METAMORPHIC HISTORY OF THE CENTRAL PYRENEES

PART II, VALLE DE ARÁN, SHEET 4

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ABSTRACT

The structural geology and metamorphic petrology of the Bosost area in the Valle de Arán (Central Pyrenees) is discussed. The rocks exposed in this area consist of Cambro-Ordovician mica-schists with numerous granite and pegmatite bodies, phyllites and limestones; Silurian slates and schists and Devonian schists and limestones.

The major structure dating from the Hercynian orogeny is the Garonne dome with essentially horizontal schistosity. Large steep folds in the Devonian accompanied by axial plane slaty cleavage are folded disharmonically with regard to the Cambro-Ordovician. Both kinds of structures date from the main phase. A second and later phase with N-S foldaxes was accompanied by laminar flow in E-W direction as shown by numerous rotated porphyroblasts. A third and fourth phase of deformation have folds with vertical axial planes in NW-SE and E-W direction. These last three phases are characterized by minor and microfolds only.

The method of investigating microstructures mainly with regard to porphyroblasts is discussed first; then its application. This resulted in the establishment of four metamorphic zones: a biotite-zone; a staurolite-andalusite-cordierite-zone; an andalusite-cordierite-zone and a cordierite-sillimanite-zone; in this order with increasing grade. The higher zones have passed through each of the lower grade ones, so that the cordierite-sillimanite-zone has the most complex history. Staurolite is the first aluminium-silicate to crystallize with increasing temperature, than andalusite, cordierite and finally sillimanite. Before sillimanite started to form, staurolite was already unstable; at the beginning of sillimanite crystallization andalusite became unstable.

Calc-silicate rocks in the Ordovician limestone in the cordierite-sillimanite-zone contain bytownite, grossularite, diopside and vesuvianite.

Granite and pegmatite bodies and sills occur in all the aluminium-silicate bearing zones, but most abundant in the cordierite-sillimanite-zone. Their emplacement lasted from shortly after the first phase until after the fourth. The culminating point lies around the fourth phase. The granites are mainly composed of albite, quartz, and muscovite; the pegmatites carry smaller or larger amounts of microcline.

Chemical analyses of phyllites and mica-schists have shown that the composition of both rock groups is essentially the same. With increasing silicium content, aluminium and potassium decrease. The granites have high alcali percentages with sodium predominating over potassium.

CONTENTS

1. INTRODUCTION

The western part of the Valle de Arán around Bosost in Spain and the headwaters of the Pique river near Bagnères de Luchon in Franche are located in an area consisting of micaschists and granites, referred to as Bosost dome or Bosost area.

The first investigations in the Bosost area by students of the Geology Department of the University of Leiden started in 1951 when R. B. Francken mapped a small area near Bosost itself. Subsequent mapping of other parts of the Bosost dome was done by M. van Loon, H. E. C. van der Meer Mohr and A. Kapel, who all submitted reports to the Geology Department. In 1956 the present author started revising the material and completed mapping of the area, at the same time collecting a large amount of specimens. He visited the area for a few weeks every summer up to 1960. During the last season he was accompanied by Dr. D. Boschma whose willingness to carry heavy packs with samples is gratefully acknowledged here.

As is shown on the map, sheet 4, and fig. 1 the Bosost dome is eccentrically situated with regard to the major structures. It forms part of the Garonne dome (De Sitter and Zwart, 1962) which consists of Cambro-Ordovician phyllites for its portion outside the Bosost area. On all sides the Garonne dome is bounded by Silurian and Devonian rocks. The Bosost dome, a metamorphic dome, lies in the SW portion of this major structure and along its southern boundary mica-schists reach all the way up to the Silurian. North of the Bosost dome the schists grade into the phyllites of the remainder of the Garonne dome. Consequently the metamorphic boundaries are oblique to the stratigraphic limits and the schists near Bosost are the stratigraphic equivalents of the phyllites north of it.

A large number of granites and pegmatites occurs as sills or irregular bodies in the mica-schists. They are related to the regional metamorphism and at least partially they are of replacement origin.

In the field several zones of metamorphism can be detected; with increasing depth these are: chlorite-zone, biotite-zone, andalusite-zone and a granite-pegmatite bearing zone with or without andalusite in the mica-schists. The metamorphic zoning is however, more complex than apparent in the field. Microscopic evidence indicated that at least three or four successive stages of metamorphism can be distinguished which proceeded contemporaneous with some kind of deformation, and that during the times between these phases of folding, metamorphism was continuous. The complexity mainly arises from the interrelations between time and depth. A large part of this paper will be devoted to the deciphering of the metamorphic history.

2. STRATIGRAPHY

2.1 CAMBRO-ORDOVICIAN

2.11 *Phyllites*

The Cambro-Ordovician sediments outside the Bosost dome consist of a rather monotonous series of dark coloured slates and phyllites, sandy phyllites and thin quartzite bands. On the north side of the Bosost dome they are somewhat richer in quartzite than usual and there typical 'schistes rubanés', thinly laminated alternations

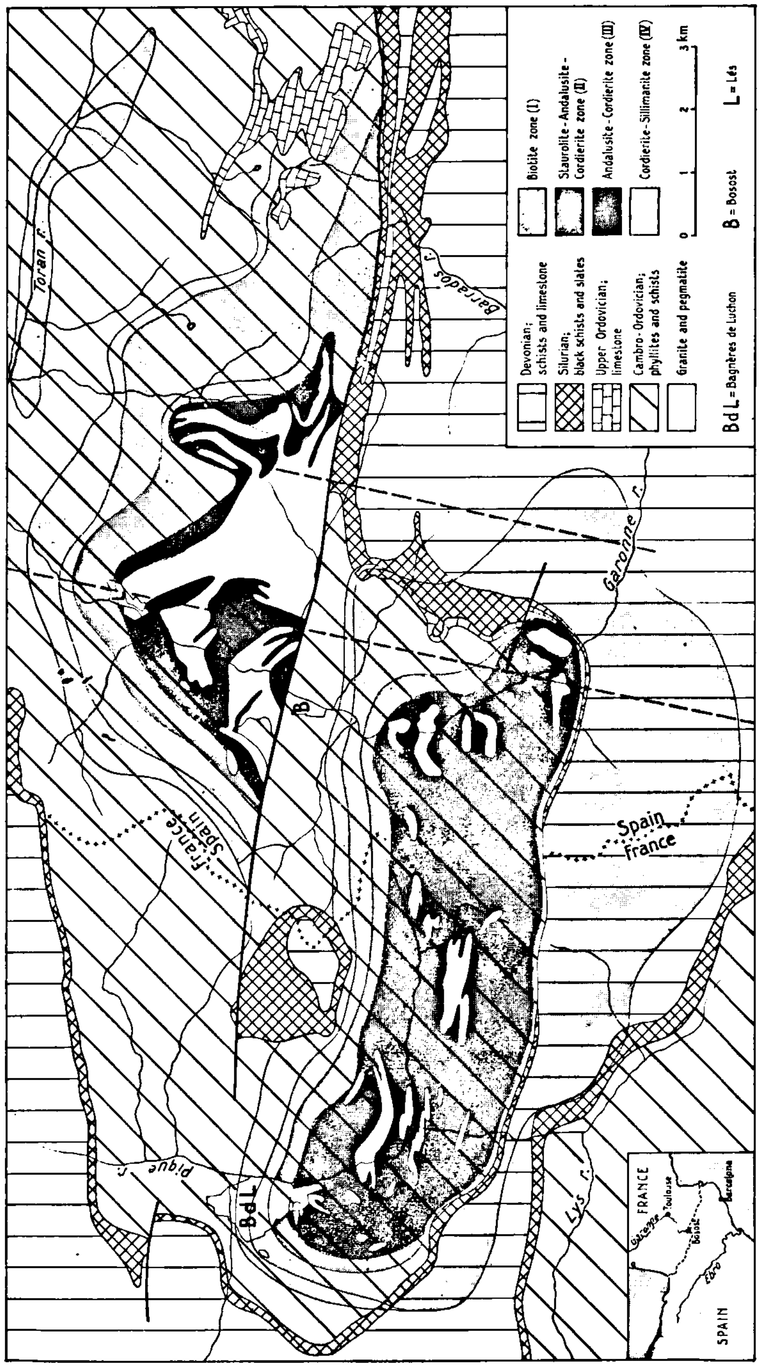

Fig. 1. Geological map of Bosost area, showing structure and metamorphic zoning.

of quartzite and phyllite are of widespread occurrence. In these rocks cleavage usually parallels bedding with the only exception of a few recumbent folds with crosscutting cleavage. The phyllites near the village of Bosost itself are less quartzitic, although exudation lenses and pods of quartz are quite frequent. At the latter locality a small outcrop of a conglomerate with flattened pebbles of a few cm. size has been found.

The cleavage in the phyllites has a variable dip although the strike is mostly close to E-W.

Microscopically the phyllites consist of quartz and sericite as main constituents with minor chlorite, iron ore and graphite. The slaty cleavage is usually well developed, but a secondary crenulation cleavage is very common.

2.12 *Mica schists*

The mica-schists of the Bosost dome show a large variation in megascopic appearance due to differences in structure and mineralogical composition. Roughly four different types can be distinguished, each occurring at specific localities. These are (1) biotite-schists, mainly outcropping in the northern half of the Bosost dome, (2) staurolite-andalusite-cordierite-schists, to be found in both parts of the Bosost dome, but mainly outside those places where a large amount of granites and pegmatites occur, (3) more or less unoriented, often feldspathic schists, occurring in the area where much granite is exposed, (4) banded mica-schists near Lès.

The biotite-schists are transitional to the phyllites and at present they are of restricted occurrence. Originally, however, all mica-schists of the Bosost dome must have been of the same kind; subsequent higher grade metamorphism has obliterated part of their original character.

Most biotite-schists are fine- to mediumgrained rocks in which biotite and muscovite are readily recognized with the naked eye. Most of these schists show, besides a good schistosity a lineation determined by elongation of mica-flakes with E-W direction. The schistosity often dips less steep than in the phyllites and the dip varies between horizontal and 40—50° (fig. 2). Most mica-schists are banded; mica-rich bands alternating with mica-poor layers of a thickness of ½ to several cm. When obvious sedimentary beds occur, like quartzite intercalations, it appears that bedding and schistosity are nearly always parallel.

Dykes or sills of pegmatite or granite are absent in the biotite-schists.

Staurolite-andalusite-cordierite-schists, often referred to as andalusite-schists, form a large part of the Bosost dome. Due to the fairly large size of the aluminous silicates they are readily recognized in the field. Some of the best outcrops occur near the Victoria mine, where the schists are studded with a large amount of andalusite and cordierite crystals with a diameter of 1 cm and a length of several cm. East of Lés also well developed andalusite-cordierite-schists are to be found. In the Southern portion of the Bosost dome andalusite-schists occur stratigraphically as high as the Silurian black slates, but near Bosost and north of it they grade into biotite-schists. Andalusite and cordierite occur as elongate crystals with rounded or elliptic cross section; the schistosity usually curves around the porphyroblasts. As a rule the long axis of the crystals lies in the plane of schistosity, but in that plane they are at random distributed. Staurolite is to be found as short equant prisms not exceeding ½ cm in size. Almost all crystals are penetration twins. In many of these staurolite-andalusite-cordierite-schists biotite occurs as somewhat larger crystals compared to the biotite-schists. They can be up to 1 mm long and usually they are oriented parallel to the lineation expressed by small mica crystals.

Folds of the schistosity plane are common and vary in size from microfolds up to several metres or tens of metres size. Pegmatites are of frequent occurrence in these schists; mostly they are small bodies or sills varying in thickness from less than 1 cm to several m. Folding of the pegmatites together with the enclosing schists is rather common. Also boudinage of the pegmatites occurs frequently; the long axes of the boudings have mainly N-S or NW-SE directions.

Badly oriented schists occur in those parts of the Bosost dome where large bodies of crosscutting granite occur, for example NE of Bosost and E of Bagnères de Luchon. These schists do not show such a perfectly oriented fabric as the described types due to the presence of randomly oriented biotite and muscovite crystals. Lineations are often lacking but a more or less vague schistosity is usually present. Transitions to linear and schistose andalusite-schists are common. Locally, for example near Bosost, these schists grade into migmatites with quartzofeldspathic bands, but this rocktype is quite rare. Large porphyroblasts of andalusite and cordierite are less common, and staurolite is altogether absent. Bluish-grey mats of fibrolite are often seen in the specimens. Similar schists also occur as inclusions in the granite bodies.

Banded mica-schists occur mainly near the village of Lés and are characterized by the presence of a peculiar banding of biotite and quartz-rich layers with a thickness of approximately 1 mm or even less. The biotite crystals in these schists are elongated but contrary to most other mica-schists in the area they have N-S lineations instead of E-W. The banding is visible across the schistosity planes and in E-W sections it can be seen that the banding often makes a small oblique angle with the schistosity (fig. 24). Very sharp, isoclinal recumbent folds with N-S axes are rather common (fig. 3). Large porphyroblasts of andalusite and cordierite are frequently observed in these schists.

2.13 *Limestone and marble*

Between Mina Victoria and la Bordeta a limestone horizon of 20—30 m thickness occurs near the top of the Cambro-Ordovician. At this locality it is immediately overlain by the Silurian black slates; elsewhere by a thin layer of Cambro-Ordovician schists. When pure, the limestone is marmorized, but when it contains a small or large amount of pelitic material it contains various calc-silicate minerals, like grossularite, diopside and clinozoisite.

Another outcrop of probably the same limestone forms the highest ridge of the Sierra de Guarbes, although here it does not occur directly underneath the Silurian. It is a rather coarsely recrystallized limestone at its base intercalated with slate and chert bands. At the Sierra de Guarbes the limestone occurs as a flatlying horizon forming a part of the Garonne dome.

2.2 SILURIAN

The Silurian slates and schists, forming an important marker bed in the area, are derived from black carbonaceous shales in euxinic facies. They have a remarkably high aluminium content and as a result of metamorphism they often contain abundant andalusite. The presence of a few percent of carbon makes the rock very black and often staining. Where occurring outside the metamorphic area they are black slates often strongly contorted due to their high plasticty. In the Bosost dome they are altered to andalusite or chiastolite-schists. Good examples of such rocks occur in the Pique valley, near Arres and on the Trona mountain. At a few places small pegmatite sills and bodies occur in the Silurian schists for instance near the Trona and Arres. They may be a few dm. thick and locally crosscutting contacts with the schists are found. Boudinage of the pegmatite sills is not uncommon and sometimes these boudins have the appearance of a string of pebbles. Small folds commonly occur in these schists. The peculiar behaviour of the Silurian as a detachment plane will be described further on.

2.3 DEVONIAN

The lower portion of the Devonian with which we are concerned consists of an alternation of pelitic rocks and limestones. On the map several limestone bands can be seen, but they represent probably only one or two different stratigraphic horizons, severely folded as careful mapping by Van Alphen (1956) has revealed.

The Silurian is overlain by a limestone horizon, the so-called basal limestone which contains intercalations of chert, sandstone and slate. Its thickness varies from almost zero up to 150 m. Usually it is a bluish limestone with white wheathering surface. It may be metamorphosed to marble when pure, or to calc-silicate rocks when impure. The basal limestone is overlain by a series of slates, the Entecada slates (Kleinsmiede 1960), with some intercalations of limestones. These slates are usually dark coloured, bluish or black. They are interbedded with sandstones and quartzites, especially near the village of Las Bordas. The thickness of this strongly folded series is probably rather small, estimated at 450 m maximum by Kleinsmiede (1960), but it covers a fairly large portion of the map. This is apparently due to considerable thickening as a result of cleavage folding.

South of the Bosost dome this series of slates is converted to schists with a large amount of porphyroblasts of staurolite, andalusite and cordierite, varying in size from less than 1 mm up to 1 cm. Most of the crystals are rounded or shortly elongate. Their presence gives the rock a peculiar spotted look. A lineation in ESE direction and visible as small corrugations is usually to be found in these schists. A few pegmatite sills have been observed in the Devonian near Arro. For further details of the Devonian stratigraphy I refer to Kleinsmiede (1960).

3. STRUCTURAL GEOLOGY

3.1 MAJOR STRUCTURES

The Bosost dome is not a separate structural unit, but it is a part of the much larger Garonne dome (De Sitter and Zwart 1962), consisting entirely of Cambro-Ordovician rocks. In the Bosost dome it is the metamorphic boundaries which are domeshaped; structurally it belongs to the Garonne dome and apparently there is no direct relation between the regional metamorphism and the large structures. The rocks of the Garonne dome, phyllites and schists, are characterized by their apparent simple structure. Bedding is in most places horizontal or has gentle dips, as for example shown by the Ordovician limestone near La Bordeta, on the Sierra de Guarbes, and outside the Bosost area in the eastern part of the Garonne dome in the headwaters of the Lez and Orle rivers. Only on north and south sides steeper dips of bedding occur, there where the Cambro-Ordovician is in steep contact with the Silurian and Devonian.

The bedding is, however, everywhere accompanied by a well developed slaty cleavage or schistosity and is with the exception of a few cases parallel to it. There can be no doubt that this flatlying attitude of bedding and cleavage dates from an early phase of deformation. As such the Garonne dome is a remarkable structure and strongly different from the phyllites elsewhere in this mountain chain. Major structures with flatlying schistosity are, however, not unique in the Pyrenees, since all regional metamorphic domes like the Aston-Hospitalet gneiss dome display the same feature. The peculiarity of the Garonne dome arises from the fact that here metamorphic structures occur in lowgrade phyllites, which usually are characterized by vertical axial plane cleavage. That some connection exists with regional metamorphism is shown by the Bosost dome where higher grade rocks occur, and it is possible that the whole of the Garonne dome is underlain by a gneiss dome like the Aston-Hospitalet massif.

The structures of the Devonian, surrounding the Garonne dome on all sides are entirely different. These structures are characterized by the occurrence of tight folds with a vertical axial plane slaty cleavage, often cutting across the bedding. This structural type is common throughout the Paleozoic of the Pyrenees outside the regional metamorphic areas. The transition between the flat Cambro-Ordovician and steep Devonian structures takes place in the Silurian, the bottom of which adapts

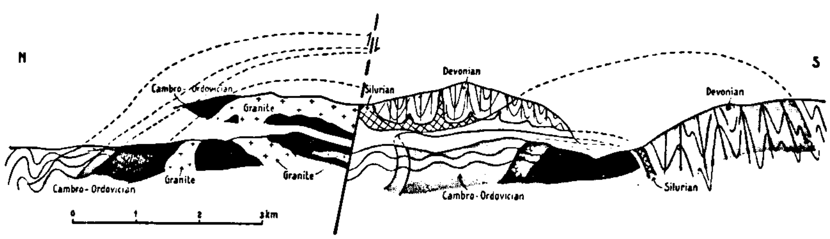

Fig. 2. Section through Bosost area.

itself to the flat upper surface of the Cambro-Ordovician and the top to the Devonian structures, as shown by the pinched Silurian in the Devonian anticlines (see fig. 2,1). On the map this is visible by the almost horizontal position of the Ordovician limestone between La Bordeta and Mina Victoria and the strongly folded Devonian east of it. This section, visible in the mountain slope is a rather unique case of disharmonic folding on a large scale. No doubt it results from the very plastic nature of the Silurian and the extremely high position of the metamorphic front.

The Bosost dome is dissected in two halves by the high angle Bosost fault with an upthrown northern block.

3.2 MINOR STRUCTURES

Minor structures which have been observed in the field include small folds, lineations, schistosities, cleavages, boudins and mullions. Several hundred measurements of such structures have been made and the results are assembled in stereograms (fig. 4—9). Although as a rule in any one outcrop only one schistosity is present, several kinds and directions of lineations have been observed in the Bosost dome. From these observations, combined with microscopic data it appeared that four different phases of deformation have been active in the Bosost dome. They will be described in chronological order; evidence for their relative age will also be given here or in the next part on microstructures.

3.21 *first phase*

The first phase, as far as structures are concerned the most important one in the area has left its traces almost everywhere. During this phase, also called main phase, the major structures together with a number of minor structures as schistosities, cleavages and certain lineations have been produced.

The Devonian and part of the Silurian is deformed by cleavage folding, resulting in strongly compressed folds with a vertical axial plane cleavage. Foldaxes and cleavage-bedding intersections have E-W direction and plunge gently to the east on the eastern side and to the west on the western side of the Bosost dome. Fig. 4 gives a stereogram of a number of measurements of foldaxes east of the Bosost dome. The structures of the Cambro-Ordovician are characterized by flatlying schistosity, but

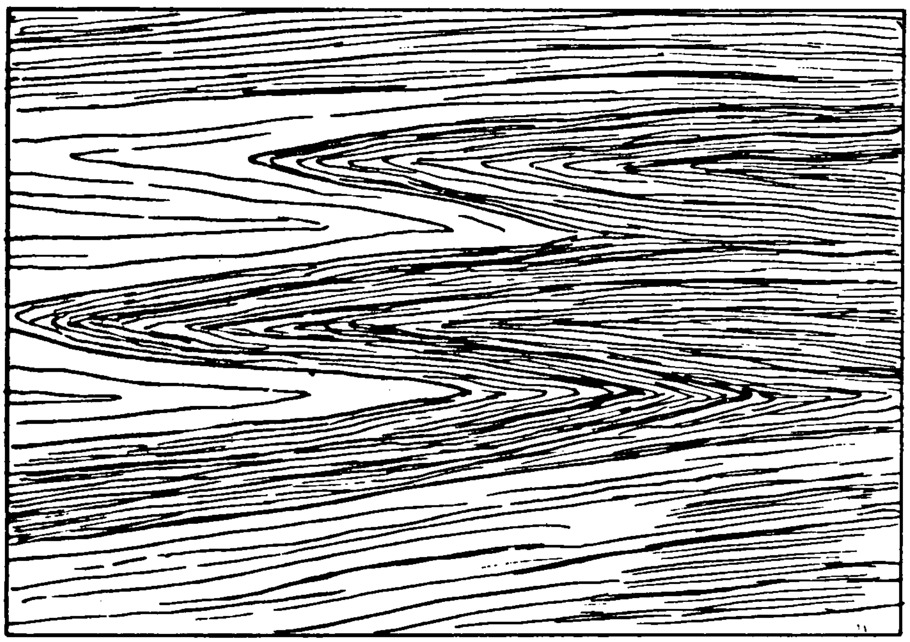

Fig. 3. Isoclinal recumbent folds with N-S axis; near Lés.

on the southside of the Bosost area it steepens rather suddenly so that it grades into the steep cleavage of the Devonian.

It is very probable that the steep cleavage in the Devonian and the flat schistosity in the Cambro-Ordovician have formed simultaneously, although actual proof is difficult to give. In any case both s-planes are older than the porphyroblastic growth of staurolite, andalusite and cordierite which at its turn is older than a second phase of deformation. Although it can be proved that originally the cleavage and schistosity in the Garonne dome had a low angle attitude, this is at present no longer true. Variations from horizontal to almost vertical occur, but in the Bosost schists dips steeper than 45° are rare (fig. 5). This variation is due to later folding of the s-planes as for instance shown by Boschma (1963).

In many outcrops the mica-schists are banded rocks, siliceous layers alternating with micaceous ones; the banding is in most cases parallel to the schistosity. This

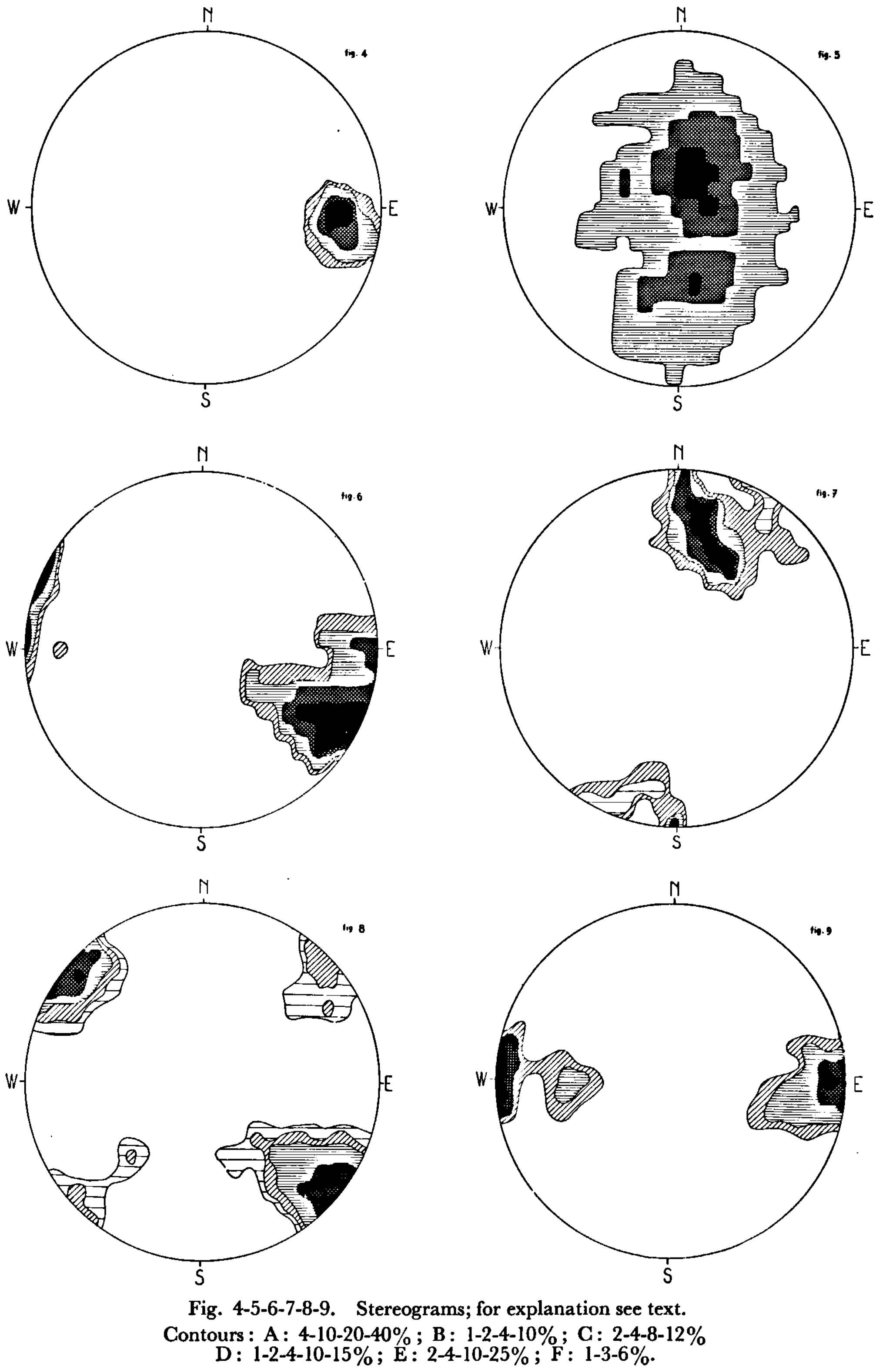

Fig. 4-5-6-7-8-9. Stereograms; for explanation see text.
Contours: A: 4-10-20-40%; B: 1-2-4-10%; C: 2-4-8-12%
D: 1-2-4-10-15%; E: 2-4-10-25%; F: 1-3-6%.

banding is often of metamorphic origin, but at some places it is evident that it represents the sedimentary bedding. Tight isoclinal folding of such bedding has been observed in few localities, for example near the Victoria mine SW of Bosost and at several places in the Garonne dome outside the Bosost area. Foldaxes of such folds are E-W to WNW-ESE parallel to the lineations in the mica-schists, indicating that this tight folding is connected with the development of lineation and schistosity, both dating from the main phase of the Hercynian folding, and is contemporaneous with the formation of the major folds. The asymmetric character of these small isoclinal-recumbent folds probably indicates that the schistosity is a plane of shearing movement. Unfortunately too few of such folds have been found to determine whether the asymmetry has everywhere the same sense and which is the direction of movement.

Lineations are present in most mica-schists and they are produced by the elongate shape of the mica flakes so that both lineations and schistosity are determined by the shape and orientation of these micas. Therefore this kind of lineation is connected with the formation of the schistosity and both must have been formed at the same time. In many mica-schists of the Bosost dome this lineation is accentuated by the presence of somewhat larger biotite-porphyroblasts which are aligned in the same direction, but which do not show a lattice orientation like the smaller biotite and muscovite crystals. In fig. 6 a number of lineations has been assembled. Evidently the maximum does not occur in E-W direction like the Devonian folds (fig. 6), but deviates to the SE with $\pm$ 25°. It has been suggested that this difference is due to the level at which the structures occur, both being separated by the incompetent Silurian. It is true, however, that also the metamorphosed Devonian, above the Silurian, shows the same deviation of lineation direction and consequently the boundary between E-W foldaxes and ESE lineations coincides approximately with the metamorphic boundary and not with stratigraphic boundaries. Since there is no doubt that the Devonian folds and the lineations in the metamorphics date from the same folding phase, this deviation has to be explained in some other way. Microscopic evidence, which will be dealt with later, indicates that this deviation may be the result of later movements and probably is not an original feature of these schists.

In the eastern part of the Bosost dome most lineations plunge gently to the east, in the western part to the west in agreement with the general plunge of the dome in both directions.

3.22 *Second phase*

Although in most parts of the Bosost dome the ESE lineations are conspicuous except near the large granite bodies, similar lineations with a different direction occur near Lès in the northern half of this area. Here they have an N-S direction. Connected with these lineations is a particular banding of the mica-schists described on p. 326. The intersection of these bands with the schistosity is parallel to the elongated mica flakes and in outcrops tight folding with axial plane schistosity in E-W section is visible, indicating that these N-S folds are related to banding and lineations (fig. 3). In some of the schists near Lés the schistosity plane itself shows minute folds in N-S direction. Evidently these microfolds are connected with the N-S lineations and they must have formed rather late. At several localities elsewhere in the Bosost dome also N-S folds have been found, some rather tight, others more open. In the Cambro-Ordovician phyllites near Sierra de Guarbes cleavage folds with N-S axes have been observed. In the Devonian limestones near the southern border of the Bosost dome N-S folds are not uncommon either. Boudins of pegmatites with N-S axes are probably connected with this phase of folding.

In fig. 7 a number of measurements of lineations and foldaxes in this direction has been assembled. Although there is some spreading of the lineations, due to variation in dip of the schistosity, it is obvious that the maximum lies about 15—25° E of north and almost at right angles to the ESE maximum of the first folding lineation. Although the time relations between both phases of folding could not be ascertained in the field, microscopic evidence left no doubt that the N-S lineations are younger than the E-W lineations and are due to another phase of deformation. This phase is probably also responsible for the deviation of the original E-W lineation of the first phase to their present ESE direction as will be explained further on. In the chapter on microstructures it will be shown that the second phase was connected with internal rotation about the N-S axis. It should be noted that during this second phase either a new planar schistosity was produced, or the old schistosity was preserved as a planar structure and not or only gently folded on the scale of the outcrop.

3.23 *Third phase*

A third period of deformation is responsible for the folding of the schistosity planes. A similar deformation has been described from the Aston-Hospitalet massif (Lapré, 1959, Zwart, 1960) where it has been referred to as crossfolding. In that area two pene-contemporaneous directions have been found, one in NW and one in NE direction, the first one being predominant. The same folding phase has left its traces in the Bosost dome; here also the the NW direction is predominant. A number of foldaxes has been measured mainly in schists and is shown in fig. 8. It is obvious that both NW and NE directions occur and that the latter is only weakly developed. Both directions are regarded as being pene-contemporaneous and no objections to this hypothesis have been found in the Bosost dome. Comparing fig. 6 and fig. 8 it is obvious that the main folding lineations almost coincide with the NW-SE folding, as also was observed in the field. In the early stages of investigation they have been considered as being due to the same folding phase (Zwart 1958). From the stereograms, however, it becomes evident that both maxima do not coincide exactly and that there is a slight difference in direction. Since both phases are separated by a phase of N-S deformation, there can be no doubt that they are not related. The folds which were produced during this period of folding are usually not very tight and vary in size from several hundreds of meters, as for instance on the Sierra de Guarbes, to folds visible in thin section. On the Sierra de Guarbes the Ordovician limestone occurs as a flatlying sheet and occurs on top of mica-schists. Locally the slates and limestones have been refolded about NW-SE axes in folds of a size of one to two hundred meters with a steep SW and a gentle NE limb. Folds of this size are exceptional in the Bosost dome but smaller ones occur at many places, for example between the Sierra de Guarbes and the Monteludo. In flatlying schists most folds are rather gentle and more or less symmetrical. In mica-schists a new crenulation cleavage rarely occurs in these folds, but in slates and phyllites such cleavage is often present. Pegmatite sills in the mica-schists are often folded in the NW direction together with the enclosing mica-schists and boudins with NW-SE axes are probably related to this phase.

3.24 *Fourth phase*

A fourth phase of deformation with folds in E-W direction is considered to be later than the NW-phase. As shown in the stereogram of fig. 9 a sharp maximum occurs in E-W direction. Folds belonging to this phase vary in size, like the NW phase, from microscopic to several hundreds of meters and probably even more. They occur at various localities in the Bosost dome as well north of it. The axial plane of the folds is usually steep to vertical. In the flatlying schists the minor folds are rather symmetric and more or less open, but in the steep slates and phyllites north of this area they are often strongly asymmetric. Pegmatite sills in mica-schists may be folded by this phase. An outstanding example is the so-called Barrados pegmatite (fig. 10) occurring in the Barrados valley. This pegmatite has been folded both by the NW and the E-W phase. As a result this pegmatite has acquired a peculiar shape and shows foldaxes in both directions. Originally, shortly after its emplacement this pegmatite was probably flatlying. Folding about a NW axis made at least one steep flank which is refolded about E-W axis making folds with vertical plunges. The gentle flank is refolded with gently plunging E-W axes.

The age relations between NW and E-W folding could not be established too easily in the Bosost dome due to the fact that both occur only rarely in one outcrop. However, the relations between the folds of the Barrados pegmatite are in favour of a younger age for the E-W folding. Microscopic relationships also are indicative for a

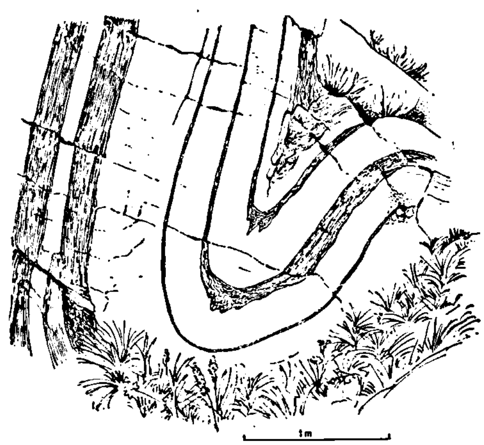

Fig. 10. Folded pegmatite in Barrados valley.

younger age. From other parts of the Pyrenees especially the Aston-Hospitalet massif, where both deformations occur frequently in one outcrop, it has been demonstrated that the E-W folding is the younger of the two. Also Boschma (1963) has supporting evidence for a younger age of the E-W phase in the phyllites north of the Bosost area.

It should be noted that the deviation of the original E-W lineations of the main phase to more southerly directions must be older than the NW-SE crossfolding since the direction of this phase does not show any departure from its usual direction.

All phases of deformation have been recognized elsewhere in the Pyrenees with the same succession. The N-S phase can probably be correlated with N-S folds and lineations in the St. Barthélemy and the Castillon massifs, although in these areas they do not occur in mica-schists but in high grade gneisses.

In the western part of the Aston massif N-S folds in mica-schists occur at several places.

From the study of a large number of thin sections it became clear that metamorphism started during the first phase, continued throughout the second and third phase and came to an end shortly after the E-W folding.

In the following pages these four phases of deformation will be referred to as phase one to four; phase one or the first phase is the main folding in E-W direction; phase two is the N-S folding, phase three the NW-SE folding and the fourth phase the late E-W folding. Metamorphism contemporaneous with either of the four phases is called synkinematic; for the first two phases early, and the last two phases late (syn) kinematic has been used. Evidence based on microscopic study of the rocks showed that between the phases of deformation episodes of tectonic quiescence occurred during which metamorphism continued. Metamorphism during such episodes is called interkinematic and is of a static kind. Three interkinematic episodes between the four phases of deformation are to be distinguished; they are numbered I to III. Metamorphism later than deformation of the fourth phase is postkinematic (or static). Prekinematic metamorphism, earlier than the first phase could not be demonstrated in the Bosost dome.

3.3 MICROSTRUCTURES

3.31 *Method of investigation*

Before the description of the structures of the rocks as seen under the microscope, it is necessary to deal with the principles involved in the determination of the sequence of events.

The mutual relations between deformation of rocks and crystallization of minerals in any regional metamorphic area are of primary importance in understanding the metamorphic and structural history of the area under consideration. This statement holds especially true for the schists of the Valle de Arán, where these relations are so strongly interwoven that unraveling the history of this area asks for a profound and detailed structural investigation on the scale of the outcrop the hand-specimen as well as that of the thin section. In total about 600 thin sections of this rather small area have been made, many from oriented specimens, and together with repeated visists to the area they have lead to a fairly complete picture of the sequence of events in the Bosost dome. This sequence is on its turn related to that of other metamorphic areas of the Pyrenees.

In deciphering the metamorphic history much use has been made of the presence of porphyroblasts and poikiloblasts of biotite, andalusite, staurolite, cordierite, garnet and sillimanite which occur in large quantities in many schists. Most of these porphyroblasts show the presence of an internal schistosity (si) inherited from an existing schistosity. The si can be compared with the external schistosity (se). They show all kinds of relations which can be checked to the field data. Besides these relations the growth of rims of one mineral around another or the replacement of minerals is of use in unraveling the metamorphic history. Part of these criteria have been published in previous papers (Zwart, 1958, 1960, 1961).

In considering the relations between si and se it is of primary importance to discuss the process in which crystals have made room while growing. According to Ramberg (1952) two main principles are involved, (1) chemical replacement and (2) concretionary growth. In chemical replacement the necessary space for the mineral is made by removing the superfluous elements from the future site of the crystal and introducing the necessary elements.

Thus the room is simply made by chemical transport on a small scale and there is no or very little mechanical disturbance of the rock outside the crystal. In concretionary growth a crystal starts to grow at a certain spot, all necessary elements are transported to this site and space is made by bodily pushing aside the surrounding rock so that bedding or an existing schistosity should curve around the crystal. According to Ramberg most minerals in metamorphic rocks probably grow by a combination of both principles, that of chemical replacement and that of concretionary growth.

Careful study of the fabric of many metamorphic rocks, however, does not support this conclusion and most, if not all, crystals grow by chemical replacement only, without disturbing the surrounding rock. Concretionary growth, to the contrary, is at least a minor feature or does not occur at all in metamorphic rocks.

As has been remarked many porphyroblasts contain rows of inclusions constituting an internal schistosity. In many cases this si runs straight through the crystal and is continuous into se (fig. 11 A); in other cases porphyroblasts contain no si, but the pattern of se is similar. Both cases are indicative of pure chemical replacement, and the absence or presence of si is of no concern. In the extreme case of concretionary growth an si cannot be produced, since schistosity is inherited from the original schist and se should curve completely around the crystal without any connection with the crystal (fig. 11 B). Such a pattern has been found in some rocks from other parts of the Pyrenees but it should be mentioned that it can be interpreted in two ways. Therefore little proof for the existence of concretionary growth can be brought forward, whereas chemical replacement is an established fact. In an intermediate case, where the crystal grows according to both principles the internal schistosity cannot be planar, but must be curved in the borders of the crystal as depicted in fig. 11 C. Such crystals have only been observed very rarely and in most cases a planar si with a curved se is present. Moreover the pattern of fig. 11 C that should be characteristic of concretionary growth combined with chemical replacement, can also be produced when the crystal grows at the same time as flattening of the matrix, and consequently such a pattern is not conclusive. In any case where it could be proved that no movement has occurred after the crystal has grown no deformation of a surrounding schist matrix by the porphyroblast was produced, independent whether the matrix was planar and not folded or contains microfolds. Also the pattern of fig. 11B is not conclusive for concretionary growth, since crystals older than the formation of a schistosity show se curving completely around the crystal without any connection due to the plastic flow of the schist around the existing crystal.

Summarizing the evidence it can be stated that chemical replacement is the main process in which crystals in metamorphic rocks grow; that growing minerals do not disturb the surrounding rock by a so-called force of crystallization, and that if the surrounding rock is deformed, it must be the result of subsequent deformation by tectonic action.

Deformation of rocks displaying a schistosity may be of three different kinds: (1) the s-plane is a plane of flattening, (2) it is a plane of slip (3) the s-planes may be thrown in microfolds. (1) and (2) may occur simultaneous and they may in part be responsible for the development of a schistosity itself, (3) takes place after a schistosity is produced. For any of these three different kinds of deformation a different pattern of si and se exists. If a mineral grows during flattening of a schist, the pattern of fig. 11 C is produced, showing a planar si in the center, and a curved si in the borders of the crystal. The se is continuous in si, but also curves partially around the crystal. When slip occurs along s-planes the results of contemporaneous crystallization is shown in fig. 11 E; the si is s-shaped. This pattern is well known in garnets, for example as snowball garnets described from several regions. Since this kind of movement is usually accompanied by flattening, se also curves around the crystal.

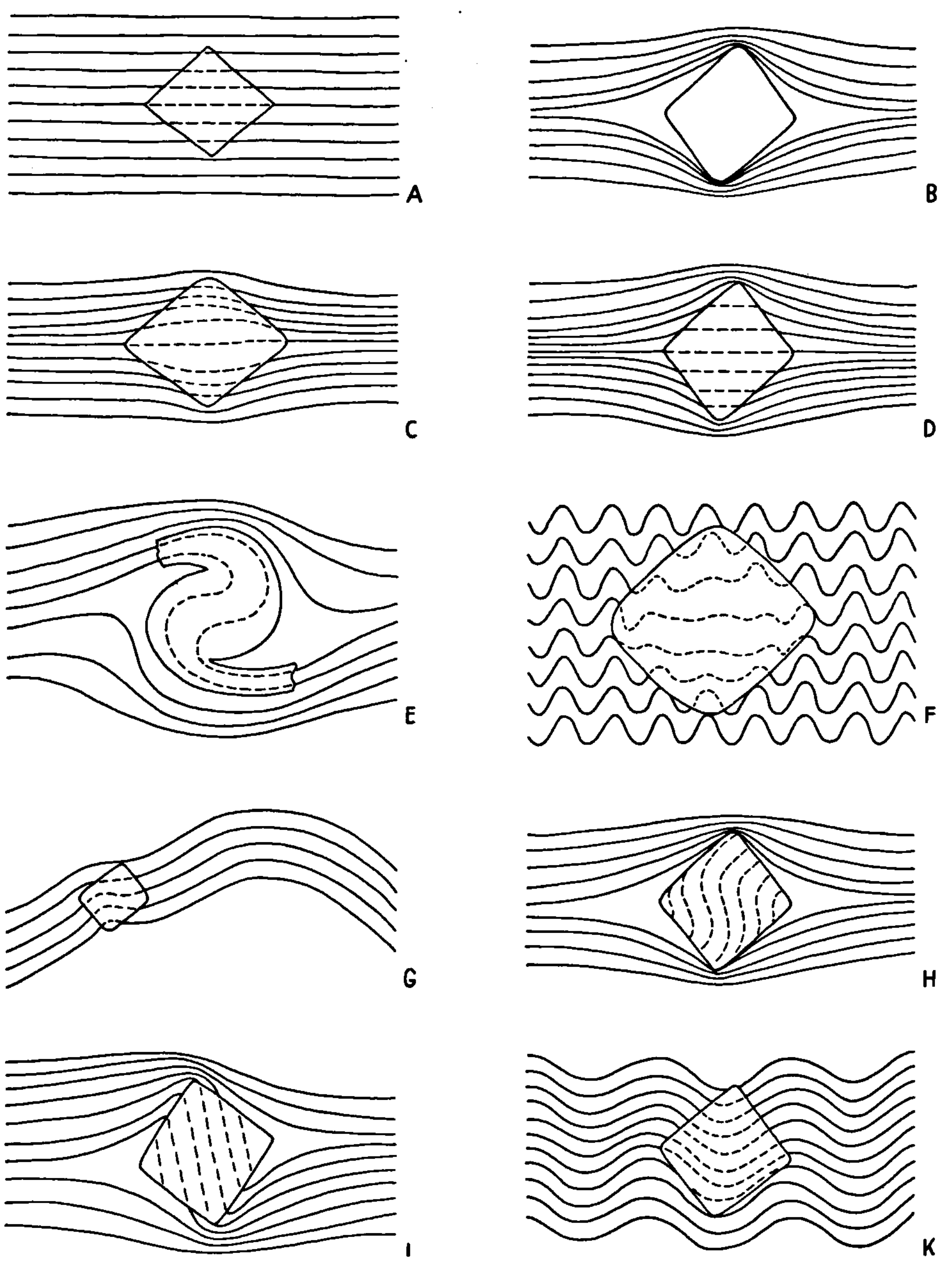

Fig. 11. Relations between porphyroblasts and schistmatrix.

When the schistosity is folded two different patterns may develop. In one case (fig. 11 F) the crystal shows the evolution of folding by the presence of weakly folded inclusions in the centre which is the oldest part of the crystal, and stronger folded inclusions towards the rim. A second pattern may develop when concentric folds have a considerably larger size than the porphyroblasts. Slip along the schistosity plane as a result of concentric folding causes the crystals to rotate resulting again in s-shaped inclusions, but since the amount of movement in such folds is relatively small the total angle of rotation usually does not exceed 45°. Moreover the sense of rotation is opposite in opposite limbs of the folds. Both cases have been found in the Pyrenean mica-schists.

The four described patterns are diagnostic for crystallization contemporaneous with the described kinds of deformation. It is understandable that crystals also may grow independently of deformation, that is before or after. In this case also special patterns of si and se develop, which may give definite clues to the history of the rocks.

Crystals older than any schistosity show the pattern of fig. 11 B which look similar to Ramberg's principle of concretionary growth. It shows a porphyroblast without si, and with se completely curving around it and not connected with the crystal. Another pattern develops when crystals have formed after a first schistosity was produced and when by subsequent deformation a completely new schistosity is produced. In this case the crystal shows an si, but an se which is not connected with it (fig. 11 H). Also transitional stages in which the second schistosity is not yet fully developed have been found.

Crystals later than a schistosity and after movement had ceased, show the pattern of fig. 11 A which is indicative of pure chemical replacement and static metamorphism. Se is continuous with si, without bowing out the schistosity. However, when the s-plane is used for renewed movements the crystal may be rotated or the matrix may be flattened or crumpled as shown in fig. 11 D, I. The main feature is a planar si in the porphyroblast. Finally when crystals are later then folding of the schistosity these folds are inherited by the crystal as so-called helicitic folds, fig. 11 K.

Many of these patterns have been observed in schists of the Bosost dome. One further result of this study is that porphyroblasts growing during any kind of deformation usually are not deformed and the crystals show straight extinction, although the record of deformation is clearly shown in the inclusions. After the active growth of the crystal, however, they may be deformed by continuing or renewed folding.

Besides the described possible relations between si and se there are other features which may help to determine a time sequence. These are the growth of rims of one mineral around the other, in which case the rim must be younger, or the replacement of one mineral by another. Both cases occur frequently in the aluminium-silicates of the Bosost dome. Also relations between the internal schistosities of interfering crystals and the external schistosity are very helpful. They will be described later on.

The description of microstructures is rendered difficult by the fact that two features interfere, the succession in time and the succession in space. Both are so strongly interwoven, that the one cannot be treated separately from the other. The difficulty arises from the fact that certain metamorphic fronts ascended or descended during the various folding phases and since moreover these fronts are not parallel to the stratigraphic boundaries several different rock types with different mineral assemblages and different histories are produced. On the coloured map two metamorphic boundaries are shown: the epi-mesozonal boundary between phyllites and biotite-schists and a line within which pegmatites and granites occur. A third boundary could be added, a staurolite or andalusite isograd, which lies between the two aforementioned boundaries. These three lines are more or less parallel and suggest a rather simple progressive metamorphic zoning. This picture, however, is not complete since such isograds could be drawn for different periods of the metamorphic history. If this should be done, there would be one biotite isograd for the first phase and a new biotite isograd for a second phase, whereas the andalusite isograd belonging to this second phase would cut across the first biotite isograd, due to the rise of the metamorphic front. Similarly a second andalusite isograd dating from a third phase could be constructed.

After unraveling the history of the whole area it became clear that at any given place a certain group of minerals was stable during a certain time, but that a second assemblage could take over, eventually followed by a third and may be a fourth one. Consequently metamorphic zoning or mineral facies can only be applied for a certain portion of the history of the rock and not for the rock as a whole since several succeeding zones or facies are present. In other words all these rocks are polymetamorphic.

Although it might be logical to describe the microstructures in a chronological sequence, dealing with the properties if the minerals in such order, this would disrupt this description so strongly as to make it unintelligible. For this reason it seemed preferable to start with those rocks which have the least complex history and then to gradually proceed with the more intricate fabrics. For this reason the schists will not be treated in a stratigraphical but in a zonal order.

3.32 *The metamorphic zones*

Four zones can be distinguished: 1) a biotite zone, coinciding with the biotite-schists (p. 325) and occurring near Bosost and in the northern half of the dome, 2) a staurolite-andalusite-cordierite zone, in the northern half underlying the biotite-schists, in the southern half comprising also the Silurian and the lower part of the Devonian, 3) an andalusite-cordierite zone, occurring as a shell below the second zone not comprising the Silurian and Devonian rocks and 4) a cordierite-sillimanite zone forming a core underneath the third zone (fig. 1).

The biotite-zone is the same as described in the chapter on stratigraphy; the staurolite-andalusite-cordierite-zone compares with the andalusite-zone, whereas the third and fourth zone fall in the granite-bearing zone. The banded schists near Lés belong partly to the second, partly to the third zone (See fig. 1).

It should be added that the zones as proposed here are not defined as those described by Barrow. In the Barrovian zones one mineral assemblage is characteristic for one zone and the rocks are considered to be monometamorphic. In the metamorphic zones of the Bosost dome only the biotite zone shows one phase of metamorphism and one mineral assemblage, but the remaining three zones show several successive mineral associations. For example the second zone contains at least two, the third at least three and the fourth at least four different assemblages. In principle the higher numbered zones have gone through the lowered numbered ones. Thus the cordierite-sillimanite zone has passed through the biotite-, the staurolite-andalusite-cordierite- and the andalusite-cordierite-zone and has a complex and longlasting history (see table fig. 22).

3.321 *Biotite-zone.* Schists of this zone, occur as already mentioned, mainly in the northern half of the Bosost area and near Bosost. Their mineralogical composition is quartz, muscovite and biotite as main constituents with occasionally some plagioclase (sodic oligoclase) and accessory apatite, zircon, tourmaline and ore. The relative amounts of quartz and micas are quite variable, depending mainly on the chemical composition of the schists. They are often banded, quartz-rich layers of a few mm to cm thickness alternating with more micaceous bands. The micas are perfectly parallel aligned and they are markedly different in size in sections parallel and perpendicular to the lineation. Usually the relation of length to width amounts to 2 or 3. The quartz crystals are small and often elongated in the direction of the lineation. When little quartz is present the crystals are embedded between the micas; when much quartz occurs it forms a sort of mosaic. In fig. 12 two sections, parallel and perpendicular to the lineation of such a linear mica-schist are shown.

Where biotite-schists are folded by the third or fourth phase, this deformation is entirely postcrystalline, indicating that metamorphism had ceased before the third phase.

3.322 *Staurolite-andalusite-cordierite-zone.* Schists belonging to this zone occur in the upper part of the pegmatite bearing-zone and above it. Part of these schists are of Cambro-Ordovician age, part is of Silurian and Devonian age. The latter

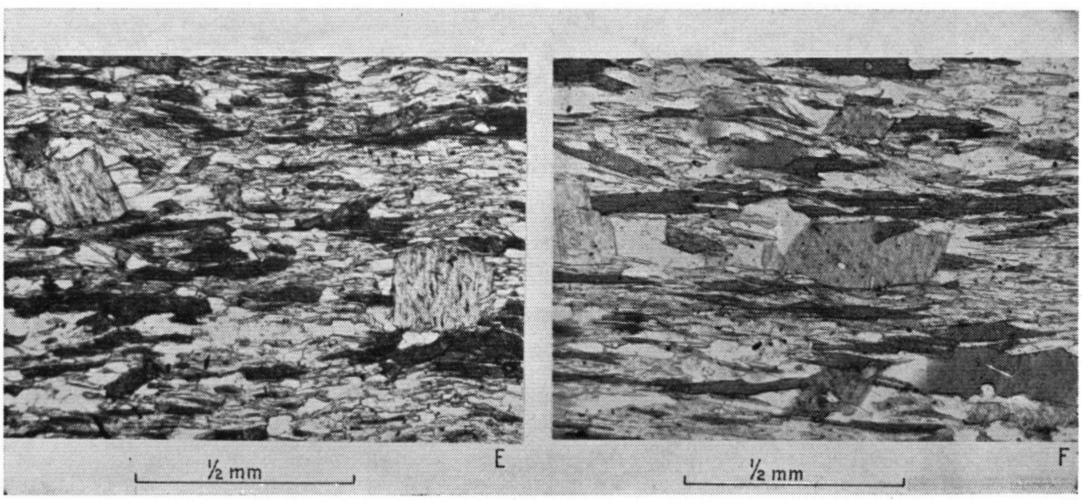

Fig. 12. Two sections through linear mica-schist.

schists are located near the south side of the Bosost dome and are separated from the Cambro-Ordovician by a narrow band of andalusite-bearing black Silurian schists. The Devonian and Silurian schists will be treated later and first the Cambro-Ordovician will be described. The matrix of these schists is comparable with the biotite-muscovite-schists described above. They contain the same minerals with a similar lineation and schistosity and of approximately the same grain size. In this matrix are set large porphyroblasts of staurolite, andalusite, cordierite, biotite and occasionally garnet. Andalusite and cordierite occur as elongated crystals with a rounded cross section of ½—1 cm diameter and a length of 1—4 cm. Although usually lying in the plane of schistosity, they are at random distributed in this plane. Staurolite occurs as short prismatic crystals of a size of ½ cm, always idioblastic and generally showing penetration twins. The biotite porphyroblasts are much smaller and usually do not exceed 1 mm in length. They show a linear arrangement parallel to the lineation produced by the elongated small mica crystals. Their cleavages, however, are not

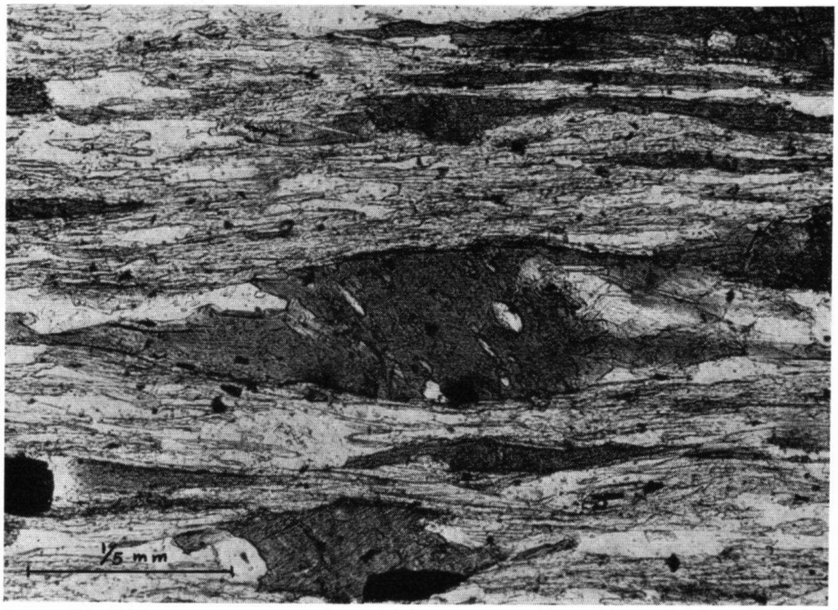

Fig. 13. Biotite porphyroblasts rotated in schistosity; si oblique to se.

Fig. 14. Biotite porphyroblast with si oblique to se.

parallel to the schistosity so that they have a form but not a lattice orientation (fig. 13, 14). Garnet occurs as idioblastic crystals of appr. 1 mm size or smaller.

Almost all porphyroblasts of staurolite, andalusite, cordierite, biotite and garnet in this zone show the presence of an internal schistosity determined by rows of inclusions usually of quartz and occasionally of micas or graphite. In most cases the si runs straight through the crystal but in some examples the si has a curved trend. The visible relationship between si and se depends strongly on the position of the section with regard to the lineation. In sections perpendicular to the ESE lineation si is parallel to se but the schist matrix is strongly curved around the porphyroblast (fig. 15) although a connection between si and se always remains present. In sections parallel to the lineation, however, the situation is different inasmuch the si of nearly all crystals makes an angle with se, but nevertheless se can be followed into si (fig. 16) The schist matrix always curves around the porphyroblasts. These relationships can be explained in two ways, either the crystals have rotated as a result of slip a long the schistosity plane or due to flattening rotation may occur. The amount of rotation is

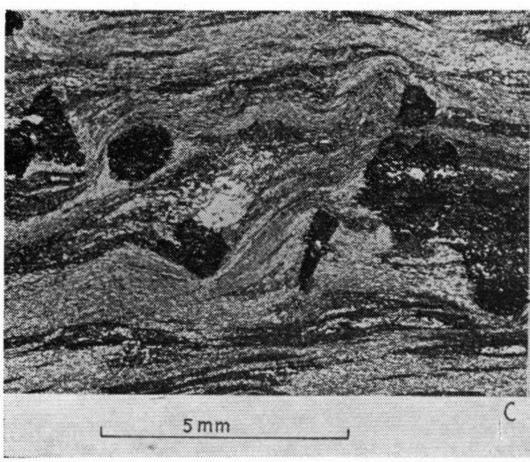

Fig. 15. Staurolite with planar si; se curved; section perpendicular to lineation.

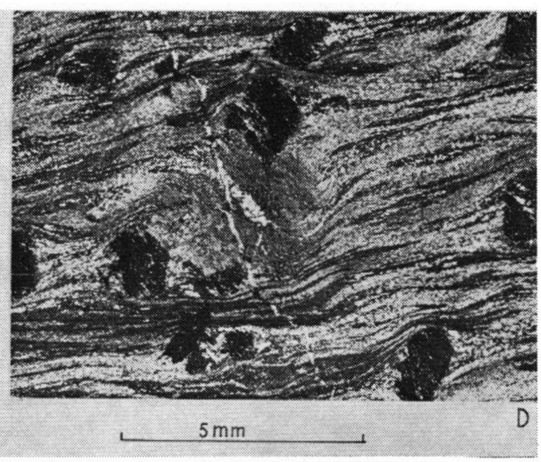

Fig. 16. Same specimen as fig. 15 but cut parallel to lineation; staurolite rotated.

not very large and usually does not exceed 90—100°. Hardly without any exception, however, all porphyroblasts of staurolite, garnet and biotite participated in the rotation, and a large number of andalusites and cordierites. The angle of rotation is largely dependent on the shape of the crystals. Long andalusite and cordierite crystals lying parallel to the lineation may show no rotation at all but crystals lying perpendicular to the lineation always show a certain amount of rotation (fig. 17).

Long crystals originally lying across the schistosity are rotated in the plane of schistosity, resulting in a random orientation of these crystals but in the plane of schistosity. Since the staurolites are short prismatic crystals they invariably show a rotation irrespective of their position with regard to the schistosity. Since moreover all crystals have the same sense of rotation, it must have been the result of slip on the schistosity plane and not of flattening only. As described above, the si is usually planar indicating that the crystal itself existed already before it started to rotate. Since all porphyroblasts contain an included schistosity, they must have formed later than the schistosity itself which at its turn can be attributed to the first phase of folding.

Moreover no crystals are influenced by this phase as shown by the absence of any rotation about E-W axes. Furthermore the random orientation of the porphyroblasts in the s-plane, and hence the absence of parallelism to the lineation of the micaschists also shows their origin later than the schistosity and ESE lineations. Therefore it seems safe to conclude that porphyroblastesis postdates the first or main phase of deformation (fig. 22).

In several crystals of staurolite, cordierite, andalusite, garnet and biotite, however, the si is s-shaped (fig. 17), indicating that movements and growth of the crystal were simultaneous. In many cases movement has outlasted crystallization and postcrystalline rotation occurred (fig. 18). From this evidence it can be concluded that crystallization of staurolite, andalusite, cordierite, garnet and porphyroblastic biotite, started sometime after the first phase and continued during interkinematic

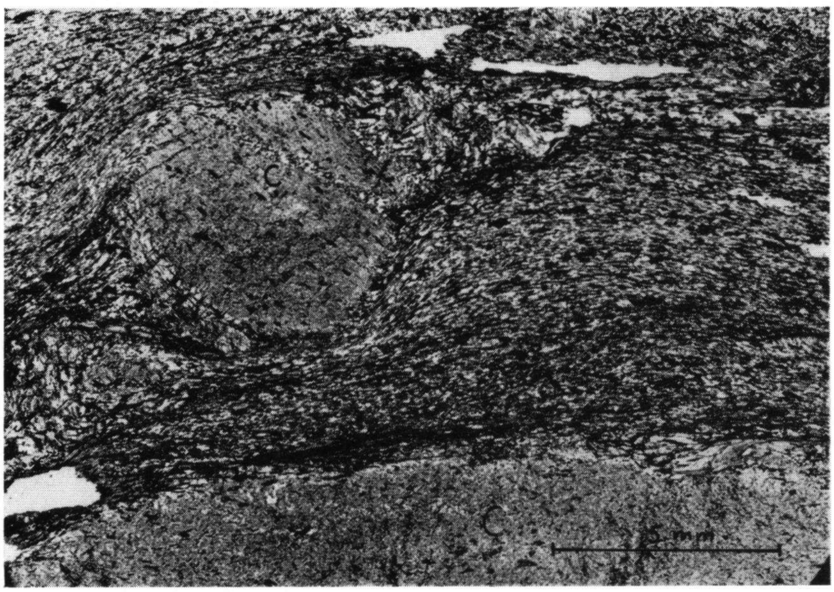

Fig. 17. Cordierite crystals in section parallel to E-W lineation. Round crystal rotated; long crystal not.

period I when static, unoriented, growth occurred. After many of the crystals had completed crystallization gliding movements on the schistosity took place resulting in the rotation of these crystals. Crystallization went on and new porphyroblasts with s-shaped inclusions were produced indicating synkinematic growth.

Summarizing the evidence it can be stated that crystallization of staurolite, andalusite, cordierite and garnet started after the main phase during a period of tectonic quiescence and continued during the second deformation phase, which is characterized by gliding movements over the preexisting s-planes.

Staurolite with s-shaped inclusions always shows some post-crystalline rotation, indicating that its formation had ceased before the end of the second phase (see fig. 18). From the abundant presence of crystals with planar si it can be concluded that the culmination of its growth lies before the second phase.

Postkinematic rotation of andalusite often does not occur and consequently this mineral will have formed up to the end of the second phase. A few crystals quietly growing in the schists indicate its continued crystallization after the second phase.

The same holds true for cordierite, especially for crystals later than the second phase.

The biotite porphyroblasts deserve special mention since they are strongly different from the first generation biotites. As has been described two types of biotite crystals occur: 1) small elongate crystals without si with a perfect lattice and form orientation and linear arrangement 2) another group of larger crystals showing a form but no lattice orientation, often more or less deformed and eye-shaped, lying with their longest axis in the direction of the lineation and showing the presence of a si which frequently makes an angle with se. In sections parallel to the lineation the relative position of si with regard to se again shows that the crystals have rotated (fig. 13) so that now their longest dimension is lying in the schistosity plane and also in the direction of the lineation as defined by the smaller mica crystals. Restoring

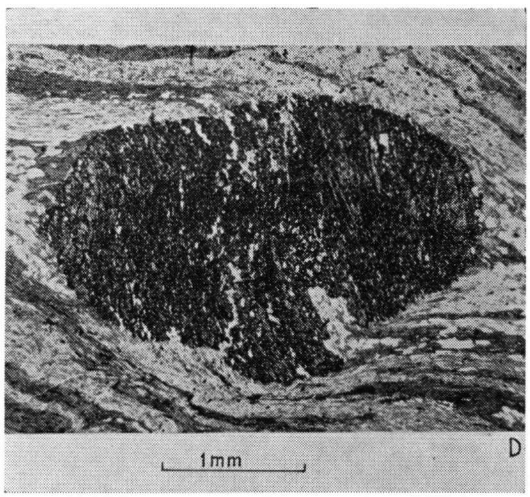

Fig. 18. Staurolite with s-shaped si; continued rotation after crystallization.

these crystals to their original position by backward rotation shows that almost all of these crystals grew across the schistosity. It is to be remarked that the si in many biotite crystals makes an angle of approximately 60° with the present schistosity, as has been observed in several thin sections (fig. 14). Originally these crystals must have grown across the schistosity but apparently they possessed a form orientation indicating a cross-schistosity making an angle of $\pm$ 60° with the present schistosity. This cross schistosity must have formed after the first but before the second phase of folding. It has not been possible to correlate this feature with any kind of deformation and hence its origin remains obscure.

Besides biotites with planar si, crystals with a curved s-shaped si have also been observed (fig. 19); they date from the second phase of deformation. The schistosity curves around all these porphyroblasts in a similar manner as around staurolite, andalusite and cordierite. This is again due to flattening of the matrix, rather than pushing aside by force of crystallization. This is corroborated by the presence of similar biotite porphyroblasts occurring in large cordierite crystals. Here the biotites

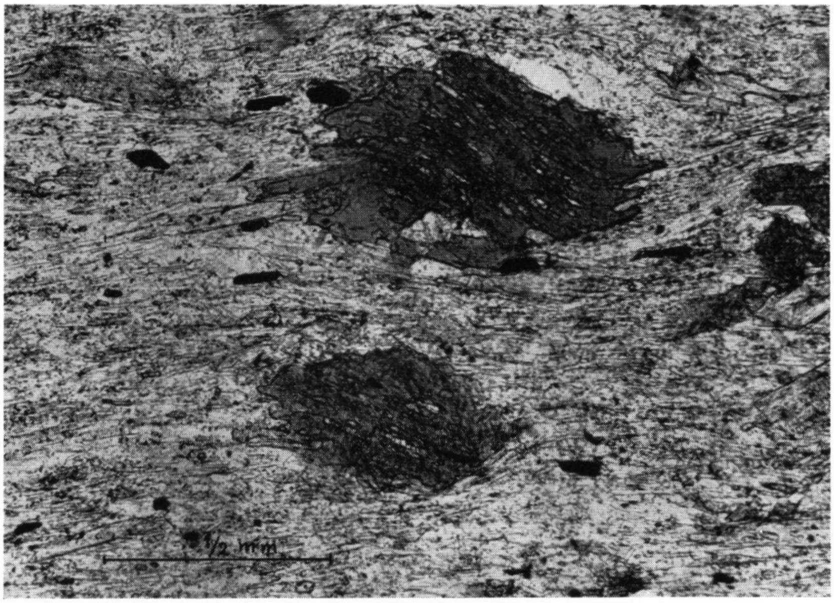

Fig. 19. Biotite with s-shaped si, dating from second phase.

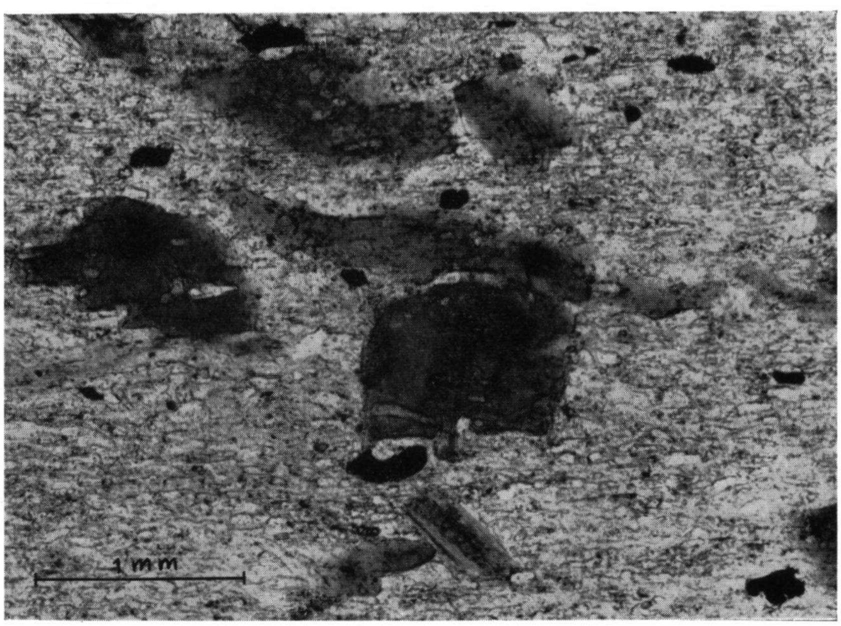

Fig. 20. Biotite porphyroblasts in large cordierite crystal; si in cordierite not curved.

have been shielded by the surrounding cordierite and neither rotation nor curving of the matrix around the biotites has occurred and in these biotites the original position and relation to se can be seen (fig. 20). Since the movements on the s_1-planes apparently were in the same direction and the largest dimension of the biotite porphyroblasts lies in the direction of movement, as demonstrated by the direction of rotation, the lineation caused by the porphyroblastic biotites is an a-lineation, superposed on an existing B-lineation as determined by the small elongated micas and dating from the main phase. Both lineations are subparallel, but have a different origin and are of different nature. The B-lineation is due to growth in a stress field whereby the micas grow fastest in the direction of least resistance—in this case the direction of the foldaxis—whereas the a-lineation is produced by rotation of crosscutting biotite porphyroblasts in that direction.

In order to evaluate the direction of movement as indicated by the rotated crystals, a large number of oriented specimens has been collected from which oriented sections have been cut. In sections of 52 different samples together containing more than 300 rotated crystals and originating from localities throughout the entire area, the sense of rotation has been determined. In all cases this sense is the same and indicates a movement from west to east. Further it has been observed in a large amount of unoriented specimens that in no single section crystals have an opposite sense of rotation, some sections containing as much as 40 rotated porphyroblasts. The movements occurring over the total thickness of schists amounts to a distributed overthrust of fairly large size. The amount of movement can be calculated from the angle of rotation of the porphyroblasts. In many cases this rotation is near 90° and crystals showing this amount of rotation occur throughout the whole series of schists, from the Lower Devonian well into the Cambro-Ordovician. In many cases where the degree of rotation is less it can be attributed to the shape and the position of the crystal. A rotation of a round crystal to 90° indicates a relative movement in a layer of thickness d of $\frac{1}{2}\pi$ d which is approximately 1.6 $\times$ diameter of the crystal. As in all sections crystals show some degree of rotation, there do not seem to be preferential zones where most of the movements have taken place alternating with zones without movements, but apparently they are equally distributed throughout the whole sequence, and it concerns here a typical affine deformation. Since the crystals are attached to the rock, rotation cannot be compared with a ball moving between two walls, and the necessary amount of slip certainly has exceeded 1.6 $\times$ the diameter of the crystal. This braking effect can be estimated as a factor 2, so that the slip has amounted to 3.2 $\times$ d. Further, flattening of the matrix has to be taken into account. As deduced from the si-se relations this adds another factor of 2, resulting in a total slip of about 600 m over a present thickness of 100 m schist.

The direction of movement during the first phase with E-W to ESE lineations and folds will have been in N-S direction and it is probable that differential movements have taken place during this phase. It is, however, not possible to prove this due to the absence of rotated crystals; neither has it been possible to prove the direction of movement. The movements during the second phase are approximately perpendicular to those of the first, but despite this relationship they are definitely later and independent. Although it is difficult to determine the stress field during this second phase, there can be no doubt that some kind of an E-W directed main stress has been present during that time, and hence it contrasted strongly to the N-S main stress during the first phase.

As staurolite, andalusite, cordierite, garnet and biotite porphyroblasts all show similar evidence of growth during the interkinematic phase between first and second phase of deformation and during the second phase, this mineral assemblage must have formed simultaneously and is essentially a stable one. The same association also occurs in other metamorphic areas of the Pyrenees for example in the Aston and Hospitalet massifs and there also good evidence for it being a stable assemblage is present. Nevertheless there is evidence that staurolite is the mineral which started to grow first, since it may be included in andalusite, garnet or cordierite, where as the reverse relation does not exist.

The staurolite cores in andalusite and cordierite are idioblastic and no replacement is involved (fig. 21) thus relations are not unstable. In several cases it has been observed that a staurolite core with an andalusite rim have rotated together and both obviously antedate the second phase. On the other hand staurolite with s-shaped inclusions must have formed simultaneous with the movements of the second phase and is younger than andalusite and cordierite with planar inclusions. Consequently

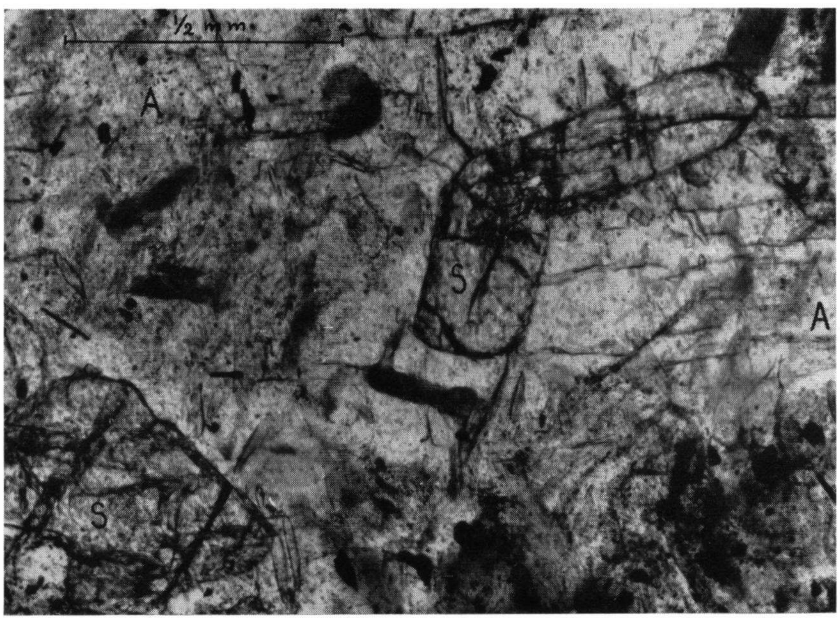

Fig. 21. Idioblastic staurolite in andalusite (Devonian schist).

there is an overlap in time of the formation of staurolite, andalusite and cordierite, but staurolite is the earliest mineral of the three (fig. 22). For these reasons it looks probable that when the temperature rose after the first phase of synkinematic metamorphism in the biotite zone, first staurolite started to crystallize and somewhat later andalusite and cordierite probably as a result of further rising temperature. Hence staurolite seems to be a lower grade mineral than andalusite and cordierite. A similar relation exists in the Barrovian zones, where the staurolite zone precedes the kyanite zone, although both minerals frequently occur together. One might expect, in view of these relations that a staurolite zone should envelop the andalusite-staurolite cordierite zone. This has not been established, probably since the higher grade staurolite-andalusite-cordierite zone overtook the staurolite zone. On its turn andalusite may be included in cordierite, which means that the former mineral started to crystallize before the latter.

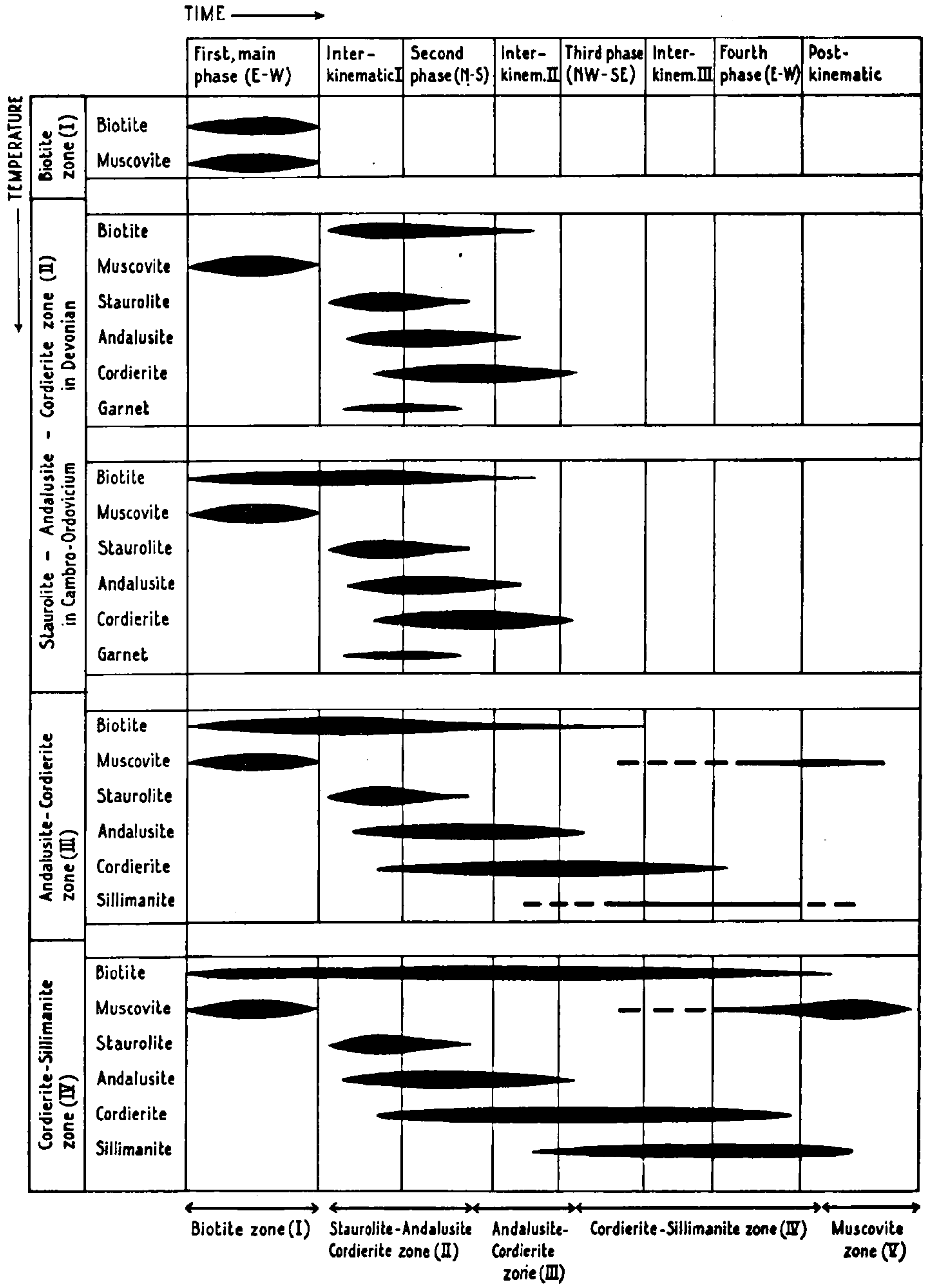

Fig. 22. Table showing relations between metamorphic zones, time and depth.

In many thin sections the effect of the third phase of folding is visible. This phase is characterized by folding of the existing schistosity planes, often on a microscopic scale. The direction of folding is NW or NE and the axial planes of the folds are steep. Also a fourth phase with E-W directed folds of s-planes occurs in this area. The effects of these deformation phases is of course best visible in sections perpendicular to the fold axes.

As far as the micas are concerned all folds in the two directions are postcrystalline the micas being bent in the fold hinges. The same holds true for the porphyroblasts of aluminium-silicates in this zone. Neither crystals with included helicitic folds in NW-SE or E-W direction have been found, nor other indications that porphyroblastesis continued during the third phase. Therefore in this zone crystallization is prekinematic with regard to the third and fourth phase of folding, and porphyroblastesis took place in the interkinematic episode between first and second phase and during the second phase of deformation, but has ceased before the third phase had started.

Summarizing the history of these Cambro-Ordovician schists it can be stated that during the first phase of the Hercynian folding the rocks were metamorphosed in the biotite zone (upper portion of the mesozone) and became biotite-muscovite-schists with a pronounced schistosity and lineation in ESE direction. After the end of this phase the grade of metamorphism rose slowly, first to the staurolite zone and then to the staurolite-andalusite-cordierite zone (warmer portion of the mesozone), resulting in the development of a large number of unoriented porphyroblasts of biotite, staurolite, andalusite, cordierite and minor garnet, all showing a planar internal schistosity. Subsequent shearing movements on the s-planes from WNW to ESE caused these minerals to rotate with a rotation axis in NNE direction. Biotite porphyroblasts were rotated so as to form a linear fabric without lattice orientation and are superposed on the earlier E-W lineations. Both lineations are almost parallel, but the first is a B, the second an a-lineation. Crystallization of staurolite, andalusite, cordierite, biotite and some garnet continued through this second phase of deformation. They show s-shaped trends of inclusions with the same axis of rotation as the earlier crystals. Subsequent folding of the schistosity about NW, NE or E-W axes brought about small folds which in this zone are postcrystalline.

On the south side of the Bosost dome the described micaschists are bounded by black Silurian schists. It seems logical to assume that these schists have experienced a similar history as the described Cambro-Ordovician schists. This has indeed found to be true although the rocks have a strongly different appearance due to their high carbon content. The matrix of the Silurian schists shows besides fine grained sericite a large quantity of graphite, up to 6 % in chemical analysis which makes even the thinnest section almost opaque. No biotite similar to the finegrained biotite in the Cambro-Ordovician schists has been found which might be attributed to lower metamorphic grade. It is also possible, however, that the absence of biotite is due to unsuitable chemical composition or hampering effect on crystallization of graphite. Anyway the matrix of the Silurian schists is different from the underlying mica-schists although the development of a schistosity is due to the same folding phase. After this main phase porphyroblasts of andalusite or chiastolite up to a size of ½ cm grew in these schists. In a few sections some crosscutting biotite occurs. No staurolite, cordierite or garnet has been found. The absence of these minerals is certainly due to the chemical composition of these schists and the same feature has been noted in other metamorphic areas of the Pyrenees.

In several sections it is evident that the andalusite or chiastolite crystals have rotated about a NNE axis like in the Cambro-Ordovician schists and also in this case rotation does not exceed 90°. In many cases the Silurian schists have been microfolded, mainly about NW axes and again in this case folding is entirely postcrystalline as shown by the occurrence of andalusite with a planar si in a microfolded matrix.

Summarizing it can be stated that, although the mineralogical composition of these Silurian black schists is different from the Cambro-Ordovician, their metamorphic and structural history is similar.

The lowest pelitic part of the Devonian at the south side of the Bosost area consists of staurolite-andalusite-cordierite schists which show a similar history as the Cambro-Ordovician and Silurian schists. They are shown on the map with a red dotted ornament. In the field the rocks look different from the Cambro-Ordovician schists, mainly due to smaller grain size and more blackish appearance. The main difference lies in the fact that during the main phase of deformation most of these schists were epizonal phyllites and not biotite-schists like the Cambro-Ordovician rocks. In thin section the phyllitic matrix is still well recognizable. Besides fine grained sericite, some quartz and a certain amount of graphite is usually present. The latter constituent causes these rocks to be black in the hand specimen and rather dark in thin section. Lineations due to unequal length of crystals like in the Cambro-Ordovician schists were hardly found although the specimens do show a lineation which in this case is mainly due to minute folding of the s-planes. In a few thin sections some fine grained, often greenish biotite with parallel orientation was found indicating that locally metamorphism just reached mesozonal conditions during the first phase. In most sections, however, such biotite is absent.

A peculiar microstructure was observed in several Devonian schists from different localities along the southern border of the Bosost dome. They show a large amount of small eyelets of sodic oligoclase of a size of 0,8—0,15 mm, nearly always containing graphite dust in the center. The schistosity curves more or less around these eyelets but also runs into it. The origin of this structure is unknown but presumably part of the Devonian is rather rich in sodium resulting in the formation of a large amount of small oligoclase porphyroblasts. The chemical analyses of three Devonian schists are, however, contradictory to this possibility, since the sodium content is extremely low. It is probable that this structure dates from the main phase of folding during which the schistosity developed, which is corraborated by the fact that these eyelets occur as relicts in some andalusite crystals and therefore must be older than this mineral which started its formation shortly after the first phase. Similar structures have not been encountered in Cambro-Ordovician schists.

A large number of porphyroblasts of staurolite, andalusite, cordierite and also biotite occur in the Devonian schists, giving them a particular knotted outlook. Further garnet and chloritoid have been observed a few times. Their orientation is at random like in the Cambro-Ordovician schists but their size is definitely smaller and seldom exceeds ½ cm. This may be due to the presence of graphite, preventing crystallization. Staurolite does not usually exceed the size of 1 mm; andalusite and cordierite are somewhat larger, up to ½ cm. Mostly the crystals are more or less round except for staurolite which shows its idioblastic shape and is almost invariably twinned. In sections parallel to the ESE lineation again the rotation of many of these porphyroblasts is clearly visible by the relations between the internal schistosity, mainly consisting of quartz or graphite and external schistosity. There are, however, certain differences between the Devonian and Cambro-Ordovician schists, mainly with regard to the aluminium silicates which need to be discussed.

Staurolite, the most abundant of the three aluminium-silicates shows clear evidence of either growth between the first (main) and second phase of deformation as deduced from the presence of a planar si rotated with regard to se, or during the second phase as shown by s-shaped si with a rotation parallel to the earlier crystals. Crystals with planar si are much more abundant than those with curved trends of inclusions. Other crystals show a core with planar si and a rim with s-shaped rows of inclusions which is interpreted as a first stage of growth in the interkinematic phase and continuing growth during the second phase. Like in the Cambro-Ordovician schists, staurolite is often included in andalusite or cordierite. In many cases the mutual relations do not show unstable relationships and the included staurolite has an euhedral shape without being corroded by the host mineral. In other cases, however, staurolite appears to be corroded and partially replaced by cordierite or andalusite and in this case the relations must be unstable. Both cases, stable and unstable relationships indicate that staurolite was the first mineral to be formed. In other sections it is evident that host and included minerals have rotated together and hence

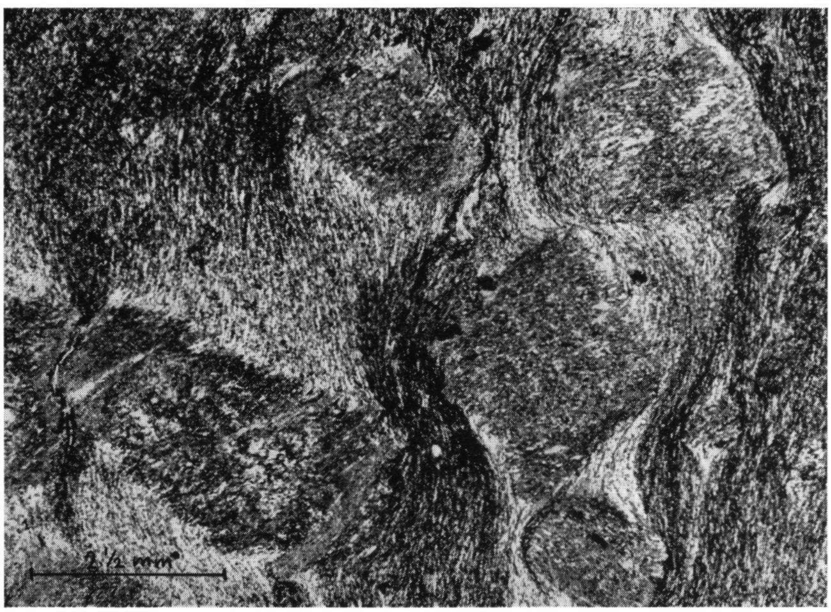

Fig. 23. Rotated andalusite crystals in Devonian schist.

both must be older than the second phase. From the fact that staurolite also crystallized during the second phase it is evident that during the last part of the interkinematic phase and the first part of the second phase, staurolite formed simultaneously with andalusite and cordierite (fig. 22).

Andalusite also shows the presence of a planar si rotated with regard to se, but more commonly it includes trends of inclusions with an s-shape clearly indicating its simultaneous development with the second phase of deformation (fig. 23). Crystals containing a core with planar si and a rim with s-shaped si are rather common. The main phase of crystallization then falls at the end of the interkinematic phase and during the first part of the second phase. This is slightly different from staurolite whose main crystalliztion took place during the interkinematic phase. The inclusion of staurolite in andalusite also indicates that the formation of the latter mineral is generally somewhat later than that of the first one, although there can be no doubt that simultaneous crystallization occurred also. The not infrequent partial replacement of staurolite by andalusite then indicates that the crystallization of andalusite lasted longer than that of staurolite resulting in unstable relationships.

Cordierite shows evidence of more prolonged crystallization. Crystals with a planar si like in staurolite and andalusite do occur but are rather scarce. Nevertheless they indicate without any doubt that formation of this mineral started before the second phase. Other crystals show an s-shaped si indicative of growth during the second phase. In a few cases it has been observed that a core of staurolite and a rim of cordierite have rotated together. In one thin section a staurolite core has a planar si and the rim of cordierite an s-shaped si which is to be interpreted as formation of staurolite in the interkinematic phase and of cordierite during the second phase of deformation. Partial replacement of staurolite by cordierite has also been observed, again indicating that the crystallization of cordierite outlasted that of staurolite. There is evidence that cordierite continued crystallization after the second phase of deformation. Some large porphyroblasts often including small staurolite crystals seem to invade the matrix of the schists without any disturbance of the schistosity and without any rotation, although the included staurolites have been rotated. These cordierites must have grown after the movements along the schistosity planes had ceased and consequently they are postkinematic with regard to this phase. A few andalusites show similar relations, but staurolite never, hence the crystallization of cordierite outlasted that of the other two minerals. In a few cases some incipient folding of si indicates that some cordierites grew during the third phase of folding but the evidence is rather scanty (fig. 22).

Biotite occurs as crosscutting crystals or as elongate crystals with a form orientation in the schistosity. The schistosity often curves around the biotites in the same manner as around the aluminium-silicates. Included si shows that they are rotated in a number of cases like in the Cambro-Ordovician schists. Consequently most of the biotite dates from the interkinematic episode between first and second phase.

Garnet has been found in one thin section near the Trona mountain; its relationships indicate a similar age as the aluminium-silicates.

Chloritoid was discovered in one thin section as small crosscutting crystals. Its relation with regard to the other minerals could not be established, but since chloritoid is definitely a lower grade mineral than staurolite it may be assumed that it is older than the latter.

Summarizing the history of the Devonian schists it can be stated that they were metamorphosed mainly to epizonal phyllites and locally to mesozonal schists during the first main phase of the Hercynian orogeny. After the end of this phase first staurolite, than andalusite and cordierite started to crystallize. Formation of these minerals continued well into the second phase of deformation, but first staurolite then andalusite ceased crystallization whereas cordierite remained stable for some time after the second phase. After the end of formation of staurolite it became partially replaced by andalusite or cordierite. Biotite formed mainly at the same time as staurolite and also garnet probably dates from this time. During the third phase of deformation most of the crystallization had ceased (fig. 22).

Thus the metamorphic and structural history of the staurolite-andalusite-cordierite zone comprising rocks of Cambro-Ordovician, Silurian and Devonian age shows remarkable uniformity. The same sequence of events can be determined in the three stratigraphic units. Going downward from the upper Cambro-Ordovician schists into the andalusite-cordierite zone the history becomes more complex and is longer lasting.

The banded schists with N-S lineations near Les belong to the second and partly to the third zone. Under the microscope the banded character is quite clear with biotite- and muscovite rich bands alternating (fig. 24). The schistosity cuts obliquely through this banding and presumably the banding is the result of metamorphic segregation dating from the main phase at which time the schistosity will have been parallel to this banding. During the second phase the first schistosity was transposed to a new one due to folding about N-S axes whereby the old banding was preserved, but a new crosscutting schistosity imposed on the rocks. A new banding parallel to this schistosity may be produced (fig. 24). Folding of the old banding has been observed in several outcrops and is shown in fig. 3.

Staurolite, neither shimmer aggregates have been found near Les, but andalusite and cordierite are common.

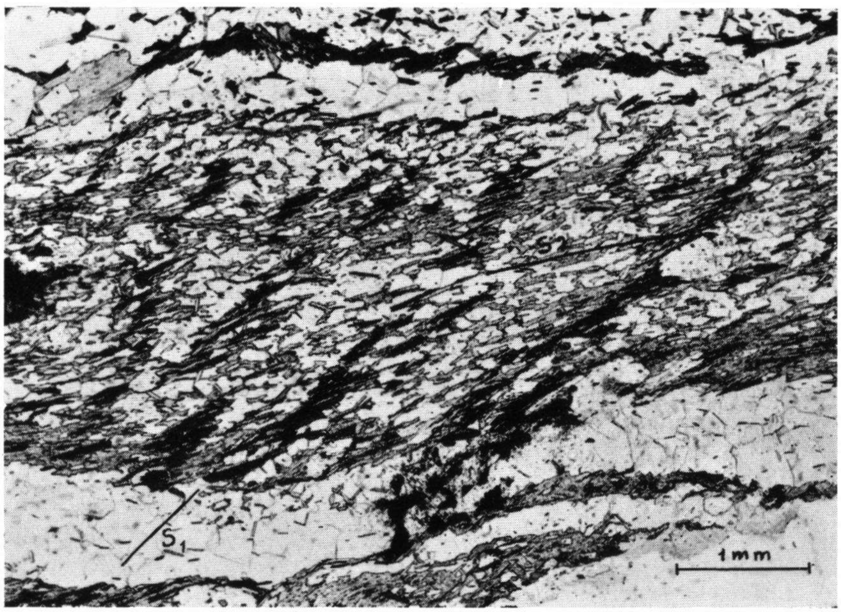

Fig. 24. Banded mica-schist near Lés; E-W section.

Most of these minerals postdate the second phase as demonstrated by the absence of rotation. Microfolds in N-S direction dating from the end of the second phase are included as helicitic folds in the cordierite and consequently these crystals are certainly younger than the second phase. Fibrolite mats have been found in a few of these banded schists.

3.323 *Andalusite-cordierite zone.* From the foregoing it is evident that the metamorphism in the Bosost area is independent of the stratigraphy and a similar metamorphic history is encountered in the upper portion of the Cambro-Ordovician, the Silurian and the Devonian. Below the described zone II an intermediate andalusite-cordierite zone III occurs, transitional to the lower zone IV. The first stages are similar to those of zone I and II and no appreciable differences have been found until the end of the second phase of deformation. In zone III the record of the early part of the metamorphic history is well preserved, contrary to zone IV where

Fig. 25. Staurolite remnants in cordierite (in cordierite-sillimanite zone).

Fig. 26. Partly muscovitized and rotated staurolite.

continuing crystallization has destroyed most of the evidence and the record of the first stages has only sporadically been retained. The andalusite-cordierite zone is characterized by the occurrence of many pegmatites and granites mostly as sills and small crosscutting bodies. The transition between the three zones is gradual and can only be mapped with the aid of a large number of thin sections.

Little has to be said about the matrix of the schists and many porphyroblasts of aluminium silicates and their relations to the groundmass, since these are fully comparable to those of the upper zone. Staurolite in this zone occurs also and its main difference with zone II are the instability of this mineral and the prolonged crystallization of andalusite and cordierite (fig. 22).

Staurolite which in zone II became locally unstable and was partially replaced by andalusite or cordierite, is definitely unstable in the andalusite-cordierite zone,

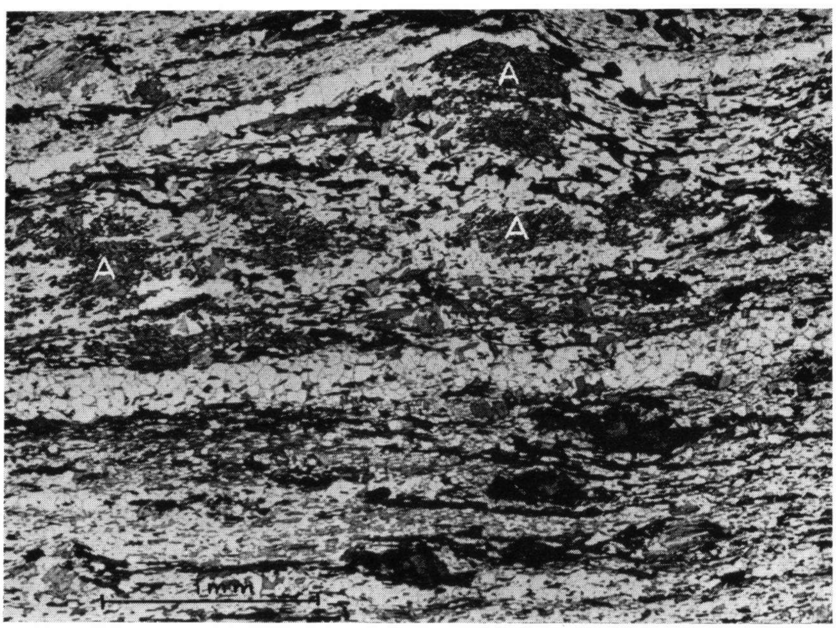

Fig. 27. Static andalusite; crystallization after second phase.

and is usually replaced by muscovite. This replacement is only partial and cores of staurolite always occur in the muscovite or muscovite-biotite aggregates. In some cases staurolite has been altered to andalusite or cordierite like in the upper zone. (fig. 25). The muscovitization always starts from the borders and gradually attacks the interior part of the crystals until only a small relic or even nothing at all is left. The muscovite and minor biotite forms a decussate intergrowth of several crystals with different orientations although there is a strong tendency to grow with the cleavages perpendicular to the border of the staurolite crystals (fig. 26). The muscovites are generally undeformed and consequently they are postkinematic with regard to the second phase. The rotation of the staurolite is often still visible in the shape and arrangement of the micas. This replacement process in the upper part of this zone is restricted to the outer fringes of the crystals and leaves most of the staurolite intact, whereas in the lower portion only small fragments of the older mineral are left. Although occasionally andalusite and cordierite are altered to muscovite, this process is much less common than the muscovitization of staurolite. When staurolite is surrounded by a rim of cordierite for instance, the first mineral may be almost completely muscovitized whereas the latter is unaltered. There is no doubt that the muscovitization is related to the emplacement of the granites and pegmatites both becoming more pronounced in the cordierite-sillimanite zone.

It is difficult to tell when the muscovitization began, but undoubtedly its main development falls rather late, after all deformation had come to an end.

Andalusite, besides showing similar characteristics as in the upper zone, has continued crystallization after the second phase of deformation. In thin sections this is illustrated by ill-bounded crystals which invade the groundmass of the schists more or less irregularly (fig. 27) or by long and thin crystals which apparently have

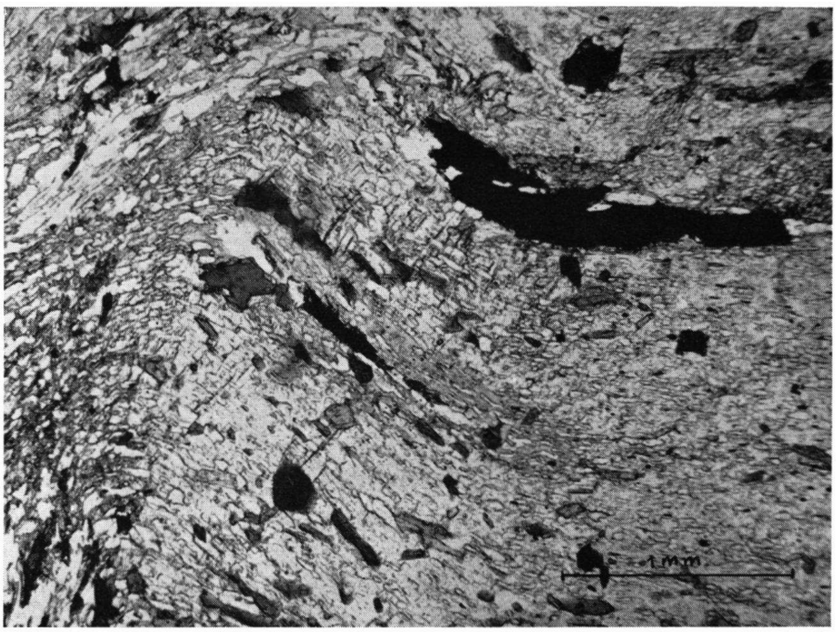

Fig. 28. Cordierite porphyroblast with steeper folds towards margin of crystal; folding of third phase.

grown mimetically in the schistosity. The schistosity outside the crystals is not or only very slightly curved and si is conformable with se, both often being planar. When the schists are folded due to the third phase of deformation andalusite is deformed in the fold hinges together with the enclosing schist indicating that this mineral is older than this phase of folding. Andalusite occurs also as rims around staurolite or muscovitized staurolite, but does not often replace it. Locally andalusite may be partially altered to muscovite. In one section an andalusite rim around a rotated staurolite contains the curved schistosity without itself being deformed. This andalusite apparently is later than this curving, hence later than phase II (fig. 22).

Cordierite occurs either as rounded or elongate crystals with planar si and rotated with regard to se, bowing out the schistosity and consequently dating from the interkinematic phase I or from the second phase, or, like part of the andalusites as static crystals which may be fairly large but have less clear boundaries than the earlier crystals. The schistosity is not disturbed by them nor are they rotated, and they postdate the second phase. Some of these cordierites are deformed by the NW third phase. Part of the cordierites developed even during or after this folding phase. Crystals which actually grew during the folding of the schistosity plane show the record of folding in the internal schistosity as helicitic folds which are steeper toward the rim of the crystal (fig. 28—29). Several of such cordierites have been observed in thin sections and in any case the inherited folds are folds in NW direction belonging to the third phase. Besides being contemporaneous to this phase some cordierites are distinctly later as evident from the occurrence of true helicitic folds. In such cases the cordierite itself is not deformed and has uniform extinction. Some crystals show the presence of a larger part of the described history. For example one cordierite contains a planar si in its central portion and helicitic folds at the tips of the crystal.

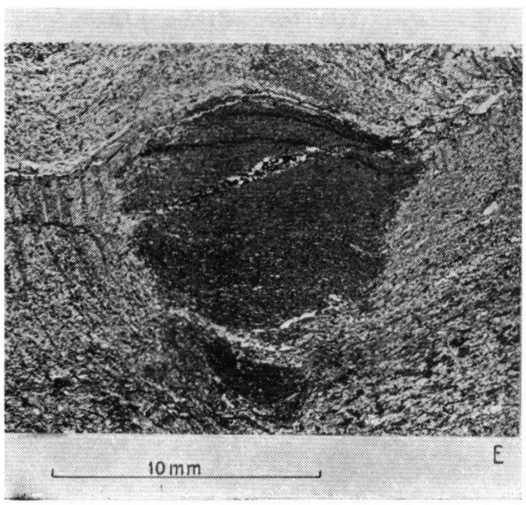

Fig. 29. Same as fig. 28.

Evidently this cordierite started to grow before the third phase and had another period of growth after it.

Special conditions arise when cordierite grows as a rim around staurolite. In some cases this rim consists of strongly deformed cordierite and the extinction of the crystal rotates at the same amount as the included schistosity is curved. Apparently cordierite and a staurolite crystal grew close together at a certain time. The less competent cordierite became deformed and curved around the more competent staurolite as a result of flattening and rotation during the second phase. In this case both crystals must predate the second phase. In other cases a cordierite rim occurs around staurolite whereby the si in cordierite shows strong curving although the cordierite itself does not show any sign of deformation. In this case staurolite is pre-, but cordierite post-kinematic with regard to the second phase. Both cases have been observed in one specimen (fig. 30—31).

When all this evidence is assembled, it appears that cordierite crystallized during a long time in the andalusite-cordierite zone. It started its development in the inter-

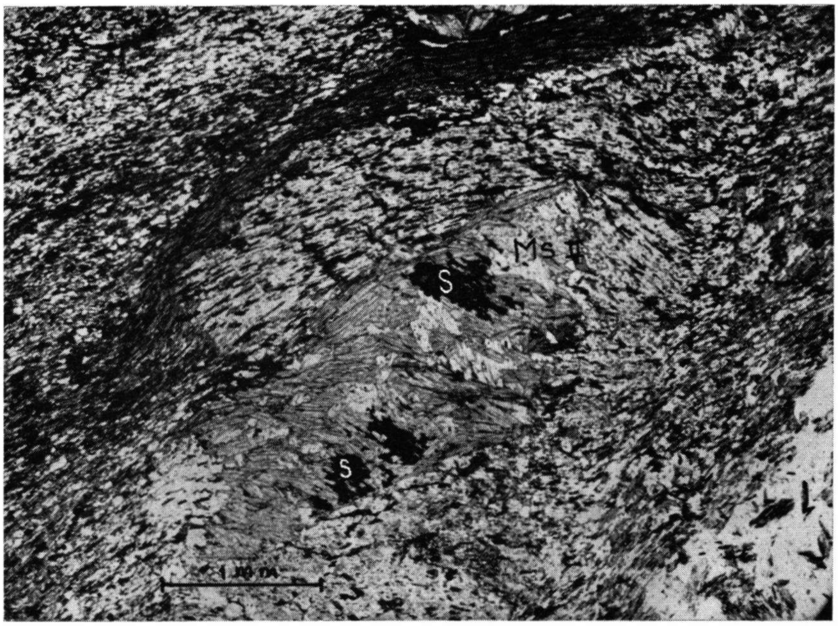

Fig. 30. Cordierite rim around muscovitized staurolite;

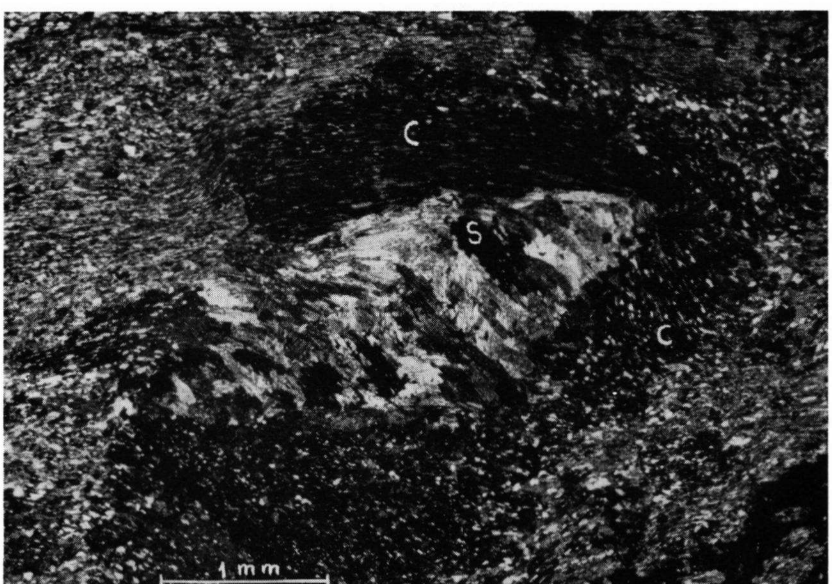

Fig. 31. Same as fig. 30 but with crossed nicols; cordierite has curved si but is undeformed; later than second phase.

val between first and second deformation, continued throughout second and third deformation and ended only after the end of the third phase. Relations with regard to the fourth E-W phase could not be established with certainty due to its erratic occurrence, but probably cordierite had ceased crystallization at that time.

Like cordierite, biotite has continued its crystallization in the intermediate zone through the second and partly through the third phase. Crosscutting crystals, not rotated in the existing schistosity are later than the second phase. Some folds of the third phase show deformed micas in the hinges, but recrystallized micas forming polygonal arcs have been observed rather frequently.

In the lower portion of the intermediate zone fibrolite occurs in some mica-schists. Usually it replaces biotite, but also grows in andalusite or cordierite. It occurs in schists with and without other aluminium-silicates. More details about these

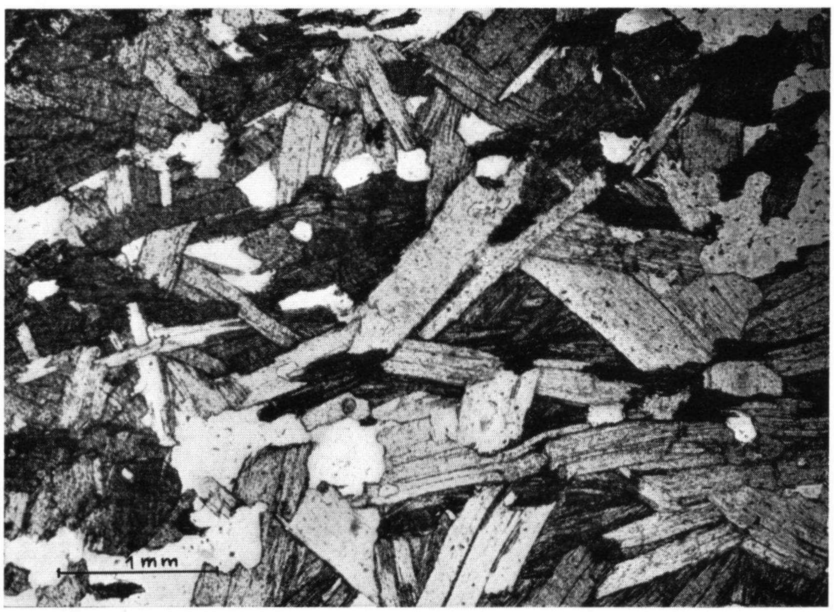

Fig. 32. Unoriented mica-schist from cordierite-sillimanite zone.

minerals will be given in the next part about the cordierite-sillimanite zone where it is of more importance.

The relationships between andalusite and cordierite on one hand and muscovite on the other indicate that the latter mineral is later than either of the two aluminium silicates. In fact it is the latest mineral to crystallize as based on observations in the cordierite-sillimanite zone (fig. 22).

3.324 *The cordierite-sillimanite zone.* This zone is characterized by the absence of staurolite and the abundant occurrence of sillimanite, mainly in its fibrous form. Further the fabric of the rock may be different from that of the higher zones and the record of the first phases has for a large part disappeared. The fabric of these schists is different in the fact that the schistosity although in most rocks still present, is less well developed mainly due to the growth of cross-cutting biotites and muscovites and the disappearance of the perfect orientation of most of the micas (fig. 32).

Although staurolite has only occasionally been found as small remnants in muscovite aggregates, it is assumed that it was as widespread in these schists as in those of the two higher zones, but it has been replaced almost completely by muscovite. In several specimens the occurrence of shimmer aggregates is suggestive of its previous presence.

Andalusite and cordierite are found in many of these rocks although less abundantly than in the upper and intermediate zone. Crystals which are rotated about N-S axes do occur, but rather exceptionally. Much of the andalusite and cordierite is later than the second phase of deformation and they replace the schist without mechanical disturbance. Both minerals occur also in rocks which show the effects of refolding in NW direction and like in the intermediate zone they may be deformed in these folds and predate this folding phase. On the other hand some cordierites

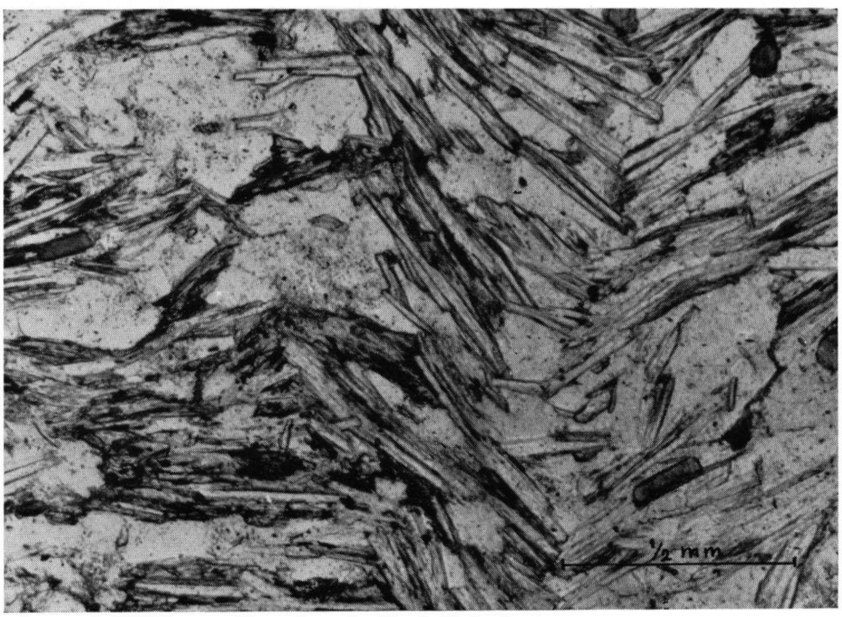

Fig. 33. E-W fold (fourth phase) with polygonal arcs of muscovite crystals (recrystallized fold)

showing the presence of helicitic folds of the third phase and fourth phase has crystallized later. No andalusite with well developed helicitic folds in E-W direction has been found and hence the crystallization of cordierite outlasts that of andalusite, like in the andalusite-cordierite zone. This relation is also ascertained by the replacement of andalusite by cordierite which has been witnessed in a few thin sections.

In the folds of the third phase micas are often bent in the hinges but polygonal arcs of micas have also been observed, indicating that crystallization lasted longer than folding. Polygonal arcs of micas occur also in folds belonging to the fourth E-W phase and crystallization must have continued until after the end of this phase (fig. 22, 33).

Both, andalusite and cordierite are sometimes partially replaced by coarse muscovite flakes in a similar fashion as the shimmer aggregates after staurolite but this process has seldom gone to completion. The decussate intergrowth and unde-

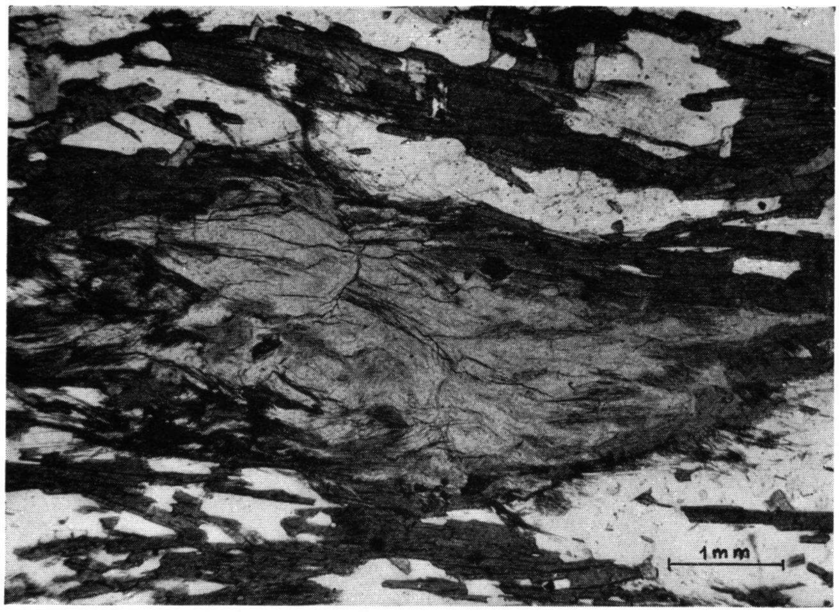

Fig. 34. Fibrolite mat in cordierite-sillimanite schist.

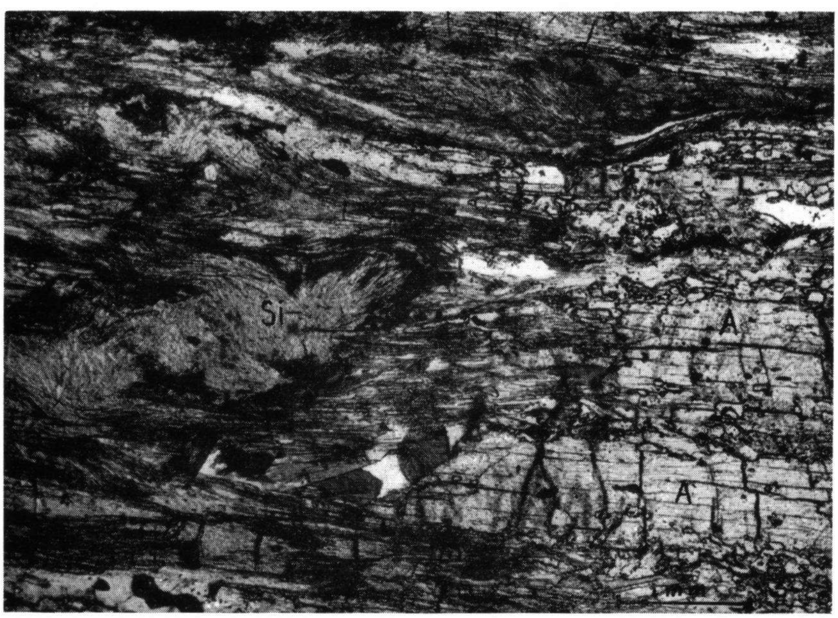

Fig. 35. Andalusite partially replaced by fibrolite.

formed nature of the muscovite indicate that this process took place under static circumstances.

Fibrolite which started to be present in the andalusite-cordierite zone is to be found in most of the schists of this zone. It occurs in schists which only carry quartz, biotite and muscovite as well as in schists with other aluminium-silicates. It forms bundles or mats lying in the schistosity and in many cases it has grown at the expense of biotite. The fibrolite mats are often considerably larger than the original biotite and apparently they have grown out in the neighbouring quartz. When it replaces linear biotite the fibrolite mats are also elongate, but this is undoubtedly due to mimetic crystallization and certainly is no proof of synkinematic origin (fig. 34). It also replaces late cross-cutting biotite. Although in a previous paper (1958) I stated that fibrolite does not replace any of the other aluminium-silicates, this cannot be considered to be correct since in several new thin sections it has been observed that fibrolite grows at the expense of cordierite and andalusite and partially replaces these minerals (fig 35). In some thin sections it has been observed that staurolite is replaced by andalusite, and at its turn andalusite in fibrolite, also staurolite-cordierite-fibrolite and andalusite-cordierite-fibrolite alterations have been noticed. This is in agreement with the general trend of the formation of the minerals, viz. staurolite-andalusite-cordierite-fibrolite, although their stability fields overlap. Sillimanite may replace cordierite or andalusite of different ages; it attacks rotated andalusite and cordierite belonging to early crystals as well as the same minerals postdating the second phase. This means that fibrolite could have started its formation rather early. Therefore the same criteria which have been applied for the other aluminium-silicates have to be used to determine the age of the fibrolite. Unfortunately this is less easy since no included schistosity is present in the fibrolite mats. It is evident, however, that fibrolite never partook in the rotation about N-S axes like the porphyroblasts of staurolite, andalusite, cordierite and biotite and hence it must be of later age than the second phase. In some thin sections it appeared that fibrolite is folded in NW-SE microfolds and further it may bow out the schistosity, clearly indicating that it had started to grow already before the third phase (fig. 35). Much of the fibrolite is not deformed nor does it disturb the schistosity and may be later than the third phase or even the fourth phase. In few cases fibrolite is deformed by the fourth phase. For these reasons the period of crystallization of fibrolite seems to start before the third phase, continues through this phase and does not end before all folding had ceased. If this is true then the formation of fibrolite overlaps that of andalusite for a very short time and that of cordierite for a longer time (see fig. 22). It is clear that the formation of fibrolite outlasts that of cordierite since the latter mineral may replace the former, but the reverse relation has never been observed. On its turn fibrolite may be replaced by muscovite and seems to be the last mineral in the whole sequence (fig. 22). In a few cases this late muscovite is deformed by the fourth E-W folding phase so that it can be assumed that this late muscovite started to develop before or during that phase. It certainly has continued crystallization throughout and after this phase. The main period of the late muscovitization probably lies after the fourth phase and could be considered as a separate fifth muscovite zone. Polygonal arcs of micas in microfolds belonging to this phase indicate that entirely postkinematic or static metamorphism was important in this region.

There is no doubt that the formation of both fibrolite and late muscovite is related to the emplacement of the granites and pegmatites and that metasomatic action has been of some importance during this time.

From the described relations between structures and the development of various minerals the following conclusions can be drawn. It appears that the metamorphic zones as described here have a complex history in the sense that every higher grade zone first passed through the preceding lower grade zones. The cordierite-sillimanite-zone for instance, has gone through the biotite-zone, the staurolite-andalusite-cordierite-zone and the andalusite-cordierite-zone. Since there is no doubt that the cordierite-sillimanite-zone is the highest grade one in the area the sequence shows a record of slowly rising temperature, resulting in the development a various mineral associations. The only indication of decreasing temperature can be seen in the late muscovitization, which apparently was accompanied by the introduction of water and probably some potassium. With increasing temperature the following mineral associations appear: biotite and muscovite; biotite and staurolite; biotite, staurolite, garnet, andalusite; biotite, staurolite, garnet, andalusite and cordierite; biotite, andalusite and cordierite; biotite, cordierite and sillimanite.

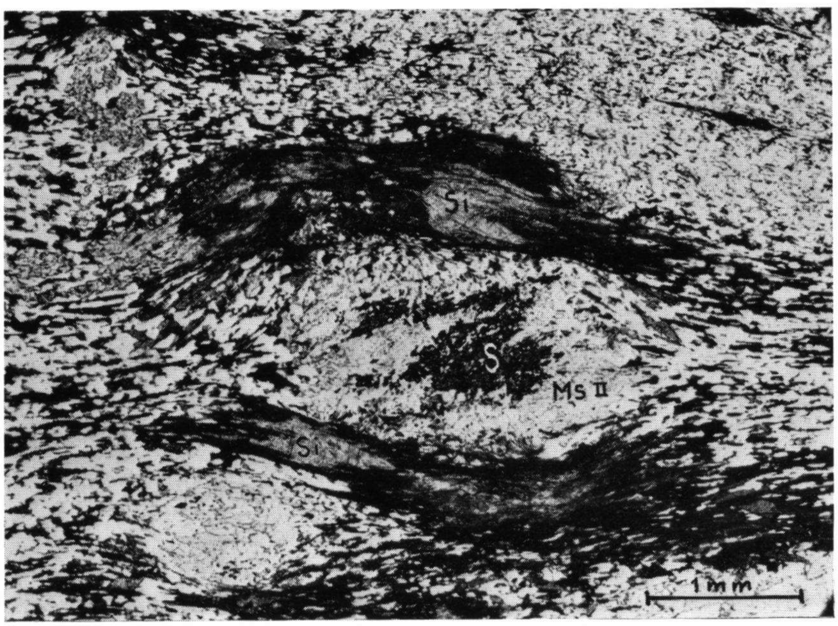

Fig. 36. Muscovitized staurolite with fibrolite borders.

From the diagram fig. 22 it is clear that andalusite and sillimanite have only a very short overlapping period of crystallization. This is in agreement with the phase diagram of kyanite, andalusite and sillimanite, since simultaneous crystallization of two of these minerals can only take place at the phase boundary lines which separate the stability fields of the three minerals. Hence with rising temperature first andalusite became stable, then passing the phase boundary both minerals crystallized together but with further increase in temperature andalusite became unstable and only sillimanite could crystallize.

A few remarks about this paragenesis seem in place here. It has been concluded by various authors (Miyashiro, Zwart) that this association is formed under conditions of low pressure. This is indeed in agreement with the situation in the Bosost area where the stratigraphic thickness of the beds above the biotite-zone reached a value of about 2000—2500 m. (1000 m. for the Dvonian and 1000—1500 m. for the

Carboniferous). For the staurolite-andalusite-cordierite-zone the tectonic thickness has to be calculated, since this metamorphism postdates the main Hercynian folding which was responsible for considerable tectonic thickening. For the top of the staurolite-zone one arrives at a figure of 3500—4000 m. corresponding to a confining pressure of 950—1100 bars. The temperature of the staurolite-andalusite-cordierite-zone can be estimated at 500—530° C (Winkler 1957). This gives a very steep geothermal gradient of about 15° C/100 m which is approximately 5 times larger than a normal continental gradient. From these relations it seems probable that in the described area the staurolite-andalusite-cordierite-paragenesis is the result of rising temperature after the biotite-zone had been installed. Apparently the stratigraphic thickness alone will have been too small to maintain sufficiently high temperatures for the formation of aluminium-silicates during the first tectonic phase. After thickening of the sequence by cleavage folding the temperature could rise enough to allow the crystallization of aluminium-silicates.

4. CALC-SILICATE ROCKS IN CAMBRO-ORDOVICIAN AND DEVONIAN

It is of some interest to discuss briefly the mineral associations in the calcareous rocks of the Lower Devonian and Upper Ordovician, mainly with regard to the metamorphic zoning. The Devonian rocks all belong to the staurolite-andalusite-cordierite-zone; the Ordovician ones partly to the cordierite-sillimanite-zone along the southern border of the Bosost area.

From the study of thin sections it appeared that these rocks do not contain such a clear record of their metamorphic history as the micaschists. This is mainly due to the absence of s-planes in these rocks which excludes a relation with the deformation phases. The occurrence of replacement features indicates, however, that succeeding mineral assemblages are present in these rocks.

In the Devonian the following minerals have been observed: calcite, diopside, zoisite, epidote-clinozoisite, tremolitic amphibole, biotite, quartz, potassium feldspar, sodic plagioclase (anorthite content not determined), sphene and muscovite. Epidote-clinozoisite often is secondary, but the other minerals probably belong to the primary paragenesis, which then will be contemporenaous with the staurolite-andalusite-cordierite metamorphism. Unfortunately no determinable plagioclase was found in these rocks. This would be of interest since it is known that plagioclase with relative high An-content is stable under relative low temperatures in areas with low pressure metamorphism. The occurrence of diopside, however, indicates conditions close to the amphibolite facies.

In the Ordovician limestone near La Bordeta in the cordierite-sillimanite-zone a distinctly higher grade assemblage has been found. Here the following minerals occur: grossularite, idocrase, diopside, bytownite, calcite and tremolite. Diopside and grossularite may be altered to clinozoisite or prehnite. This association clearly belongs to the amphibolite facies and formed simultaneous with the cordierite-sillimanite metamorphism in the schistose rocks.

5. GRANITES AND PEGMATITES

5.1 OCCURRENCE

Especially in the cordierite-sillimanite-zone granites and pegmatites are abundant, but they occur also in the staurolite- and andalusite-zones. Most of these rocks therefore are to be found in the Cambro-Ordovician, but along the southside of the

Bosost area where the metamorphic fronts have risen into the Silurian and Devonian, a few pegmatites occur as thin sills and boudins in these formations. Most pegmatites occur as sills or small discordant bodies in the mica-schists or as irregular patches and masses in the granites. The granites usually form larger bodies, the largest one being that on the eastside of the Garonne river between Lés and Bosost. They are muscovite- or muscovite-biotite-granites of intermediate grain size and usually completely unoriented. The pegmatites may show some orientation of muscovite flakes perpendicular to the walls. They are medium to coarse grained. Both, granites and pegmatites contain frequently smaller or larger inclusions or mica-schist. A detailed survey of one of these bodies has shown that neither these inclusions nor the neighbouring wall rock is influenced by these bodies, at least not in a structural sense (fig. 38, 39). This relationship has lead to the conclusion that many of these bodies are not intrusive but of replacement origin, which is in accordance with the fact that all these granites and pegmatites are limited as far as their occurrence is concerned, to rocks of a certain metamorphic grade, in this case the staurolite-andalusite-cordierite-zone

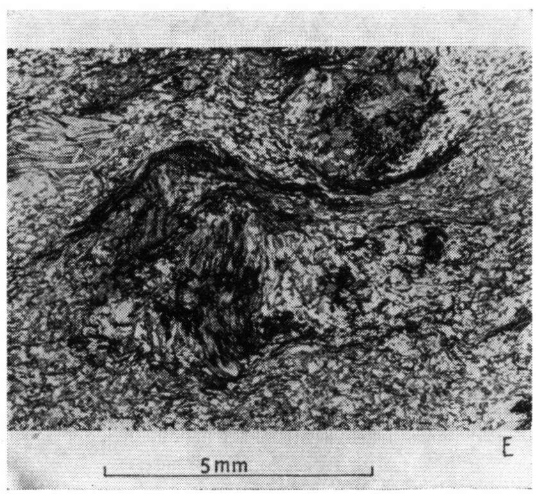

Fig. 37. Folded fibrolite mat.

or higher grade zones. Nowhere in the described area nor elsewhere in the Pyrenees similar muscovite-granites occur in lower grade rocks.

Their age can be determined with the aid of structural analysis of these rocks with regard to the folding phases. In the Bosost area no granites or pegmatites were emplaced during or before the main phase of the Herynian orogeny. This can be deduced from the fact that none of these rocks is folded, sheared or flattened by deformation belonging to this phase. A few pegmatite sills are, however, influenced by the, N-S, second phase, as shown, for instance, by boudins with N-S axis and folded pegmatites in the same direction. Pegmatites folded by the third NW-SE and the late E-W phase are rather common throughout the area. A good example is the Barrados pegmatite (fig. 10) which is folded by both phases. The relations between the larger granite bodies and the folding phases are less obvious. In general they are more or less concordant, but in detail many discordant contacts have been observed. This indicates that they are later than the first or second phase, as these would have imposed a schistosity on these rocks. Moreover many NW-SE folds are

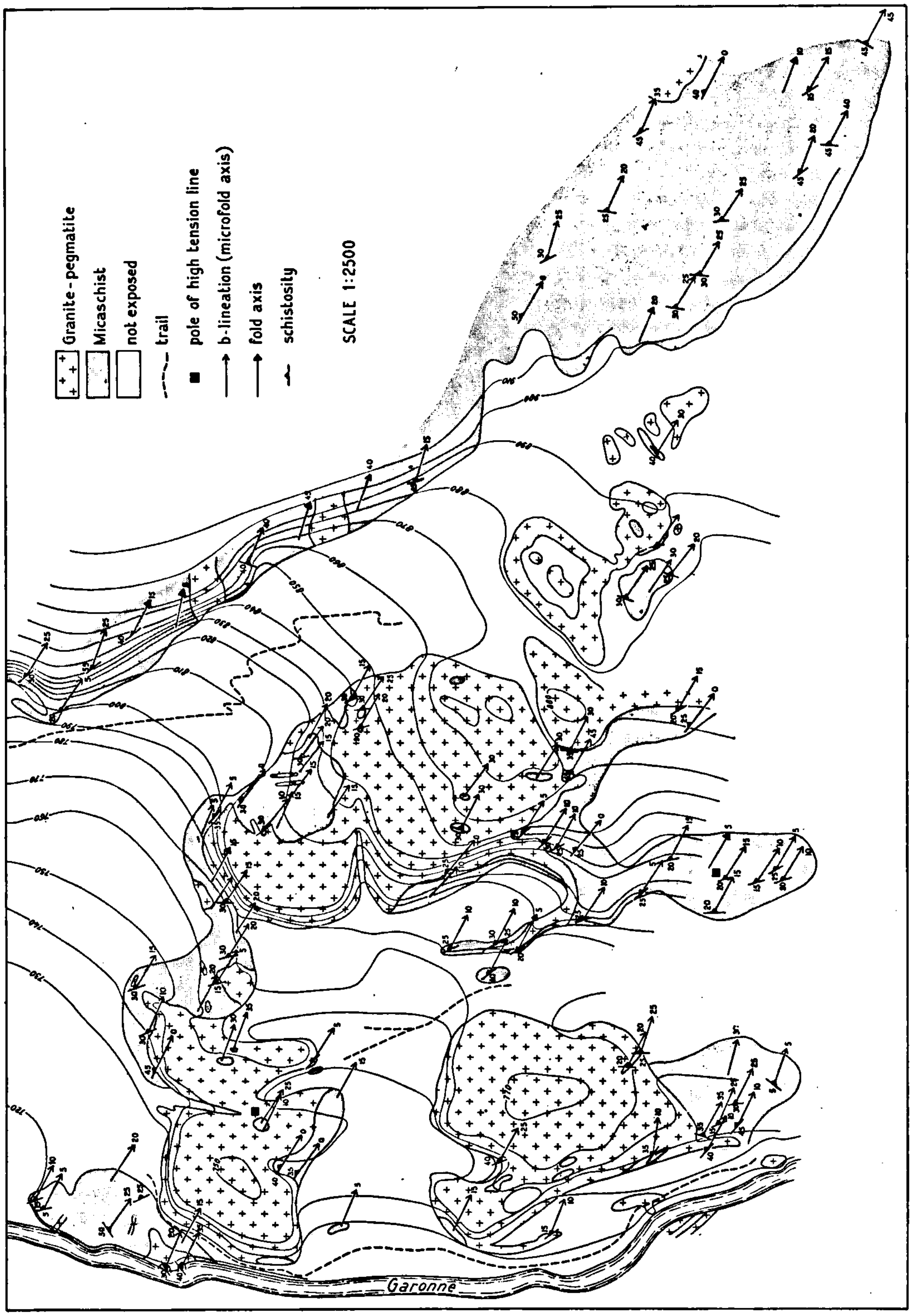

Fig. 38. Geological map of pegmatite in mica-schist south of Bosost; no disturbance of schists by the granite.

cut off by the granites so that at least they are in part younger than this phase. This is corroborated by the fact that schist inclusions in the granites often contain these folds. E-W folds are also cut off locally but included schists seldom contain folds in this direction (fig. 40). Consequently the main time of emplacement of the granites falls probably around and partly after the fourth E-W phase and is contemporaneous with the cordierite-sillimanite metamorphism and the culminating point of sillimanite crystallization. The whole period of granite and pegmatite emplacement seems to be rather long and extends from before the second phase until after the fourth, but with gradually increasing intensity. Although there is a clear connection between the granites and pegmatites and the higher grade metamorphism, it cannot be considered as a contact metamorphism, since the regional character of the metamorphism is evident for the whole of the Garonne dome and more especially the Bosost area where metamorphism in the biotite-zone started before any granites or pegmatites were emplaced.

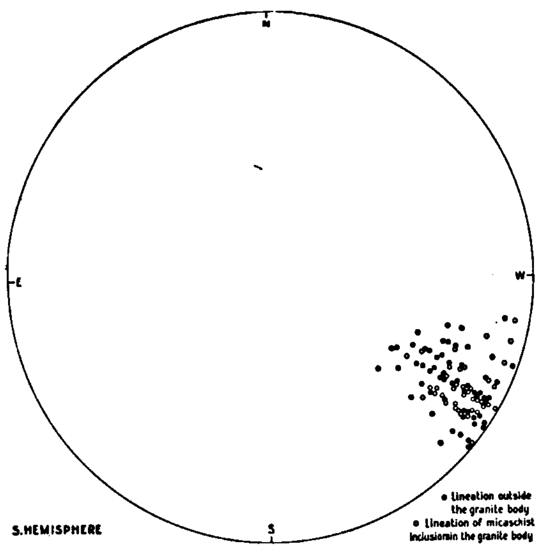

Fig. 39. Stereogram showing lineations and foldaxes in schist in area of fig. 38.

5.2 PETROGRAPHY

Most of the granites are medium to fine grained rocks and consist of quartz, albite, potassium feldspar and muscovite as main constituents. Some specimens also carry biotite. Accessories are apatite, sometimes garnet, fibrolite and zircon. In the finegrained varieties potassium feldspar is only a minor component, but in the coarser rocks which gradually change into pegmatites it is more important and may occur as large crystals. The finegrained rocks therefore tend to a trondjemitic composition. Most of the minerals are xenomorphic, but some albites tend to a hypidiomorphic shape. The structure of the rock is completely unoriented. Alteration of albite to sericite is rather common; biotite may be chloritzed. The pegmatites are often characterized by large (10—20 cm) potassium feldspar crystals which may show graphic intergrowth with quartz. Plumose mica, an intergrowth of muscovite and quartz may occur in these feldspar crystals and probably is a replacement product of it. In some pegmatites cordierite occurs as crystals of a size of 1 cm. Tourmaline is quite common and beryll has been found a few times. In the pegmatite sills the muscovite crystals near the contacts are often oriented perpendicular to the wall. In folded pegmatites typical fan-shaped muscovites occur in the hinges. The schists along the contacts with pegmatites are often strongly tourmalinized; this mineral occurs then as small crystals abundant in a zone of some cm. thickness.

6. PETROCHEMISTRY

The petrochemical work which was started on rocks of sheet 3 has been continued for the Bosost area and a few other localities in the surroundings. Analyses have been made from phyllites, mica-schists and muscovite-granites. They have been executed by Mrs. Dr. C. M. de Sitter-Koomans, except for the numbers 117, 118, 120, 198, 129 which were done by Miss H. M. I. Bik.

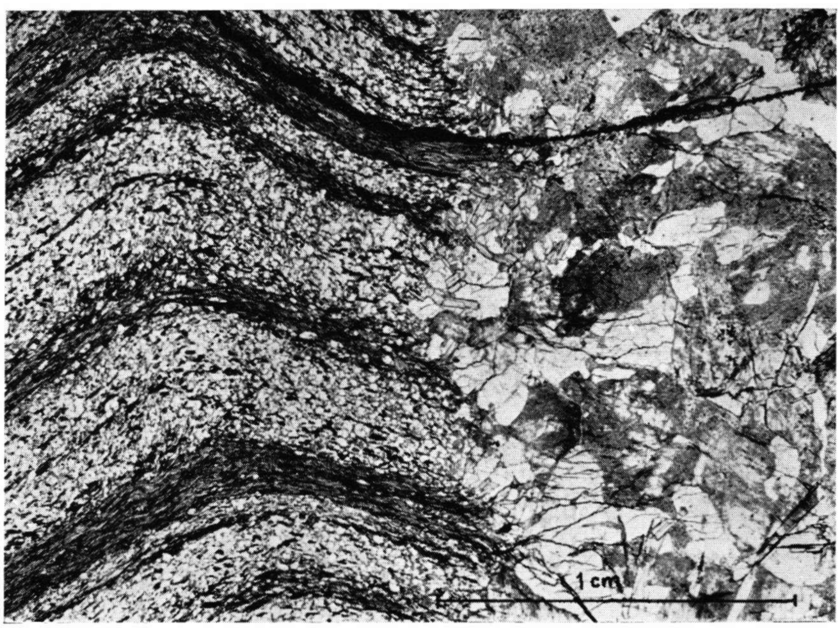

Fig. 40. Microfolds of fourth E-W phase, cut off by pegmatite dyke.

6.1 CAMBRO-ORDOVICIAN PHYLLITES

In order to know the composition of the rocks constituting the initial material for the metamorphics, five analyses (no. 102—106) of composite samples of Cambro-Ordovician phyllites have been made. Each of the samples is made of a mixture of ten specimens which have been collected at one locality, usually along a section of about hundred metres long. Two of these localities are in the Bosost area, viz. near Bosost itself on the east side of the Garonne river, and north of the village of Lés along the Garonne river. Two samples were collected near Esterri de Aneu situated on sheet 5 along the road from the Bonaigua pass to Esterri. The fifth locality is also on sheet 4 near the village of Alos in the upper Pallaresa valley.

The analyses are first given in the usual weight percentages and then in cation percentages, in the same way as the analyses of sheet 3 have been recalculated. In the diagrams also the cation percentages are shown.

These five analyses show certain differences as well as similarities (fig. 41, 42). Both analyses of the Bosost area (105, 106) are quite similar and show higher Si and lower Al percentages than the analyses of the Cambro-Ordovician farther east. This difference was already anticipated, since the phyllites in the Bosost area are somewhat more quartzitic than elsewhere in the Pyrenees. The Alos sample (102) has the lowest Si and the highest Al content; connected with these values are high potassium and low sodium percentages. Both analyses from Esterri show intermediate values. The variation of these five analyses is rather similar to those published from sheet 3 (Zwart, 1959). Also the average of these six analyses and of these five new ones are in almost every respect similar. The only considerable difference lies in the

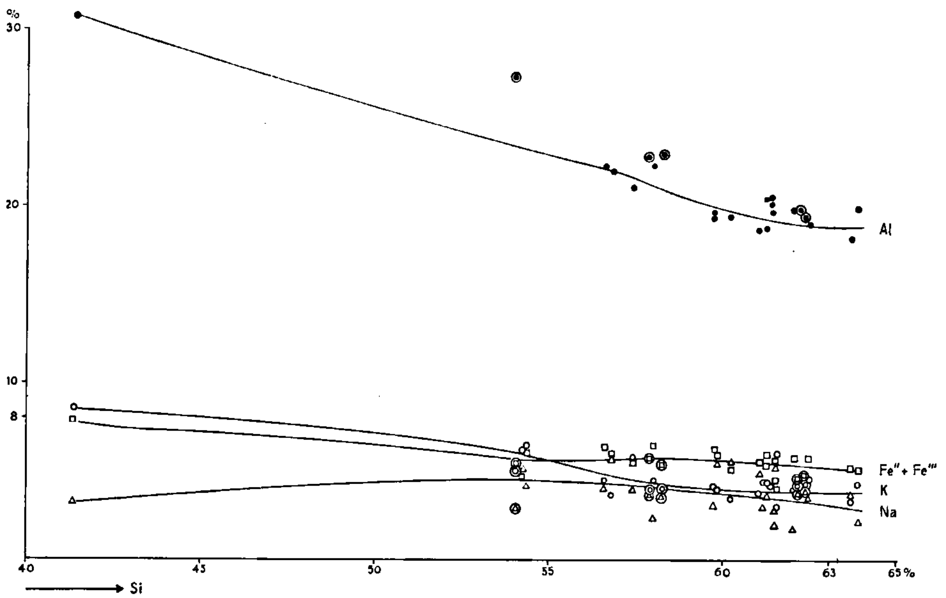

Fig. 41. Variation diagram of phyllites and mica-schists.
Dots are mica-schists; dots with circle phyllites.

magnesium content which is higher in the new analyses of the Bosost area. From these analyses it becomes clear that the composition of the average Cambro-Ordovician does not vary very much, although it has to be remarked that analyses of single specimens will show a larger variation than shown in the analyses of the composite samples. In any case, however, there are certain rules to which the variation in composition obey. There are mainly that low Si percentages are accompanied by low sodium and high aluminium and potassium percentages. The other elements show very little variation.

6.2 MICA-SCHISTS

Twenty analyses of single samples of mica-schists of the Bosost area have been executed (no. 107—126). These 20 specimens are from all zones of metamorphism higher than the chlorite-zone. Further one analyses of a composite sample of 20

TABLE 1 *Weight percentages*

	102	103	104	105	106	Average
SiO_2	55.24	58.95	59.42	63.95	63.45	60.20
TiO_2	1.19	1.09	0.82	0.98	0.87	0.99
P_2O_5	0.20	0.17	0.17	0.23	0.28	0.21
Al_2O_3	23.62	19.80	19.80	17.44	16.90	19.51
Fe_2O_3	2.58	2.81	3.41	1.72	0.92	2.28
FeO	4.22	4.38	3.63	4.14	4.95	4.26
MnO	0.04	0.04	0.06	0.02	0.05	0.04
MgO	2.36	2.48	2.72	2.30	1.75	2.32
CaO	0.78	0.98	0.74	1.23	1.52	1.05
Na_2O	1.55	2.09	1.92	1.95	2.30	1.96
K_2O	4.12	3.28	3.19	3.45	3.34	3.47
H_2O	4.30	4.08	4.02	2.89	3.50	3.75
	100.20	100.15	99.90	100.30	99.83	

Cation percentages

	102	103	104	105	106	Average
Si	54.0	57.8	58.3	62.1	62.3	58.9
Ti	0.9	0.8	0.6	0.7	0.6	0.7
P	0.2	0.2	0.2	0.2	0.2	0.2
Al	27.2	22.8	22.9	19.9	19.5	22.4
Fe‴	1.9	2.1	2.5	1.2	0.6	1.7
Fe″	3.5	3.6	3.0	3.3	4.1	3.5
Mg	3.5	3.6	4.0	3.4	2.5	3.4
Ca	0.8	1.0	0.8	1.3	1.6	1.1
Na	2.9	4.0	3.7	3.7	4.4	3.8
K	5.1	4.1	4.0	4.2	4.2	4.3
	100.0	100.0	100.0	100.0	100.0	100.0

Analyses 102—106: composite samples (each 10 specimens) of Cambro-Ordovician phyllites.
102 near Alos (Pallaresa valley)
103 near Esterri (Pallaresa valley)
104 near Esterri
105 near Lés (Bosost area)
106 near Bosost.

mica-schists has been made (no. 127). This latter analysis shows remarkable similarity to the two phyllite analyses of the Bosost area (105—106). The average of the 20 analyses shows somewhat lower Si percentage and again Na is lower and Al and K higher. Consequently the variations fall into the same category as the phyllites. In fig. 42 where the potassium versus the sodium content is shown, the phyllite

TABLE 2 *weight percentages*

	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	Average	127
SiO_2	43.42	57.05	56.80	58.65	58.60	60.25	59.98	62.10	61.43	62.98	63.85	62.15	63.65	62.95	63.50	64.60	63.35	64.52	65.45	65.45	61.04	64.15
TiO_2	1.47	0.74	1.04	0.77	0.99	0.97	1.05	0.97	0.84	0.89	1.00	0.95	0.87	0.83	1.10	0.80	0.99	0.94	0.92	0.84	0.95	0.93
P_2O_5	0.14	0.23	0.25	0.09	0.12	0.10	0.16	0.48	0.16	0.15	0.15	0.26	0.21	0.23	0.34	0.12	0.16	0.12	0.12	0.07	0.18	0.20
Al_2O_3	27.52	21.40	19.60	19.96	19.20	18.70	19.65	17.42	17.10	17.32	16.65	17.78	16.70	17.76	17.95	17.60	17.30	16.80	15.92	17.38	18.49	17.80
Fe_2O_3	7.46	1.18	1.05	3.32	3.88	2.33	2.72	2.04	2.72	3.28	3.10	2.94	2.17	3.15	2.44	2.07	4.23	3.23	2.56	2.87	2.94	1.14
FeO	3.40	4.98	6.79	4.98	4.11	5.12	5.75	6.28	4.84	3.58	4.25	4.10	5.54	4.23	3.52	3.62	3.39	3.32	4.31	3.89	4.50	4.55
MnO	0.07	0.04	0.04	0.07	0.05	—	0.05	tr.	0.04	0.04	0.04	0.01	0.03	tr.	tr.	tr.	0.05	0.04	0.05	0.04	0.34	0.02
MgO	4.25	2.23	2.34	2.88	2.24	2.88	2.93	2.95	1.90	2.54	2.48	2.38	3.33	2.77	2.58	2.48	3.45	2.44	2.70	1.85	2.68	2.32
CaO	1.09	1.82	2.16	0.61	1.60	0.93	0.63	1.18	1.74	1.65	1.50	0.74	0.66	0.52	1.16	1.18	0.68	1.05	0.94	1.05	1.14	1.31
Na_2O	1.74	2.84	2.32	2.32	3.01	2.15	1.28	1.70	2.91	3.00	2.68	1.63	1.85	1.55	1.00	2.94	0.85	1.90	1.95	1.12	2.04	1.92
K_2O	7.00	5.15	5.25	3.75	2.97	4.85	3.80	3.52	3.27	2.88	3.18	3.65	3.40	3.35	4.90	3.08	3.18	3.64	2.70	3.48	3.85	3.28
H_2O	2.45	2.63	2.54	2.80	3.15	1.68	2.08	1.66	2.49	1.76	1.13	2.54	1.68	1.84	2.00	1.81	2.38	2.12	2.14	1.83	2.14	2.11
	—	—	—	—	—	—	—	—	C = 0.12	—	S_2 = 0.49	C = 0.38										
	100.01	100.29	100.18	100.20	99.92	99.96	100.08	100.30	99.56	100.07	100.50	99.51	100.09	99.18	100.49	100.30	100.01	100.12	99.76	99.87		99.73
											—0 0.12											
											100.38											

TABLE 2 *Cation percentages*

	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	Average	127
Si	41.3	54.2	54.3	56.6	56.8	57.4	58.0	59.7	59.7	60.2	61.0	61.2	61.2	61,3	61.3	61.3	62.1	62.3	63.6	63.8	58.9	62.1
Ti	1.0	0.5	0.7	0.6	0.7	0.7	0.8	0.7	0.6	0.6	0.7	0.7	0.6	0.6	0.8	0.6	0.7	0.7	0.7	0.6	0.7	0.6
P	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.4	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Al	30.8	23.9	22.5	22.7	22.0	21.0	22.4	19.8	19.6	19.5	18.7	20.6	18.9	20.5	20.4	19.7	19.9	19.2	18.2	20.0	21.0	20.3
Fe‴	5.3	0.8	0.7	2.4	2.8	1.7	2.0	1.4	2.0	2.3	2.2	2.1	1.6	2.3	1.7	1.5	3.1	2.3	1.9	2.1	2.1	0.8
Fe″	2.7	4.0	5.4	4.0	3.3	4.1	4.7	5.1	3.9	2.9	3.4	3.4	4.4	3.5	2.8	2.9	2.8	2.7	3.5	3.2	3.6	3.7
Mg	6.0	3.2	3.3	4.1	3.2	4.1	4.2	4.2	2.7	3.6	3.5	3.5	4.7	4.0	3.7	3.5	5.0	3.5	3.9	2.7	3.8	3.3
Ca	1.1	1.8	2.2	0.6	1.7	1.0	0.7	1.2	1.8	1.7	1.5	0.7	0.7	0.5	1.2	1.2	0.7	1.1	1.0	1.1	1.2	1.3
Na	3.2	5.2	4.3	4.3	5.7	4.0	2.4	3.2	5.4	5.6	5.0	2.1	3.5	2.9	1.9	5.4	1.6	3.6	3.7	2.1	3.8	3.6
K	8.5	6.2	6.4	4.6	3.7	5.9	4.7	4.3	4.1	3.5	3.9	4.5	4.2	4.2	6.0	3.8	4.0	4.5	3.4	4.3	4.7	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	100.0	100.0	100.0	100.0	100.0

Analyses 107—126: Cambro-Ordovician mica-schists of Bosost area.
Mineralogical composition (without accessories):

107: quartz, biotite, muscovite, cordierite, sillimanite
108: quartz, biotite, muscovite, staurolite, cordierite, garnet.
109: quartz, biotite, muscovite, staurolite, andalusite, cordierite
110: quartz, biotite, muscovite, cordierite, andalusite
111: quartz, biotite, muscovite, andalusite, cordierite
112: quartz, biotite, muscovite, sillimanite
113: quartz, biotite, muscovite, oligoclase
114: quartz, biotite, muscovite, sillimanite
115: quartz, biotite, muscovite, cordierite, sillimanite
116: quartz, biotite, muscovite, sillimanite
117: quartz, biotite, muscovite, staurolite, cordierite, sillimanite
118: quartz, biotite, muscovite
119: quartz, biotite, muscovite, sillimanite
120: quartz, biotite, muscovite, andalusite, sillimanite
121: quartz, biotite, muscovite
122: quartz, biotite, muscovite, sillimanite
123: quartz, biotite, muscovite, cordierite, sillimanite
124: quartz, biotite, muscovite, cordierite, sillimanite
125: quartz, biotite, muscovite, cordierite, sillimanite
126: quartz, biotite, muscovite, andalusite, cordierite, sillimanite
127: composite sample of 20 mica-schists Bosost area.

field lies wholly within that of the mica-schists. With the exception of the first analysis 107 the variation of these schists again shows the same relations between Si, Al, K and Na percentages. The remaining elements show little variation throughout the whole series. Consequently it can be stated that during the transition of shale to phyllite and shale to mica-schist the changes in chemical composition are negligeable and apparently no introduction or removal of elements other than water, has accompanied the metamorphism.

This conclusion is different from that drawn for rocks of sheet 3. There it looked probable that some potassium and magnesium were introduced in the mica-schists

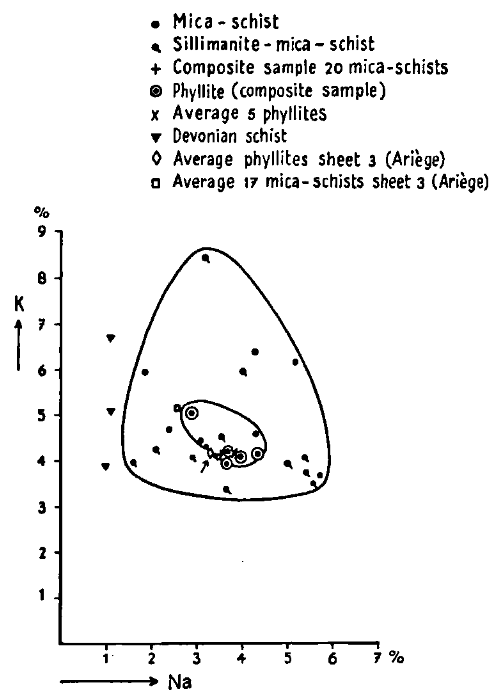

Fig. 42. Na-K diagram of phyllites and mica-schists.

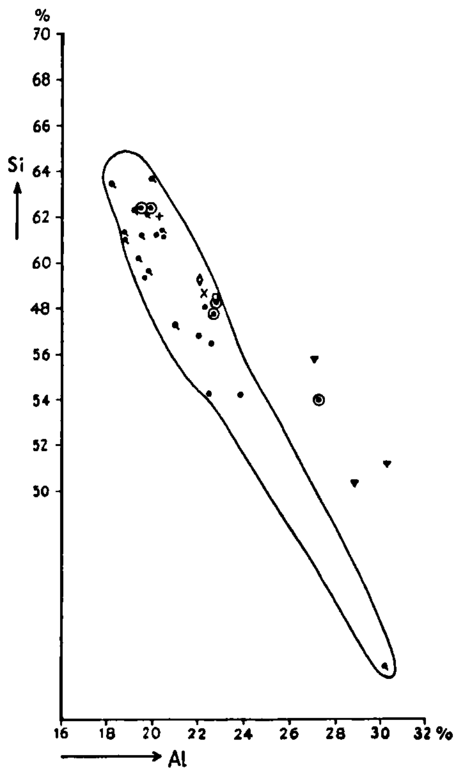

Fig. 43. Al-Si diagram of phyllites and mica-schists; (explanation of symbols see fig. 42)

if compared with the phyllites. It should be noted, however, that the schists of sheet 3 are in a different geological situation since these are underlain by migmatitic rocks in which certain, though small, chemical changes have taken place during their transformation from sediment to migmatite. These changes may have affected the mica-schists also. The mica-schists of the Bosost area contain many muscovite-granites but migmatites like those of the Ariège region are not exposed there with the exception of one small outcrop near Bosost.

When the mineralogical composition is compared with the chemical composition it becomes evident that sillimanite-schists generally show higher Si and lower Al percentages than schists without sillimanite but with other aluminium-silicates.

Exceptions to this rule exist, however; for instance analysis no. 107 with very low Si content carries sillimanite. In the Na-K diagram (fig. 42) also most sillimanite-schists show a certain position due to low sodium content, but this is quite logical since as we have seen, sodium percentages are linked to those of silicon. Furthermore some of the sillimanite-schists fall in the phyllite field and therefore it is doubtful whether this correlation between chemical and mineralogical composition has any significance

Besides the Cambro-Ordovician rocks, three Devonian specimens have been analysed (no. 218—130). Two of those are staurolite-schists; the third is a slate. All three analyses show a rather low Si percentage and consequently high Al and K percentages. Contrasted to Cambro-Ordocivian schists and phyllites of similar

TABLE 3

	weight percentages			*cation percentages*		
	128	129	130	128	129	130
SiO_2	52.03	51.20	57.90	50.8	51.2	55.9
TiO_2	1.06	1.08	1.47	0.7	0.7	1.1
P_2O_5	0.26	0.24	—	0.2	0.2	—
Al_2O_3	25.37	25.67	23.70	29.2	30.3	27.0
Fe_2O_3	3.27	3.77	5.76	2.4	2.8	4.2
FeO	5.94	5.06	—	4.8	4.2	—
MnO	0.08	0.04	—	3.9	2.9	2.4
MgO	2.67	1.96	1.64	3.1	1.5	1.6
CaO	2.96	1.40	1.51	1.0	1.1	1.1
Na_2O	0.53	0.60	0.60	3.9	5.1	6.7
K_2O	3.15	4.00	5.42			
H_2O	2.45	4.74	n.d.	100.0	100.0	100.0
			C= 0.24			
	99.77	99.76	98.24			

Analyses 128—130: Devonian schists and slate of Bosost area.
128: schist with quartz, muscovite, staurolite
129: schist with quartz, muscovite, staurolite
130: slate with mainly sericite.

composition, the Devonian rocks show a remarkable low sodium content with even higher aluminium percentages. Therefore they fall outside the field of the Cambro-Ordovician rocks in the diagrams (fig. 42, 43). Consequently they are a different kind of sediment and possibly the result of more mature chemical weathering.

6.3 THE GRANITES

Six analyses of muscovite-granites have been executed. These analyses (no. 131—136) show little variation in composition, although it is not inconceivable that pegmatites would have a different composition. These have not been analysed due to their large grainsize. Since the microscopic examination proved that pegmatites

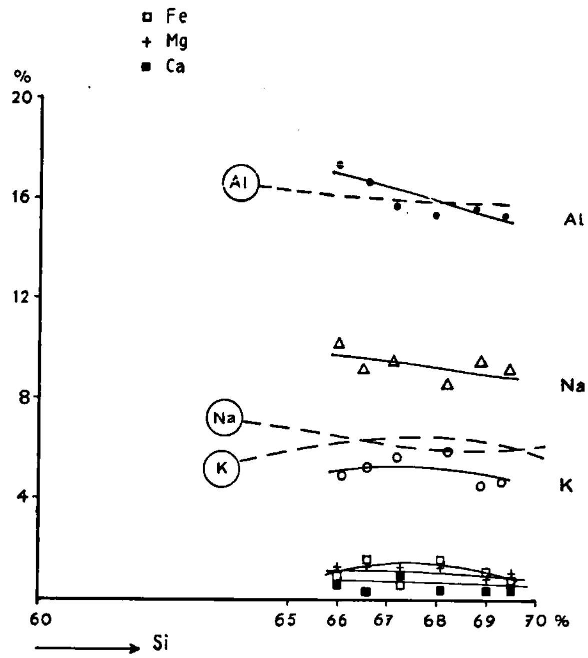

Fig. 44. Variation diagram of muscovite-granites; dashed lines represent data of sheet 3 Ariege.

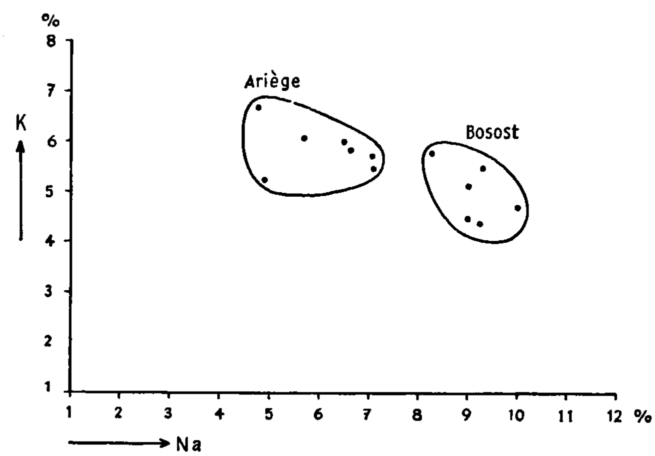

Fig. 45. Na-K diagram of Muscovite-granites Bosost area and Ariege (sheet 3)

are richer in microcline, it is probable that they are richer in potassium and poorer in sodium.

Except for Si, Al, Na and K all elements show low percentages (fig. 44). Sodium predominates over potassium, in the mineralogical composition resulting in high albite and low potassium feldspar contents. If indeed these rocks are produced by replacement of mica-schists, fairly large changes in chemical composition are in-

TABLE 4 *weight percentages*

	131	132	133	134	135	136	Average
SiO_2	71.50	71.82	73.00	73.05	74.62	74.40	73.06
TiO_2	tr.	tr.	tr.	tr.	tr.	tr.	—
P_2O_5	0.27	0.13	0.13	0.14	0.15	0.25	0.17
Al_2O_3	14.99	15.90	14.30	13.88	13.80	14.24	14.51
Fe_2O_3	0.87	0.54	0.40	1.31	0.48	0.53	0.68
FeO	1.09	0.46	0.07	0.53	0.32	0.65	0.52
MnO	—	—	—	—	—	—	—
MgO	0.18	0.24	0.64	0.17	0.21	0.14	0.26
CaO	1.13	0.83	1.14	0.98	0.80	0.63	0.91
Na_2O	5.02	5.60	5.18	4.58	5.00	5.11	5.08
K_2O	4.38	3.98	4.68	4.92	3.82	3.75	4.25
H_2O	0.67	0.59	0.45	0.78	0.89	0.63	0.66
	100.10	100.09	99.99	100.34	100.09	100.33	

Cation percentages

	130	131	132	133	134	135	Average
Si	66.5	66.1	67.2	68.1	69.5	69.0	67.7
Ti	—	—	—	—	—	—	—
P	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Al	16.4	17.2	15.5	15.2	15.2	15.5	15.9
Fe'''	0.6	0.4	0.3	0.9	0.3	0.4	0.5
Fe''	0.8	0.4	0.1	0.4	0.3	0.5	0.4
Mg	0.2	0.3	0.9	0.2	0.3	0.2	0.4
Ca	1.1	0.8	1.1	1.0	0.8	0.6	0.9
Na	9.0	10.0	9.3	8.3	9.0	9.2	9.1
K	5.2	4.7	5.5	5.8	4.5	4.4	5.0
	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Analyses 131—136: Granites from Bosost area.
All rocks contain quartz, albite, muscovite.

volved. Silicon and sodium should have to be introduced and Al, Fe, Mg, Ca and Ti would be expelled. The destination of these removed elements remains uncertain. That aluminium would be fixed in neighbouring schists, like previously supposed, seems unlikely in view of the composition of the sillimanite-schists. Also the composition of the schists is so similar to that of the phyllites, that it is excluded that large scale changes in chemical composition have taken place during metamorphism.

With regard to the muscovite-granites from sheet 3 (Ariège) the Valle de Aran rocks are different by their high sodium content and low potassium percentage. For the rest they are quite similar (fig. 45).

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