PETROGRAPHICAL AND GEOLOGICAL INVESTIGATIONS IN THE MERDARET-LAC CROP REGION
(Belledonne Massif, France)

BY

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CONTENTS

PREFACE

Petrographical and geological investigations in the Belledonne Massif by students of Leyden University started in 1946 under the direction of Prof. Dr. E. Niggli. The results obtained in the years up to 1955 are laid down in one thesis (E. den Tex, 1950), in several papers and in a number of unpublished reports. After 1955 the investigations were continued under Prof. Dr. W. P. de Roever.

The present study concerns that part of the Belledonne Massif indicated by a heavy line on Fig. 6. The southern part of this region is also covered by an unpublished report by Mr. A. J. A. Janse. His results were used in the preparation of the map.

The field work was carried out mainly during the summer months of 1953, 1954 and 1956.

I take the opportunity to thank all those who guided my steps during the study, who were helpful with advice or discussion during the preparation of the thesis, and who provided me with X-ray powder diagrams, chemical analyses, and thin sections. The photographs of thin sections and hand specimens were made by Mr. J. Hoogendoorn; Mr. J. Bult has drawn the map and the text figures.

I am grateful to Mr. D. F. Taylor who read the greater part of the English text, and to Mrs. C. B. B. Palm-Lazard who corrected the French summary.

CHAPTER 1

THE BELLEDONNE MASSIF: AN INTRODUCTION

GEOGRAPHICAL OUTLINES

The Belledonne Massif (taken in its geological sense) is part of the arc of Hercynian massifs forming the NW, W and SW boundary of the Pennine Alps (Fig. 1). The western boundary of the Belledonne Massif (Fig. 2) is largely formed by the broad valley of the Isère. On the other side of this valley we find the mountain range of the Grande Chartreuse, belonging to the outermost arc of the Alpine orogene. The eastern boundary of the Belledonne Massif is less clearly expressed by the topography. Despite its relative

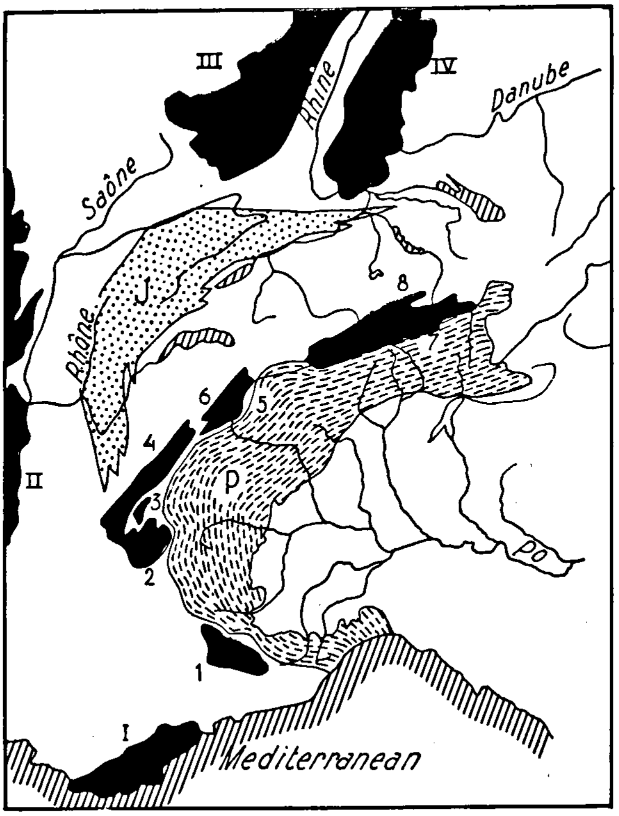


Fig. 1. The Hercynian massifs of the Alps and their surroundings (indicated in black): 1 Argentera-Mercantour; 2 Pelvoux; 3 Grandes Rousses; 4 Belledonne; 5 Mt. Blanc; 6 Aiguilles Rouges; 7 Gotthard; 8 Aar; I Esterel; II Central Plateau; III Vosges; IV Black Forest. J = Jura Mountains; P = Pennine Alps.

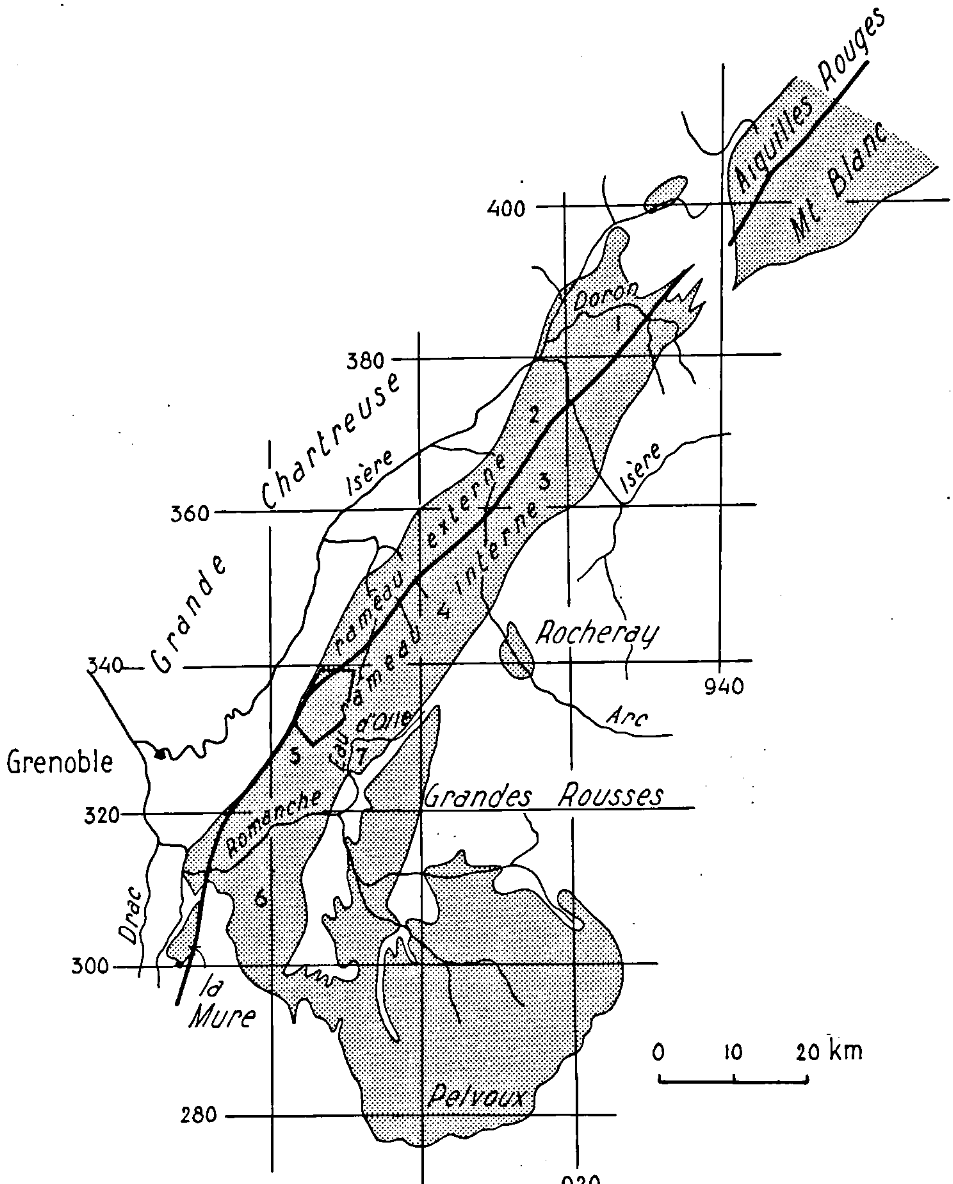


Fig. 2. Situation of the Belledonne Massif. The median syncline is indicated by a heavy line. Geographers distinguish a number of smaller massifs: 1 Beaufortin; 2 Grand Arc; 3 Lauzière; 4 Sept-Laux or Allevard; 5 Belledonne (*sensu stricto*); 6 Taillefer; 7 Rochers Rissiou. The national ("Lambert")grid, on which the author has based all references, is drawn in as 20-km squares. The mapped area is indicated by a drawn line.

narrowness, the massif is of a rather complex morphological structure. It is perhaps best described as a system of separate NNE trending chains, situated closely together, en echelon, and connected by a few short transverse chains. The highest summits, frequently consisting of amphibolite, reach an altitude of just below 3000 m. On the western side there is a great difference in altitude between the central chains and the Isère valley (alt. 250 m above sea-level). Strong erosion, however, is prohibited by a low range of Liassic hills ("collines liasiques") lying between these two morphological units. Greater influence in this respect has to be ascribed to the rivers which have cut their way through the massif: Romanche, Arc, Doron and Isère (in its transverse part). The Bréda and Eau d'Olle rivers, tributaries of Isère and Romanche respectively, play also an important part in the erosion of the area.

As the Belledonne chains are among the first obstacles in the way of the western winds, the western part of the massif is rather humid. The frequent occurrence of cloud-banks at altitudes of 1800—2000 m was a real hindrance to the field work. In spite of the rather heavy precipitation the glaciers are slowly diminishing in size. From a number of small glaciers indicated on the older maps of this region only two are left: those of Freydane (868-255) [1]) and Gleyzin (988-402). The numerous torrents descending from the ranges drain the melt-water of the extensive snow-fields. Although the eastern part of the massif is less humid, temporary torrents carrying melt-water in spring often create deep gullies in the slopes (e. g. in the Romanche and Eau d'Olle valleys). The many lakes of various sizes, usually situated in the higher parts, are — if not artificial — due to glacial erosion.

The natural timber-line is situated at an altitude of about 1700 m. On the eastern side deforestation has locally caused the development of badlands in the Lias. The spruce-fir is most frequent, fir and larch are rarer; in the lower parts of the valleys beautiful deciduous woods may be found. The alps above the timber-line are chiefly browsed by sheep; cattle-breeding, in former times an important means of subsistence, seems to have become less profitable nowadays. Some arable land is found in the valleys and particularly on the Liassic hills. On the lower slopes of the latter, bordering the Isère, vineyards occur. Both crops and wine are for private use only. The forests are of greater economical importance.

The industrial activity is chiefly based on the easily available water-power. In the Isère valley paper-mills are situated (plenty of timber and water of good quality available!); in the gloomy canyon of the Romanche large electro-metallurgical factories cause a perpetual smoke-screen. In many places electricity is generated by the E. D. F. (Electricité de France), while numerous new projects are being studied. In former times mining was also important. Iron ore was mined intermittently in many places, particularly in the neighbourhood of Allevard (Fig. 6), where a blast-furnace is working up to this day, be it with imported ore. At the end of the 18th century the silver-mines of Chalanches, near Allemont (Fig. 6), were the richest of France. Small quantities of coal are mined for the exclusive use of the above-mentioned paper-mills (e. g. Mine de la Boutière, abandoned, 854-320 and Mine de Chenevrey, producing, 830-286). Rather important coal-mines are situated in the small La

[1]) References are based on the Lambert grid, see Fig. 2 and 5.

Mure Massif (Fig. 6). Further details about mining in this region will be given in the thesis of Mr. P. J. M. Ypma of Leyden University.

Compared to other parts of the Alps the Belledonne Massif is of little importance from a touristic point of view. This fact, however, makes it all the more attractive for those who are not keen to encounter the blessings of modern tourist industry. Uriage (Fig. 6) and Allevard are watering-places of some national renown. Near to the former town an aerial railway has been constructed, leading to the summit of the Chamrousse (2253 m altitude). An interesting road with beautiful views over the Isère valley connects the two competing towns. The passes of Glandon and Croix-de-Fer are frequented by touring-cars. Beautiful trips can be made everywhere in the massif. For alpinism the possibilities are restricted, the only ascent of interest being that of the "Trois Pics de Belledonne".

As almost everywhere in France there is a gradual migration of the population to the towns. Especially on the higher alps many chalets (here sometimes named "habert") lie in ruins, while many pastures have been converted into forests.

TOPOGRAPHICAL AND GEOLOGICAL MAPS; SYSTEM OF REFERENCE

It seems convenient to give a brief review of the various maps covering the Belledonne Massif. The official topographical maps are published by the "Institut Géographique National".

The modern topographical map is oriented upon true North. The repartition of the 1:20.000 and 1:50.000 sheets is given in Fig. 3. Those available in 1956 are marked with a black corner. It will be seen that the author, having particularly studied part of the western border of the massif, did not have these modern sheets at his disposal. In some cases older 1:20.000 contour-maps, frequently entitled "Plans Directeurs de l'Armée", could be used, in other cases aerial photographs were employed. Other maps used comprise a provisional topographic map of part of the central chains, published in 1946 for touristic purposes (drawn line on Fig. 3), and a rough sketch published by the "Syndicat d'Initiative de Theys", which gives many local names (dashed line on Fig. 3). The 1:20.000 sheet XXXIII-34 (Domène), covering the area mapped by the author, has been published after the completion of the field work. The geological map has been redrawn on this sheet. Finally, the numbers of the well-known Michelin road-maps relating to the region are indicated in Fig. 4.

Most geological maps of the region are still based upon the obsolete 1:80.000 hachure-maps, which often date from the end of the 19th century. The repartition of the sheets is shown in Fig. 4. The area in which we are particularly interested is covered by sheets 178 (Grenoble) and 179 (St. Jean-de-Maurienne). New geological maps based on the modern 1:50.000 sheets are in preparation. For a general review of the whole massif the 1:320.000 sheets may be used. The intermediate 1:200.000 map, showing contours instead of hachures, has not been used for geological purposes. There are, however, two other maps on that scale, viz. those of L. Moret (1929) and F. Hermann (1937), covering Savoy and the Western Alps, respectively (Fig. 4). None of the maps mentioned gives special attention to the metamorphic rocks, as has for example been done by F. Corbin and N. Oulianoff in their beautiful 1:20.000 map of the Mt. Blanc Massif.

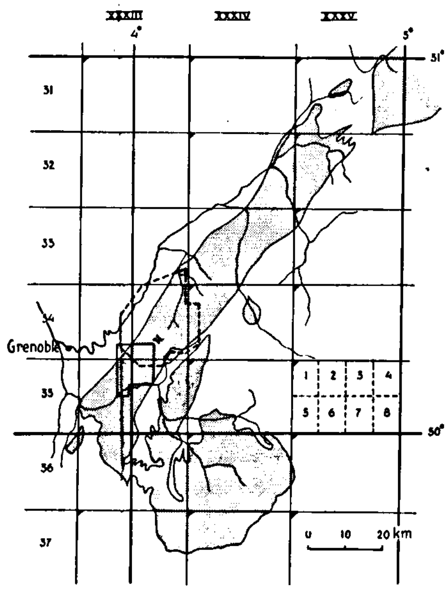


Fig. 3. Situation of the Belledonne Massif with indication of (French!) longitude and latitude, and of the modern 1: 20.000 and 1: 50.000 sheets of the Institut Géographique National. The same division is used for both maps. The subdivision of the former is shown in one sheet. Two other maps referred to in the text are drawn in. Sheets available in 1956 are indicated by a black corner.

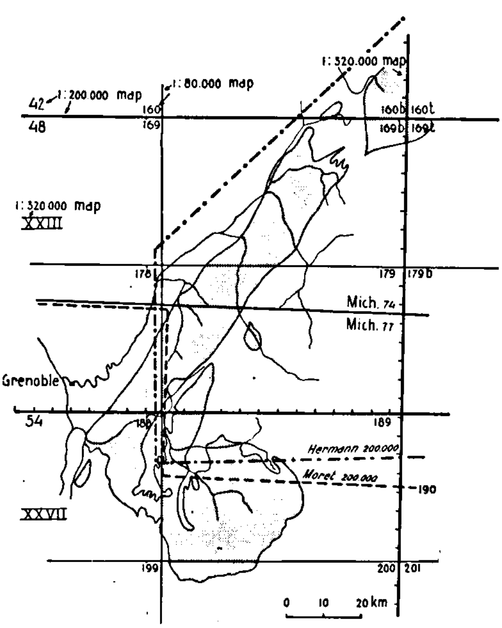


Fig. 4. Situation of the Belledonne Massif with indication of the 1: 80.000, 1: 200.000 and 1: 320.000 sheets of the older hachure maps, on which most geological maps are still based. Hermann 200.000, Moret 200.000: other geological maps, published in 1937 and 1929, respectively, see References. Mich. 74, 77: sheets of touristic Michelin road-map.

The modern maps indicated in Fig. 3 show a grid, the "Quadrillage Kilométrique Projection Lambert III Zone Sud". In the area considered the direction of grid North is 2°.85 E. In Fig. 2 this grid has been drawn as 20-km squares, in Fig. 6 as 10-km squares. The grid will be used throughout the present work to give references of localities. On the geological map the grid is shown as 1-km squares. In giving the co-ordinates the first figure of the grid number is omitted — which in the region considered gives no ambiguity —, while tenths of kilometres are added. To facilitate the readings a reference card is included with the map. Fig. 5 shows the way it should be used.

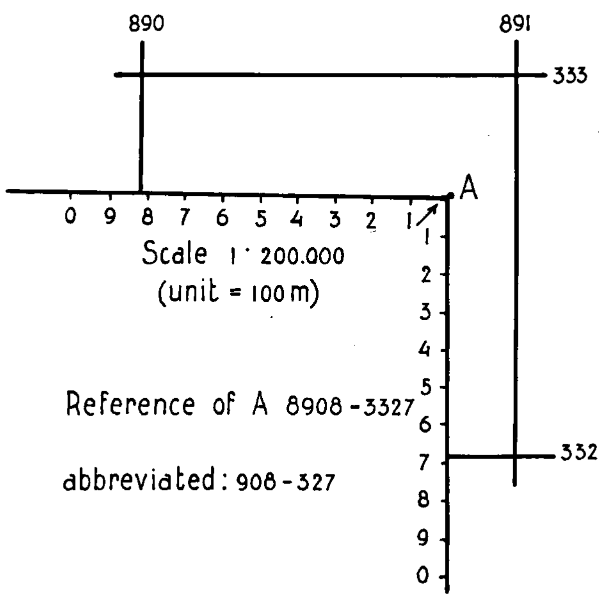
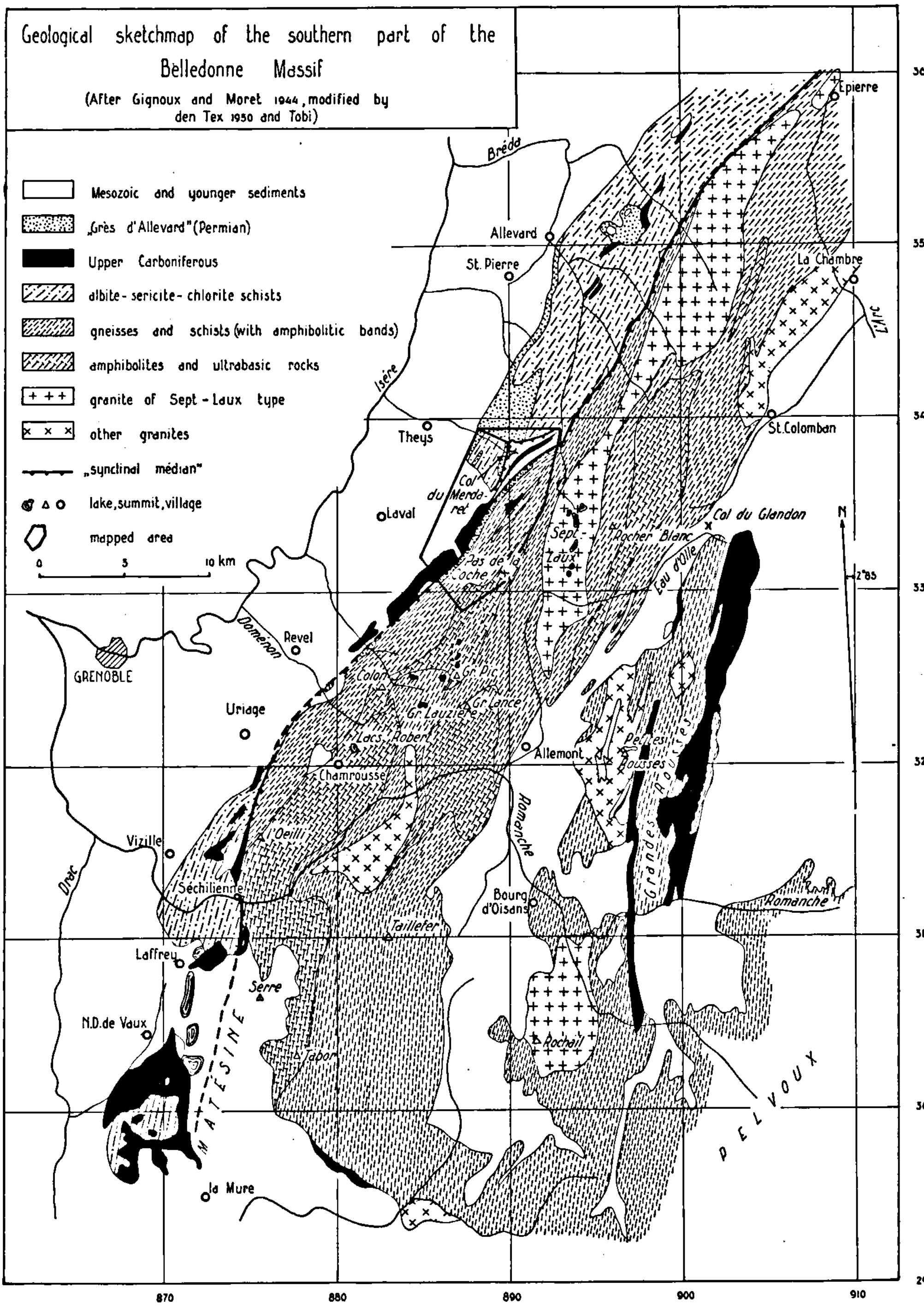


Fig. 5. The use of the reference card included with the geological map.

THE GEOLOGICAL FORMATIONS (cf. Fig. 6)

The following brief introduction is based chiefly upon the existing 1:80.000 geological maps (particularly sheets 178 and 179) and upon the excellent book of M. Gignoux and L. Moret (1952). Some additional remarks are based upon later publications or own observations.

The Belledonne Massif consists mainly of mica-schists, amphibolites and granites with subordinate Palaeozoic and Mesozoic rocks. On the whole, amphibolitic rocks seem to be more important than in the other Hercynian Massifs of the Western Alps. The strikes in the various formations are roughly parallel to the general trend of the massif; the dips are often steeply eastward or vertical. P. Lory (1925) was the first to divide the massif into a "rameau externe" (external zone) and a "rameau interne" (internal zone), as far as the Alpine structure is concerned corresponding with the Aiguilles Rouges and Mt. Blanc Massifs, respectively (Fig. 2). They are separated by a tightly compressed "synclinal médian" (median syncline) which locally contains both



Geological sketchmap of the southern part of the Belledonne Massif
(After Gignoux and Moret 1944, modified by den Tex 1950 and Tobi)
Mesozoic and younger sediments
„Grès d'Allevard" (Permian)
Upper Carboniferous
albite-sericite-chlorite schists
gneisses and schists (with amphibolitic bands)
amphibolites and ultrabasic rocks
granite of Sept-Laux type
other granites
„synclinal médian"
lake, summit, village
mapped area
0
5
10 km
Epierre
Brédá
Allevard
St. Pierre
La Chambre
L'Arc
Isère
Theys
St. Colomban
Col du Merdaret
Laval
Sept-Laux
Rocher Blanc
Col du Glandon
N
Pas de la Coche
Eau d'Olle
Doménon
Revel
GRENOBLE
Colon
Gr. Pic
Gr. Lance
Gr. Lauzière
Uriage
Lacs Robert
Allemont
Chamrousse
Rousses
Grandes Rousses
Romanche
l'Oeilly
Vizille
Drac
Séchilienne
Bourg d'Oisans
Taillefer
Laffrey
Serre
N.D. de Vaux
MATÉSINE
Tabor
Rochail
PELVOUX
La Mure
360
350
340
330
320
310
300
290
870
880
890
900
910

Fig. 6.

Permo-Carboniferous and Mesozoic sediments, but is usually only marked by the occasional presence of lenses of Triassic cavernous limestone.

During the Hercynian and Alpine orogenies, the crystalline schists seem to have moved mainly as rigid blocks. Part of the sedimentary cover glided down by gravity from the rising blocks, the main glide-plane being situated in the gypsiferous layers of the Upper Triassic. Thus all Pre-Tertiary sediments, those of Carboniferous and Permian age not excepted, are found either as a comparatively little folded cover on the blocks, or in a more or less vertical position between them.

A detailed study of the crystalline schists meets with great problems because of the very complex geological history of the region. Recently, a stratigraphy of the crystalline schists of the Belledonne Massif has been proposed by P. and Cl. Bordet (1956). This stratigraphy is partly based upon the present megascopical appearance of the rocks. According to the present author, however, this appearance is often largely determined by retrograde metamorphism of Hercynian and Alpine age. A further discussion of the problems involved would be confusing rather than clarifying if taken up in this brief introduction.

R. Michel and P. Berthet (1958) have divided the crystalline schists of the section of the Romanche valley into the "Groupe de Vizille", the "Groupe de Séchilienne" and the "Groupe de l'Aveyna". These groups correspond roughly to those distinguished by the auhtor in the Merdaret-Lac Crop region.

1. *Amphibolites and related rocks*

A comparatively large part of the internal zone is built up by amphibolites. These rocks consist essentially of plagioclase and amphibole and usually show an alternation of light- and dark-coloured bands. Dioritic or gabbroic parts (with diallage) are rarer; these may be associated with ultrabasic rocks (serpentinites, hornblendites) occurring as lenses or small masses within the amphibolite formations. The largest of these masses are found in the neighbourhood of the Lacs Robert (814—207) and in the Taillefer Massif (Fig. 2, massif 6). In a thesis for Leyden University (E. den Tex 1950) the petrography of the former region was dealt with elaborately, with a review of the work previously done.

In the Merdaret-Lac Crop region the mountain-range from the Sommet Colomb to the sharp-dented crest in the Pleynet valley consists of amphibolites (see map). Incidentally, we may mention that a large part of this chain — between the Sommet Colomb and the Pas de la Coche — is indicated on the official geological map as consisting of mica-schists and gneisses. In reality, we are dealing here with the same zone of amphibolitic rocks as was described by den Tex in his above-mentioned thesis. Ultrabasic rocks, however, are of far rarer occurrence. Throughout the present work this zone of amphibolitic rocks is designated as "Ferrouillet amphibolites".

2. *Schists and gneisses*

On the official geological maps the schists and gneisses are not treated in any detail. Sometimes all are mapped as one group (e. g. on sheet 178), sometimes two groups are distinguished, viz. mica-schists and gneisses (e. g. on sheet 179).

The *external zone* consists mainly of albite-sericite-chlorite-schists, in which the albite has the porphyroblastic habit so frequently found in this kind of rock. In the present study rocks of this type, which are only rarely found in the internal zone, are designated as "St. Hugon schists".

In the *internal zone* the rocks may show a higher degree of metamorphism, while the formations are of a less uniform character. They are usually banded, and consist of mica-schists with occasional bands of amphibolite. Within the mapped area, rocks of this type have been designated as "Lac Crop formation". A special problem is offered by the chloritic rocks which occur all over the massif and which have often been interpreted as weakly metamorphosed sediments. Those occurring within the mapped area are all held by the author to be retrograde-metamorphic representatives of the Lac Crop formation and the Ferrouillet amphibolites.

3. *Granites*

The granites of the Belledonne Massif may be divided roughly in two types. The central granite of the southern part of the massif is called "Sept-Laux granite" after the region where it is best exposed. It is mainly a rather light-coloured granodiorite, often distinctly schistose (in French "protogine"). It has been the subject of petrographical studies by Prof. Dr. E. Niggli and a team of Leyden university from 1949 till 1953. Two short papers about the intrusive character of acid dykes in this region have been published (E. Niggli 1952, 1953); a general report of the work done, especially in the petrochemical field, is being prepared by H. Koning. The age of this granite is assumed to be Hercynian; it was probably not yet exposed during the Upper Carboniferous. According to P. Bordet the same granite is found in the western part of the Grandes Rousses; this opinion has been adopted in Fig. 6.

The granitic masses that occur for example in the northern part of the Grandes Rousses and on the slopes above St. Colomban-des-Villards appear to be less uniform. They consist mainly of a rather dark granodiorite with large megacrysts of potash feldspar; part of it is amphibole-bearing. A large part of these masses must have been exposed during Triassic or even Upper Carboniferous times: a comparatively flat erosion surface is found to be overlain by Triassic sediments in the Grandes Rousses and the northern part of the Belledonne, and locally — in the Beaufortin (Cl. Bordet 1957) — by Upper Carboniferous sediments.

4. *Upper Carboniferous ("Houiller")*

The oldest sediments dated with fossils belong to the Upper Carboniferous. The greater part of the occurrences is found in the external zone and in the tightly compressed median syncline.

In the external zone conglomerates predominate in most occurrences. They form steeply dipping beds a few tens of metres thick, roughly parallel to the schistosity of the adjoining crystalline schists. Plant remains may be found in the black pelitic rocks accompanying the conglomerates. Determinable imprints, however, are very rare due to tectonic deformation. The occurrences have usually been considered as compressed synclines. A fair example is given by Fig. 32.

In the median syncline black slates are far more important than conglomerates. These slates occur together with Mesozoic rocks, and may even be intermingled with them in a complicated manner. The Carboniferous sediments are only found where the syncline is rather broad, as for example near Cevins (215-740) and from the Col du Merdaret southward. In this direction the sediments gradually occupy a broader zone and contain an increasing number of coal seams. The sediments can best be studied in the La Mure Massif (Fig. 2), where the only important coal-mines of the region are situated. Numerous fossil plants are found here, indicating a Westphalian D to Stephanian A age (A. Bouroz 1952). The flora is well preserved because the folding is less intensive than in the median syncline proper due to the plunge of the external zone.

In the internal zone the Upper Carboniferous sediments build mainly small, almost horizontal, caps on some summits of the central ranges, at an altitude of about 2700 m. Evidently, these almost undisturbed remnants roughly indicate the land surface during the Upper Carboniferous. These sediments and their fossils were described by L. Moret (1945, Gignoux & Moret 1952); they are similar to those of the La Mure Massif. In the Beaufortin a similar cap of Carboniferous conglomerate covers granite (330-910). The angular unconformity between the Upper Carboniferous and the crystalline schists is clearly demonstrated by these caps. It was first noted near Chalanches (868-223) by Héricard de Thury (1803), who, however, thought the sediments to be Mesozoic. On the cross-sections of the Belledonne and Grandes Rousses Massifs by Ch. Lory (1881) they occur with their correct age. According to B. G. Escher (1911) this was the first time that mention was made of such an unconformity in the Western Alps. Nowadays only loose blocks of Upper Carboniferous are encountered at the locality described by De Thury. The unconformity is best studied near the summits of the Grande Lauzière (850-238) and the Rochers Rouges (864-250).

All sediments are continental. The arenaceous and pelitic rocks probably were deposited in long and narrow basins, while the conglomerates might represent alluvial fans. The conglomerates probably occur at various levels in this formation and do not necessarily represent a basal conglomerate.

In the Grandes Rousses Massif the Upper Carboniferous covers a large area. In its northern part thick masses of lava (mostly rhyodacite) are found, in its southern part coal is being mined. The volcanic complex has been the subject of a recent publication (Lameyre 1957). In a later section (p. 258) we will see that Carboniferous volcanism has played a part in the Belledonne Massif as well.

5. *Permian ("Grès d'Allevard")*

The "Grès d'Allevard" are continental deposits occurring over a limited area in the western part of the Belledonne Massif. They reach from the "Grand Collet" (970-510) in the North to the slopes above Revel (795-245) in the South. They have their greatest thickness in the section of the "Grand Rocher" (912-403) described by P. Gidon (1950). The lower part of this section, about 100 m in thickness, consists of conglomerates, grey micaceous sandstones and dark-grey pelites, with a few beds of black dolomite. The upper part, at least 100 m in thickness, consists chiefly of purple-red pelites. The appearance of red beds in the upper part probably points to a change in climate. In a fine-grained grey sandstone in the lower part P. Gidon (op. cit.) found an imprint of *Calamites cisti* Brogn. indicative of a Carboniferous or Lower Permian age. Some years later the present author found imprints of *Cordaites* and *(?)Pseudovoltzia* in similar sandstones in the immediate vicinity. The joint occurrence of these fossils points to a Lower Permian age (P. Corsin and A. C. Tobi, 1954).

Formerly the Grès d'Allevard were thought to be of Upper Permian or even Triassic age. This opinion was chiefly based upon the description by P. Lory (1895) of an angular unconformity between the Upper Carboniferous and the Grès d'Allevard: a tightly compressed syncline of Upper Carboniferous sediments was said to be flanked by schists and overlain by nearly horizontal beds of Grès d'Allevard. P. Gidon has tried to reconcile the stratigraphical and the palaeontological evidence by assuming the lowermost part of the Permian (the Autunian) to be absent. Yet, the Grès d'Allevard and the Upper Carboniferous sediments may resemble each other closely in type of sediment and in degree of dynamic metamorphism. Re-examination of this unconformity at the localities mentioned by P. Lory seemed therefore desirable. At one of these (Pierre Herse, 1240 m, Fig. 41, 42) no Upper Carboniferous sediments were found, at the other (Grand Collet) post-Permian movements are at least partly responsible for the present position of the sediments. No definite conclusion could be reached; this question will be treated more fully in a later section (p. 245, Fig. 39).

The Grès d'Allevard belonging to the internal zone differ slightly from those of the external zone: the micaceous or feldspathic sandstones are poorer in carbonates and richer in ilmenite and chlorite; the pelites are dark blue-purple instead of red.

6. *Triassic*

The Triassic can be divided roughly into three parts vaguely reminiscent of Buntsandstein, Muschelkalk and Keuper, respectively.

The lower part, represented by light coloured conglomerates and arkoses, is of little importance. It occurs chiefly in the neighbourhood of the eastern granitic masses, from which it has drawn the greater part of its material, for example grains of pink feldspar. The arkoses may also contain a pink jasper. It is an equivalent of the well known "jasper of St. Gervais" (near Chamonix) and characteristic for the Triassic. A conglomerate is also found in the La Mure Massif, where it covers Upper Carboniferous sandstones in angular unconformity.

The middle part consists of grey dolomites and white fetid limestones. Their extension is somewhat greater than that of the just mentioned arkoses and conglomerates. Yet, they are rather rare in the southern part of the Belledonne Massif, because the latter has generally been eroded below the Triassic erosion surface. The dolomites were divided by P. Termier into "dolomie capucin" and "dolomie nankin". The difference is in alteration colour — brown or yellow, respectively —, caused by a different iron content.

The upper part consists of purple and green argillites, anhydrite, gypsum and cavernous limestone ("cargneule", "Rauhwacke", often wrongly described as dolomite, see discussion on p. 263). Spilitic flows occur between cavernous limestone and Lias (Gignoux and Moret) or intraformational below the cavernous limestone (at Chamrousse, den Tex).

Fossils are extremely rare. In the Belledonne Massif proper small shells were found for the first time in 1956 by Prof. Dr. W. P. de Roever near the Col du Merdaret in a partly cavernous limestone. Since this limestone was found in the intensely intermingled sediments of the median syncline, its exact stratigraphical position is not known. The shells were determined tentatively in the Geological Institute of Grenoble University as *Myophoria goldfussi* Alb. Similar shells have been reported from the La Mure region, where they occur together with diplopores. The total thickness of the sediments may reach a few tens of metres, but is usually far less.

This brief description of the Triassic would not be complete without mention being made of the peculiar role played by these sediments during the Alpine orogeny. The very incompetent gypsiferous layers of the Upper Triassic have acted as a detachment plane, causing, as everywhere else in the Alps, a pronounced disharmonic folding of the higher Mesozoic rocks with respect to the underlying crystalline schists. Thus Upper Triassic, Liassic and possible younger Mesozoic sediments were heaped up in large masses at both sides of the Belledonne and Grandes Rousses Massifs. Consequently, in these masses cavernous limestone and gypsum often occur intermingled with Liassic sediments in a complicated manner. For that reason the gypsiferous layers were formerly held to be intraformational in the Lias. The close association of the same Upper Triassic rocks with Upper Carboniferous slates in the median syncline (Col du Merdaret, p. 249) is of course also of tectonic origin, though less easy to understand.

The stratigraphical relation of the Triassic to the older sediments is seldom clearly visible. The angular unconformity between Upper Carboniferous and Triassic in the La Mure Massif has already been mentioned. Where Grès d'Allevard and Triassic are seen in non-tectonical contact they appear to be conformable, as for example N of Allevard, where both formations are reduced to a few metres.

7. *Jurassic*

The younger Mesozoic sediments found in the Belledonne Massif have a "schistes lustrés" ("Bündnerschiefer") facies. Apart from the Triassic dolomites and limestones, they represent the only truly marine sediments in this region. Fossils are rather rare, but point thus far to a Liassic age in most cases. Yet, surprises are possible: in the immediate vicinity of the region mapped by the present author, between Froges and La Pierre (SW of Theys), an ammonite of Bajocian age was described by F. Bernard and P. Lory (1936) in the "Lias Calcaire" of the official geological map. The author leaves a further study of this difficult subject to the stratigrapher and the palaeontologist. For the time being, it seems most convenient to maintain the traditional bipartition of the formation into "Lias Calcaire" and "Lias Schisteux".

The lower part of the formation ("Lias Calcaire") is characterized by a monotonous alternation of black limestone and black calcareous slate. The bands usually have a thickness of a few decimetres. The cleavage in the slates is often at angles to the stratification. Belemnites, broken and torn apart by tectonic movements, are not uncommon. The rocks are readily recognized by their light-grey alteration colour and their lime content: effervescence with cold diluted HCl, and occurrence of veins of white calcite.

The upper part ("Lias Schisteux") comprises black non-calcareous shales and slates often closely resembling those of the Upper Carboniferous. They are eroded more easily than the Lias Calcaire, which fact is largely responsible for the depression situated between the Belledonne range proper and the Liassic hills. The greater part of the Lias Schisteux is covered by moraines. The Aalenian, mapped separately on the St Jean-de-Maurienne and Grenoble sheets, is included in the Lias Schisteux by Gignoux & Moret (1952). It is characterized palaeontologically by some very rare ammonites and by *Posidonomya alpina* Gras. Locally it contains conglomerates with large rounded pebbles, for example at the Col de Barioz between Theys and Allevard and at Malbuisson near Theys.

8. *Quaternary*

During the Quaternary period the Belledonne Massif was modelled into its present form. As must have happened here several times before in geological history, erosion was far more important than deposition. As a general introduction into the morphology of the region the few remarks made in the geographical section may suffice.

As regards the sediments, most of them have a glacial origin. All moraine deposits belong to the "moraines internes" (Würm age or younger). The older of these (Würm and "Neo-Würm") are chiefly found between the Liassic hills and the Belledonne Massif proper, and on the western slopes of the latter. Their morphology is seldom clearly expressed by the topography. The subrecent and recent moraines occur chiefly in the higher valleys above the timber-line; here, the glacial morphology has not much changed since the time of their deposition. These moraines are easily confused with screes and other accumulations of rock-debris. In the opinion of the author, the morphology of the mountain-chains has changed considerably between the deposition of the older and the younger moraines; possible moraines of intermediate age will therefore be difficultly recognized as such. This is not in accordance with the views held by P. Lory, as will be shown in a later section (p. 268).

Alluvial sediments occur on the bottom of the larger valleys, where many tributaries have formed alluvial fans. Peat has sometimes been mapped separately; it is usually found in glacial corries.

SYNOPSIS OF THE GEOLOGICAL UNITS DISTINGUISHED WITHIN THE MAPPED AREA

In the following chapters our attention will be focussed on the Merdaret-Lac Crop region, a 1:20.000 map of which is inserted in this thesis. The situation of this area is shown in Fig. 2 and Fig. 6. The NW part belongs to the external zone, the SE part to the internal zone. In the area under consideration the median syncline is exceptionally broad and filled with sediments of different ages.

Because of the limited extent of the area it was often found useful to include observations made in other parts of the massif, sometimes because certain phenomena were better seen there, sometimes for comparison.

The rocks encountered in the mapped area will be treated in the following groups:

(1) The *St. Hugon schists,* albite-sericite-chlorite-schists which build up the external zone and are rare in the internal zone.

(2) The *Lac Crop formation* (banded mica-schists and amphibolites) and the *Ferrouillet amphibolites,* which occupy the greater part of the internal zone within the mapped area. Showing approximately the same degree of regional metamorphism, they are treated as one group in the petrographical section. They are often altered into greenschists by a younger, dynamic metamorphism. The intensity of this metamorphism is indicated on the map in a diagrammatical way.

(3) The *Upper Carboniferous* and *Permian sediments.* Within the mapped area the former are exclusively found in the median syncline, while the latter occur as a cover on the external zone and along the western boundary of the internal zone. Again, their petrographical similarity has lead to their treatment in one group.

(4) The *younger sediments.* The Triassic and Liassic sediments are found in the median syncline and W of the external zone. The Quaternary sediments are mostly of glacial origin.

CHAPTER II

THE ST. HUGON SCHISTS

FIELD OBSERVATIONS

The St. Hugon schists are mainly sericite-chlorite-schists and albite-sericite-chlorite-schists. They form a remarkably homogeneous formation comprising nearly all the crystalline schists of the external zone in the southern part of the Belledonne Massif. In the northern part the schists are essentially the same, but contain gradually more biotite in place of chlorite.

Within the mapped area the outcrops are scarce and poor, because the slopes W of the Col du Merdaret are wooded. Sections are provided by the Merdaret and Pierre Herse torrents (Fig. 40). The dips are generally steeply eastward (which direction is taken over as cleavage by the overlying Permian sediments!), but westward in the extreme western part. This is probably the same "A" structure as has been described by Ch. Lory (1874—75) in the Romanche canyon further to the South.

The formation is best studied outside the mapped area along the forest road from La-Chapelle-du-Bard to a small dam in the Bens torrent (St. Hugon valley). Here in a large road-cut at about 900 m altitude (980-528) the rocks have an unaltered appearance. Dips (stratification parallel to schistosity) are vertical or steeply eastward. The recently finished motor road to the Collet has also furnished numerous outcrops. Here the St. Hugon schists are far more weathered and have been subjected to surface creep.

When fresh, the St. Hugon schists show a green-silvery lustre on their schistosity planes, due to the presence of sericite and chlorite. Their iron-content colours them brown on weathering. Flakes of muscovite are sometimes visible; biotite has only once been found megascopically (B 650). Quartz is mainly visible in veins and lenses. The presence of albite porphyroblasts is the most characteristic feature of the St. Hugon schists. They are best seen in surfaces transverse to the schistosity as clear crystals a few mm in diameter. They are not evenly distributed throughout the formation, but are concentrated chiefly in more or less irregular zones which need not be parallel to the stratification. Their presence seems therefore not to be dictated merely by the chemical composition of the original sedimentary strata (cf. p. 208). On the scale of a hand specimen, however, the porphyroblasts prefer a micaceous environment. Where the stratification is visible it is found to be parallel to the schistosity. Part of the section in the St. Hugon valley is distinctly banded. The bands differ mainly in their content of micaceous matter. The whole formation is intensely folded; microfolding and false cleavage are of common occurrence. Where in the St. Hugon valley fold axes could be measured, their plunge was found to be rather steep (about 40°) in a NNE direction (according to Mr. N. A. L. Touwen of Leyden University). Black schists with irregular conchoidal schistosity planes, rarely covered with some graphite, are of mylonitic origin. Real graphite-schists have once been found, SE of the Grand Collet (980-494), as a band about 1 m in thickness (B 654). A sample that may represent an albitized granite-porphyry (B 752) was collected near the Col de Clarand (988-490, see p. 206). Veins are frequently met with; they are usually filled with quartz or with quartz and siderite with minor amounts of galena, sphalerite, chalcopyrite, etc. In the St. Hugon section a quartz-tourmaline vein was found.

In the internal zone the St. Hugon schists are rare. Within the mapped area they form a wedge-shaped zone in which the Col du Pipay is situated. As their NW boundary is a fault plane, they may have belonged to the same mass as the external zone. Their SE boundary against amphibolites of the Lac Crop formation has a dip of about 25° to the SE, parallel to the banding and schistosity in both formations. For all that is known this contact might be a fault, too. The schists are of the same type as those of the St. Hugon section, though on an average somewhat poorer in micaceous matter.

PETROGRAPHY

Under the microscope the main constituents of the St. Hugon schists appear to be quartz, sericite-muscovite and commonly also chlorite and albite. Biotite is seldom found in unaltered condition; as small remnants in chlorite it occurs in several samples. Wide-spread accessory constituents are apatite, zircon, tourmaline, rutile and ilmenite, while clinozoisite, orthite and magnetite are rare. Younger vein-filling and secondary minerals include quartz, chlorite, siderite, dolomite, (?) stilpnomelane, pyrite, limonite, leucoxene and rarely adularia, albite and calcite.

The most characteristic type of the St.Hugon schists shows undulating microfolded bands of sericite to muscovite and chlorite. These bands, which sometimes show false cleavage, alternate with quartz-rich granoblastic bands of a rather fine grain. Generally, the stratification and the schistosity are found to be parallel to one another. Many samples furthermore contain porphyroblasts of albite of up to 2 mm in diameter. Especially in the bands of sericite-muscovite and chlorite the albite porphyroblasts commonly show folded trends of minute inclusions parallel to the schistosity in the adjoining parts of the rock. In many instances, however, narrow rims of the porphyroblasts are devoid of these inclusions. In the quartz-rich bands the albite porphyroblasts usually contain many inclusions of quartz (Fig. 7 and 8). These are generally more or less flattened parallel to the schistosity and distinctly smaller in size than the quartz crystals occurring outside the porphyroblasts. Within porphyroblasts intersecting the boundaries of quartz-rich and micaceous layers, these boundaries can be followed by the distribution of the quartz inclusions.

Porphyroblasts of muscovite, showing microfolded trends of minute inclusions in a similar way, are of rather local occurrence. Contrary to the sericite-muscovite of the main body of the rock, they are hardly influenced by folding. A blastopsammitic structure was observed in the quartz-rich layers of one of the samples studied.

Many samples show the result of crushing. Prisms of apatite and tourmaline are often bent or broken and torn apart. The albite porphyroblasts then show cracks filled with chlorite, quartz, dolomite, siderite or pyrite. They may be replaced to a considerable extent by siderite or — rarely — by chlorite. Siderite, dolomite and pyrite are probably always secondary minerals, whether they occur in the way just mentioned or dispersed through the rock as small euhedral crystals. By the same movements which have caused the crushing the porphyroblasts are often turned, so that their trends of inclusions may take a position at angles to the schistosity. Under these circumstances an S-shaped structure in the trends might be — wrongly — interpreted as resulting from synkinematic growth of the porphyroblasts.

When crushing grades into mylonitization the porphyroblasts develop strain-shadows filled with secondary minerals, while quartz assumes the fine-grained recrystallization structure typical of such dynamic metamorphism. As some migration of quartz has now become possible, porphyroblasts with many quartz inclusions may lie in a quartz-free environment and vice versa.

The samples of St. Hugon schists mentioned in the following pages are listed in Table I, with indication of their localities.

TABLE I.

Samples of St. Hugon schists referred to in the text.

No.	Rock name	Locality	Grid refer.
B 56	Mylonitic sericite-schist	Prodin	001—560
B 131	Muscovite-schist	Pierre Herse	888—377
B 223	Albite-sericite-schist	„	886—377
B 224	Quartzitic part in B 225	„	„
B 225	Sericite-phyllite	„	„
B 278	Albite-muscovite-chlorite-schist	„	893—374
B 423	Crushed albite-sericite-chlorite-schist	Pipay	902—355.5
B 565	Albite-muscovite-chlorite-schist	Veyton	942—491
B 624	Crushed albite-sericite-schist	St. Hugon	982—527
B 625	Albite-sericite-chlorite-schist	„	981—527
B 630	Albite-sericite-schist	„	„
B 650	Sericite-biotite-schist	Veyton	971—484
B 654	Graphitic schist	Pierre du Carré	980—494
B 750	Quartz-tourmaline vein	St. Hugon	982—527
B 752	Albitized granite-porphyry (?)	Col de Clarand	987—490
T 257	Albite-sericite-chlorite-schist	Petit Collet	956—501

MINERALOGY

Quartz. Always present; mostly concentrated in bands or lenses with granoblastic texture. Its grain size is usually about 0.05—0.1 mm, in veins sometimes coarser, in crushed parts very finely recrystallized. The extinction is always more or less wavy. Inclusions with two phases occur, but not abundantly.

In one sample (B 224) a blastopsammitic structure was encountered. In some quartz crystals the boundaries of smaller well-rounded grains were recognized by the presence of minute inclusions.

Sericite-muscovite is always present. In places it may form 80 per cent of the rock (e. g. B 225). It is chiefly found as rather homogeneous microfolded bands. In these bands it is often difficult to recognize the individual flakes. Yet, interference colour and mode of extinction point to a coarser grain than that of common sericite. As an intermediate form between sericite and muscovite it has been indicated by both names. As muscovite cannot be distinguished from paragonite in thin section, X-ray powder diagrams were made of the mica-component of several samples. In all cases the result pointed unambiguously to pure muscovite.

Larger flakes of up to 0.2 mm in thickness may occur as porphyroblasts across the schistosity (e. g. in B 131). They have already been mentioned in the preceding section.

Chlorite. Nearly always present; less abundant than, and usually interlayered with, the sericite-muscovite. In most cases there is a marked pleochroism in green with low birefringence (abnormal blue or brown interference colours). At least part of it has originated from the alteration of biotite, as is sometimes shown by small remnants of this mineral within the chlorite flakes. The frequent occurrence of ore grains and of rutile — sometimes in sagenitic structure — points to the same origin.

In crushed rocks it occurs as a vein-filling mineral. Rarely it replaces porphyroblasts of albite (e. g. in B 131).

Biotite. Within the mapped area biotite occurs very rarely, for example where it is completely surrounded by one crystal of quartz or albite. In the neighbourhood of the Grand Collet chloritization has been less complete: in many of the larger chlorite flakes remnants of biotite are still to be found; at one locality in the Veyton valley (971-484) an almost unaltered albite-sericite-biotite-schist has been encountered, with flakes of biotite up to 0.2 mm in thickness (Fig. 12). In all cases the biotite is uniaxial and has a warm-brown colour. Inclusions of rutile in sagenitic structure are common.

Stilpnomelane (?) occurs not unfrequently in the neighbourhood of the ore minerals, together with muscovite or chlorite. Its identity has not been established with certainty: the flakes are too small to be separated or to see the absence of mottled extinction. Their brown colour is, however, more golden, and their pleochroism weaker than that of the biotite; neither is the mode of occurrence typical for the latter mineral.

Plagioclase. The plagioclase is almost exclusively present as porphyroblasts of albite. The distribution of these porphyroblasts is irregular: sometimes they are absent, while rarely they may form more than 60 per cent of the rock.

These porphyroblasts usually have a rounded form, though sometimes crystal forms may be recognized (Fig. 9, 11). Most of them have a diameter of ½—2 mm; they are found by preference in bands rich in micaceous matter. They are remarkably clear because of the rarity of the normal alteration products kaolinite and sericite. As these porphyroblasts occur in much the same way in similar low-grade metamorphic rocks all over the world, they seemed worthy of closer examination. Separate paragraphs will be devoted to their inclusions and their characteristic kind of twinning, with reference to other literature on the subject.

Measurements on the universal stage disclose a composition of 0—7 % An in nearly all cases. Sometimes the porphyroblasts show reversed zoning, which phenomenon is held to be typical of a metamorphic origin. In this case the rims of the crystals may reach the composition of oligoclase.

As has already been stated above (p. 199), the porphyroblasts have often been broken or rotated by movements which occurred after their growth. In one of the samples studied (B 278), undulatory extinction in a cluster of porphyroblasts points to a different mechanism. Here, some of these appear to have been bent parallel to a microfold with an amplitude of several mm. Obviously some folding must have occurred after their formation.

Only very rarely the albite occurs together with quartz in granoblastic structure or in large irregular crystals (e. g. in B 278), showing sericite as an alteration product. In these cases we have probably to do with altered lime-rich plagioclase or altered potash feldspar.

As a secondary mineral albite is occasionally found in veins.

Inclusions. The porphyroblasts usually show more or less dense clouds of dark "dust" (Fig. 9). On using the highest magnification the greater part of this dust is seen to consist of minute rutile needles (Fig. 10). They are recognized by their extreme refringence and birefringence (needles of 0.001 mm thickness already show lively interference colours!) and by their characteristic "elbow" and "arrowhead" twins. They are probably identical to the rutile described by A. Harker (1939, p. 161) as a newly formed mineral in hardly metamorphic slates. In similar rocks A. Gansser (1937, p. 393) has described albite porphyroblasts with S-shaped trains of rutile needles. In accordance with the explanation given by P. Niggli (1913) of this "helicitic" structure in chloritoid, he assumes that the porphyroblasts were rotated during their growth by slow movements along the schistosity planes. J. T. Singewald Jr (1932) arrives at a different conclusion in his description of the Wissahickon schists (Maryland). These schists are microfolded and show a distinctly higher degree of metamorphism than those described by Gansser. In fact, they closely resemble the St. Hugon schists. According to Singewald, the folded trends of inclusions found in the albite porphyroblasts of the Wissahickon schists are a relict structure of an older microfolding. Incidentally, the minute needles forming the trends are described as epidote by him as well as by later authors (a. o. A. Hietanen in E. Cloos and A. Hietanen, 1941).

The observations made by the present author in the St. Hugon schists correspond closely to those made by Singewald. In those parts of the rock which have not been subjected to later movements, the trends of inclusions are often seen to be arranged parallel to the microfolded structure of their surroundings. Obviously, here again the microfolding must be older than the formation of the porphyroblasts. In similar rocks in the La Mure Massif J. Sarrot-Reynaud (1958) described "sigmoid" trends of inclusions, implying a synkinematic growth of the porphyroblasts, in the sense of Gansser. These facts will be discussed in the concluding section of this chapter.

The porphyroblasts often show narrow rims devoid of inclusions. The photographs are not very representative in this respect. In Fig. 7 the rims are very narrow or absent, while the rim shown in Fig. 9 is exceptionally broad.

Other minute black inclusions, of irregular form and opaque even when studied with the highest magnification, are probably graphitic. They occur in the same manner in the adjoining rock. Mention should also be made of the well-rounded quartz inclusions that have been described in the preceding section.

In crushed parts of the rock the porphyroblasts may contain small flakes of chlorite and other secondary minerals. In this case a large quantity of

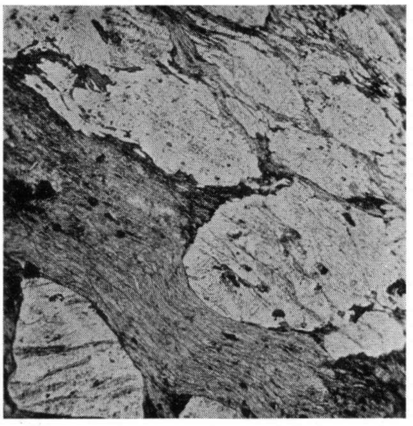


Fig. 7. St. Hugon schist with albite porphyroblasts. The quantity of the quartz inclusions within the porphyroblasts depends upon the quartz content of the layer in which the latter were formed. Sample B 630, plane-polarized light, 17 ×.

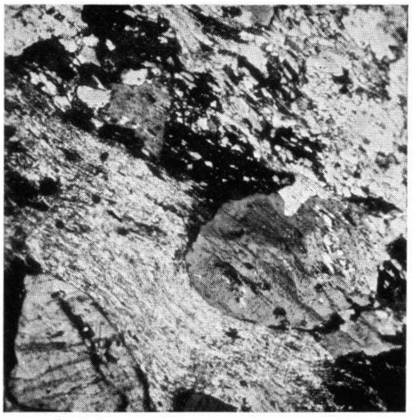


Fig. 8. Same as Fig. 7, crossed nicols.

Fig. 9. St. Hugon schist with albite porphyroblast showing a broad clear rim and a core with numerous rutile needles. The matrix consists of microfolded muscovite and chlorite. A string of green tourmaline prisms appears to be younger than the porphyroblast. Sample B 565, plane-polarized light, 30 ×.

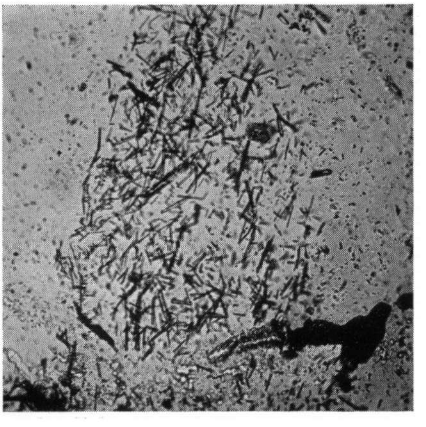


Fig. 10. Rutile needles in centre of albite porphyroblast. Same sample as Fig. 9, plane-polarized light, 175 ×.

liquid and two-phase inclusions may occur in much the same way as those so frequently found in quartz. They may be evenly distributed or arranged in zones. In the latter case the zones are often found to be roughly vertical to the schistosity in the adjoining rock (e. g. in B 423, B 625).

Twinning. In many regions of the world simple twins have been described in albite porphyroblasts. F. J. Turner (1951) describes the albite law as normal for albite in low-grade metamorphic schists. This is in agree-

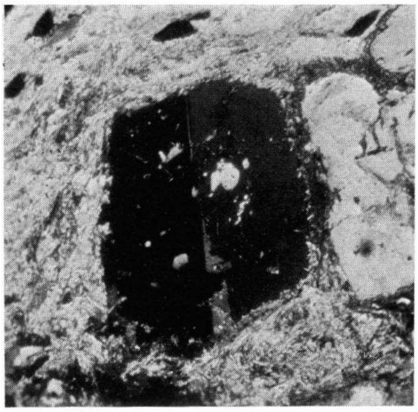


Fig. 11. Composite twinning in albite porphyroblast of the St. Hugon schists. The large individuals are twinned according to the complex albite-Carlsbad law. The wedge-shaped central lamella forms an albite twin with the left and a Carlsbad twin with the right individual. Sample B 223, crossed nicols, 50 ×.

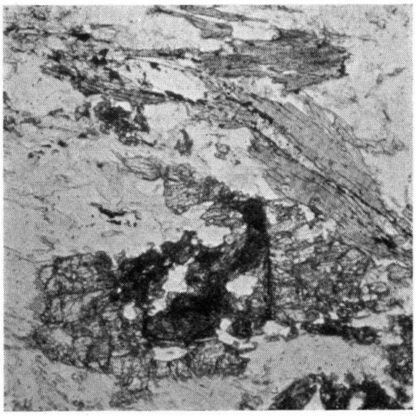


Fig. 12. Orthite (dark, in reality brown-red) and clinozoisite (lighter) in sericite-biotite-schist (St. Hugon schists). Sample B 650, plane-polarized light, 70 ×.

ment with the investigations of M. Gorai (1951). According to A. Hietanen (E. Cloos and A. Hietanen, 1941, p. 102), however, most twins of the albite porphyroblasts of the Wissahickon schists are Carlsbad twins. The existence of such twins in these rocks had previously been denied by J. T. Singewald Jr (1932). A. Gansser (1937) in his study of the Tambo overthrust-sheet of the Alps describes both types of twinning, with predominance of the albite law.

In the St. Hugon schists Carlsbad twins were described by S. E. Nicolet (1931), who measured them on the universal stage. Some twins studied in the same manner by the present author proved to be albite twins. After this confusing evidence it was decided to study the twinning of the porphyroblasts more thoroughly.

First it should be noted that it is impossible to determine the type of twinning without the aid of the universal stage. Because in albite n_α lies in, or nearly in, the plane (010) and is at the same time almost perpendicular to the Carlsbad twinning axis [001], there is little optical difference in the results of the albite and Carlsbad symmetry operations. Because of this similarity the extinctions of the Carlsbad twin are often nearly symmetrical in the zone ⊥ (010). If the (010) face is not exactly vertical it is even more difficult to distinguish between the two laws. For example, when the (010) face makes an angle of 80° with the thin section, the extinction angles of a Carlsbad twin differ less than 2° in 50 per cent of the cases, whereas those of an albite twin generally differ more than 2° in that position.

Even with the aid of the universal stage the distinction is not always easy. When the indicatrix axes of an albite twin are plotted on a stereographic (Wulff) net (1—1′ in Fig. 13), the approximate coincidence of the two axes n_α leaves two possibilities for the construction of the twinning axis (method of Berek). If the wrong one were chosen (that between the axes n_β 1 and n_β 1′), it would be easily confused with the twinning axis of the Carlsbad twin (situated between the axes n_β 1 and n_β 2 of Fig. 13). Fortunately, however, there are characteristic differences in the angles between corresponding indicatrix axes. It will be seen from Fig. 13 that the albite (1—1′) and the Carlsbad (1—2) twins differ in this respect chiefly in the angle between the axes n_α. The angles may also be read from the well-known graphs of A. Köhler (1942). For albite (0—10 % An) they are as follows:

	albite	Carlsbad	albite-Carlsbad
$n_\alpha \wedge n_\alpha$	0—2°	8—21°	8—23°
$n_\gamma \wedge n_\gamma$	25—36°	25—36°	3—5°

The procedure chosen by the author to determine the kind of twinning was based upon the "zone method" of A. Rittmann (1929). First the composition face was oriented perpendicular to the axis A 4 (corresponding to the outer east-west axis of the 5-axis stage). The (010) face is characterized by the elongation remaining negative on rotation around A 4 in the 45° position. Without a single exception, all plagioclase twins of the St. Hugon schists appeared to have (010) as composition face. If the composition face is now brought in a N—S position, the albite twin should remain invisible on turning about A 4, the Carlsbad twin not. Owing to the above-mentioned optical similarity of the twins and to the fact that the composition face need not always be exactly parallel to the (010) plane, the results were sometimes ambiguous. In those cases the axis n_α of one twin individual was brought in a position parallel to A 4. When the axes n_α of both individuals (nearly) coincided — as is the case with the albite twin — the whole twin remained dark on turning about A 4. As a final check of the method several twins were plotted and worked out completely on the stereographic net.

Both twin types appeared to be present, but the Carlsbad law was found to be far rarer than the albite law. Apart from these, simple twins according to the complex albite-Carlsbad law were encountered. These twins are easily overlooked, because the extinctions of the two individuals are nearly always situated at the same side of the composition face. Once recognized as a twin, their identification offers no difficulty for the same reason. On closer examination many twins appear to be composite in a remarkable way. They consist essentially of two individuals, but along their composition face one or — rarely — two thin lamellae or wedges of other extinction are found. In most cases, the larger individuals are twinned according to the albite-Carlsbad law, while the central lamella forms an albite twin with one individual and a Carlsbad twin with the other. Nevertheless, similar lamellae may also be found in cases where the larger individuals form an albite or Carlsbad twin.

Here they are less easily recognized, because the direction of the extinction is now similar to that of one of the larger individuals. Some examples of twinned porphyroblasts are given in Fig. 14. It will be seen that the trace of the composition face is often straight in the albite twin and somewhat curved in the Carlsbad twin. In rare cases the composition face of the latter does not follow the direction (010) at all, which gives rise to a curious pattern of twinning (Fig. 14g, h). It should be noted that these and following drawings of plagioclase twins are made from their appearance at the universal stage. In cases where the stage had to be inclined to make the twins visible, the crystal boundaries as seen in the inclined section will usually differ from those that would be seen if the crystal were cut normal to the composition face.

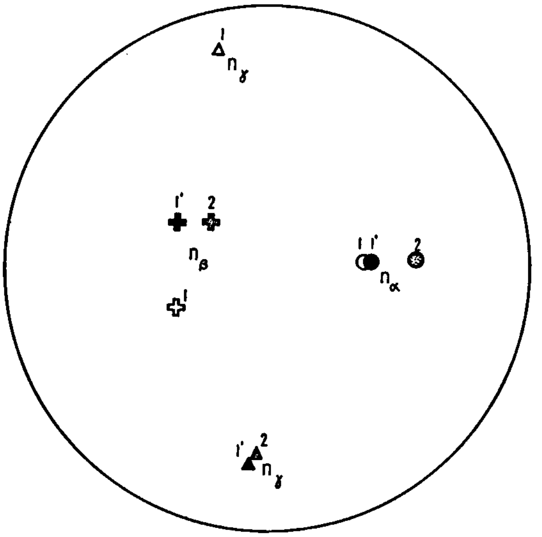


Fig. 13. Wulff net diagram showing the position of the axes n_α, n_β and n_γ of composite albite and Carlsbad twins (4 % An). Note the similar results of the albite (1—1′) and Carlsbad (1—2) symmetry operations.

The relative frequency of the types of twinning may vary considerably from one thin section to another. Usually a large majority of the porphyroblasts are untwinned. Lamellar twins are not common. Where present, they often do not continue over the whole length of a porphyroblast. Twins with (001) or (021) as composition face are not found. Most twins consist essentially of two individuals. Among these, the albite twin is most frequent, followed at some distance by the complex albite-Carlsbad twin; the Carlsbad law is of rare occurrence. In the albite-Carlsbad twins thin central lamellae or wedges occur in more than 50 per cent of the cases; in albite and Carlsbad twins they are rarely found. Two diagrams of thin sections with a comparatively large number of porphyroblasts may serve to give an idea of their mode of occurrence. The porphyroblasts are rendered in their proper position, though often somewhat rotated to show the twins. Fig. 15 is a normal case, with the exception of the lamellar albite twins, which usually are less numerous. Fig. 16 has been selected especially for its richness in complex albite-Carlsbad twins.

Obviously, examples as this are contrary to what would be expected in low-grade metamorphic rocks according to Turner and Gorai. Yet, the twinning differs from that found in igneous rocks in the rarity of lamellar twins and in the absence of twins according to (001) and (021).

P o t a s h f e l d s p a r is not found as a primary constituent. In one sample from the Col de Clarand megacrysts of albite up to 4 mm in length were found in a fine-grained granoblastic matrix (B 752). On megascopical examination, they differ from the albite porphyroblasts in their oblong and euhedral shape. In thin section they prove to consist entirely of albite with fine lamellar twinning, while smaller more or less euhedral albite crystals with complex twinning are enclosed. This mode of occurrence strongly suggests that we are dealing with large crystals of potash feldspar with enclosed plagioclase, which were both altered into albite after their formation. If this were true, the

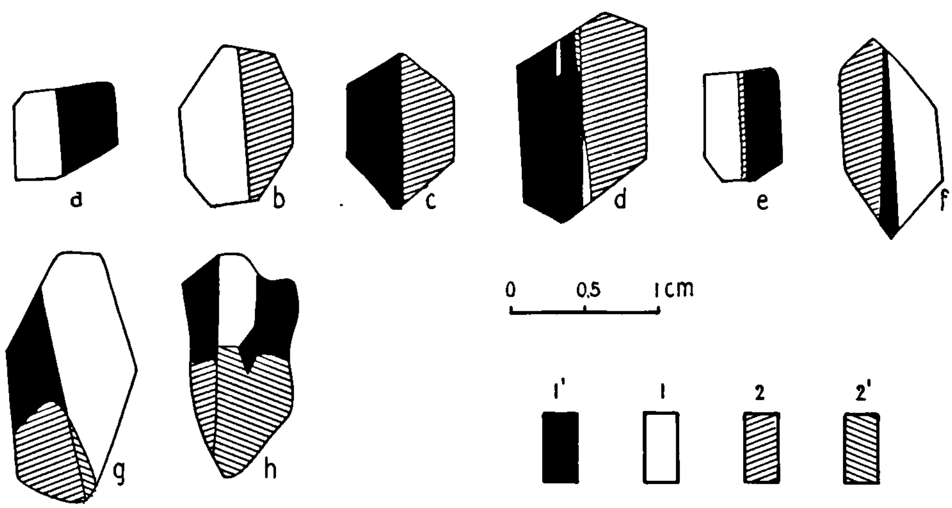


Fig. 14. Some twinned albite porphyroblasts of the St. Hugon schists. 1—1′ (or 2—2′) albite twin, 1—2 (or 1′—2′) Carlsbad twin, 1′—2 (or 1—2′) albite-Carlsbad twin. The Carlsbad composition face is often not parallel to (010), which fact gives rise to wedge-shaped individuals (d, f) or even to quite irregular patterns of twinning (g, h).

rock could be an albitized granite-porphyry. In any case, potash feldspar does not belong to the metamorphic mineral association of the St. Hugon schists.

As a hydrothermal mineral, adularia is of rare occurrence in younger tension joints.

A c c e s s o r i e s. Apatite is always present; it seems to have no preference for certain host minerals. The crystals are usually small, but may reach 0.1 mm in diameter. Rarely they occur in strings parallel to the schistosity. In a few cases hollow crystals were found.

Zircon is also very common. Though the larger crystals usually have a rounded form, sometimes square (110) prisms with small (100) faces may be recognized in basal sections. Pleochroic haloes are occasionally found in chlorite.

Tourmaline, though less frequent than apatite, is a rather characteristic

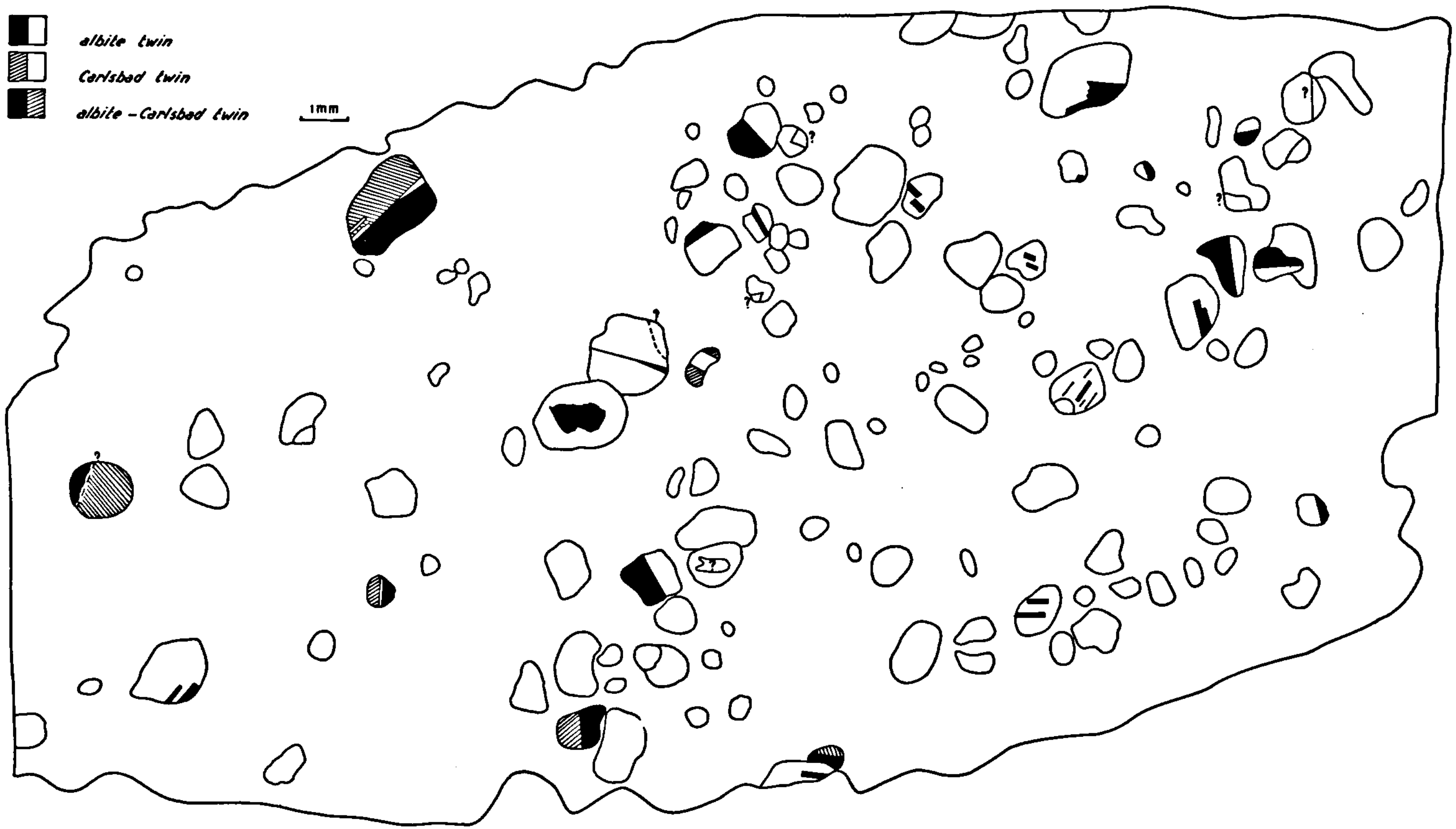


Fig. 15. Diagram of a thin section, indicating mode of occurrence and twinning of the albite porphyroblasts. St. Hugon schists (Sample T 257).

constituent of the St. Hugon schists. Larger crystals often show zoning: core greenish- or pale-blue, rim brown- or olive-green. Fig. 9 shows a string of tourmaline prisms which must be younger than the formation of the porphyroblasts of albite. Rarely hollow crystals are encountered (e. g. in B 630). A quartz-tourmaline vein was found in the St.Hugon Valley (B 750).

Rutile is usually present as exceedingly small needles in the albite porphyroblasts; elsewhere it is found in the same habit, but in lesser amount, and as large rounded grains of a yellow colour. In biotite and chlorite it may be found in sagenitic structure.

Clinozoisite and orthite were both only found in a sericite-biotite-schist of the Veyton Valley (B 650, Fig. 12, cf. p. 200). The birefringence of the orthite is rather weak; it has a pleochroism from bright purple-brown to light brown. Both properties show some variation within the same crystal.

Ilmenite is the most frequent ore mineral. It occurs dispersed through the rock as tabular crystals often at angles to the schistosity. Usually it is partly altered to leucoxene. Magnetite is rare. Pyrite may be present in irregular masses or as cubes, usually with a rim of limonite. It is a secondary mineral, often bound to small faults or crushed zones.

Siderite and dolomite are probably always secondary; they are often found around, or in cracks in, the albite porphyroblasts. Siderite may replace the porphyroblasts to a considerable extent (e. g. in B 131). Sometimes sharply euhedral rhombohedrons occur dispersed through the rock. Siderite (perhaps ankerite p. p.) is recognized in thin section by its brown alteration rims and its higher refringence. Calcite is very rare.

CHEMICAL COMPOSITION

In Table II some analyses of St. Hugon schists are given, together with their Niggli-values. The analyses (1), (2) and (3) are new, while number (4) is quoted from a publication by S. E. Nicolet (1931). The numbers (1) and (2) have an appreciable amount of albite porphyroblasts. Yet, the k-value exceeds 0.50 because of the high content in muscovite. It would have been possible, however, to select a sample with a far higher amount of Na_2O, as in places the albite porphyroblasts make up more than 50 per cent of the rock. In other samples the porphyroblasts may be absent or nearly so. Of these, analysis number (3) is an example. The rock the analysis of which has been shown as number (4) was named "mica-gneiss" in the original publication on account of the megascopical visibility of the albite porphyroblasts. Its analysis is not essentially different from (1) and (2); it seems to be somewhat richer in ores and poorer in quartz.

The analyses (5) and (6) of rocks from Switzerland are inserted for comparison. Number (5) is of a phyllite showing a lower degree of metamorphism and containing the synkinematic porphyroblasts mentioned on a former page (p. 201). Number (6) is of a similar type as the St. Hugon schists. According to A. Gansser Na_2O must have been introduced in both cases. In fact, we frequently meet this opinion in cases where the feldspar occurs in such a conspicuous way. The analysis number (7) shows, however, that certain clays may show an appreciable amount of Na_2O. In deep sea deposits it may be even higher.

In our case, there is no reason to suppose that Na_2O was introduced from outside the formation. In the section on the field observations it was stated

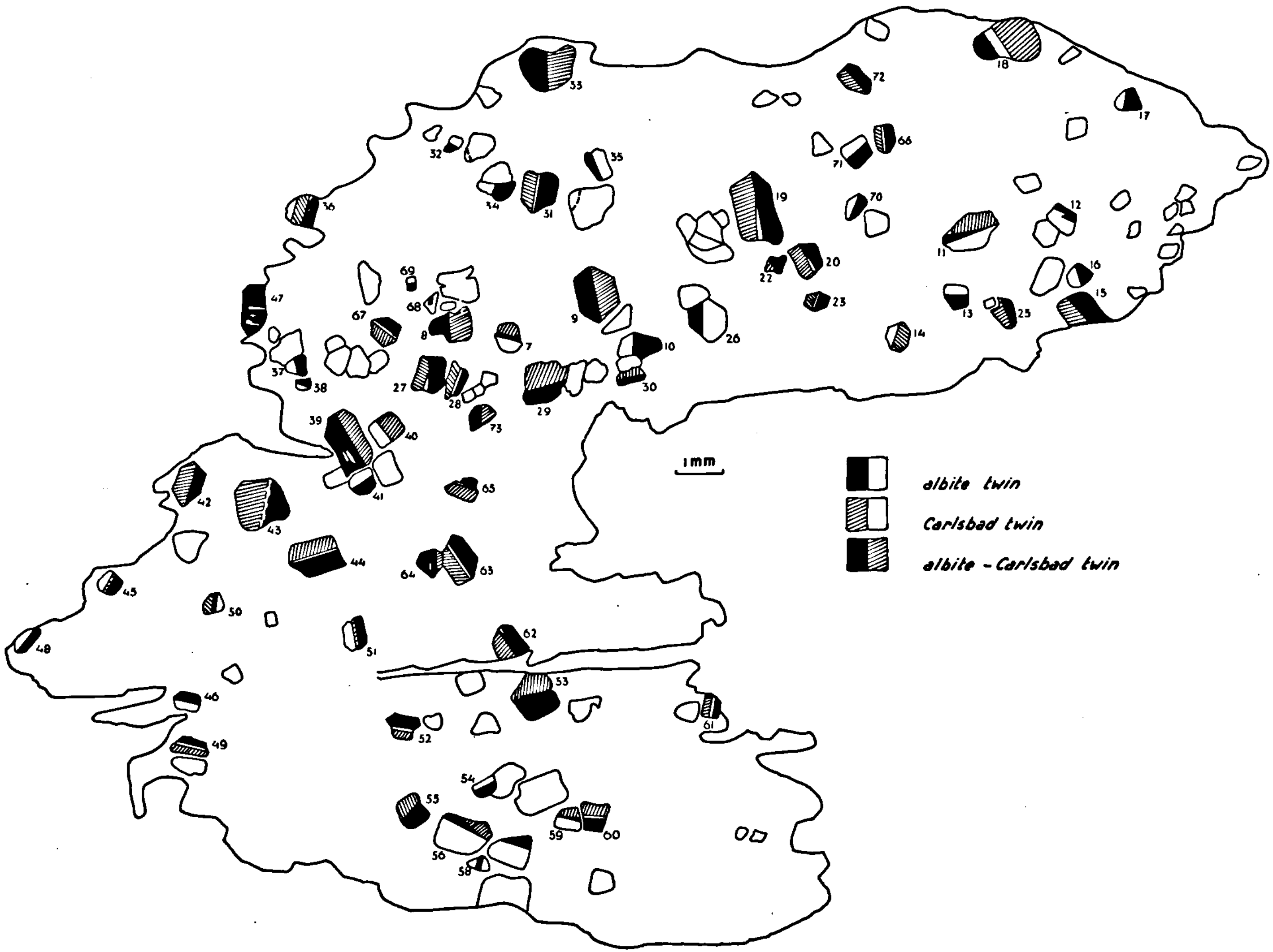


Fig. 16. Diagram of a thin section, indicating mode of occurrence and twinning of the albite porphyroblasts. St. Hugon schists (Sample B 223).

TABLE II.

Chemical composition of the St. Hugon schists (1—4), compared with similar rocks of other regions (5—6) and with a clay (7).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SiO_2	64.95	51.99	48.06	49.14	51.95	51.85	66.01
Al_2O_3	17.25	24.94	32.28	19.82	24.66	21.22	14.47
Fe_2O_3	2.98	3.70	1.24	7.79	5.02	2.07	3.54
FeO	4.51	4.83	0.48	7.41	—	6.24	1.11
MnO	0.06	0.12	0.02	0.26	0.03	0.04	0.05
MgO	1.14	3.05	2.54	2.92	2.64	4.70	2.30
CaO	0.22	0.75	1.17	0.54	0.49	0.85	1.01
Na_2O	1.43	1.50	0.59	2.06	4.21	3.45	2.04
K_2O	3.18	4.75	7.80	4.82	3.77	2.40	3.41
H_2O+	3.86	4.03	4.49		4.45	5.44	3.42
H_2O-			0.31			0.25	1.65
CO_2			0.38				0.25
TiO_2	0.18	1.13	0.67	0.48	1.50	1.32	0.76
P_2O_5		0.13	0.08		0.04	0.38	0.25
Loss on ignition				4.89	0.72		
Total	99.76	100.92	100.11	100.13	99.48	100.21	100.27
Niggli-values:							
si	302	145	155	145	176.5	162	317
al	47	41	61	34	49.5	39	41
fm	36	32	17	49	26	44	34
c	1	2	4	2	2.5	3	5
alk	16	25	18	15	22	15	20
k	0.60	0.68	0.89	0.61	0.37	0.32	0.52
mg	0.22	0.40	0.74	0.26	0.51	0.51	0.48

(1) Albite-sericite-chlorite-schist, somewhat crushed (B 624), St. Hugon valley. Analyst: H. M. I. Bik 1956.

(2) Albite-muscovite-chlorite-schist (B 565), Veyton valley, along the motor road. Analyst: H. M. I. Bik 1956.

(3) Black mylonitic sericite-schist (B 56), Prodin. Analyst: B. Hageman 1953.

(4) Albite-muscovite-chlorite-schist, Allevard. Analyst: S. E. Nicolet (1931, p. 41).

(5) Albite-phyllite, "Bündnerschiefer", San Bernardino Pass, Switzerland. Analyst: J. Jacob (A. Gansser 1937, p. 394).

(6) Albite-sericite-chlorite-schist ("Knötchenschiefer"), Curaglia, Switzerland. Analist: L. Hezner (P. Niggli, 1913).

(7) Red clay, Aquitanian, Marbach (Luzern), Switzerland (P. Niggli and E. Niggli, 1952, Table 48, No. 16).

that the distribution of the porphyroblasts often seems to be independent of the original stratification. In the opinion of the author this distribution must have been brought about by pore solutions rich in albitic constituents circulating over comparatively short distances.

GENERAL REMARKS CONCERNING ORIGIN AND METAMORPHISM

The St. Hugon schists are clearly of sedimentary origin. With their high content in micaceous matter, reflected in the chemical analyses by a high content in Al_2O_3 and K_2O, they represent a rather homogeneous formation of argillaceous sediments. As a rule these sediments must have shown a bedding some cm in width caused by small differences in the composition of the sediment. Sandstones are of rare occurrence. As was mentioned in a former section, quartz grains of the original sediment were recognized in a sample with blastopsammitic structure. The age of the sediments is unknown. Since they show a higher degree of metamorphism, they must at least be older than the adjoining Upper Carboniferous sediments.

Some time after their formation a slight synkinematic metamorphism must have converted the argillaceous sediments into microfolded slates or phyllites with numerous minute needles of rutile. After the movements had come to an end, comparatively large porphyroblasts of albite, muscovite and — locally — of biotite were formed across the schistosity. In the first stage of their growth the albite porphyroblasts enclosed the rutile needles which were present everywhere in the microfolded slaty or phyllitic bands. The microfolds remained visible in the porphyroblasts in the structure of the trends of inclusions. During a later stage many albite porphyroblasts developed rims practically devoid of rutile needles. Apparently, the needles were no longer present during the growth of these rims. Part of the rutile may have been incorporated in newly formed minerals such as biotite, while another part was concentrated into larger grains. Moreover, the quartz inclusions in the albite porphyroblasts are generally of smaller dimensions than the quartz grains occurring in the matrix. These facts seem to indicate a recrystallization of the matrix to a larger grain size after the formation of the inclusion-rich cores of the porphyroblasts. Probably the undulating bands of micaceous matter were transformed at this stage into a coarser aggregate of sericite-muscovite, biotite and chlorite.

At this stage the St. Hugon schists had reached their highest degree of metamorphism. Subsequent processes can all be described as retrograde metamorphism or alteration. They must have taken place under conditions of lower temperature and pressure. In the southern part of the Belledonne Massif nearly all of the biotite has been altered into chlorite. This chloritization affecting the whole formation is not directly related to the crushed or mylonitic zones caused by the late-Hercynian and Alpine movements: these are of more local occurrence. Nevertheless the results of these destructive processes could be studied in many samples. They were briefly mentioned in the petrographical section.

Finally, some special attention should be paid to the albite porphyroblasts. Being the most characteristic and the most interesting feature of the St. Hugon schists, their mode of occurrence, their inclusions and their twinning have been described rather elaborately in the mineralogical section. From this description and from observations mentioned in other sections the following conclusions may be drawn:

(1) The porphyroblasts belong to the main period of metamorphism of the St. Hugon schists; they have not originated during the later stages of retrograde metamorphism. This fact is clearly illustrated by their presence in completely unaltered sericite-biotite-schists in the Veyton valley and in the northern part of the Belledonne Massif, and by the minute needles of rutile occurring in their cores.

(2) The trains of inclusions are traces of an earlier microfolded structure; an eventual sigmoid form of the trends is not due to a rotation of the porphyroblasts during their growth. This point has been stressed sufficiently in the separate paragraph on the inclusions (p. 201).

(3) As was argued in the chemical section, the presence of the porphyroblasts need not be explained by an introduction of albitic constituents from outside the formation.

These conclusions differ from those arrived at by J. Sarrot-Reynaud (1958) in a recent publication on the metamorphism of the La Mure Massif, where, as we have seen, a southern continuation of the St. Hugon schists is exposed. According to this author the porphyroblasts are synkinematic in the sense of Gansser, and of Alpine age. Although albite may certainly be an Alpine mineral — we have already encountered it in the younger veins — the present author holds the above-mentioned conclusions to be true in a great majority of the cases.

CHAPTER III

THE LAC CROP FORMATION AND THE FERROUILLET AMPHIBOLITES

FIELD OBSERVATIONS

In the following pages the banded formation consisting of mica-schists and amphibolites and occupying the western part of the internal zone within the mapped area will be designated as *Lac Crop formation.* Its "type locality" is the region between Lac Crop and the Col de la Mine de Fer. It is the only part within the mapped area where the original metamorphism can be studied adequately: elsewhere the rocks are altered by later mylonitization, crushing or chloritization. The formation shows a great variety of rocks in bands often not more than a few cm to a few tens of cm in thickness. We find mainly fine-grained muscovite-biotite-schists, biotite-schists, amphibole-schists, amphibolites and light-coloured schistose rocks of leucogranitic composition. A selection of specimens will be described below. Near the Col de la Mine de Fer a "dyke" of hornblendite was found, about 50 cm in thickness and intersecting the above-mentioned banding at a small angle.

The structure of the Lac Crop formation is more complicated than that of the St. Hugon schists. Probably isoclinal folding occurs frequently, but the observation of these folds is often prohibited by the comparatively poor character of the exposures. Another type of folding may be younger than the development of the schistosity. Its amplitude may vary from several tens of metres to some cm. Often one of the limbs is about horizontal, the other about vertical. Further complications are offered by a fault pattern indicated by mylonitic zones, and sometimes also by the topography. These faults are due to younger movements, which are also responsible for the alteration of the Lac Crop formation elsewhere in the mapped area.

Between Lac Crop and the median syncline the appearance of the rocks is usually altered by chloritization. In many cases the banding is still distinctly visible, but the different rock types are less easily recognized and have the appearance of greenschists. Crushing and mylonitization, which are here confined to certain bands only, become gradually more important when we go in a NNE direction. In the Pleynet valley almost all rocks have been subjected to these destructive processes, with the exception of the sharply dented crest consisting of comparatively unaltered Ferrouillet amphibolites. Crushing, that is a tectonic diminution of the crystals of a rock, usually accompanied by alteration, is a common phenomenon in crystalline rocks. It has been described, for example, from the Aiguilles Rouges Massif by J. Meyer (1916), who reported a granite to have been altered by crushing into a massive green aphanitic rock forming a zone several tens of metres in thickness along a major fault plane. The crushed amphibolitic rocks in the Pleynet valley often show a quite characteristic pattern of open cracks, which, as can be seen in less weathered parts, were originally filled with calcite (Fig. 17). The

Fig. 17. Crushed and altered amphibolites of the Lac Crop formation (Pleynet valley). The cracks, which usually have contained calcite, are characteristic of this kind of rock.

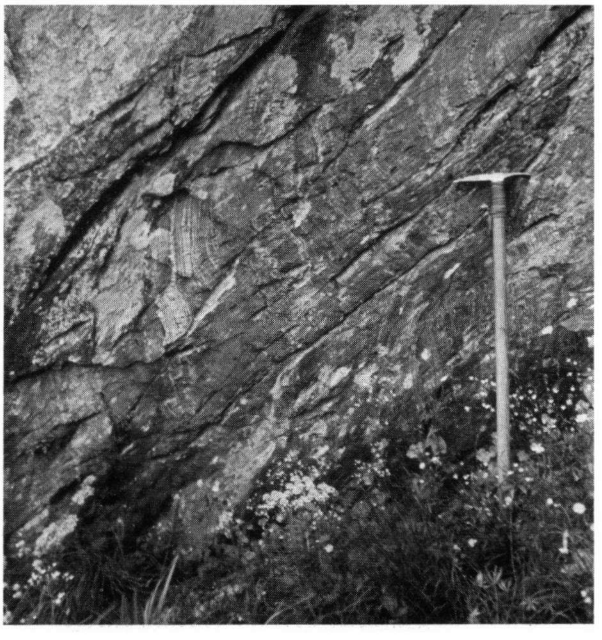


Fig. 18. Amphibolitic banding preserved in crushed and altered amphibolites of the Lac Crop formation (Pleynet valley).

cracks are often more or less rectilinear; with their limited extension and haphazard directions they give the impression of shrinkage cracks. Their origin is not clear. Perhaps the alteration went with decrease in volume, because part of the constituents were carried away in solution. It is also possible that they originated during the deformation of a banded sequence, the mica-schists being deformed plastically, whereas the amphibolitic parts were torn apart to a certain extent. In places broader amphibolitic bands have escaped most of the alteration, so that they are easily recognized (e. g. near the Crêt du Boeuf and the Dents de Pipay, Fig. 18). More often the megascopical appearance of the rocks has altered completely to that of a greenstone or a greenschist. Yet, microscopical examination often reveals their retrograde-metamorphic nature (cf p. 218).

The mylonites are very fine-grained laminated rocks of phyllonitic character, often resembling slates or low-grade metamorphic phyllites. Seen on surfaces transverse to the schistosity the mylonites frequently betray their true nature by the presence of small drawn-out lenses (about 1 mm in thickness) of coarser-grained rock.

The name of *Ferrouillet amphibolites* is proposed here to designate the amphibolites exposed in the eastern part of the mapped area. They form the mountain range from the Sommet Colomb in the South to the sharp crest which ends in the Pleynet valley N of the Dent du Prat (Fig. 19). Many parts of the chain show the dented crests and tower-like summits often so typical of amphibolitic rocks. That part of the chain between the Sommet Colomb and the Pas de la Coche is wrongly indicated as "micaschistes et gneiss" on the official 1:80.000 map. In reality, we are dealing here with a northern continuation of the amphibolites described by den Tex (1950) in his thesis on the region of the Lacs Robert. With the exception of the ultrabasic rocks most of the separate rock types distinguished by this author are encountered again. For most purposes, however, it will suffice for the reader to visualize a formation of banded amphibolites, heterogeneous at the scale of an exposure, but homogeneous at the scale of a mountain range.

The bands may vary in colour from white to dark brown or almost black; their thickness is usually of the order of a few cm. In some parts the boundaries between them are rather vague, in others very sharp and rectilinear. The banding is caused by differences in the relative abundance of only a few minerals. The white bands consist almost exclusively of plagioclase, whereas the dark-coloured bands contain appreciable amounts of amphibole, usually in rather small crystals. Not infrequently the amphibole shows a nematoblastic or fibrous structure with more or less linear arrangement. More often roughly equal amounts of plagioclase and amphibole occur evenly distributed in a granoblastic structure not unlike that displayed by the fine-grained mica-schists of the Lac Crop formation. The Ferrouillet amphibolites differ from the Lac Crop formation chiefly in the rarity of non-amphibolitic rocks: amphibolites from both formations may resemble each other closely. Yet, some differences may be noted. In the Lac Crop formation most amphibole has a dark green or dark brown colour megascopically. In the Ferrouillet amphibolites a blue-green hornblende prevails which is pitch-black megascopically. Porphyroblasts of this amphibole may show different-looking greenish cores which on microscopical examination prove to consist of pyroxene. Further-

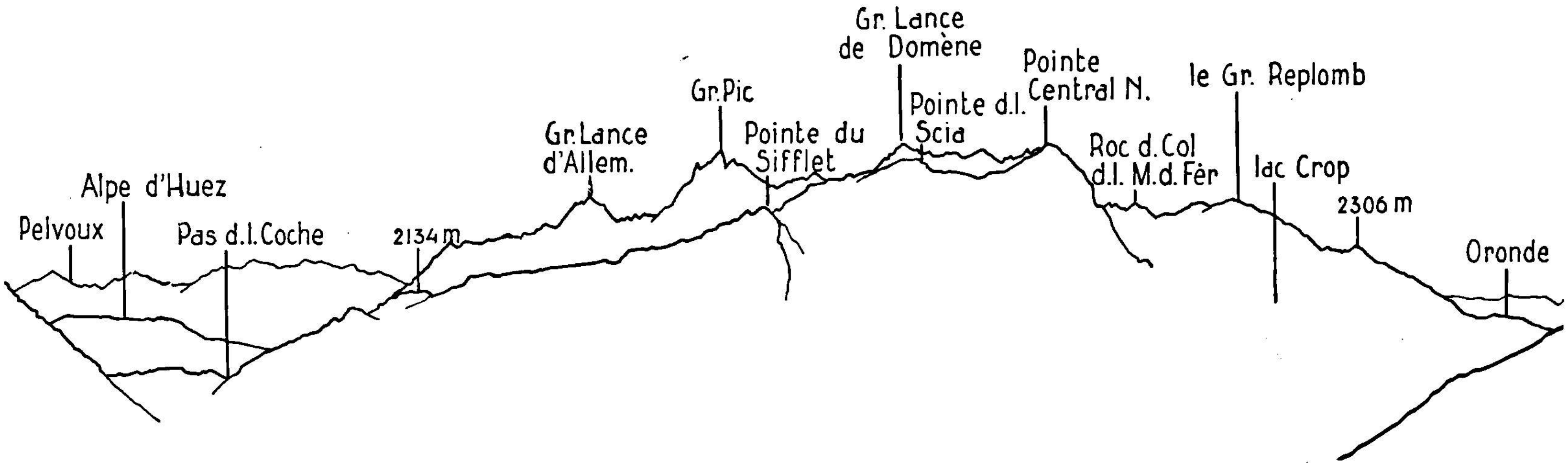


Fig. 19. The Ferrouillet range as seen from the NE (898-323). In the background the highest parts of the Belledonne Massif.

more, lenses or bands of dioritic structure may be encountered, which are not found in the Lac Crop formation.

The structural features in both formations are essentially the same. The detailed folding is often intersected by small faults. Probably both types of deformation are approximately of the same age: they must be older than or contemporaneous with the main phase of metamorphism, because no dynamic metamorphism seems to be involved. Not infrequently, such a fault is seen to be parallel to the banding on one side and oblique to that on the other side. In cases where this phenomenon continues over some distance it may create the suggestion of an angular unconformity. The younger faults occur here in the same way as in the Lac Crop formation. They are usually of large extension; some may even be followed over a considerable distance on the aerial photographs. In the field their presence may be indicated by tectonic breccias or mylonites.

On the whole, younger dynamic metamorphism has had far less effect here than in the Lac Crop formation. Apparently, the amphibolites are more resistant against tectonic forces. This is best seen in the Pleynet valley, where the above-mentioned amphibolitic crest has remained fairly fresh in completely crushed or mylonitized surroundings. The numerous veins of epidote (green) or clinozoisite (grey) may, however, be regarded as a result of the younger dynamic metamorphism.

GENERAL PETROGRAPHY

On microscopic examination there appears to be no essential difference between comparable samples of the Lac Crop formation and the Ferrouillet amphibolites. Therefore, from a petrographical point of view they can be treated together. As was stated in the preceding section, the Lac Crop formation shows a greater variety of rock types in banded alternation. Nevertheless, under the microscope these appear to consist of a limited number of minerals.

The main constituents are quartz, plagioclase, muscovite, biotite, amphibole and commonly also garnet. In some slightly altered samples staurolite and kyanite have been observed. Muscovite, staurolite or kyanite are never found together with amphibole in the same band. Potash feldspar occurs in some bands of granitic composition. In some samples of the Ferrouillet amphibolites clinopyroxene is found in the cores of amphibole porphyroblasts. As accessory constituents titanite, apatite, zircon, rutile, tourmaline and ore minerals are frequently encountered. Orthite is rare. Vein-filling and/or secondary minerals are chlorite, albite, adularia, epidote, quartz, sericite-muscovite, titanite, carbonates, barite and ore minerals. The plagioclase may contain up to 25 % An in schists containing muscovite, up to 40 % An in biotite-schists and most of the amphibolites, and may reach 70 % An in some amphibolites. In most samples it shows reversed zoning. The twinning is generally lamellar according to the pericline, acline or albite law.

Even in rocks comparatively rich in micas or amphibole the structure is predominantly granoblastic, with occasional porphyroblasts of amphibole, plagioclase or garnet. Owing to this structure and to the larger grain size microfolding is less common here than it is in the St. Hugon schists. Mylonitic zones are easily recognized by the diminution of the grain size, notably that of quartz and the micas. Where a large part of the formation has been crushed and altered, as for example in the Pleynet valley, often only microscopical examination reveals the rocks to belong to the Lac Crop formation or to the Ferrouillet amphibolites. In many cases the mica-schists prove to be chloritized rather than crushed (see Fig. 24). The larger chlorite flakes have originated by alteration of biotite, remnants of which are sometimes found. The more or less round aggregates of smaller flakes of chlorite usually represent altered garnets. The amphibolites and amphibole-schists react in a different way to the later movements. Where they occur interlayered with the mica-schists, they are frequently crushed in such a manner that the original structure of the rock is completely demolished. Their original nature is then demonstrated exclusively by the abundance of titanite and angular or partly chloritized fragments of amphibole. The amphibolites occurring in larger masses are usually very resistant against mechanical influences, and have often remained in a comparatively unaltered condition, the secondary minerals being chiefly confined to veins of varying dimensions.

Some characteristic samples of both formations will be described separately in another section. All samples mentioned in the text are listed in table III, with indication of their localities.

TABLE III.

Samples of the Lac Crop formation and the Ferrouillet amphibolites.

A. Lac Crop formation.

No.	Rock name	Locality	Grid reference
B 251	Greenschist	Dents de Pipay	904—365
B 398	Amphibolite	Pré de l'Arc	877—326
B 574	Muscovite-biotite-schist	Col de la Mine de Fer	870—282
B 574a	Fine-grained garnet-biotite-schist	„	„
B 579	Amphibolite	Col de Pipay	918—364
B 673	Biotite-garnet-amphibole-schist	Lac Crop	867—285
B 673b	Kyanite- and staurolite-bearing garnet-biotite-schist	„	„
B 674	Garnet-biotite-schist	„	„
B 675	Altered biotite-amphibolite	„	„
B 676	Amphibolite	„	„
B 692	Altered garnet-muscovite-biotite-schist	„	861—299
B 697	Muscovite-gneiss with chloritized garnets	Col de la Mine de Fer	868—286
B 698	Amphibolite	„	869—283
B 702	Garnet-epidote-gneiss	Ferrouillet	873—201
B 703	Crushed garnet-muscovite-biotite-schist	„	871—297
B 705	Fine-grained garnet-biotite-schist	„	872—302
B 707	Altered garnet-biotite-schist	„	„
B 708	„	„	„
B 718	Crushed leucogranitic gneiss	La Jasse	902—333
B 720a	Altered banded garnet-biotite-gneiss	Barlet	863—309
B 736	Amphibole-epidote-gneiss	Pré de l'Arc	885—323

No.	Rock name	Locality	Grid reference
B 739	Crushed amphibolite	Dents de Pipay	900—359
74538	Quartz-bearing garnet-amphibolite	Barlet	860—310
74539	Hornblendite	Col de la Mine de Fer	868—283
74543	Crushed amphibolite	Pré de l'Arc	873—315
74545	Staurolite- and kyanite-bearing garnet-biot.-musc.-schist	Lac Crop	867—293
74546	Staurolite-bearing garnet-biotite-schist	Col de la Mine de Fer	868—283
74559	Garnet-biotite-schist	Lac Crop	870—292
74578	Leucocratic gneiss	„	871—297
74580	„	Pas de la Coche	896—309
75047	Amphibolite	Crêt du Boeuf	915—378
75071	Crushed amphibolite	Dents de Pipay	903—364

B. Ferrouillet amphibolites.

B 373	Amphibolite	Barlet (moraine)	857—321
B 678b	Crushed leucogranitic gneiss	Pas de la Coche	902—308
B 679	„	„	„
B 680	„	„	„
B 694	Amphibolite with band of light-coloured amphibole-gneiss	Lac Crop	867—291
B 712	Massive amphibolite	Ferrouillet	877—296
B 713	Coarse-grained pyroxene-bearing amphibolite	„	„
74528	Amphibolite	„	881—301
74529	Pyroxene-bearing amphibolite	Pointe de la Scia	891—305
74532	Banded amphibolite	Pic du Sifflet	889—302

MINERALOGY

Quartz. Generally present, except in many amphibolites. It usually has a wavy extinction and occurs in a granoblastic structure.

Potash feldspar is of rare occurrence as a primary constituent. It has been found as large crystals in crushed rocks of leucogranitic composition on the Crête de la Jasse (B 718) and N of the Pas de la Coche (B 678b, 679, 680). In one sample (B 678b) the characteristic twinning of microcline was observed. In many cases the crystals are largely altered into albite with fine lamellar twinning. In the mica-schists and amphibolites potash feldspar is found only as a secondary or vein-filling mineral.

In veins it may occur alone, or associated with minerals as quartz, chlorite, titanite or epidote. In some cases its acute-angled crystal boundaries show the predominance of the faces (110) and ($1\bar{1}0$) (Fig. 20). As an alteration product of plagioclase it may occur as cloudy patches, usually situated in the centre of the crystals (e. g. in B 574a, 579, 702, 708) or, rarely, as small sharply

Fig. 20. Adularia and quartz in a vein in a biotite-schist of the Lac Crop formation. The acute angles are caused by the (110) and ($1\bar{1}0$) crystal faces of the adularia. Sample B 574a, plane-polarized light, 125 ×.

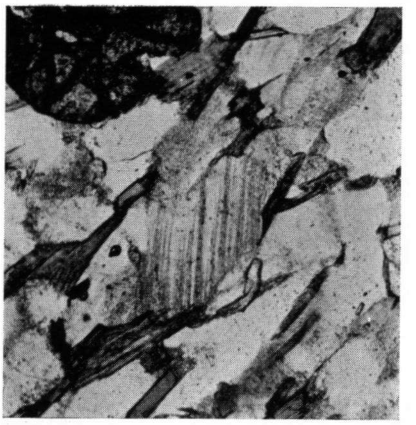


Fig. 21. Twinned plagioclase crystal, in which one set of lamellae is more altered than the other. Same sample as Fig. 20, plane-polarized light, 85 ×.

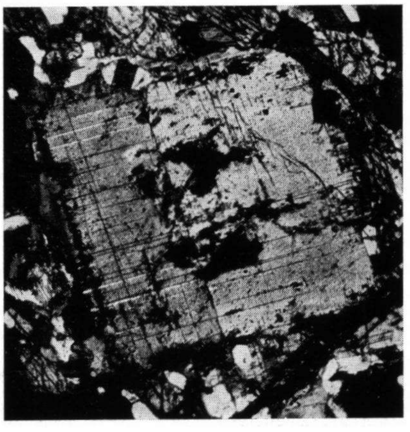


Fig. 22. Ala A twin in plagioclase megacryst. Note the (010) traces — with some albite lamellae — passing undisturbed through the composition face, which phenomenon is one of the characteristics of the Ala twin. Amphibolite, found in the moraines, probably belonging to the Ferrouillet amphibolites. Sample B 373, crossed nicols, 20 ×.

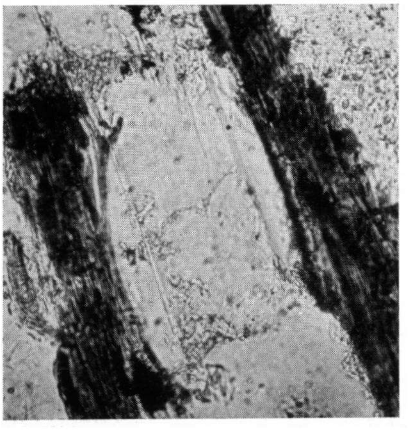


Fig. 23. Rims of albite along flakes of biotite. The rims seem to have grown at the expense of the biotite; they have the same crystallographical orientation as the adjoining plagioclase crystal. Sample B 674, plane-polarized light, 260 ×.

Fig. 24. Completely chloritized biotite in "greenschist" of the Lac Crop formation near the Dents de Pipay. Sample B 251, plane-polarized light, 45 ×.

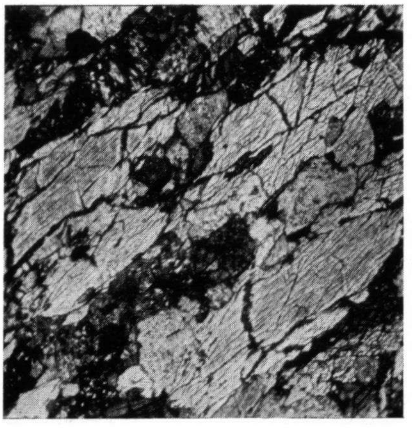


Fig. 25. Crushed amphibole with some chloritization along the fractures. Sample B 739 (Lac Crop formation, Dents de Pipay), crossed nicols, 50 ×.

bounded rectangles (B 574a). Its optic axial angle varies from very small to about 60°(—); in the former case the interference figure resembles that of nepheline. The birefringence is about 0.006. According to several authors these properties are characteristic of adularia of hydrothermal origin. A comprehensive review of the literature on the process of adularization was given by W. P. de Roever (1942, p. 275—279). Secondary or vein-filling potash feldspar with adularia-like habit and small optic angle was reported by G. v. Szádeczky (1909) from Transylvania, by W. P. de Roever (op. cit.) from Timor and by U. Chaisson (1950) from Switzerland, Austria, Italy and Mexico. According to F. Laves (1952) from a structural point of view adularia represents an unstable intermediate stage between sanidine and microcline, which would explain the variation in the optical properties.

Plagioclase is always present. The anorthite content is more or less dependent upon the composition of the rock. In muscovite-bearing schists it does not surpass 25 % An. In amphibole- and biotite-schists it may reach about 40 % An. Reversed zoning is of common occurrence, with differences of up to about 10 % An between core and rim (e. g. in B 673, 673b).

Some of the Ferrouillet amphibolites, especially those with a more or less dioritic structure, show large megacrysts of plagioclase with different properties. In these crystals, which may show normal zoning, the anorthite content may reach 70 %. Furthermore, Carlsbad and Ala twins may be observed, usually in combination with lamellar twinning. In short, we may be dealing here with a relict feldspar of igneous origin.

Most of the plagioclase is more or less altered into albite and sericite. In lamellar twins one set of lamellae may be more sericitized than the other (e. g. B 720a, 74545, Fig. 21). It is not known whether this is caused by an original difference in composition, or by the different position of the lattices, for example with respect to the direction of stress during their alteration. Alteration into adularia is of rare occurrence (see potash feldspar).

Twinning. In many samples roughly half of the plagioclase crystals are twinned, in others untwinned crystals are predominant. Almost all twinning is lamellar. In the intermediate plagioclase in question there is little difference in the position of the pericline and acline composition faces: at 40 % An the two faces coincide. Yet, in sections showing negative elongation with regard to the composition face, pericline lamellae are often seen to make a small angle with the (001) cleavage or with acline lamellae (see Fig. 27). On an average the former appear to be broader than the latter.

In plagioclase with less than 70 % An pericline or acline twins can be distinguished from albite twins with sufficient accuracy without the aid of the universal stage. A lamellar twin of intermediate or sodium-rich plagioclase is twinned according to the pericline or acline law if one or more of the following conditions are fulfilled:

(1) Positive elongation with regard to the composition face;
(2) Distinct asymmetrical extinction in a section normal to the composition face;
(3) One or both individuals remaining (nearly) dark on turning the stage, in sections roughly normal to the composition face [1]);

[1]) This is caused by one or both of the optic axes making a small angle with the (001) face. In the plagioclase under consideration the optic axes are never near to (010).

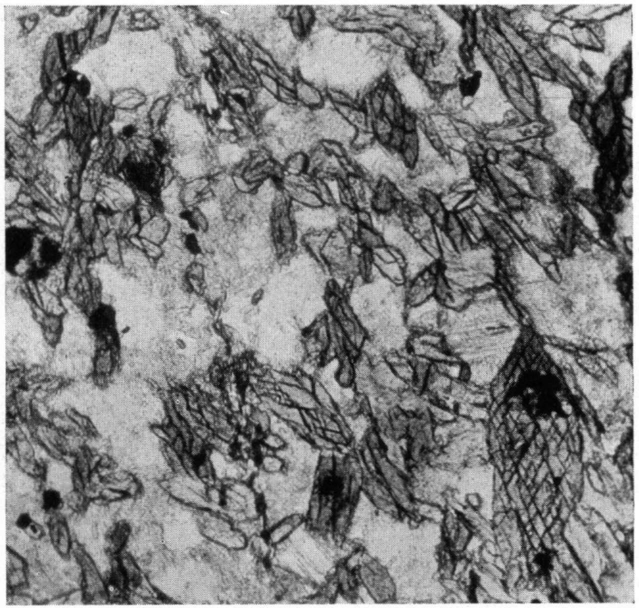


Fig. 26. Amphibolite of the Lac Crop formation, consisting of green hornblende, partly altered plagioclase and some grains of ore and titanite. The thin section is normal to the lineation. Sample 75047 (Crêt du Boeuf), plane-polarized light, 75 ×.

Fig. 27. Plagioclase crystals with lamellar twinning in amphibolite of the Lac Crop formation. Below the centre of the photograph a plagioclase crystal in extinction position shows a pericline band making a small angle with some thin acline lamellae. Sample B 698 (Lac Crop), crossed nicols, 70 ×.

(4) Extinction angles larger than the maximum allowed for that plagioclase in the zone normal to (010);
(5) The composition face making an angle of 0°—37° with the cleavage (pericline law);

For the varieties of plagioclase under consideration the albite twin was assumed to be present when none of the above-mentioned conditions were fulfilled. On checking with the aid of the universal stage this assumption appeared to be correct in more than 90 per cent of the cases. Deviations are mainly due to the use of sections which are not cut normal to the composition face. The above considerations will be dealt with more elaborately in a future paper.

The plagioclase twins occurring in the different rock types of both formations were investigated in this manner. In all schists and amphibolites acline or pericline twins were found to be more frequent than albite twins. A count performed in a thin section of an amphibolite (sample B 698) gave the following approximate distribution: 20 crystals with the acline or pericline law, 6 with the albite law and 9 with both laws; for a staurolite-bearing garnet-biotite-schist (B 673b) these figures were 104, 18 and 8, respectively.

These results are in close agreement with observations by F. J. Turner (1951), who concluded that the presence of many untwinned crystals, the absence of complex twinning and the relative frequency of the pericline and acline twins are characteristic of the plagioclase of metamorphic rocks. Furthermore, lamellar twinning, usually considered comparatively rare in metamorphic rocks, is described by this author as a normal feature of certain quartz-biotite-oligoclase-schists and of amphibolites with plagioclase of 20—45 % An.

We have already seen that part of the plagioclase crystals in the amphibolites are of a different nature (p. 221). Here Carlsbad and even Ala twins may be found, alone or combined with lamellar twinning according to the albite, pericline or acline laws. If occurring alone they generally cannot be identified without the aid of the universal stage. A favourable case (unfortunately occurring in a sample found in a moraine deposit!) is presented by Fig. 22, which shows a plagioclase megacryst in a section almost perpendicular to the [100] axis. Positive elongation shows the composition face of the simple twin — which is parallel to one of the cleavage directions — to be (001). The cleavage and lamellae transverse to this composition face represent the direction (010). The simple twin is almost invisible, because the extinction directions are almost parallel in both individuals. Furthermore, the cleavage and lamellae according to (010) are seen to pass undisturbed through the composition face of the simple twin. These facts indicate that [100] must be the twinning axis of this twin. Thus, we are dealing with an Ala A twin with transverse albite lamellae. According to F. J. Turner (op. cit.) and the author, plagioclase crystals with such twins occurring in amphibolites generally represent relict minerals of igneous origin.

Feldspar rims along biotite. In many samples rims of felspar with low refractive indices and up to 0.03 mm in width are found along the boundaries between plagioclase crystals and the basal faces of biotite flakes. The rims are usually convex towards the biotite and always bounded by a flat plane towards the plagioclase. This seems to indicate that the rims have grown at the expense of the biotite. It should be noted, however, that this replacement must be independent of the process of chloritization, as the rims are often found along completely unaltered biotite flakes.

Identification of the feldspar proved to be difficult. The refractive indices are always distinctly smaller than those of the bordering plagioclase. In some cases the rims were seen to be associated with veinlets of adularia. On the other hand, the birefringence was often found to be too high for this mineral: measurements with the Berek compensator gave maximum values near 0.010. An interference figure could be made of one comparatively broad rim cut perpendicular to one of the optic axes. The optic sign was found to be positive, the axial angle being about 70°. Of course, these optical properties point rather to albite than to any kind of potash feldspar. It was therefore decided to determine the refractive indices of the feldspar with greater accuracy. To this end the balsam of a thin section of one sample (B 674) was dissolved. With the aid of other immersion media both refractive indices of some rim sections were found to be very near to 1.526. In most cases, however, the values proved to be distinctly higher. On combining this result with the above-mentioned observations, it may be concluded that the rims are of two different kinds, consisting of either albite or adularia. In the sample studied rims of albite predominated. Judging from the frequent occurrence of quartz-like interference colours this will probably be the general rule.

There is no great difference between the directions of extinction of a feldspar rim and a bordering plagioclase crystal. On insertion of the gypsum plate in the 45° position they always show the same behaviour. If rims are found on either side of a plagioclase crystal, both have the same interference colour and the same extinction position. In a few cases thin twin lamellae occurring in a plagioclase crystal were found to continue undisturbed into the rim. These facts suggest that the rims and the bordering plagioclase crystals have the same crystallographic orientation, the differences in interference colour and extinction being caused by a difference in composition. It was not easy to verify this possibility, because crystallographic directions are seldom visible in the rims. In one case a rim and its bordering plagioclase crystal could be measured on the universal stage. The crystals did not show cleavage or twinning. After the indicatrix axes of both crystals had been indicated on a stereographic net, the [001] axis of the rim was plotted with the aid of data from literature, assuming a composition of 0 % An. The position of this same axis with regard to the optical indicatrix of the plagioclase crystal was found to correspond closely to that found in plagioclase with 25 % An, a value to be expected for a plagioclase crystal in this sample. Obviously at least in this case plagioclase crystal and rim had the same crystallographic orientation.

Where the biotite is completely chloritized the rims remain visible (e. g. in B 251, 398). Similar rims are rarely found along muscovite (in 74578) or amphibole (in 75047). The author has found no indication of similar phenomena in the literature on this subject. Of course there is no relation to the granular potash feldspar described by F. Chayes (1954) as a "by-product of biotite-chlorite transformation".

B i o t i t e is a main constituent of the mica-schists. It may also be found in some amphibole-schists of the Lac Crop formation. In the Ferrouillet amphibolites it is of rare occurrence. Two types may be distinguished, having a warm brown and a brown-green colour, respectively, the former being more frequent than the latter. Both are unaxial; no difference was observed in their mode of occurrence. The flakes sometimes show curious rims of feldspar (see separate section). In the vicinity of Lac Crop the biotite is little altered, but in the northern and western parts of the mapped area it is almost entirely altered into chlorite. The chloritized flakes may show needles of rutile.

M u s c o v i t e, though less frequent than biotite, is found in many mica-schists of the Lac Crop formation. It does not occur together with amphibole. In contrast to its mode of occurrence in the St. Hugon schists, it usually occurs in isolated flakes; even in fine-grained rocks the individual flakes are easily recognized on megascopical examination. The optic axial angle is that of pure muscovite: about 45° (—). In muscovite-schists poor in feldspar and biotite, which rock type is of rare occurrence, the flakes are larger than in the gneisses.

Occasionally muscovite is found in veins (e. g. in B 705). As sericite it plays its usual role as an alteration product of plagioclase, staurolite and kyanite. Once (in B 574) it was seen to form fringes around biotite.

G a r n e t is a common mineral in the mica-schists, and is occasionally found in the amphibole-bearing rocks. In all these rock types it may occur as porphyroblasts with sizes from 0.1 mm to a few mm. The porphyroblasts are usually more or less round and may contain numerous inclusions of quartz. Most of them are colourless in thin section, some are pink. In one sample (B 702) the cores were found to be pink, the rims colourless. This phenomenon most probably indicates the pink garnet to be older than the colourless one. In the same sample the cores show two-phase inclusions in the shape of negative crystals. The vapour bubbles are less easily seen than, for example, in quartz, because of the large difference in refractive index between liquid and garnet.

Apart from these porphyroblasts, numerous minute colourless garnets were found in certain mica-schists (Fig. 28). Most of them are euhedral crystals of smaller size than the other main constituents of the rock (about 0.025 mm on an average). From one sample (74559) the garnets were separated in order to measure the size of the unit cell and the refractive index. The results are compared below with data for two other garnets of the region, viz. a small pink garnet occurring in an aplite of the Sept Laux granite (HK 87), and a porphyroblastic pink garnet occurring in a kyanite-bearing garnet-mica-schist found near La Traverse (898-208, B 157).

Sample No.	X-ray strip	refractive index	size of unit cell
B 157	2135	$n_D = 1.812 \pm 0.002$	$a_0 = 11.598 \pm 0.002$
74559	2091	$n_D = 1.803 \pm 0.002$	$a_0 = 11.569 \pm 0.005$
HK 87	2092	$n_D = 1.825 \pm 0.002$	$a_0 = 11.546 \pm 0.003$

The charts recently published by R. Frietsch (1957) and A. Sriramadas (1957) do not as yet allow conclusive determination of the composition of a garnet from these data. It is seen from them, however, that the garnet of HK 87 is probably a rather pure almandite, whereas those of 74559 and B 157 could be spessartites with an admixture of almandite. A comparative chemical test carried out on a quantity of powder from the whole rock showed the Mn-content to be higher than that of B 574a, which sample had

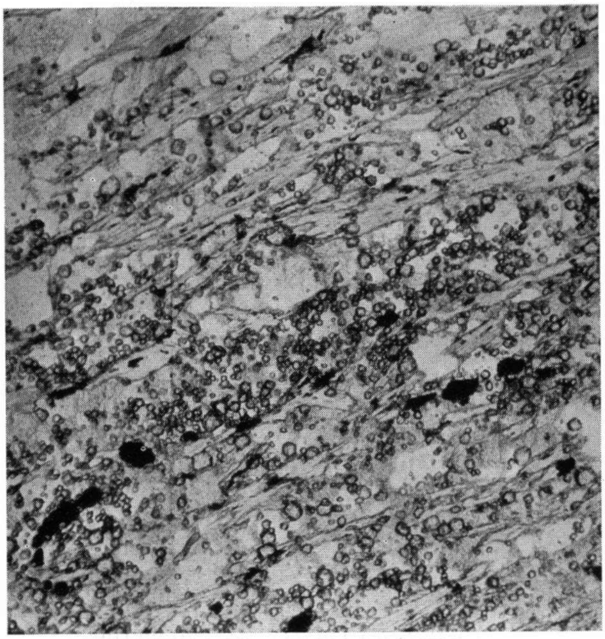


Fig. 28. Numerous very small garnets in garnet-biotite-schist of the Lac Crop formation. Sample 74559, plane-polarized light, 55 ×.

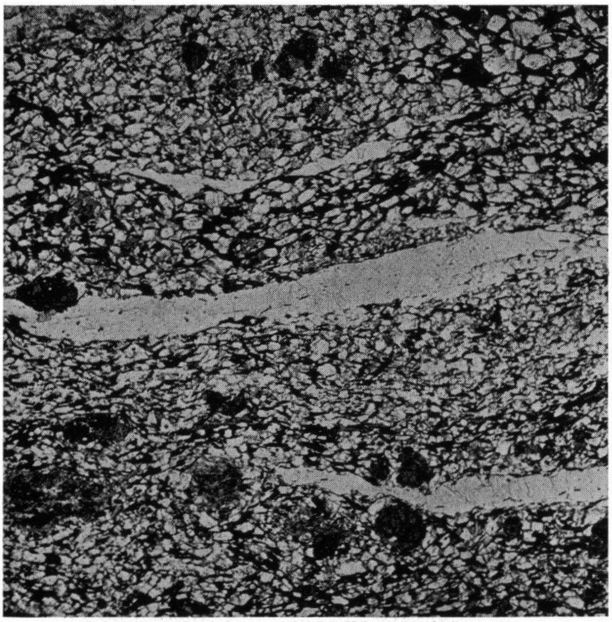


Fig. 29. Garnet-biotite-schist with some partly sericitized staurolite and kyanite (lower left, better seen in Fig. 30 and 31). At this low magnification the granular structure of the rock is clearly seen. The brown biotite flakes appear black on the photograph. Sample B 673b (Lac Crop), Lac Crop formation. Plane-polarized light, 6 ×.

0.33 weight % MnO (see chemical analysis). The comparative richness in this element seems to confirm the presence of spessartite.

The garnet is often altered into chlorite. Less common alteration products include sericite, (?) stilpnomelane (together with chlorite, in B 697), and granular zoisite, in patches (in B 692).

Amphibole is a common mineral in both formations. In the Lac Crop formation a light green or light brown amphibole is prevalent. It has a negative optic angle of 80°—85°. Another variety with blue-green and grass-green colours — of n_γ and n_β respectively — has a negative optic angle of about 70°. Probably this variety is a common green hornblende. It is rare in the Lac Crop formation and common in the Ferrouillet amphibolites. It must be said that the choice of these two types is a rather arbitrary one. In reality we are dealing with numerous shades of colour. Again, colour and optical properties vary to a certain extent independently of one another. It seemed, however, not worth while to study these variations in greater detail.

Sometimes, especially in the Ferrouillet amphibolites, the amphibole is found in two sizes. The larger crystals may be porphyroblasts with a pronounced sieve structure. In many basal sections these crystals appear to be stretched in the direction of the b-axis (up to 5 mm, e. g. in sample 74538). Rarely do the porphyroblasts show cores of a colourless clinopyroxene. In this case, the crystals are not poeciloblastic and more or less equant in form. Perhaps this habit might be explained by a growth at the expense of clinopyroxene megacrysts. In some samples the cores of the porphyroblasts show dark clouds of rutile needles, similar to those encountered in the albite porphyroblasts of the St. Hugon schists.

Younger light-coloured or colourless amphibole occurs in veins, either as minute needles or as growths on the older amphibole (e. g. in 74543).

In crushed rocks the amphibole crystals are frequently broken. Some chloritization may occur along the fractures (Fig. 25). Nevertheless, the amphibole is far more resistant to alteration than are most of the other minerals.

Clinopyroxene is occasionally found in the cores of large amphibole megacrysts in the Ferrouillet amphibolites (e. g. in samples B 713, 74529). It has a rounded or irregular form, and is considered to be an igneous relict mineral, alien to the metamorphism of the Ferrouillet amphibolites.

Staurolite and kyanite are chiefly confined to the mica-schists in the vicinity of Lac Crop and the Col de la Mine de Fer (e. g. in B 673, 674, 74545, 74546; see Fig. 30, 31). Both minerals are often altered to a considerable extent into masses of sericite. Where sufficiently large fragments of the original crystals remain, they are easily identified. The staurolite shows its usual pleochroism from light yellow to colourless and has a distinct axial dispersion r > v. In rare cases a simple twinning was observed.

Tourmaline, though less frequent than in the St. Hugon schists, is a common accessory, especially in the mica-schists. It usually has a yellow-brown colour. In some cases greenish or pale-blue cores were observed. On one occasion an aggregate of crushed brown tourmaline fragments was found in a mylonitic zone (B 703). Some of these fragments showed fringes of authi-

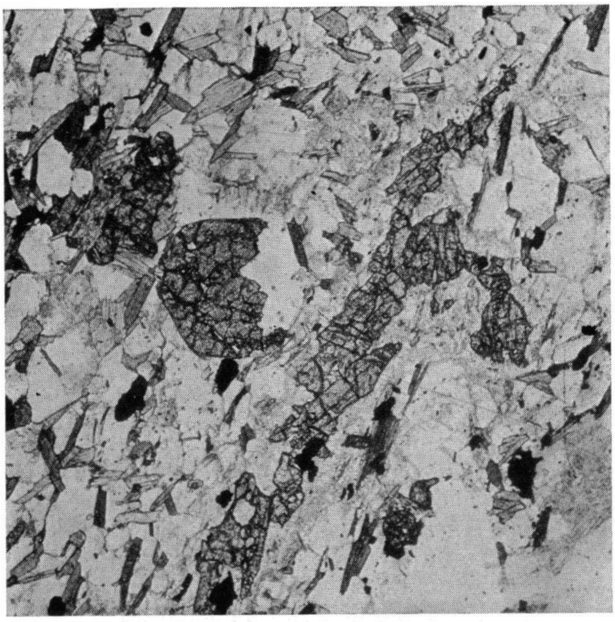


Fig. 30. Garnet (left) and staurolite (right) in biotite-schist of the Lac Crop formation. Same sample as Fig. 29, plane-polarized light, 30 ×.

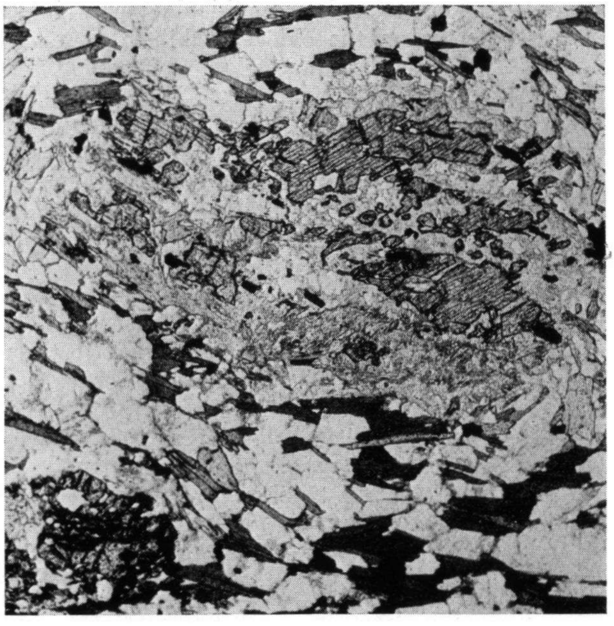


Fig. 31. Garnet (lower left) and partly sericitized kyanite in biotite-schist of the Lac Crop formation. Same sample as Fig. 29, plane-polarized light, 32 ×.

genic blue tourmaline, though less conspicuous than those occurring in the Grès d'Allevard (cf. p. 257).

E p i d o t e may be present in both amphibolites and mica-schists. In some epidote-amphibolites containing light-coloured amphibole the epidote crystals may have the same age as the other main constituents of the rock.

Generally, however, the epidote occurs as a secondary mineral, either in veins or in small crystals dispersed through the rock. One sample with massive structure (74541) was found to consist exclusively of amphibole and grey clinozoisite. A curious case is presented by B 736, where part of a band of biotite-schist has been replaced by epidote; the former biotite flakes are recognized by their form and brown colour.

O r t h i t e is rather rare, but it may occur in both mica-schists (e. g. B 574a, 707) and amphibolites (75071). The pleochroism is in brown-red.

T i t a n i t e is one of the most abundant accessories. It is a typical constituent of the amphibolites, but it is sometimes equally found in the mica-schists. Especially in the former rocks the mineral often displays its characteristic lozenge-shaped sections. In crushed rocks the mineral is not altered, but seems to be spread out easily into vein-like trends (e. g. B 251). Perhaps transport during dynamic metamorphism is sometimes responsible for its presence in chloritized mica-schists.

R u t i l e is sometimes found as tiny needles within biotite or green hornblende. It may also occur as rounded yellow-brown grains dispersed through the rock (e. g. in B 674, B 675), or — rarely — as euhedral prisms (B 574a).

A p a t i t e and z i r c o n are present in most sections. The size of the former may reach 2 mm in rare cases (B 674).

O r e m i n e r a l s such as *magnetite* (small octahedrons), *pyrite* (cubic, with rims of limonite), *ilmenite* (with leucoxene, sometimes with rims of titanite) or *hematite* occur in most sections, usually in small quantities.

C h l o r i t e is abundant as an alteration product of biotite and garnet, and in lesser degree, of amphibole. It is not uncommonly found in veins as vermicular aggregates in quartz (e. g. in B 676, 74580). Its birefringence is usually weak, with abnormal interference colours.

S t i l p n o m e l a n e (?) is probably present in much the same way as in the St. Hugon schists: its pleochroism is less pronounced than that of biotite, and it is limited to altered zones. In sample B 697 it accompanies chlorite as an alteration product of garnet.

DESCRIPTION OF SOME SPECIMENS

A. Lac Crop formation.

B 673b. Staurolite- and kyanite-bearing garnet-biotite-schist, Lac Crop (± 867-285).

A green schist, slightly foliated by the presence of thin bands of quartz. Flakes of green-black biotite are readily distinguished. Here and there pink garnets with a diameter of about 1 mm are observed. Dark green very fine-grained bands with a dull lustre represent mylonitic zones.

Under the microscope the main body of the rock is seen to consist of plagioclase and olive-green biotite in granoblastic structure (Fig. 29). Many biotite flakes with sizes of 0.1—0.9 mm show the curious rims of feldspar described on a former page (p. 223, Fig. 23). The plagioclase has a composition of about 35 % An and may show reversed zoning. Lamellar pericline and acline twinning are of more frequent occurrence than albite twinning; other types of twinning are not found. Numerous faintly pink or colourless garnets occur in more or less even distribution. Their form may be euhedral, as in Fig. 28, or very irregular with numerous inclusions. The size of the garnets is roughly equal to the length of the biotite flakes. Quartz is confined chiefly to veins, where it may form large anhedral crystals up to 3 mm in diameter with pronounced undulatory extinction. Staurolite and kyanite are rather sparsely present: apart from a few small crystals one thin section contained only one group of larger staurolite crystals (Fig. 30), another thin section a group of kyanite crystals (Fig. 31). Crystals of apatite, rutile and (?) magnetite are numerous; the apatite may reach the size of the garnets in rare cases. Zircon and brown tourmaline are less frequent. Small crystals of epidote and pyrite are associated in clusters. On the whole the rock is little altered. There is some sericitization of the plagioclase, chiefly along the crystal boundaries. Chlorite is rather sparsely present as an alteration product of biotite or garnet. It is generally characterized by a distinct pleochroism in green and by anomalous brown or smoke-grey interference colours. A mylonitic part visible in one of the thin sections consists of a very fine-grained mesostasis of chlorite, sericite, quartz, (?)titanite, epidote, etc., with larger, rounded or lens-shaped, but little altered plagioclase crystals. Coarser-grained chlorite and epidote with some carbonate occur in a vein-like zone between the unaltered rock and the mylonite.

B 574a Fine-grained garnet-biotite-schist, Col de la Mine de Fer (± 870-282).

This sample is of a grey schist without banding. On the schistosity planes numerous individual flakes of dark biotite are seen with a diameter of about 0.5 mm on an average. Thinner flakes are brown or may even closely resemble muscovite. Surfaces transverse to the schistosity show a predominance of the light-coloured constituents. The whole, with its fine grain and its uniform mineral distribution, gives the impression of a schistose hornfels.

Under the microscope small flakes of brown biotite (up to 0.7 mm in length) are seen to be evenly distributed in a parallel arrangement. They are embedded in a granoblastic mass consisting of plagioclase and quartz. The plagioclase crystals are 0.1—0.3 mm in diameter, the quartz crystals are somewhat smaller. No banding is visible. The plagioclase crystals show less twinning than in sample B 673b, the laws are the same in both cases. Rims of feldspar along biotite are again found; they are thinner and less numerous than those occurring in sample B 673b. The plagioclase is partly altered into albite and sericite (see Fig. 21), rarely also into adularia. In the latter case the altered parts may be small sharply bounded rectangles. Numerous colourless garnets with a diameter of 0.1—0.7 mm occur dispersed through the rock. Some chloritization of biotite and garnet occurs in the vicinity of veins filled with adularia (Fig. 20), quartz, carbonate or chlorite. A single crystal of orthite (0.4 mm in diameter) was found. Other accessory constituents include apatite, rutile, ore minerals and some brown tourmaline.

B 698 Amphibolite, Col de la Mine de Fer (869-283).

The sample has a rather massive structure, apparently without banding. It consists of roughly equal amounts of plagioclase and dark green amphibole. The short amphibole prisms, with sizes of 1—2½ mm, show an indistinct linear arrangement. Thin white veins of feldspar — with some ore — intersect the sample in a direction transverse to the poorly developed schistosity.

Seen under the microscope the amphibole crystals show a tendency to form meshy aggregates stretched in the direction of the schistosity. The rest of the rock is essentially made up of plagioclase crystals with sizes of up to 0.7 mm. The amphibole shows a pleochroism from light grey-green to colourless. Its birefringence was found to be about 0.019, its optic axial angle about 85°(—), its extinction about 13° (c/n_γ). Many of the larger amphibole crystals show rather sharply defined patches consisting of minute inclusions. The composition of the plagioclase may reach 40 % An. A count was made of the different types of twinning encountered in the plagioclase crystals of this sample (see p. 223, Fig. 27). Apart from these two main constituents, a few flakes of red, brown biotite were found, partly altered into a nearly colourless chlorite with weak birefringence and negative elongation. Titanite is of frequent occurrence, mostly in elongated clusters of rounded grains. Other accessory minerals are apatite and ilmenite (partly altered into leucoxene).

75047 Amphibolite, Crêt du Boeuf (915-378).

A grey-green rock of much smaller grain size than the former amphibolite. On fresh surfaces the feldspar is almost invisible. The majority of the tiny green amphibole needles point in the same direction, which gives the rock a somewhat fibrous character. Here and there porphyroblasts of amphibole are seen, more equant in shape and up to 3 mm in diameter.

Under the microscope the main body of the rock appears to consist of equal amounts of plagioclase and a blue-green hornblende. Fig. 26 shows a section transverse to the lineation. In a section parallel to the lineation, the lengths of most of the hornblende needles are seen to vary from 1 to 1½ mm; their thickness rarely exceeds 0.1 mm. The hornblende is distinctly pleochroic, with n_γ pale blue, n_β grass-green, n_α light yellow. Twins according to (100) are of frequent occurrence. Porphyroblasts of hornblende, which may show inclusions in the same way as described from the former sample, are occasionally found. The size of the plagioclase crystals, in which twinning is not abundant, usually varies between 0.2 and 0.3 mm. Here and there thin bands of about 1—2 mm in thickness are found, consisting almost entirely of plagioclase crystals, with diameters of 0.3—0.8 mm, in a mosaic structure. Granular aggregates of clinozoisite may be found in the centre of these bands. Numerous ore crystals and dark golden grains of rutile occur dispersed through the rock. Veins of adularia may be bordered by finely granular epidote, while almost non-birefringent chlorite may occur near the centre of the veins.

B 673 Biotite-garnet-amphibole-schist, Lac Crop (867-285).

On the schistosity planes the sample shows numerous biotite flakes of dark or golden colour in a fine-grained dark green mesostasis. The schistosity planes are rather irregular and show an indistinct lineation due to microfolding.

Garnets occur as protruding nodules with diameters of up to 7 mm. Surfaces transverse to the schistosity show the greater part of the sample to consist of amphibole and plagioclase with some garnets. The biotite seems to be chiefly present in thin bands along which the rock usually fractures.

Under the microscope the main constituents appear to be amphibole, plagioclase, quartz, biotite and garnet. The amphibole is a blue-green hornblende. The numerous porphyroblasts of this mineral (measuring up to 2.5 mm in the direction of the b axis, and up to 6 mm in the direction of the c axis) show a pronounced poeciloblastic structure chiefly due to the presence of inclusions of quartz and plagioclase. Green-brown flakes of biotite in a more or less decussate arrangement are mostly confined to certain thin bands of the rock. The plagioclase crystals, up to 0.5 mm in diameter, often show reversed zoning and pericline twinning. Garnet is present as large poeciloblastic crystals. The anhedral quartz crystals show some undulatory extinction.

74539 Hornblendite, Col de la Mine de Fer (868-283).

A green-black rock consisting of tiny needles of amphibole. The lineation is less pronounced than in most of the amphibolites. The thickness of the needles is of the order of 0.5 mm or smaller; occasionally megacrysts about 5 mm in diameter are encountered.

Under the microscope the rock is seen to consist almost entirely of a blue-green hornblende. There is a considerable variation in the sizes of the crystals. Although the direction of the lineation may be recognized in the thin section, many crystals show a haphazard orientation. The following optical properties were measured:

n_α	1.657	colourless to light yellow
n_β		bright green
n_γ	1.675	blue
$n_\gamma - n_\alpha$	0.018	
$(-)2V$	70°	

These values should be handled with care, because the optical properties are often seen to vary within the same crystal. The cores of many crystals show lighter colours and a stronger birefringence than the rims. Alongside veins of calcite some hornblende crystals are partly altered into a colourless amphibole. Grains of ore (ilmenite?) with rims of titanite occur in various sizes. Both minerals are also found separately, or associated with calcite, which mineral fills veins, and rarely interstices between hornblende crystals. Apatite is of frequent occurrence, isolated or in clusters of a few euhedral crystals.

B. Ferrouillet amphibolites.

B 694 Amphibolite with band of light-coloured amphibole-gneiss, Lac Crop (867—291).

The amphibolitic part of the sample is almost black and of a very fine grain. It seems to consist largely of minute needles of green-black amphibole in strictly linear arrangement. An indistinct banding is visible in a direction roughly parallel to the boundary with the gneiss.

The amphibole-gneiss shows a rather massive structure with a grain size of 0.5—2 mm on an average. But for the linear arrangement of the amphibole prisms its appearance is dioritic. The gneiss is richer in light constituents than most of the amphibolites and amphibole-schists.

Under the microscope, the amphibolitic part is seen to consist of equal amounts of a blue-green hornblende and plagioclase. The hornblende needles show a great variation in size; a length of 4 mm is reached in exceptional cases. The needles are rather evenly distributed through the rock. In the plagioclase crystals twinning is of rare occurrence. Numerous crystals of ore and some prisms of apatite occur dispersed through the rock.

In the gneissic part plagioclase is by far the most important mineral. The other main constituents are blue-green hornblende, quartz and epidote. Some porphyroblasts of plagioclase with diameters of up to 4 mm are poeciloblastic due to the presence of numerous drop-like inclusions of quartz. The size of these inclusions is much smaller than that of the quartz crystals occurring outside the porphyroblasts. Crystals of epidote are chiefly found in clusters. These occupy a considerable part of the rock in the neighbourhood of the boundary with the amphibolite.

B 713 Amphibolite with coarse-grained pyroxene-bearing band, Ferrouillet (877—296).

On megascopical examination the sample is not much different from B 694. The amphibolitic part forms a fold, in the core of which the pyroxene-bearing rock is found. The amphibolite seems to have a rather uniform structure; a band, 0.5—1 cm in thickness and somewhat finer in grain size, occurs along the boundary with the pyroxene-bearing rock. In both rock types the lineation is less distinct than in the corresponding parts of B 694.

Under the microscope 50—60 per cent of the amphibolite is seen to be made up of a green hornblende. Plagioclase is the only other main constituent: quartz is not found. Rounded or spindle-shaped crystals of titanite occur in comparatively large quantities.

The pyroxene-bearing rock is of a rather chaotic structure. The mesostasis consists chiefly of plagioclase crystals of 0.1—0.4 mm in diameter, frequently with lamellar twinning. In this mesostasis megacrysts of plagioclase and clinopyroxene are found with diameters of up to 4 mm. In the plagioclase megacrysts combined Carlsbad and albite twinning is of frequent occurrence. The crystals may show reversed zoning; often an irregular pattern of extinction is found, due partly to zoning, partly to deformation of the crystals. Epidote, carbonate and sericite occur as alteration products of the plagioclase. The clinopyroxene crystals are partly altered into hornblende, especially the rims. The clinopyroxene has a lighter colour, a stronger birefringence and a larger extinction angle than the hornblende. Thin bands of amphibolite associated with aggregates of epidote and finely granular carbonate are occasionally found in this part of the sample.

The An content of the plagioclase may reach 70 %. This figure is based upon the supposition that we are dealing here with low-temperature plagioclase, which is probably the case.

B 678b Crushed leucogranitic gneiss, Pas de la Coche (902—308).

The sample is almost white and looks like a schistose aplite. On the schistosity planes numerous isolated flakes of muscovite are found with diameters of 0.5—2 mm. On a polished transverse section the structure is seen to be lenticular, the lenses — of the order of 1—3 mm — consisting of feldspar.

TABLE IV.

Chemical composition of samples of the Lac Crop formation and the Ferrouillet amphibolites.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO_2	58.85	65.66	49.93	49.70	67.02	51.62	52.20	63.09	49.74
Al_2O_3	17.21	17.16	17.99	14.40	20.64	15.74	17.28	17.58	20.27
Fe_2O_3	2.92	1.00	1.90	4.01	0.33	3.54	4.72	2.85	2.24
FeO	5.24	4.52	5.59	8.80	0.13	5.11	5.22	1.82	4.92
MnO	0.03	0.33	0.19	0.21	tr.	0.17	0.23	0.08	0.58
MgO	3.58	2.28	8.90	6.70	0.14	7.67	5.64	2.00	5.62
CaO	3.58	2.32	8.45	6.73	2.75	8.69	5.69	3.00	9.79
Na_2O	3.73	3.40	3.45	4.07	8.94	4.00	5.88	7.18	3.40
K_2O	1.80	1.43	1.08	0.95	tr.	0.43	0.18	0.25	0.80
H_2O+ H_2O-	1.80	1.32	1.90	2.47	0.25	1.88	1.21	0.74	1.75
TiO_2	1.15	0.88	0.93	2.13	0.28	1.20	1.64	0.84	1.13
P_2O_5	0.25	0.17	0.16	0.23	0.10	0.13	0.22	0.25	0.20
Total	100.14	100.47	100.47	100.40	100.58	100.18	100.11	99.68	100.44
Niggli-values:									
si	189	264	114	122	275	136	135	231	122
al	33	40.5	24	21	50	24.5	26	38	29
fm	39	32.5	45	17.5	2.5	40	43	24	35.5
c	12.5	10	21	50.5	12	24.5	16	12	26
alk	15.5	17	10	11	35.5	11	15	26	9.5
k	0.24	0.23	0.23	0.13	0	0.07	0.02	0.03	0.14
mg	0.47	0.39	0.68	0.49	0.40	0.76	0.51	0.44	0.57

A. Lac Crop formation

(1) B 673b Staurolite- and kyanite-bearing garnet-biotite-schist, Lac Crop. Analyst: H. M. I. Bik 1958.

(2) B 574a Fine-grained garnet-biotite-schist, Lac Crop. Analyst: H. M. I. Bik 1958.

(3) B 698 Amphibolite, Lac Crop. Analyst: H. M. I. Bik 1958.

B. Ferrouillet amphibolites

(4) 74528 Amphibolite, Pic de Ferrouillet. Analyst: H. M. I. Bik 1958.

(5, 6) 74532 Banded amphibolite; (5) white band, (6) dark band; Pointe du Sifflet. Analyst H. M. I. Bik 1958.

(7, 8) B 694 Amphibolite (7) with band of light-coloured amphibole-gneiss (8), Lac Crop. Analyst: H. M. I. Bik 1958.

(9) B 712 Massive amphibolite with plagioclase megacrysts, Ferrouillet. Analyst: H. M. I. Bik 1958.

A few thin veins filled with quartz occur in a direction transverse to the schistosity.

Under the microscope the rock is seen to consist essentially of crystals of plagioclase, microcline and muscovite in a mesostasis built chiefly by finely recrystallized quartz. The microcline may be identified by its characteristic type of twinning. The crystals are comparatively clear and may show patches of myrmekite along their border. In exceptional cases the myrmekite appears to have replaced a large part of the microcline crystals. The plagioclase crystals usually show a fine lamellar twinning. Many crystals are bent (as is shown by the lamellae) or broken. In the latter case, the fractures may be mended with a filling of albite. All plagioclase seems to be altered into albite and sericite, so that the original content in An is not known. The muscovite flakes, although bent in many cases, seem to have survived the crushing to a surprising degree. They show "tails" of sericite, which mineral is also found dispersed through the mesostasis. Almost all quartz appears to be recrystallized into the finely granular aggregates characteristic for the process of mylonitization.

CHEMICAL COMPOSITION

In Table IV some chemical analyses are given of samples from both formations under consideration. The analyses reflect of course the mineralogical composition of the rocks. In future they will perhaps serve in a review of the chemical composition of all crystalline schists of the Belledonne Massif.

GENERAL REMARKS CONCERNING ORIGIN AND METAMORPHISM

In the former sections we have found the Lac Crop formation to consist of bands of varying composition. A large part of these bands is obviously of sedimentary origin. Pure sediments such as limestones, dolomites and sandstones must have been rare in this formation: we are dealing with a metamorphosed bedded sequence in which the mica-schists represent original shales. As to the amphibolitic bands, it is often difficult to tell whether we are dealing with rocks of sedimentary or of volcanic origin.

As far as the Ferrouillet amphibolites are concerned, an igneous origin seems to be indicated by the uniform composition of the formation, by the occasional presence of possible relict igneous minerals and by the abundance of titanite. Evidence of basic intrusion is rarely encountered. A dyke of hornblendite occurring in the Lac Crop formation was mentioned in a former section (p. 232). Certain bands found in the Ferrouillet amphibolites have a rather massive appearance, but this habit does not necessarily point to a plutonic origin. At all events, all basic igneous activity under consideration, whether intrusive or extrusive, must have happened before the main period of regional metamorphism. It has already been stressed before that the amphibolites occurring in both formations may resemble each other closely. From this fact it may be inferred that the same regional metamorphism has affected both formations. This medium-grade metamorphism is best characterized by the minerals found in the mica-schists in the neighbourhood of Lac Crop, viz. muscovite, biotite, garnet (almandite-spessartite), staurolite and kyanite. The mineral assemblage is indicative of the amphibolite facies. In the classification of J. Jung and M. Roques (1952) the rocks belong to the "micaschistes inférieurs" or the "gneiss supérieurs". It should be noted that the An-content of the plagioclase is higher than that allowed for in this classification. Staurolite and kyanite are the most valuable indicators of the degree of metamorphism. Unfortunately, both minerals are easily destroyed by retrograde metamorphism. Therefore, it is not known whether their absence in the Pleynet valley points to a diminishing of the original grade of metamorphism. More likely, these minerals have disappeared as a result of the younger dynamic metamorphism.

The bands of leucogranitic composition occasionally found in both formations may well be younger than the regional metamorphism. In this case they could perhaps be related to the Sept-Laux granite. There is, however, no conclusive evidence to settle the point. The bands are usually crushed to such an extent that the original relationship to the adjoining rocks is completely obscured.

As was already stated in a former section, younger tectonic forces caused crushing and mylonitization in a large part of the rocks in the mapped area. These phenomena are best studied in the Pleynet valley.

CHAPTER IV

THE UPPER CARBONIFEROUS AND PERMIAN SEDIMENTS

FIELD OBSERVATIONS

The Upper Carboniferous sediments

The occurrences are often small and change quickly in character. Since a study of these sediments appears to be of interest for the unraveling of the geological history of the massif, a brief description of some occurrences outside the mapped area will be included. The following occurrences will be discussed:

External zone	a) Granges de Prodin b) St. Hugon valley c) Pinsot
Median syncline	d) Col du Merdaret e) Pré de l'Arc
Internal zone	f) Roche Noire du Pleynet g) Grande Lauzière h) Rochers Rouges

a) Granges de Prodin

About 600 m SE of a small chapel an abandoned quarry and mine entrance (001-561) provide rather poor exposures of various Carboniferous sediments: micaceous sandstone (B 57), black laminated pelites [1] (B 50), coal (B 55), and a black conglomerate with white quartz components about ½—1 cm in diameter (B 47). Though there are slight differences in facies, the occurrence is probably a continuation of that in the St. Hugon valley.

b) St. Hugon valley

An interesting section occurs near the Bens torrent along the forest road from Allevard to St. Hugon at about 930 m altitude (984-524), where a rivulet descends over the vertical Carboniferous strata (dip: 110/90; Fig. 32, 39). Unfortunately, the contacts with the St. Hugon schists on both sides are not exposed. The total thickness of the strata is of the order of 30 m. P. Lory (1895) considered the occurrence to be a pinched syncline. The present author, however, has found no indication of axial folding: probably, at least the eastern contact is a fault. The sediments are chiefly rather coarse conglomerates with a dark quartzitic matrix. This is one of the most resistant rock types of the massif. Although strong stresses must have been exerted

[1]) It may be borne in mind that this term comprises silts as well as clays. A more detailed classification of the sediments is generally impossible because of recrystallization caused by the later dynamic metamorphism.

Fig. 32. Upper Carboniferous conglomerate in the St. Hugon valley (near the Bens torrent, cf. Fig. 39). Note the vertical dip.

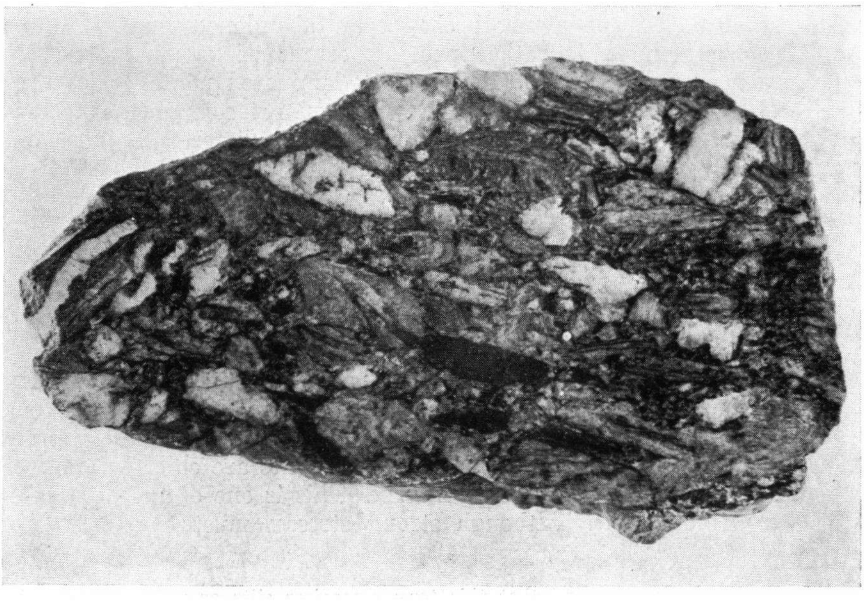


Fig. 33. Upper Carboniferous conglomerate from Pinsot (946-473). Sample B 26, polished surface, natural size.

on the strata, the amount of flattening of the components is negligible. The components, with diameters of up to 8 cm, are chiefly well-rounded pebbles of quartz and quartzite; lenticular pebbles of mica-schist and black graphitic schist are also common. Other rock types, as for example granite, were not found. Thin beds of a black laminated pelite are intercalated between the conglomerates. A few poorly preserved imprints of plant stems were found.

On a higher level, for example at 500 m E of the summit of the Grand Collet, the conglomerate develops into a boulder conglomerate with components up to 40 cm in diameter. It then closely resembles the boulder conglomerate of Vallorcine, which covers a large area between Vallorcine and Martigny (Aiguilles Rouges Massif). The boulders were not studied because of the difficult accessibility of the vertical cliffs in which they are exposed.

c) Pinsot

On the official geological map two lenticular outcrops of Upper Carboniferous rocks are drawn near Pinsot. According to P. Lory (1895) they were exposed as tightly compressed synclines during the construction of the motor road to Fond de France. Nowadays these outcrops have disappeared. The solid rock is to be found near the watershed on the Montagne des Rambaudes and on the western slope of Mont Mayen (e. g. B 20, 960-477). Both general situation and rock types are the same as in the St. Hugon valley. It is obviously a continuation of the same structure; a dip measure: 280/75. Large blocks of the quartzitic conglomerate (B 26, 27, Fig. 33) are found in a wide arc below the outcrops mentioned, especially along the Veyton torrent below 900 m altitude. They are often bounded by thin beds of black pelite along which they have broken off.

d) Col du Merdaret (see map)

There are some differences between the sediments described in the preceding paragraphs and those that are folded and thrust between the external and the internal zone. Conglomerates are far less common here, and instead of the black thinly bedded pelites which accompanied them we find ordinary black slates (B 259), usually showing intense folding and microfolding (Fig. 34). Sometimes beds a few cm in thickness of a grey micaceous sandstone are intercalated. Where the stratification is visible it is usually at angles with the cleavage in the slates (B 275). Conspicuous is the occurrence of disk-shaped impregnations with pyrite, iron oxide or light grey dolomite (B 46). The alteration colour of the slates may be light brown to almost white.

e) Pré de l'Arc (see map)

The zone of Upper Carboniferous sediments passing near the Col du Merdaret continues in a SSW direction. Owing to the gradual downward plunge of the external zone in this direction, the position of the sediments is somewhat different: they are probably situated partly on the crystalline schists of the external zone, partly between the two zones. In this way their position would be transitional to that found farther southward, where the Upper Carboniferous sediments lie simply folded on the La Mure Massif, which has to be considered as a continuation of the external zone.

Along the lower part of the motor road to Pré de l'Arc some outcrops of black slates are found, while a conglomerate associated with such slates occurs near Pré de l'Arc (see description of this section on p. 251).

The hill S of La Boutière consists almost exclusively of black non-calcareous slates (sample B 367), very similar to those occurring near the Col du Merdaret. Light-coloured sandstones are occasionally intercalated. Furthermore, the slates contain some coal seams, corresponding to those found in the La Mure Massif. A small coal-mine situated near La Boutière is now abandoned; mining is difficult here because the coal seams are often deformed or broken by tectonic movements. In the rock debris of the mine numerous

Fig. 34. Intense folding of Upper Carboniferous slates in the median syncline (near the Col du Merdaret).

fragments of coal may still be found. Plant imprints are not rare, but usually in poor condition. Disk-shaped impregnations with pyrite are again found (sample B 364). A capping of the hill with Triassic and Liassic sediments, as indicated on the official geological map (sheet 178, Grenoble), is not present. Calcareous slates of Liassic age and Permian feldspathic sandstones are only found in detached blocks near to the boundary with the internal zone. To the WNW the Upper Carboniferous slates building the hill are bordered by Triassic cavernous limestone.

f) Roche Noire du Pleynet (see map)

This summit is wrongly indicated on most topographical maps, including the just-published 1 : 20.000 Domène sheet. The Roche Noire is not the summit between the Col de Pipay and the Col des Oudis, with its gentle grassy slopes, but the small crag (2129 m altitude, 899-351) immediately N of the Col de Pipay. Its dark colour is due to the presence of Carboniferous conglomerates and slates. A small fault divides the summit in a northern part consisting of slates and a southern part consisting of conglomerates. The slates (B 417), having excellent qualities for roofing, were formerly mined in several quarries on both slopes. They may show a curious "Knitterfaltung" looking like ripple marks. Stratification and cleavage, though in places at angles with each other, are generally almost horizontal, and roughly parallel to the contact with amphibolites of the Lac Crop formation. This contact, exposed on the western slope about 70 m below the summit, is probably a fault, as the amphibolites are mylonitic in its neighbourhood. On the southern side the conglomerates are bounded by another fault with a dip of 130/45. Traces of Carboniferous sediments are found along this plane on the western slope of the "false Roche Noire", while siderite occurs here and there along the same plane. SE of this fault, for example in the Col de Pipay, St. Hugon schists are encountered. This occurrence has already been mentioned in a preceding section.

g) Grande Lauzière

This is a mountain with a complex triangular summit. The "Etude provisoire du Massif de Belledonne" mentions only the name "Tête Noire" for the southern top of the triangle (851-235). Unfornately, this is the only part of the summit consisting of light-coloured gneiss (see p. 262). The gneiss is separated by a small E—W fault from the slightly undulating Carboniferous sediments which cover the rest of the summit. On the western part of the summit the dip is eastward (about 100/10, see Fig. 35), on the eastern part it is westward (about 270/20), so that the capping may be regarded as part of a syncline with gentle slopes. The thickness of the formation is about 50 m on the western summit. Unfortunately the section shown in Fig. 35 was rather difficult to reach, so that a review of the stratigraphy had to be obtained by comparison of a number of smaller outcrops on the complex summit. The contact with the crystalline schists is seen NE of the eastern summit on the crest leading to the Pic du Grand Doménon. Here the schists have a dip of 270/50.

The stratigraphy of the formation and its fossils have been described by L. Moret (1945; see also p. 192). At the base a conglomerate or breccia is found with a thickness of a few metres or less. On closer examination it appears to be a peculiar sediment. Well-rounded components of crystalline schists are rather sparsely distributed in a dark pelitic matrix. Usually, however, the rock has the appearance of a breccia, the components being angular fragments of quartz with diameters of up to 2 cm (B 82). Upward follows a heterogeneous complex of fine- or coarse-grained micaceous sandstones with occasional beds of breccia (B 311) or pelite. Microscopical examination shows part of these rocks to be of volcanic origin (see p. 259, 262). In the black pelitic sandstones flakes of clastic muscovite up to 3 mm in diameter are the most conspicuous element (B 85). Coarser sandstones (B 310) form a transition to the breccias. The

Fig. 35. Weakly folded Upper Carboniferous strata. Western part of Grande Lauzière summit, as seen from the southern part.

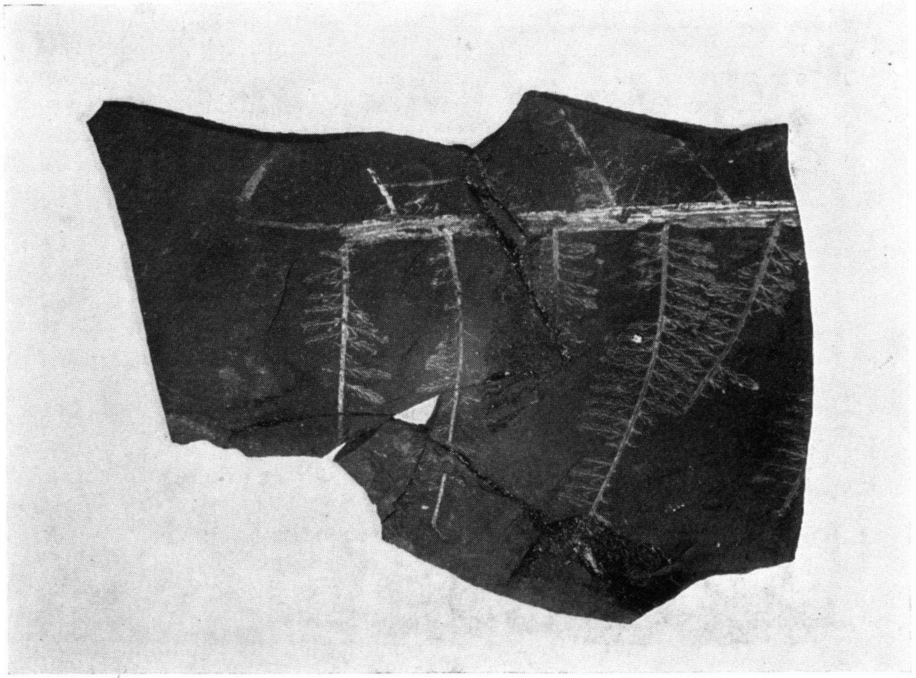


Fig. 36. Upper Carboniferous slate with *Pecopteris feminaeformis* (Schloth.); Grande Lauzière, sample B 301, natural size.

black pelites may show fine neatly parallel layers with a thickness of 0.5—10 mm (B 316, Fig. 37). Here and there beds of grey chert, up to 6 cm in thickness, are intercalated in this part of the formation (B 84). As far as we know chert was not described before from this region. Especially the pelitic rocks may show a brick-red alteration colour, obviously due to the oxidation of iron (e. g. in B 316). It is interesting to note that this colour is frequently found in the Carboniferous sediments occurring on the summits (cf. names as Grandes Rousses, Rochers Rouges, etc.), whereas it is not seen at lower altitudes. The colour is probably caused by the absence of any vegetation at the former localities, which are covered with snow a large part of the year. The explanation would thus be similar to that proposed for the colour of red beds, although the climatic circumstances are very different in each case!

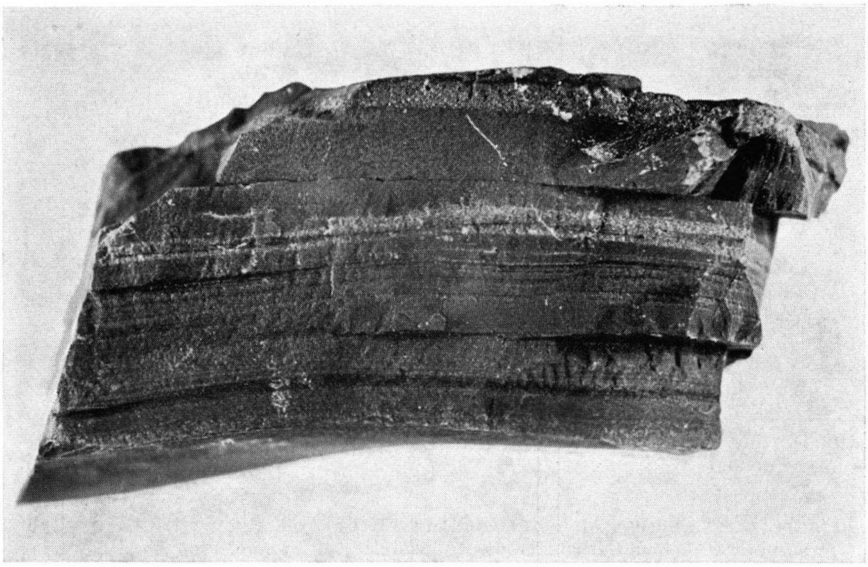


Fig. 37. Thinly layered black pelite. Upper Carboniferous, Grande Lauzière. Sample B 316, natural size.

In the upper part of the formation black slates become important. They are well exposed near the western summit, and may contain very well preserved imprints of ferns. Fig. 36 gives a fair example of *Pecopteris feminaeformis* (Schloth.), a fossil which fits very well in the Stephanian A age already established by L. Moret (op. cit.). The material which gives these imprints their lustre proves to be sericite. On the western summit the slates are overlain by dark micaceous sandstone with debris of plants. The formation is topped by brittle black slates with microfolding (B 89).

h) Rochers Rouges

Another important occurrence of Carboniferous sediments is the tabular summit of the Rochers Rouges (Fig. 38, 864-250) situated between the Croix de Belledonne and the Col de Freydane. Although the distance between the Grande Lauzière and the Rochers Rouges is not more than 2 km, the sediments are distinctly different in each case. Here, their position is again nearly horizontal. The thickness of the formation probably does not surpass 20 m. Micaceous sandstones, graywackes and conglomerates are the only rock types found. The conglomerates are chiefly confined to the lower part of the formation.

The formation is cut by two perpendicular systems of almost vertical joints. One of these systems, of about E—W trend, is visible in Fig. 38; the other, with a dip of about 115/80, is more important and causes the graywackes to part into vertical slabs. In the central part of the summit a block bounded

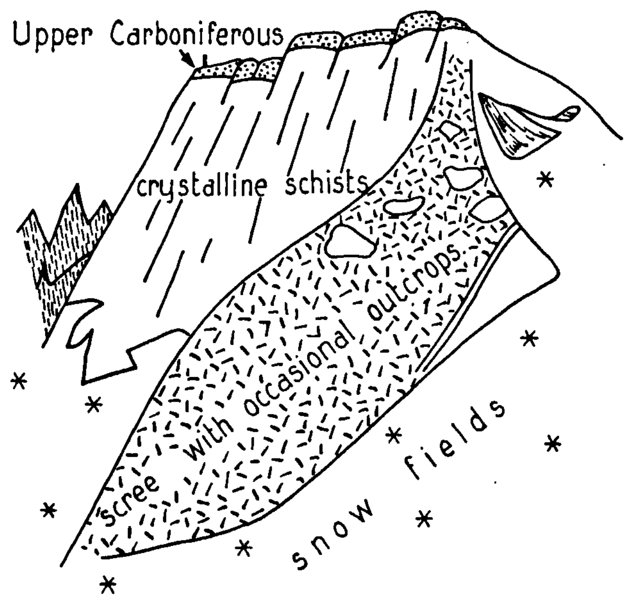


Fig. 38. Field sketch of the Rochers Rouges seen from the West. The horizontal capping of Upper Carboniferous sediments is cut by numerous small faults.

by planes with the same trend has moved upward, so that the conglomerates occurring at the base of the formation are exposed. Finally, a similar trend is found for the schistosity of the underlying crystalline schists, which closely resemble those of the Lac Crop formation. The graywackes (B 95) contain many feldspar fragments and have a dirty green matrix rich in chloritic material. The dark micaceous sandstones (B 327) are very similar to those of the Grande Lauzière. The conglomerates (B 96, 97, 319) differ only from the graywackes in the presence of larger components, which often are rather sparsely distributed through the rock. Microscopic investigation shows both graywackes and conglomerates to consist largely of volcanic material (p. 262). In the field this volcanic origin is not apparent. The larger components, which in exceptional cases reach a diameter of 20 cm, are chiefly rounded pebbles of quartz and light-coloured quartzitic schist. Black pebbles, mostly consisting of serpentinite, do occur (e. g. in B 319), but less frequently than has been suggested by L. Moret (1945) and E. den Tex (1950). There is a gradual transition from the conglomerates to the graywackes, either because the pebbles diminish in size or because they become rarer. Again, single pebble layers occur anywhere in the graywacke. Both rock types show the red-brown alteration colours to which the summit owes its name. All sediments appear to be indurated by silicification. Occasionally thin veins of siliceous material (chalcedony?) are found penetrating the underlying crystalline schists.

The tabular form of the summit illustrates the resistance offered by the sedimentary cover against erosion.

The Permian sediments (Grès d'Allevard)

After the general remarks made in the Introduction we will consider some characteristic Permian exposures in greater detail. With the exception of the Grand Collet all are situated within the mapped area. The Pierre Herse torrent and the road to Pré de l'Arc provide cross sections through the mapped area. Although these sections contain rocks of various ages, their description is included in this paragraph because the Permian rocks appear to be their most interesting feature.

a) The Grand Collet

The Grand Collet (974-509) is a summit with comparatively gentle slopes situated in the immediate vicinity of Allevard. It is one of the localities from which an angular unconformity between Permian and Upper Carboniferous sediments was described by P. Lory (1895; cf. Introduction, p. 193). When we study a geological map of the Grand Collet (Fig. 39) we get the impression that his opinion is right. The narrow elongated outcrop of almost vertical Carboniferous strata, which is best exposed near the Bens torrent in the St. Hugon valley, was described in a former paragraph (see p. 237). The Carboniferous sediments are bounded on both sides by St. Hugon schists. A characteristic section of these schists, occurring some distance downstream, was described on p. 197. On a higher level, the Grès d'Allevard are found over a comparatively large area in a weakly folded almost horizontal position. Seen from a distance, this structure is clearly denoted by the beds of conglomerate or feldspathic sandstone occurring near the base of the formation in the southern slope of the Grand Collet. On close examination, however, the stratification is only visible where the boundaries between different types of sediment are exposed. On the other hand, the cleavage, which has a steep eastward dip, is a conspicuous feature in all pelitic and arenaceous rocks of the formation [1]). On crossing the Grès d'Allevard region from W to E over the ridge situated S of the Grand Collet, we find many abrupt changes in the nature of the sediments, while traces of Triassic cavernous limestone recur several times. As the very gentle folding cannot be responsible for these facts, we may assume the existence of a number of small faults of about NNE direction (parallel to the general trend of the massif). The eastern boundary of the Permian sediments, which here show a gentle dip to the ESE, is formed by a larger fault with the same strike as the smaller ones. Since the tectonic structure appears

[1]) In a recent paper received after the completion of the manuscript, J. Dondey (1958) gives a brief review of the various rocks encountered in this area. With J. Sarrot-Reynaud (1958) he considers the albite porphyroblasts of the St. Hugon schists to be of Alpine age. The dips of the Permian sediments are described as rather steep: probably the author has confused cleavage and stratification.

to be more complex than it would seem at first sight, we may ask to what extent the relative position of the Carboniferous and Permian sediments is caused by later tectonic movements. In this connection two instances may be mentioned which do not seem to fit very well into the concept of a simple angular unconformity. At 1230 m altitude crushed purple phyllites (T 376, see Fig. 39) were found next to the vertical Carboniferous strata of the "compressed syncline". If these phyllites belong to the Grès d'Allevard — which seems probable — the boundary between the St. Hugon schists and the Grès d'Allevard would run as indicated diagrammatically by a dashed line in

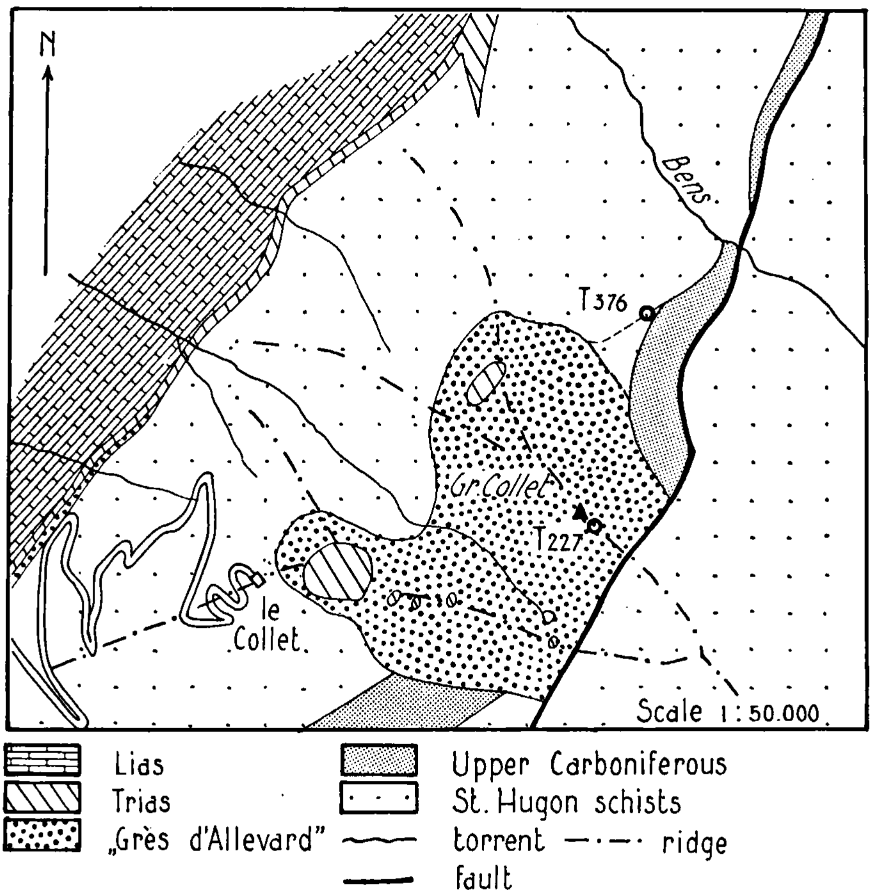


Fig. 39. Geological sketch map of the Grand Collet region, with location of problematic hand specimens (see text). After N. A. L. Touwen, unpublished report.

Fig. 39. On the other hand, the sediments encountered in the lower part of the horizontal formation often resemble the Carboniferous sediments in the "compressed syncline". Immediately SE of the summit of the Grand Collet plant imprints were found by Mr. N. A. L. Touwen of Leyden University, in a dark micaceous pelite (T 227, see Fig. 39). Prof. P. Corsin, who kindly identified them as *Annularia stellata* Schloth. and *Calamites undulatus* Sternberg, considers an Upper Carboniferous (even Westphalian!) age most probable.

These examples suffice to show that a more detailed structural analysis is needed before a definite conclusion can be reached regarding the stratigraphical relations of the Carboniferous and Permian sediments. Perhaps we are dealing with an original disconformity rather than with an angular unconformity. The relative position of the Carboniferous and Permian sediments would then be essentially similar to that described by J. Debelmas (1955) a. o. in more eastern units of the French Alps (e. g. the Briançonnais).

b) Section of the Pierre Herse torrent (Fig. 40)

When we follow the Pierre Herse from the motor road immediately S of Theys upstream, we find at about 900 m altitude in the bed of the torrent between blocks of moraine a few outcrops of nearly horizontal Liassic and Triassic sediments. The Lias is of the usual type: alternating bands of dark limestone (B 202) and calcareous slates (B 201), with occasional drawn-out belemnites. The Triassic occurs as multicoloured dolomite with small cubes of pyrite (B 203, 204) and some cavernous limestone. We are probably dealing here with a mass of sediments glided down from the external zone. An analogous occurrence of Triassic sediments along the Merdaret torrent (870-394) is almost entirely covered with recent travertine (B 353).

At 1000 m altitude the Grès d'Allevard appear as red pelites with a dip of 45° WNW. In spite of their cleavage the rocks are rather resistant to erosion; the bed of the torrent is often smoothly polished and occasionally shows pot-holes. The pelites contain clastic flakes of muscovite in varying amounts; locally, they are rich in dolomite. These pelites, which are similar to those found in the upper part of the Grand Rocher section (see p. 192) occur as a monotonous formation from 1000 m to 1090 m altitude (cf. B 356), interrupted solely by a band of white feldspathic sandstone about 3 m in thickness (at 1050 m, sample B 207).

At about 1090 m, near the base of a small waterfall, the red colour is seen to disappear gradually over a distance of 3 metres (B 209—212). The dip has become steeper here (about 75°). Dolomites are of local occurrence in this sequence (sample B 211).

Upstream of the fall, from 1100 to 1140 m, beds of white or light grey feldspathic sandstone (B 215) alternate with dark thinly layered pelites (B 218). The bands are a few cm to a few dm in width. The black pelites resemble the red ones in their varying content of muscovite and dolomite. Apart from the content in dolomite, they are very similar to the Carboniferous pelites of Pinsot and the St. Hugon valley.

From 1140 to 1200 m altitude the St. Hugon schists are found. Due to the rapid alteration of these schists the outcrops are poorer than those of the Grès d'Allevard. The western contact with the Grès d'Allevard is not exposed. Measurements of the schistosity in the St. Hugon schists reveal the existence of an anticlinal structure: the dip changes gradually from 55° WNW near the western contact to 37° ESE near the eastern contact.

Some small faults cause the Grès d'Allevard to reappear from 1200 to 1240 m altitude. The sediments, which show a gentle dip to the NNW, consist chiefly of conglomerates (B 371, 383) with intercalated beds of light-coloured feldspathic or micaceous sandstone (B 357, 361) and green or grey pelite (B 130). At the upper end of this occurrence, where a forest road crosses the torrent (892-389), P. Lory (1895) described a steeply dipping syncline with Carboniferous sediments, unconformably overlain by the Grès d'Allevard

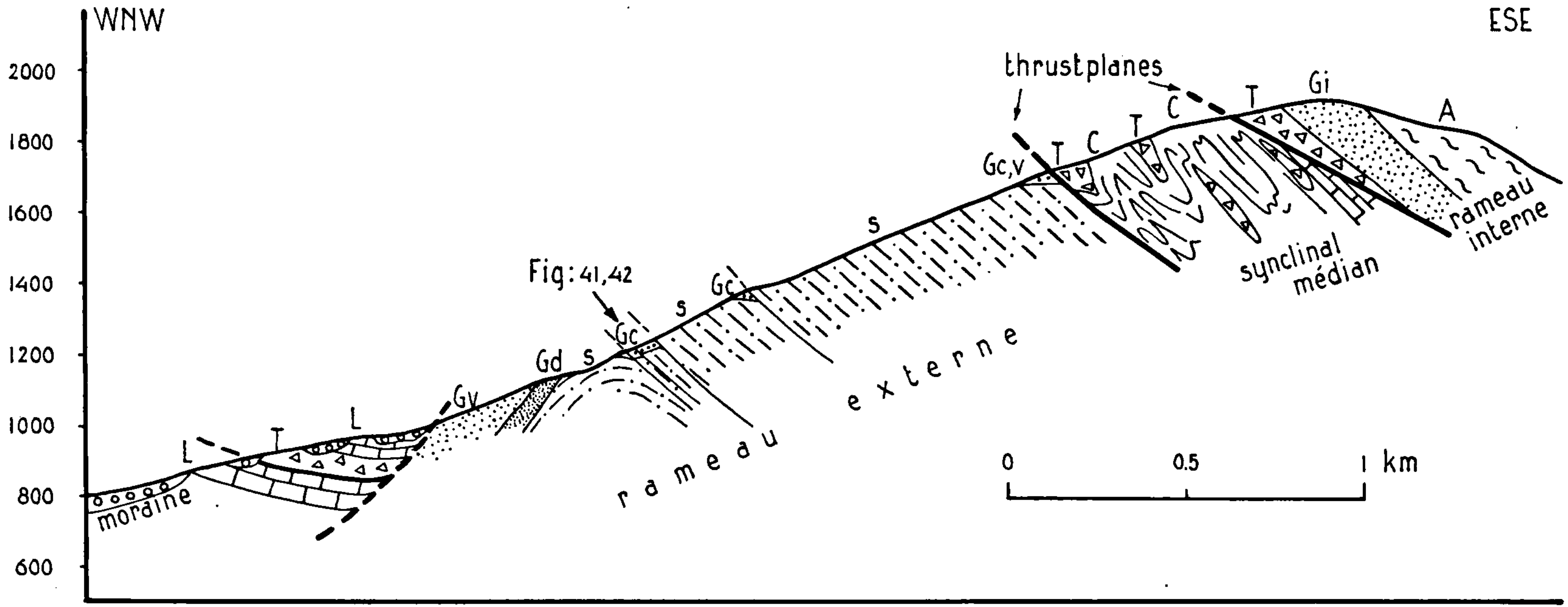


Fig. 40. Section along the Pierre Herse torrent (see map).

L Lias (dark calcareous slates and limestones)
T Triassic (dolomites and cavernous limestones)
G Grès d'Allevard (Permian); v: purple, d: dark, c: conglomerate, i: of internal zone.
C Upper Carboniferous (black slates)
S St. Hugon schists (albite-sericite-chlorite-schists)
A Lac Crop formation (chiefly crushed amphibolites)

(Fig. 41). Plant remains were recorded to occur in the alleged Carboniferous rocks. Unfortunately, Lory's samples are no longer available.

The present author, on the contrary, is convinced of the absence of Carboniferous sediments at this point. The fine-grained members of the formation show a conspicuous cleavage with a steep dip to the ESE, roughly parallel to the small faults. In the banks of the torrent the stratification is the more obvious phenomenon, because the different layers are seen one above the other. In the bed of the torrent, however, the stratification is often not apparent. Here, Lory has possibly mistaken the cleavage and the contacts caused by the small faults for the stratification. As far as the plant remains are concerned, we now know that they may equally occur in the Grès d'Allevard. The interpretation of the present author is illustrated by Fig. 42. A few metres upstream of the forest road the fault contact between Grès d'Allevard and St. Hugon schists is well exposed in the bed of the torrent; it is marked by a quartz vein with chloritic bands of crushed rock.

From 1240 to 1670 m altitude St. Hugon schists are exposed, with a constant steep dip to the ESE (B 278). At 1300 m the torrent follows over some distance a quartz-siderite vein about 1 m in thickness (dip about 75/45). At 1340 m a few metres of Permian conglomerate recur, probably in a similar structure as those found at 1240 m.

At 1670 m altitude the Grès d'Allevard appear again as a conglomerate about 10 m in thickness. The contact with the St. Hugon schists, not exposed in the section proper, is only seen in a small outcrop (902-382) in the immediate vicinity of the Merdaret chalets. The contact is sharp and almost horizontal, signifying an angular unconformity between the two formations. Near to the chalets, the Grès d'Allevard occur over a comparatively large area, the conglomerate being capped by red beds of considerable thickness. In the Pierre Herse valley, these beds are reduced to a thin bed of green pelite and a few metres of red pelite, the whole with an eastward dip of 10°. They are followed by Triassic purple argillites and cavernous limestone. As was stated in the Introduction (p. 194), these sediments usually have moved from their original position during the Alpine folding. Here, they probably belong to the median syncline rather than to the external zone. As is seen on the map, the western boundary of the Triassic sediments appears to be independent of the structure within the external zone: it passes undisturbed the fault situated N of the Merdaret torrent. The following part of the section, from 1700 to 1850 m altitude, intersects the source region of the Pierre Herse torrent. It consists of an intensely folded mixture of Upper Carboniferous slates (B 259) and Triassic cavernous limestone: here we are certainly in the median syncline. Owing to the softness of the rocks the region is marshy, with thick layers of peat. Fortunately, the banks of the small tributaries of the Pierre Herse and the Merdaret often show the underlying rocks. The Liassic slates exposed W of the Crêt du Boeuf and along the Vaugelas torrent are diagrammatically indicated in the section. These, too, belong to the median syncline.

Next comes a white fetid limestone (B 255). Being a representative of the lower part of the Triassic, it probably belongs to the overturned flank of the internal zone (cf. p. 266).

Beyond this limestone, which may have a thickness of about 20 m, the Grès d'Allevard of the internal zone are found at about 1900 m altitude. They are rather heterogeneous, consisting chiefly of coarse feldspathic sandstones (B 411, 413) and micaceous pelites (B 412). Both rock types are purple, but

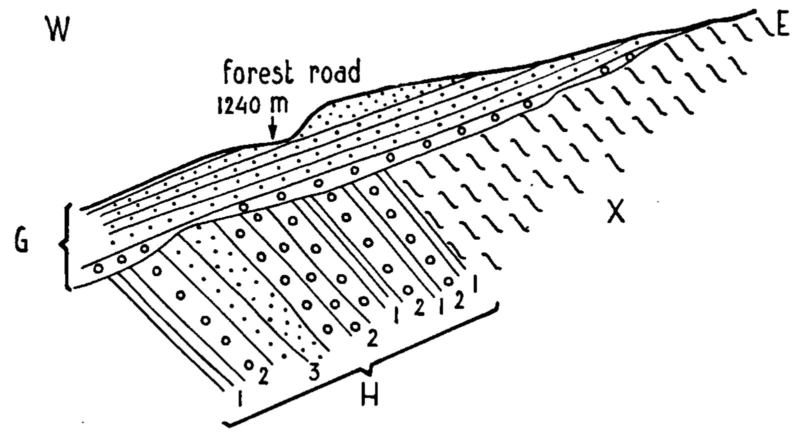


Fig. 41. Section along the Pierre Herse torrent at 1240 m altitude, interpreted by P. Lory (1895) as an angular unconformity of Grès d'Allevard (G) over steeply dipping Upper Carboniferous sediments (H); X: crystalline schists.

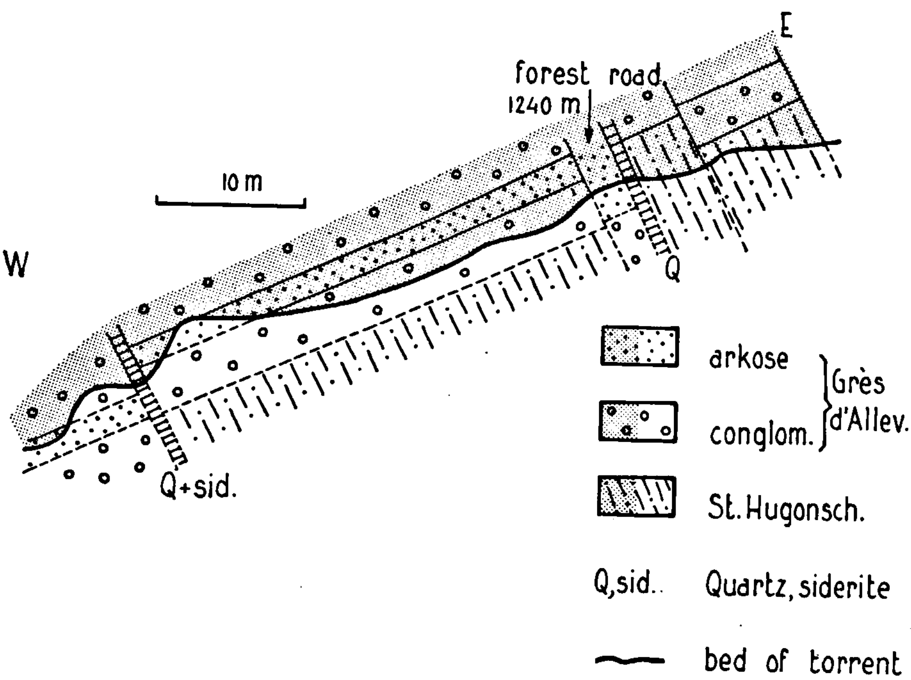


Fig. 42. Roughly the same section as Fig. 41, interpreted by the author as Grès d'Allevard beds cut by a number of small faults. In the bed of the torrent the cleavage in the finer-grained sediments often simulates stratification.

darker and more bluish than the pelites belonging to the external zone. The difference in colour is probably caused by a higher content in chlorite and hematite. The quartz components of the sandstones are mostly of a bright red colour. The Grès d'Allevard of the internal zone will be treated more fully in the description of the Pré de l'Arc section.

The section ends with crushed rocks generally looking like greenschists. Fortunately, certain parts have escaped most of the destructive metamorphism and are easily recognized as amphibolites. Under the microscope the greenschists appear to be partly crushed amphibolites, partly chloritized biotite-schists. Therefore, these rocks were placed in the Lac Crop formation (cf. also p. 213).

Discussion of the Pierre Herse section. The description of this section gives us a welcome opportunity to discuss the complicated stratigraphy and structure in this part of the Belledonne Massif. Firstly we may note that within the area under consideration the Upper Carboniferous sediments are found exclusively in the median syncline. If this is due to Hercynian folding and faulting and subsequent erosion, Alpine movements must still be held responsible for the presence of Triassic cavernous limestones in the same syncline. Besides, both in the external and in the internal zone the Grès d'Allevard are found in direct contact with the crystalline schists. When we focus our attention on the Grès d'Allevard, it appears that a detailed stratigraphical correlation of the various occurrences is very difficult. Comparing the apparently rather complete section occurring from 1000 to 1140 m with that of the Grand Rocher described by P. Gidon (cf. p. 192), the only points of agreement are the total thickness of the sediments and the existence of a stratigraphically lower part of dark colour and an upper part of purple-red colour. The occurrences at 1240 and 1340 m consist chiefly of conglomerate, which rock is not found at the base of the Grès d'Allevard at 1140 m, nor anywhere else in that part of the section. Again, the conglomerate at 1680 m altitude is directly overlain by red pelites which should belong to the upper part of the Grès d'Allevard. Thus the Pierre Herse section furnishes ample proof of the haphazard and rapidly varying type of sedimentation during the Permian.

c) *The northern part of the mapped area*

The reader will see from the map that the Merdaret torrent offers a section very similar to that of the Pierre Herse. Immediately N of the Merdaret a fault is situated. The region N of it is downthrown, so that the Grès d'Allevard, here dipping generally WNW at low angles, cover a considerable part of the western slopes of the Grand Rocher ridge. A large angle between stratification and cleavage (generally dipping steeply SE) is again found in many outcrops (Fig. 43). Sometimes even the sandstones part into slabs parallel to the cleavage. The plant imprints mentioned in the Introduction were found 1 km SW of the Grand Rocher (902-399). In an abandoned quarry 400 m to the SW (900-390) black pelites (B 239) and grey feldspathic sandstones and dolomites of the lower part of the Grès d'Allevard are well exposed; here the dip is about 50° NW.

d) *The section of the road to Pré de l'Arc*

The Grès d'Allevard of the internal zone are best studied along this motor road, which branches off from the main road from Allevard to Uriage in the village of Prabert, at 1000 m altitude.

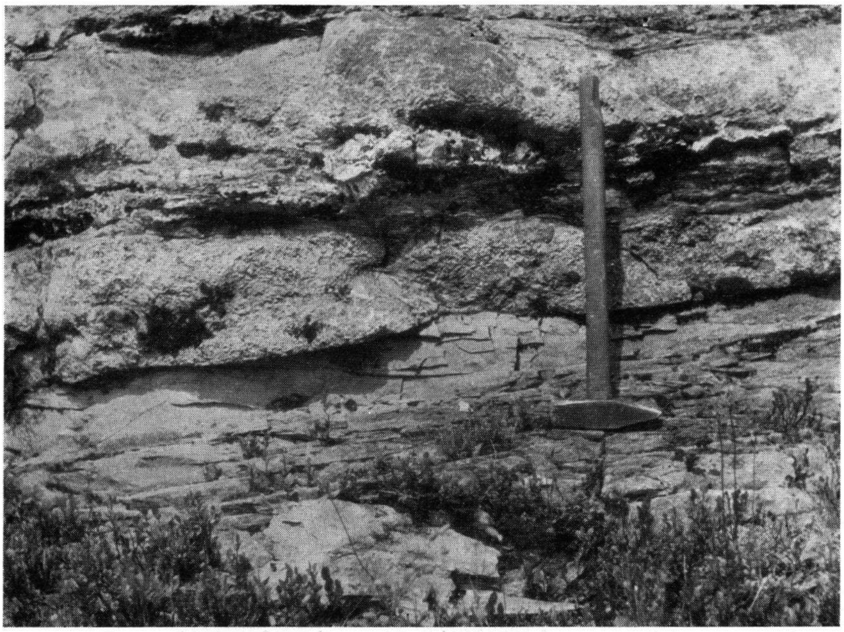


Fig. 43. Alternating sandstones and pelites of the Grès d'Allevard between the Col du Merdaret and the Grand Rocher. The stratification dips about 25° NW, the cleavage in the pelites about 60° SE.

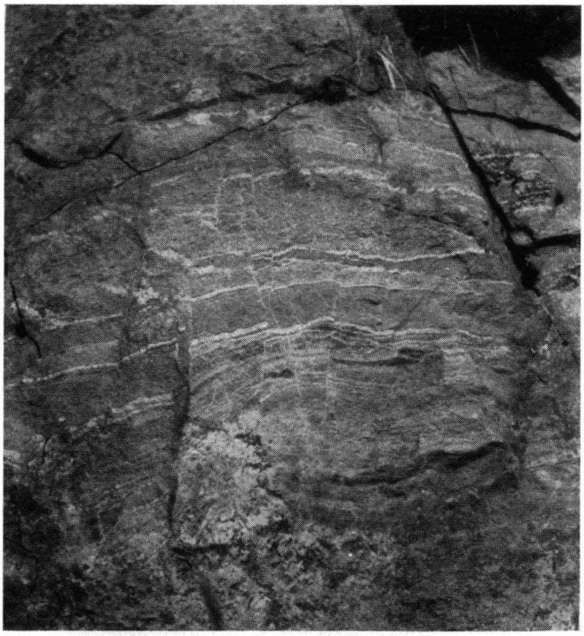


Fig. 44. Small faults in thinly bedded Grès d'Allevard, along the motor road to Pré de l'Arc at 1490 m altitude.

From 1000—1090 m moraine deposits are found, covering the depression between the Belledonne range and the Liassic hills. At 1090 m the cavernous limestone of the Triassic is found in a number of exposures over a distance of about 250 m (74381). It contains angular components of white limestone and small fragments of purple or green phyllite (74384). The cavernous limestone is often weathered and broken up in detached blocks, so that it is difficult to ascertain its original position. Just before a small bridge near the end of the exposure a blue-grey dolomite with white dolomite veins occurs.

From 1140—1200 m altitude isolated outcrops of black Carboniferous slates occur, suggesting the existence of one coherent zone of Upper Carboniferous similar to that S of La Boutière (cf. p. 240). A first small outcrop of Grès d'Allevard is found at 1300 m altitude. Immediately beyond this outcrop crushed rocks of the Lac Crop formation are exposed from 1300 to 1450 m altitude. Their banded character is often clearly visible, for example behind the ruins of a hut in the turn of the road.

At 1450 and at 1490 m altitude the Grès d'Allevard of the internal zone are well exposed in large road-cuttings. The whole sequence, dipping about 20° to the SE, is cut by two conspicuous vertical joint-systems with strikes of 130° and 220°, respectively. Two distinctly different rock types are found here, viz. dark blue-purple pelites and light-coloured feldspathic sandstones. The pelites usually show a distinct cleavage approximately parallel to the stratification. On closer examination beds of slightly differing grain sizes may be distinguished (B 375, 378). The feldspathic sandstones are rather coarse-grained and nearly white, with many green (chlorite) fragments (B 376). They contain quartz-hematite veins which end abruptly against the pelites. The pelites and sandstones usually alternate in beds several metres in thickness, rarely in very thin beds (Fig. 44). Mr. A. J. A. Janse of Leyden University has made an effort to determine top and bottom of the sequence. He found current bedding in pelite cut off by a bed of sandstone (Fig. 45a), cracks and a scour channel in pelite filled with sandstone (Fig. 45b), and graded bedding (Fig. 45c). All these point to an overturned position of the Grès d'Allevard. This is in accordance with their actual position underneath the crystalline schists of the internal zone, on which they were probably deposited.

At 1520 m altitude in a turn of the road just before the hairpin of Pré de l'Arc the Triassic reappears over a distance of about 20 m as light yellow, partly cavernous limestones. A comparison with the Pierre Herse section suggests that we have now arrived in the median syncline. Continuation of the section removes all doubt: pelites and sandstones of the Grès d'Allevard recur over a distance of 1 m, followed by some metres of various Permian and Triassic rocks such as purple argillites (74621), dolomitic limestones and purple and green slates. It did not seem worth while to study them in any detail: they represent an intensively deformed zone along the thrust plane of the internal zone.

In the hairpin of Pré de l'Arc from 1540 to 1570 m altitude black Carboniferous slates are exposed, comparable to those found in the Pierre Herse section. Locally beds of sandstone are intercalated. Rather coarse conglomerates are also found, for example 60 m beyond the hairpin along the motor road, on the ridge W of the hairpin, and in numerous detached blocks NNW of the Pré de l'Arc chalet. Ten metres after the conglomerate along the road the purple argillites are again found in a small quarry (they were used for the

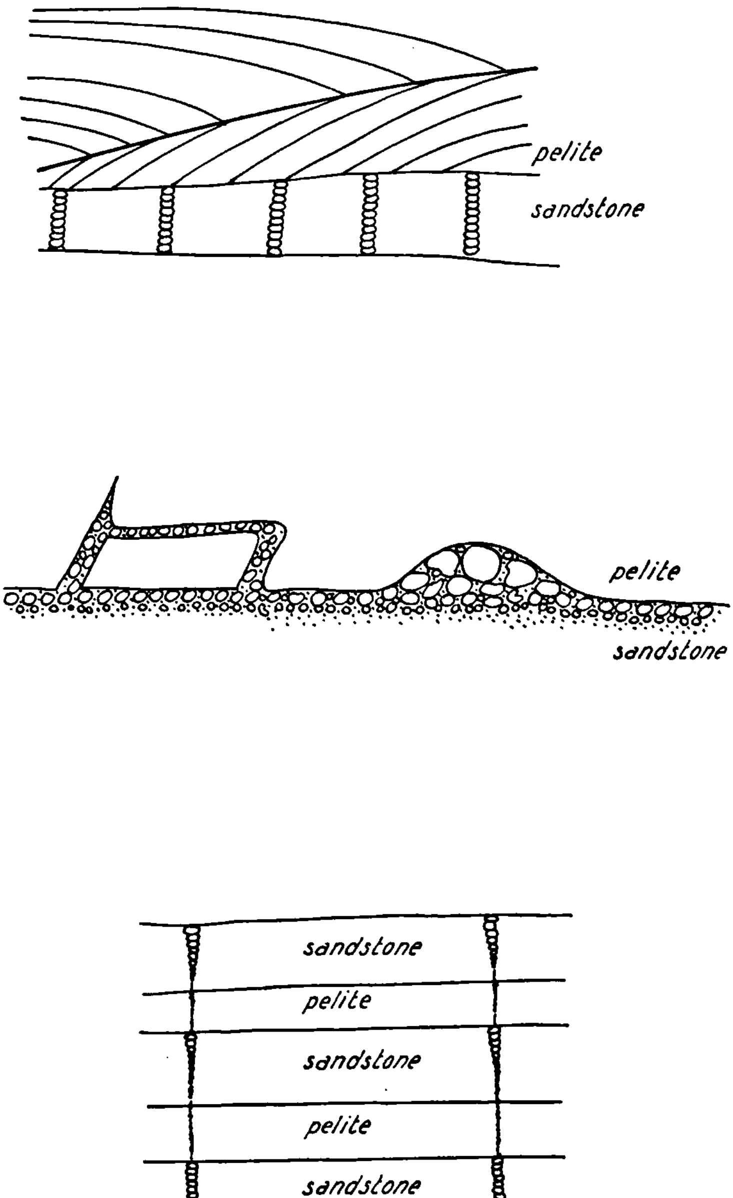


Fig. 45. Top and bottom criteria suggesting an overturned position of the Grès d'Allevard of the internal zone. The grain size of the sandstones is diagrammatically indicated by the vertical columns. Pré de l'Arc (A. J. A. Janse, unpublished report).

construction of the road). From here up to 1590 m nothing but a few blocks of cavernous limestone are found.

Between 1590 and 1600 m altitude over a distance of about 200 m we cross again the Grès d'Allevard of the internal zone. Measured in a direction perpendicular to the stratification we find:

± 5 m	conglomerate with pink quartz fragments (B 392);
± 20 m	dark blue-purple pelites (B 393) (not exposed continuously);
± 10 m	somewhat coarser pelite (B 394) alternating with greenish micaceous sandstone (B 395); in the upper part some slaty pelite;
± 4 m	white feldspathic sandstone;
± 1 m	dark blue-purple pelite;
± 4 m	green slaty pelites (B 402) and sandstone (B 400);
± 3 m	white feldspathic sandstone;
± 3 m	green slaty pelite.

It will be seen that the total thickness of the Grès d'Allevard of the internal zone is here of the order of 50—60 m.

From 1600 m onward the Lac Crop formation is seen overlying the Grès d'Allevard. Near the contact, which is not exposed, the rocks of the Lac Crop formation are intensely crushed to greenschists. Possibly, the contact is a thrustplane. Yet, this plane should be far less important than that between the Grès d'Allevard and the median syncline: the little folded Grès d'Allevard obviously belong to the internal zone. Near the first small ravine at about 1610 m altitude the amphibolitic members of the Lac Crop formation are easily recognized.

After the completion of the field work the construction of the road by the "Electricité de France" was continued to an altitude of about 1750 m.

PETROGRAPHY

In the microscopical study of the sediments no attempt was made to apply the specific methods of sedimentary petrology. There seems to be no fundamental difference between the Upper Carboniferous and the Permian sediments as far as their petrography is concerned. Therefore, they are treated together in this section.

The boulders and pebbles of the conglomerates are usually well-rounded. Under the microscope the conglomerates appear to be ill-sorted. The smaller fragments are usually subrounded or subangular. Conglomerates with such properties usually belong to the polymictic group. However, the rocks in question are oligomictic in that almost all components consist of quartz or quartzitic schist. Few crystalline schists known from the Belledonne Massif were recognized with certainty among the components. The quartzitic schist might derive from the St. Hugon schists.

The finer-grained sediments and the matrix of the conglomerates are generally very similar. Both usually contain feldspar (albite). Therefore, the former are named feldspathic sandstones throughout the present work. Some albite crystals have been identified as original porphyroblasts of the St. Hugon schists. They may show the same simple twins and the same trends of included rutile needles. The presence of the latter excludes the possibility that the porphyroblasts were formed within the conglomerate. Besides, sometimes only part of a porphyroblast is found, which also suggests a clastic

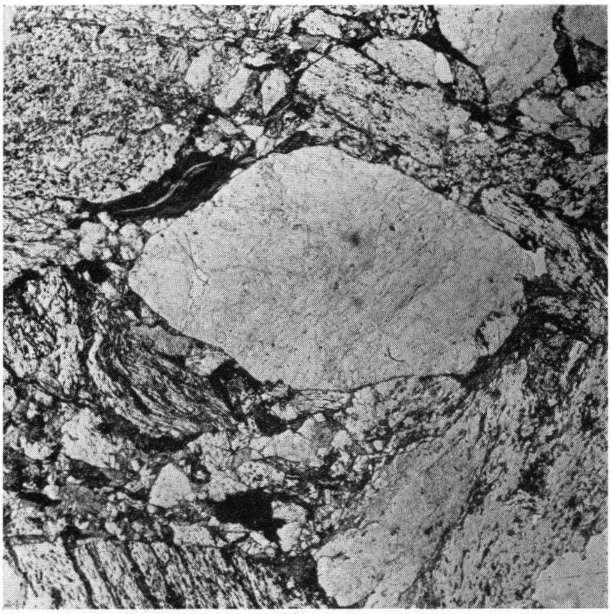


Fig. 46. Ill-sorted conglomerate with poorly rounded components (mainly quartz and sericite-chlorite-schists). Sample B 27, Upper Carboniferous, Pinsot. Plane-polarized light, 6 ×.

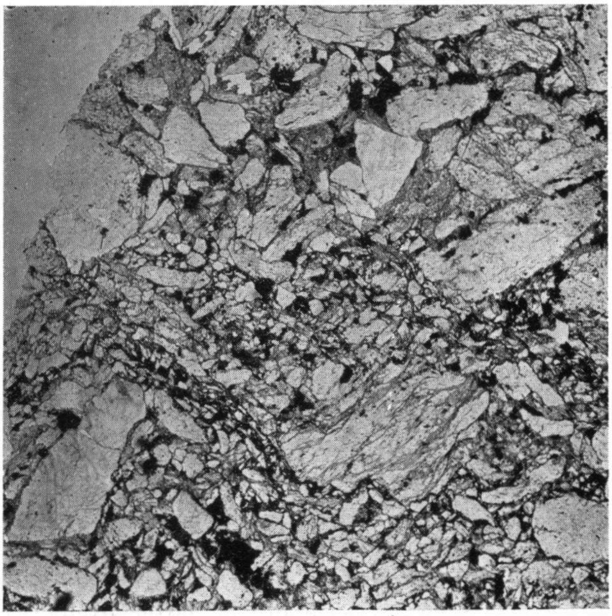


Fig. 47. Conglomerate of essentially the same type as in Fig. 46, though less dark megascopically. Sample B 39, Grès d'Allevard, Grand Collet. Plane-polarized light, 6 ×.

origin. Other feldspar grains show lamellar twinning. Flakes of colourless mica, biotite and chlorite are of common occurrence. All may show inclusions of rutile. Part of the colourless mica seems to have a phengitic composition ($-2V = 0°$). The biotite is always brown, but the intensity of the colour may vary from one sample to another. Most of the chlorite displays the same optical properties as that in the crystalline schists: weak birefringence, abnormal interference colours and distinct pleochroism from light green to almost colourless. Another type of chlorite, which is most frequently encountered in the Grès d'Allevard of the internal zone, shows a higher birefringence (about 0.009) and a negative elongation; it is pleochroic from light bluish green to colourless. The dark mesotasis of a quartz-conglomerate of the Grande Lauzière (sample B 82) was found to consist mainly of an intergrowth of

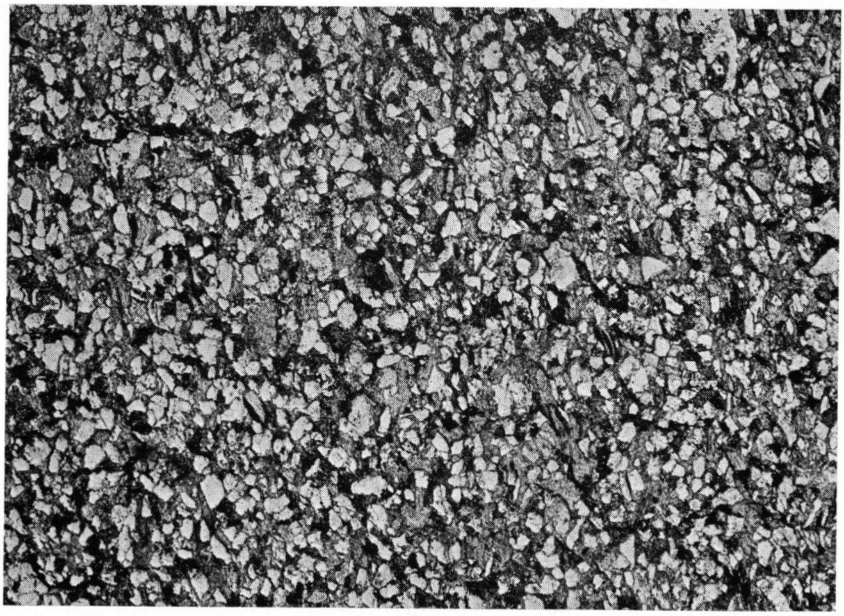


Fig. 48. Feldspathic sandstone. The components are for a large part of rhyolitic origin. Sample B 41, Grès d'Allevard, Grand Collet. Plane-polarized light, 12 ×.

chlorite and brown stilpnomelane. The mode of occurrence of these minerals strongly suggests an authigenic origin. Clastic grains of brown or olive-green tourmaline are not uncommon. In a few cases fringes of authigenic blue tourmaline were observed along clastic grains of brown tourmaline (e. g. in B 41, Fig. 50). Similar fringes were reported by F. Ellenberger (1949) as products of Alpine metamorphism in sediments of the Vanoise. Regardless of the surface on which they have grown, the fringes are always stretched in the direction of the c axis. The hemimorphic symmetry of tourmaline is reflected by the fringes being chiefly confined to one side of the grains. A similar habit of authigenic tourmaline was reported by M. H. Stow (1932) in the Oriskany sandstone. Pyrite may be present in well-formed pentagonal dodecahedrons.

The pelitic rocks usually contain flakes of colourless mica, biotite or chlorite. The mesostasis is generally too fine-grained to permit further determination. Local recrystallization is due to the younger dynamic metamorphism. In some cases the mesostasis consists largely of sericite, carbonates or hematite.

Traces of acid volcanism in the Upper Carboniferous and Permian rocks

A rhyolitic fragment found in a feldspathic sandstone of the Grès d'Allevard at Bout du Monde (933-496) near Allevard gave the first clear proof of acid volcanic activity before or during the Permian (Fig. 49). In this fragment

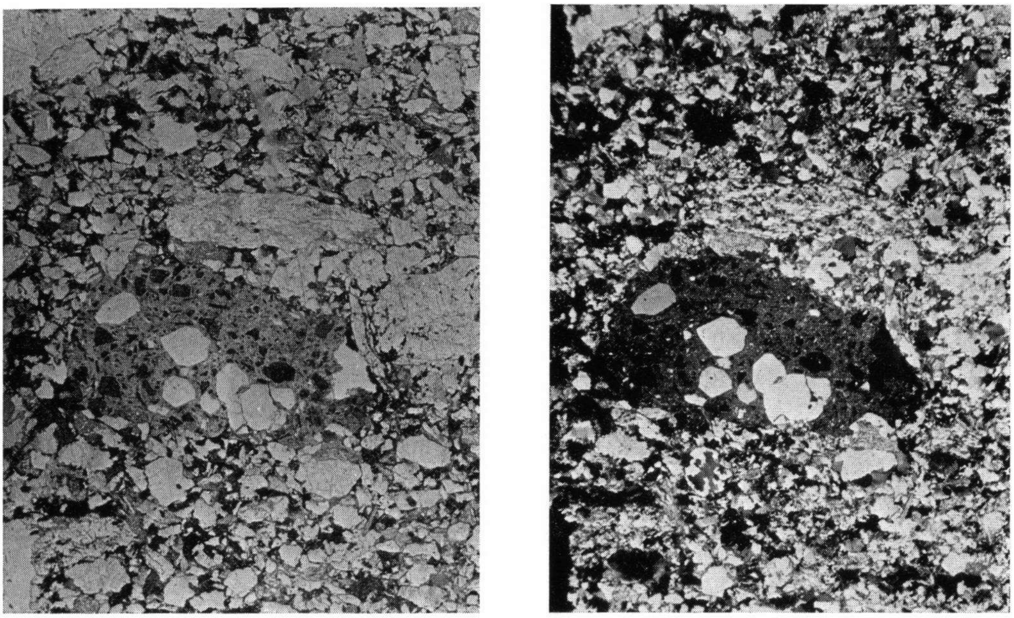


Fig. 49. Rhyolitic fragment in feldspathic sandstone. Note bipyramidal form and absence of wavy extinction of the quartz phenocrysts. The dark phenocrysts are completely chloritized. The groundmass is microcrystalline. Sample Y 62, Grès d'Allevard, Bout-du-Monde. Left: plane-polarized light, right: crossed nicols, 6 ×.

the phenocrysts are clear bipyramids of quartz and completely chloritized dark constituents. The groundmass is microcrystalline. A careful study of phenocrysts and groundmass enabled the author to recognize smaller rhyolitic fragments in many Permian and Upper Carboniferous rocks. The quartz phenocrysts are identified by their euhedral bipyramidal form and by the absence of wavy extinction. In favourable cases small remnants of the groundmass still attached to the phenocrysts facilitate recognition. The groundmass itself might be confused with the very fine-grained quartz aggregates caused by mylonitization. In cases where the microcrystalline mass appears to be associated with crystals not showing any trace of deformation, the choice is not difficult, however.

In many samples the mesostasis of the pelites strongly resembles the groundmass of the rhyolite. The frequent occurrence of muscovite or biotite flakes in these rocks is consistent with a tuffaceous origin. In one sample found in the Upper Carboniferous of the Grande Lauzière (848-238) this origin is clearly demonstrated by the presence of neatly six-sided flakes of biotite and of a sharply euhedral crystal of zircon (Fig. 51). The traces of

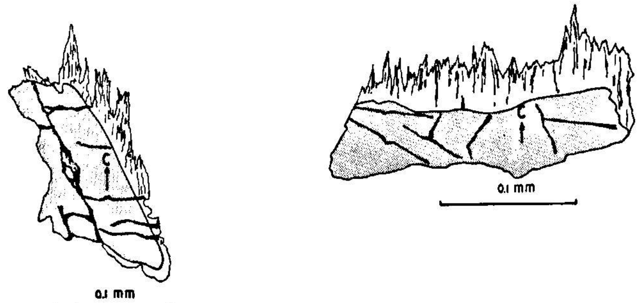


Fig. 50. Clastic grains of brown tourmaline with fringes of authigenic blue tourmaline. Note that the fringes have grown parallel to the c-axis of the clastic grain, and almost exclusively in one direction, reflecting the hemimorphic symmetry of tourmaline. Sample B 41, Grès d'Allevard, Grand Collet.

volcanism thus far mentioned were found in Upper Carboniferous and Permian pelites and feldspathic sandstones of all occurrences described in the present work. Within the mapped area they are most numerous in the Grès d'Allevard. When we further take into consideration the rarity of material derived from

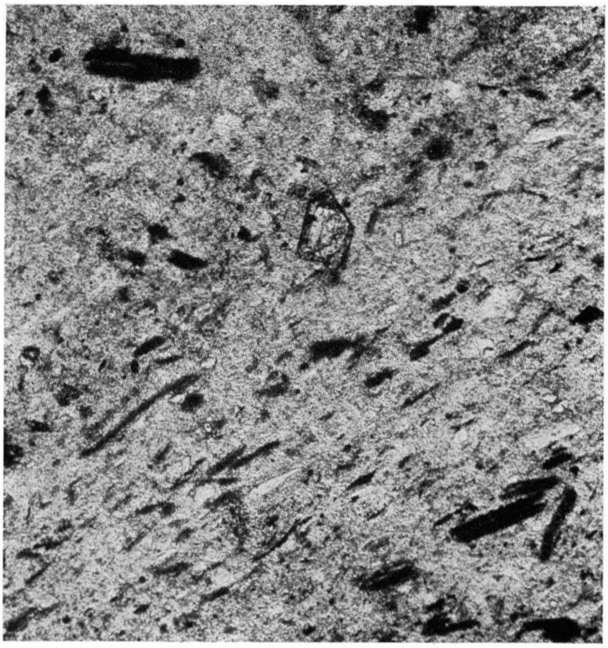


Fig. 51. Fine-grained tuff with many flakes of brown biotite and a perfectly euhedral crystal of zircon. Sample B 83, Upper Carboniferous, Grande Lauzière. Plane-polarized light, 75 ×.

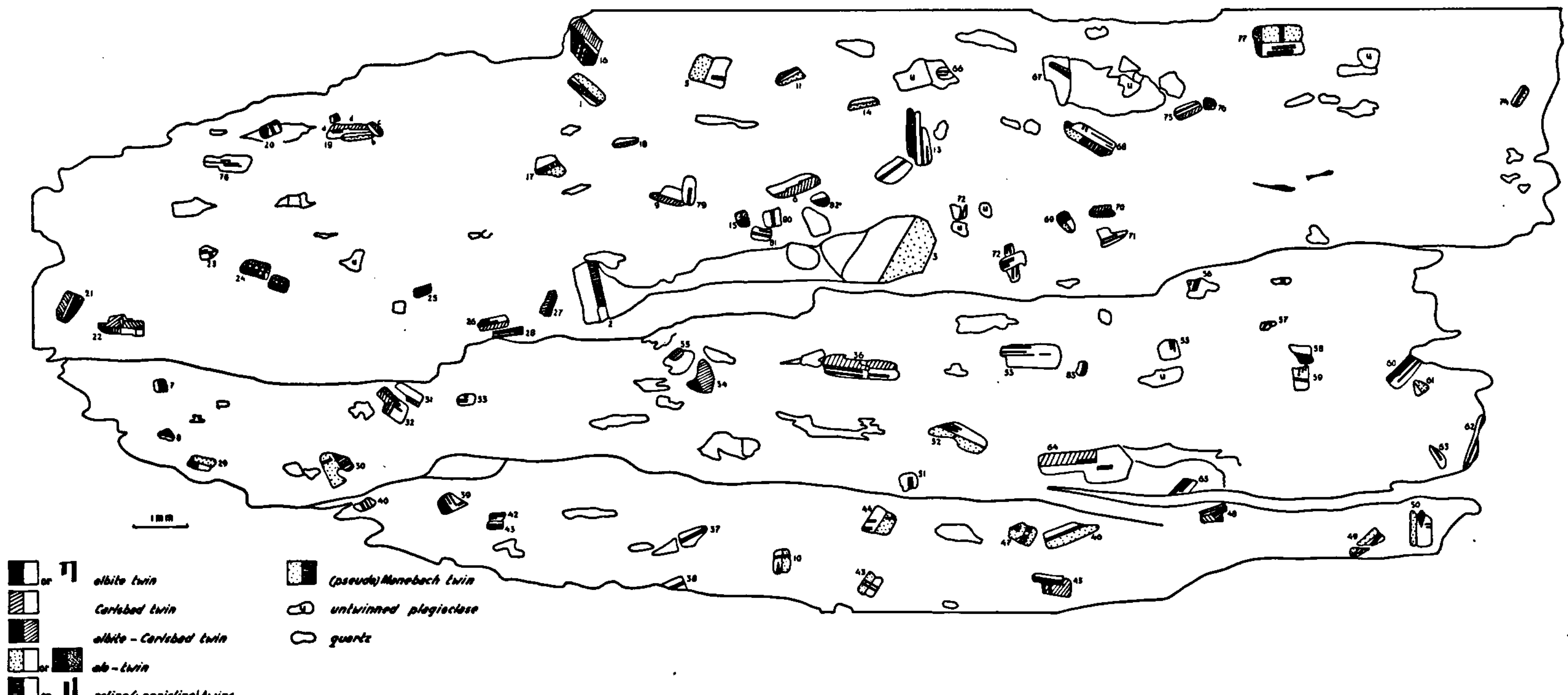


Fig. 52. Diagram of a thin section, indicating mode of occurrence and twinning of the albite megacrysts in a schistose rhyodacitic dyke (B 81, Grande Lauzière).

TABLE V

Chemical composition of some samples of the Upper Carboniferous and the Grès d'Allevard.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SiO_2	85.47	59.22	55.49	56.86	76.22	74.18	81.54	60.80
Al_2O_3	6.92	18.41	29.23	22.04	13.49	9.38	7.62	20.70
Fe_2O_3	0.36	3.68	1.02	4.32	0.89	0.63	1.03	6.53
FeO	1.52	5.60	1.34	3.74	2.12	1.04	0.90	tr.
MnO	0.03	tr.	tr.	0.06	0.07	0.15	0.06	tr.
MgO	0.84	2.39	0.39	2.07	0.84	4.08	1.42	1.52
CaO	0.96	0.36	0.53	0.60	0.10	2.25	1.82	0.25
Na_2O	0.73	1.97	0.60	1.06	0.47	1.43	1.42	1.03
K_2O	1.16	2.43	6.72	3.64	3.00	1.69	1.81	5.38
H_2O+	1.19	4.24	4.49	4.55	2.85	1.50	1.08	2.90
H_2O-	0.10			0.20	0.07	0.08	0.05	0.22
CO_2	—	—	—	0.24	0.12	2.96	1.04	—
TiO_2	0.43	1.13	0.39	0.74	0.21	0.10	0.17	1.04
P_2O_5	0.26	0.08	0.21	0.24	0.10	0.34	0.27	0.09
Total	99.97	99.51	100.41	100.36	100.55	99.81	100.23	100.46
Niggli-values:								
si	922	228	220	215	536	414	647	254
al	44	42	68.5	49	56	31	35	51
fm	30	43	10	36	26	42	29	30
c	11	1.5	2.5	2	1	13	16	1
alk	15	13.5	19	13	17	14	20	18
k	0.50	0.45	0.88	0.70	0.80	0.44	0.45	0.77
mg	0.46	0.32	0.24	0.33	0.33	0.81	0.58	0.32

Upper Carboniferous

(1) B 27 Conglomerate, Pinsot (946-473). Analyst: B. Hageman 1953.

(2) B 95 Greenish graywacke, Rochers Rouges (863-250). Analyst: H. M. I. Bik 1958.

(3) B 83 Grey fine-grained tuff, Grande Lauzière (848-238). Analyst: H. M. I. Bik 1958.

(4) B 417 Black slate, Roche Noire du Pleynet (902-358). Analyst: B. Hageman 1953.

(5) B 84 Bedded chert, Grande Lauzière (848-238). Analyst: B. Hageman 1953.

Grès d'Allevard

(6) B 376 Feldspathic sandstone, Pré de l'Arc (873-321). Analyst: B. Hageman 1953.

(7) B 354 Feldspathic sandstone, Merdaret (877-391). Analyst: B. Hageman 1953.

(8) B 356 Purple micaceous pelite, Merdaret (879-390). Analyst: B. Hageman 1953.

the crystalline schists (especially those of the internal zone), it becomes clear that volcanism must have played an important part in the formation of the sediments. The occurrence of bedded chert (Grande Lauzière) and the general silicification of the sediments are probably related to this volcanism.

Finally, mention should be made of the basal conglomerate at the Grande Lauzière and of the conglomerates and graywackes of the Rochers Rouges. As stated before (p. 244) the conglomerates of these summits contain only a few components of serpentinite or amphibolite. Under the microscope, this observation is confirmed. The majority of the components consist of quartz and of a leucocratic gneissose rock with megacrysts of albite. Exactly the same gneiss was found on the southern summit of the Grande Lauzière, separated by a fault from the Upper Carboniferous sediments covering the northern summits. The mesostasis of this gneiss consists of a fine granoblastic mass of quartz and feldspar with some isolated flakes of muscovite and chlorite. The more or less euhedral megacrysts of albite are twinned in a complicated manner (Fig. 52). Among the twins with (001) as composition face, the apparent presence of the Manebach twin seems to be due exclusively to the joint occurrence of the Ala and acline (or pericline) twins. Baveno twinning is found in a few crystals. This complicated pattern of twinning is thought by Gorai and other authors to be characteristic of igneous rocks. Indeed, it is not found in the normal mica-schists and amphibolites of the Belledonne Massif. We are probably dealing here with a schistose dyke of rhyodacitic composition. Notwithstanding its schistose structure, the author supposes this dyke to be a product of Carboniferous volcanism. Otherwise, it would be difficult to explain the abundance of this particular type of rock in the conglomerates. Moreover, the mesostasis of these conglomerates usually consists largely of a mixture of rhyolitic and rhyodacitic material: the bipyramids of quartz and the very fine-grained matrix described above occur here together with the albite phenocrysts embedded in a somewhat coarser matrix.

CHEMICAL COMPOSITION

In Table V some chemical analyses are given of Upper Carboniferous and Permian rocks. The abundance of SiO_2 is partly due to silicification of the sediments. The abundance of muscovite in some of the samples is illustrated by a comparatively high content of Al_2O_3 and K_2O.

CHAPTER V

THE MESOZOIC AND QUATERNARY SEDIMENTS

The petrography of the Mesozoic and Quaternary sediments was not studied in any detail. A few remarks about their mode of occurrence within the mapped area may suffice.

TRIASSIC

In the external zone the lower ("adherent") part of the Triassic is not represented. The small outcrops of multicoloured dolomite and cavernous limestone along the western boundary of the external zone (cf. p. 247) belong to the upper part of the Triassic. They have probably glided down from the external zone together with the overlying Liassic sediments.

The cavernous limestones of the Merdaret-Vaugelas region belong to the median syncline. They pass the fault N of the Merdaret torrent without showing any offset, and are associated tectonically with Carboniferous slates (cf. p. 249). Being the most characteristic Triassic sediment of the Alps the cavernous limestones merit a brief description. They are usually "exposed" in grassy slopes as apparently detached blocks looking like "gruyère" cheese (Fig. 53). Since such blocks would not endure much transport, they usually indicate fairly well the actual position of the sediments. The stratification is seldom visible. Comparatively fresh parts have the appearance of a breccia (Fig. 54). The white angular fragments consist of dolomite, the matrix of calcite. Rarely, fragments of purple or green phyllite are encountered (74384). On further weathering the rock develops its cavernous character. Another type of cavernous limestone consists essentially of a network of calcitic veins apparently more resistant against weathering than the host rock. Blocks of this type, found near the Col du Merdaret, furnished the small shells mentioned in the Introduction (B 755, 904-380). Several French authors (e. g. E. Haug; A. Cailleux & A. Chavan, 1954; M. Gignoux & L. Moret, 1952) describe the matrix of the "cargneules" as consisting of dolomite. On the other hand, our observations (and those of den Tex, 1950) are in accordance with the extensive studies of W. Brückner (1941) on the cavernous limestones of the Swiss Alps. According to Brückner these rocks have originated by weathering from anhydrite(gypsum)-dolomite deposits, which are frequently found in fresh condition in tunnels. Initially, beds of dolomite interlayered with occasional argillaceous sediments were broken up by veins of anhydrite. Subsequent hydration of the anhydrite to gypsum brought about a sort of brecciation. Finally, most of the gypsum and part of the dolomite were converted into calcite. In the Belledonne Massif, too, important masses of anhydrite have been encountered in tunnels (see e. g. Cl. Bordet 1957). They are usually situated along important fault- or thrust-planes, in a position equivalent to that of the cavernous limestones at the surface. Closely associated with the cavernous limestone a peculiar "schist" is sometimes found (B 245). Its chief constituents are quartz and a bright

Fig. 53. Characteristic outcrop of Triassic cavernous limestone (907-385). In the background the Grand Rocher.

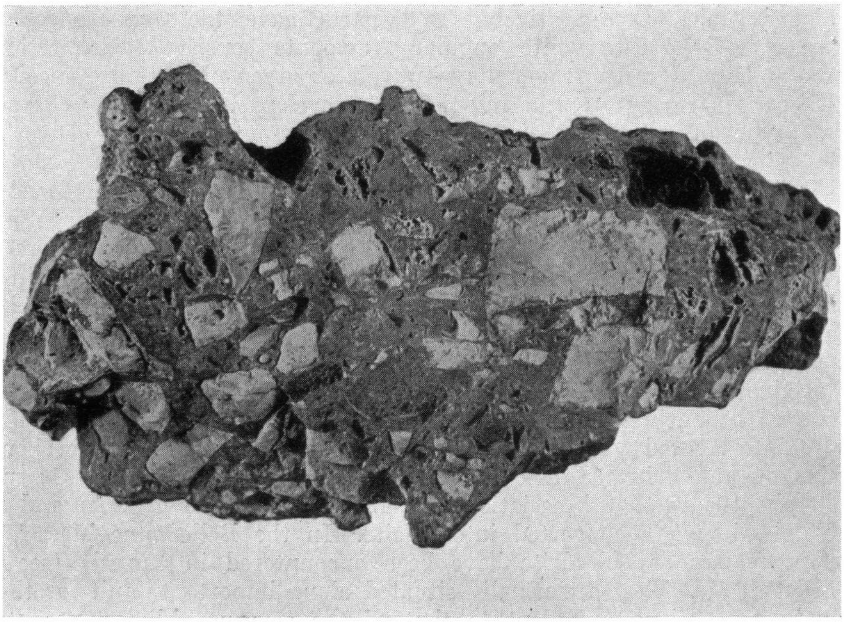


Fig. 54. Triassic limestone with dolomite fragments; when the latter weather out a cavernous limestone results (Grand Collet, sample B 45a, natural size).

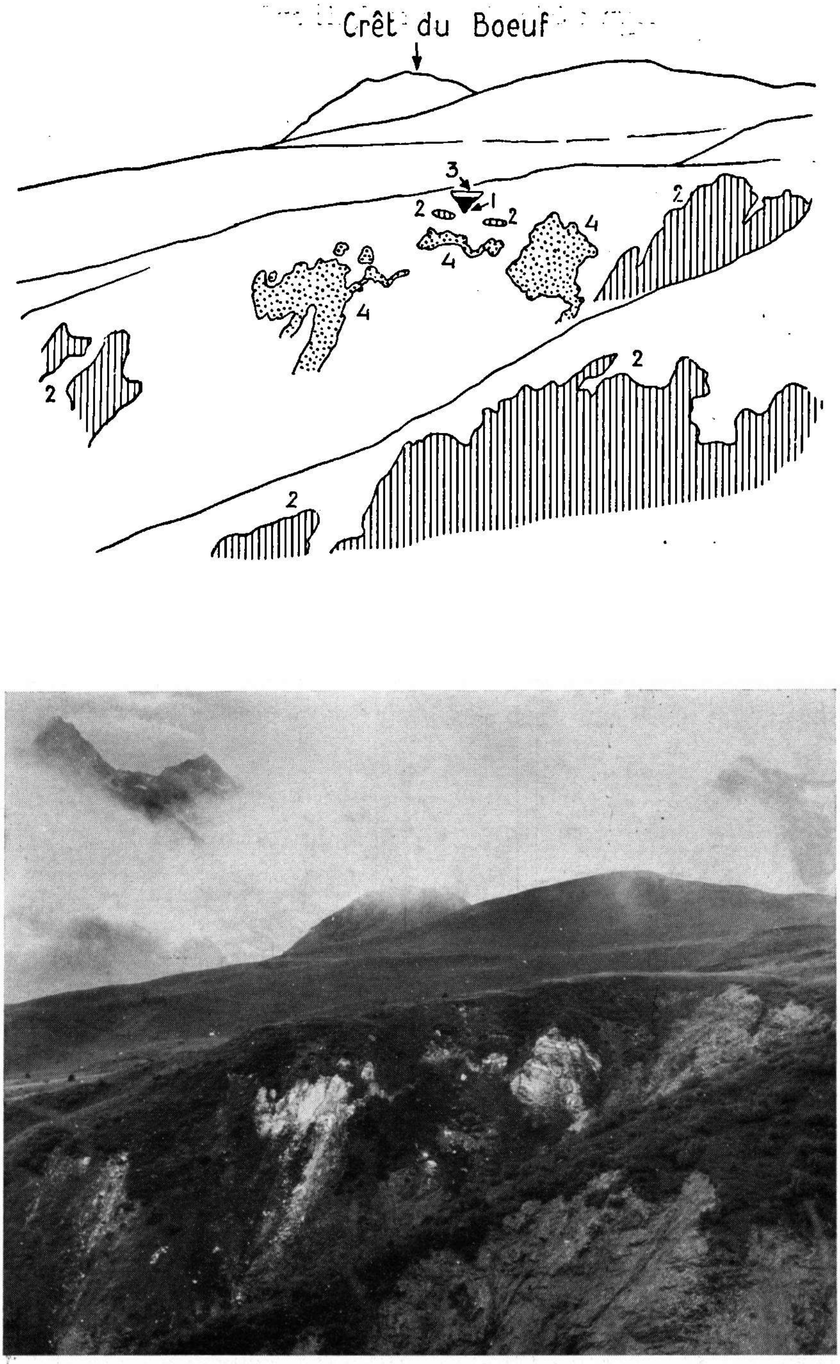


Fig. 55. Situation of the gypsiferous outcrops along the Vaugelas torrent in the median syncline (910-379). 1. Upper Carboniferous conglomerate; 2. Upper Carboniferous slates; 3. Triassic dolomite; 4. Triassic limestone with gypsum.

green mica of unknown origin. X-ray analysis and optical properties of this mineral point to ordinary muscovite. Gypsum has been found surrounded by Upper Carboniferous slates in the southern slope of the Vaugelas torrent (Fig. 55). At one point near the Chalet de Pipay a fetid laminated limestone was found (Fig. 56, B 573, 891-362) adjoining cavernous limestone. The large grain size of the former (average 1 mm) is rather exceptional for the Triassic of the Belledonne Massif.

Along the motor road to Pré de l'Arc, the outcrops of Triassic between 1090 m and 1140 m altitude have the same appearance as in the Merdaret region (cf. p. 253). At 1520 m altitude the Triassic reappears on the other side of the Carboniferous zone. It seems to be mixed by faulting with the

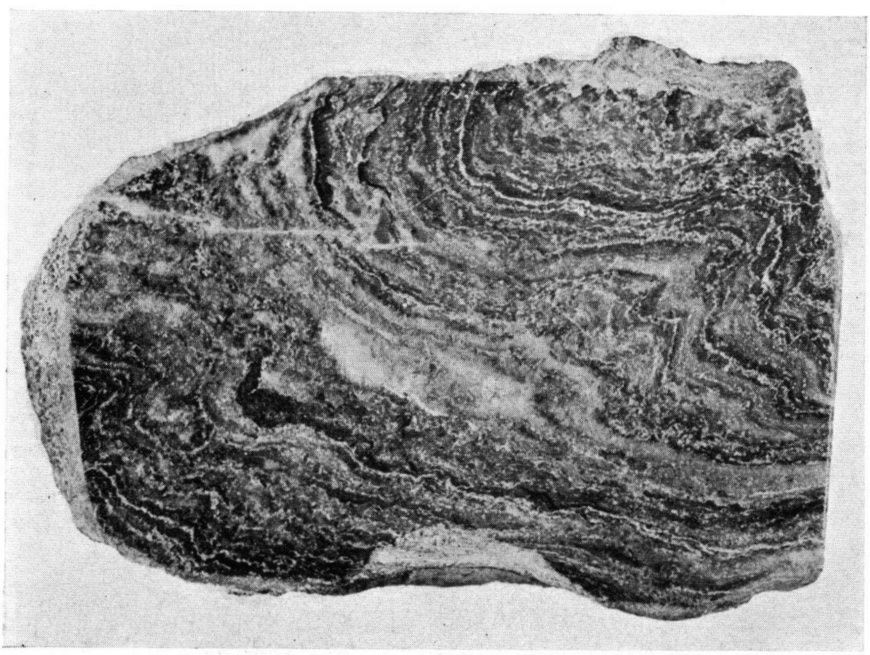


Fig. 56. Triassic fetid limestone from Pipay (891-362). Sample B 573, polished surface, natural size.

Grès d'Allevard of the internal zone. We are obviously dealing with the upper part of the Triassic: cavernous limestone, purple and green phyllites and blue-grey dolomite. The presence of the phyllites is exceptional: in this part of the Belledonne Massif they are chiefly found as fragments in the cavernous limestone. The purple colour corresponds to that of the Grès d'Allevard: reddish near the external zone, a dark bluish tinge here.

Within the mapped part of the internal zone Triassic sediments are found exclusively along its western boundary. Thus, their position is not very different from that of the rocks described in the preceding paragraph. Yet, the author has preferred to treat them separately, because they are thought to belong to the lower, "adherent" part of the Triassic. The most interesting occurrence in this respect is found in the Pierre Herse section at about 1860 m altitude (cf. p. 249). We are no longer dealing with the irregular patches of cavernous limestone of the median syncline, but with a coherent formation chiefly consisting of white fetid limestone. Some 20 m in thickness, it borders the Grès d'Allevard of the internal zone. The outcrops can be followed over a distance of at least 500 m. The author has the impression that no important movements have occurred between the two formations. The contact is not exposed. The second occurrence is situated about 200 m W of the Crêt du Boeuf summit (on the official map both have been drawn as one continuous zone). Here grey dolomites are exposed in a narrow zone between crystalline schists of the Crêt du Boeuf and Liassic slates of the median syncline. The contact with the crystalline schists is not exposed. It could be a transgressive contact, but far more likely the Grès d'Allevard occurring further to the S are cut off obliquely by a fault which passes between the Grès d'Allevard and the Triassic dolomite.

Though the two occurrences under consideration are probably separated from the internal zone by faults, they should nevertheless be distinguished from the occurrences mentioned in the preceding paragraph because of their coherent character and their extension along the boundary of the internal zone.

JURASSIC

About the Jurassic sediments within the mapped area little need be said. They are only found W of the external zone (see for example description Pierre Herse section p. 247) and in the median syncline. In both cases their present position is due to tectonic movements: probably all contacts with other rocks are faults. In the median syncline the Jurassic sediments are found exclusively at the northern and southern ends of the mapped area. It is interesting to note that along the western boundary of the crystalline schists of the internal zone the Jurassic sediments and the Grès d'Allevard are alternately present. Probably they belong to different tectonic units. The southern occurrence has already been mentioned in the paragraph on the Carboniferous of Pré de l'Arc-La Boutière (p. 240).

Nearly all of the encountered Jurassic sediments belong to the "Lias Calcaire", the properties of which are so constant that they could be given in a few lines in the Introduction (p. 194). Non-calcareous slates of the "Lias Schisteux" were found in a small outcrop at the Col de Prabert (74625, 852-345). They are very weathered, but contain identifiable shells (*Posidonomya*) The coarse conglomerate near Theys (Malbuisson, 873-397), which according to the official map is Aalenian, has already been mentioned in the Introduction.

QUATERNARY

In the Introduction a brief description of the Quaternary deposits was given, based on the subdivision of the official geological map. On the present author's map the older (lower) moraines are rendered as one unit. They are found chiefly in the depression between the Liassic hills and the external zone, and cover part of the western slopes of the latter. They are seldom well exposed. Some years ago two different moraines were seen one above the other in a fresh road-cutting along a forest road E of Theys (about 830 m altitude, 879-399). Both are real glacial conglomerates, the lower one with a dark blue clayey matrix (probably reworked Lias), the upper one with a brown sandy matrix. Erratic blocks may be found everywhere in the mapped region; they consist frequently of granite of the Sept-Laux type. As at present all outcrops of this granite lie on the other side of the western mountain chain (Sommet Colomb, Dent du Prat, Cime de la Jasse, Grand Rocher), the granitic blocks must have been transported during an older glaciation by ice flowing across the divide. Outside the mapped area glacial pavements belonging to this glaciation appear to have been conserved e. g. NE of the Rocher Blanc (2800 m altitude, 964-340) and on the Crête de Mouchillon (2500 m altitude, 951-347). The flattened appearance of some cols (Pas de la Coche, Col de Pipay, Col du Merdaret) is partly due to glacial erosion. If, in the light of this evidence, we try to imagine what the morphology of the Belledonne Massif looked like during this older glaciation, it will be clear that enormous changes must have taken place since then, and, especially, that the higher parts of our western chain must have been entirely reshaped. Traces of older glaciations, except occasional erratics, should therefore be scarce in these higher parts of the Belledonne Massif. The author considers all moraines found here to be subrecent or at any rate much younger than the older moraines, because they generally fit well into the present morphology.

A different opinion was held by P. Lory (1922), who described six successive terminal moraines in the Bédinat valley (within the mapped area, 880-332). The lowest one, at 980 m altitude, would be of "néo-würmien" age, the five others would represent as many glacial stadia (at 1420, 1600, 1760, 1940 en 2110 m altitude, respectively), the highest one dating from the 19th century. According to the present author Lory's evidence is not conclusive. The "terminal moraines" found above 1000 m altitude are in reality rock bars with little, if any, covering of moraine. Thus, they could better be considered as rock steps, which occur in most glaciated valleys, but are often of unknown origin. As was set forth above, the Bédinat valley in its present form is probably very young, so that the glacial deposits it contains should for the greater part be subrecent.

On the map the younger moraines have been taken together with screes and other accumulations of rock debris, from which they are not easily distinguished. Terminal moraines were indicated where clearly visible in the topography. Some of these could have been formed by extensive snow fields.

Creep [1]) is an important phenomenon everywhere in the Alps. In the Belledonne Massif it is most frequently met with in the external zone, which is largely built by usually weathered uniform St. Hugon schists. In the N the road to Chamonix through the Gorges d'Arly has recently been abandoned, because it was time and again demolished by creep. Nearer to the mapped area, creep is apparent along the motor road to the Grand Collet (Fig. 39), where the originally steeply dipping schistosity has everywhere been bent over in the direction of the slope ("Hakenwurf"). Within the mapped area the relatively small occurrence of St. Hugon schists in the external zone does not show creep to any significant extent.

On the other hand, creep is rather frequently found in the Pleynet valley, where the major thrustzones are often more or less parallel to the slope. We have already seen that this valley is almost exclusively situated in mylonitic

[1]) In the sense of Stokes and Varnes (see Glossary A. G. I.): An imperceptibly slow, more or less continuous downward and outward movement of slope-forming soil or rock.

and crushed rocks (p. 213). For this reason, it is often difficult to say which parts of the hummocky irregular topography is due to selective weathering of such rocks, and which part to creep. Only obvious cases of creep have been indicated as such.

Sources. Most water descending from the Belledonne Massif derives from the melting of snow in the higher parts of the valleys. The torrents often vanish in Quaternary deposits, to reappear for example on the rock steps, where they frequently form falls. Where the snow has melted away many torrents run dry.

The greater part of the sources situated at altitudes below 2000 m are found in the median syncline; another source occurs in the thrustzone NE of the Roche Noire, which is also filled with Carboniferous slates. The source region of the Merdaret and Pierre Herse torrents is nearly horizontal (Fig. 12); here thick peat layers are found covering the soaked sediments of the median syncline.

Lakes. Both Lac Crop and Lac de la Jasse are corries (cirques). The rock bar of the former is partly covered by a terminal moraine, which is probably younger than the formation of the corrie. The water reappears at the base of the moraine, some tens of metres below its culmination. The small lakes in the valley S of the Cime de la Jasse are perhaps partly embedded in a moraine with a clayey matrix (boulder clay).

CHAPTER VI

SUMMARIZING CONCLUSIONS

GENERAL

The Belledonne Massif, consisting mainly of older crystalline schists and granites, is divided into an external and an internal zone by a compressed "median syncline" filled with varying amounts of Permo-Carboniferous and Mesozoic sediments. These zones were brought into their present position by late-Hercynian and Alpine movements bringing about a dynamic metamorphism in both the sediments and the crystalline schists. This younger metamorphism was particularly active in the crystalline schists, where it often tends to obliterate the original metamorphism. Therefore, it is undesirable to base a subdivision of the crystalline schists mainly upon their present megascopical appearance, as has been done by P. Bordet (1956) and Cl. Bordet (1956, 1957) in distinguishing between a "série satinée" and a "série verte". The present author has tried to subtract the younger, dynamic metamorphism from the present state, and to subdivide the crystalline schists according to their composition and their original metamorphism. In many cases vestiges of this metamorphism were only found after thorough microscopical examination. As a rule, the grade of this main phase of metamorphism is higher in the internal than in the external zone. Thus, the distinction between the two zones, based upon structural considerations, is shown to be of petrographical importance as well.

The various formations distinguished in the present paper may be grouped as follows:

(1) The crystalline schists of the external zone;
(2) The crystalline schists of the internal zone;
(3) The sediments (Upper Carboniferous and younger).

(1) THE CRYSTALLINE SCHISTS OF THE EXTERNAL ZONE

The crystalline schists of the external zone within the investigated area are described as St. Hugon schists. This name was introduced by the author to designate a remarkably uniform formation of sedimentary origin, mainly consisting of sericite-chlorite-schists with a variable amount of albite porphyroblasts. A large part of the chlorite has originated by alteration of biotite on a regional scale, largely independent from the numerous mylonitic zones found all over the area. Both chloritization and mylonitization are to be attributed to the younger dynamic metamorphism mentioned above.

The albite porphyroblasts may show simple twinning according to the albite or albite-Carlsbad law. The Carlsbad law is only rarely encountered. In some cases the twins are composite by the presence of a central lamella of other extinction. Twins with (001) or (021) as composition face are not found.

The cores of many albite porphyroblasts contain folded trains of minute rutile needles. In the adjoining rock the rutile crystals are less numerous and in part larger, which indicates that the growth of the porphyroblasts took place early in the history of the rocks, i. e., during the main phase of metamorphism. The folding shown by the trains reflects a pre-metamorphic microfolding, and is not due to rotation of the porphyroblasts during their growth. According to J. Sarrot-Reynaud (1958) the porphyroblasts would be products of the Alpine dynamic metamorphism. This opinion does not agree with the above-mentioned observations, nor with the presence of identical porphyroblasts in completely unaltered sericite-biotite-schists, nor with their absence in the Upper Carboniferous sediments of the St. Hugon valley, which are bordered on both sides by albite-bearing St. Hugon schists, the chemical composition of the rocks of both formations being rather similar.

Outside the investigated region, the properties of the crystalline schists of the external zone are essentially the same. Those found in the section of the Romanche were designated as "groupe de Vizille" by R. Michel & P. Berthet (1958). Their description agrees with that of our St. Hugon schists, except for the local occurrence of sericitized feldspar other than the albite porphyroblasts. In the northern part of the Belledonne Massif the schists are also similar; locally they have escaped chloritization. P. and Cl. Bordet (op. cit.) class all schists of the external zone as the "série satinée", which also comprises schists of the internal zone.

(2) THE CRYSTALLINE SCHISTS OF THE INTERNAL ZONE

Here, the main phase of metamorphism generally reached a higher grade than in the external zone. One of the exceptions to this rule is a rather large wedge-shaped occurrence of St. Hugon schists within the mapped part of the internal zone.

The other crystalline schists of the internal zone occurring within the mapped area have been divided into a western and an eastern unit, designated as Lac Crop formation and Ferrouillet amphibolites, respectively.

The *Lac Crop formation* is a banded formation, mainly consisting of garnet-mica-schists and amphibolites of varying composition and structure. Their original metamorphism is best studied in the neighbourhood of Lac Crop. The garnet-mica-schists contain muscovite, biotite, plagioclase, quartz, garnet and, occasionally, staurolite and kyanite. The last two minerals particularly indicate the rather high grade of metamorphism as compared to the schists of the external zone. The plagioclase is oligoclase or andesine, commonly with reversed zoning and lamellar twinning, pericline and acline twins being more numerous than albite twins.

The *Ferrouillet amphibolites* are distinctly banded. The formation differs from the Lac Crop formation in the rarity of non-amphibolitic rocks and not in grade of metamorphism. The amphibolites of both formations consist mainly of blue-green or light-coloured amphibole and of plagioclase with approximately the same properties as that of the mica-schists. The abundance of titanite might indicate an igneous origin. Quartz, garnet and biotite are occasionally found. Some of the Ferrouillet amphibolites contain cores of clinopyroxene within amphibole crystals, and megacrysts of labradorite with complicated twinning. Both are to be considered as igneous relicts alien to the main phase of metamorphism.

Schistose leucogranitic bands are occasionally found in both formations. They may be related to the Sept-Laux granite, which is exposed immediately E of the Merdaret-Lac Crop region.

In the northern part of the mapped area the younger dynamic metamorphism has modified the rocks to a large extent. Here, the western part of the internal zone has apparently been squeezed between the external zone and the massive block containing the Sept-Laux granite. The Ferrouillet amphibolites and the broader amphibolitic bands of the Lac Crop formation have usually remained in a comparatively unaltered condition, and thus allow recognition of the original metamorphism in the field. All other crystalline schists, however, have assumed the appearance of greenschists or mylonites. On microscopical examination, the narrower amphibolitic bands are recognized by the presence of angular fragments of amphibole and of numerous grains of titanite. The mica-schists have preserved much of their original structure, but biotite and plagioclase are completely altered. P. and Cl. Bordet (e. g., P. Bordet 1956) include all such fine-grained green rocks in the upper part of their "série verte". As argued above, however, the present megascopical appearance of these rocks has nothing to do with the main phase of metamorphism, and even less with the stratigraphical position of the original sediments. This point has been stressed before by P. Bellair (1957), who described similar rocks as "fausses ectinites".

Outside the mapped area garnet is also a common mineral in many mica-schists of the internal zone. Staurolite and kyanite were found in the mica-schists of a banded formation situated E of the Ferrouillet amphibolites. This formation, which strongly resembles the Lac Crop formation, was designated as "groupe de l'Aveyna" by R. Michel and P. Berthet (1958) in their description of the section of the Romanche valley. In the southern continuation of the Ferrouillet amphibolites ultrabasic and gabbroic rocks are found. If these rocks are of the same age as the igneous relicts found within the mapped area, their emplacement must have happened before the main phase of metamorphism. This would be in accordance with the views of G. Choubert (1934—35) and contrary to the opinion of E. den Tex (1950). The amphibolites were designated as "groupe de Séchilienne" by R. Michel and P. Berthet (op. cit.). Other varieties of rocks encountered in the internal zone outside the mapped area include the granites and their crushed derivatives, and a zone of low-grade metamorphic rocks passing W. of St. Colomban.

The main phase of metamorphism must be older than the Upper Carboniferous sediments, which are not affected by it. According to P. and Cl. Bordet (e. g. Cl. Bordet 1957) this metamorphism would be Hercynian, but as yet there is little evidence to support this opinion.

As a rule, the crystalline schists of the external and of the internal zone differ not only in grade of metamorphism, but also in composition. Even the mica-schists of the Lac Crop formation differ in this respect from the St. Hugon schists. The difference is shown by Fig. 57, based on two Niggli-values of the analyzed samples of the various formations. Obviously, the St. Hugon schists derive almost exclusively from argillaceous sediments, whereas the Lac Crop formation contained a considerable quantity of marls or basaltic rocks. The monotonous formation of the Ferrouillet amphibolites, with its abundance of titanite and its igneous relicts, is probably of igneous origin.

(3) THE SEDIMENTS

The Upper Carboniferous, Permian and Mesozoic sediments have retained their sedimentary characteristics. They have only been affected by late-Hercynian or Alpine stages of dynamic metamorphism, resulting in some recrystallization of quartz and micaceous matter.

The Upper Carboniferous mainly comprises conglomerates, sandstones and black non-calcareous slates occasionally containing plant remains of a Westphalian D or Stephanian A age. Coal seams are of local occurrence. All Carboniferous sediments are continental. The arenaceous and pelitic rocks were

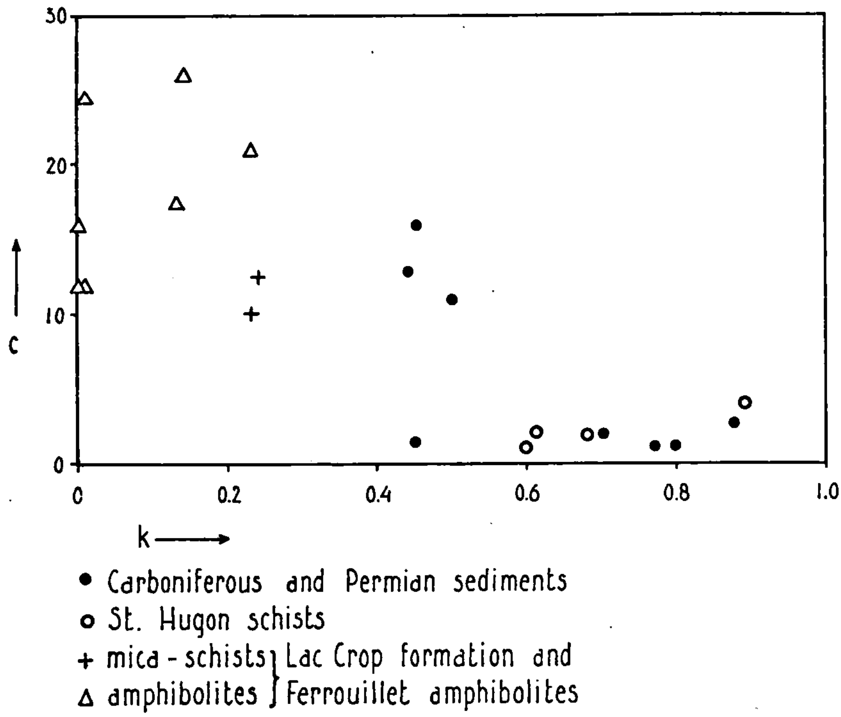


Fig. 57. The difference in chemical composition of the various formations, as illustrated by the Niggli-values k and c.

probably deposited in narrow basins, while the conglomerates may represent alluvial fans. Among their pebbles, which are generally well rounded, few could be identified as crystalline schists from the Belledonne Massif. Within the mapped area the sediments are confined to the median syncline, where they are intensely folded, and to a small occurrence with tectonic contacts within the internal zone. Outside the mapped area, the Carboniferous sediments are also found as a folded cover over the continuation of the external zone (i. e., the La Mure Massif), as vertical strata bordered by St. Hugon schists and as almost horizontal cappings on some of the central summits in the internal zone.

The Grès d'Allevard (Permian) consist mainly of feldspathic sandstones, pelites and conglomerates. In the lower part of the formation, where the pelitic members are of a dark-grey colour, Lower Permian plant remains were found by P. Gidon (1950) and by the author (P. Corsin & A. C. Tobi, 1954). The upper part consists mainly of purple pelites. The different colours of the two parts are suggestive of a change of climate during the Permian. For the rest, the sediments may resemble closely those of the Upper Carboniferous. Within the mapped area the Grès d'Allevard occur as a weakly folded cover over part of the external zone, and — probably in an overturned position — along the boundary between the internal zone and the median syncline. North of this area, near the Grand Collet, P. Lory (1895) has described an angular unconformity between the Upper Carboniferous and the Grès d'Allevard. According to the present author, however, the relative position of the sediments there is mainly brought about by the Alpine movements. The existence of an unconformity between the two formations cannot be denied, but it is considered improbable that a major folding took place between the Upper Carboniferous and the Lower Permian.

On microscopical examination many Upper Carboniferous and Permian sediments appear to contain rhyolitic or rhyodacitic material. Within the mapped area this material is most plentiful in the Grès d'Allevard. The original quartz phenocrysts are recognized by their bipyramidal form and by the absence of wavy extinction. Part of the micaceous pelites are in fact tuffaceous. Outside the mapped area an obvious volcanic tuff was found in the Carboniferous capping of the Grande Lauzière. The presence of bedded chert in the same sequence, and the silicification of the whole formation, are probably related to this volcanism. The conglomerates of the Grande Lauzière and the Rochers Rouges contain large quantities of a schistose rhyodacitic rock with albite phenocrysts twinned in a complicated manner.

The petrography of the Triassic and Liassic sediments was not studied in detail. Within the mapped area, Triassic cavernous limestones are found W of the Grès d'Allevard along the western boundary of the external zone. The same rocks are frequently encountered in the median syncline, where they may occur intermingled with Carboniferous slates. Beds of fetid limestone or dolomite are found W of the Grès d'Allevard along the boundary of the internal zone. Fossils are extremely rare. In the investigated area the Jurassic sediments belong mainly to the "Lias calcaire", consisting of alternating dark limestones and dark calcareous slates. These sediments are occasionally found in the median syncline, and form large masses W of the external zone. A large part of them is thought to have glided off the external zone during the Alpine movements. As almost everywhere in the Alps, the gypsiferous beds of Triassic cavernous limestone have provided the glide-plane.

The Quaternary deposits are mainly of glacial origin. The western part of the mapped area and the lower parts of the valleys are covered by older moraines. In the upper parts of the valleys younger moraines occur, together with screes and other accumulations of rock debris.

RELATIONS WITH THE ADJOINING HERCYNIAN MASSIFS

The Belledonne Massif being part of an arc of Hercynian Massifs, it may be interesting to compare its crystalline schists with those of the adjoining massifs. According to A. Faure-Muret (1955) the main phase of metamorphism in the Argentera-Mercantour Massif, chiefly characterized by the production of sillimanite, would be definitely older than that in the

Belledonne Massif, which was assumed to be Hercynian by P. and Cl. Bordet. Even if these age relations are uncertain, the difference in degree of metamorphism is obvious: sillimanite is hardly found in the Belledonne Massif.

In view of their analogous Alpine structure — a median syncline being present in both cases — we are tempted to compare the external and the internal zone of the Belledonne Massif with the Aiguilles Rouges and the Mt. Blanc Massif, respectively. This comparison, however, leads to the conclusion that the crystalline schists are very different in each case. The largest difference exists between the external zone and the Aiguilles Rouges Massif, in which rather highly metamorphic and calcium-rich rocks such as garnet-amphibolites are of frequent occurrence (J. Bellière 1957—1958). According to Cl. Bordet (1957) the older structure delimiting the various metamorphic units is cut obliquely by the trend of the median synclines. Thus, the continuation of the Aiguilles Rouges and Mt. Blanc Massifs — as far as the character of the metamorphic rocks is concerned — would have to be sought in the Rocheray and Pelvoux Massifs.

The Grandes Rousses Massif corresponds to the northern part of the internal zone, although it is separated from this zone by another Alpine synclinal structure.

Summarizing, we can say that the grade of the main phase of metamorphism is on the whole lower in the Belledonne Massif than in the adjoining massifs. As a rule the grade of this metamorphism rises when going from the outside to the inside of the arc of massifs. The Belledonne Massif seems to represent one of the originally most external parts of this arc.

SAMENVATTING

Het Belledonne Massief wordt overlangs in tweeën gedeeld door een samengeknepen synclinale zone, die plaatselijk permocarbonische of mesozoïsche sedimenten bevat. Het onderzochte gebied strekt zich ter weerszijde van deze zone uit.

Het westelijke of externe deel bestaat in hoofdzaak uit sericietchlorietschisten, veelal met albietporfieroblasten (St. Hugon schisten). Deze porfieroblasten zijn geen latere vormingen, doch behoren tot de oorspronkelijke metamorphose van deze schisten. Het oostelijke of interne deel bestaat overwegend uit granieten, amfibolieten en glimmerschisten. De metamorfosegraad is hier meestal hoger dan in het externe deel, zoals blijkt uit het anorthietgehalte van de plagioklaas en uit de aanwezigheid van de mineralen granaat, stauroliet en distheen. In het onderzochte gebied zijn onderscheiden de Lac Crop formatie, bestaande uit in banden afwisselende glimmerschisten en amfibolieten, en de Ferrouillet amfibolieten. De laatste zijn waarschijnlijk van magmatische herkomst, gezien de eentonigheid van de formatie, de rijkdom aan titaniet en de aanwezigheid van klinopyroxeenkernen en complex vertweelingde plagioklaasmegacrysten, die beiden als magmatische relicten worden opgevat. Vergelijken we het kristallijn van het Belledonne Massief met dat van de naburige hercynische massieven, dan blijkt de metamorfosegraad in het algemeen minder hoog te zijn dan elders het geval is. Vermoedelijk vertegenwoordigt het Belledonne Massief een structuurelement dat oorspronkelijk verder naar buiten (westelijk) heeft gelegen dan de andere massieven.

De zojuist beschreven regionale metamorfose, die zeker ouder is dan het Boven-Carboon, is op vele plaatsen grotendeels uitgewist door laathercynische of alpiene dynamometamorfose. Dit is o. a. in het noordelijk gedeelte van het gekarteerde gebied het geval. Herkenning van de oorspronkelijke metamorfe gesteenten is vaak slechts microscopisch mogelijk. De dynamometamorfose uit zich soms in mylonitisatie, soms in verbrijzeling en omzetting zonder dat aanzienlijke bewegingen in het gesteente schijnen te hebben plaatsgevonden. Deze jongere metamorfose hangt uiteraard samen met de hercynische en alpiene tektogenesen. In beide gevallen heeft niet zozeer plooiïng als wel intensieve beweging van kristallijnblokken plaatsgehad.

De permocarbonische en mesozoïsche sedimenten komen òf wel ingeklemd tussen deze blokken, òf als een weinig geplooid dek op de blokken voor. Het Boven-Carboon (Westphalien D—Stephanien A) bestaat grotendeels uit zwarte continentale afzettingen: conglomeraten, fijngelaagde zandstenen, leien en wat kool. In de „Grès d'Allevard" (continentaal Perm) zijn twee gedeelten te onderscheiden. Het onderste gedeelte bevat grijze of zwarte pelieten en lichtgekleurde veldspaathoudende zandstenen. Enkele plantafdrukken wijzen op een onder-permische ouderdom. In het bovenste deel, waarin paarsrode muscoviethoudende pelieten overheersen, zijn geen fossielen gevonden. Microscopisch onderzoek wijst uit dat zowel de boven-carbonische als de permische sedimenten vaak grote hoeveelheden rhyolitisch of rhyodacitisch materiaal bevatten. De vooral in het Carboon veelvuldig voorkomende verkiezeling houdt waarschijnlijk verband met dit vulkanisme. In de Trias spelen, zoals bijna overal in de Alpen, caverneuze kalken de hoofdrol. Gips- en anhydrietrijke lagen hebben als glijvlak gediend, waarover het erboven liggende sedimentaire dek — voornamelijk Jura in Bündnerschieferfacies — van de omhoogkomende kristallijnblokken is afgegleden. Op deze wijze zijn de ten Westen van het eigenlijke Belledonne Massief gelegen „collines liasiques" ontstaan.

RÉSUMÉ

Le Massif de Belledonne est binaire par l'existence d'un "synclinal médian" fermé, localement rempli par des sédiments houillers, permiens ou mésozoïques. La région étudiée s'étend de part et d'autre de cette zone. La partie occidentale ("rameau externe") est surtout formée de schistes à séricite et chlorite avec des phénoblastes d'albite. Dans la région étudiée, l'auteur les a nommé "schistes de St. Hugon". Les phénoblastes résultent du métamorphisme original, et non de rétromorphoses postérieures. La partie orientale ("rameau interne") consiste essentiellement en granites, amphibolites et micaschistes. La teneur en An des plagioclases de même que la présence de grenat, de staurotide et de disthène témoignent d'un métamorphisme régional nettement plus élevé que dans le rameau externe. L'auteur a distingué, dans son travail, la "formation du Lac Crop" et les "amphibolites du Ferrouillet". La formation du Lac Crop consiste en une alternance de rubans de micaschistes et d'amphibolites. Les amphibolites du Ferrouillet sont plus monotones. Riches en titanite, elles sont probablement d'origine magmatique. De rares noyaux de clinopyroxène dans l'amphibole, et des mégacrystes de plagioclase maclés selon des lois complexes, représenteraient des reliques magmatiques. Si on compare les roches cristallophylliennes du Massif de Belledonne et celles des massifs hercyniens voisins, on constate que le degré du métamorphisme y est en général moins élevé qu'ailleurs. Il se peut que le Massif de Belledonne représente un élément hercynien originellement plus externe que les autres massifs.

Ces observations concernent le métamorphisme régional, antérieur au Westphalien D. L'aspect macroscopique des roches cristallophylliennes est, malheureusement, souvent déterminé largement par des rétromorphoses. Dans la partie septentrionale de la région cartographiée, la plupart des schistes de la formation du Lac Crop ont ainsi été transformés en mylonites ou en schistes verts. Bien que d'importants mouvements n'aient jamais affecté ces dernières roches, les minéraux y sont broyés ou altérés. Sans doute, ces rétromorphoses sont-elles liées aux orogénèses fin-hercyniennes et alpines. Il semble que lors de ces orogénèses, les mouvements subverticaux entre des blocs cristallins aient été plus importants que les plissements.

On trouve les sédiments houillers, permiens ou mésozoïques, ou pincé entre ces blocks, ou subhorizontaux sur ceux-ci. Le Houiller (Westphalien D — Stéphanien A) est surtout formé de sédiments noirs continentaux: conglomérats, grès lités, ardoises, et localement du charbon. Dans les grès d'Allevard, on peut distinguer deux parties. La partie inférieure, comportant des pélites grises ou noires et des grès clairs feldspathiques, a fourni quelques empreintes de plantes du Permien inférieur. La partie supérieure présente surtout des schistes stériles rouges violacés. Il ressort de l'étude microscopique que les sédiments houillers et permiens contiennent souvent des quantités considérables de matériel rhyolitique ou rhyodacitique. La silicification de ces sédiments est probablement liée à ce volcanisme. Comme presque partout dans les Alpes, les cargneules sont les sédiments les plus répandus du Trias. Leur composition

est, en général, calcaire et non dolomitique. Les couches gypsifères ont servi comme surface de décollement à la couverture jurassique sus-jacente. Ainsi ont pris naissance les "collines liasiques" bordant l'Ouest du Massif de Belledonne.

Le volcanisme dans les Grès d'Allevard et le Houiller d'une part, les roches cristallophylliennes du massif d'autre part, ont donné lieu à deux courtes notes écrites en français (A. C. Tobi 1958a, 1958b).

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