METAMORPHIC HISTORY OF THE CENTRAL PYRENEES PART 1; ARIZE, TROIS SEIGNEURS AND SAINT-BARTHELEMY MASSIFS (SHEET 3)

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Abstract

The relation between orogenic movements and metamorphism is discussed. Schistosity and especially lineations are characteristic for metamorphites of the synkinematic phase. Lineations show a regular pattern. Late-kinematic metamorphism accompanied by different kinds of movement result in irregular rock flowage and rheomorphism. The structures of synkinematic mica-schists, gneisses, amphibolites and marbles are discussed.

In the three satellite massifs a series of gneisses and granitic rocks exists which are the products of silica and sodium metasomatism of originally pelitic rocks. The time and duration of the metamorphism determines the final state of the rocks. Synkinematic metamorphism alone gave rise to the garnet-augen-gneisses which, being rather dry, can be classified in the granulite facies. The lower part of these augen-gneisses are converted into schistose (not linear) gneisses and granites by post-kinematic feldspathisation. At the same time many anhydrous minerals are replaced by hydrous ones. Late-kinematic feldspathisation without a preceding synkinematic feldspar phase, leads to the formation of migmatites (sillimanite-gneisses), and by continuing metamorphism to quartz-diorites. The transitional rocks between the garnet-augen-gneisses and the migmatites are the granitic biotite-muscovite-gneisses. Rheomorphism and mobilization of the quartz-diorites is an important feature and probably leads finally to the intrusive biotite-granodiorites.

The muscovite-granites and gneisses which in part are also synkinematic, show a strong late phase of microclinization, due to potash metasomatism, originating from the underlying migmatites. In the mica-schists also, a syn- and post-kinematic phase of metamorphism can be detected.

The biotite-granodiorites show a different texture compared with the quartz-diorites of the migmatite-series. Their age is younger than the last phase of metamorphism, since the biotite-granodiorites did not participate in a late stage of muscovitisation, which is characteristic for most of the metamorphic rocks. These granodiorites are considered as intrusive magmatic bodies, originating from deeper levels, where continuing rheomorphism has lead to complete liquefaction.

Chemical analyses showed that the migmatites and the basal gneisses are enriched in silica, sodium and some calcium. Aluminium, iron, some magnesium, and titanium are removed. The quartz-diorites lost part of their potash. The muscovite-granites and gneisses show a strong enrichment in silica, sodium and potash. Aluminium, iron and magnesium are expelled.

Characteristic for the synkinematic phase is abundance of anhydrous minerals which suggest metasomatism in a dry state. Post-kinematic metasomatism goes together with introduction of water. The behaviour of water is considered to be responsible for the structural difference between syn- and post-kinematic rocks.

Finally the repartition of the various gneisses in the three satellite massifs is discussed.

CONTENTS

Introduction

Mapping of the Central Pyrenees by geology students of Leiden University has been in progress during the past ten years. The first final map, sheet no 3 which appears in this issue, shows the areas where mapping started. The three satellite massifs shown on this map, contain several types of gneisses and granites, whose relations have become clear after many months of fieldwork and the examination of several thousand thin sections. These relations are now described with emphasis on microscopic properties, since the megascopic features of the rocks have already been dealt with in the explanatory text of sheet 3 (De Sitter and Zwart 1958). Many features of the Trois Seigneurs massif have recently been published by Allaart (1958) and in general we refer to his work for a detailed description of that area.

The Hercynian metamorphism made a definite imprint on the three satellite massifs, and the unravelling of the metamorphic history is therefore of great importance. In general it appears that the metamorphism can be split in two main phases: — syn- and post-kinematic —, a fact which was at the same time independently discovered by Guitard (1955) and Zwart (1956). The division is based on structural relationships of the various rock types. Most of the metamorphic rocks are probably allochemical; they have been enriched in some way with new materials, whereas at the same time other elements were removed. The isochemical mica-schists and calc-silicate rocks form a transitional zone between the gneisses and the unmetamorphosed Palaeozoic sediments.

The metamorphic sequence can be fully explained in terms of the various metamorphic agents as deformation, changing temperature, depth and metasomatism. Of this sequence the essential feature is a splitting up in layers of different nature, a fact on which Guitard (1955) has laid special emphasis and which is explained by him as representing the original sedimentary stratification.

General principles

Before entering into a detailed analysis of the various rock types the behaviour of these rocks under the different metamorphic agents will be treated. These agents are 1) high temperature, which causes the minerals to recrystallize, 2) deformation, which may destroy the minerals, 3) metasomatism, especially introduction of silica and alkalis, which favours feldspar growth, 4) depth and the associated confining pressure, which in deep seated rocks tend to form relatively dense minerals, and 5) the water content which will be considered apart from the metasomatism of other elements.

Temperature is a very important factor during metamorphism. It will be clear that high temperature will have been preceded and followed by a time of lower temperature. As in most metamorphic areas, the record of increasing temperature has completely vanished and the rocks in which the oldest trace of metamorphism can be observed are already of a high grade. The record of decreasing temperature has, however, been preserved rather well. This record is represented by various mineral associations, succeeding one another. In the Pyrenees the final phase falls somewhere in the upper part of the meso-zone or even in the epi-zone. The starting point of the first record of metamorphism lies somewhere in the Hercynian folding, but in a rather early stage, since the high grade rocks have undergone a very thorough deformation. It is not impossible that metamorphism started before the deformation, but no evidence for this supposition has been found. During the whole period of deformation, metamorphism was of a high grade type approaching the granulite facies. Only after the end of the folding did the temperature start to drop and several mineral associations then followed one another. A factor which complicates the interpretation of these various successive assemblages is the behaviour of water. The examination of many thin sections indicates that during the synkinematic phase most new minerals are anhydrous, whereas post-kinematic minerals are frequently hydroxyl-bearing. This leads to the conversion of, for example, feldspars into muscovite or clinozoisite; cordierite and garnet into phlogopite or biotite; diopside and hypersthene into amphiboles (see also fig. 12 and 37). Whether these reactions are to be explained by falling temperatures or by introduction of water after the synkinematic phase at constant temperature, or both, is not at all certain. This can only be established by experiments.

A very important factor in regional metamorphism is deformation of the rocks. Different kinds of deformation can act one after another, but it appears that a certain kind of deformation is always typical for a certain phase of the metamorphism. Two main types of deformation can be distinguished, one of a highly ordered character which produces linear rocks, and one of an irregular type with the appearance of rock flowage. Some restriction has to be made with regard to the composition of the rocks, since limestone for instance shows evident rock flowage during the first kind of deformation. The described features are mainly valid for mica-schists and quartzo-feldspathic gneisses.

The first type of deformation is contemporaneous with the shear folding in higher unmetamorphosed strata, and actually deforms newly grown minerals. It also produces form and lattice orientations of these. This deformation results in the development of mica-schists and gneisses with a distinct schistosity and lineation expressed by mica- and feldspar crystals, stretched in the direction of the lineation, which mostly is a b-lineation. The lineations are strongly parallel over large areas, and rocks which suffered only this kind of metamorphism show a very regular pattern of schistosity and lineation (see map sheet 3 and fig. 13 in explanatory text). No pre-existing rocks have escaped this deformation, but it is of course possible that certain types have been completely rebuilt after the folding, resulting in rocks without any trace of deformation. We must bear in mind, however, that, except in the case of post-kinematic intrusives such as the biotite-granodiorite, we are dealing with materials which once were tectonites.

The second type of deformation is of quite different character. It is always later than the first, but in many cases is absent. It consists of folding of the schistosity planes, which originally were undeformed. In general it is found to occur only where gneisses or mica-schists are granitized or migmatized. In the field this deformation is visible as small irregular folds, often with varying fold axes. Lineations are not produced, but seem to disappear whenever they were present. In extreme cases even the schistosity becomes indistinct. It should be emphasized that the folding in this case means folding of the schistosity plane. If there is still any bedding visible it will again be deformed. Under the microscope it appears that the minerals may or may not be deformed during these movements and their intergrowths always indicate conditions which — if the term were not misleading — might be called "static". Furthermore form and lattice orientations may disappear during this phase.

These relationships make it clear that this deformation took place after the first phase of the folding of the mountain chain and need not be due to a general compression, since it is restricted to places with a certain kind of metamorphism. In the unmetamorphosed supra-structure it is probably characterized by a period of inactivity, but still it is a tectonic phase. To distinguish it from the first deformation, we call this one late-kinematic, thus ascribing to the word "synkinematic" the special significance that it is a penetrative deformation which attacks all the rocks and minerals. In this sense the term synkinematic is used in a rather restricted way and is equivalent to what GUITARD (1955) has called "éosyntectonique". The term syntectonic is here used in a much wider meaning. For example the intrusion of a granite stock is a tectonic phenomenon, going together with flow movements, but it is post-kinematic, since the minerals are not deformed and their mutual intergrowths are not controlled by strong movements. So the synkinematic phase is relatively short compared with the whole tectonic phase which in the Pyrenees comprises everything from the first record of folding to the intrusion of the granodiorites and the still later faulting phase.

Summarizing it can be stated that synkinematic metamorphism produces linear rocks with undeformed schistosity planes. Late-kinematic metamorphism often is accompanied by deformation of the s-planes and the disappearance of lineations, whereas post-kinematic metamorphism is not accompanied by any visible movement.

These relations between the various deformations and recrystallization are very important since they enable us to divide the whole metamorphic period into a number of time intervals which can be correlated over large areas. The division is based on the fundamental assumption that the synkinematic phase, which represents the strongest phase of folding in the whole mountain chain, is contemporaneous over a large region.

Since geology is a historical science we have to compare events of the rocks during corresponding time intervals. A petrologist can do this by dividing the metamorphic cycle in periods which, from a general point of view can be considered as being contemporaneous throughout the region in question. One such a period is the synkinematic phase, the end of which can often be recorded in thin sections by a change in textures and mineral assemblages.

Another example of contemporaneous events are certain metamorphic reactions, which take place under similar circumstances in different rocks. Such a case is, for instance, represented by a late stage of muscovitisation, which attacks several minerals in augen-gneisses, mica-schists and migmatites. It may be rash, however, to correlate these replacement features too far, since in other rocks a similar muscovitisation may be somewhat earlier or later. Another case of probably incorrect correlation of such processes is the microclinization, which several rocks have undergone in a rather late stage. In the intrusive biotite-granodiorite a similar process has taken place, but here it is probably much later than in the gneisses and migmatites.

Before dealing with the different structural types, the influence of metasomatism will be treated. I believe that the introduction of metasomatizing fluids together with introduction of heat is in general responsible for the metamorphism. Already in the earliest stage feldspathisation took place and this process continued for a long time. This also accounts for the fact that many thousands of metres of gneissose and granitic rocks occur with the same grade of metamorphism, whilst in the overlying isochemical mica-schists the grade of metamorphism decreases rapidly. In general it can be stated that introduction of silica and alkalis is responsible for the growth of large feldspars whereas in isochemical rocks the feldspars stay small and inconspicuous. The occurrence of metasomatism is a fairly well established fact for certain rocks; for example in the basal gneisses and migmatites, where it can be deduced that they were originally of pelitic composition. Whether the muscovite-augen-gneisses are metasomatic rocks, cannot be established, since the composition of the original material is unknown, due to its absence is unmetamorphosed strata.

Although there is a certain sequence in the whole metamorphic series, it is improbable that this is caused by differences in depth. Similar rocks occur at various levels and it is likely that, at least in part, this sequence is due to original sedimentary stratification combined with difference in metamorphic history, and is not influenced by depth. The mineral associations of the Pyrenean metamorphics, however, may be controlled by the relatively shallow depth of the metamorphism. These mineral associations are characterized by the abundance of minerals with a low specific gravity and scarceness of dense minerals. For example, andalusite and cordierite occur instead of kyanite and staurolite; garnet is rather rare.

Some remarks have been made about the role of water; this subject will be treated later.

Of course, there is a fundamental difference, depending on metasomatism during or after the synkinematic phase. Both cases are present as well as transitional ones.

In general, we deal in the Pyrenees with four different types of deformed metamorphic rocks connected by transitions. These are mica-schists, gneisses, amphibolites, and marbles with associated calc-silicates. The response of these different rocktypes to orogenic deformation is of fundamental significance for the explanation of their structures, megascopically as well as microscopically.

The mica-schists, in which the occurrene of platy minerals is typical, develop a schistosity and a lineation due to synkinematic deformation. These two structural elements result from the shape of the micas, which are elongated plates. Moreover, a crumpling of the schistosity plane in the same direction may add to this lineation. When large andalusite crystals occur they have a perfect form orientation with their c-axes parallel and in the direction of the lineation. These mica-schists are S-B-tectonites. A second lineation oblique to the first one is sometimes present and is probably caused by continuing deformation in a somewhat different stress field.

The original bedding is seldom visible, but if so, it often parallels the schistosity. In some cases, however, one will observe that isoclinal folding of the bedding is a rather common feature. In thin section the results of deformation are visible by the occurrence of folded micas and close association of muscovite and biotite often in bands; individual bands being separated by thin quartz layers. When aluminium silicates such as staurolite, andalusite or cordierite are present the influence of deformation will be observable in well-known features like broken and rotated crystals, wavy extinction, stress shadows and s-shaped trends of inclusions. A new phenomenon is introduced when the minerals of the mica-schist have a different competency with regard to movements, as for example staurolite or andalusite. These constituents behave as much more rigid crystals in a matrix of micas and quartz, resulting in a strong deviation of the schist matrix around such crystal which often develops as a porphyroblast. Around such porphyroblasts the schistosity curves sharply, caused by movements of the matrix which flows around the more competent crystal. Moreover stress shadows often develop on both sides of the porphyroblast (see fig. 1 and 2).

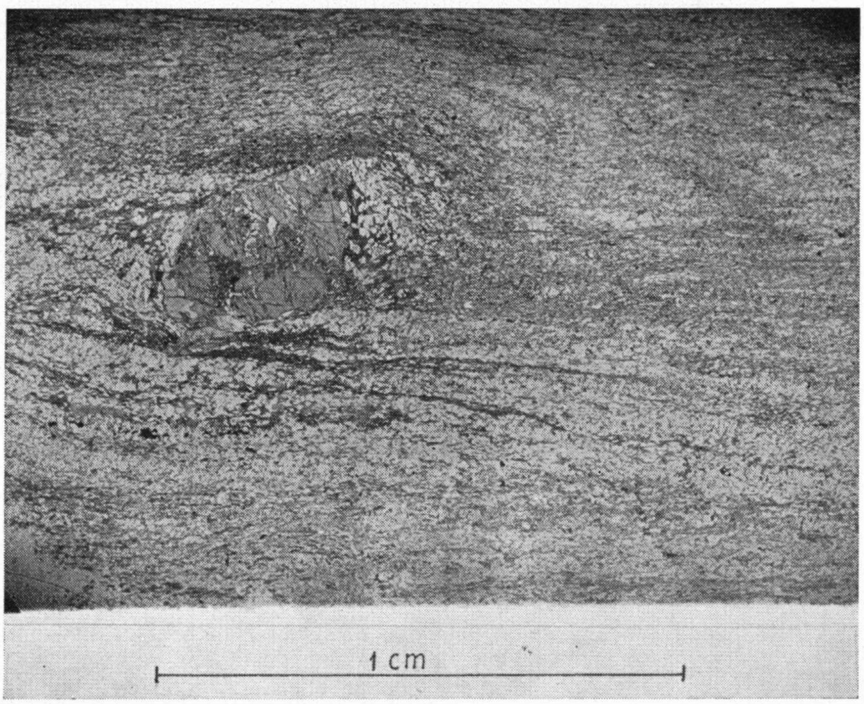

Fig. 1. Synkinematic andalusite crystal in mica-schist; schist matrix is pushed aside; stress shadows occur on both sides.

This pushing aside of the schistosity is, however, not a definite proof of synkinematic growth of such crystal, because also porphyroblasts which grow under static conditions might show the same features, but in this case this is not due to differential movements during folding, but by the force of crystallization. In our experience, however, pushing aside by growing crystals without other movements being involved, is a doubtful feature.

On the other hand synkinematic crystals can grow as vague porphyroblasts, sieved with schist inclusions, without deforming the schistosity. This happens for instance with cordierite. In many cases such cordierite has trends of inclusions which are curved, and also the extinction of the porphyroblast may vary from one end of the crystal to the other. Sometimes, however, it is not possible to find conclusive evidence as to the time of formation of certain minerals. The examination of many thin sections of one rock unit will mostly reveal their nature. When, however, certain minerals have formed, both during and after the deformation, for example andalusite and cordierite, it is not possible to determine the age of every crystal.

A very characteristic case in which differential competency plays an important role, is seen in the feldspar bearing rocks. In these the feldspar

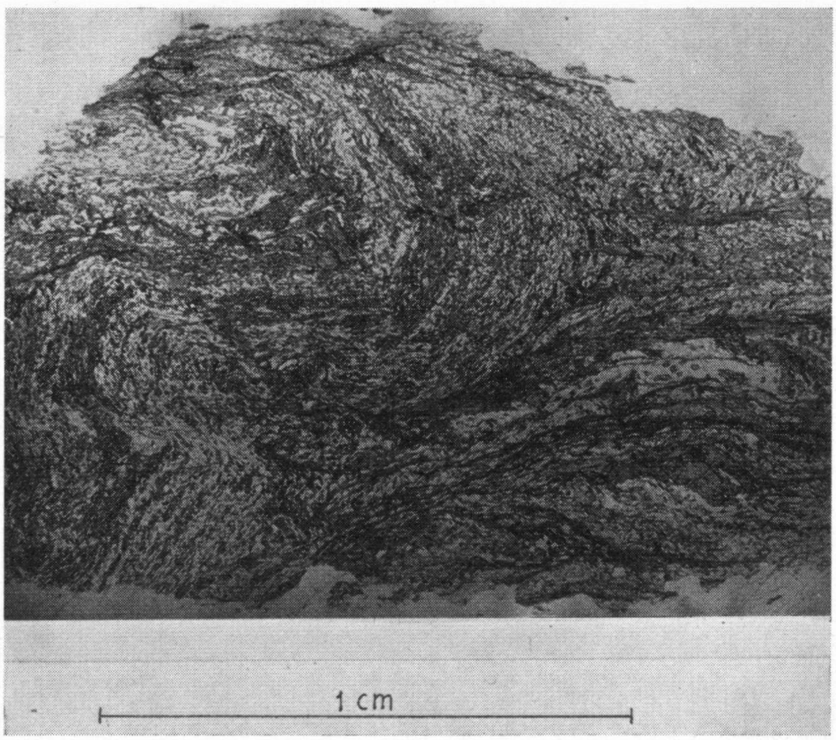

Fig. 2. Synkinematic folded andalusite crystals with rotated trails of inclusions.

crystals act as competent bodies whereas micas and quartz are relatively incompetent. Due to differential movements the feldspars obtain an "augen"-shape. Since the rocks during deformation have three different values for the three perpendicular stress directions, the shape of the augen is different in these directions. Their sections in the a—c and b—c-planes are characteristic. In the a—c-plane length and thickness of the augen are in general not much different, although the crystal lies with its longest axis in the s-plane. In the b—c-plane the eye is many times longer than thick (see fig. 3). In the a—b-plane the shape is more or less ellipsoidal. As a result such a rock has a schistosity plane as well as a lineation and consequently they are S-B-tectonites [1]). The lineation is often visible is a distinct striping on the s-plane. These structures are always clearly revealed in the field and

[1]) They may also be S-A-tectonites. See footnote explanatory text p. 388.

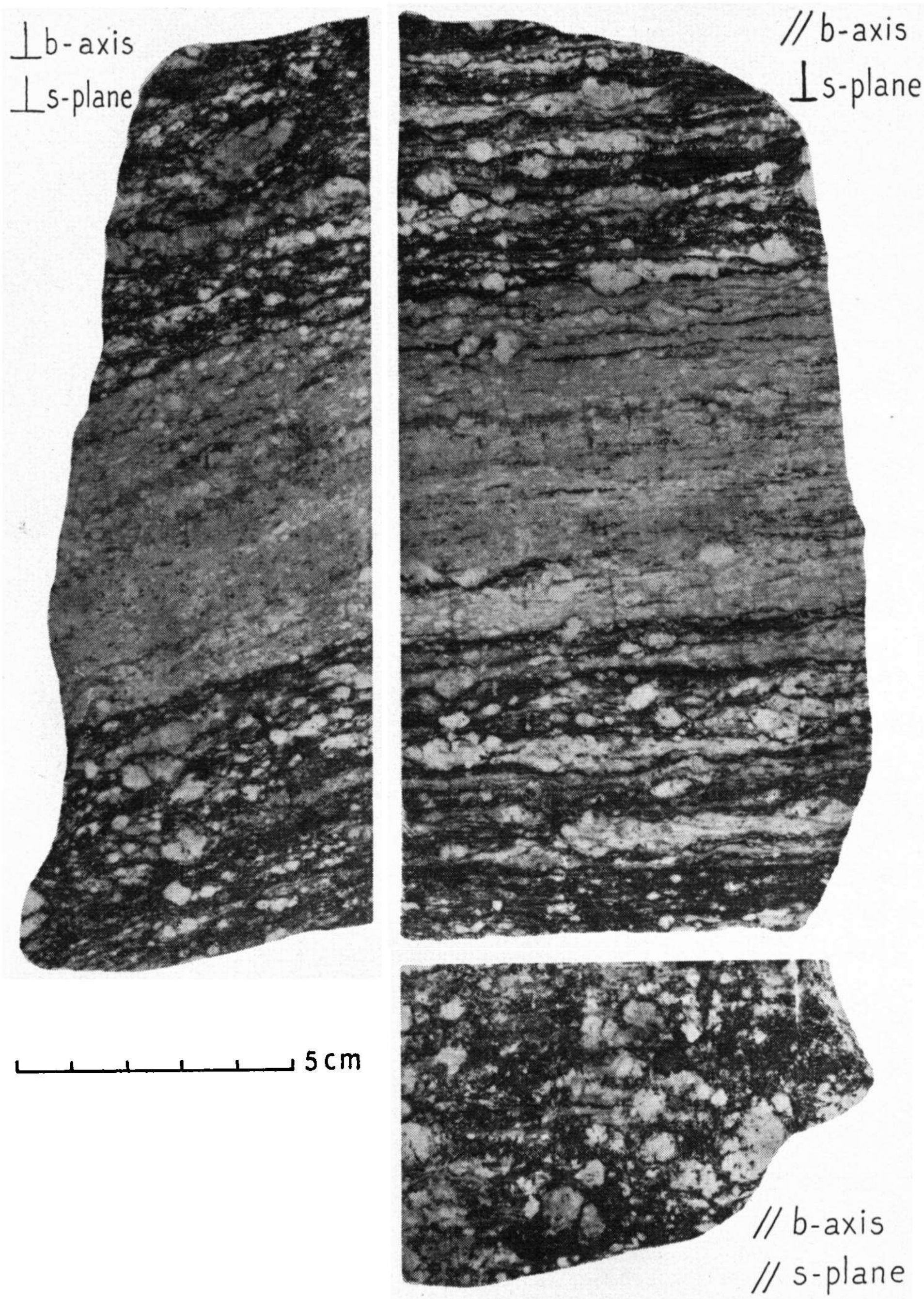

Fig. 3. Three perpendicular sections of linear and schistose banded garnet-augen-gneiss (S-B-tectonite): note the different shape of the felspars in these three sections, and lineation visible on section // S-plane.

under the microscope, and are very typical for synkinematic gneisses without much post-kinematic recrystallization.

Locally, pure B-tectonites occur. In these rocks the feldspars are round rods lying in the lineation (see fig. 4). When augen-gneisses are banded, the bands are often pushed aside by big feldspars (see fig. 5). This feature is similar to that of the mica-schist matrix which is pushed aside by andalusite crystals.

The feldspar augen behave for example as boudins of quartzite in mica-schists; the movements take place around, not in the boudin. This also explains why in strongly deformed augen-gneisses the feldspars themselves are

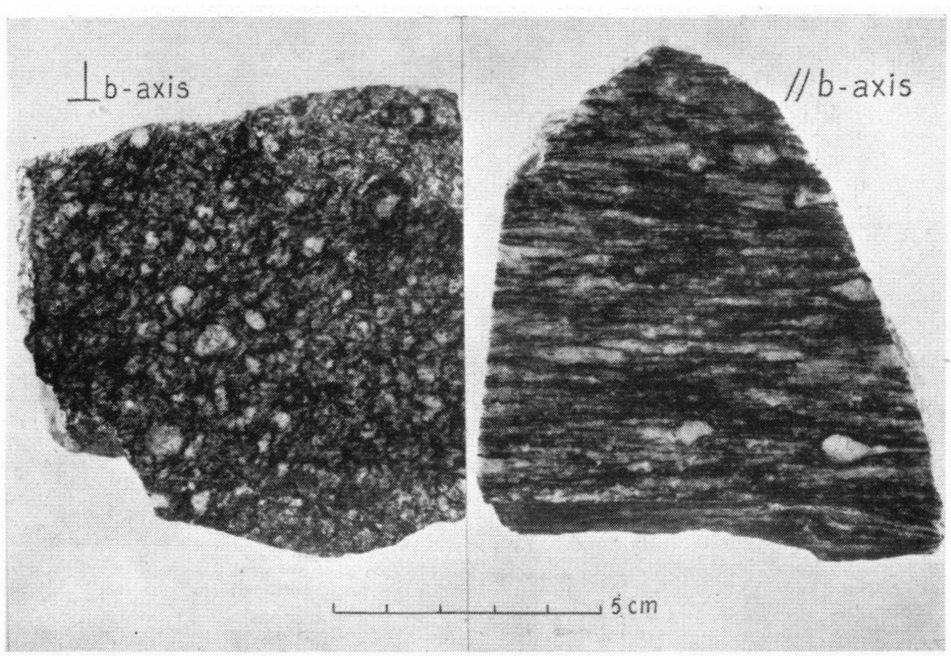

Fig. 4. Two perpendicular sections of linear garnet-augen-gneiss (B-tectonite).

usually not bent or broken. Similarly, biotite flakes within these feldspar augen are not deformed, whereas biotite outside may be completely sheared and shredded.

Furthermore one must emphasize that mechanically it does not make much difference whether the feldspars are pre-kinematic and already existed before the deformation started, or whether the feldspars were actually growing during the deformation, although we think the second case to be much more important than the first one. The size of the feldspar augen does not have any bearing on their structural relations, so that one finds exactly the same structures in rocks with feldspars not bigger than ½ mm and in rocks with augen of 10 cm. The composition of the matrix also has little influence on the structural behaviour. The same typical augen structure exists in biotite-rich gneisses, in which the biotite is sheared around the augen, as well as in aplitic gneisses where only quartz lies around the feldspar.

As well as plagioclase and potash feldspar, some other minerals develop an augenshape. In the basal gneisses are found beautiful augen of cordierite of exactly the same shape as the feldspars. Garnet can also have the same properties, although they are probably much more brittle since they are often broken in a direction perpendicular to the schistosity. The cracks are always filled with biotite, indicating that this deformation took place during the metamorphism and not later. Quartz augen have also been found.

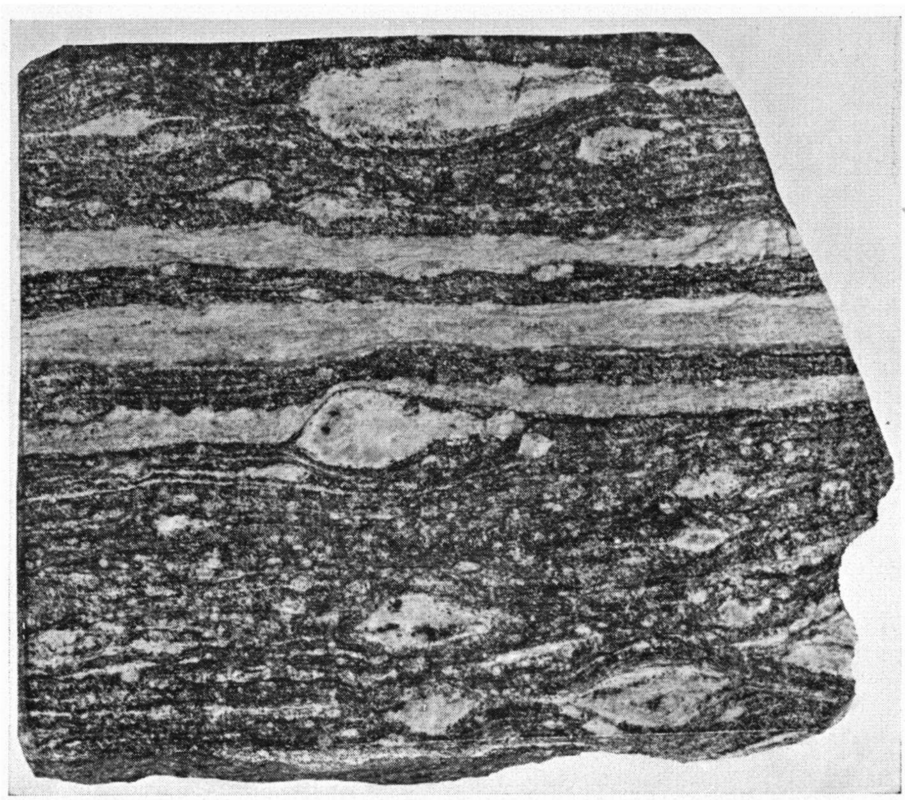

Fig. 5. Banded garnet-augen-gneiss; section // lineation.
Note the bending of one of the leucocratic bands around a feldspare eye.

Similar views with regard to the structural properties of augen-gneisses have been described by GUITARD (1955).

A third rock group, occurring as small inclusions, layers and boudins are amphibolites, either of sedimentary or igneous origin. Only two minerals are prevalent in these rocks, calcic plagioclase and green hornblende. Biotite, quartz, cummingtonite and diopside have sometimes been found, but always in minor quantities. When those rocks occur in augen-gneisses where recrystallization has not outlasted deformation, there is always a rather pronounced linear texture, caused by parallel arrangement of the acicular hornblende crystals. It is parallel to the lineation in the augen-gneisses. Also these rocks are S-B-tectonites. Remarkably, however, very little signs of strong deformation, which is easily recognized in the augen-gneisses, can be observed in the amphibolites. Neither plagioclase nor hornblende have deformed or broken crystals; only the arrangement of the hornblende crystals indicates that these rocks are tectonites. In my opinion this can be explained by the nature of basic rocks in metamorphic terrain. They are always more competent than the enclosing rocks, mica-schists or gneisses, a feature which frequently results in boudinage of these basic rocks indicating that most of the movement has taken place outside and along these rocks, rather than inside. This can be compared with the feldspar augen in the augen-gneiss. Inside, these augen are not deformed, because the movements take place along the borders. A similar mechanism explains the absence of strong deformation in the amphibolites.

When recrystallization continues after the termination of the deformation, this will result in disorientation of the amphiboles, but it is more difficult to distinguish between a pure synkinematic and a partly post-kinematic amphibolite, than between a syn- and a post-kinematic gneiss, at least when the amphibolites occur as small inclusions and layers.

Finally the behaviour with regard to deformation of the last rock group, the marbles and associated lime-silicates, will be treated. In general, it is much more difficult to determine synkinematic mineral assemblages in these rocks than in most other rocks. Although metamorphic marbles are megascopically strongly deformed, often in flow folds, microscopically no distinctive textures have been found. In a matrix of calcite crystals, more or less rounded grains of diopside, feldspar, titanite and other minerals are present, but no signs of deformation occur because all the movements took place in the calcite matrix, which easily recrystallizes. It is true that by petrofabric analysis these marbles can be recognized as tectonites, but this does not tell us anything about an eventual post-kinematic recrystallization since maxima in the diagrams can be more or less well preserved.

In lime-silicate rocks without or with little calcite, it is difficult also to determine relations between deformation and recrystallization. This is probably mainly due to the shape of the prevailing minerals, plagioclase and diopside which are often more or less equidimensional, and give neither schistose nor linear textures. In order to establish the successive mineral associations, we can compare these calc-silicates with the gneisses in which they occur and in this way account for the metamorphic history in the marbles and lime-silicate rocks.

The basal gneisses

Introduction

As has been described in the explanation of sheet 3 of the map of the Central Pyrenees, the basal gneisses are exposed only in the Saint-Barthélemy massif and in the eastern part of the Arize massif. Four different units have been distinguished. From top to bottom these are: 1) granitic biotite-muscovite-gneiss, 2) linear and folded garnet-augen-gneiss, 3) schistose garnet-bearing granitic gneiss and 4) granite and gneissose granite. Although a petrographic description in this order would seem to be the most logical one, we start with the augen-gneisses, because these rocks are structurally and mineralogically the most simple. In the following pages first the main type of each gneiss unit will be described, and then various rock types occurring in the gneiss, as lime-silicates and amphibolites.

Linear and folded garnet-augen-gneiss

Petrography of the augen-gneiss. — The characteristics of augen-gneisses have been explained in the first part of this paper and need not be repeated here. The augen of these garnet-gneisses consist of: 1) plagioclase, ranging in anorthite content from 5—20 %, 2) potash feldspar, mostly microperthitic, 3) garnet, 4) cordierite and 5) occasionally quartz. The plagioclase is untwinned or shows a simple twinning, often according to the albite law. Potash feldspar usually predominates over plagioclase and varieties have been found without plagioclase. In such cases, however, the microperthite is extremely rich in albite veinlets, indicating that sodium is incorporated in the microperthite. Cross-hatched microcline has not been observed in these gneisses.

Garnet often shows a similar shape as the feldspars, although the crystals are usually still more elongated. Many cracks occur perpendicular to the longest axis, filled with brown or light-green biotite. Probably these are due to stretching normal to the schistosity and in the direction of the lineation as a result of deformation. The biotite filling indicates that this process must have taken place under metamorphic conditions, or in other words, that crystallization and deformation were going on at the same time. X-ray analysis shows that the garnet has a mixed composition but that the almandine component prevails.

Cordierite is only rarely present in these augen-gneisses. This mineral is always completely fresh and only the pleochroic haloes around zircon betray its true nature. Except for their shape, and the cracks in the garnets, these minerals do not usually show signs of internal deformation; neither twin lamellae nor biotite crystals in the feldspars are bent.

The behaviour of quartz and biotite is completely different. Quartz lies nearly always as sheared and mylonitic masses around the eyes. Biotite is often completely shredded and torn into small pieces or is bent around the augen.

Occasionally sillimanite has been encountered in these gneisses. This mineral occurs in thick prisms, independent of biotite and is quite different from the fibrolite in the migmatites, which always forms at the expense of biotite. Especially near the top and the bottom of the garnet-gneisses, but also locally elsewhere a little muscovite, mostly replacing biotite, has been observed. Andalusite has been found a few times. As accessories zircon, apatite and ore occur. Zircon is often present as unusually large crystals up to a size of ½ mm. The complete absence of tourmaline is characteristic.

It should be emphasized that microscopically there is no difference between the normal linear and the folded augen-gneisses; the same minerals and the same micro-structures are present. Further, it is important to remember that the typical mylonitic augen structure prevails through the whole gneiss series and that they are not local shear zones. Although the possibility of a later wholesale mylonitization of this rock series cannot be excluded, subsequent examination of the under- and overlying gneisses rules this possibility out. In this way the augen-gneisses are a series of synkinematic rocks, in which deformation outlasted crystallization, or, in other words post-crystalline deformation occurred. A comparison of fig. 6 and 7 with, for example, MEHNERT's (1957) figure of a rock with post-crystalline deformation shows much the same picture. A difference is how-

A

B

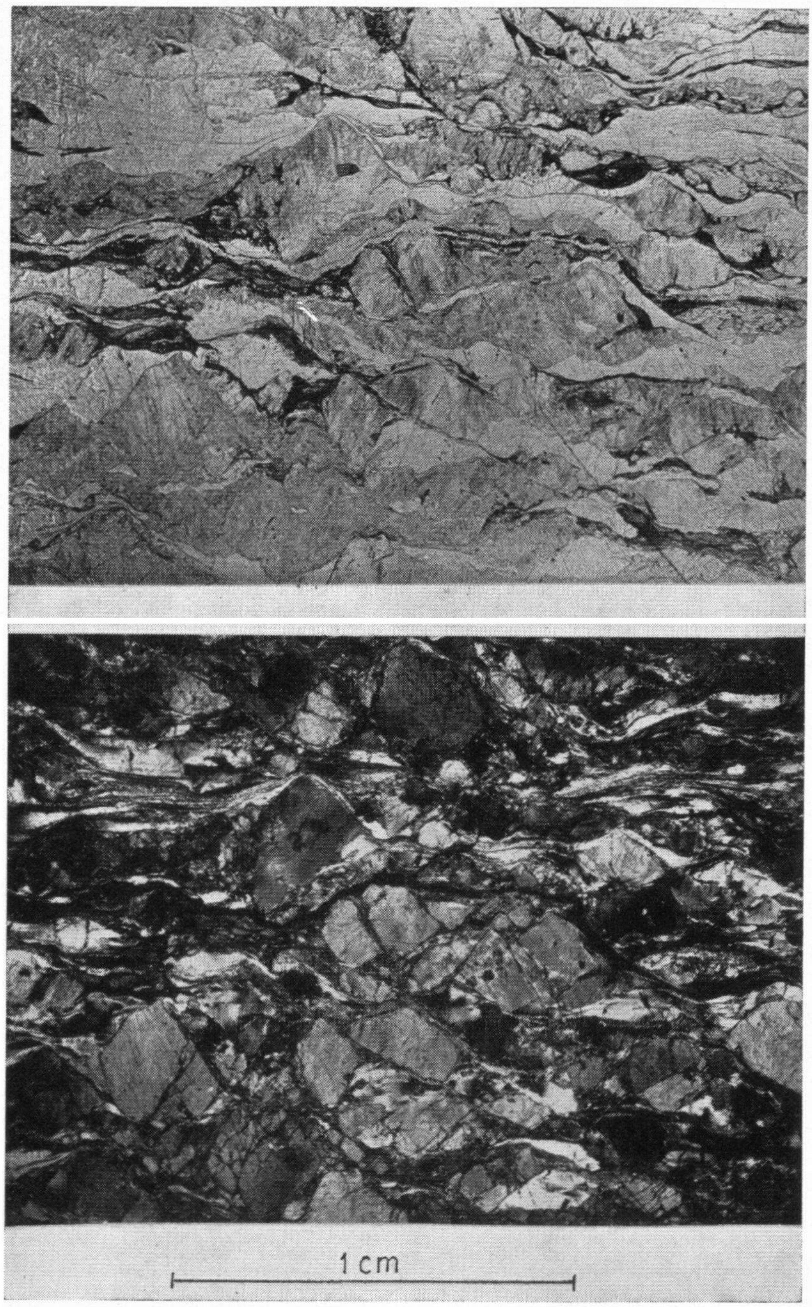

Fig. 6. Garnet-augen-gneiss // b-axis, ⊥ s-plane. A: plain light, B: polarized light.

ever, that in MEHNERT's case this deformation is altogether later than the crystallization, whereas our gneisses are synkinematic, but with deformation acting longer than crystallization.

The folding of the garnet-augen-gneisses also must be due to the same process and is probably caused by a still greater overlap in time between synkinematic deformation and crystallization, than the not folded, linear gneisses. The striking parallelism between fold axes and lineations in the folded gneisses indicates that this folding cannot be the result of a deformation which is altogether later. Also the complete absence in the folded gneisses of any static recrystallization, which occurs near the top and bottom of the linear augen-gneisses points into the same sense. This type of folding of the s-planes seems in general to be quite rare.

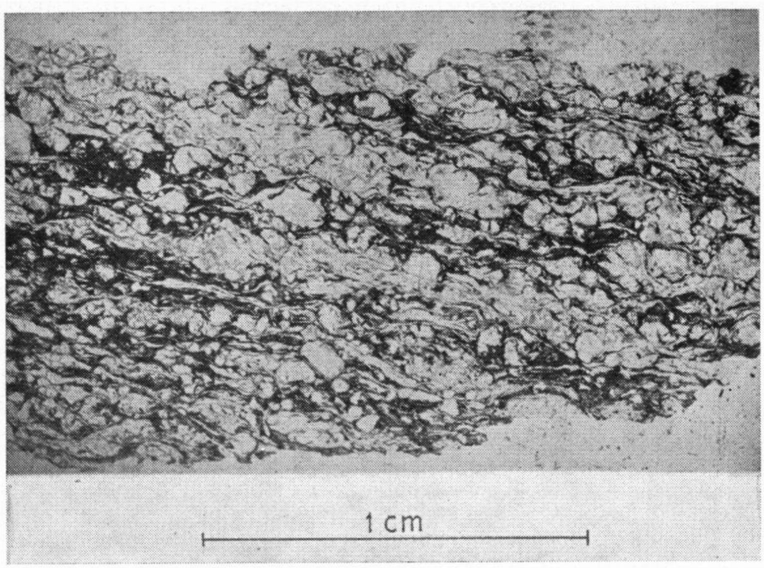

Fig. 7. Garnet-augen-gneiss, ⊥ b-axis; plain light.

Finally it should be stated that these augen-gneisses are equilibrium rocks in which no unstable relics occur.

Calc-silicate augen-gneisses. — Occasionally, rocks have been found which show a more or less evident augen structure, but which contain calc-silicates, as for example diopside, hornblende, and basic plagioclase (andesine to bytownite). In these rocks the plagioclase forms the augen whereas quartz and biotite surround the feldspar as sheared or bent crystals. Garnet, hornblende, or diopside occur as rounded, more or less euhedral crystals and do not show much effects of deformation. According to the chemical composition of the gneiss several mineral associations are possible, for example: 1) basic plagioclase, quartz, biotite, garnet, 2) plagioclase, quartz, garnet, hornblende and 3) plagioclase, quartz, biotite, hornblende, diopside.

Replacement of the minerals of these gneisses have not been observed. Apparently they are also equilibrium rocks.

A somewhat different rock type is a hypersthene-gneiss, consisting of hypersthene ($-2V = \pm 50°$, weakly pleochroic), andesine, quartz and green hornblende, with zircon and apatite as accessories. A clear augen texture is present. Some of the minerals of this rock are partially replaced by others. Hypersthene is replaced along its borders and its cleavage by biotite and cummingtonite; the hornblende is also partially cummingtonized.

Amphibolites. — Layers of amphibolite occur frequently either as straight bands or as boudins in the augen-gneisses. The thickness of these layers does not usually exceed one metre; the minimum thickness can be as small as one centimetre. The boundaries with the gneiss are nearly always sharp. The amphibolites lie in the schistosity and often show an evident linear texture, which is due to parallel arrangement of hornblende needles and coincides with the lineation of the enclosing gneiss.

Microscopically these amphibolites are remarkable for their fresh appearance. Except for their lineation, there are no signs of strong deformation as is found in the surrounding gneiss (see fig. 8). This feature can be explained by the concentration of the movement around and not inside the amphibolite. According to the mineralogical composition two varieties can be distinguished. The first consists of calcic plagioclase (labradorite or bytownite), dark green hornblende; biotite and quartz occur in minor quantities. Accessories are apatite, ilmenite and zircon. The plagioclase is often zoned with a somewhat more basic core. Oscillatory zoning has not been observed. The hornblende shows the following characteristics $Z \wedge c = 14—18°$, Nx light yellow-green; Ny green Nz dark green; $-2V = 72—80°$. The shape of the hornblende crystals is often subhedral and sometimes euhedral. Between the hornblende prisms the plagioclase occurs as more or less round grains. Biotite of a dark brown variety lies as plates between the plagioclase and hornblende or penetrates the amphibole crystals, but apparently does not replace these crystals. Quartz is frequently present as small round grains in the plagioclase (tropfen-quartz).

Although a megascopical lineation of the hornblende is evident, this is less pronounced in thin section. In sections perpendicular to the lineation most of the crystals show indeed the characteristic hornblende cleavage, but there are many crystals with a different orientation.

The second type of amphibolite consists of bytownite, hornblende, and diopside. The diopside is of a light green variety, and can be replaced by green amphibole. A part of the hornblende is, however, probably primary. The lineation in these amphibolites is much less pronounced than in the first type.

Since these amphibolites are not associated with calc-silicate rocks or marbles, it is quite possible, that they are metamorphosed igneous rocks, but definite proof cannot be given.

Schistose garnet-bearing granitic gneiss

Towards the bottom the augen-gneisses undergo a gradual change, which in the field is characterized by the disappearance of the lineation and the marked augen texture. Locally linear augen-gneisses were found in the schistose gneisses.

Microscopically this change is revealed by a different texture and behaviour of the minerals. The texture of these gneisses indicates that a certain amount of post-kinematic recrystallization has been active. Although in many cases relics of augen texture are still visible, typical mylonitic structures are absent. In the first stages quartz recrystallizes and forms along the feldspar eyes elongated zones with more or less uniform extinction. Biotite also recrystallizes as larger, undeformed plates, which may lie oblique to the schistosity. In a somewhat more advanced stage the feldspar augen are attacked. The microperthite is replaced from outside by plagioclase, often accompanied by the formation of myrmekite which in this case is clearly later than potash feldspar. The early plagioclase is not replaced by other minerals, but recrystallizes, looses its augen shape, and obtains a more or less subhedral form. Another new feature is the local occurrence of cross-hatched microcline, which either replaces the microperthite or grows as new crystals in the groundmass. Muscovite is often present, mostly as small crystalls, growing

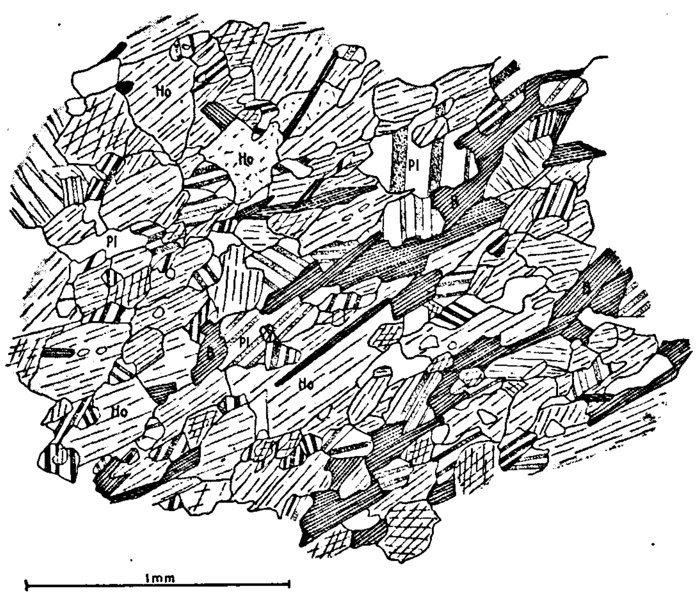

Fig. 8. Amphibolite, in garnet-augen-gneiss. No deformation of the minerals; fairly good linear texture; section // lineation.
Pl = bytownite, Ho = green hornblende, B = biotite.

at the expense of biotite or feldspar. The garnets are no longer stable and are replaced by biotite or, more often, by light green phlogopite; in most cases this replacement is only partial. Also cordierite is altered into similar phlogopite. The texture becomes granoblastic.

In these schistose gneisses near Appy some remarkable rocks, belonging to the granulite facies have been found. Here dark coloured gneisses occur as layers in more leucocratic gneiss. These dark rocks consist of hypersthene-gneiss with a faint augen texture. The hypersthene can be present in quantities up to 30 %, and shows its wellknown pleochroism; $-2V = 50$—$55°$. The other minerals are plagioclase (oligoclase, sometimes antiperthitic), garnet, quartz and little biotite; potash feldspar may be absent, when found it occurs as microperthite, which sometimes shows microcline twinning. Accessories are zircon, apatite and ore. The hypersthene and the garnet are partially replaced by biotite, whereas the feldspar has locally been muscovitised. Myrmekite has been observed a few times.

The primary mineral association of the schistose gneisses is the same as of the augen-gneisses, viz. quartz, sodic plagioclase, microperthite, almandine, biotite, cordierite and hypersthene. Replacement of part of these minerals gave rise to the formation of twinned microcline, muscovite, phlogopite, biotite (second generation) and myrmekite.

The relationships of all these replacement features indicate that they occurred under post-kinematic circumstances. This means that in the schistose gneisses crystallization outlasted synkinematic deformation, and that the boundary between these gneisses and the augen-gneisses is a surface at which deformation and crystallization ended approximately at the same time (see fig. 24).

The occurrence of augen-gneiss relics in the schistose gneisses is proof that the schistose gneisses are recrystallized augen-gneisses. It is remarkable that the two kinds of metamorphism — the first one synkinematic, the last one post-kinematic — brought about different mineral associations. The synkinematic phase is rather dry, with only biotite and hornblende as hydrous minerals, whereas the post-kinematic phase is characterized by replacement of water-free minerals by water-bearing minerals, for example feldspar is muscovitised; garnet, hypersthene and cordierite are altered into biotite, phlogopite or muscovite. The same tendency can be observed in the amphibolites and calc-silicate rocks, which will be described in the following chapter.

Granite and gneissose granite

Petrography of the granite. — Going stratigraphically downward from the schistose gneisses there is a gradual change in character. The schistosity disappears more or less, and the rocks become more coarse grained and often leucocratic, but locally, clearly schistose gneisses and even augen-gneisses are exposed. The whole picture of this unit is one of great variety. Microscopically the same tendencies as in the schistose gneisses can be discerned. They are replacement of potash feldspar by sodic plagioclase often accompanied by myrmekite formation, muscovitisation of feldspar and biotite, and replacement of garnet and cordierite by muscovite and green phlogopite. Plagioclase (oligoclase) is abundant in these rocks and predominates greatly over potash feldspar; locally they are quartz-dioritic. Sometimes the plagioclase is antiperthitic; its shape is subhedral and augenshape is very rare. Biotite occurs as rather large and undeformed plates; it is sometimes chloritised. Quartz is more or less interstitial. Sillimanite has been found a few times and occurs as thick prisms. It may form at the expense of cordierite or garnet. The texture is granoblastic.

Linear augen-gneisses, which occur as relics in these granites and gneissose granites, are also statically recrystallized; the augen have been attacked by plagioclase and quartz but the original texture is still very well visible. Locally rocks very rich in garnet or cordierite have been found.

Accessories are zircon, often rather large, apatite and ore.

Especially in the gneissose granite, but also in the schistose gneiss, many inclusions of amphibolites and marbles occur as an interrupted zone, which probably represents an original stratigraphic horizon. Various rock types can be distinguished on the basis of chemical and mineralogical composition. Most of them are of sedimentary origin, since they are clearly related to marbles.

Hypersthene-bytownite rock. — Hypersthene-bytownite rocks have been found particularly in the calc-silicate zone near Appy, and also at some other localities in the Saint-Barthélemy massif. The two most abundant minerals are hypersthene, with a faint rose pleochroism and $-2V = \pm 55°$, and bytownite. Hypersthene builds more or less round elongated grains, usually of a size of $0{,}2 \times 0{,}5$ mm, but occasionally crystals up to a size of 1 mm or more are observed. Interstitially, plagioclase, mostly bytownite, but sometimes a calcic labradorite, occurs. Quartz, if present, is found as small round grains in the plagioclase. Diopside may be present as a primary constituent of about the same size and shape as hypersthene, but in most thin sections it is clear that at least part of the diopside has originated at the expense of hypersthene. These two minerals are on their turn partially replaced by a brown biotite and to a lesser extent by green or brown amphibole. Also, alteration into cummingtonite has been observed. The plagioclase is always fresh.

Accessories are apatite, ore and titanite.

Diopside-bytownite rock and diopside-scapolite rock. — Near the marble outcrops in the gneissose granites, and also more or less isolated in the gneisses and granites many black or dark green, often banded, rocks have been found. The two most important minerals of these rocks are calcic plagioclase, often bytownite but labradorite and anorthite have been encountered, and a very light green diopside which nearly always shows a diallage cleavage. Quartz also occurs. Together with a few accessories as titanite, apatite, zircon and ore these three minerals form the primary mineral association. Although there is no structural proof, it is very probable that this paragenesis is contemporaneous with the formation of the augen-gneisses and thus is synkinematic. The diopside builds more or less rounded rectangular subhedral crystals, frequently with their longest axes parallel. Sometimes, however, embayed forms occur. The size of the diopside is usually 0,2 to 0,5 mm, but in coarse grained varieties crystals up to a size of 1 cm and more have been found. The diopside shows the following properties: $+2V = 60$—$64°$; $Z \wedge c = 35°$—$45°$.

The plagioclase forms interstitial aggregates of isometric crystals of approximately the same size as diopside. The quantities of both components vary: diopside alone can make up the whole rock, but mostly plagioclase predominates over diopside.

In a few cases grossularite was observed in the thin sections. Titanite is always present, often in small rounded grains, but sometimes, near Appy, in big euhedral crystals up to 2 cm across. Microcline occurs rarely. In one thin section it is abundant and replaces plagioclase.

This primary assemblage is in most cases no longer fully preserved, because both principal components can be replaced by other minerals. The first change is to be observed in the plagioclase, which is replaced by a calcic scapolite. This scapolite has the following properties: $N_E = 1.550 - 1.553$, $N_O = 1.574 - 1.578$, $N_O - N_E = 0.024 - 0.026$; the mineral is uniaxial negative, corresponding to a mizzonite (WINCHELL, 1954). In incipient stages the scapolite grows in cleavages and twinning planes, but in more advanced examples whole plagioclase grains are replaced by scapolite leaving only little traces of the original bytownite. Finally all the plagioclase can be replaced and a diopside-scapolite rock results in which scapolite is present in the same shape and size as the original plagioclase (see fig. 9 and fig. 17). It is remarkable that in many cases where all the bytownite has been scapolitized the diopside is still entirely fresh and unaltered, an indication that both minerals together are stable. With this scapolitization the metamorphism was not yet ended. In a following stage the diopside is attacked and partially replaced by a green or light green amphibole, which results in diopside-hornblende-scapolite (-bytownite) rocks. Scapolitization does not necessarily precede the formation of hornblende, since bytownite-diopside-hornblende rocks also occur. In most cases, however, the replacement of diopside by hornblende seems to be preceded by the formation of scapolite. Occasionally diopside has been scapolitized and grossularite also may have undergone this alteration, together with the formation of calcite. Since scapolitization does not occur in calc-silicates in the pure synkinematic augen-

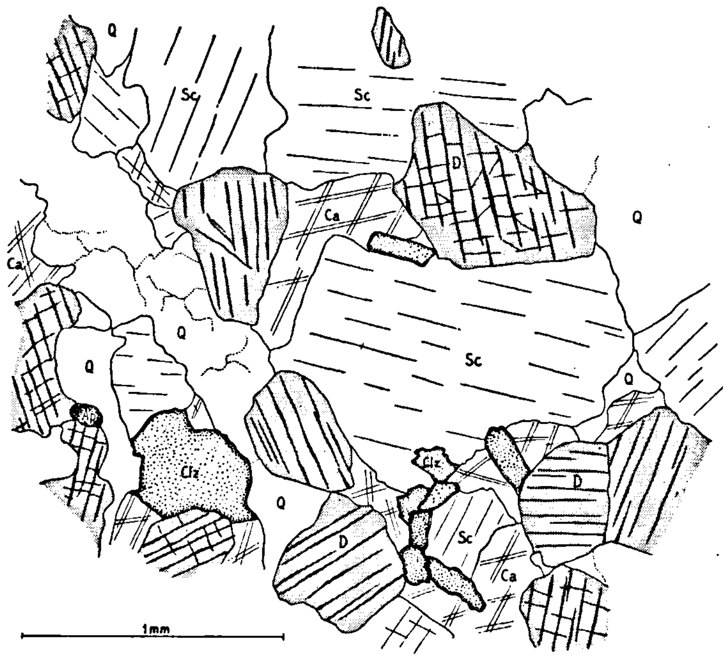

Fig. 9. Calcite-bearing diopside-scapolite-rock, in basal gneiss series. No relics of plagioclase; scapolite partly replaced by clinozoisite. D = diopside, Sc = scapolite, Q = quartz, Ca = calcite, Clz = clinozoisite, Ap = apatite.

gneisses, this process must be post-kinematic, but it will have initiated immediately after the folding.

Thus far these changes have occurred under kata- to meso-zonal conditions, but the following step takes us to the meso- and afterwards even to the epi-zone. In a number of cases diopside, bytownite and scapolite are replaced by clinozoisite or epidote (see fig. 10). This alteration is possibly contemporaneous with the formation of a light green actinolitic amphibole. In many thin sections a fairly large part of the original minerals have been preserved, but in some cases all the primary constituents have been replaced, resulting in rocks consisting of epidote-clinozoisite, actinolite, albite, quartz and titanite.

A few peculiar rock types occur in this series. One is a biotite-diopside augen-gneiss from Appy with a calcic plagioclase (labradiorite) which is partially replaced by scapolite with unusual opaque borders. A little diopside, partially altered into biotite and green hornblende, is present. Further biotite is an important constituent. Accessories are apatite and zircon.

Another peculiar rock, also found near Appy, shows large (½ cm) green spinel crystals, completely surrounded by scapolite, forming a sphere around the spinel. Between these spheres lies a matrix of diopside, green hornblende and scapolite, of which diopside is older than the latter two minerals. In this case scapolite replaces spinel.

In all these features, we see the same tendency as in the surrounding schistose gneiss and gneissose granite, the replacement of anhydrous minerals (diopside, grossularite, plagioclase) by hydrous minerals, hornblende, epidote, clinozoisite and actinolite. This is strong evidence, that the first mineral association is contemporaneous with the augen-gneisses and is synkinematic,

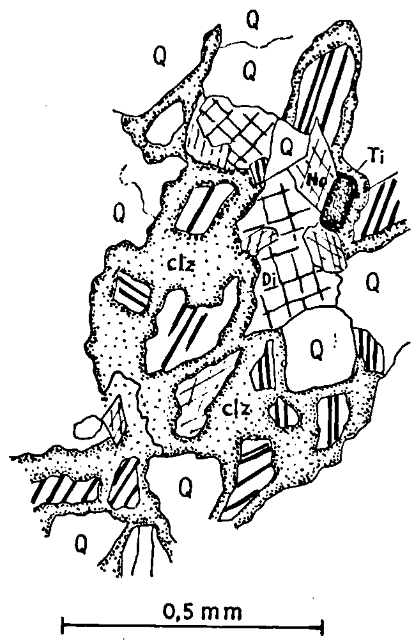

Fig. 10. Diopside-bytownite-gneiss in basal gneiss series. Bytownite replaced by clinozoisite; diopside by hornblende. Q = quartz, Di = diopside, Ho = hornblende, Clz = clinozoisite, Ti = titanite.

whereas the replacing association can be correlated with the muscovitisation and biotitisation of feldspar, cordierite, garnet and hypersthene.

Close association of these diopside-bytownite and diopside-scapolite rocks with marbles indicates that they are of sedimentary origin.

Diopside-bytownite marble and diopside-scapolite marble. — Metamorphic marbles are abundantly exposed in the basal part of the gneisses of the Saint-Barthélemy massif, for example near Cazenave, Appy, and Axiat. Dependent on the original calcium content of the sediment a whole series of rocks occurs, ranging from a pure marble, through rocks with less calcite and various metamorphic minerals, to the diopside-bytownite rocks just described. As in the latter, we can distinguish in the marbles different succeeding mineral parageneses. The primary association consists of calcite, diopside and bytownite-anorthite as main constituents. Quartz is often present in small quantities, whereas grossularite has been found a few times. The diopside has the same properties as in the diopside-bytownite gneisses; it often has diallage cleavage. In most marbles the plagioclase is replaced by scapolite, but if still present it has a very high anorthite content. Accessories are titanite, apatite, potash feldspar, tourmaline and ore. Titanite especially is often abundant and large-sized.

When much calcite is present it forms a matrix in which the isolated, more or less rounded grains of diopside and plagioclase up to a size of 1—2 mm are embedded. With decreasing calcite content the texture develops towards that of the diopside-bytownite rock, and calcite occurs only interstitially between diopside, and plagioclase or scapolite.

In many cases the plagioclase has been scapolitized in the same way as in the diopside-scapolite rocks. This scapolite is again of the same composition, viz. mizzonite. In the marbles replacement of plagioclase by scapolite is, however, even much more abundant than in rocks without calcite. This is probably due to the need of $CaCO_3$ for the formation of scapolite, which was more readily available in the marbles than in other rocks. This accounts for the fact that diopside-scapolite marbles without any relic of plagioclase are very abundant.

Diopside and grossularite are occasionally altered into scapolite. More important is the replacement of diopside by green or light green actinolitic amphibole. Finally epidote-clinozoisite can form at the expense of diopside, grossularite, or scapolite, sometimes accompanied by the development of sodic plagioclase.

Magnesian marble. — Near Appy some rocks of this type have been found which contain various magnesium silicates. In a groundmass of calcite occur forsterite, diopside, and green spinel as more or less rounded grains up to a size of 0,5 mm, and light brown phlogopite as smaller or larger plates. In part the phlogopite is clearly an alteration product of forsterite, but it may also be a primary mineral. Diopside is often partially replaced by light green or colourless amphibole. The replacement of forsterite and spinel by a colourless clinochlore is probably somewhat later. Finally forsterite can be altered into serpentine.

Amphibolite and scapolite-amphibolite. — Associated with marbles, but also as isolated inclusions or layers in the gneisses and granites, amphibolites are exposed on many places. In part these amphibolites closely resemble those in the augen-gneisses, but widely differing varieties also exist.

As in the calc-silicate rocks already described, we can distinguish a primary, synkinematic paragenesis which is essentially the same as in the amphibolites in the augen-gneisses, viz. calcic plagioclase (labradorite, bytownite or occasionally andesine), green hornblende and biotite. Diopside is occasionally present, thus forming a transition to diopside-bytownite rocks. The structure of these amphibolites is also very similar. A marked difference is, however, that this association stayed stable in the augen-gneiss-amphibolites, and that these rocks in the schistose gneisses and granites show more than one mineral association witnessed by unstability of some of the minerals. This instability leads to replacement of plagioclase by scapolite, thus forming scapolite-amphibolites. Complete replacement is rare, however, probably due to lack of $CaCO_3$. Afterwards plagioclase and amphibole may be altered into epidote-clinozoisite, which is very common in these rocks. Also the green hornblende is sometimes changed into a pale green actinolitic amphibole, or into cummingtonite. At the same time the basic plagioclase may be albitized, but this feature is rather restricted.

Accessory minerals are apatite, zircon, titanite, potash feldspar, quartz and ilmenite.

These amphibolites are partly of sedimentary origin, and have a somewhat lower Ca-content than the diopside-bytownite gneisses. It is possible, however, that the amphibolites which occur as isolated inclusions in the gneisses, and are not accompanied by marbles, are of igneous origin.

In conclusion we can state that in the schistose gneisses and associated lime-silicate rocks there is a primary, synkinematic mineral association, characterized by dry minerals: feldspar, garnet, cordierite, hypersthene, diopside, grossularite, spinel and forsterite. The only hydroxyl-bearing minerals of this paragenesis are biotite and green hornblende. The later post-kinematic mineral associations are characterized by replacement by water-bearing minerals as muscovite, biotite, amphibole, epidote, clinozoisite and chlorites. Very characteristic is the scapolitization, mainly of plagioclase, still under high grade conditions. Apparently, with decreasing temperature the hydrous minerals appear, and the association epidote-clinozoisite, light-green amphibole may be placed somewhere in the meso-zone whereas the latest assemblage of epidote, actinolite, albite is epi-zonal. This latter assemblage is however of restricted occurrence. In figure 12 the stability fields of the various minerals are represented.

Granitic biotite-muscovite gneiss

Petrography of the gneiss. — Towards their top, the garnet-augen-gneisses undergo certain changes, which at first are very similar to those in the schistose gneisses but higher in the series become markedly different. The first noticeable difference in the field is the appearance of muscovite, which goes more or less together with the disappearance of garnet. Certain structural features also become different, for example the augen structure and the lineation disappear and even the schistosity gets indistinct. The shape of the feldspars becomes more or less rectangular and euhedral. On the map the boundary between the garnet-augen-gneisses and the granitic gneisses has been drawn where for the first time muscovite is megascopically visible, but one has to bear in mind that this whole granitic gneiss zone is a transitional member between the garnet-augen-gneisses and the overlying migmatites (see fig. 24).

Microscopic examination reveals that somewhat below the boundary a few small muscovite crystals are to be found in the garnet-augen-gneisses. This muscovitisation is accompanied by other features: 1) formation of myrmekite in the potash feldspar augen, 2) occurrence of twinned microcline, 3) alteration of cordierite into muscovite and phlogopite, 4) the formation of sillimanite, often as rather large crystals, 5) gradual disappearance of garnet and 6) gradual disappearance of the augen texture. The first four of these changes are similar to those in the underlying schistose gneisses.

The new muscovite often forms at the expense of, and pseudomorphous after, biotite and potash feldspar. The undeformed nature of these alteration products indicates that these changes took place under post-kinematic conditions. Myrmekite grows as cauliflower-like masses, starting from the borders of the potash feldspar augen towards the center. In this case the plagioclase and myrmekite are clearly later than the potash feldspar. This transformation also, is of post-kinematic age. Typical cross-hatched microcline forms at first in the augen of potash feldspar. In a more advanced stage newly formed, twinned microcline grows in the groundmass of the gneiss. This new microcline is clear whereas the potash feldspar of the augen becomes kaolinized, probably an indication that the latter becomes unstable (see fig. 11).

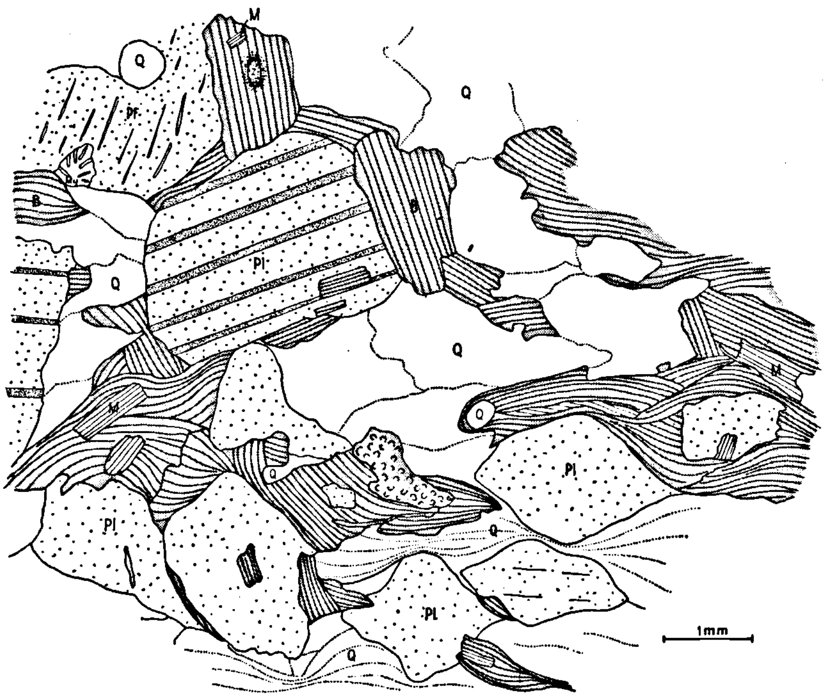

Fig. 11. Granitic biotite-muscovite-gneiss; synkinematic quartz-plagioclase-potash feldspar-biotite-augengneiss with post-kinematic plagioclase, muscovite and biotite. Note deformed biotite around the eyes in contrast to undeformed crosscutting biotite and muscovite. Myrmekite grows into potash feldspar.
Pl = oligoclase, Q = quartz, PF = potash feldspar, My = myrmekite, B = biotite, M = muscovite, Z = zircon.

The transformation of cordierite into light green phlogopite and muscovite is similar to that described in the schistose gneisses and that described by ALLAART (1958). Less evident is the significance of the formation of sillimanite, because this mineral is present in a different variety than in the migmatites, where it is clearly post-kinematic and originates at the expense of biotite. As in the garnet-augen-gneisses the sillimanite in the granitic gneisses is always coarse grained and does not form at the expense of biotite. Although almost all of the sillimanite in the Pyrenees is of post-kinematic origin and is related to granitization, this cannot be stated with certainty about the sillimanite in these gneisses which might as well be synkinematic (see also GUITARD, 1957). On the other hand sillimanite has not been found in the augen-gneisses in which no signs of static recrystallization are present.

Moreover, towards the migmatites the sillimanite in the granitic gneisses grades into the fibrolite which is typical for the first rocks. This, of course, does not prove that both kinds of sillimanite are contemporaneous, since there may be a gradual change in time of formation from the granitic gneisses to the migmatites.

In the lower part of the granitic gneisses some garnet is still present, but this mineral soon disappears on going higher into the series. A typical augen texture often is still present, but quartz and biotite have started to recrystallize. Higher in the series the augen texture generally looses its conspicuous character due to the growth of plagioclase porphyroblasts, which has taken place at least partially at the expense of earlier potash feldspar, and the growth of large randomly-oriented biotite crystals.

Very large feldspar crystals, as in the augen-gneisses, are no longer present and the plagioclase does not exceed a size of some millimetres. Therefore the granitic gneisses are medium-grained rocks. Some sparsely distributed large microcline crystals may be observed. The muscovite is distinctly larger and more abundant than in the schistose gneisses. It is always the latest mineral and replaces biotite, feldspar and sillimanite.

Although in the basal part of the granitic gneisses linear augen-gneiss textures prevail, partly as relics, these textures disappear towards the migmatites. Neither lineations nor feldspar augen have been observed in the latter rocks. These relationships indicate a fundamental difference between the gneisses which lie stratigraphically above and below the garnet-augen-gneisses. Those below the garnet-gneiss are synkinematically feldspathized schists with continuing post-kinematic recrystallization; those above the garnet-augen-gneisses are only post-kinematically feldspathized; during the synkinematic phase they were still mica-schists (see fig. 24).

Calc-silicate rocks. — The metamorphic history of the calc-silicate rocks occurring in the granitic gneisses is very similar to that in the schistose gneisses and granites. The following types have been found:

1) marbles with bytownite or anorthite, and diopside;
2) diopside-bytownite gneisses;
3) amphibolites, with basic plagioclase, green hornblende and biotite.

These three rock types are very similar to those in the basal part of the series. Also the succeeding changes are in many respects the same. For example the plagioclase may be altered into scapolite, but this feature is rather rare. More common is the replacement of diopside by green hornblende. Alteration of plagioclase, diopside or hornblende into epidote or clinozoisite is common; it is sometimes accompanied by the formation of sodic plagioclase. Hornblende may be cummingtonized.

In figure 12 the time of stability of all minerals in gneisses, granites, migmatites and their inclusions has been recorded. It will be clear that most of the anhydrous minerals, except feldspars, are characteristic for the synkinematic phase.

The migmatite—quartz-diorite series

Introduction

Although in the Saint-Barthélemy massif the migmatites are transitional to the basal gneisses and thus in fact are not completely separated from these rocks, there are certain reasons for treating this group as a separate unit, mainly because the fact that migmatites and associated quartz-diorites are present in all the Pyrenean gneiss massifs, whereas the basal gneisses are much rarer.

There are two main rock types in this series, viz. the sillimanite-gneisses

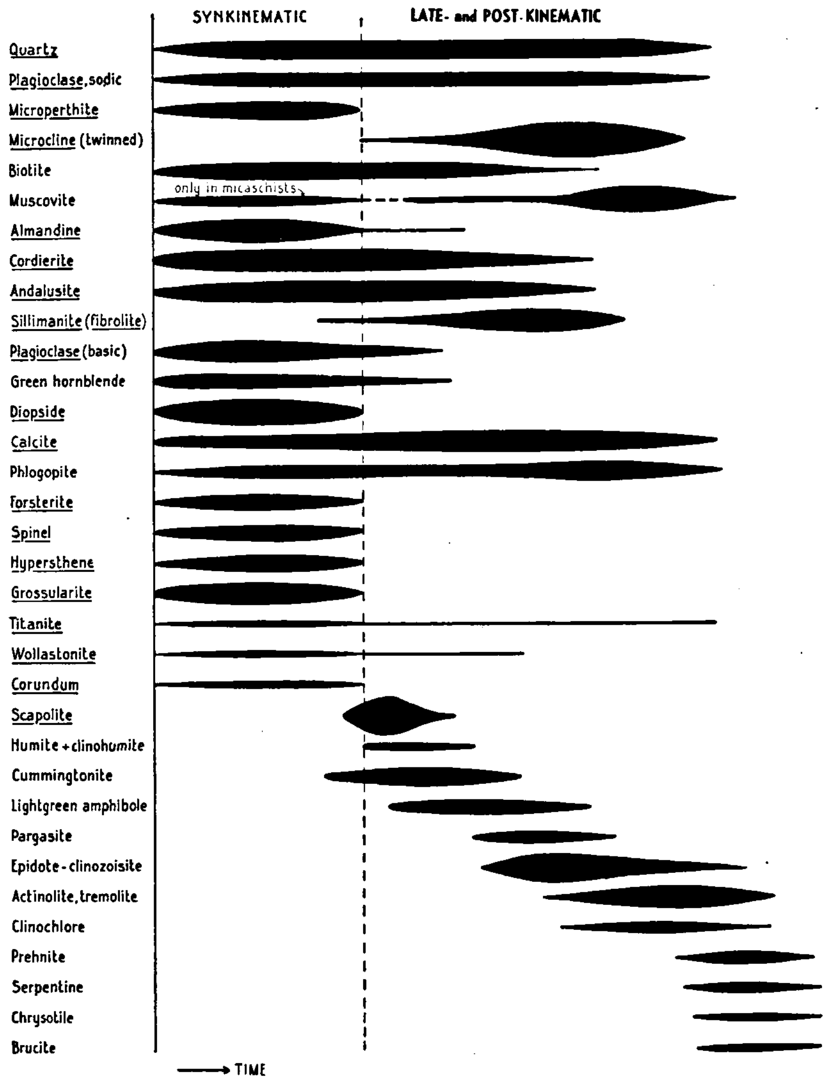

Fig. 12. Relation between time and formation of minerals. The underlined minerals are anhydrous. Note abundance of these minerals in synkinematic phase.

or migmatites s.s. and the quartz-diorites. From the Trois Seigneurs massif two more rock types have been described by ALLAART (1958): the quartz-dioritic gneisses and the homogeneous biotite-gneisses. These are subordinate with regard to the main types. Further, many kinds of inclusions occur in the migmatites and quartz-diorites as for example marbles, calc-silicate rocks and amphibolites. In the Arize and Trois Seigneurs massifs the quartz-diorites are the deepest exposed rocks, and are overlain by a layer of sillimanite-gneisses of variable thickness. In the Saint-Barthélemy massif the sillimanite-gneisses are the dominant rock type and overlie the granitic muscovite-biotite-gneisses. In this massif quartz-diorites occur as small or large masses in the sillimanite-gneisses. In all three massifs the migmatites are overlain by mica-schists or, locally in the Saint-Barthélemy massif, by a leucocratic gneiss.

Sillimanite-gneisses

As has been mentioned before, the silimanite-gneisses are typical migmatites — mixed rocks in which schistose mica-rich foliae alternate, often in a very irregular way, with layers of granitic appearance. The whole rock is distinctly gneissose, due to the parallel arrangement of the mica-schist foliae, but it should be emphasized that the leucocratic layers themselves show an unoriented texture. This is in sharp contrast with the banded augen-gneisses, which have been described before. In these the leucocratic bands show the same augen texture as the normal, more basic gneiss. In the migmatites, however, a foliated rock alternates with an unfoliated one, the leucocratic layer. This is of a certain genetic significance, which will be discussed further on. It is felt desirable to restrict the term migmatite to this kind of gneiss, since in the original definitions of migmatite by Sederholm the leucocratic part is always referred to as a granite and not as a gneiss. In this sense the banded augen-gneisses are not migmatites, because the leucocratic foliae are clearly schistose and linear.

The thickness of the two components of the migmatites is variable, but does not usually exceed a few cm, although the granitic layers can grade into real pegmatites up to a thickness of several decimetres or metres. The leucocratic bands are always conformable, but often they are folded together with the schistose foliae, and they sometimes show boudinage.

The leucocratic foliae have a quartz- to granodioritic composition and consist almost entirely of oligoclase and quartz with minor biotite, and occasionally some potash feldspar. Cordierite is sometimes an important mineral of these light-coloured bands.

The grain size of the plagioclase generally varies from 1—4 mm but occasionally larger crystals occur. Their shape is rather irregular but a tendency towards the development of more or less rectangular sub- to euhedral shapes may be noted, especially when quartz is scarce. Augen-shaped deformed feldspars have not been found. Simple zoning of the plagioclase with a somewhat more basic core than rim is rather common. The An-content of the plagioclase usually falls in the oligoclase range, albite and andesine being rare. Approximately one third to one half of the plagioclase crystals is twinned; most twins according to the albite law. Quartz is interstitial to the plagioclase or occurs as elongated crystals in the biotite-sillimanite foliae. Microcline or microperhite are usually minor constituents; their crystals can attain a rather large size and are then of a very irregular shape. Sometimes it encloses other minerals or penetrates between quartz and plagioclase. Myrmekite is frequently present between the contacts of plagioclase and potash feldspar. In many cases it is not possible to establish the age relationships between the feldspars and the myrmekite, but in a number of cases it is evident that microcline is the latest mineral and replaces plagioclases accompanied by the formation of myrmekite. It is probable, however, that the reverse reaction also has taken place. Biotite occurs in the quartz-dioritic layers as a minor constituent and does not generally show a preferred orientation. Cordierite is a rather common mineral of the sillimanite-gneisses (see fig. 13). In the leucocratic band it occurs as fore or less equidimensional crystals of a size of 1—2 mm. It is often partially or completely replaced by an aggregate of unoriented muscovite and light green phlogopite crystals. Complete sericitization of the cordierite is also common. Pleochroic haloes around zircon are widespread.

The mica-rich foliae consist mainly of biotite and sillimanite, the latter

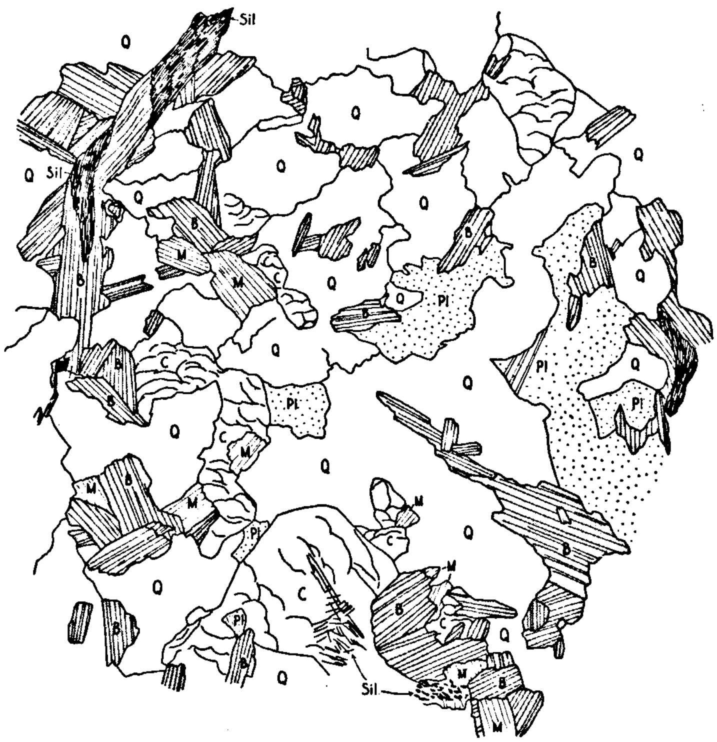

Fig. 13. Nebulitic sillimanite-gneiss with late sillimanite and muscovite replacing biotite and cordierite. × 35.
Q = quartz, Pl = oligoclase, C = cordierite, B = biotite, M = muscovite, Sil = sillimanite (fibrolite).

in the form of fibrolite. Biotite occurs as plates of a few mm diameter and often shows a good parallel arrangement, but a decussate intergrowth is not uncommon. The fibrolite is closely associated with biotite and it has formed at the expense of this mineral. The typical knots of fibrolite, replacing biotite, certainly grew under static conditions. Prisms of sillimanite are sometimes observed in quartz or feldspar. Muscovite is clearly the latest mineral in the sillimanite-gneisses. It forms at the expense of biotite, sillimanite or feldspar. In the mica-rich bands it develops as small or large (up to 3—4 mm) crystals which usually lie completely at random and clearly replace biotite and sillimanite. When muscovite forms at the expense of feldspar, preferably potash feldspar, it sometimes forms well-built crystals but more often irregular meshwork-like crystals sieve the feldspar. Fine quartz worms often lie in, but also cross the cleavage planes of the white mica which replaces feldspar. Apparently this quartz has been released during the transformation of feldspar into muscovite. This process is similar to the formation of plumose mica, an intergrowth of quartz and muscovite, which replaces big microcline crystals of pegmatites.

As accessory components the following minerals have been found: tourmaline, zircon, apatite, ilmenite, garnet, pyrite, and hematite.

Summarizing we can state that the following features are of importance in the sillimanite-gneisses:

1. there is no deformation structure of the leucocratic layers: the feldspars are irregularly shaped or tend to a sub- to euhedral shape;
2. there is generally a preferred orientation of the biotite in the mica-rich foliae, but this is a mimetic schistosity after the original mica-schist, formed under late- to post-kinematic conditions;
3. quartz, biotite, plagioclase and cordierite seem to be contemporaneous; there is no primary muscovite;
4. sillimanite is later than the main paragenesis and forms at the expense of biotite;
5. a part of the microcline is also later than this main paragenesis;
6. muscovite is the latest mineral and may replace any of the earlier minerals.

The fact that the structure of the leucocratic layers is of undeformed nature is of great importance, particularly for the age determination of the migmatization. After the foregoing it will be clear that the growth of the feldspars, or in other words the feldspathization, in the migmatites is late- to post-kinematic. The complete absence of any augen-gneiss texture or relic of such texture in the migmatites excludes the possibility of statically recrystallized synkinematic gneisses. In this way the migmatites are really mixed rocks, because they consist of an older synkinematic mica-schist and a younger post-kinematic quartz-diorite, or — in different words — they are late- to post-kinematically feldspathized mica-schists.

Frequent, but rather irregular folding of the migmatites does not prove their early synkinematic origin. This folding is of the type of rock flowage and is later than the synkinematic deformation, which is characterized by an undeformed schistosity and the occurrence of linear textures. Boudinage of the quartzo-feldspathic layers also is probably due to the same late-kinematic folding.

Comparison of chemical analyses of mica-schists and sillimanite-gneisses shows that there is a very small enrichment of sodium in the latter gneisses. It will be clear that introduction of sodium favours the formation of plagioclase, which will be of a rather acidic type, since the original sediments were poor in calcium. The transformation of biotite into fibrolite takes place under the release of potash and presumably this process is the cause of the fibrolitization. A part of this potash probably was used for the formation of microcline, whereas the rest was transported to higher levels and influenced other rocks.

Since the total addition of new material is very small, the formation of the quartzo-feldspathic layers must be due mainly to metamorphic differentiation, rather than replacement of the original schist.

Quartz-diorites

The sillimanite-gneisses usually show transitional contacts with the quartz-diorites. The boundaries between the schistose and granitic layers become gradually less distinct (nebulite) until finally the differences between both components disappear and a homogeneous quartz-diorite prevails. The mineralogical composition of sillimanite-gneisses is identical with that of the quartz-diorites.

Plagioclase (An 10—35) has often irregular shapes, but there is a tendency to develop as sub- to euhedral crystals. Zoning, with a slightly more basic core than rim, is quite frequent, but oscillations are rare. Approximately half of the plagioclase is twinned, mostly according to the albite law (ZWART,

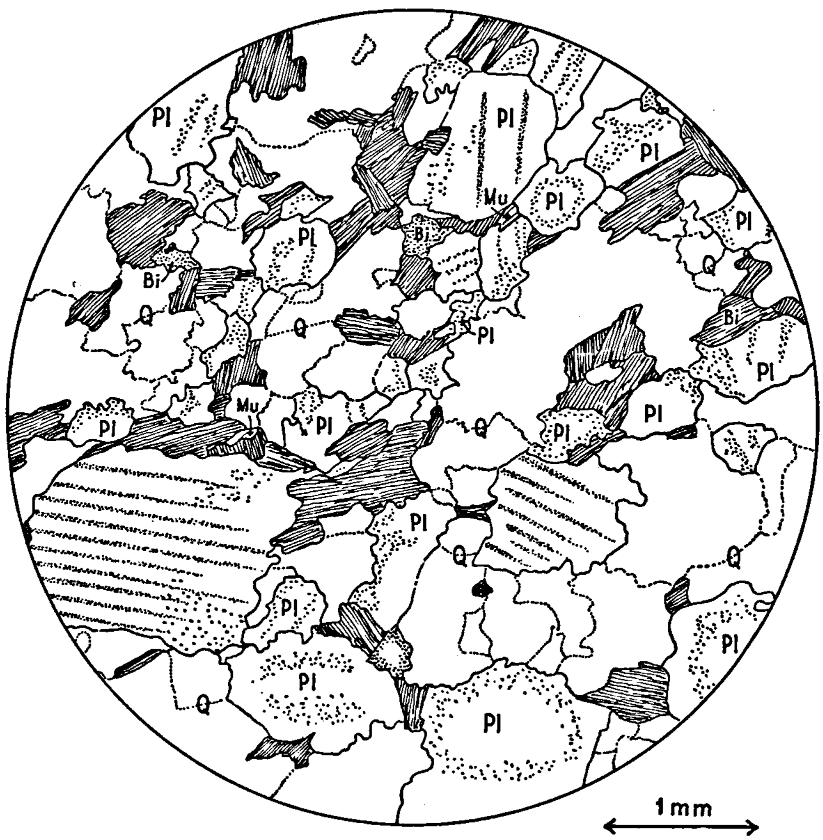

Fig. 14. Quartz-diorite with late muscovite.
Pl = oligoclase, Q = quartz, Bi = biotite, Mu = muscovite. (After ALLAART, 1958).

1954, p. 87—88). Potash feldspar, frequently with microcline twinning, builds irregularly shaped crystals, often interstitially between quartz and plagioclase. Myrmekite is frequent, but again it is difficult to establish the age relationships between both feldspars and myrmekite. Quartz forms irregular crystals or is interstitial. Biotite occurs as plates which generally do not show preferred orientation. Its outlines are often rather irregular. Muscovite may form rather large crystals up to a size of one half cm and commonly replaces potash feldspar, but it occurs also as cross-cutting crystals with straight edges in biotite. The muscovite is clearly later then the other minerals, as is the case with the white mica of the sillimanite-gneisses (see fig. 14).

Sillimanite builds independent prisms and is no longer present as biotite-replacing fibrolite. Cordierite is rather frequent and is often altered into the same muscovite-phlogopite intergrowths as in the sillimanite-gneisses. Alteration into sericite is also common. Acessories are zircon, apatite, tourmaline, ore, garnet, and orthite.

Fig. 15. Rotated inclusion in rheomorphic nebulitic quartz-diorite. Trois Seigneurs massif.

From field and microscopical examinations it is clear that the quartz-diorites formed at the expense of sillimanite-gneisses by continuing post-kinematic recrystallization, favoured by introduction of silica and sodium, as shown by chemical analyses. The age of this recrystallization is therefore later than the formation of the sillimanite-gneisses and also later than the fibrolitization, but is earlier than the muscovitisation, which has affected both rocktypes (cf. fig. 24).

An important and interesting feature which seems to accompany the formation of the quartz-diorites is rheomorphism and mobilization, for the detailed description of which we again refer to Allaart (1958). This mobilization occurred on a large scale in the Trois Seigneurs massif, but the quartz-diorites of the Arize and Saint-Barthélemy massifs have undergone the same process (see fig. 15, and fig. 11, 12, explanatory text p. 386). The results of this rheomorphism are visible by the disorientation of inclusions and the occurrence of flow structures. The relationships with the surrounding rocks are, however, still normal, that means there was no intrusion connected with the mobilization, or movement of whole quartz-diorite bodies to other places. It is more a kind of internal movement, large enough to create flow structures and to disorient inclusions, but not large enough to do anything more. As to the cause of the rheomorphism there can be little doubt that water, or at least solutions, have played an important role, especially so, since many water-free minerals were replaced by water-bearing minerals during this process of mobilization. Apparently there was plenty of water available during late-kinematic granitization and the quartz-diorites seem to have been soaked with fluids. Although it is impossible to estimate the amount of liquid substance during the mobilization, I assume that 5—10 % will be enough to bring about a great degree of mobility. Since the microscopic structures of these quartz-diorites are markedly different from those of the igneous biotite-granodiorites of the Pyrenees, which have almost the same chemical composition, there seem to be good reasons to state that the quartz-diorites have a clear metamorphic texture in contrast with the igneous texture of the biotite-granodiorite. Although the conclusion that continued soaking and mobilization of the quartz-diorites leads to these biotite-granodiorites seems warranted, there exists still a large gap in texture, time, and occurrence.

In the Pyrenees this rheomorphism is the most extreme and advanced stage of the late-kinematic deformation, which also occurs in many other rocks, but to a lesser extent.

Biotite- and hornblende-gneisses and quartz-diorites

Although the sillimanite-gneisses and quartz-diorites are essentially derived from pelitic sediments with a large aluminium excess, many outcrops occur in the three massifs, of which the parent rock was of semi-pelitic, or marly nature. Since in these rocks no such high aluminium contents occur, aluminium-silicates are absent. Dependent upon the calcium content of the original sediment they changed into biotite-gneisses and quartz-diorites or hornblende-gneisses and hornblende-quartz-diorites. The plagioclase is usually more calcic: andesine or labradorite. Potash feldspar and muscovite are absent. When these rocks occur in the migmatites they do not show a migmatitic texture, but are homogeneous gneisses or quartz-diorites. If they are gneissose, they do not show a deformation structure. The quartz-dioritic gneisses which ALLAART (1958) described, also belong to this group of original calcareous sediments. When the calcium content is still higher, the rocks do not recrystallize as coarse grained gneisses or quartz-diorites, but are converted in fine grained calc-silicate gneisses, which mostly occur as inclusions in the migmatites or quartz-diorites.

Inclusions in the migmatites and quartz-diorites

Since a great variety of inclusions in the migmatite—quartz-diorite series recently has been described by ALLAART (1958), a summary of his main rock types and their history, combined with data form the Arize and Saint-Barthélemy massifs, will here suffice. In general it can be said that the syn-kinematic mineral assemblages closely resemble those of the inclusions in the basal gneisses; also their metamorphic history shows much similarities.

Marbles. — Metamorphic marbles, in part dolomitic, have been found in all three satellite massifs. Well known examples are the marble zone of Mercus-Arignac in the Arize and that of Lapège in the Trois Seigneurs massif. Small scattered outcrops of marbles occur in many places in the three gneiss massifs.

These marbles have yielded a great number of minerals of which most of the earliest, probably synkinematic, are again characteristically anhydrous constituents. These are diopside, spinel, anorthite, forsterite, grossularite, wollastonite, titanite, corundum and calcite. Besides these, three hydrous minerals have been observed — biotite, phlogopite and green hornblende.

The structure of these rocks is similar to that of the marbles in the basal gneisses. When much calcite is present the different minerals lie as more or less rounded crystals in a calcite matrix. With decreasing calcite content a mostly unoriented intergrowth of the calcium and magnesium minerals prevails.

The successive mineral assemblages are also similar to those of the inclusions in the basal gneisses. Calcic scapolite forms mainly at the expense of basic plagioclase, but this replacement feature is much rarer in the migmatite marbles than in those of the basal gneisses. It has been observed in a few cases in the Saint-Barthélemy massif and in the marbles of Arignac.

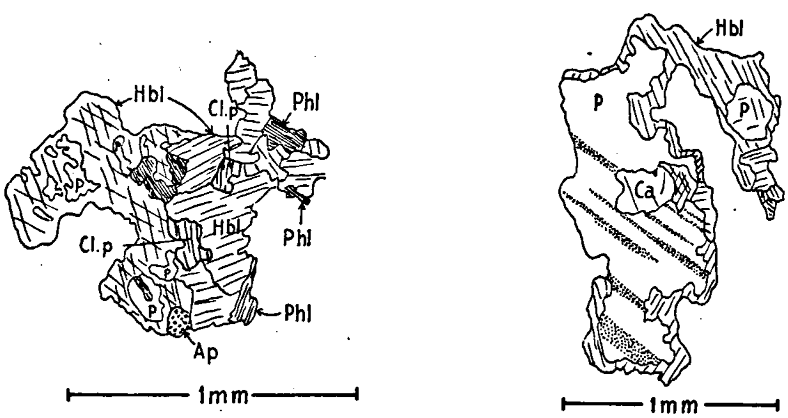

Fig. 16. a. Pargasite aggregate in marble. b. Plagioclase crystal partly enveloped by pargasite.
Ap = apatite, Clp = diopside, Hbl = pargasite, Phl = phlogopite. (After ALLAART, 1958).

More or less contemporaneous with the scapolitization is the partial replacement of forsterite by humite or clinohumite. Diopside may be converted into green hornblende. Then with decreasing temperature and more introduction of water a third mineral association becomes stable. The new minerals are epidote-clinozoisite, cummingtonite, pargasite, phlogopite and sodic plagioclase. Epidote-clinozoisite forms at the expense of scapolite, diopside, hornblende or basic plagioclase. Clinozoisite especially forms reaction rims around plagioclase. Pargasite or sometimes cummingtonite partially replace diopside, anorthite, spinel, or forsterite, whereas forsterite and pargasite both may be replaced by phlogopite (see fig. 16). Still later and of lower grade are clinochlore, replacing humite, forsterite, spinel or pargasite, actinolite and tremolite replacing hornblende and finally serpentine replacing forsterite or humite. Spinel and humite are sometimes partially converted into chrysotile or brucite.

Diopside-bytownite-gneiss. — Diopside-bytownite-gneisses occur only as small inclusions in the migmatites and quartz-diorites. They are fine grained greenish rocks and sometimes associated with marbles. Microscopically they are made up of an aggregate of quartz, bytownite and diopside with minor titanite (see fig. 17). Often green hornblende is present, and diopside- and hornblende-bearing layers alternate. Sometimes diopside is replaced by hornblende, but more frequent is replacement by clinozoisite. The latter mineral also attacks bytownite. In a few cases biotite is present as primary constituent. Accessories are microcline, apatite, ilmenite, zircon and calcite.

Hornblende-bytownite-gneiss. — Occurrences of this gneiss are similar to

Fig. 17. Diopside-bytownite-gneiss in migmatite. Hornblende forms at the expense of diopside.
Pl = bytownite, D = diopside, Ho = hornblende, Q = quartz, Ca = calcite, Ti = titanite.

those of the diopside-bytownite-gneisses; both rock types often alternate. The mineralogical composition is quartz, bytownite, and green hornblende. The hornblende has usually a good form orientation, the prism lying parallel. Sieving with small quartz grains is rather common. The grain size varies from 0.5 up to 2 mm. Plagioclase builds elongated crystals up to 0.6 mm length. When much quartz is present it is interstitial. With decreasing amount of quartz this rock type is transitional to the amphibolites. Replacement of bytownite by clinozoisite is not uncommon; alteration into scapolite has been observed only a few times. The hornblende can be actinolitized (see fig. 18).

Biotite-plagioclase gneiss. — Rocks consisting of biotite, quartz and more or less basic plagioclase have been found on several places in the migmatites and quartz-diorites. Alternations with hornblende-bytownite-gneisses are common. The biotite-plagioclase-gneisses are generally fine grained schistose rocks in which biotite occurs as plates with a diameter of 0.4—0.6 mm, mostly parallel, but also crosscutting the schistosity. Plagioclase is present as elongated crystals to a size of 0.6 mm. Its anorthite content varies from 30 up to 85 %, but mostly it is a rather basic plagioclase which is sometimes altered into clinozoisite. The amount of quartz is variable and transitions to quartzitic rocks are not uncommon. The accessories are the same as in the bytownite-gneisses described above.

Amphibolite. — Several types of amphibolites occur in the migmatites and quartz-diorites of the three satellite massifs. They are always schistose and

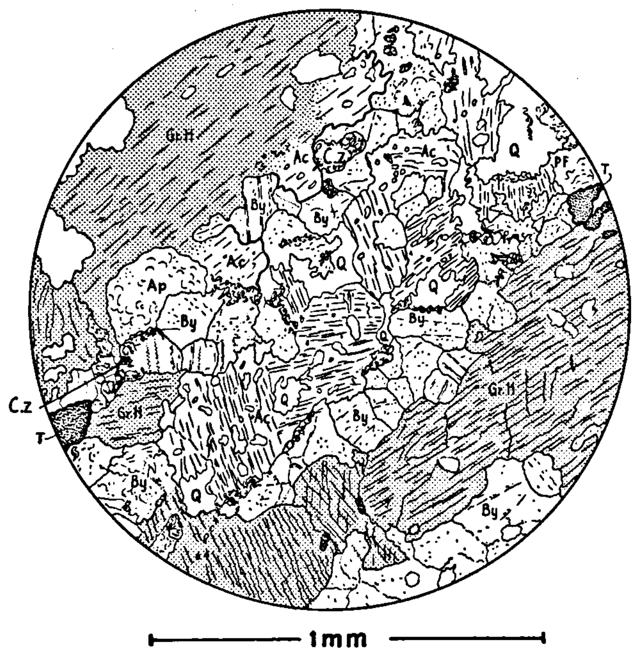

Fig. 18. Late actinolite in hornblende-bytownite-gneiss (near cross-cutting pegmatite). Ac = actinolite, Ap = apatite, By = bytownite, Cz = clinozoisite, Gr.H. = green hornblende, PF = potash feldspar, Q = quartz, T = titanite. (After ALLAART, 1958).

linear rocks, but under the microscope it is clear that they have undergone a post-kinematic recrystallization.

The two main minerals are plagioclase (andesine, labradorite or bytownite) and green hornblende, forming the synkinematic paragenesis. Depending upon the chemical composition other minerals may occur in minor quatities, for example quartz, biotite, garnet, and diopside. During post-kinematic metamorphism plagioclase can be replaced by epidote-clinozoisite and sodic plagioclase; diopside and hornblende are sometimes altered to cummingtonite or biotite, and also to light green actinolitic amphibole. Accessories are ilmenite, titanite, apatite, zircon and orthite.

Quartz-gabbro. — Due to continuing strong post-kinematic recrystallization of amphibolites or bytownite-gneisses unoriented quartz-gabbros can be produced. They consist of an intergrowth of biotite, green hornblende, basic plagioclase (labradorite or bytownite) and little quartz. Biotite often grows at the expense of hornblende; cummingtonite also may replace hornblende. The plagioclase is usually homogeneous with regard to anorthite content; its shape is often euhedral, but it is generally intimately intergrown with hornblende, which then has a skeletal appearance and is enclosed by plagioclase crystals. Plagioclase is usually sieved with small quartz grains.

Quartz-gabbros occur especially in the Trois Seigneurs massif.

Quartzite. — Quartzites also occur as small inclusions in the migmatite—quartz-diorite series. They are usually impure and contain various calcium silicates such as basic plagioclase, green hornblende, or diopside. Originally they were calc-sandstones.

In thin sections they consist of a mosaic of quartz grains (0.1—0.5 mm) in which sub- to euhedral crystals of basic plagioclase (mostly labradorite), green or light green hornblende, diopside, biotite, or garnet are embedded. The labradorite is often zoned with a more basic core than rim. Alteration of the primary constituents into clinozoisite, sericite, or actinolite is not uncommon.

Conclusions. — A complete series of original sediments varying from pure limestone and dolomite over marls and sandy marls to calcareous sandstones has been found in a metamorphic state in the migmatites and quartz-diorites. The chemical composition of the original rocks evidently controls the final product, with the exception of the quartz-gabbros. Moreover rocks of igneous origin as gabbros or diorites probably were present and have subsequently been metamorphosed. In general little signs of metasomatism on these inclusions have been observed; they acted as resisters. The metamorphic history of these rocks is similar to that of the basal gneisses, with the exception of the inclusions in the garnet-augen-gneisses, which only show one stage of metamorphism.

The occurrence of scapolite is remarkable, its main distribution being in marbles. This is probably due to CO_2 necessary for its formation, which in other rocks was not so much available.

The muscovite-granite and gneiss series

As has been indicated in the explanatory text, the muscovite-granites and gneisses form a separate and complex unit which often occurs rather high in the metamorphic sequence. In general the rocks are leucocratic and homogeneous. The mineralogical composition is rather constant; sodic plagioclase, potash feldspar, quartz, muscovite and biotite are the main constituents, and there is remarkably little variety in composition. There is, however, a great variety in structure ranging from schistose and linear augen-gneiss to massive granite.

Linear muscovite-augen-gneiss and linear muscovite-augen-gneiss with euhedral potash feldspar porphyroblasts

Muscovite-augen-gneisses occur in the Saint-Barthélemy massif and the eastern part of the Arize massif. Outside the map area a great development of this type of augen-gneiss is found in the Ax-Montcalm massif, south of sheet 3. The augen-gneisses occur in general on top of the migmatites and below the mica-schists as a layer of at most 700 m thick. Megascopically it is a medium-grained augen-gneiss in which the feldspar-augen do not generally exceed ½ cm in length. Only the augen-gneiss near Prayols and on the opposite side of the Ariège river has feldspars of 2 cm length. The gneiss always shows rather big muscovite crystals and biotite is often subordinate.

The mineralogical composition is quartz, potash feldspar, plagioclase (An 5—25), muscovite and biotite; accessories are apatite, often in rather large crystals, zircon, ilmenite, tourmaline, and garnet.

Although these gneisses are megascopically, and from a structural point of view rather similar to the garnet-augen-gneisses, the microscopical structures are different. Contrasted to the monometamorphic garnet-augen-gneisses, these muscovite-augen-gneisses show a distinct polymetamorphic history in which two succeeding phases can be distinguished. The augen-gneiss texture which only occurs as a relic, is preserved by the presence of the original mica "schlieren" around the feldspar eyes, leaving the shape of the augen more or less undisturbed; the feldspar augen, however, have been partially or completely replaced by a fine-grained intergrowth of quartz, and microcline, with relics of the old feldspar, which in most cases was a plagioclase. At first sight this intergrowth very much resembles a cataclastic texture, but the nature of the boundaries between quartz and the feldspars, rules this out. It is a typical pseudocataclastic texture (= mesostase II of GUITARD, 1956), which formed as a result of replacement of the old feldspars under post-kinematic conditions.

Most of the plagioclase is old plagioclase, which in a number of cases still forms part of an eye (see fig. 19), but often it is strongly corroded by microcline and quartz and then has very irregular outlines. In contrast with microcline the plagioclase is often sericitized and kaolinized or partially replaced by muscovite. The contacts with microcline are generally albitized, these albite rims mostly being clear. Myrmekite is frequent and in a number of cases there is strong evidence that the microcline has replaced the plagioclase. Fig. 20 gives a picture of this feature, in which a large microcline crystal replaces a rather strongly sericitized and kaolinized plagioclase. It is interesting to note that a few quartz-worms of the myrmekite have been preserved in the microcline, indicating that first the plagioclase becomes myrmekitized and then replaced by microcline (see also DRESCHER-KADEN, 1948). Also the fresh appearance of the potash feldspar against the altered plagioclase points into the same direction.

As far as could be ascertained no second generation of plagioclase, except for the albite fringes, is present.

Microcline occurs as small or large irregularly bounded crystals, which locally may attain a porphyroblastic habit. Gneisses in which these porphyroblasts are megascopically visible have been mapped as such, but they are not essentially different from the normal augen-gneisses. The typical microcline twinning is in most cases present. Microperthite is rather frequent. The large euhedral porphyroblasts are always perthitic and are twinned according to the Carlsbad law; often they also show microcline cross-hatching. The small crystals have irregular contacts, but the porphyroblasts are more or less euhedral and frequently replace an old plagioclase eye; they do not form a pseudomorph of the eye, but develop an idioblastic shape. Inclusions of plagioclase and biotite have often been observed. Sometimes these inclusions of plagioclase have the same orientation, so as to indicate that one large crystal was replaced, but they are never arranged in a zonal pattern. Randomly oriented plagioclase inclusions have also been found. The potash feldspar is always remarkably clear and is only rarely sericitized or kaolinized; alteration in muscovite is very rare.

Quartz occurs in two generations. Associated with the micas, which form the boundaries of the original feldspar augen, it forms drawn-out crystals, accentuating the augen texture. Later, quartz was introduced contemporaneous with the microcline and builds small rounded or elongated crystals, often with irregular contacts.

The micas occur in zones which formerly separated the augen. Often large muscovite crystals up to a size of a few mm are present, and then biotite is in less quantity. The big muscovite may be slightly bent, but in

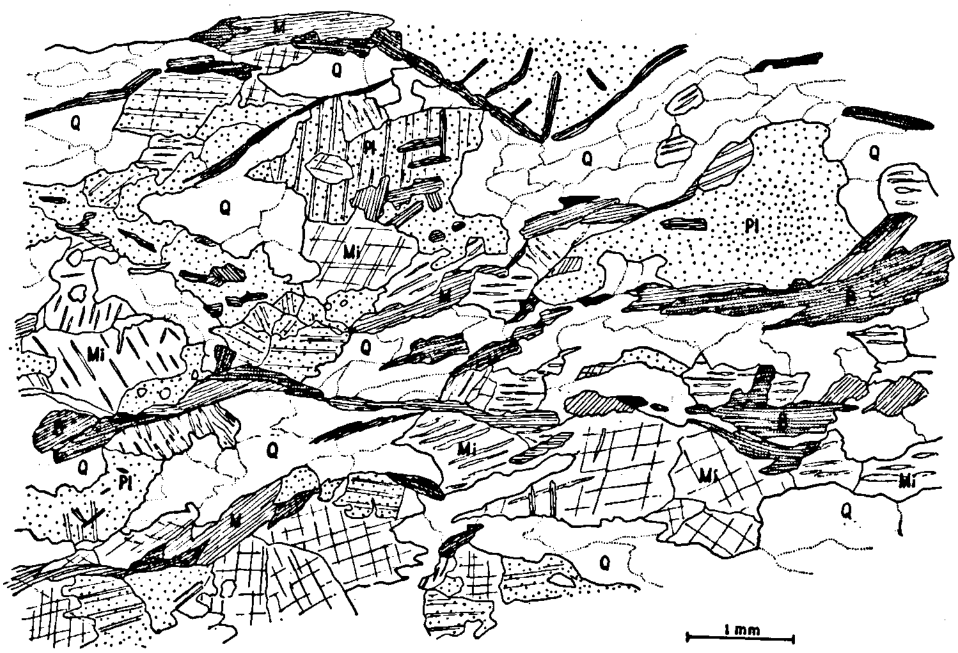

Fig. 19. Post-kinematically recrystallized muscovite-augen-gneiss (Saint-Barthélemy). Note old plagioclase eyes partially replaced by muscovite, quartz and microcline; muscovite also replaces biotite. The shape of the original eyes is well visible, but the biotite and muscovite crystals around it are undeformed.
Pl = oligoclase, Mi = microcline, Q = quartz, B = biotite, M = muscovite.

many cases this is due to some later movement, since part of these muscovite plates are undeformed or cross-cutting and are certainly not the original augen-gneiss micas. When more biotite is present most of the muscovite clearly develops at the expense of the first mineral. Since the undeformed nature and sometimes decussate intergrowth of the biotite suggests a post-kinematic recrystallization of this mineral, a similar history as in the migmatites is indicated. This is the more so, since, although very seldom, biotite may be converted into fibrolite. There is, however, one important difference with the migmatites; in these rocks muscovite is clearly the latest mineral and replaces not only biotite and sillimanite, but also both feldspars. In the muscovite-augen-gneisses the plagioclase is always muscovitized, but the microcline only to a very small extent. This suggests that the microcline is con-

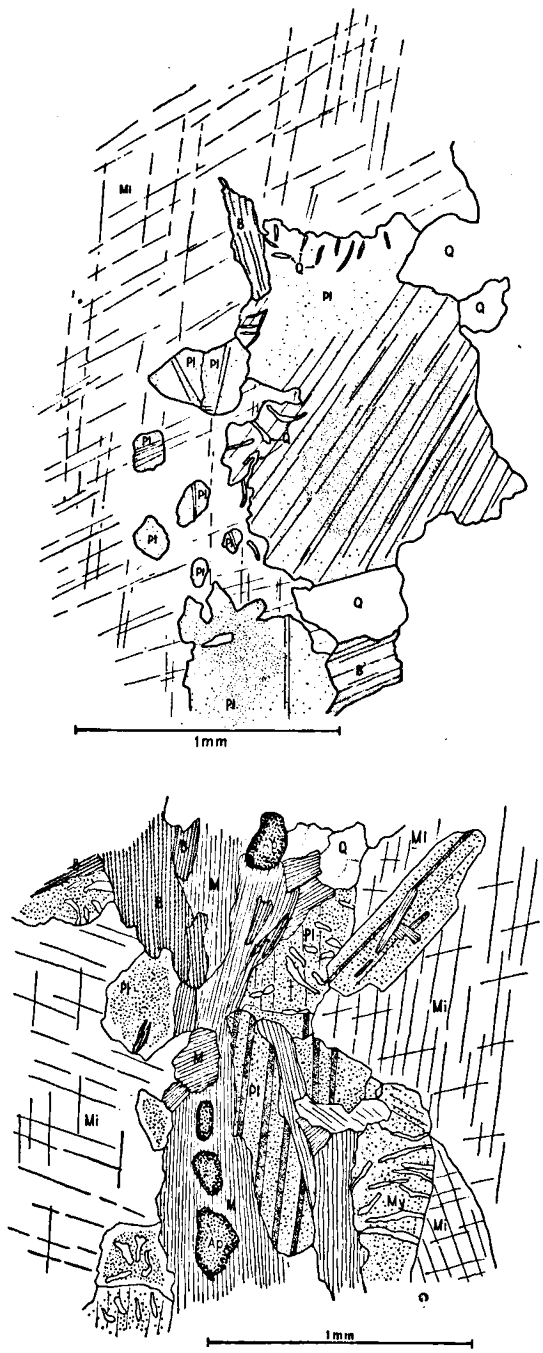

Fig. 20. Muscovite-augen-gneiss with potash feldspar porphyroblasts. Microcline and muscovite replace plagioclase under formation of myrmekite.
Mi = microcline, Pl = oligoclase, Q = quartz, My = myrmekite, B = biotite, M = muscovite, Ap = apatite.

temporaneous with or even later than the muscovite, but since an incipient muscovitisation is present, both minerals are probably almost of the same age. Since the formation of late muscovite in the migmatites and in the augen-gneisses is probably contemporaneous, the microcline in the latter gneisses is later than in the migmatites. As far as could be concluded from the thin sections no clear indications of the presence of potash feldspar as primary mineral of the augen-gneisses have been found. It may have been present, but then only in subordinate amounts.

In this way three generations of potash feldspar are present in the metamorphic rocks of the Pyrenees, viz. 1) synkinematic microperthite (according to GUITARD untwinned microcline), 2) post-kinematic pre-muscovite microcline II in the migmatites and 3) post-kinematic, microcline III contemporaneous with muscovite in the recrystallized muscovite-augen-gneisses.

Locally these recrystallized augen-gneisses have been sheared by later movements. Examples of this shearing occur on many places, for example in a fault zone due west of the Trimouns quarry, and on the fault, south of Trimouns, which separates the garnet-augen-gneisses from the muscovite-augen-gneisses with euhedral feldspar-porphyroblasts. Especially in this latter fault zone beautiful mylonite zones are exposed. Here zones with intense movement alternate with layers of little movement. In the mylonite the idioblastic feldspars are again sheared to augen, whereas in the layers with little or no movement the feldspars are still preserved as rectangular crystals (see fig. 21). It will be clear that these faults are later than the post-kinematic recrystallization and hence later than the main phase of he orogeny.

From the facts presented it may be concluded that

1) the augen-gneisses were mainly quartz-biotite-plagioclase-gneisses with minor potash feldspar; they are synkinematic.
2) microcline, muscovite, and a part of the quartz are post-kinematic.
3) the metamorphic history is in many respects similar to that of the migmatites, but the microcline of the augen-gneiss is probably somewhat later.
4) the microclinization and muscovitisation will have been the result of potash-metasomatism (cf. fig. 24).

Muscovite-biotite granitic gneiss

These gneisses have been mapped in the Trois Seigneurs and Arize massifs. In the Trois Seigneurs massif this rock occurs as big lens-shaped bodies in the mica-schists, not far above the migmatic boundary. It has the same mineralogical composition as the muscovite-augen-gneisses, but the texture is somewhat different; lineation and augen-texture are not, or only faintly, present.

The metamorphic history, however, is for a large part similar to that of the augen-gneisses. The original gneiss was probably also a quartz-biotite-plagioclase rock, which formed rather late with regard to the folding, so as to form a gneissose texture without feldspar augen.

Biotite is for a large part replaced by unoriented muscovite plates, which also attacked the plagioclase. More or less contemporaneous cross-hatched microcline developed, mainly at the expense of plagioclase, often accompanied by the formation of myrmekite. The microcline is never penetrated by large muscovite crystals, but sometimes fibrous offshoots of this mica replace some of the potash feldspar. A few fibrolite bundles in muscovite indicate that the fibrolitization stage also occurred before the muscovitisation. These various replacements gave rise to an intricate intergrowth of quartz, plagioclase and microcline.

Summarizing, we can state that in these granitic gneisses the absence of lineations and augen textures indicates a late- to post-kinematic age, but the same post-kinematic processes, accompanied by potash introduction, which

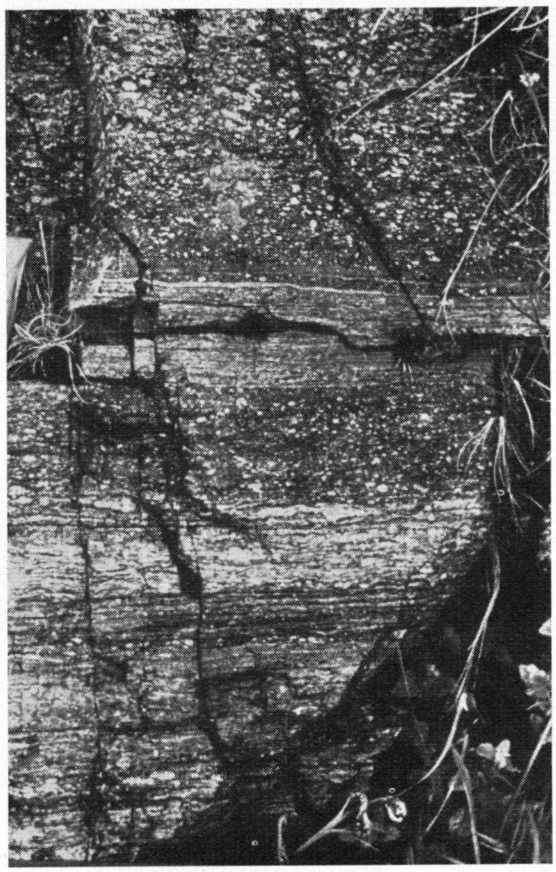

Fig. 21. Muscovite-augen-gneiss with euhedral feldspar porphyroblasts, in mylonitic zones again deformed to augen-gneiss. Fault movements stronger in certain zones than in others.

influenced the augen-gneisses of the Saint-Barthélemy massif, changed the texture of these granitic gneisses.

Some of the muscovite granites of the Arize massif show locally the same gneissose texture as the granitic gneisses of the Trois Seigneurs massif, but the greater part of these bodies is megascopically unoriented.

Muscovite- and muscovite-biotite-granite

Several small bodies of muscovite-granite occur in the migmatites of the Arize massif and some large bodies in the mica-schists of the Trois Seigneurs massif.

The mineralogical composition again is similar to that of the augen-gneiss and granitic gneiss. The texture is, however, completely unoriented and is in fact very much the same as in the muscovite-biotite granitic gneisses.

Plagioclase is often sericitized and kaolinized and has very irregular shapes. It is often partially replaced by microcline accompanied by the formation of myrmekite, also indicating that potash feldspar is the youngest mineral (see fig. 22 and 23). The shape of this mineral often tends to be subhedral. When little microcline is present, the plagioclase also has more or less subhedral outlines.

Quartz fills the interstitial space between the feldspars. Muscovite builds

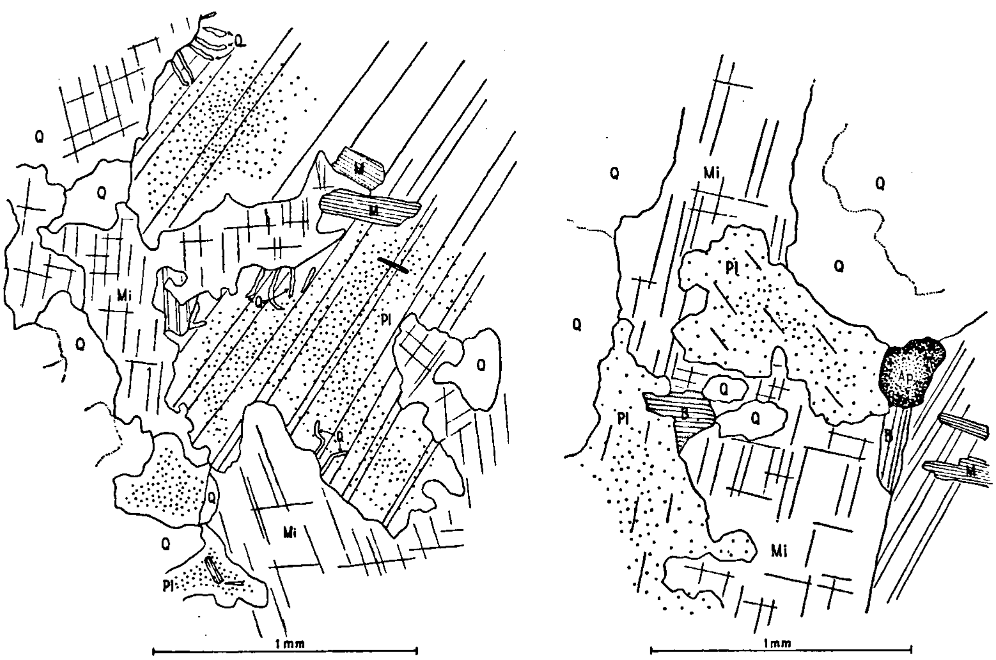

Fig. 22. Muscovite- and muscovite-biotite-granite. Plagioclase replaced by microcline and muscovite. No muscovite in microcline.
Mi = microcline, Pl = oligoclase, Q = quartz, M = muscovite, Bi = biotite, Ap = apatite.

large plates and often shows fibrous offshoots which penetrate plagioclase or microcline. Muscovite evidently replaces plagioclase, but, apart from the fibrous offshoots, never attacks microcline. When biotite is present, it is clear that at least part of the muscovite has formed at the expense of the dark mica. Biotite is usually a minor constituent.

The complete absence of any preferred orientation in these granites excludes the possibility that they are recrystallized augen-gneisses. Moreover relics of such gneisses could be expected to occur in some of these larger granite bodies, but apart from mica-schist inclusions, these granites are quite homogeneous. Also the shape and mutual relationships of the plagioclase shows that even in the earliest stage these rocks must have been unoriented.

Conclusions

The most remarkable feature of the four units in which the muscovite-granite and gneiss series can be divided, is that all rocks have undergone the same replacement by microcline and muscovite at the expense of older plagioclase. This replacement is of post-kinematic age and falls rather late in the metamorphic history, since in general the muscovitisation is the last record of the Hercynian metamorphism. The microclinization and muscovitisation indicate an important introduction of potash, which, being a more general feature, probably will be contemporaneous in the three satellite massifs. The original plagioclase-gneisses and granites have however not the same age. They range from syn- to post-kinematic. In the post-kinematic granites the formation of the plagioclase rock will have been followed immediately by the microclinization, but between the formation of the synkinematic augen-gneisses and the microclinization there will have been a considerable gap in time of which no records have been preserved. Consequently, in the augen-gneisses both phases of metamorphism have been separated by a time of inactivity.

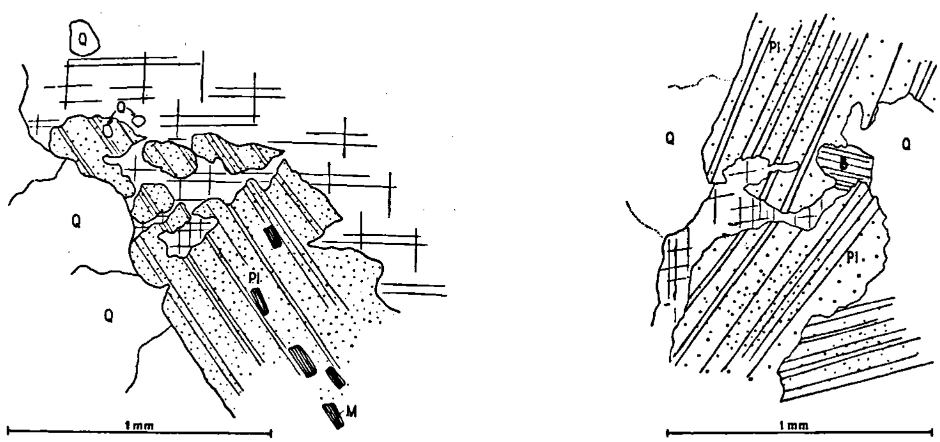

Fig. 23. Explanation see fig. 22.

It is evident that all these gneisses and granites have been made in two steps: the first is feldspathization of the original schist by introduction of silica and sodium either syn- or post-kinematically, resulting in plagioclase-rich gneisses and granites; the second step, favoured by addition of potash, was microclinization and muscovitisation of plagioclase and biotite (cf. fig. 24).

Of course the question rises as to the origin of the introduced potash. This will be treated in the chapter on the chemical migrations, but it may be here stated that the potash originates most probably from the migmatites, from which it was expelled in a rather late stage.

The mica-schists

Three units can be distinguished in the Pyrenean mica-schists, the chlorite-sericite schists, the muscovite-biotite schists and the andalusite-cordierite (-staurolite) schists. These three zones form the transition between the non-metamorphic Palaeozoic cover above, and the gneisses and granites below.

Excepting most of the sericite-phyllites, the mica-schists are for their greater part polymetamorphic, and show a development which is similar to that in the underlying gneisses; a synkinematic phase is followed by a post-kinematic phase, giving rise to different mineral associations and different structures (see ZWART, 1958).

The sericite-phyllites are the epizonal Cambro-Ordovician schists and have been described by ALLAART (1958) from the Trois Seigneurs massif. These phyllites show the same characteristics in the Arize and Saint-Barthélemy massifs; the mineralogical composition is sericite, chlorite (penninite and

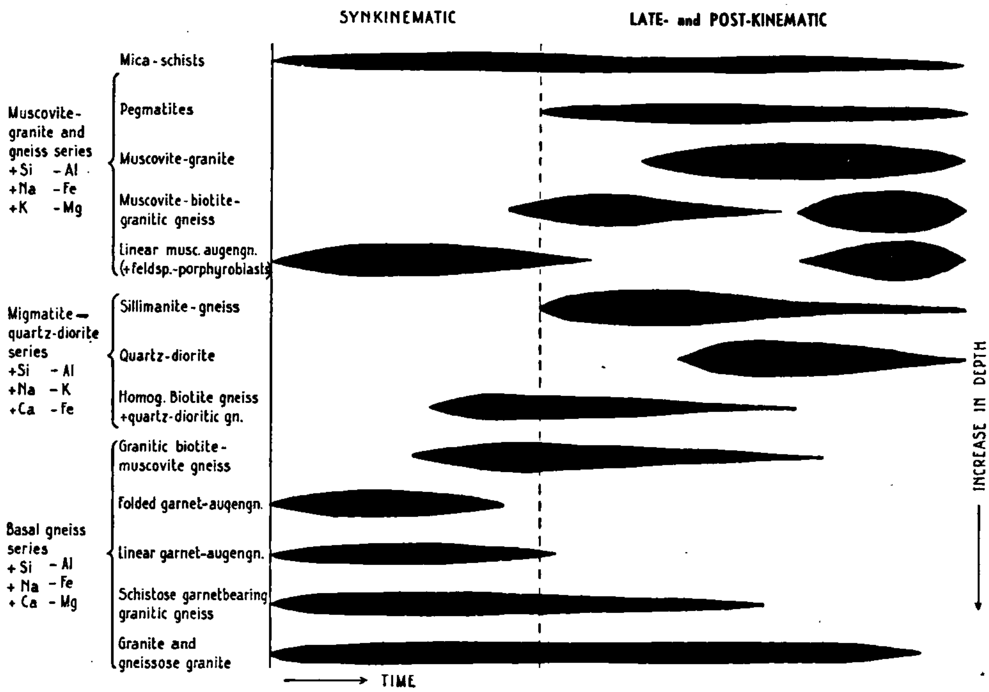

Fig. 24. Time and depth relationships of mica-schists, autochthonous granites and gneisses.

clinochlore), quartz (often in exudation bands), and albite as main constituents, and tourmaline, rutile, graphite, zircon, apatite, ilmenite and pyrite.

The chlorite-sericite-schists grade downward into muscovite-biotite-schists with a gradual increase in grain size. At first biotite is stable in association with chlorite, but approaching the andalusite zone the chlorite disappears. The influence of static recrystallization is clearly visible in thin section; it is indicated by such features as polygonal arcs of micas and cross-cutting mica crystals. No new minerals are formed during the post-kinematic phase.

The schists of the andalusite zone contain several aluminium silicates; only kyanite is entirely lacking. Andalusite, cordierite, and sillimanite are common; staurolite is rather scarce.

During the synkinematic phase two different mineral associations were stable in the aluminous mica-schists; in both types quartz, oligoclase, biotite, muscovite and cordierite are present, but in the first andalusite occurs and in the second staurolite. In the chapter on general principles the criteria for the synkinematic nature of the various minerals have been explained and there is nothing to be added to it.

Synkinematic andalusite (see fig. 4, 5) is present in many mica-schists of the Trois Seigneurs and Arize massifs, but it was not found in the Saint-Barthélemy massif. It often forms large porphyroblasts up to a size of one or more cm, which sometimes are clearly rotated. Staurolite is much rarer than andalusite. It has been found in mica-schists in the eastern part of the Arize massif and in the Saint-Barthélemy massif. It has been mentioned by LACROIX from the Trois Seigneurs massif.

Synkinematic andalusite is absent in staurolite-schists. The controlling factor as regards the development of andalusite or staurolite is unknown; it may be chemical (high or low iron content) or physical and then dependent on confining pressure, as I once suggested (ZWART 1956) [1]). Most of the mica-schists of the andalusite zone have recrystallized under post-kinematic conditions, which results in a decussate intergrowth of biotite, the formation of polygonal arcs and cross-cutting biotite. Muscovite did not generally form in this first period of post-kinematic recrystallization, but andalusite went on crystallizing and much of the andalusite is in fact post-kinematic. Staurolite became unstable and in many instances it is replaced by andalusite, sometimes leaving some isolated staurolite relics, thus proving the time sequence of these minerals. Cordierite also is in part a post-kinematic mineral.

In a later stage a second generation muscovite formed at the expense of andalusite, cordierite, or biotite. It often builds large undeformed plates which are completely cross-cutting.

Near the transitional zone with the migmatites fibrolite may be present. Knots of this mineral have originated at the expense of biotite, but it is earlier than the late muscovite. In the Trois Seigneurs a whole zone of these sillimanite-schists occurs between the andalusite zone and the migmatites, but in the Arize and Saint-Barthélemy massif sillimanite-schists are only locally present. The fibrolization and the late muscovitisation in the migmatites are contemporaneous and similar in character with the features in the sillimanite-schists.

In figure 24 the formation of all kinds of autochthonous gneisses and granites with regard to time and depth, has been recorded.

The biotite-granodiorite to quartz-diorite

The biotite-granodiorites and quartz-diorites are considered as intrusive rocks which in the Pyrenees generally are emplaced in unmetamorphosed Upper Palaeozoic sediments. They are disharmonious granodiorites (WALTON 1955) in contrast with all other gneissose and granitic rocks which occur in a regionally metamorphosed environment. They are considered as intrusive bodies mainly on structural grounds; this is especially evident in case of some of the smaller stocks, for example the granodiorite of Foix and of the Pic des Trois Seigneurs (ALLAART 1958).

The mineralogical composition of the grano- and quartz-diorites is very

[1]) During fieldwork in the Hospitalet massif in Andorra in 1958, it appeared that andalusite, staurolite and cordierite are stable together in pure synkinematic mica-schists.

constant; plagioclase (andesine), quartz, microcline and biotite are the main constituents, although microcline sometimes occurs only as an accessory. The plagioclase is sub- to euhedral and is often oscillatory zoned sometimes with as much as 10—20 zones; these zones are always idiomorphic. This plagioclase is distinctly different from that of the autochthonous quartz-diorites of the migmatite—quartz-diorite series, of which the plagioclase is usually somewhat more sodic, and never shows this complicated oscillatory zoning. Also its shape is not euhedral.

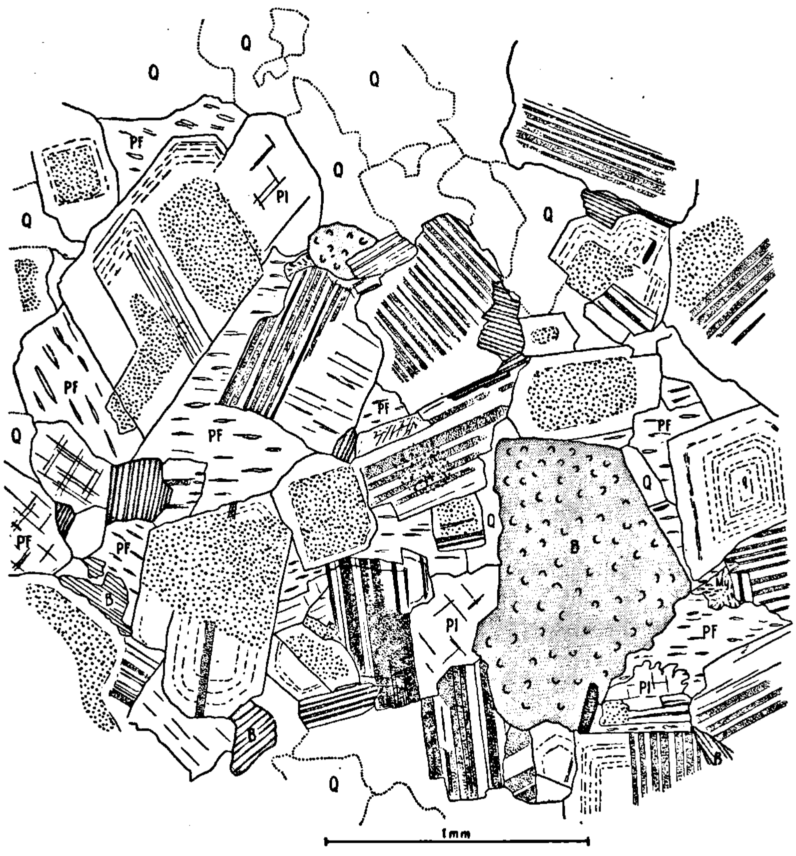

Fig. 25. Intrusive biotite-granodiorite. Note igneous texture with euhedral, zoned plagioclase. Quartz and potash feldspar are interstitial. Compare with autochthonous quartz-diorite, fig. 14.
Pl = andesine, PF = potash feldspar, Q = quartz, B = biotite.

Quartz occurs as irregularly bounded crystals often interstitial to plagioclase. Microcline also builds irregular crystals up to a size of 1 cm and often contains idiomorphic inclusions of plagioclase. It is evident that in many cases microcline replaces plagioclase accompanied by the formation of myrmekite. Although the process is similar to that in the migmatites, this does not necessarily indicate the same age for both processes. In fact, a similar microclinization occurs in many orthomagmatic granitic rocks and is a normal feature due to autometasomatism of a consolidating granite.

Biotite forms sub- to euhedral plates, which often are corroded. It can be altered into epidote, prehnite, or penninite. Accessories are zircon, apatite, orthite, ilmenite, and occasionally green hornblende.

It is important to date these granodiorites with regard to the regional metamorphism. This can be done in the Trois Seigneurs massif because there such a granodiorite occurs low down in the mica-schists just above the migmatite front. As has been explained, all migmatites and mica-schists have undergone a last stage of metamorphism which is characterized by general replacement or biotite, sillimanite and feldspar by muscovite. Although in all the rocks which surround the biotite-granodiorite of the Pic des Trois Seigneurs, this muscovitisation is quite evident, the process did not occur in the biotite-granodiorite. This leads to the conclusion that the consolidation of the stock occurred later than the latest stage of the regional metamorphism, and consequently the microclinization of the biotite-granodiorite is later than and independent from that of the migmatites.

In most cases the biotite-granodiorite occurs in the unmetamorphosed Upper Palaeozoic rocks and then no relationship between the intrusive granodiorite and the regional metamorphic rocks can be established.

Our conclusion is not in accordance with the opinion of GUITARD (1958) who thinks the biotite-granodiorite to be of the same age as the post-kinematic phase of the regional metamorphism. This may be true in some cases (granite of Mont Louis, Quérigut) but, to my opinion it does not hold for the granodiorite bodies of the Central Pyrenees.

Petrochemistry of the metamorphism

Introduction

In order to get an impression of the chemical changes which have taken place during the formation of the various metamorphic units, a great number of chemical analyses has been prepared by Dr C. M. de Sitter-Koomans at the petrochemical laboratory of the Leiden Geology department. Although this work is still in progress, we already obtained enough data from rocks of sheet 3, to permit some definite conclusions.

The greatest difficulty to determine chemical changes in metasomatism is the composition of the original rock, which as a matter of fact, does no longer exist. One method which has been used to overcome this difficulty is to follow a distinctive layer from the unmetamorphosed into the metasomatic area. It is, however, almost impossible to follow one layer through a considerable number of metamorphic zones and even than such a layer would have a rather extreme composition, in which we are not primarily interested. Further, the comparison of only a few analyses of metasomatic with non-metasomatic rocks is useless as long as the variation in composition is not known. As lateral facies changes and structural complications prevent an adequate direct comparison between unmetamorphosed rock series with their metamorphic and metasomatic counterparts, only a comparison of averages of the most common rock types can inform us about systematic chemical changes.

During the last ten years some discussions have been going on as to the calculation of metasomatic changes (BARTH, 1948, 1955, ESKOLA, 1954, POLDERVAART, 1953). Barth considers that metasomatism occurs without change in volume and he uses the standard cell with the same number of oxygens. POLDERVAART thinks the number of $(Si, Al)O_4$ tetrahedra to be constant. In reality we do not know whether metasomatism is an isovolumetric process or acts with a constant number of $(Si, Al)O_4$ tetrahedra, but personally I believe that during feldspathization the volume is not constant; field observations, however, neither indicate an appreciable increase or decrease in volume. The volume changes are dependent both on the loss, and later the addition of water and the eventual introduction or removal of other elements, with the result that the end product, the metasomatic rock, cannot inform us about the total volume change it has suffered. This is the more so when the metasomatism is synkinematic. Since the volume changes remain unknown, extensive petro-chemical calculations based on analyses cannot give us reliable results.

The procedure I follow here consists of a comparison of averages and composition ranges with the help of variation diagrams. This method, which requires a great number of analyses, gives much better results than a complicated system of calculations on a small number of analyses. Of course the amounts of introduced and removed elements will then only be known within rough limits.

In the first place we must make sure that the metasomatic rocks have most probably originated from the same kind of sediments as the unmeta-morphosed ones. This will be achieved if enough chemical analyses have been made and especially so if the metamorphic front in a certain region lies not always on the same level, but is deep at one locality and very high at another. Than we can be relatively certain that we compare unmetamorphosed rocks which are in lateral continuity with their metasomatic counterparts, without the need to follow some marker bed. This situation is found in the Pyrenees where the key horizon of the Silurian gives a measure of the variable strati-graphic depth of the metamorphic front.

Not only is it necessary to know the average composition of the various units, we have also to determine the range in composition. For computing the average composition it is sufficient to make a few analyses of composite samples of a great number of specimens. If we do this for various parts of the metamorphic region, then a reliable average of a certain unit will be known. On the other hand, in order to determine the range in composition we have to analyze a large amount of single samples, which on their turn, can be used for calculating an average.

Once the average and the variation in composition of the original material is sufficiently known, we have to follow the same procedure with the meta-somatic rocks. Averages and composition ranges can then be compared. It is necessary that both comparisons of the averages and of the composition ranges give the same results, since otherwise there is no adequate proof of introduction or removal of a certain element.

Obviously the relative enrichment of one element can be due either to an addition of that particular element or to removal of others, since volume changes remain unknown. When only elements are introduced without removal of others and without appreciable increase in specific gravity, there will be a relative dilution of the other elements. This effect is represented in fig. 26. On the ordinate the weight percentages are shown and on the abcissa the introduction of new material in percentages of the original rock weight. Three different cases are figured, one with 50, one with 60 and one with 70 % SiO_2 in the original rock. When in the last case 20 % SiO_2 is introduced, the real increase of the SiO_2 percentage is about 5 %, due to the fact, that the weight is now calculated on 120 and not on 100 %. At the same time the total of all other elements decreases with 5 %, that means they are diluted. For a certain case with Al_2O_3 20 % this dilution affect is only 2½ %. It should be noticed that the line starting at 20 % is the same, regardless of the original silica-content. So when comparison of analyses shows a decrease of the aluminium content of more than 2½ % with not more then 20 % addition of SiO_2, there must be removal of aluminium.

Comparison of many chemical analyses showed that the introduced elements (Si, Na and Ca) show an increase in percentage of 6—12 %. That means that, if no elements were removed, and with 60—65 % $SiO_2 + Na_2O$ the total introduction would not be 6—12 % but 20—45 %, accompanied by a volume increase of approximately the same amount, assuming no great changes of specific gravity. This would lead to a really extravagant introduction of new material and an enormous swelling up of the infrastructure of a mountain chain, which is not confirmed by field observations. Therefore metasomatism will most

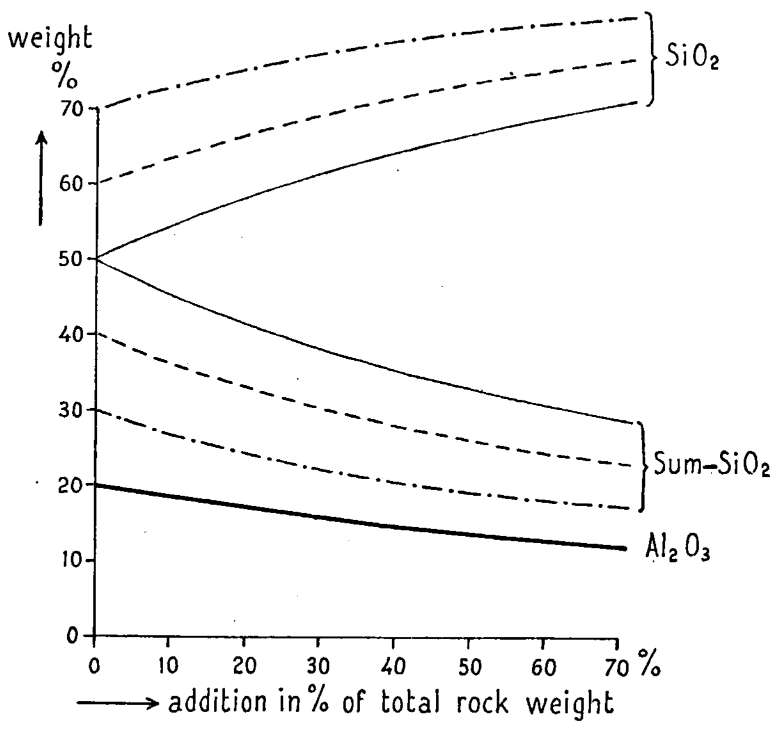

Fig. 26. Increase in SiO_2 percentage with regard to introduced amount of SiO_2, without removal of any element and with increase in volume; no change in specific gravity.

probably have taken place with only small volume changes, and introduction of certain elements generally implies removal of others. This is also in accordance with the fact that the percentages of the removed elements usually decrease more than can be accounted for by the dilution effect.

To compare the analyses we did not use the weight percentages of the oxides, but recalculated these to cation-percentages, according to BARTH and

ESKOLA (1954 and 1955). The diagrams also give these percentages. The tables with the weight percentages of the oxides have been published in the explanatory text of sheet 3 (DE SITTER and ZWART, 1958); here we give only the cation-percentages.

Since the Pyrenean regional metamorphism is restricted to pre-Silurian rocks, our first goal was to determine the composition of the unmetamorphosed, or in this case low grade, pre-Silurian sediments. These Cambro-Ordovician phyllites can be supposed to be the original material from which gneisses, migmatites and granites have been made. Then a number of mica-schists, which are supposed to be isochemically (water not being considered), metamorphosed pelites, have been analyzed. Since most of the sediments are rather pure pelites with intercalated quartzites, a large aluminium excess could be presumed and this was indeed confirmed by the analyses and by the presence of aluminium-silicates.

Our main interest on sheet 3 lies in the petrochemistry of the migmatite—quartz-diorite series and the basal gneiss series. Together with phyllites and mica-schists almost 70 chemical analyses of these rock have been made. Less work has as yet been done on the muscovite-granite and gneiss series.

Phyllites

Six analyses have been made from Cambro-Ordovician phyllites. Each of these analyses is made of a mixture of ten different rock samples, collected along a section of the Cambro-Ordovician. Thus every analysis represents the average of those ten samples. Two of these analyses are from the Ax-Montcalm massif, two from the Arize massif and two from the Trois Seigneurs massif. The samples from the latter massif are taken from the upper part of the Cambro-Ordovician, those of the two other localities from a much lower part.

The mean of these six analyses, made of 60 samples, should be a fairly representative composition of the phyllites. Analyses of single specimens have not been made, since a number of such analyses of the mica-schists are already available. These six analyses show a range in composition and, of course, individual specimens will have a far greater variation. Yet, there are only two elements which show important variations; these are silica and aluminium. They have a very simple relation; the higher the Si-content, the lower is the Al-percentage. The silica-percentage is normal for a pelite, but the Al-content is quite high, even for a pelite. The total iron content is rather constant; magnesium varies, but its values are low anyway. Calcium also is low and remarkably constant. Sodium shows some variation but independent of the silica-content. The potash percentage is fairly high and usually distinctly higher than sodium. This is a wellknown feature in pelites and due to the adsorption of potash on clay minerals, whereas sodium stays in solution in sea water.

The mean value of the six analyses will not be quite the same as the whole Cambro-Ordovician, since the quartzites are omitted. Therefore the average of all Cambro-Ordovician sediments will be slightly higher in silica and somewhat lower in aluminium. Since quartzites remain almost unchanged in the feldspathised rocks, there is little need to analyze them. The same holds true for limestones and marls, which locally occur in small quantities in the Cambro-Ordovician. Therefore the calcium content of the average Cambro-Ordovician will be somewhat higher.

TABLE I

Cation-percentages of the phyllites
(Each analysis is made of a mixture of ten samples)

Analysis no.	Ax-Montcalm		Arize massif		Trois Seigneurs massif		Average
	10	11	12	13	14	15	
Si	55.0	56.5	58.0	59.5	62.1	63.9	59.2
Ti	0.9	1.0	1.2	1.0	0.8	0.8	0.8
P	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Al	23.4	24.2	23.3	22.3	20.2	18.8	22.0
Fe‴	2.9	3.0	4.0	4.1	2.0	2.1	3.0
Fe″	5.3	3.5	3.5	3.0	3.9	3.4	3.8
Mg	3.2	2.2	1.1	1.7	2.1	1.3	1.9
Ca	1.7	1.6	1.7	1.3	1.1	1.4	1.5
Na	3.1	3.1	2.8	2.9	3.2	4.7	3.3
K	4.3	4.6	4.2	4.0	4.4	3.4	4.1
	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Mica-schists

Only analyses of single specimens of mica-schists have been made; average analyses of composite samples will be executed in the near future. Most of the 17 mica-schist analyses are from the andalusite zone, but some originate from the biotite zone. These 17 analyses are arranged according to increasing SiO_2 percentage and give a great range in composition, starting with a mica-schist of pure pelitic composition with a very high aluminium content to a quartzitic mica-schist with 73 % SiO_2 and low Al_2O_3 percentage (Table II). As in the phyllites, Al decreases with increasing Si-content. The average Si and Al of these mica-schists is almost the same as the average of the phyllites. Total iron is fairly constant and is only distinctly lower in the last analysis of the quartzitic mica-schist. The average mica-schist shows somewhat less iron than the average phyllite, but it is doubtful whether the difference is of any significance. Magnesium has some variation but is usually rather low. The mica-schist average of 3 % is about 1 % higher than the average phyllite and although this difference is considerable, the data do not yet permit to draw definite conclusions whether there is an increase of Mg in the mica-schists or not, with regard to the phyllites. The calcium content of mica-schists and phyllites is rather constant and the averages are almost identical.

Of great importance are the alkalis. As in the phyllites there is a predominance of potash over sodium. The average sodium content of the mica-schists is somewhat lower than of the phyllites, but the potash percentage of the mica-schists is considerable higher than that of the phyllites. In similar rocks of the Valle de Arán equally high potash percentages have been noted. The author considers this difference too large to be accounted for by accidental factors, and it would imply that the mica-schists are enriched in potash, but more analyses are needed to establish this hypothesis more firmly. The enrichment in potash and eventually in magnesium could be the result of the removal of these elements from underlying gneisses and granites. If this is true, then the mica-schists are not such isochemical rocks as often upposed. Although

TABLE II

Cation-percentages of the mica-schists

Analysis no.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	Average
Si	44.7	53.2	54.3	54.3	54.2	56.8	56.2	57.0	56.7	59.9	58.7	61.0	62.1	63.1	62.9	66.1	70.9	58.4
Ti	1.1	0.6	0.8	0.7	0.8	0.8	1.1	0.6	0.7	0.7	0.8	0.9	0.7	0.8	1.0	0.7	0.7	0.8
P	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2
Al	31.7	23.6	24.9	26.2	24.5	24.2	25.6	21.2	20.4	24.4	23.5	22.8	21.2	19.3	19.4	17.4	16.3	22.7
Fe‴	1.5	0.6	1.8	2.1	2.3	2.3	3.3	2.2	1.9	3.2	2.4	2.5	1.9	1.3	0.8	1.5	1.0	1.9
Fe″	3.6	5.0	4.1	4.7	4.3	3.5	2.0	3.6	4.3	3.7	3.6	3.7	3.9	3.2	3.5	4.0	1.7	3.7
Mg	2.8	5.0	4.4	2.3	2.8	4.0	1.6	5.0	4.8	2.0	4.2	2.3	3.3	0.9	2.9	0.9	0.5	2.9
Ca	1.3	1.4	2.3	0.8	1.7	0.7	2.2	1.0	2.6	0.7	0.9	—	1.1	4.1	1.5	1.8	2.9	1.6
Na	6.3	1.9	2.0	2.5	4.3	1.7	1.4	4.0	3.6	0.6	1.0	1.8	2.0	2.4	2.5	2.7	2.7	2.6
K	6.8	8.5	5.2	6.2	4.9	5.8	6.5	5.0	4.8	4.6	4.7	4.8	3.6	4.7	5.3	4.8	3.1	5.2
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE III

Cation-percentages of the sillimanite-gneisses

Analysis no.	37	38	39	40	41	42	43	44	45	46	Average
Si	49.6	54.2	55.6	54.8	54.5	57.6	58.7	60.2	59.6	63.3	56.9
Ti	0.8	0.8	0.9	0.7	0.6	1.0	0.8	1.0	0.7	0.5	0.8
P	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
Al	26.9	26.5	23.5	25.2	22.9	19.3	21.3	18.6	21.2	18.6	22.4
Fe‴	3.2	1.9	2.7	1.1	1.7	1.2	1.5	1.3	0.2	1.1	1.5
Fe″	3.4	2.7	4.8	3.2	2.9	4.5	2.8	4.8	4.2	2.9	3.6
Mg	2.9	1.4	4.7	5.7	4.9	4.3	2.8	3.9	4.5	3.7	3.9
Ca	4.1	3.6	0.9	1.2	2.8	2.4	2.5	1.9	1.8	1.8	2.3
Na	3.5	3.1	2.4	3.8	5.5	3.0	3.0	2.4	3.3	4.7	3.5
K	5.4	5.6	4.4	4.2	4.1	6.6	6.5	5.8	4.3	3.3	5.0
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE IV

Cation-percentages of the quartz-diorites

Analysis no.	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	Average
Si	53.8	57.2	57.2	56.4	58.8	60.1	60.7	62.0	61.7	61.5	62.3	64.0	65.2	65.4	66.5	65.6	61.2
Ti	0.7	0.7	0.6	0.7	0.5	0.4	0.5	0.2	0.5	0.7	0.4	0.4	0.4	0.4	0.4	0.3	0.5
P	0.2	0.2	0.2	0.4	0.2	0.2	0.2	0.8	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.2
Al	19.7	22.3	21.8	19.9	20.1	19.8	19.8	17.3	19.1	17.6	18.3	19.1	16.1	16.4	17.7	18.1	18.9
Fe‴	0.2	1.9	1.3	0.5	1.0	0.7	0.9	1.7	1.8	1.7	1.3	1.2	0.6	0.5	2.5	0.7	1.2
Fe″	3.9	3.6	3.7	2.7	2.8	2.6	2.4	2.8	2.3	2.6	2.6	1.5	2.2	2.0	1.2	0.8	2.5
Mg	9.4	4.0	3.5	2.3	3.5	3.1	3.0	4.4	2.5	3.0	4.3	0.9	2.5	2.0	3.0	0.4	3.2
Ca	3.3	1.4	1.8	4.9	3.6	4.2	3.4	2.2	1.4	2.0	1.6	1.8	2.6	2.1	1.1	2.4	2.5
Na	4.2	4.3	5.8	8.1	5.3	5.2	5.4	4.7	5.5	6.4	4.9	6.2	4.7	6.8	4.8	9.2	5.7
K	4.6	4.4	4.1	4.1	4.2	3.7	3.7	3.9	5.1	4.4	4.1	4.7	5.5	4.3	2.7	2.4	4.1
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

there is a common belief that potash metasomatism should lead to feldspathisation, one should bear in mind, that this is not necessarily the case. Especially, addition of potash and magnesium could easily lead to the formation of biotite instead of feldspar.

For this reason the phyllite analyses are more reliable to represent the composition of the original material than the mica-schists.

In the variation diagram (fig. 27) the silica-percentages of mica-schists and phyllites have been put against the values for aluminium, iron, sodium, potash and calcium. The other elements have been omitted in order to make the diagrams more concise. Lines have been drawn to represent the average variation of the recorded elements with increasing Si-percentage, taking care to let the phyllites have their proper share.

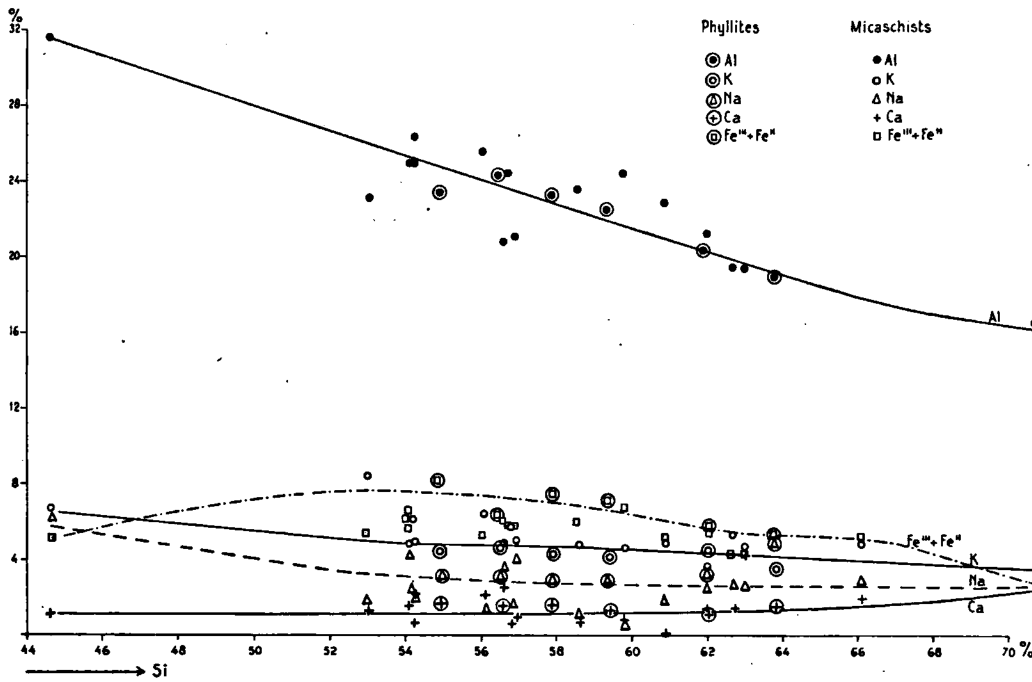

Fig. 27. Variation diagram of phyllites and mica-schists.

Sillimanite-gneisses and quartz-diorites

Twenty-six analyses have been made from single samples of rocks of the migmatite—quartz-diorite series; ten analyses are sillimanite-gneisses and sixteen are quartz-diorites. The obtained data have been recorded in variation diagrams (fig. 28 and 29) and table III and IV.

The sillimanite-gneisses are chemically very close to mica-schists and show similar variations. The Si-percentages are not very high; with increasing Si, Al decreases, but the aluminium excess is considerable. The average Si-percentage of the sillimanite-gneisses is even somewhat lower than of the mica-schists, but this is due to the fact in the schist-average some quartzitic members

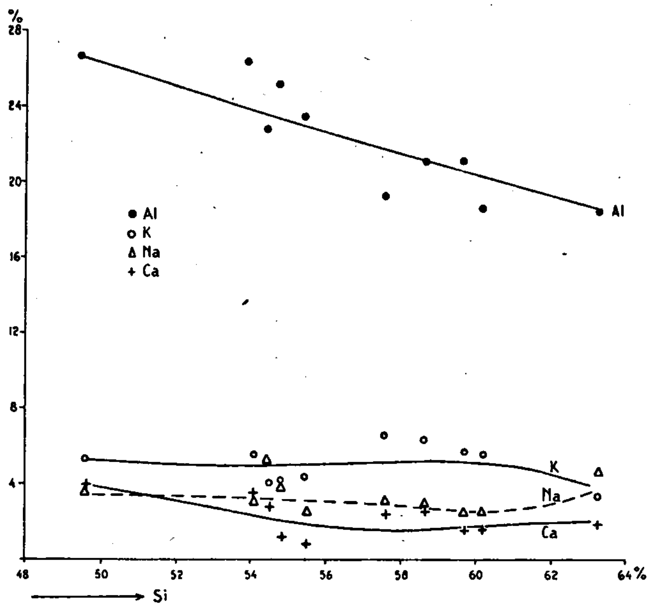

Fig. 28. Variation diagram of sillimanite-gneisses.

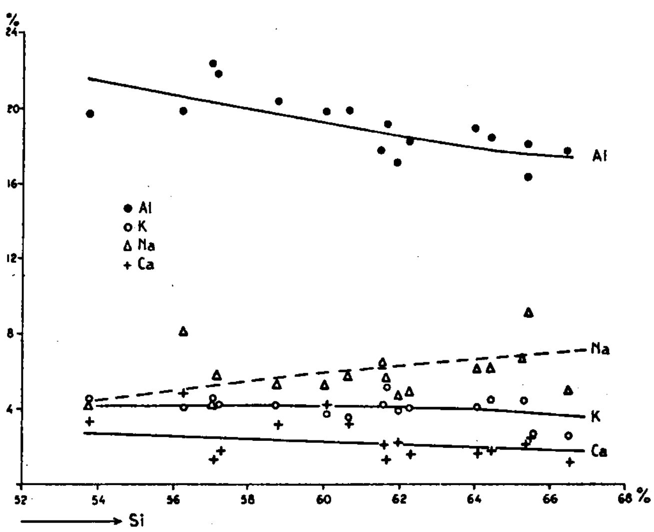

Fig. 29. Variation diagram of quartz-diorites.

are incorporated. These schists do not change into migmatites but are preserved as quartzitic schists in the sillimanite-gneisses.

Iron is a little lower in the sillimanite-gneisses and magnesium higher; the average Na- and Ca-percentages also are slightly higher. The variation diagram (fig. 30) shows that the calcium line of the sillimanite-gneisses indeed lies a little higher than that of the schists, but the two sodium lines almost coincide. The iron line lies distinctly lower. Therefore an introduction of some calcium is probable, but addition of Na is not very evident, whereas iron seems to be expelled. The potash contents of migmatites and mica-schists are almost equal.

In conclusion, it can be stated that introduction of new material in the sillimanite-gneisses is very small; some sodium and calcium probably are added.

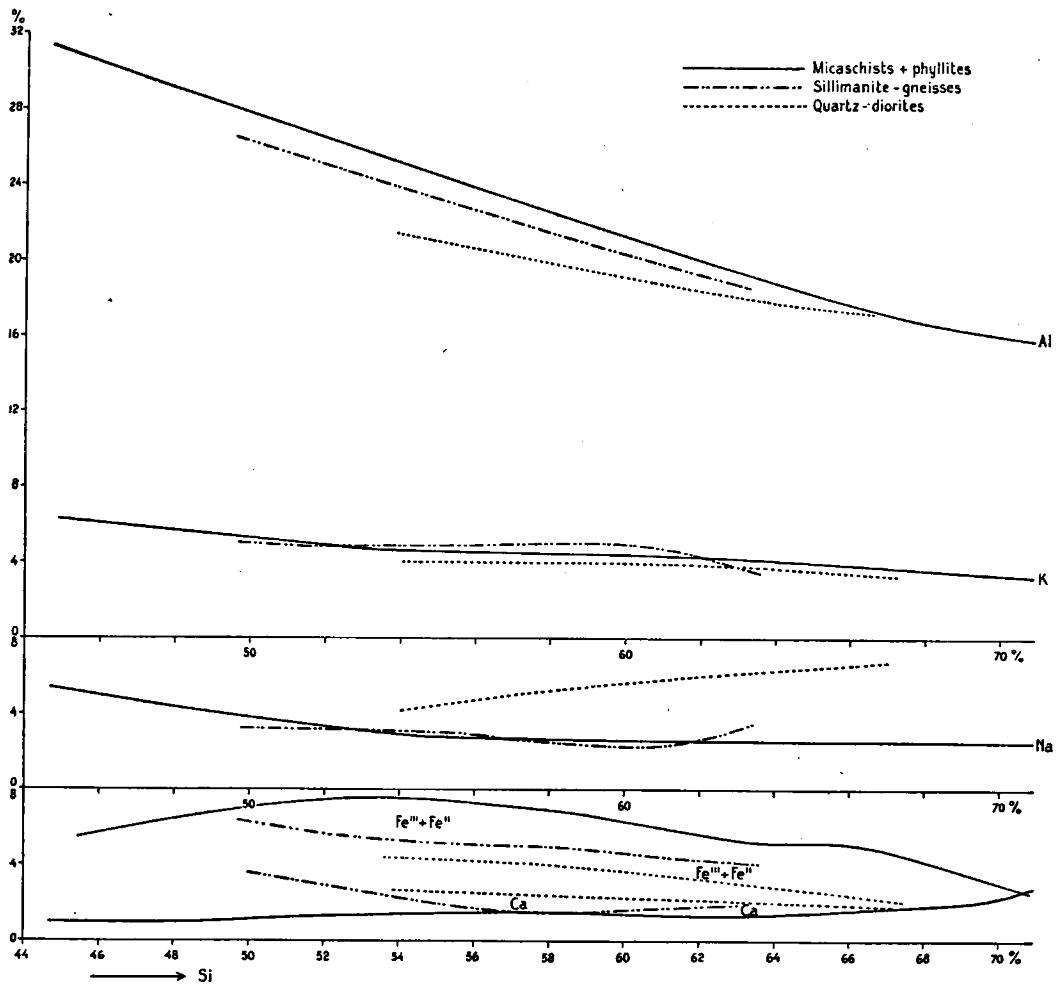

Fig. 30. Comparison between variation diagrams of mica-schists, sillimanite-gneisses and quartz-diorites.

The quartz-diorites which formed at the expense of the sillimanite-gneisses by continuing post-kinematic recrystallization, show marked changes compared with the mica-schists and sillimanite-gneisses. Moreover the quartz-diorites, being homogeneous rocks, are much better suited for chemical analyses than the inhomogeneous sillimanite-gneisses, since sampling errors of the latter rocks can hardly be avoided.

If we compare the average of the schists with that of the quartz-diorites (see table IX) it will be evident that Si, Na and Ca show clearly an increase, the percentages of Al, K and total Fe are lower and Mg is approximately the same. The same difference can be noticed in the variation diagram, where the K- and Al-lines lie below and the Ca- and Na-lines above the corresponding lines of the mica-schist (see fig. 30). Introduction of silica, sodium and calcium can therefore be considered as a proved fact. At the same time aluminium, iron and potash were expelled and the differences are so large that they cannot be accounted for by the dilution effect if the volume should have been increased. These conclusions are in complete accordance with the microscopical observations. The large increase in plagioclase must have been the result of addition of Si and Na, whereas the fibrolitization of the sillimanite was caused by the removal of potash. A part of this potash was used for the formation of late microcline and muscovite, but part of it disappeared, probably in the muscovite-granites and gneisses. Some of the expelled potash may be incorporated in late pegmatites. The removed aluminium may be responsible for the fibrolitization of part of the overlying mica-schists. It may be noted that fibrolite-bearing mica-schists occur especially in the Trois Seigneurs massif, where a very thick layer of quartz-diorites underlies the mica-schists, whilst in the Saint-Barthélemy massif sillimanite-gneisses prevail without hardly any removal of aluminium, and consequently very little fibrolitized mica-schists are exposed in that area. In the latter massif, however, another example of aluminium-metasomatism just above the migmatite boundary has been found. In the talc quarries of Trimouns and Porteille the presence of a smaller or larger amount of clinochlore in the talc-schists has lead to the conclusion that the necessary aluminium must have been introduced together with silica. Most probably this aluminium was originating from the migmatites.

Iron may have travelled much farther and its ultimate destination is unknown, but it may be present as iron ore in the lower Palaeozoic sediments as proposed by AUTRAN and GUITARD (1957) for the eastern Pyrenees (cf. RAGUIN 1953).

In a similar way the iron ores in the eastern Alps can be explained as a result of the regional metamorphism of the High Tauern (cf. CLAR 1953).

Finally it should be stated that the chemical changes which are involved in the formation of the quartz-diorites are in accordance with the results of AUTRAN and GUITARD (1957).

Granitic biotite-muscovite-gneisses and garnet-augen-gneisses

Ten analyses of the garnet-augen-gneisses and eight of the granitic biotite-muscovite-gneisses have been made. One of the augen-gneisses is not taken into consideration, since it is not a normal type, but has a particular composition.

The garnet-augen-gneisses have a rather small range in composition and consequently they are chemically quite homogeneous (see table V and fig. 31). The Si-percentage is much higher than that of mica-schists and quartz-diorites, resulting in a distinctly lower Al-content. Iron is a little lower than in the mica-schists but it is almost the same as in the quartz-diorites. The magnesium percentage is distinctly less, whereas calcium shows a somewhat higher value. Sodium has greatly increased with regard to the mica-schists, but potash is only slightly lower. These changes, which are evident from the averages as well as in the variation diagrams, lead to the same conclusion as we already have drawn for the quartz-diorites: there is addition of silica and sodium, and to a less extent of calcium, whereas aluminium is removed. Some iron

TABLE V

Cation-percentages of the garnet-augen-gneisses

No. of analysis	72	73	74	75	76	77	78	79	80	Average
Si	62.3	62.5	64.7	64.8	65.1	65.8	66.8	66.6	67.9	65.2
Ti	0.7	0.6	0.6	0.5	0.6	0.4	0.5	0.5	0.3	0.5
P	0.2	0.2	0.2	0.2	0.1	0.3	0.2	0.2	0.1	0.2
Al	18.7	17.8	16.1	15.6	15.9	15.3	15.5	16.8	16.5	16.5
Fe‴	1.8	2.2	1.1	2.6	1.9	0.6	1.8	1.6	0.9	1.6
Fe″	1.7	1.7	3.1	1.5	1.5	2.3	1.9	0.4	0.7	1.6
Mg	1.9	2.2	1.6	1.1	2.0	1.7	1.4	0.8	0.9	1.5
Ca	2.1	2.5	2.2	2.6	2.2	2.8	2.0	1.6	1.5	2.2
Na	6.2	6.2	5.6	6.9	7.0	6.9	5.8	5.6	5.4	6.2
K	4.4	4.1	4.8	4.2	3.7	3.9	4.1	5.9	5.8	4.5
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE VI

Cation-percentages of the granitic biotite-muscovite-gneisses

No. of analysis	63	64	65	66	67	68	69	70	Average
Si	61.7	61.8	61.5	62.0	63.6	64.1	68.3	70.5	64.2
Ti	0.6	0.7	0.7	0.6	0.5	0.5	0.3	0.2	0.5
P	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.2
Al	19.4	18.3	18.5	18.0	17.8	17.1	17.0	13.6	17.5
Fe‴	2.6	2.1	1.2	1.6	1.5	1.3	0.2	1.2	1.4
Fe″	2.1	2.8	3.1	2.7	1.7	2.4	1.5	1.4	2.2
Mg	3.0	2.8	2.8	3.6	0.8	2.8	0.7	0.9	2.2
Ca	2.4	2.7	2.9	1.6	3.6	2.4	2.0	1.4	2.4
Na	5.1	5.5	5.0	4.8	6.1	4.9	5.4	4.8	5.2
K	2.9	3.1	4.0	4.9	4.1	4.3	4.4	5.8	4.2
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

and magnesium also seem to have disappeared, but removal of potash, which was evident in the quartz-diorites, is rather doubtful. This accounts for the fact that the quartz-diorites have little potash feldspar, in contrast to the garnet-augen-gneisses. The strong silica-introduction and the high alkali content, together with the removal of aluminium, reduced the aluminium excess to zero and therefore aluminium-silicates are rare in the garnet-augen-gneisses.

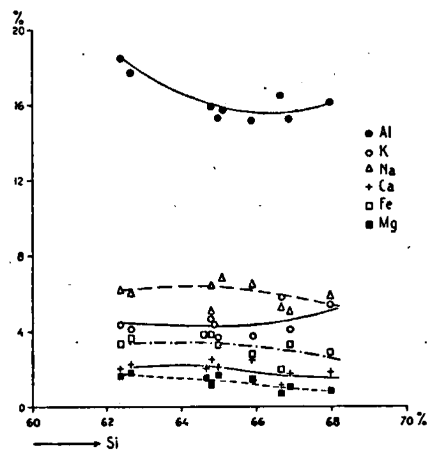

Fig. 31. Variation diagram of garnet-augen-gneisses.

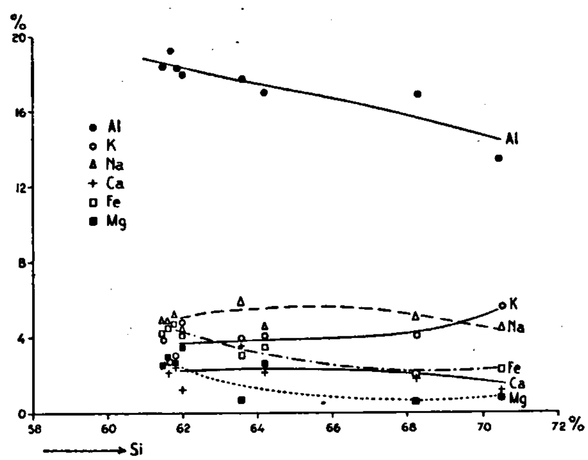

Fig. 32. Variation diagram of granitic biotite-muscovite-gneisses.

The chemical composition of these rocks is comparable to that of a granite and since these rocks are of unquestionable sedimentary origin, there is adequate prooof that this type of metasomatism of a pelite leads to rocks of granitic composition as a result of the reaction:

$$\underbrace{Al + K}_{\text{originally in pelite}} + \underbrace{Si + Na}_{\text{introduced}} \rightarrow \text{feldspar}$$

The structure of these rocks is not granitic, but that is due to synkinematic feldspathisation. Post-kinematic feldspathisation of the same chemical type, however, can lead to normal granitic rocks.

Since the granitic biotite-muscovite-gneisses form a transition between the augen-gneisses and the migmatites, it can be expected that there is also a gradual change in chemistry. Indeed, the percentages of Si and Al show intermediary values, whereas iron, magnesium, calcium and both alkalis are

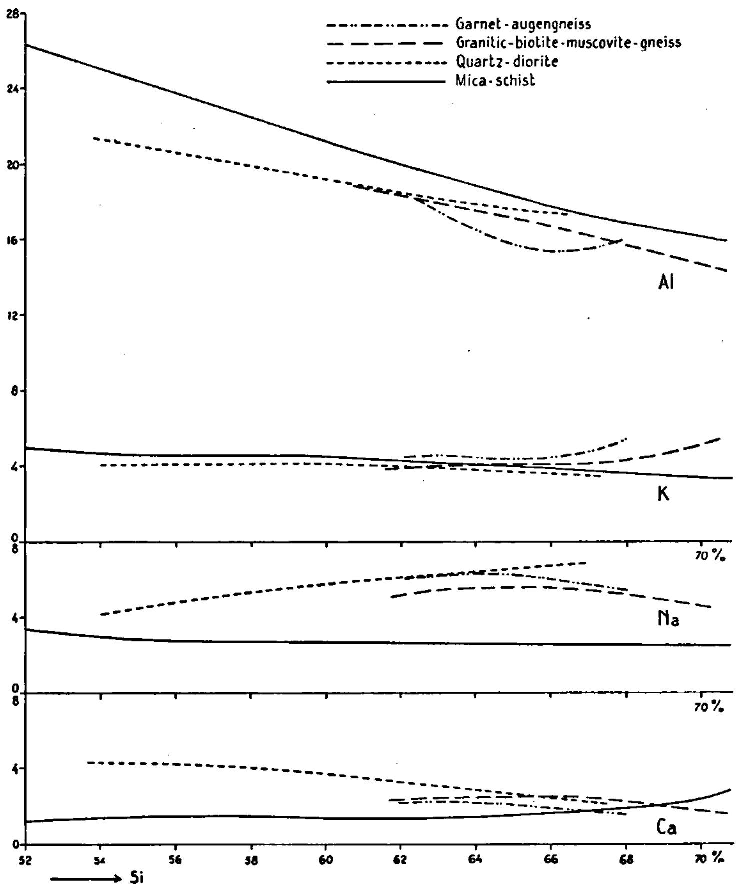

Fig. 33. Comparison between variation diagrams of mica-schists, quartz-diorites, granitic biotite-muscovite-gneisses and garnet-augen-gneisses.

almost equal in the three rock types. The somewhat lower Si content and higher Al content of the granitic gneisses with regard to the garnet-augen-gneisses leaves a small aluminium excess in the granitic gneisses, which is confirmed by the mineralogical composition (see table VI and fig. 32).

Introduction of silica, sodium, and some calcium and removal of aluminium, some iron and magnesium are the metasomatic changes which occurred in the garnet-augen-gneisses and the granitic biotite-muscovite-gneisses (cf. fig. 33).

Muscovite-granites and gneisses

The chemical work on the muscovite-granites and gneisses is only in a preliminary stage. Only four analyses of rocks from sheet 3 and three of comparable rocks of the Aston massif have been executed. The chemical composition of these rocks, however great their variation in structure may be, is so similar that some conclusions can be drawn as to their chemical changes. There remains but one difficulty, that is that the original composition of the rocks which later were metamorphosed to the muscovite-augen-gneisses is unknown. As has already been mentioned before, this gneiss occurs as a layer with sharp contacts in the migmatites or mica-schists. Therefore it is not impossible that originally these gneisses had a different composition than that of a pelite and in such a case a comparison with mica-schists does not hold. Since, however, the muscovite-granites are, at least partially, meta-

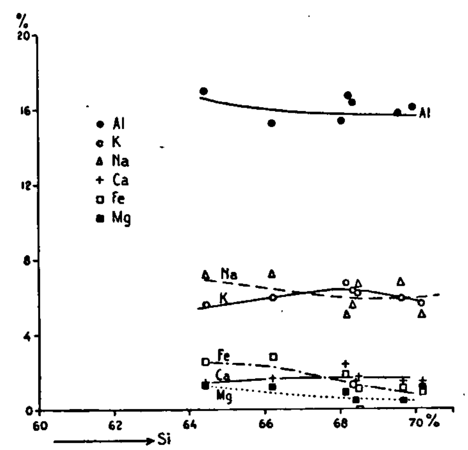

Fig. 34. Variation diagram of muscovite-granites and gneisses.

somatic mica-schists or sillimanite-gneisses, the comparison would seem to be reasonable.

In contrast to the garnet-augen-gneisses and the quartz-diorites, which have formed in one metamorphic stage, either syn- or post-kinematically, these muscovite-granites and gneisses are more complicated, since an originally plagioclase-rich rock has been microclinized in a later stage.

In part, the same tendencies can be recognized as in the garnet-augen-gneisses and quartz-diorites; these are higher Si- and Na-percentages than in mica-schists, and lower iron, magnesium and aluminium (see fig. 34 and table VII). The amount of calcium differs, but is equal to that of the mica-schists, while potash is distinctly higher. The amounts of the introduced and removed elements are still higher than in the garnet-augen-gneisses, resulting in a leucocratic rock with four main elements, Si, Al, Na and K. Iron, magnesium and calcium are very low.

Since we know, that the last stage of metamorphism was one of microclinization, the chemical composition of the rock before that stage will have been rather close to that of the garnet-augen-gneisses: a rock of granitic composition, with Na dominating over K. Whether this rock was already poor in Fe and Mg, is hard to evaluate, since we only know the final result.

It is of interest to note, however, that a rock without aluminium excess can be subject to further feldspathisation as a result of potash metasomatism. In this case the source of the potash are the underlying migmatites from which it was expelled. Since this removal in the quartz-diorites took place during the post-kinematic stage and the microclinization seems to be somewhat later, the time relations do not contradict this.

It can be concluded that the formation of muscovite-granites and gneisses took place in two steps, the first one with introduction of Si and Na, the second one with introduction of K; this potash was redistributed.

TABLE VII

Cation-percentages of muscovite-granites and gneisses

Analysis no.	81			82	84		83	Average
Si	64.4	66.2	68.1	68.4	68.4	69.6	70.2	67.9
Ti	0.5	0.1	0.3	0.2	0.2	—	0.1	0.2
P	0.4	0.2	0.2	0.2	0.2	0.2	0.5	0.3
Al	17.2	15.1	15.2	16.6	16.3	15.3	15.8	15.9
Fe'''	0.6	0.9	0.3	0.6	0.5	0.8	0.5	0.6
Fe''	1.7	1.9	1.5	0.7	0.5	0.2	0.4	0.9
Mg	1.2	1.1	0.7	0.2	—	0.3	1.2	0.7
Ca	1.4	1.6	2.2	1.3	1.4	1.1	1.2	1.4
Na	7.1	7.1	4.8	5.7	6.5	6.6	4.9	6.1
K	5.5	5.8	6.7	6.1	6.0	5.9	5.2	6.0
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The biotite-granodiorites to quartz-diorites

Nine analyses of biotite-granodiorites have been prepared. The results are represented in fig. 35 and it will be clear that their composition is rather constant and has a small range. The most important features are the predominance of sodium over potash and a rather high calcium content. Since these rocks are intrusive, but most probably the result of anatexis, one might

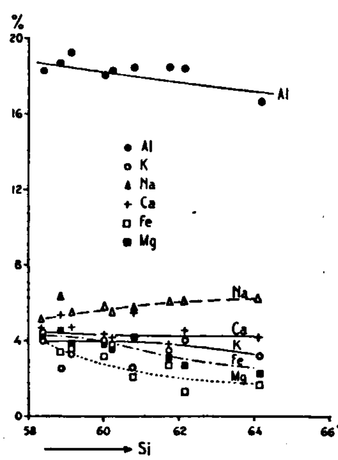

Fig. 35. Variation-diagram of biotite-granodiorites.

try to find chemically similar rocks in one of the autochthonous gneisses or granites. Such a rock can indeed be found; the quartz-diorites of the migmatite-quartz-diorite series have almost the same composition as the biotite-granodiorites. The only difference is the higher calcium content in the latter rocks (see fig. 35). Since the quartz-diorites are the rocks which show the most evident signs of rheomorphism, one might assume that continuing mobilization and metasomatism leads to complete liquefaction and finally to intrusion. The higher calcium content of the granodiorites can easily be explained by the assimilation of the inclusions, which for the greater part are marbles and calc-silicates. These inclusions do not occur in the biotite-granodiorite, but are very abundant in the quartz-diorites.

TABEL VIII

Cation-percentages of the biotite-granodiorite

No. of analysis	1	2	3	4	5	6	7	8	9	Average
Si	58.4	58.8	59.1	60.0	60.8	60.2	61.8	62.1	64.2	60.6
Ti	0.6	0.5	0.5	0.5	0.6	0.5	0.3	0.3	0.4	0.5
P	0.2	0.2	0.2	0.2	0.2	0.1	—	0.1	0.1	0.2
Al	18.4	18.8	19.3	18.0	18.6	18.1	18.7	18.6	16.6	18.3
Fe'''	0.4	1.1	0.8	0.8	1.1	1.1	0.4	0.5	0.6	0.8
Fe''	3.9	3.3	2.9	3.0	3.0	2.4	2.7	2.3	2.2	2.8
Mg	4.3	3.2	3.6	3.2	2.0	3.8	2.8	1.4	1.8	2.9
Ca	4.6	5.4	4.8	4.4	5.5	4.1	3.7	4.6	4.2	4.6
Na	5.2	6.3	5.6	5.8	5.6	5.7	6.0	6.1	6.2	5.8
K	4.0	2.4	3.2	4.1	2.6	4.0	3.6	4.0	3.7	3.5
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE IX

Average cation-percentages of the analyzed rock groups

	60 phyl-lites	17 mica-schists	10 sill. gneisses	16 quartz-diorites	9 biotite-granodior.	8 granitic gneisses	9 garnet-augengn.	muscovite granites and gneisses
Si	59.2	58.4	56.9	61.2	60.6	64.2	65.2	67.9
Ti	0.8	0.8	0.8	0.5	0.5	0.5	0.5	0.2
P	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.3
Al	22.0	22.7	22.4	18.9	18.3	17.5	16.5	15.9
Fe	6.8	5.6	5.1	3.7	3.6	3.6	3.2	1.5
Mg	1.9	2.9	3.9	3.2	2.9	2.2	1.5	0.7
Ca	1.5	1.6	2.3	2.5	4.6	2.4	2.2	1.4
Na	3.3	2.6	3.5	5.7	5.8	5.2	6.2	6.1
K	4.1	5.2	5.0	4.1	3.5	4.2	4.5	6.0

Conclusions

In table IX and fig. 36 the average composition of the various rock types has been compiled. It will be clear that the mica-schists, sillimanite-gneisses, quartz-diorites, granitic muscovite-biotite-gneisses and the garnet-augen-gneisses together form a related group. The largest increase in silica has occurred in the garnet-augen-gneisses and the smallest increase in the sillimanite-gneisses, where it is practically nil. Sodium is evidently enriched in all the rocks with regard to the original mica-schist; also calcium increased, but to a small extent only. Aluminium and iron show a definite decrease, whereas magnesium does not change much. Potash remains also rather constant but we concluded already that it is expelled from the quartz-diorites and redistributed. From chemical point of view the biotite-granodiorites are closely related to the quartz-diorites.

The muscovite-granites and gneisses have a different composition. The silica content is higher; there is a distinct potash introduction, which is responsible for the microclinization. Further aluminium, iron and magnesium are for a great part removed, resulting in rather leucocratic rocks.

One element which in all gneisses and granites seems to have partly

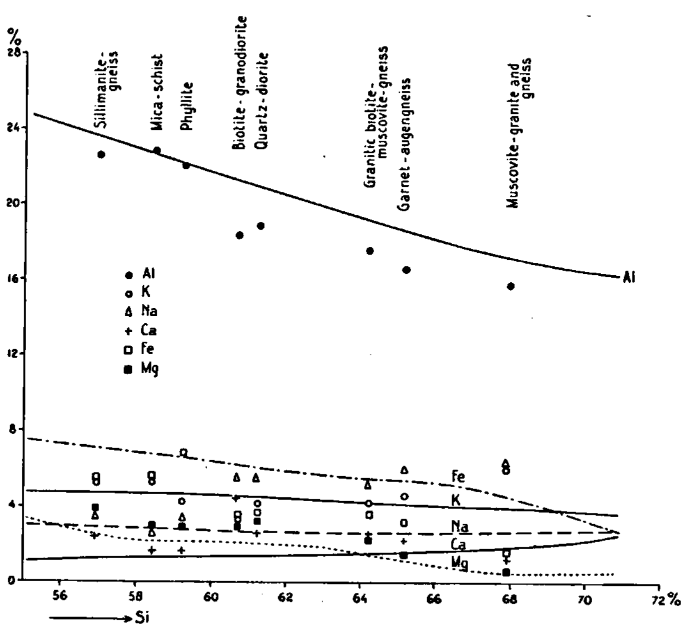

Fig. 36. Variation diagram of averages of all rock types.
Lines represent mica-schist variation.

disappeared is titanium. In the phyllites and mica-schists the Ti-percentage is 0.8 and in all granites and gneisses only 0.5. Whether this element is driven out to higher levels or concentrated and redistributed in metamorphic marbles and calc-silicates could not be established, since no chemical analyses of these rocks are available. It is a fact, however, that many marbles in the gneisses have a rather high content of titanite, sometimes in big crystals.

Another element with obviously is concentrated by metamorphic action is boron. Although this element generally is not determined in chemical analyses, microscopical work showed that all basal gneisses are completely devoid of tourmaline, whereas in the migmatites and mica-schists this mineral is quite common, especially in and near pegmatites. It is believed, that during synkinematic metasomatism in the basal gneisses the boron has been removed and is carried to higher levels in metasomatic fluids which were responsible for the migmatization and pegmatization, resulting in concentration of tourmaline in migmatites and mica-schists, especially near pegmatites.

As to the amounts of introduced elements, the following remarks can be made. Supposing that the volume stayed more or less constant during the metamorphism, the total amount of introduced material with regard to the original phyllites and mica-schists varies from almost nothing in the sillimanite-gneisses, ± 5 % in the quartz-diorites to ± 15 % in the muscovite-granites. In the quartz-diorites ± 2 % SiO_2, in the garnet-augen-gneisses 6—7 % SiO_2 and in the muscovite-granites and gneisses approximately 9 % SiO_2 was introduced. About 3 % sodium was added in most gneisses and granites and 1 % calcium. In the muscovite-granites and gneisses no calcium was introduced, but potash increased with at least 1—2 %. Approximately 4—6 % aluminium, 2—4 % iron and 1—2 % magnesium were removed during these processes (see table IX).

Mineral facies and the role of water during the metamorphism

In ACF-diagrams (fig. 37—38—39—40) the successive mineral parageneses of all gneisses, migmatites and granitic rocks, together with their inclusions, are represented. Of course this separation into four different mineral associations is more or less artificial. In fact, the metamorphism is one continuous

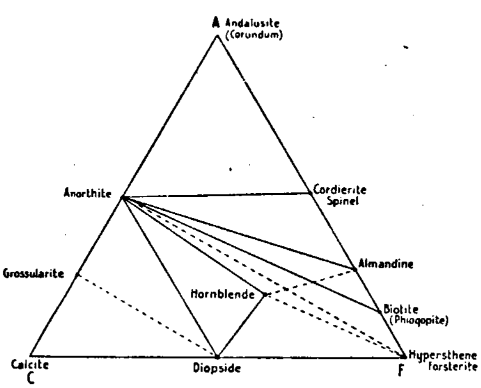

Fig. 37. A C F diagram, synkinematic phase.

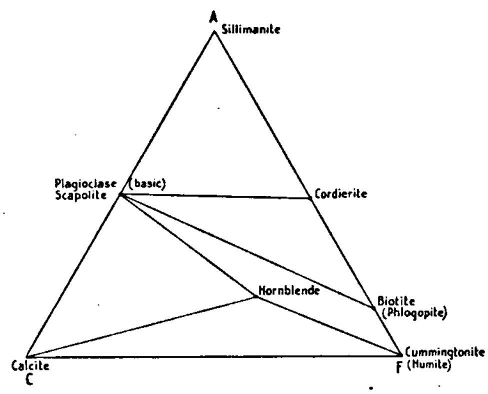

Fig. 38. A C F diagram, late-kinematic phase.

process which becomes lower grade as time advances and consequently the stability fields of minerals of different phases overlap one another. These four diagrams are composite; in other words the data have been assembled from a great number of thin sections of different rock types. Not one rock shows clearly all four phases one after another; several show three, but most two or only one.

The first of these four mineral associations formed during the synkinematic phase; the remaining three are late- and post-kinematic. These four assemblages can easily be ascribed to Eskola's mineral facies; they are respectively granulite, amphibolite, epidote-amphibolite and greenschist facies.

The most characteristic feature of the basal gneisses which are the granulite facies rocks is the abundance of anhydrous minerals (see fig. 12 and 37). Only biotite and hornblende occur as hydrous minerals. Although most of the garnet-augen-gneisses are biotite-bearing and hypersthene is not very common, the remarkable dryness warrants its classification in the granulite facies, but it certainly is rather close to the amphibolite facies. It is very probable that the dryness controls the formation of abundant garnet in these basal gneisses, rather then a high confining pressure. In all rocks which are post-kinematically feldspathised, and also in the mica-schists, garnet is a rare mineral. Also, in other north-Pyrenean gneiss areas, as the Agly and Castillon massif, garnet is abundant in the same type of synkinematic augen-gneiss. In the more leuco-

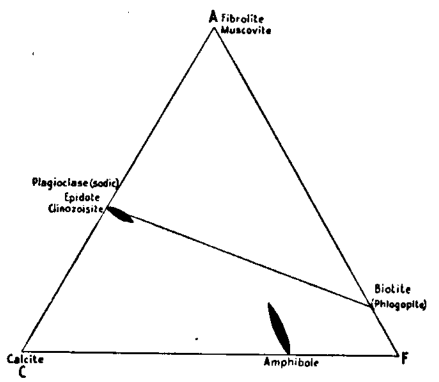

Fig. 39. A C F diagram, late- to post-kinematic phase.

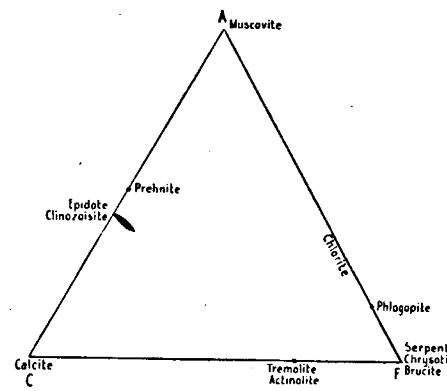

Fig. 40. A C F diagram, post-kinematic phase.

cratic augen-gneisses of the gneiss massifs of the axial zone no garnet is present, but this is probably due to the chemical composition of these augen-gneisses, which further do not show kinship to the granulite facies; moreover they do not contain inclusions and consequently the only minerals are quartz, feldspars and biotite. The same holds true for the muscovite-augen-gneiss of the Saint-Barthélemy massif, which also was originally a biotite-gneiss.

The classification of these rocks in the granulite facies is the more interesting since the depth of formation of these gneisses is rather small, its overburden not exceeding 4—5 km. Further it is important to note that the first observable stage of metamorphism is also the most anhydrous one, at least in the metasomatic rocks. Since all these gneisses were originally of pelitic composition an enormous amount of water has been driven out in order to arrive at such dry conditions. It is even more remarkable that after this dry stage water was introduced anew during the replacement of dry minerals by hydrous ones. This occurred only in the metasomatic rocks; in the mica-schists muscovite and biotite were both stable during the synkinematic phase and consequently these schists were not unusually dry, that is, with the exception of marbles and calc-silicates occuring in the mica-schists, which show the same mineral associations as the marbles in the basal gneisses. Even garnet is a common mineral in and near these calc-silicates in mica-schists and migmatites which themselves are entirely devoid of this mineral. This means that granulite facies conditions can locally prevail in a rock series which is metamorphosed essentially in the amphibolite facies, which is more or less in contradiction with the facies concept.

Another consequence of the lack of water during synkinematic metamorphism, is the absence of synkinematic pegmatites. It is well-known that hydrous solutions are required, or at least have a favourable influence on the development of pegmatites. It is indeed remarkable that pegmatites are very abundant in all post-kinematic rocks, either as conformable or as cross-cutting bodies. In the garnet-augen-gneisses and the augen-gneisses of the axial zone coarse grained pegmatitic rocks are extremely rare.

The dryness of the synkinematically metasomatized rocks leads to an interesting conclusion concerning the transporting medium of the introduced elements. It is often stated that silica and alkalis are transported in hydrous solutions in a supercritical state which travels through the intergranular film. It is difficult to conceive, however, how in our case such kind of metamorphism can result in rather dry rocks. It gives much more the impression of a metasomatism in which no water was involved, other than the water of the original sediment, which certainly is driven out towards the surface. Of course one could suppose that movements during the synkinematic phase squeezed the water out of the rocks, but nothing of such a process can be seen in the mica-schists, which were subject to the same movements as the gneisses. Therefore it is likely that synkinematic metasomatism occurred by dry diffusion, probably along the grain boundaries. This is the more remarkable since post-kinematic metasomatism seems to be of a different kind, because here again water is introduced so as to convert dry minerals into hydroxyl-bearing ones. In this case metasomatism obviously will take place in hydrous solutions in a fluid phase. In both cases of syn- and post-kinematic metasomatism silica, sodium, and calcium are the introduced elements, whereas potash seems to be redistributed during the post-kinematic phase only. These relationships almost exclude the possibility of sodium enrichment by connate water as proposed a.o. by NIEUWENKAMP (1948).

The relative amounts of water most probably play a very important role in the physical conditions of the rocks during their metamorphism. In the first chapter we drew the attention to the behaviour of the metamorphites during syn- and late-kinematic metamorphism. Synkinematic gneisses are characterized by their highly ordered pattern of schistosity and lineation and they give the impression of high rigidity during their formation. Late-kinematic feldspathization and migmatization, to the contrary, are accompanied by irregular movements on a small scale; the rocks seem to have been in a much more plastic state. It seems very attractive to suggest that introduction of water in the post-kinematic phase is responsible for this different behaviour. Experiments which have been carried out by GORANSON (1931, 1938) SAUCIER (1952), SABATIER (1954) and WYART (1955) are similarly suggestive.

GORANSON proved that introduction of water considerably lowers the melting point of rocks of granitic composition. This means that during the synkinematic phase under dry conditions the rocks in the granulite facies were still far removed from the melting point, at least 200—300° assuming the temperature of the granulite facies rocks at 600—700° and the melting point with less than 1 % water about 900°.

Even more interesting for our purpose are the experiments of SAUCIER, who measured viscosities of glasses of rhyolitic composition under hydrous and anhydrous conditions. With a water vapour pressure of 163 kg/cm^2 and a temperature of 980° a certain kind of rhyolite has a viscosity of 8.10^6 poises; without water the same rhyolite has at the same temperature a viscosity which is thousand times higher. In a granite glass the viscosity is 200 times higher in an anhydrous state than with 1.25 % water. Other experiments by SABATIER gave similar results. An obsidian in free air (that is without water) has at 750° a viscosity of 2.10^{13} poises, but with a water vapour pressure of 750 bars he found 5.10^{9} poises; a considerable difference. According to WYART alkaline solutions tend to lower the viscosity even more than pure water.

These experiments are in good agreement with the conclusions which could be drawn from field and microscopical work. During the synkinematic phase, when the rocks were in an almost anhydrous state, their viscosity must have been high. Due to intense orogenic movements schistosity and lineations are produced, probably as a result of stretching in the s-plane and more particularly in the direction of the lineation. This is accompanied by a mechanical breaking down of the minerals, since high viscosity prevented easy plastic flow. These cataclastic structures can only be completely healed after the end of the synkinematic phase by continuing metamorphism. When during the late-kinematic phase hydrous sodium and silica bearing solutions are introduced, the viscosity of the rocks decreases considerably, without needing a higher temperature, and they acquire a different physical state. This again is in agreement with field observations which lead us to the conclusion that the feldspathised rocks during the late-kinematic stage must have been in a much more plastic state, which resulted in rock flowage and finally in rheomorphism. Another effect of the introduction of these solutions is probably the more easy recrystallization of the minerals; no deformation of minerals due to these post-kinematic movement is present. It is remarkable indeed, that this rock flowage only occurs there, where a clear late-kinematic metamorphism together with granitization is present. In the gneisses which do not show this stage, that means with only a synkinematic metamorphism or only a slight post-kinematic metamorphism, this second deformation did not act and the gneisses preserved their regular appearance. According to these arguments granitization in the strict sense and migmatization are typical late- and post-kinematic processes as a result of introduction of hydrous silica-sodium bearing fluids.

Of course from this rock flowage to a real intrusive granite will be only one step, which certainly will have taken place in the Pyrenees. The most extreme example of this rock flowage and rheomorphism in the autochthonous crystalline massifs of the Pyrenees are the quartz-diorites of the Trois Seigneurs massif which are unoriented rocks with numerous disoriented inclusions and flow structures. They resemble closely the rheomorphic breccias which are described by GOODSPEED from his Cornucopia area (1953). Still further "soaking" will finally lead to real anatexis without need for increase in temperature. As soon as such anatectic products are mobile enough and have found their way by some means to higher levels, a complete body of mobilized rock matter will be squeezed out from its place of origin, simply by the weight of the overlying rocks and become an intrusive granite. It is noteworthy that in the Pyrenees the rocks of the quartz-diorite series finally yielded the intrusive biotite-granite, whereas the muscovite-granite and gneiss series only rarely and locally reached an intrusive stage. This is probably due to the composition of both rocktypes, the quartz-diorites being more basic and consequently less viscous than the more leucocratic muscovite-granites. Again this agrees with field observations. Mobilization and rheomorphism of the quartz-diorites occurs in a much more advanced stage and is much more common than in the muscovite-granites and gneisses.

The described relationships do not only occur in all Pyrenean gneiss massifs, also in other regions the same succession of events with similar results have been observed, for example in Galicia, the Pennides, and the Central massifs of the Alps. These relations and the behaviour of water during metasomatism make it clear why most intrusive granites and granodiorites in mobile belts are of post-kinematic, late tectonic age.

Relations of the three satellite massifs

Field observations as well as examination of thin sections made it evident that the three satellite massifs together with the large gneiss dome of Ax-Montcalm south of sheet 3, originally formed one continuous metamorphic area, which by later faulting was divided into separate blocks. Yet, the three massifs

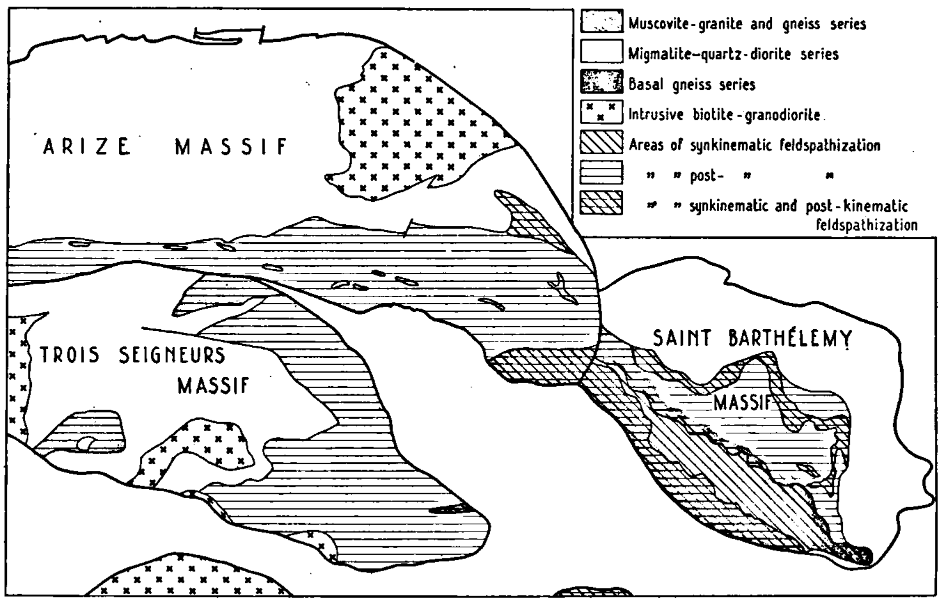

Fig. 41. Sketchmap showing distribution of syn- and post-kinematic feldspathization in the three satellite massifs.

show remarkable differences with regard to their metamorphic rocks. This is mainly due to gradual change in the nature of metamorphism going from east to west. In fig. 41 the repartition of syn- and post-kinematically feldspathised rocks is shown. It will be clear that in the Saint-Barthélemy massif synkinematic feldspathisation occurred on a rather large scale. Not only all basal gneisses but also the muscovite-augen-gneisses are truly synkinematic. The garnet-augen-gneisses without any post-kinematic recrystallization gradually wedge out towards the west; this is due to the approaching of the post-kinematic feldspathisation fronts above and below these gneisses, so as to join in the eastern part of the Arize massif. In the latter area muscovite-augen-gneisses are still exposed, but they also wedge out in western direction and further west no synkinematic gneisses occur in the Arize massif. The same situation prevails in the Trois Seigneurs massif, where only near Lapège some vestiges of the garnet-augen-gneisses have been found, but they are recrystallized. On a few other places in this massif some synkinematic gneisses have been described by ALLAART (1958) but these also have a definite post-kinematic phase of recrystallization. They are relatively unimportant with regard to the quartz-diorites which almost exclusively build up the crystalline rocks of this area.

Not only synkinematic gneisses disappear towards the west, also the intensity of post-kinematic feldspathisation increases in that direction. This is shown by the repartition of sillimanite-gneisses and quartz-diorites, the latter rocks being recrystallized and feldspathised sillimanite-gneisses. In the Saint-Barthélemy massif relatively small masses of quartz-diorite occur in the sillimanite-gneisses. In the eastern part of the Arize massif a thick layer of sillimanite-gneiss occurs on top of quartz-diorites but westwards quartz-diorites gradually replace the sillimanite-gneisses until only a few hundreds of metres of migmatites lie above the quartz-diorites. In the Trois Seigneurs massif the same situation prevails; here an enormous amount of quartz-diorites underlies a thin layer of sillimanite-gneisses. Without any doubt this crystalline massif is by far the most strongly influenced by post-kinematic metamorphism in the Pyrenees.

Again, still further to the west, synkinematic gneisses are exposed in the Castillon massif, but they also have a post-kinematic phase.

It is remarkable that in the large gneiss dome of Ax-Montcalm the same relationships between syn- and post-kinematic feldspathisation can be detected which change in the same direction. In this area augen-gneisses are abundant in the central part, but towards the west they are gradually replaced by post-kinematic flaser-gneisses and granites, without any synkinematic feldspathisation.

An important difference between the North-Pyrenean massifs and the gneiss domes of the axial zone is the occurrence of the basal gneisses in granulite facies in the first mentioned areas (Agly, Saint-Barthélemy, Arize, Castillon), whereas in the gneiss domes especially leucocratic augen-gneisses prevail, which are rare in the North-Pyrenean massif. Part of this difference is probably due to difference in sedimentation, for the rest a different metamorphic history is responsible.

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