses have much in common with those found in rather deep-seated zones of tectonic movement (see Müller 1958, Plate I, II and IV).

TABLE 36

THE DIFFERENT METAMORPHIC PHASES AND THEIR MINERAL ASSEMBLAGES

Hercynian minerals	Alpine phase I	Alpine phase II (main phase)	Alpine phase III
Quartz	QUARTZ Albite?	QUARTZ ALBITE	QUARTZ ALBITE
ORTHOCLASE (igneous) Microcline?		Microcline	
Muscovite	MUSCOVITE Phengite? ——— ?	MUSCOVITE	MUSCOVITE
BIOTITE (red-brown)		BIOTITE (brown and green) Phlogopite?	BIOTITE (green)
	Chlorite? CROSSITE	CHLORITE FERROHASTINGSITE	CHLORITE
DUSTY BLUE-GREEN AMPHIBOLE	GLAUCOPHANE	BLUE-GREEN AMPHIBOLE	ACTINOLITE
	SODIUM-PYROXENE		
Epidote?	EPIDOTE	EPIDOTE	EPIDOTE ZOISITE
GARNET	GARNET CHLORITOID Kyanite? ——— ?	GARNET	
	RUTILE	Rutile? SPHENE	SPHENE
Calcite?	Calcite	CALCITE	CALCITE

- Ad point 3. The chemical composition of the amphibolites does not correspond to that of marls, cf. p. 548.
- Ad point 4. The absence of remnant minerals or structures of such hornfels is striking. Another point against this hypothesis is the low K content of the amphibolites.
- Ad point 5. The absence of small amphibolite bodies within the phengite-gneiss does not support this hypothesis.
- Ad point 6. According to Müller (1958), who made an extensive study of the problem, this seems the most probable origin of the amphibolites. Müller's elegant hypothesis, however, is not supported by the low K content of the amphibolites as compared with that of the mica-schists and the phengite-gneisses.
- Ad point 7. This possibility is similarly contradicted by the low K content of the amphibolites. Furthermore, the amphibolites and allied rocks frequently contain sodium-pyroxene and glaucophane. Thus the eventual basification of the mica-schists should have taken place during the Alpine metamorphic phase I, i. e., under the production of glaucophane and sodium-pyroxene, minerals that cannot be expected to occur in a basic front. An objection to this line of arguing may come from those students who assume sodium metasomatism a necessary source for the formation of glaucophane. Real glaucophanites, however, are not present and glaucophane never exceeds one tenth of the volume of a sample (the volume percentage in general is even lower than 1 %).

Hence the only reasonable conclusion so far seems to be that the amphibolites and allied rocks are metamorphosed Hercynian or older igneous rocks of a dioritic composition.

THE AGE OF THE ORIGINAL MATERIAL OF THE PHENGITE-GNEISSES

Since the accompanying amphibolites in all probability do not represent a basic front, one of the main arguments for a granitization origin of the phengite-gneisses is apparently refuted. The occurrence of grossularite-rich garnet, commonly a high temperature mineral, supports an igneous derivation of these rocks. The occurrence of orthoclase porphyroclasts, partly altered into microcline and showing Carlsbad twins, may denote an older granite. Other relic minerals and relic structures are hard to find. The absence of microcline in the immediate vicinity of the contacts with other rocks might be due to obliteration of this mineral during Alpine phase I which probably did not produce microcline. That this mineral was not completely obliterated might be ascribed to the fact that the alteration of all microcline into the only potassium minerals of phase I, viz muscovite and phengite, would involve the metasomatic transport of too much material, the microcline usually forming about 20 % of the larger bodies of phengite-gneiss.

According to this scanty evidence the phengite-gneisses would be metamorphosed Hercynian or older igneous rocks. These rocks may be compared with the pre-Alpine granitic rocks of Fibbia, Scai, Medelser, etc., and therefore the original igneous rocks might be of Hercynian age; the absence of red-brown biotite may be ascribed to the production of phengite at the expense of biotite, muscovite, potassium-feldspar and quartz (see p. 538).

Summarizing conclusions

The rocks of the northern Adula region were influenced by three successive phases of metamorphism of Alpine age. Some of the rocks even show traces of pre-Alpine metamorphic processes. During *the first Alpine phase*, a. o., glaucophane, crossite, sodium-pyroxene, garnet, epidote and chloritoid were produced, while *the second Alpine phase* gave rise to the production of, a. o., blue-green amphibole, ferrohastingsite, garnet, albite, epidote and biotite, and *the third Alpine phase* produced, a. o., actinolite, chlorite, green biotite, epidote, zoisite and albite.

The existence of these three Alpine phases was proved by making use of the following phenomena:

- a. The occurrence of armoured relics
- b. The difference between the mineral assemblages of the host-rock and of narrow veins originated during the metamorphism
- c. The zonal habit of amphiboles
- d. The frequency of occurrence of a number of mineral associations in a group of about 300 samples, a result of a quantitative investigation with the aid of an International Business Machines equipment.

Moreover it was proved that zonal amphiboles may be of great help in unravelling the metamorphic history of a region that has gone through more than one metamorphic phase.

As to the original material of the amphibolites and allied rocks, the only reasonable conclusion seems that these rocks are metamorphosed mafic igneous rocks of Hercynian or older age. Scanty evidence suggests that the phengite-gneisses are the products of metamorphism of Hercynian igneous rocks.

CHAPTER VII

GENERAL CONSIDERATIONS ON THE ALPINE METAMORPHIC PHASES

(with special reference to the distribution and origin of glaucophane)

The successive occurrence of at least three different metamorphic phases of Alpine age, characterized by the production of glaucophane, blue-green amphibole and actinolite, respectively, is a primary feature of the post-Palaeozoic metamorphism in the northern Adula region.

Since a similar succession of several metamorphic phases, each characterized by its own mineral assemblage, has not yet been reported from adjoining Alpine areas, a comparison can best be made with more remote regions of post-Palaeozoic folding where similar methods of investigation were used, i. e., eastern Celebes (cf. de Roever 1947, 1950, 1953, 1956) and Corsica (cf. Brouwer and Egeler 1952; Egeler 1956). In the above regions, however, the results of the investigations were interpreted in terms of the metamorphic facies concept of Eskola.

In this paper the facies classification was not used for three reasons:

1. The facies classification has not been used in adjoining regions, because Swiss petrographers prefer the zone classification of Grubenmann (1904, 1910), especially after the modifications of P. Niggli (1924). Moreover, the polymetamorphic rocks of the Alpine regions — i. e., the rocks that suffered both Hercynian and Alpine metamorphism — in contrast to the rocks of the Orijärvi or the Oslo regions, never reached an equilibrium status.
2. The metamorphism of Alpine age in the northern Adula region is characterized by the production of successive mineral assemblages belonging to different facies or subfacies.
3. There is at present a considerable confusion in the nomenclature as well as in the definition of a number of facies.

Our first Alpine metamorphic phase corresponds to a subfacies of the glaucophane-schist facies typical for most Swiss glaucophane-bearing rocks, with garnet, epidote, chloritoid and chloromelanite-like sodium-pyroxenes. The second metamorphic phase corresponds to, e. g., Barth's (1952) albite-epidote-amphibolite facies. The third Alpine metamorphic phase produced a typical greenschist facies assemblage.

Apart from pre-Mesozoic metamorphism a succession of two metamorphic phases of Alpine age has been elaborately described from both eastern Celebes and Corsica, viz an older phase producing glaucophane and kindred sodium-amphiboles, and a younger greenschist phase. The succession of an older phase of metamorphism of Alpine age, producing glaucophane, and a younger phase, producing green (or blue-green) amphibole, is considered to be of rather wide distribution in the Alps, in view of the frequent occurrence of zonal crystals of amphibole with glaucophane cores and rims of green or blue-green amphibole (usually called actinolite), described by, a. o., Rosati (1902), Grubenmann (1906), Zambonini (1906), Bianchi and Dal Piaz (1929).

For a comparison with adjoining regions two maps are added showing respectively the distribution of glaucophane and kindred sodium-amphiboles

in the immediate surroundings of the mapped area, cf. fig. II, and the distribution of these amphiboles and lawsonite in the Alps (fig. I). These maps were compiled partly with the aid of a large number of data collected over a period of more than 10 years by Professor Dr W. P. de Roever. The most important and most recent references are to be found on p. 587. From these maps it is obvious that *the occurrence of glaucophane s.l. and lawsonite is restricted to the Penninides and their nearest surroundings*, lawsonite being of rare occurrence in the Swiss part of the Alps. A map of Europe and a world map showing the distribution of glaucophane s.l. and lawsonite, see fig. V and VI, and p. 587, (cf. also Schürmann 1951) bear out the statement already made by Eskola (1929) that glaucophane is mainly restricted to regions of Cenozoic folding. According to de Roever (1956) lawsonite is not known from regions of pre-Mesozoic folding. The occurrence of lawsonite in Antarctica, viz in Adelie land (Stewart 1951) may point to the existence of post-Palaeozoic folding in this area, especially since Adelie land can be considered as a prolongation of the New Caledonia—New Zealand arc.

A similar study concerning its distribution can be made for another mineral that belongs to the glaucophane-bearing assemblage of our region, viz chloritoid. Here we touch upon the investigations on the regional distribution of certain minerals in the Swiss Alps carried out by E. Niggli, the results of which are known to a large number of Swiss geologists through lectures given on the subject at Zürich and Bern as early as 1956. Unfortunately these results are not yet available in print* but for a few remarks in the following papers: E. Niggli (1955, 1956); E. Niggli et al. (1956); Streckeisen and E. Niggli (1958); van der Plas et al. (1958). As a result of these investigations four different zones were established in the Swiss Alps, viz a sillimanite zone, a zone of Alpine kyanite, a chloritoid zone and a stilpnomelane zone. The mineral sillimanite appears to be concentrated in the regions around Locarno and Bellinzona. Kyanite of Alpine age is found in the immediate surroundings of Zermatt and in the region between Airolo and the sillimanite area. North of this kyanite zone the existence of a chloritoid zone was established, running from the Val de Bagnes to Chur, along Brigg, Airolo, Andermatt, Disentis, Vals and Ilanz. North of this chloritoid zone a zone of low-grade metamorphic rocks is found, characterized by the occurrence of stilpnomelane and an occasional sodium-amphibole (rhodusite or bababudanite according to E. Niggli et al., 1956). Moreover it was pointed out by E. Niggli that brown biotite of Alpine age, with a coarse-flaky habit, is found in an area partly covering these zones, extending from the sillimanite region around Locarno and Bellinzona in a northern direction as far as Airolo. This area of coarse-flaky brown biotite is of limited extension in a western and an eastern direction. It coincides with and is about as large as the conspicuous gap in the glaucophane zone south of the Gotthard Massif, cf. fig. I. The distribution of glaucophane in the Swiss Alps falls well within Niggli's chloritoid and stilpnomelane zones.

Turning again to our limited area, it was established in chapters V and VI that the production of glaucophane in this region was not caused by sodium metasomatism but that it depended on certain physical circumstances prevailing during the first Alpine metamorphic phase, the rocks having a chemical composition that made it possible to produce at least locally a few volume

* They will be published at the Intern. Geol. Congr. in Copenhagen (1960).

percentages of this mineral. In fact, most leading authors on the subject seem to be convinced at present that the production of glaucophane is controlled not only by chemical but also by physical conditions, as originally proposed by Eskola (1929, p. 165), cf. de Roever (1947, p. 164—165; 1950; 1955 a & b), Routhier (1953, p. 152), Iris Y. Borg (1956, p. 1582), Miyashiro (1957, p. 65), Miyashiro and Banno (1958, p. 97), Fyfe, Turner and Verhoogen (1958, p. 224—227) and Ellenberger (1958, p. 403). For a review of the various views concerning the causes of the production of glaucophane the reader is referred to Iris Y. Borg (1956, p. 1581—1582).

The preferential occurrence of glaucophane and lawsonite in zones of post-Palaeozoic folding, see fig. VI, was tentatively explained by de Roever (1956a). He condensed his views in a pithy abstract that is quoted here in full:

“Many regionally metamorphosed rocks found in post-Palaeozoic orogenic zones show important mineralogical differences from the corresponding rocks in older orogenic belts. Metamorphism in the glaucophane-schist facies, for instance, shows a striking preferential distribution in the post-Palaeozoic orogenic belts. Furthermore, it seems that all known lawsonite is of post-Palaeozoic age. It is suggested that post-Palaeozoic regional metamorphism, when compared with pre-Mesozoic regional metamorphism, is characterized by the predominance of less steep geothermal gradients during the main phase of metamorphism. There may have been a general, though possibly oscillating, decrease in the steepness of the geothermal gradients during the main phases of regional metamorphism from the early pre-Cambrian toward the youngest orogenic epochs, involving certain changes in the character of the metamorphic mineral assemblages produced. Seen in this light, it seems by no means impossible, for instance, that lawsonite will indeed appear to be a guide mineral for post-Palaeozoic metamorphism. It is hoped that the results of this study will encourage further investigations in this interesting field of historical mineralogy and petrology.”

The results of the foregoing lead to the following conclusion about the Alpine metamorphism:

The metamorphic processes that took place during the first Alpine metamorphic phase and caused the production of glaucophane and kindred sodium-amphiboles, may be called a genuine Pennine metamorphism. The slight differences between the outlines of the glaucophane area and the outlines of the Penninides as a structural unit point to the fact that the tectonical boundaries do not exactly coincide with petrographical boundaries. The absence of lawsonite from the northern Adula region and from almost the entire Swiss Alps may be due to physical circumstances. Apparently lawsonite needs a still less steep geothermal gradient for its formation than glaucophane. The mineral assemblage of the first Alpine metamorphic phase shows an abundance of garnet, chloromelanite-like sodium-pyroxene, epidote and chloritoid, while lawsonite, stilpnomelane and pumpellyite are absent. It corresponds very well to the assemblage found in the Val de Bagnes, Switzerland and to that of Ile de Groix, France (see also p. 559).

The second metamorphic phase of Alpine age, during which, a. o., blue-green amphibole, ferrohastingsite, epidote, albite, microcline, biotite and garnet were produced, has apparently not been recognized as such in other parts of the Alpine mountain system. Mineral assemblages holding some of these minerals were among others described by the following authors: Gansser (1937), Forster (1947), Güller (1947), Hasler (1949), Graeter (1951) and Bearth (1958). In the rocks described by these authors albite may be absent and plagioclase with a higher percentage of anorthite is found instead. Bearth (1958) discusses the boundaries of an area where albite is the current plagioclase with an area where albite is replaced by plagioclase with a higher per-

centage of anorthite. In the transition zone between these areas the plagioclase still shows an occasional core of albite.

Most probably the second metamorphic phase of Alpine age is contemporaneous with the genesis of the coarse-flaky brown biotite of Alpine age, the distribution of which was investigated by E. Niggli, see p. 569. The kyanite and sillimanite of Niggli's zones may well be of similar age. The chloritoid and the stilpnomelane are assumed to be older minerals with an age similar to that of the glaucophane and kindred sodium-amphiboles produced during the first Alpine metamorphic phase. Consequently the Niggli zones are thought to represent zones of minerals with different ages.

It is most probable that the mineral assemblage of the second phase is restricted in its distribution to an area N and NW of the Italian lakes, more or less coinciding with Niggli's kyanite zone and biotite area. Its origin may be connected with that of the post-Palaeozoic granitoid rocks in the neighbourhood of Bellinzona and in Tessin, about 30 to 45 km SW of the mapped area. This presence of granitoid rocks, especially the abundance of pegmatites, led Bearth (1958) to a similar conclusion when he tried to explain the relatively late origin of the basic plagioclase, already mentioned, in the region about Domodossola.

Most probably the conspicuous gap in the glaucophane zone south of the Gotthard Massif as well as the rarity of lawsonite in the Swiss Alps are genetically connected with the origin of these post-Palaeozoic granitoid rocks. The question whether in the regions under consideration the glaucophane and lawsonite have been obliterated during the second phase or have not been produced at all, must be left to future investigations.

The third metamorphic phase of Alpine age, which is characterized by a greenschist assemblage, is again apparently of wide-spread occurrence in all parts of the Alpine mountain chain and can be considered as a phase of retrogressive metamorphism.

SUMMARY

Geological and petrographical investigations were carried out in the northern part of the so-called Adula Nappe, one of the deepest Pennine nappes. The area under consideration lies in the SE of Switzerland, near Vals, S of Ilanz. This area is situated north of the Lepontine gneiss-region, the deepest part of the Alpine orogen.

The rocks of the mapped area fall into four groups, viz gneisses; mica-schists; amphibolites and allied rocks; and Mesozoic rocks, either of sedimentary or of igneous origin. The first three of these groups presumably represent metamorphic Hercynian or older rocks.

Structurally three units were distinguished, viz the Valserschuppen, the Fanellalappen and the Zervreilerlappen. The investigations clearly showed the important role of thrusting, isoclinal folding being of minor importance.

The fissure-filling and rock-making minerals, a. o., chloritoid, chloromelanite, ferrian phengite, garnet, crossite, glaucophane and ferrohastingsite, are described in chapter III. They are listed on p. 451.

A petrographical description of the region is to be found in chapter IV. The four different groups of rocks are treated separately, with a summary at the end of each section.

The phengite-gneisses have a blastic structure pointing to a total recrystallization of the original granitoid material. Generally the feldspars do not show alteration. The large orthoclase porphyroclasts in some samples are assumed to represent relics of an older mineral assemblage.

The mica-schists show the influence of several different phases of metamorphism as witnessed by, e. g., the chloritization of garnets, the replacement of chloritoid by transverse muscovite, the occurrence of several successive generations of amphibole and the occurrence of biotite fringes around the muscovites.

The amphibolites and allied rocks vary in mineralogical composition. The latter comprise, a. o., sodium-pyroxene garnet rocks with occasional glaucophane and rocks rich in albite with subordinate quartz, amphibole and/or garnet. The amphibolites and allied rocks are mainly found between mica-schists and phengite-gneisses. The occurrence of zonal amphiboles and of very narrow veins filled with a different metamorphic mineral assemblage, points to a polyphasic metamorphic history. The mineral assemblage of such a narrow vein is assumed to have originated within a relatively short time and to represent a stable association of approximately contemporaneous minerals.

The Mesozoic rocks mainly comprise metamorphic carbonate-bearing sediments and metamorphic ophiolites. These rocks inform us about the age of a large number of metamorphic minerals, since these minerals can only have been produced during metamorphism of Alpine age. A list of such minerals is given on p. 521. The occurrence of zonal amphiboles, the replacement of chloritoid by garnet and that of chloritoid and garnet by chlorite, point to polyphasic metamorphism.

Chapter V treats the chemical composition of the various groups of rocks. If the chemical composition of the rock-making minerals is approximately known, the chemical composition of a sample can be calculated from the mode. In this way a number of chemical compositions of samples was added to those obtained by chemical analysis.

A theoretical discussion of point counter analysis is given first. The

results are summarized on p. 530—531. In order to avoid correlation between the measurements it seems advisable to choose as the distance between the points, the diameter of the largest grains that occur in appreciable quantities, or any larger distance. *The theory that the grain size is irrelevant in modal analysis, is disproved.*

In chapter V 26 chemical analyses and 35 calculated analyses of rocks have been used to study the characteristic differences between the various groups by means of statistical methods. Differences in the chemical composition of both groups of rocks strongly suggest that the amphibolites did not derive from ophiolites. In view of their low potassium content it is highly improbable that the amphibolites represent a basic front of the phengite-gneisses at their boundaries with the mica-schists. Hence it is the author's opinion that the amphibolites, the mica-schists and the phengite-gneisses have no genetical relation whatsoever.

In chapter VI the results of the mineralogical, petrographical and chemical investigations are combined in order to arrive at a synthesis. The rocks of the northern Adula region are shown to have been influenced by *three successive phases of metamorphism of Alpine age*. Some rocks even show traces of pre-Alpine metamorphism. The first Alpine metamorphic phase produced, a. o., glaucophane, crossite, sodium-pyroxene, garnet, epidote and chloritoid. The second phase is characterized by the production of, a. o., blue-green amphibole, ferrohastingsite, garnet, albite, epidote and biotite. The third phase produced, a. o., actinolite, chlorite, green biotite, epidote, zoisite and albite. The existence of these three Alpine phases was proved by making use of the following phenomena: (a) the occurrence of armoured relics; (b) the difference between the mineral assemblages of the host-rock and of narrow veins originated during the metamorphism; (c) the zonal habit of amphiboles; (d) the frequency of occurrence of a number of mineral associations in a group of about 300 samples, a result of a quantitative investigation with the aid of an International Business Machines equipment.

The amphibolites and allied rocks seem to be metamorphosed mafic igneous rocks of Hercynian or older age. Scanty evidence suggests that the phengite-gneisses are the products of metamorphism of Hercynian igneous rocks. The fact that the amphibolites are nearly always found between mica-schists and phengite-gneisses might be explained by assuming a tectonical cause for this association.

In chapter VII some general aspects of the results obtained in the Adula region are discussed, as well as the bearing of these results on the geology and petrology of the southern part of the Swiss Alps. The tentative conclusion is reached that the Alpine glaucophane was produced simultaneously with the chloritoid and stilpnomelane of E. Niggli's different zones, whereas the blue-green amphibole may be contemporaneous with the kyanite and the coarse-flaky brown biotite of Alpine age. Consequently the typical minerals of Niggli's zones may be of different age. The distribution pattern of glaucophane in the Penninides and their immediate surroundings shows a conspicuous gap south of the Gotthard Massif, more or less coinciding with the area of brown biotite of Alpine age. This phenomenon may be connected with the occurrence of post-Palaeozoic granitoid rocks in the regions of Bellinzona and Tessin.

Maps showing the distribution of glaucophane and lawsonite in Europe and in the rest of the world are added, as well as a bibliography giving localities of these minerals.

SAMENVATTING

Het noordelijke gedeelte van het zogenaamde Adula dekblad was het onderwerp van geologische en petrografische onderzoeken. Dit gebied ligt in het zuidoosten van Zwitserland, ten zuiden van Ilanz, en ten noorden van het Lepontinische gebied, waar de onderbouw der Alpen ontsloten is, het diepste gedeelte der Penninische zone.

Men treft in dit gebied vier verschillende groepen van gesteenten aan, nl. phengietgneisen, glimmerschisten, amfibolieten en aanverwante gesteenten en mesozoische gesteenten, zowel van sedimentaire als van magmatische oorsprong. Het oorsprongsmateriaal der eerste drie groepen is vermoedelijk tenminste van Hercynische ouderdom.

Het gebied is uit drie tektonische eenheden opgebouwd, de Valserschuppen, de Fanellalappen en de Zervreilerlappen. Bij het onderzoek bleek duidelijk de belangrijke rol, die overschuivingen in dit gebied hebben gespeeld; de isoklinale plooijing is van veel minder belang dan de intensieve verschubbing.

De mineralen die in rekspleten voorkomen en de gesteentevormende mineralen, zoals chloritoid, chloromelaniet, ferririjke phengiet, granaat, crosiet, glaukofaan en ferrohastingsiet, worden afzonderlijk besproken in hoofdstuk III. Een volledige lijst van deze mineralen is te vinden op bladz. 451.

De verschillende gesteentegroepen worden afzonderlijk beschreven in hoofdstuk IV; de belangrijkste resultaten zijn aan het eind van iedere afdeling samengevat.

De phengietgneisen hebben een blastische structuur, hetgeen wijst op een volledige rekristallisatie van het oorspronkelijke granitoïde materiaal. De veldspaten vertonen in het algemeen geen omzettingsverschijnselen. De grote orthoklaasporfyroklasten, die in sommige handstukken voorkomen, worden als relictien van een vroeger mineraalgezelschap beschouwd.

De glimmerschisten vertonen de invloed van verschillende fasen van metamorfose, zoals bijvoorbeeld blijkt uit de chloritisering van granaat, de vervanging van chloritoid door dwarsmuscoviet, het voorkomen van verschillende generaties van amfibool en van muscovietblaadjes met zomen van biotiet.

De mineralogische samenstelling der amfibolieten en aanverwante gesteenten wisselt sterk. Tot deze laatstgenoemde gesteenten behoren o.a. granaathoudende natriumpyroxeen-gesteenten, soms met glaukofaan, en albietrijke gesteenten met een weinig kwarts, amfibool en/of granaat. De amfibolieten worden hoofdzakelijk gevonden tussen glimmerschisten en phengietgneisen. Het voorkomen van zonaire amfibolen en van aders, die gevuld zijn met een afwijkend mineraalgezelschap van metamorfe oorsprong, wijst op een meerfasige metamorfose. De conclusie schijnt gerechtvaardigd, dat de mineralen in zulk een uiterst smalle ader binnen een betrekkelijk korte tijd zijn ontstaan en een stabiel mineraalgezelschap vertegenwoordigen.

De mesozoische gesteenten zijn voornamelijk metamorfe carbonaathoudende sedimenten en metamorfe ophiolieten. De waarnemingen aan deze groep van gesteenten leveren gegevens op over de ouderdom van een groot aantal metamorfe mineralen, aangezien de in deze gesteenten voorkomende metamorfe

mineralen uitsluitend van Alpiene ouderdom kunnen zijn. Een lijst van dergelijke mineralen is te vinden op bladz. 521. Het voorkomen van zonaire amfibolen, de vervanging van chloritoid door granaat en de vervanging van granaat en chloritoid door chloriet wijzen ook voor deze gesteentegroep op een meerfasige metamorfose.

Hoofdstuk V behandelt de chemische samenstelling der verschillende gesteentegroepen. Men kan de chemische samenstelling van een gesteente berekenen uit de modus, indien de chemische samenstelling der gesteentevormende mineralen voldoende nauwkeurig bekend is. Op deze wijze werd de chemische samenstelling van een aantal gesteenten berekend. In dit verband werd eerst een theoretische studie gemaakt van de zogenaamde "point counter" analyse. Een engelse samenvatting der belangrijkste resultaten hiervan is te vinden op bladz. 530—531. Teneinde correlatie tussen de meetresultaten te vermijden dient men de afstand tussen de punten niet kleiner te kiezen dan de doorsnede van de grootste kristallen, welke in aanmerkelijke hoeveelheden voorkomen. *De theorie, dat bij modale analyse de korrelgrootte van geen belang is, wordt weerlegd.*

Een aantal van 26 chemische analyses en 35 berekende analyses werd gebruikt voor een statistisch onderzoek naar karakteristieke verschillen tussen de diverse gesteentegroepen. Uit verschillen in chemische samenstelling tussen beide gesteentegroepen blijkt, dat de amfibolieten naar alle waarschijnlijkheid niet uit ophiolieten zijn ontstaan. Gezien hun lage kaliumgehalte is het zeer onwaarschijnlijk, dat de amfibolieten een basisch front van de phengietgneisen aan de grens met de glimmerschisten vertegenwoordigen. De schrijver is derhalve van mening dat er geen genetisch verband bestaat tussen de phengietgneisen, de glimmerschisten en de amfibolieten.

De resultaten van het mineralogische, het chemische en het petrografische onderzoek worden in hoofdstuk VI met elkaar in verband gebracht om tot een synthese te geraken. De gesteenten van het noordelijke Adula-gebied blijken de invloed van *drie opeenvolgende metamorfe fasen van Alpiene ouderdom* te hebben ondergaan. Enkele gesteenten vertonen zelfs sporen van prealpiene metamorfose. De eerste Alpiene metamorfe fase is o.a. gekenmerkt door de vorming van de mineralen glaukofaan, crossiet, natriumpyroxeen, granaat, epidoot en chloritoid, de tweede fase o.a. door het optreden van blauwgroene amfibool, ferrohastingsiet, granaat, albiet, epidoot en biotiet, de derde fase o.a. door de vorming van aktinoliet, chloriet, groene biotiet, epidoot, zoisiet en albiet.

Het bestaan van deze drie metamorfe fasen van Alpiene ouderdom werd aangetoond met behulp van de navolgende verschijnselen: 1) het voorkomen van gepantserde relieten; 2) de verschillen tussen de mineraalgezelschappen in nauwe, tijdens de metamorfose ontstane aders en in de doorsneden gesteenten; 3) de opeenvolging van verschillende amfiboolsoorten in zonaire kristallen; en 4) de veelvuldigheid van het voorkomen van een aantal mineraalassociaties in een groep van ongeveer 300 gesteentemonsters, welke bepaald werd met behulp van een I. B. M. machine. De amfibolieten en aanverwante gesteenten schijnen metamorfe basische stollingsgesteenten van tenminste Hercynische ouderdom te zijn. Er zijn slechts enkele aanwijzingen te vinden over de oorsprong der phengietgneisen, welke aanduiden dat deze gesteenten mogelijk uit Hercynische stollingsgesteenten zijn ontstaan. Het voorkomen van de amfibolieten tussen glimmerschisten en phengietgneisen zou een tektonische oorzaak kunnen hebben.

In hoofdstuk VII worden enige algemene aspecten van de in het Adulagebied verkregen resultaten besproken, zowel als de betekenis van deze resultaten voor de geologie en petrologie van de zuidelijke Zwitserse Alpen. Deze bespreking leidt tot de voorlopige conclusie, dat de Alpiene glaukofaan gelijktijdig gevormd werd met de chloritoid en de stilpnomelaan van de door E. Niggli onderscheiden mineraalzones. Anderzijds is de blauwgroene amfibool waarschijnlijk in dezelfde periode gevormd als de distheen en de grofbladerige bruine biotiet van Alpiene ouderdom. Hieruit volgt, dat de kenmerkende mineralen van E. Niggli's zones waarschijnlijk van verschillende ouderdom zijn. De verbreiding van glaukofaan in de Penniniden en hun onmiddellijke omgeving vertoont een opvallend hiaat ten zuiden van het Gotthard massief, in een gebied dat min of meer samenvalt met het verbreidingsgebied van de Alpiene bruine biotiet. Dit verschijnsel staat waarschijnlijk in verband met het optreden van postpalaeozoische granitoïde gesteenten in het gebied van Bellinzona en Tessin.

De verbreiding van glaukofaan en lawsoniet in Europa en in de rest van de wereld is op een aantal kaarten aangegeven, terwijl eveneens een bibliografie van vindplaatsen van deze mineralen wordt gegeven.

ZUSAMMENFASSUNG

In der vorliegenden Arbeit handelt es sich um geologische und petrographische Untersuchungen in der nördlichen Adula. Das Gebiet liegt in der südöstlichen Schweiz, südlich Ilanz, am Rande der lepontinischen Gneisregion, d.h. des Unterbaues des alpinen Orogens.

Im untersuchten Gebiet trifft man vier Gesteinsgruppen an, nämlich Phengitgneise, Glimmerschiefer, Amphibolite und verwandte Gesteine, und mesozoische Gesteine, u.a. metamorphe karbonathaltige Sedimente und metamorphe Ophiolite. Das Ausgangsmaterial der erstgenannten drei Gruppen ist wahrscheinlich schon voralpin vorhanden gewesen.

Das Gebiet wird von drei tektonischen Einheiten gebildet, den Valser-schuppen, dem Fanellalappen und dem Zervreilerlappen. Überschiebungen spielten eine wichtige Rolle. Isoklinalfaltung ist für die Grossstruktur weniger wichtig als die intensive Verschuppung.

Die Kluftmineralien und die gesteinsbildenden Mineralien, u.a. Chloritoid, Chloromelanit, ferrireicher Phengit, Granat, Crossit, Glaukophan und Ferrohastingsit, wurden im dritten Kapitel beschrieben. Für eine vollständige Liste dieser Mineralien siehe S. 451.

Kapitel IV gibt die petrographische Beschreibung. Die unterschiedenen Gesteinsgruppen sind getrennt beschrieben worden und jeder Abschnitt wird von einer Zusammenfassung abgeschlossen.

Die Phengitgneise zeigen ein blastisches Gefüge, das kaum granitische Züge aufweist. Die Feldspäte zeigen meistens keine Umwandlungsercheinungen. Vereinzelte Orthoklasporphyroklasten sind die einzigen Relikte eines älteren Mineralbestandes.

Die Glimmerschiefer zeigen die Spuren einer mehrphasigen Metamorphose, wie Chloritisierung von Granaten, Umwandlung von Chloritoid in Quermuskovit, und das Vorkommen von mehreren Amphibolgenerationen und von Muskoviten, die stellenweise von Biotit umsäumt werden.

Die Amphibolite und verwandte Gesteine zeigen einen wechselnden Mineralbestand. Die letztgenannten Gesteine sind u.a. granatführende Natrium-pyroxenfelse, stellenweise mit Glaukophan, und quarzführende Albitfelse mit vereinzelt Granaten oder Amphibolkristallen. Die Feldbeobachtungen zeigen, dass die Amphibolite sich immer dort auffinden lassen, wo Phengitgneise und Glimmerschiefer zusammentreffen. Das Vorkommen zonarer Amphibole und schmalster, von einer abweichenden metamorphen Mineralgesellschaft gefüllter Adern entspricht einer mehrphasigen Metamorphose. Es wird angenommen, dass die Mineralparagenese einer solchen Ader innerhalb verhältnismässig kurzer Zeit entstanden ist und einer Gleichgewichtsparagenese entspricht.

Die mesozoischen Gesteine sind meistens metamorphe karbonathaltige Sedimente und metamorphe Ophiolite. Die Mineralgesellschaft dieser Gesteine lässt uns die alpin entstandenen metamorphen Mineralien erkennen. Eine Liste solcher Mineralien findet man auf S. 521. Granatisierung von Chloritoid und Chloritisierung von Granat und Chloritoid sowie das Vorkommen zonarer Amphibole weisen auf eine polyphasische Metamorphose hin.

Die chemische Zusammensetzung der Gesteinsgruppen wird in Kapitel V diskutiert. Die chemische Zusammensetzung lässt sich aus der mineralogischen errechnen, wenn die chemische Zusammensetzung der gesteinsbildenden Mineralien annähernd bekannt ist. Deshalb geht eine theoretische Diskussion der "Point Counter" Methode voraus, deren wichtigste Resultate man auf S. 530—531 findet. Zur Vermeidung von Korrelation zwischen den Messergebnissen sollte man die Distanz zwischen den Punkten nicht kleiner wählen als der Diameter der grössten in beträchtlichen Mengen auftretenden Körner. *Die Theorie, dass die Korngrösse bei der modalen Analyse ohne Bedeutung ist, wurde widerlegt.*

Mittels statistischer Methoden wurden die charakteristischen Unterschiede der verschiedenen Gesteinsgruppen anhand 26 chemischer und 35 errechneter Gesteinsanalysen untersucht. Die Amphibolite sind sehr wahrscheinlich keine Ophiolitderivate, wie durch Differenzen in Zusammensetzung zwischen den beiden Gesteinsgruppen gezeigt wird. Hinsichtlich ihres niedrigen Kaliumgehalts sind die Amphibolite ebensowenig als eine basische Randzone der Phengitgneise am Rande der Glimmerschiefer zu deuten. Nach der Auffassung des Verfassers sind die Phengitgneise, die Glimmerschiefer und die Amphibolite genetisch unabhängige Gesteine.

Kapitel VI fasst die mineralogischen, chemischen und petrographischen Ergebnisse zusammen, und versucht eine Synthese. Es ergibt sich, dass die Gesteine der nördlichen Adula *drei sukzessive metamorphe Phasen alpinen Alters* erfahren haben. Einige Gesteine zeigen ausserdem Spuren einer vor-alpinen Metamorphose. Die erste Phase der alpinen Metamorphose ist u.a. gekennzeichnet durch die Bildung von Glaukophan, Crossit, Natriumpyroxen, Granat, Epidot und Chloritoid. Die zweite Phase zeigt Bildung von blaugrünem Amphibol, Ferrohastingsit, Granat, Albit, Epidot und Biotit. Die dritte Phase ist gekennzeichnet durch Aktinolit, Chlorit, grünen Biotit, Epidot, Zoisit und Albit.

Zur Ermittlung der Existenz dieser drei verschiedenen Phasen der alpinen Metamorphose wurden die folgenden Phänomene benutzt: 1) das Vorkommen gepanzerter Relikte; 2) die Unterschiede zwischen dem Mineralbestand der Hauptmasse eines Gesteins und demjenigen schmäler, während der Metamorphose entstandener Adern; 3) die Reihenfolge verschiedener Amphibolarten in zonaren Kristallen; und 4) die Frequenz des Vorkommens einer Anzahl Mineralgesellschaften in einer Gruppe von etwa 300 Handstücken, ermittelt mit einer I. B. M. Machien.

In den Amphiboliten scheinen metamorphe herzynische oder ältere basische Eruptivgesteine vorzuliegen. Es gibt nur wenig Hinweise für den Ursprung der Phengitgneise. Sie sind aber wahrscheinlich aus herzynischen Eruptivgesteinen entstanden. Das Vorkommen der Amphibolite zwischen Phengitgneisen und Glimmerschiefern könnte auf eine tektonische Ursache zurückzuführen sein.

In Kapitel VII werden einige allgemeine Aspekte der Untersuchungsergebnisse, sowie die Bedeutung dieser Ergebnisse für die Geologie und Petrologie der südlichen Schweizer Alpen diskutiert. Diese Diskussion führt zur vorläufigen Folgerung, dass der alpine Glaukophan ungefähr gleichzeitig gebildet wurde wie der Chloritoid und der Stilpnomelan der von E. Niggli unterschiedenen Mineralzonen. Andererseits ist der blaugrüne Amphibol wahrscheinlich gleichalterig mit dem Disthen und dem grobblättrigen braunen Biotit alpinen Alters. Es gibt also wahrscheinlich einen Altersunterschied zwischen den Mineralien der Nigglishen Zonen. Die Verbreitung des Glaukophans in

den Penniniden und ihrer nächsten Umgebung zeigt eine auffällige Lücke südlich des Gotthardmassivs, die ungefähr zusammenfällt mit der Verbreitung des grobblättrigen braunen alpinen Biotits. Diese Erscheinung steht wahrscheinlich in genetischem Zusammenhang mit dem Auftreten postpaläozoischer granitoider Gesteine in der Gegend von Bellinzona und Tessin.

Die Verbreitung der glaukophanartigen Amphibole und des Lawsonits in Europe und in den anderen Weltteilen ist auf Karten dargestellt. Eine Bibliographie von Fundorten dieser Mineralien ist beigegeben.

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The references are listed according to the alphabetical order of the countries, in which the localities are situated. For each country a separate list of glaucophane (s.l.) and lawsonite literature is given (the name glaucophane in this list is meant to denote glaucophane proper, crossite and gastaldite). The author will be indebted for additional information concerning the locations of glaucophane, crossite, gastaldite and lawsonite. Therefore, the readers are kindly requested to send comments and additional information to the author, c/o Prof. Dr W. P. de Roever, Geological Institute, Nieuwe Prinsengracht 130, Amsterdam-C, Holland.

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 Horaisan, near Mitsuishi, Prov. Hidaka.
 Honshu Chichibu district, Pref. Saitama.
 Novimoto, Pref. Aichi.
 Futamiura near Yamada city, Pref. Mie.
 Shikoku Otakisan near Tokushima city, Pref. Tokushima.
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Ryukyu islands

Yaeyama island.

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MEXICO

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Table 37

Rock-samples referred to in the text

Sample number	Rock-name	coord.	alt.	locality
LP 1	garnetiferous epidote-amphibolite	7322—1626	1580	Chäserli
LP 2	garnetiferous mica-schist	7325—1629	1400	road Vals-Zervreila
LP 4	garnetiferous epidote-amphibolite	7330—1631	1420	road to Peil
LP 4a	cf. LP 4			
LP 5	epidote-amphibolite	7307—1605	2100	Alp Ampervreila
LP 12	chlorite-mica-schist	7306—1606	2040	Section DD
LP 13	mica-schist	7307—1605	2075	Section DD
LP 14	amphibole-bearing mica-schist	7307—1604	2090	Section DD
LP 15	garnetiferous stromatitic amphibolite	7307—1604	2091	Section DD
LP 17	phengitic augen gneiss	7307—1603	2100	Section DD
LP 18	garnetiferous epidote-amphibolite	7307—1603	2120	Section DD
LP 18a	cf. LP 18			
LP 19	epidote-chlorite-schist	7307—1603	2120	Section DD
LP 24	garnet-epidote-amphibolite	7313—1593	2377	Ampervreilasee
LP 28	epidote-amphibolite	7326—1598	2450	Schwarzsee
LP 32	garnetiferous mica-schist	7293—1602	1740	Zervreila-dam site
LP 38a	garnetiferous mica-schist	7296—1605	1720	road Vals-Zervreila
LP 39	epidote-amphibole-schist	7301—1609	1680	road Vals-Zervreila
LP 41	albite-amphibolite	7304—1612	1660	road Vals-Zervreila
LP 42	phengite-gneiss	7313—1585	2908	Guralätschhorn
LP 43	„Metatekt“ (quartz-albite-rock)	7315—1585	2750	Guralätschhorn
LP 44a	sodium-pyroxene amphibolite	7315—1585	2755	Guralätschhorn
LP 44b	cf. LP 44a			
LP 47	phengite-gneiss	7312—1603	2200	Ampervreilabach
LP 56	albite-mica-schist	7328—1604	2450	Hohbühl
LP 58	phengite-gneiss	7333—1605	2300	E of Hohbühl
LP 62	phengite-gneiss	7287—1598	1800	Zervreila dam
LP 65	garnetiferous mica-schist	7301—1588	2160	Guralätschbach
LP 72	garnetiferous mica-schist	7300—1607	1815	road Vals-Zervreila along Calvariberg
LP 76	quartzite	7309—1613	1730	waterdrift entrance Ampervreila
LP 79	phengite-gneiss	7290—1597	1905	Zervreila dam
LP 81	garnetiferous mica-schist	7346—1598	1725	Peil
LP 82	„pseudodiorite“ of Peil	7346—1598	1725	Peil
LP 83	„pseudodiorite“ of Peil	7347—1599	1710	Peil
LP 84	phengite-gneiss	7348—1600	1700	Peil
LP 85	garnetiferous mica-schist	7348—1602	1700	Peil
LP 87	chlorite-epidote-amphibolite	7323—1597	2540	Schwarzsee
LP 88	epidote-ferrohastingsite-rock	7326—1604	2400	Hohbühl
LP 95	folded mica-schist	7330—1615	2210	Heinisch Stafel ridge
LP 96	„Metatekt“ (quartz-albite-rock)	7331—1616	2160	Heinisch Stafel ridge
LP 99	marble with red mica	7302—1588	2225	Heinisch Stafel
LP 100	phengite-gneiss	7309—1617	1595	road Vals-Zervreila
LP 102	amphibole-mica-schist	7314—1622	1560	tunnel section road Vals-Zervreila
LP 105	phengitic augen gneiss	7314—1622	1555	tunnel section road Vals-Zervreila
LP 112	garnet-amphibolite	7316—1624	1550	tunnel section road Vals-Zervreila
LP 116	„pseudodiorite“ of Peil	7346—1598	1730	Peil
LP 116b	cf. LP 116			
LP 121	„pseudodiorite“ of Peil	7346—1598	1730	Peil
LP 125	phengite-gneiss	7330—1624	1810	Marchegga

Sample number	Rock-name	coord.	alt.	locality
LP 134	garnetiferous mica-schist	—	1730	waterdrift Amper-vreila-Peil
LP 135	biotite-phengite-gneiss	—	1730	waterdrift Amper-vreila-Peil
LP 136	biotite-mica-schist	—	1730	waterdrift Amper-vreila-Peil
LP 143	albite-mica-schist	—	1730	waterdrift Amper-vreila-Peil
LP 152	phengite-gneiss	7305—1606	2010	Section DD
LP 164	amphibole-schist	7309—1594	2500	Hennensädel
LP 168	mica-schist	7319—1627	1490	road Vals-Zervreila
LP 170	amphibole-bearing schist	7317—1625	1520	road Vals-Zervreila
LP 182	amphibole-bearing mica-schist	7299—1607	1720	road Vals-Zervreila
LP 184	amphibole-epidote-mica-schist	7301—1609	1690	road Vals-Zervreila
LP 189	blastomylonite	7302—1611	1690	road Vals-Zervreila
LP 204	albite-chlorite-schist	7331—1616	2120	Heinisch Stafel
LP 223	mica-schist	7291—1601	1760	Zervreila plant
LP 227	garnetiferous epidote-amphibolite	7290—1601	1780	Zervreila plant
LP 234	phengite-dolomite	7291—1588	2245	Finstererbach
LP 243	garnetiferous amphibolite	7293—1581	2540	Weissgrätli
LP 247	garnet-amphibolite	—	2450	SW Hohbühl
LP 276	chloritoid- and garnet-bearing quartzite	7306—1592	2560	Hennensädel
LP 276a	garnet-bearing calciferous mica-schist	7306—1592	2560	Hennensädel
LP 278	stromatitic garnetiferous albite-amphibolite, „pseudodiorite” of Peil	7346—1598	1730	Peil
LP 280	garnetiferous sodium-pyroxene rock	7346—1598	1730	Peil
LP 281	sodium-pyroxene amphibolite	7348—1598	1730	Peil
LP 282	sodium-pyroxene rock with garnet	7348—1598	1730	Peil
LP 283	stromatitic albite-amphibolite	7348—1598	1730	Peil
LP 284	garnetiferous sodium-pyroxene rock	7348—1598	1730	Peil
LP 295	garnetiferous chloromelanite rock	7312—1603	2210	Ampervreila
LP 297	phengite ribbon gneiss	7334—1637	1360	Peilerschlucht
LP 299	phengite-gneiss	outside the region		Lentatal
LP 325	mica-schist	7348—1600	1720	Peil
LP 335	phengite-gneiss	7348—1600	1720	Peil
LP 375	garnetiferous albite-mica-schist	7314—1622	1600	road Vals-Zervreila
LP 380	amphibolite	733 —1615	2180	Heinisch Stafel ridge
LP 381	amphibolite	cf. LP 380		
LP 382	amphibolite	cf. LP 380		
LP 383	amphibolite	cf. LP 380		
LP 384	„Metatekt” (quartz-albite rock)	cf. LP 380		
LP 385	amphibolite	cf. LP 380		
LP 386	amphibolite	cf. LP 380		
LP 387	glaucofane-bearing amphibolite	cf. LP 380		
LP 388	glaucofane-bearing amphibolite	cf. LP 380		
LP 389	glaucofane-bearing amphibolite	cf. LP 380		
LP 397	glaucofane-bearing amphibolite	cf. LP 380		
LP 434	cf. LP 295			
LP 435	garnetiferous sodium-pyroxene amphibolite	7321—1608	2300	Selvasee
LP 460	phengite-gneiss	7279—1587	1950	Zervreilasee
LP 479	epidote-glaucofane-schist	7285—1624	2510	Fuorcla de Puozas
LP 497	garnet-amphibolite	7291—1601	1760	Zervreila plant
LP 502	phengite-gneiss	7315—1422	2200	Val Calanca

Sample number	Rock-name	coord.	alt.	locality
LP 522	garnetiferous sodium-pyroxene rock	7302—1425	1360	Val Calanca, Pian d'Asc
LP 523	cf. LP 522			
LP 531	phengitic augen gneiss	734 —148	1800	pass of San Bernardino
LP 534	phengitic augen gneiss	7333—1511	2040	pass of San Bernardino
LP 555	ophiolite	7342—1657	1400	Tomülbach
M 50c	phengite-gneiss of contact zone			Zervreila dam
M 51	„Metatekt" (quartz-albite-rock)	7287—1601	1850	Zervreila dam
M 56	amphibole-bearing mica-schist	7287—1601	1850	Zervreila dam
M 57	„Metatekt" (quartz-albite-rock)	7287—1601	1850	Zervreila dam
M 60	biotite-muscovite-schist	7287—1601	1850	Zervreila dam
M 62	phengite-gneiss			Zervreila dam
M 67	chlorite-mica-schist			
M 70	chlorite-mica-schist			
M 74e	phengite-gneiss			Zervreila dam
M 114	phengite-gneiss			
M 164	phengite-gneiss			Zervreila dam
M 248	garnetiferous amphibolite with sodium-pyroxene			Zervreila dam
M 305	phengite-gneiss			
M 371	phengite-gneiss			Kanaltal
M 373	mica-schist			
M 395	garnetiferous amphibolite			
M 431	garnetiferous sodium-pyroxene rock			Ampervreila
M 484	phengite-gneiss			Lentatal
T 10	garnetiferous mica-schist	7300—1618	1990	Pedanatsch
T 28	amphibole-bearing mica-schist	7299—1613	1870	Pedanatsch
T 37	mica-schist	7288—1604	2000	Frunt
T 116	glaucophane-epidote-schist	7317—1637	1740	Stafelti
T 207	albite-epidote-biotite-schist	7308—1632	1945	Moos
T 413	garnetiferous mica-schist	7289—1605	1990	Frunt
T 432	„Riesenaugengneis"	7291—1635	2570	E of the Faltschönhorn
A 1	phengite-gneiss	7288—1599	1740	Zervreila dam
A 5	amphibole-bearing albite-mica-schist	7287—1601	1850	Zervreila dam
A 15	amphibole-biotite-schist	7287—1601	1850	Zervreila dam
A 17	mica-schist	7287—1601	1850	Zervreila dam
A 19	mica-schist	7287—1601	1850	Zervreila dam
A 22	albite-mica-schist	7287—1601	1850	Zervreila dam
A 24	amphibole-schist	7287—1601	1850	Zervreila dam
A 29	muscovite-schist	7287—1601	1850	Zervreila dam
B 1	granitic phengite-gneiss	7288—1599	1740	Zervreila dam
B 6	cf. B 1			
L 5	garnetiferous albite-mica-schist	7255—1588	1870	Aetzmäder
St 2/200	garnetiferous mica-schist	7307—1609	1730	waterdrift Zervreila
St 2/900	garnetiferous mica-schist	7301—1604	1730	-Ampervreila
St 2/1400	garnetiferous mica-schist	7297—1602	1730	waterdrift Zervreila
St 3/600	albite-mica-schist	7305—1608	1730	-Ampervreila
St 3/900	phengite-gneiss	7308—1607	1730	waterdrift Amper-
St 3/2000	mica-schist	7328—1604	1730	vreila-Peil
				waterdrift Amper-
				vreila-Peil