LEIDSE GEOLOGISCHE MEDEDELINGEN, deel 33, blz. 191-254, separate published 1-11-1965

GEOLOGICAL MAP OF THE PALEOZOIC OF THE CENTRAL PYRENEES

SHEET 6, ASTON, FRANCE, ANDORRA, SPAIN.
1 : 50.000

Published by the Geological Institute, Leiden University
edited by L. U. de Sitter and H. J. Zwart

EXPLANATORY TEXT

BY

H. J. ZWART

(With one coloured geological map 1 : 50.000, plate I and six coloured sections, plate II)

ABSTRACT

The geology of the map sheet 6, Aston, is described. The stratigraphic sequence consists of Paleozoic rocks from Cambro-Ordovician to Carboniferous age and some Cretaceous rocks along the northern border of the axial zone. The lower part of the Cambro-Ordovician is strongly metamorphosed and consists of micaschists, migmatites and granites. A leucocratic augengneiss, probably an orthogneiss, forms the core of the Aston-Hospitalet massif. Two intrusive granites occur in the Paleozoic rocks. Two types of major structures are distinguished, the metamorphic infrastructure and the non-metamorphic suprastructure. Several phases of deformation, all belonging to the Hercynian orogeny have been recognized. The relationships of the metamorphism to these deformation phases and the metamorphic events of the orthogneisses are described.

CONTENTS

1. INTRODUCTION

After publishing the 1 : 50.000 maps no. 1—5 (1959—1962), the geology of sheet 6 is described in this explanatory text. This sheet proved to be one of the most interesting, firstly because it contains a complete stratigraphic succession of the Paleozoic and secondly because of the presence of one of the large gneiss anticlines of the axial zone of the Pyrenees.

Although reconnaissance excursions were made earlier, systematic mapping started in the summer of 1956 and most of the mapping was finished in 1960. The map is largely the effort of J. F. Lapré, G. Verspyck and the author and for this reason a good coordination of the assembled data was possible. The results of the work of Lapré and Verspyck appear as separate publications in this issue of the L.G.M. In a previous paper by J. H. Allaart (1953) the stratigraphy and structure of the northern sedimentary border of the Aston massif was described.

At about the same time as our survey, the Aston massif was mapped by Professor E. Raguin and J. P. Destombes from Paris. Disregarding a few minor details their map closely resembles ours, but as far as the interpretation of the gneisses is concerned, different opinions exist. Our map is a lithologic one and whatever its interpretation, we think that the presentation of the field data will remain valid on this scale.

Mapping was mostly done with the aid of aerial photographs, but the map is drawn for its largest portion from the preliminary 1 : 20.000 maps of the French topographical survey, and for the remainder from the rather inaccurate 1 : 50.000 map of Andorra.

Almost the whole of sheet 6 is a part of the axial zone, only some Cretaceous rocks with small parts of the Saint-Barthélemy and Trois Seigneurs massif on this map do not belong to it. These rocks have been dealt with in the explanatory text of sheet 3 (1959).

The following large units can be distinguished:

1. the sedimentary zone north of the Aston massif
2. the sedimentary zone south and west of the Hospitalet massif
3. the regional metamorphic Aston-Hospitalet massif
4. the two granodiorites of Auzat and Andorra.

2. STRATIGRAPHY

2.1 METAMORPHIC CAMBRO-ORDOVICIAN

The oldest sediments in the area belong to the Cambro-Ordovician of which the deepest exposed parts are strongly metamorphosed. The highest grade metamorphics occur in the migmatite-quartz-diorite series, exposed north of the Mérens fault in the Aston massif. They underlie a series of leucocratic gneisses and granites, and they can be followed all the way from Mérens in the Ariège valley to the Siguer valley in the western part of this massif. Like the migmatites of sheet 1, 2 and 3, these rocks were produced by high grade metamorphism of the mainly pelitic sediments of presumably Cambro-Ordovician age. Two rocktypes prevail in this series:

1. migmatites or sillimanite-gneisses, rather heterogeneous rocks in which the schistose part is still preponderant
2. more homogeneous quartz-dioritic rocks which are derived from the migmatites by continued recrystallization, mobilization and homogenization.

In general the quartz-diorites form a deeper zone, as the leucocratic gneisses are always underlain by the migmatitic rocks. In this series, especially near Etang Blaou, but also at other places along the Mérens fault, marbles and amphibolites occur frequently and this zone has to be considered as a stratigraphic unit. Destombes and Raguin (1960) correlate these marbles and amphibolites with the Canaveilles formation which has been described by Cavet (1958) from the eastern Pyrenees. This formation occurs rather deep in the Ordovician and is considered to be of Cambrian age, although paleontological evidence is lacking. In the eastern Pyrenees this formation contains volcanic rocks and it is quite probable that the amphibolites of Etang Blaou are metavolcanics. The volcanic agglomerates which have been described by Raguin from this locality are in my opinion formed by metamorphic processes and do not really prove the volcanic origin of these rocks. Nevertheless the attribution of these rocks to the Canaveilles formation seems justified and they belong undoubtedly to the deepest exposed rocks on sheet 6. Farther east the marbles and amphibolites are probably cut off by the Mérens fault, although the occurrence of the Canaveilles formation has been mentioned from near the village of Mérens by Destombes and Raguin (1960). According to these authors it concerns again metavolcanics (gneiss granulé), which, however, to our opinion are strongly sheared gneisses and migmatites occurring in the mylonite zone of the Mérens fault, and which consequently have no stratigraphic significance.

Towards the west the migmatites grade into micaschists which occupy the valleys of Artiès and Mounicou. These schists are often andalusite- and cordierite-bearing and some of the largest crystals may attain lengths of more than 50 cm. They are mostly at random oriented in the schistosity plane (fig. 4). Small and a few large bodies of muscovite-granite and sills of pegmatite occur at many places in the andalusite-schists especially in the Mounicou valley.

The migmatites of the Aston massif are overlain by a several thousand metres thick sheet of leucocratic gneisses and granites which on their turn are overlain by micaschists forming the northern border of the Aston massif. This gneiss unit covering many square miles of the Aston massif is from a mineralogical and chemical point of view quite homogeneous, but structurally it is a strongly heterogeneous. Several kinds of gneisses as augengneisses, flasergneisses, granitic gneisses with small and large bodies of muscovite-granite occur in this unit. In the westernmost outcrops these gneisses have a rather granitic and regular appearance, but towards the east they become flasergneisses with a more irregular habit and farther north and east these flasergneisses grade into irregular augengneisses which usually are strongly mobilized. The boundaries of these gneisses with migmatites below and micaschists above are without exception sharp.

The gneisses in the Hospitalet massif are structurally less heterogeneous; they are augengneisses comparable to the Aston augengneisses but more regular and not mobilized. They are also overlain by micaschists, but the lower contact is nowhere exposed. The contact with the micachists is also sharp. The Aston and Hospitalet gneisses are probably orthogneisses, derived from an intrusive granite, whose age is unknown.

On the northern side of the Aston gneisses a small zone of micaschists occurs which is followed by phyllites and near the village of Aston by Silurian black slates. Hence the micaschists and phyllites belong to the Cambro-Ordovician and are underlain by the gneisses. The contacts as well as the schistosity are rather steep all along the northern border of the Aston massif, contrasted with the gentle dipping schistosity elsewhere in the Aston and Hospitalet massif.

The gneisses of the Hospitalet massif are overlain by micaschists, occurring north of the gneiss anticline near Mérens, on top of it near the Port de Fontargent and south of it from Hospitalet to the Coll de la Mina. In these schists the absence of pegmatites or granites distinguishes them from those of the Aston massif. Staurolite, andalusite and cordierite occur in great quantities in these schists. They are for a large part the stratigraphic equivalent of the Cambro-Ordovician farther west and will be treated below.

2.2 CAMBRO-ORDOVICIAN

The Cambro-Ordovician in its non-metamorphic or low grade state consists mainly of pelitic rocks with intercalated quartzites, microconglomerates and limestones.

2.2.1 *Aston massif*

In the Aston massif the upper part of the Cambro-Ordovician consists of dark coloured slates with a few limestone bands in which badly preserved fossils (Brachiopods) have been found (Destombes 1952). This horizon is correlated with the Caradocian which elsewhere in the Pyrenees is well dated and represents the oldest paleontologically dated formation. South of the Auzat granodiorite in the Vicdessos valley the following section has been recorded from north to south (Allaart, 1953):

1. dolomitic marble with quartzite and hornfels layers, in contact with the granodiorite, 30—100 m.
2. black and dark coloured slates and hornfelses with some limy intercalations, 500 m.
3. hornfels with some limestone bands, 200 m.
4. limestone and marble in layers up to 10 m thick with a few thin graphite schist bands, alternating with slate and hornfels beds, 40—100 m.

Farther east the northern limestone layer disappears, whereas the southern one approaches the Silurian near the Pic de Lercoul and disappears also. In the Siguer valley and near Luzenac a few limestone intercalations may belong to the same horizon. South of Castelet banded epidote-clinozoisite-hornblende schists and hornfelses occur in the micaschists of the Aston massif. They resemble strongly the "gneiss à silicates de chaux" described by the author from the St. Barthélemy massif (1954), which also underlie the Silurian at a short distance. These rocks are derived from limy sediments and transformed by the regional metamorphism; the difference is mainly due to the composition of the original sediment.

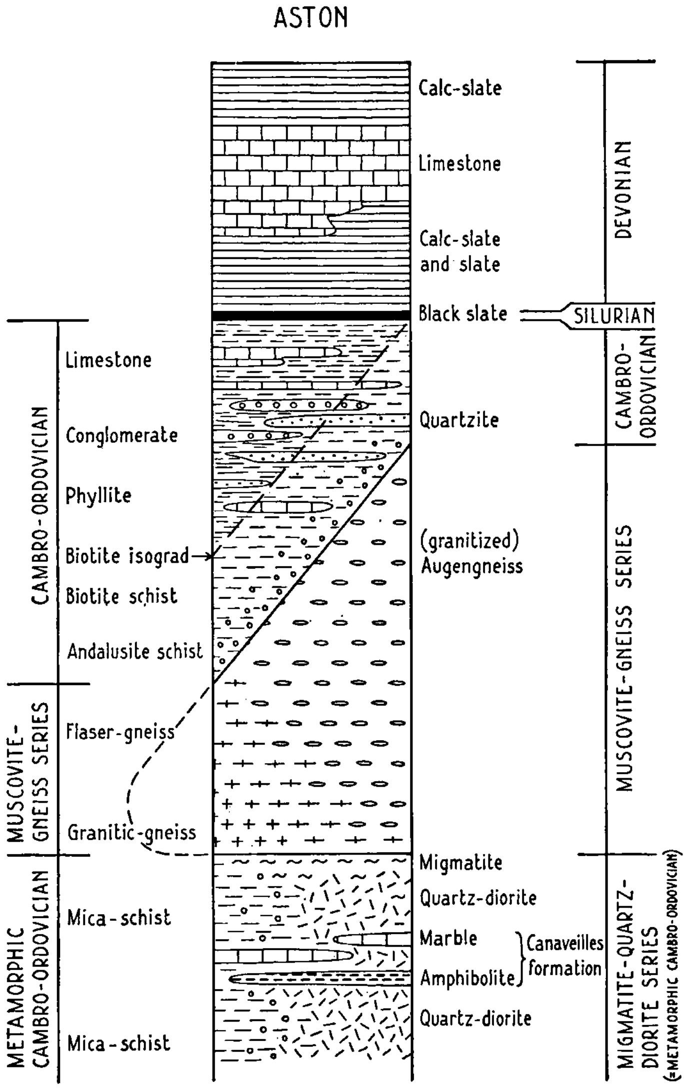

Fig. 1. Stratigraphic column of the Paleozoic of the Aston massif

South of the Auzat granodiorite a large area is covered by Cambro-Ordovician sediments. Underneath the Caradocian limestone a series of dark coloured slates and phyllites with many quartzite and microconglomerate layers is exposed. These conglomerates have already been described by Caralp (1888) and more recently

Destombes (1950) suggested that these conglomerates form the boundary of the Ordovician with the Cambrian. Since, however, discontinuous microconglomerate layers occur at many localities, there is no reason to assign them to a special stratigraphic level and they do not represent an unconformity or even an important break in the sedimentation. As shown on the map individual conglomerate beds cross the epi-mesozonal boundary, a clear indication that metamorphic fronts and stratigraphy do not coincide. Nowhere these conglomerates can be seen to enter the leucocratic gneisses.

It is quite probable that the boundary of the gneisses with the micaschists also cuts across the stratigraphy, since in the northern part of the Aston massif the boundary lies close to the Silurian but gradually retires from it to the east and west (fig. 1).

In the western part of the massif the upper part of the Cambro-Ordovician, rich in quartzites and microconglomerates is underlain by a series of micaschists, which is decidedly poorer in siliceous sediments, although a sharp boundary is nowhere to draw. Most of these pelitic sediments occur as micaschists. In this formation occur the metamorphic limestones and basic rocks which may belong to the Canaveilles formation (fig. 1).

2.2.2 *Hospitalet massif*

The Cambro-Ordovician of the Hospitalet massif is in several respects similar to that of the Aston massif, but it contains a particular horizon that can be followed over a large distance. Again the Cambro-Ordovician consists mainly of pelitic rocks with some intercalated quartzites and limestones. The lower part is metamorphosed to micaschists which overlie leucocratic gneisses (fig. 2).

Only in the western part of this sheet a normal, conformable sequence of Silurian and Cambro-Ordovician exists. North of the Tor syncline the Silurian black slates are underlain by a thin layer of dark coloured slates. East of the Arinsal valley a blue quartzite of 100—200 m thickness is exposed. To the east and west this layer can no longer be followed although thin quartzite beds occur frequently near the top of the Ordovician. Underneath the quartzite a discontinuous horizon of grey or greyish-blue bedded limestone, varying in thickness from a few metres up to several tens of metres is found. Although no fossils have been found, the situation close to the Silurian warrants its Caradocian age and its correlation with the limestones on the north side of the Aston massif. The limestone is immediately underlain by a conglomerate which to the east is interrupted and only locally present. Near the village of Tor the pebbles of this conglomerate are very large, up to 40 cm diameter. The thickness of the conglomerate layer is 20—40 m and it has a few intercalations of slate. The pebbles are flattened and occur in a cleaved matrix. Most pebbles consist of vein quartz or quartzite. The conglomerate is underlain by a series of grey and dark coloured slates, phyllites and quartz-phyllites with a characteristic black slate horizon near the Pic de Bayau. This horizon forms an anticline, the Valpeguera anticline; north of this structure the grey slates and phyllites with one conglomerate bed are again exposed. Near the frontier with Andorra at the Pic de Cataperdis the black slate horizon reappears and here it is accompanied by discontinuous limestone layers and a few rather thick quartzite beds. These rocks occur in an anticlinal structure, which to all probability is the continuation of the Hospitalet anticline to the east, and of the Lladorre anticline to the west (Zandvliet 1960). The black slates and limestones are probably to be correlated with the black slates of the Pic de Bayau and consequently still belong to the upper part of the Cambro-Ordovician.

The limestones, black slates and quartzites of the Pic de Cataperdis can uninterruptedly be followed to the east, where they bend around the large Silurian outcrop of Llorts. The quartzite beds grow in importance and east of the Valira del Norte a massive, white quartzite layer of several hundred metres thickness can be mapped to north of Ransol. Here this horizon is underlain by a black slate-limestone horizon which also is continuous from El Serrat to Ransol. The thick quartzite, the black slate and the limestone form an easily recognizable group of marker beds in

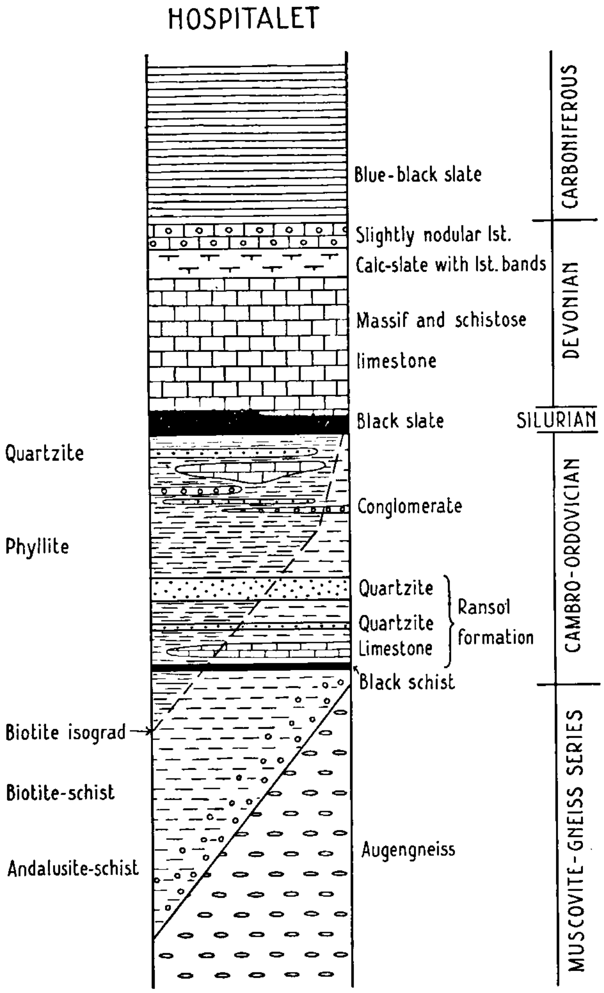

Fig. 2. Stratigraphic colum of the Paleozoic of the Hospitalet massif.

Andorra and is called the Ransol formation (fig. 2). North of Soldeu it forms a gentle syncline, the Ransol syncline, of which the southern limb passes through the village of this name. The black slate can be followed to the west, but the limestone is no longer present. Farther west this south limb is cut off by a fault. Although in this central part of Andorra the relation with the Silurian is unknown due to the Soldeu fault, it seems obvious, seen the continuity to the Pic de Cataperdis, that the Ransol formation occurs high in the Ordovician. This could not be checked with paleontological evidence.

As a whole the upper part of the Cambro-Ordovician of the Hospitalet massif is rather rich in quartzite and it can certainly be correlated with the higher, quartzitic part of the Cambro-Ordovician at the north side of the Aston massif, although the Ransol formation cannot, with certainty be recognized there. It is possible that the southernmost limestone near the Auzat granodiorite is stratigraphically equivalent with the Ransol formation, or perhaps the isolated limestone outcrops near the Pic de Montcalm, but due to the absence of fossils, there is no way to check these possibilities.

West and south of the Mérens fault the Ransol formation can be followed to the Cardos valley where it has been mapped by Zandvliet (1960) under the name of Lleret-Bayau series. There also black slates and limestones occur in the continuation of the Hospitalet anticline. Zandvliet was of the opinion that this formation might belong to the Canaveilles formation from the eastern Pyrenees, but seen its occurrence high in the Cambro-Ordovician this seems unlikely.

The Ransol formation can also be followed in the north limb of the Hospitalet anticline, where it occurs on the Pic de Varilles and from there can be continued in a zone between the Aston and Hospitalet massifs. This zone has been described by the author (1958) as a zone of sediments with black slates and limestones between the gneisses of both massifs. In this publication it has tentatively been identified as the Canaveilles formation, but new data which are presented here make this correlation unlikely and it is quite certain that it concerns the Ransol formation.

In the Hospitalet massif the Ransol formation is underlain by series of micaschists which on its turn overlie the Hospitalet gneisses. It is evident that near the Port de Fontargent and the Pic de la Cabanette the limestones of the Ransol formation overlie almost immediately the gneiss, whereas farther west the intercalated micaschist layer becomes gradually thicker. Still more to the west the Ransol formation leaves the metamorphic zone of the Hospitalet massif and occurs all the way in epizonal phyllites to the Cardos valley on sheet 5. Like in the Aston massif the upper boundary of the gneiss is discordant with regard to the stratigraphy. The highest position of this boundary occurs probably in the Aston massif near the village of Aston where the distance to the Silurian is very small (see map and fig. 1, 2).

Like always in the Cambro-Ordovician lateral facies changes are quite rapid and this applies also to the Ransol formation. The massive quartzite north of Ransol is towards the west replaced by an alternation of quartzite and slate layers with a decreasing proportion of quartzite, so that at the western edge of the map it cannot be mapped any longer as one unit. Although the limestone is more continuous it also is interrupted to the west.

This facies change is also evident from the Cambro-Ordovician south of the Hospitalet massif and in the Massana anticline, where the Ransol formation has not been observed. This may, however, be due to the level of erosion which possibly is not deep enough. Nevertheless the Upper Ordovician is much less quartzitic here then farther north although at several places the upper part of the Cambro-Ordovician begins with a quartzite horizon. The Upper Ordovician limestone has been found only south of the Tor syncline, but disappears to the east. The conglomerate occurs in the same region and on the southside of the Massana anticline near Os de Civis. Farther east is has only been found south of the Envalira pass where it occurs in contact with the Silurian.

Near the Puymorens mine a black slate and limestone horizon occurs which has been correlated with the Canaveilles formation by Cavet (1951). As it lies in the continuation of a Silurian-Devonian syncline north of the Envalira pass, we presume that it concerns these formations, although there is no direct connection with the rocks at the Puymorens mine and those farther west. Another layer of black slates has been mapped north of Porté near the Puymorens pass. Its stratigraphic position is not certain. Cavet supposes it to belong to the Canaveilles formation; we have tentatively correlated it with the Ransol formation, and finally it is not excluded that is is Silurian. As no fossils have been found the age of these slates rests uncertain.

Two chemical analyses have been prepared from Cambro-Ordovician microconglomerates from the Mounicou valley in the Aston massif. As could be expected, the silicon content is high. In the first analysis some admixture of pelitic material is present, in the second sample the calcium percentage of nearly 3 % is to be noted. The locality of the specimens is indicated on fig. 3.

TABLE 1

Analysis no.	137	138
SiO_2	78.05	87.81
TiO_2	1.04	0.43
P_2O_5	0.20	0.19
Al_2O_3	11.05	3.68
Fe_2O_3	1.62	1.17
FeO	2.39	1.30
MnO	0.04	0.12
MgO	1.11	1.43
CaO	0.67	2.95
K_2O	0.10	0.15
Na_2O	2.33	0.10
H_2O	1.56	0.24
	100.16	99.57

Analyses by petrochemical Laboratory, Department of Geology, University of Leyden.

2.3 SILURIAN

The Silurian occurs in its usual Pyrenean facies as black carbonaceous slates and schists, which distinguish them from the Ordovician underneath and the Devonian above. Only in the NE corner of the map the Silurian is less typical and seems to be transitional to the Devonian. In the Siguer valley also it may be present as dark bluish-black slates and is not very typical here. On the northern side of the Aston massif the Silurian forms long and continuously mappable horizons. Graptolites have been found near Unac (Caralp, 1888) and south of Olbier.

The Silurian of Andorra is everywhere very typical with black and often strongly contorted slates. It is relative thick, especially in the valley of the Valira del Norte near Llorts, but undoubtedly this mass represents some sort of a tectonic accumulation and must be strongly thickened by folding. The Silurian in this region is metamorphosed and contains a large amount of chiastolite and andalusite porphyroblasts up to a size of 1 cm.

Fossils have been found at the port Nègre (named after the black Silurian slates) where at the contact with the Devonian limestones well preserved cups of

Fig. 3. Tectonic map of the Aston-Hospitalet massif indicating locality of analysed specimens

crinoids have been found. According to determinations by A. Breimer it concerns Scyphocrinus sp., typical for the uppermost Silurian. The black slates grade into darkgrey limestone and then lighter coloured limestones of the Devonian.

One chemical analysis has been made from a Silurian schist. The sample has been collected near Llorts and contains a number of andalusite crystals. The analysis shows a very high proportion of aluminium like in all analyses of Silurian rocks from the Pyrenees.

TABLE 2

Analysis no.	181
SiO_2	52.50
TiO_2	1.37
P_2O_5	0.09
Al_2O_3	30.65
F_2O_3	2.00
FeO	1.62
MnO	0.05
MgO	0.80
CaO	1.31
Na_2O	0.65
K_2O	3.08
H_2O	4.15
C	2.00
	100.27

Analysis by Petrochemical Laboratory, Department of Geology, University of Leiden.

2.4 DEVONIAN

The Devonian of the northern border of the Aston massif consists of calcslates with layers and lenses of well bedded, finegrained limestone. The Silurian is usually followed by calcschists; stratigraphically higher the limestones occur and often occupie synclinal structures. The limestone is grey, white or reddish but brown when dolomitized, a process which occurred frequently. The distribution of the limestones in the calcslates is variable and they may reach thicknesses of 400 m, or even occasionally 800 m like near the Pic de Lercoul, but at that locality it is certainly doubled by folding. The limestone may wedge out, either stratigraphically or tectonically in the direction of the strike. The slates are strongly cleaved; the limestones are more or less massive. Near the castle of Lordat an outcrop of nodular limestone (griotte) which probably belongs to the Upper Devonian, occurs. It is most probably in fault contact with the underlying Devonian, but its definite situation is difficult to establish.

The Devonian south of the Hospitalet massif occurs mainly in a limestone facies. The limestones are white or grey and usually rather strongly cleaved and badly bedded in the outcrop. In large exposures it can be seen that even the massive limestones are bedded. Slaty limestone or greenish slates occur locally and always show a well developed axial plane slaty cleavage. At a few places nodular limestones have been found, for instance near the Col d'Ordino. The slaty limestone and slates and the nodular limestone occur stratigraphically higher than the massive limestones. Crinoid remains have been found at several places but identifiable fossils were not encountered.

Although the Devonian occupies large surfaces on the map, especially in the Tor syncline, its stratigraphic thickness is rather limited, as can be seen in the Llavorsi syncline. At many places the limestones are strongly thickened by folding.

2.5 CARBONIFEROUS

The only rocks on sheet 6 attributed to the Carboniferous system occur in the western part of the map in the Llavorsi syncline where this structure enters Andorra and in the north in the St. Barthélemy massif. The Devonian limestones in Andorra are overlain by monotonous bluish black and blue-grey slates with a well developed cleavage. The difference with the Cambro-Ordovician which also is slaty is evident from the complete absence of quartzites in the Carboniferous. Fossils have not been found in these slates and its Carboniferous age is entirely based on lithologic comparisons with the Carboniferous of sheet 5 and 4. On this latter sheet it has been dated with plant fossils as probably Westphalian.

The transition to the Devonian is abrupt and no chert horizon has been found. The stratigraphic thickness is unknown, mainly due to strong cleavage folding.

Carboniferous cherts occur in the NE corner of the map in the St. Barthélemy massif, where they alternate with Devonian nodular limestones. More details can be found in the explanation to sheet 3, De Sitter and Zwart, 1959.

2.6 CRETACEOUS

Cretaceous rocks occur along the northern border of the Aston massif, where they form the boundary of the axial zone. As these outcrops have also been described in the explanation to sheet 3, I refer again to this publication.

2.7 QUATERNARY

The quaternary deposits on sheet 6 are of glacial and postglacial origin. Their distribution is essentially restricted to the valleys which formerly were occupied by glaciers. Most glacial deposits consist of rather coarse grained material which has been transported only over a small distance. Most of these deposits in the valleys are covered with vegetation and therefore not accessible for further study. A special type of glacial and late glacial deposits are the rock glaciers, strongly curved ridges consisting of coarse angular blocks and occurring in glacial cirques or in the stepped valleys behind rock bars. Many of such rock glaciers occur especially in the gneiss areas of the Aston and Hospitalet massifs. They show up beautifully on aerial photographs.

Alluvial stream deposits, scree slopes and fans are of postglacial age as they overlie the glacial deposits. They occur in most valleys. The distinction with material of glacial origin is often difficult to make and therefore sometimes arbitrary.

3. PETROGRAPHY

3.1 PHYLLITES

The Cambro-Ordovician outside the Hospitalet and Aston massifs is usually present as phyllites, quartz-phyllites and quartzites, which mineralogically consist mainly of sericite and quartz. Besides these minerals, chlorite, graphite or carbonaceous material and ore may be present but usually in small amounts. The phyllites show always a strongly oriented fabric mainly due to parallel sericite crystals and to a lesser degree to flattened quartz crystals. Chlorite is sometimes present as cross-cutting, apparently later crystals. Banding, due to an alternation of quartz- and micarich layers is commonly present. It represents either a sedimentary bedding, or a metamorphic banding, resulting from strong deformation. In the latter case it cuts across the bedding. The slaty cleavage is at many places folded and often shows a secondary crenulation cleavage. Sometimes two or even more of such sleavages have been found. Towards the regional metamorphic areas the grainsize generally increases and small, microscopically visible biotite crystals may be present in these rocks.

In the western part of the Aston and Hospitalet massifs the phyllites have been subject to a later, higher grade metamorphism.

3.2 MICASCHISTS

Micaschists form the cover of the gneisses of the Aston and Hospitalet massifs. According to the grade of metamorphism they can be divided in biotite-muscovite-schists, staurolite-andalusite-cordierite-schists and cordierite-sillimanite-schists.

The biotite-muscovite-schists are transitional to the phyllites on one side and to the staurolite-andalusite-cordierite schists on the other. They occur mainly along the northern border of the Aston massif and along the southern border of the Hospitalet massif. They contain the following minerals: biotite, muscovite, quartz as main constituents, and minor oligoclase, tourmaline, ore, zircon and apatite. Both micas occur as elongated and oriented crystals, thus indicating both a schistosity and a lineation which has approximately an E-W direction. Banded schists occur quite frequently. Folds of the schistosity plane in various directions are usually met with. They will be treated in the chapter on structural geology.

In the western part of the Aston massif a large area of micaschists is exposed in the valleys of the Vicdessos and Artiès. Many of these schists carry large andalusites and cordierites; staurolite is less widespread here. Especially the andalusite porphyroblasts reach large sizes, for instance on the eastern slope of the Artiès valley and in the Subra valley where some crystals have a length of 50 cm or even more. The crystals lie in the schistosity plane but within this plane they are unoriented (fig. 4). The groundmass of these schists is comparable to that of the biotite-muscovite-schists; they are rather finegrained, linear rocks.

The micaschists of the Hospitalet massif occur as erosion remnants on top of the gneisses, and to the south and west. They are also characterized by the abundant occurrence of porphyroblasts of staurolite, andalusite and cordierite. Staurolite is far more widespread in the Hospitalet massif then in the Aston massif. The matrix of these schists is again a biotite-muscovite-schist with E-W trending lineations due to the fabric habit of the minerals. Also andalusite crystals are sometimes oriented in the same direction. Another lineation with NW-SE direction and determined by andalusite and cordierite porphyroblastst with a preferred orientation is common in most micaschists of the Hospitalet massif. The length of these crystals is usually not more then 10 cm. In this massif the biotite- and andalusite isograds both cut across the stratigraphy as is evident from the map.

A particular area occurs around El Serrat in the Valira del Norte valley. Here large amounts of porphyroblasts of biotite, staurolite, andalusite and cordierite occur in strongly folded schists. Like in the western part of the Aston massif the groundmass of the rocks is not a biotite-schist but a phyllite in which porphyroblasts developed later. Besides the Cambro-Ordovician, the Silurian participates also in this metamorphism. In the Silurian black slates porphyroblasts of andalusite or chiastolite up to a size of one cm developed abundantly, especially in the valley near Llorts.

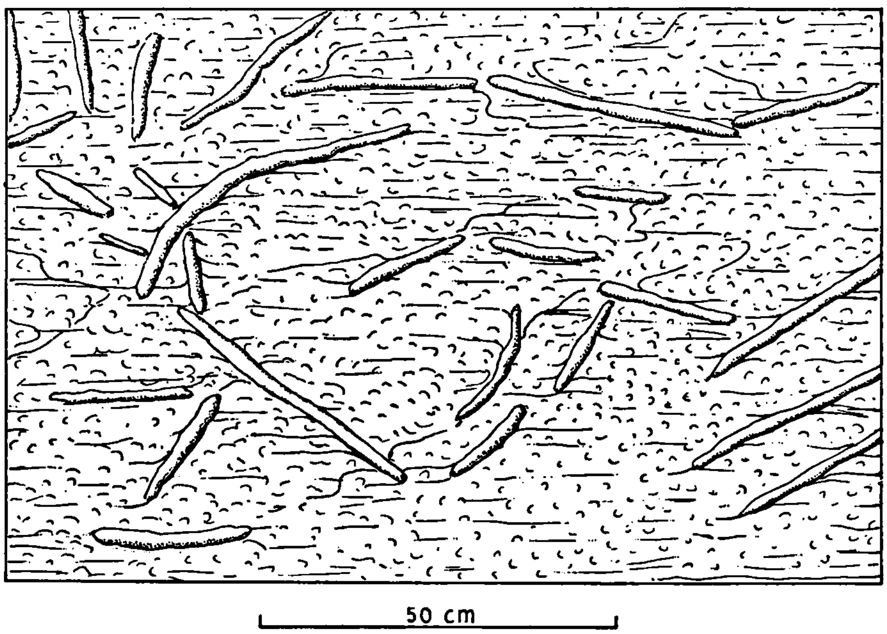

Fig. 4. Mica-schist with unoriented andalusite crystals lying in s-plane.

Sillimanite-schists occur in the Aston massif in the Mounicou valley where they are exposed near the small bodies of muscovite-granite. At a few places sillimanite occurs in rosettes of a size of 1—2 cm across. In other rocks it has been observed as small mats growing at the expense of biotite. In the Hospitalet massif some sillimanite-bearing micaschists have been found in the area north of the Ariège river due north of the Puymorens mine.

The petrochemical work on metamorphic and igneous rocks was continued with rocks of sheet 6. Analyses have been made from micaschists, migmatites, leucocratic gneisses and granites, a few mylonites and one Silurian black schist. The analyses were executed by Dr. C. M. de Sitter-Koomans, except for the numbers 136, 137 and 174 which were done by Mrs H. M. I. Bult-Bik.

Nine analyses of micaschists are reproduced in table II and arranged according to increasing silicium content. Like in other analyses of Pyrenean micaschists, aluminium and potassium decrease in this direction. The remaining elements do not show a significant change. The composition of these schists is quite similar to that of Cambro-Ordovician phyllites and micaschists from other parts of the Pyrenees. Therefore changes in chemical composition during metamorphism from phyllite to micaschist will have been negligeable.

TABLE 3

	139	140	141	142	143	144	145	146	147
SiO_2	43.45	58.75	59.35	61.70	62.52	63.20	63.25	63.78	68.25
TiO_2	1.52	0.99	0.91	0.80	1.02	0.88	0.52	0.63	0.45
P_2O_5	0.22	0.12	0.12	0.23	0.16	0.14	0.25	0.23	0.14
Al_2O_3	24.90	20.28	21.17	17.88	18.18	18.35	17.62	17.72	14.77
Fe_2O_3	0.30	0.18	0.34	1.38	1.90	1.08	1.03	1.28	2.77
FeO	10.01	7.40	6.88	3.57	5.36	5.55	3.23	2.99	1.10
MnO	0.08	0.10	0.12	0.02	0.04	0.06	0.02	0.02	—
MgO	4.20	3.08	3.02	2.27	2.78	2.97	2.14	2.12	1.46
CaO	1.24	0.84	0.67	3.52	1.16	1.42	4.09	3.35	4.90
Na_2O	2.20	1.55	1.65	2.87	0.95	1.02	2.77	2.95	3.45
K_2O	4.35	3.48	3.56	3.45	3.74	3.17	3.04	3.02	1.22
H_2O	2.75	2.37	2.40	1.74	2.02	1.98	1.76	1.62	1.24
C	0.10	—	—	—	—	—	—	—	—
S_2	3.09	1.59	—	—	—	—	—	—	—
O–	–0.77	–0.40	—	—	—	—	—	—	—
	97.64	100.33	100.19	99.63	99.83	99.82	99.72	99.71	99.75
insoluble	1.88								
	99.52								

Analyses by petrochemical laboratory, Department of Geology, Leiden.
The locality of the specimens is indicated on fig. 3.

Mineralogical composition of analyzed micaschists

139. Quartz, biotite, muscovite, cordierite, staurolite
140. Quartz, biotite, muscovite, andalusite
141. Quartz, biotite, muscovite, andalusite, staurolite
142. Quartz, biotite, muscovite, andalusite, staurolite, cordierite
143. Quartz, biotite, muscovite, andalusite, cordierite, staurolite, garnet
144. Quartz, biotite, muscovite, andalusite, staurolite, cordierite
145. Quartz, biotite, muscovite, andalusite, cordierite
147. Quartz, biotite, muscovite, andalusite, cordierite, staurolite, garnet.

3.3 MIGMATITE-QUARTZ-DIORITE SERIES

Micaschists grade into migmatitic rocks in the western part of the Aston massif, mainly in the valley of the Gnioure river. They underlie the orthogneisses, not only at this place, but also farther east. On the south side they are cut off by the Mérens fault.

Two rocktypes can be distinguished: 1) heterogeneous migmatites in which the schistose parent rock can be easily recognized and 2) more homogeneous quartz-dioritic rocks, derived from the first type by continued recrystallization and mobilization. In general the heterogeneous migmatites underlie as a zone of a few hundred metres thickness the leucocratic gneisses. The migmatites grade into and are underlain by the homogeneous quartz-diorites.

The migmatites, also called sillimanite-gneisses, are composed of schistose, biotite-rich layers of about ½—2 cm thickness alternating with layers and lenses of an unoriented quartz-feldspar rock of about the same thickness, or locally thicker, but then containing biotite as well. Sillimanite occurs in most of these rocks and is usually associated with biotite, at the expense of which it may grow. Muscovite occurs mostly as crosscutting crystals and seems to be later then the former two minerals. Cordierite is less widespread then sillimanite but has been found regularly. It occurs also in the quartzo-feldspathic layers. It may be altered to chlorite and sericite. The biotite bands are strongly schistose, but nevertheless their fabric is different from the neighbouring micaschists as no linear orientation is present. The grainsize of the biotite crystals is also larger in the migmatites. Garnet and epidote occur locally.

The leucocratic bands contain mainly quartz and oligoclase with minor potassium feldspar, biotite and cordierite. At a few places, like near Etang de Soulanet the feldspars are augenshaped and the rocks have a linear structure, but usually such deformation structures are absent in the migmatites. More or less irregular folding of the schistosity planes, however, is very common in most migmatites. These folds apparently do not have any influence on the orientation of the minerals.

At some localities the micaschists grade into rather homogeneous biotite-gneisses, for instance on the eastern slope of the Gnioure valley. These rocks contain besides biotite and quartz: microcline, plagioclase — sometimes as augen —, muscovite, sillimanite, garnet and minor epidote and ore. They probably are a transitional rock from micaschist to migmatite. For further details I refer to the publication of Verspyck in this volume.

In the migmatites many layers and remnants of quartzites and calc-silicate rocks occur which are described in more detail by Verspyck.

The migmatites grade with an intermediary stage of nebulitic rocks into more or less homogeneous quartz-diorites with a granitic texture. The sedimentary origin of these rocks is, however, still evident from the mineralogical composition with aluminium-silicates as sillimanite and cordierite, and from the frequent inclusion of quartzites, calc-silicate rocks and marbles. Locally the quartzdiorites occur as small pods in the sillimanite-gneisses, but they occupie rather large areas in the Siguer valley and the upper Aston valley.

The rockforming minerals are quartz, oligoclase, biotite, sillimanite (as prisms), cordierite and minor potassium feldspar and muscovite. Apatite, zircon and ore occur as accessories. Muscovite grows mainly at the expense of biotite or feldspar and forms rather late, like in the migmatites.

Mobilization as can be seen from disoriented inclusions, has been observed at a few places, for instance in the Gnioure valley, but this process was certainly less important here than in the adjoining Trois Seigneurs massif (Allaart, 1959).

From field and microscopic evidence it seems clear that these quartz-dioritic rocks are derived from the heterogeneous sillimanite-gneisses by continued recrystallization and partial anatexis. Similar rocks occur and have been described from the Saint-Barthélemy, Arize and Trois Seigneurs massifs (Allaart, 1959, Zwart, 1959, 1962).

The occurrence of sillimanite and cordierite and the absence of andalusite and staurolite places the rocks of the migmatite-quartz-diorite series in the cordierite-sillimanite zone (Zwart, 1962) which belongs to the warmer portion of the amphibolite facies.

Four rocks of the migmatite-quartzdiorite series have been analyzed chemically. These four are rather homogeneous quartz-dioritic rocks and they show a strong resemblance to the quartz-diorites of sheet 3, Ariège. Compared with the micaschists from which they were produced, the main difference is the high silicium and low aluminium content in the quartzdiorites. This may be due to introduction of silicium, like also was deduced from chemical analyses of rocks of sheet 3. The other elements show about the same proportions as in the micacshists.

TABLE 4

	148	149	150	151
SiO_2	68.60	69.50	70.24	71.58
TiO_2	0.75	0.69	0.65	0.65
P_2O_5	0.24	0.26	0.35	0.29
Al_2O_3	15.78	14.52	15.25	14.05
Fe_2O_3	0.78	0.84	0.76	0.41
FeO	4.11	3.65	3.22	2.95
MgO	2.02	1.66	1.58	1.32
CaO	1.32	1.05	1.15	1.29
Na_2O	1.88	2.44	2.04	3.30
K_2O	3.12	3.70	3.80	3.28
H_2O	1.10	1.52	1.00	0.99
	99.70	99.83	100.04	100.11

Analyses by petrochemical laboratory, Department of Geology, Leiden.

3.4 MUSCOVITE-GNEISS AND GRANITE SERIES

Rocks belonging to this series occupie large parts of sheet 6. Both in the Aston and Hospitalet massifs these gneisses and granites form the core of these large structures. Although chemically and mineralogically quite homogeneous, there exists a large variety of structurally different rock types. The Hospitalet massif has the least variation; the Aston massif contains many different types.

3.4.1 *Hospitalet massif*

In the western part of the Hospitalet massif the gneisses form the core of a large, gentle anticlinal structure. These rocks are very monotonous and homogeneous throughout this area and have a very regular schistosity and lineation. They are augengneisses in which the feldspars occur as eyeshaped crystals surrounded by a matrix of quartz and micas. The schistosity in this area is generally rather flat lying and parallel to that of the overlying micaschists. In handspecimens the schistosity is determined by the flat shape of the augen and the oriented quartz-mica fabric of the matrix. Lineations are due to fabric habit of these minerals; feldspars and micas have an elongate shape. The lineations in the Hospitalet massif trend E-W to ENE and are parallel to the mica-lineations and fold axes in the overlying micaschists. The grainsize is medium to large. The augen have a size varying from ½—3 cm.

They are usually not thicker than 1 cm. Muscovite and biotite appear as small flakes. Near the contact with the micaschist the grainsize decreases, this is probably due to mylonitization along the contact. In the gneisses some finegrained aplitic bands up to 10 cm thickness occur at several places. Their contacts are parallel to the schistosity of the gneiss. These bands also show a schistosity and a lineation. Folds have not been found, probably due to the extreme homogeneity of the gneisses. In the western part of the Hospitalet massif no crosscutting dykes have been found, but approximately east of Etang Joucla crosscutting pegmatites of a thickness of several decimetres have been found. Their number increases eastwards and is accompanied by a less strong preferred orientation of the gneiss. This is especially clear in the valley of the Ariège river between Mérens and the village of Hospitalet. Here the gneiss is no longer linear and also the schistosity has become vague, resulting in rocks with a rather granitic character. This tendency continues farther east.

Mineralogically the gneisses consist of quartz, plagioclase (albite), potassium feldspar, muscovite and biotite. Most of the augen are potassium feldspars, often perthitic. Frequently they contain large inclusions of plagioclase. Muscovite and biotite form together with quartz a matrix between the feldspar eyes (fig. 8).

The thickness of the gneis is considerable and amounts to at least 2000 m.

3.4.2 *Aston massif*

In the Aston massif a greater variety of gneisses occurs compared with the Hospitalet massif. They are chemically and mineralogically similar to the Hospitalet gneisses and there is no doubt that the gneisses of both massifs originally belonged to the same unit. Three main types have been distinguished in the Aston massif: 1) augengneisses, 2) flasergneisses and 3) granitic gneisses.

3.4.2.1 *Augengneisses.* — Augengneisses occur especially in the eastern and northern part of the Aston massif. They are different from the Hospitalet gneisses by their less regular schistosity, the less pronounced or even absent lineations and the presence of small and large patches, lenses and masses of unoriented muscovite-granite. The schistosity is often strongly folded and contorted in such a way that no regular system of fold axes can be detected. Lineations, if present have an irregular orientation. Near the northern border the schistosity is more regular. The gneisses here are also much finer grained.

The amount of granite in the augengneisses is quite variable; at some places only small relicts of gneiss remain, at others only little granite occurs (fig. 5, 6, 7). Large, mappable homogeneous granite bodies occur at a few localities. The largest one is the granite near Ax-les-Thermes. Mostly gneiss and granite are so intimately interwoven, that for mapping a gliding scale had been used, giving the approximate percentages of gneiss and granite. The thickness of these gneisses in the eastern part of the Aston massif is about 3000 m. Their upper contact is formed by Cambro-Ordovician micaschists, their lower contact by migmatites in the eastern part of the massif or by flasergneisses in the central part.

Under the microscope the typical augencharacter is much less evident than in the Hospitalet gneisses or as the outcrop suggests. The texture is rather granitic and badly oriented (fig. 9). The augen usually consist of composite crystals of potassium feldspar, plagioclase and quartz. They may reach a size of 5 cm. A deformation texture like in the Hospitalet gneisses does not occur in the Aston gneisses. Further constituents are biotite and muscovite often present as undeformed flakes.

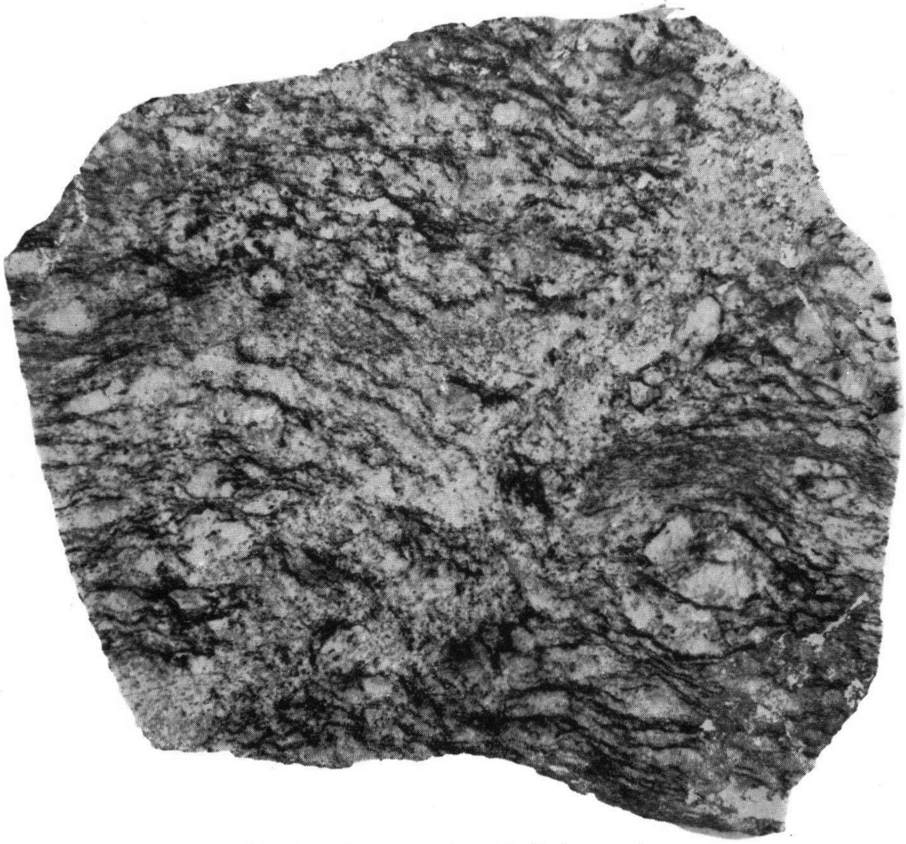

Fig. 5. Augengneiss with little granite.

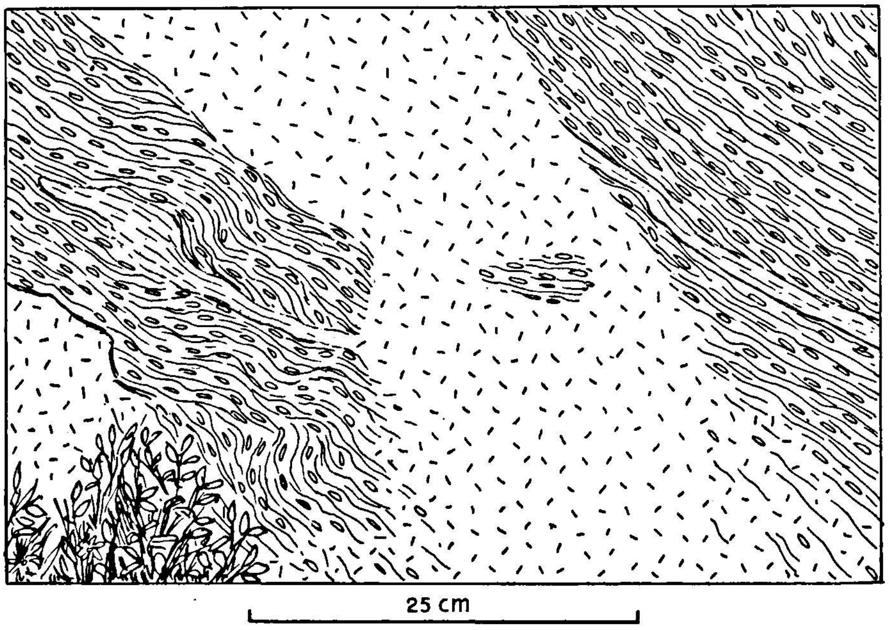

Fig. 6. Augengneiss with granite vein.

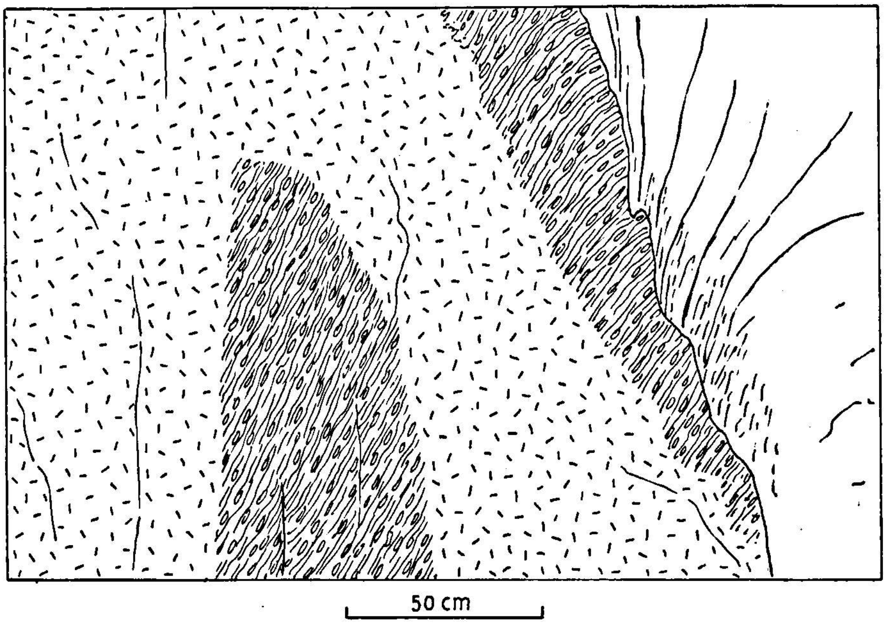

Fig. 7. Augengneiss with granite veins.

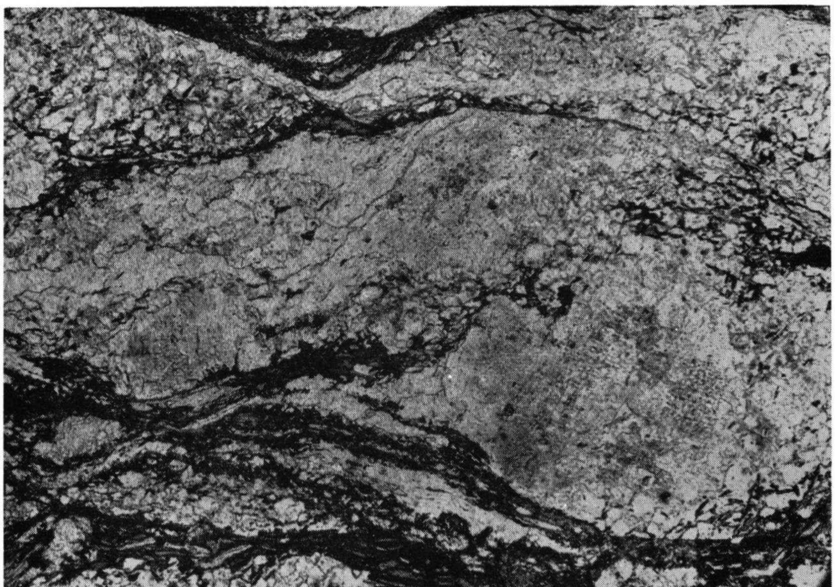

Fig. 8. Thin section microphotograph of augengneiss.

Fig. 9. Microphotograph of thin section of augengneiss; crossed nicols; note replacement of feldspar eye by mosaic of quartz and feldspar.

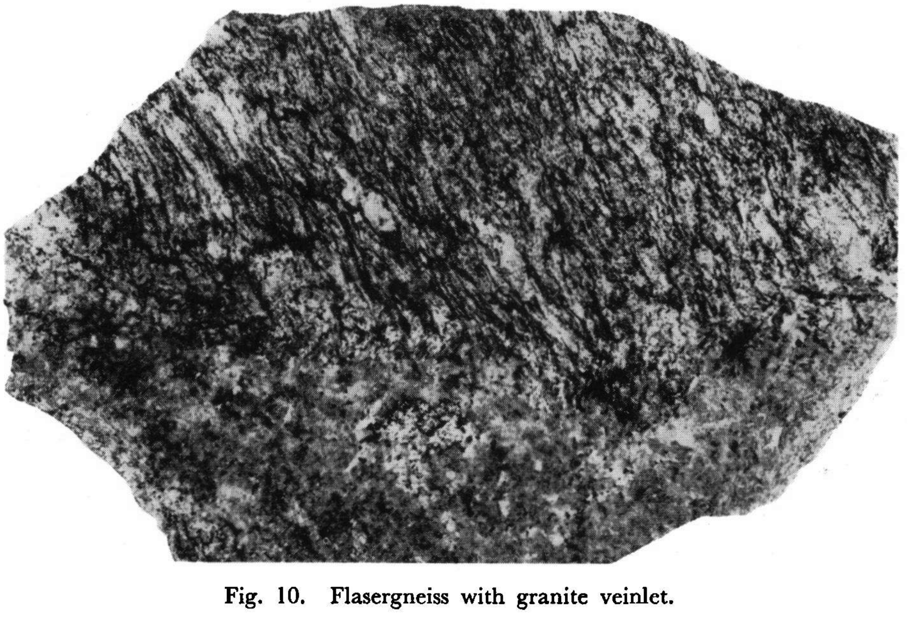

Fig. 10. Flasergneiss with granite veinlet.

3.4.2.2 *Flasergneisses.* — Flasergneisses occur in the southern and central part of the Aston massif. They are overlain by the augengneisses in which they grade slowly. Their lower contact is formed by the migmatites and quartz-diorites along the southern border of the leucocratic gneisses.

The flasergneisses are characterized by the scarcity or absence of feldspar augen and they have a more or less irregular or wavy schistosity which is indicated by thin biotite streaks (fig. 10). The schistosity is sometimes strongly contorted and folded like in the augengneisses (fig. 11). The grainsize of the flasergneisses is medium, but locally large feldspar megacrysts of a size of 3—4 cm occur frequently, for instance in the area south of the Pic du Col de Gos. The flasergneisses grade into augengneisses with an increasing amount of feldspar augen. Irregular patches and masses of muscovite-granite varying in size from a few cm up to several hundreds of metres occur at most places in the flasergneisses. For mapping purposes the same gliding scale as in the augengneisses has been used.

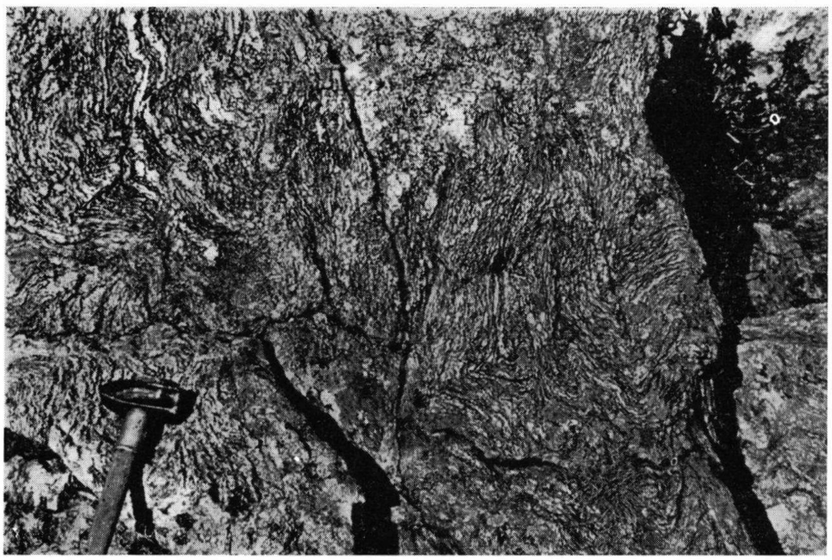

Fig. 11. Mobilized flasergneiss.

From cartographic relations it is clear that besides the general superposition of the augengneisses on the flasergneisses also a lateral change of both gneisstypes is present, whereby going from west to east the flasergneiss grades into augengneiss. Furthermore large inclusions of augengneiss in the flasergneiss have been found, for instance in the Milleroques valley.

Mineralogically the flasergneisses contain quartz, sodic plagioclase (An 5—12), potassium feldspar (microcline), biotite and muscovite; moreover some fibrolite has locally been observed. The granitic texture is evident under the microscope, despite the schistose character of the rock in handspecimen. Like in the augengneiss the schistosity has in general a rather flat attitude.

3.4.2.3 *Granitic gneisses.* — Granitic gneisses occur in the western part of the Aston massif, roughly west of the divide between the Aston and Siguer valleys. These gneisses have been called "Gne iss de Peyregrand" by Raguin and Destombes (1955).

They are more regular than the flasergneisses, although still characterized by thin biotite streaks. They are somewhat finer grained and large feldspar crystals are absent. Strong folding and contortion of the schistosity is usually lacking and also patches and masses of granite are rare. A few inclusions of micaschist, and amphibolite have been found in these gneisses. They do not exceed a size of a few decimetres.

Mineralogically these gneisses are similar to the flasergneisses, but in addition garnet may be present. The textures are rather granitic, although some preferred orientation of the micas is present.

The granitic gneisses grade laterally into the flasergneisses in a rather wide transitional zone.

In these gneisses occur at several places, e.g. near their base layers or bands of peculiar finegrained gneissose granites containing quartz-sillimanite nodules (fig. 12). These nodules are always elongate lenses with a longest dimension in NW to NNW

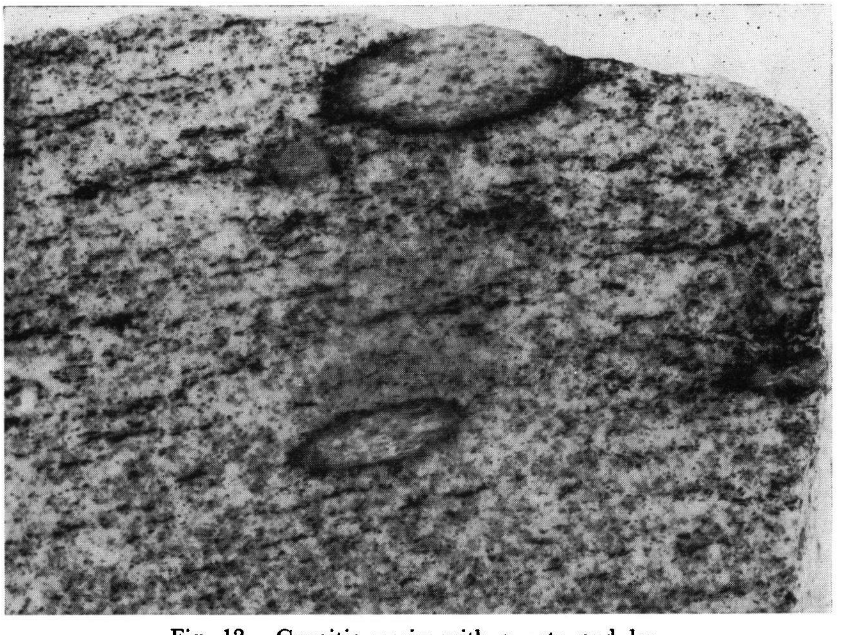

Fig. 12. Granitic gneiss with quartz nodules.

direction. They are flat and lie in the plane of schistosity. Their size is often about 2—3 cm length, 1 cm width and ½ cm thick, but smaller as well as larger nodules occur frequently. The contacts of these nodular gneisses are usually parallel to the schistosity of the enclosing gneiss, but exceptions to this rule have been found occasionally (fig. 29). They occur most frequently in the granitic gneisses, but less abundantly they have also been found in the flaser- and augengneisses. In the Hospitalet massif they are absent.

According to Raguin and Destombes they represent metamorphic conglomerates of Cambro-Ordovician age, but we have serious doubts as to the correctness of this opinion. Anyway, nowhere is a transition of the Cambro-Ordovician metasediments into these gneisses exposed and there are good reasons to consider these gneisses as a special type of metamorphic rock derived from original augengneisses, rather then as metaconglomerates. Later on in this explanation I will give a more extensive treatment of these rocks.

3.4.2.4 *Muscovite-granite in leucocratic gneisses.* — Unoriented and rather finegrained muscovite-granites occur abundantly in the gneisses of the Aston massif. They usually invade the gneisses on a minor scale as small patches, bands and lenses often with discordant contacts with the enclosing gneiss. The smallest units are of the size of a few cm but these grade into larger bodies and small stocks which may reach a mappable dimension, like for instance the granite of Ax-les-Thermes. In general it is impossible to map gneiss and granite as separate units. The largest sheet like granite body occurs near Ax-les-Thermes and has a size of 2 × 3 km. Smaller, mappable ones occur west of Riète. Elsewhere the granite percentage may be as high as 70—80 % but then many gneiss inclusions occur in the granite. Sometimes these inclusions are clearly rotated as has been observed near the divide of the Aston and Siguer rivers and between Ax and Mérens. In these outcrops small inclusions of augen- or flasergneiss of a size of about 10 cm occur in the unoriented granite. From the orien-

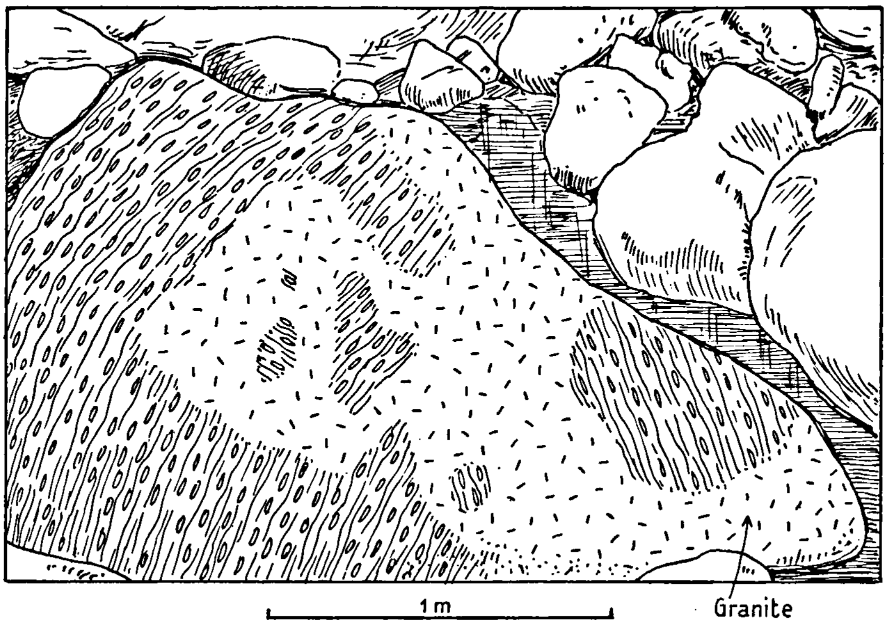

Fig. 13. Rotated inclusions of augengneiss in granite.

tation of the schistose inclusions it is obvious that these have rotated and probably flowed in the granite (fig. 13).

The composition of the granites is quartz, sodic plagioclase (albite), microcline, biotite and muscovite and sometimes garnet. The texture is unoriented.

3.4.2.5 *Muscovite-granites outside the leucocratic gneisses.* — Similar granites, both in composition and mineralogy occur in migmatites and micaschists. A large body occurs in the migmatites east of Etang Blaou. This mass is rather rich in pegmatites and contains inclusions of migmatite and micaschist. The contacts with the surrounding migmatites are sharp. Several small stocks occur in micaschists in the Mounicou valley. They form crosscutting bodies often rich in pegmatitic portions and schist inclusions. They contain the same minerals as the granites in the gneisses. In addition

TABLE

	Augengneiss Hospitalet massif						Augengneiss, Aston massif						
	152	153	154	155	156	157	158	159	160	161	162	163	164
SiO_2	71.00	71.10	71.90	72.80	72.98	73.02	69.06	70.72	71.55	71.57	72.40	72.50	72.60
TiO_2	0.55	0.60	0.46	0.50	0,30	0.42	0.58	0.20	0.52	0.35	0.27	0.41	0.43
P_2O_5	0.15	0.21	0.29	0.23	0.12	0.16	0.22	0.19	0.27	0.26	0.20	0.25	0.18
Al_2O_3	14.12	13.31	13.28	12.62	13.52	12.50	16.00	13.60	14.05	13.61	14.89	13.92	13.55
Fe_2O_3	0.87	1.42	0.79	1.16	0.63	0.45	1.31	1.27	1.28	0.44	0.47	0.53	0.52
FeO	2.70	2.69	2.39	2.92	2.01	2.97	2.67	2.39	2.22	1.93	1.61	2.33	2.47
MgO	0.84	1.03	0.88	0.63	0.50	0.48	0.83	0.79	0.73	0.52	0.26	0.53	0.64
CaO	1.35	1.37	1.27	1.29	1.14	1.24	1.60	1.58	1.82	2.11	1.20	1.28	1.45
NaO	3.31	2.94	3.10	3.02	2.62	2.95	3.56	3.90	3.18	2.59	3.22	3.28	3.57
K_2O	4.02	4.55	4.25	4.28	5.45	4.68	3.68	4.80	3.68	5.58	4.90	4.55	4.15
H_2O	1.23	0.59	1.16	0.54	0.71	1.07	0.53	0.70	0.75	0.82	0.28	0.38	0.33
	100.14	99.81	99.77	99.99	99.98	99.94	100.04	100.14	100.05	99.78	99.70	99.96	99.89

Analyses by Petrochemical Laboratory, Department of Geology, Leiden.
For locality of specimens see fig. 3.

the pegmatites often carry tourmaline and sometimes andalusite, cordierite or garnet. For more details I refer to the publication of Verspyck in this volume.

A rather extensive survey of the chemical properties of the muscovite-gneisses and granites has been made. In total twenty six analyses have been executed. Six of the samples are from gneisses of the Hospitalet massif, eight of Aston augengneisses, nine of flasergneisses and granitic gneisses of the western part of the Aston massif, two of granites occurring in these gneisses and one pegmatite (table V).

At first sight it is evident that there is very little variation throughout the table, despite the great variability in structure of the rocks. The chemical composition of almost all rocks is about that of an acid granite. For this reason it seems probable that these rocks were originally intrusive granites which during the Hercynian orogeny have been deformed and became augengneisses. In a late phase of the same orogeny these gneisses were mobilized and recrystallized again to granitic rocks. During all these transformations little changes in chemical composition have taken place in view of the similarity of all analyses.

Gneisses of a similar composition occur in the St. Barthélemy massif where they have been described as orthogneisses by Zwart (1954). Furthermore they are widespread in the Canigou massif where recently they have been recognized as orthogneisses (Guitard 1963).

3.5 LATE CARBONIFEROUS INTRUSIVES

3.5.1 *Granodiorite*

Parts of two large bodies of intrusive biotite-granodiorites occur on sheet 6. These are the Bassiès-Auzat granodiorite in the NW corner of the map, and the Andorra-Mont Louis granodiorite in the SE. Both batholiths have the same properties as many other biotite-granodiorites in the Pyrenees. They have sharp, often crosscutting contacts with the enclosing sediments, but their general shape follows the

5

		Flasergneiss, granitic gneiss, Aston massif								Granite and pegmatite, Aston massif		
165	166	167	168	169	170	171	172	173	174	175	176	177
72.70	74.58	71.40	73.68	74.55	75.35	75.50	75.95	76.10	76.64	72.05	72.91	73.93
0.28	0.11	0.44	0.27	0.14	0.24	0.11	0.18	0.16	0.20	0.20	—	—
0.24	0.44	0.19	0.20	0.43	0.20	0.19	0.19	0.19	0.25	0.31	0.21	0.26
14.75	14.20	15.30	13.00	12.91	13.22	13.85	13.05	12.75	12.06	15.10	14.66	13.74
0.69	0.17	1.40	0.68	0.49	0.60	0.49	0.37	0.64	1.59	0.97	1.06	1.26
1.58	0.92	2.06	1.75	1.34	1.45	1.11	1.21	1.46	0.93	1.05	0.30	0.31
0.31	0.23	0.82	0.74	0.37	0.21	0.01	0.09	0.01	0.15	0.25	0.26	0.18
1.20	0.92	1.35	0.93	1.05	0.84	0.64	0.71	0.88	0.63	1.05	0.78	1.13
3.14	3.10	2.85	2.50	2.93	3.30	3.12	2.94	3.30	2.65	3.12	2.25	3.59
4.80	4.68	3.90	4.85	5.65	4.40	4.80	5.02	4.05	4.45	5.15	7.01	4.94
0.24	0.71	0.55	1.44	0.32	0.43	0.41	0.37	0.47	0.29	0.83	0.49	0.66
99.93	100.06	100.26	100.04	100.18	100.24	100.23	100.08	100.01	99.84	100.08	99.93	100.00

E-W trend of the Paleozoic structures. The Auzat granodiorite is in contact with Cambro-Ordovician rocks only and is cut off by the North-Pyrenean fault on its north side. The Andorra-Mont Louis granodiorite is in contact with rocks from Cambro-Ordovician to Carboniferous age. In the valley of the Valira between Encamp and Las Escaldes the granodiorite is strongly sheared.

The granodiorite itself is an unoriented rock of medium grainsize and is usually quite homogeneous throughout the massifs. The rock consists of quartz, plagioclase (oligoclase-andesine), potassium feldspar and biotite as main constituents, and zircon and apatite as accessories. The texture is typically igneous with more or less idiomorphic and strongly zoned plagioclase. Quartz and potassium feldspar (often microcline) fill the interstices between plagioclase and biotite. Alteration to sericite, chlorite and clinozoisite occurs locally, but mostly the rocks are rather fresh.

In the Vicdessos valley many finegrained, dark xenoliths occur in the granodiorite. They consist mainly of biotite and plagioclase. Close to the contacts the granodiorite often contains some hornblende.

For further details and chemical analyses of similar granodiorites I refer to the explanation of sheet 3.

3.5.2 *Contact metamorphic rocks*

Both batholiths have caused a zone of contact metamorphism in the enclosing rocks. These zones may reach a width of about 1 kilometre. In the slates of Cambro-Ordovician age hornfelses and spotted slates are produced which may contain biotite, muscovite and rounded porphyroblasts of 1—3 mm size. They consist usually of a mass of sericite and chlorite and in most cases originally were cordierite or andalusite. Their shape is often elliptic and they are more or less oriented in the cleavage plane presumably by mimetic growth.

In the Silurian rocks north of the Andorra-Mont Louis granodiorite long andalusite and chiastolite crystals were produced by contact metamorphism. They grow completely at random across the cleavage planes.

The limestones south of the Auzat granodiorite are altered to marbles and contain grossularite and vesuvianite as large crystals. Limy slates have been transformed to dense bluish hornfelses with hornblende, clinozoisite, muscovite, biotite and calcite. Mica-rich layers often alternate with calcsilicate layers.

3.5.3 *Dykes*

Dykes or small stocks of rather leucocratic rocks occur at several localities in Andorra, for instance on the Tosal de la Lladosa. The rocks are usually white and finely cristalline and can be called aplite. Microscopically they consist of quartz, altered feldspar and some muscovite. Some of these dykes, for example south of the Envalira pass are strongly sheared and have a schistose appearance.

A hornblende-biotite porphyrite has been found about 300 m north of Etang Sourd, approximately 2.5 km south of the southern contact of the Auzat granodiorite. This rock consists of plagioclase, biotite and hornblende.

3.6 *Lherzolites and ophites*

Basic and ultrabasic rocks have been found near the North-Pyrenean fault, mainly in the Mesozoic limestones. As they have been described in the explanation to sheet 3 I refer to this text for further details.

4. STRUCTURAL GEOLOGY

(*see map and sections*)

4.1 FIRST PHASE; MAJOR AND MINOR STRUCTURES

The structures occurring on this sheet can be classified according to their situation and to their time of formation. It appeared that two fundamentally different types of structures occur which formed simultaneously during the first folding period, and that afterwards several other phases of deformation were active. These two major structures are the large, gentle structures of the Aston and Hospitalet massifs with mesozonal regional metamorphic rocks, and the lowgrade dynamometamorphic Cambro-Ordovician, Devonian and Carboniferous outside these regional metamorphic areas. The first-mentioned structure is often called the infrastructure, the second one the suprastructure. From the coloured sections 1—6, these differences are evident.

4.1.1 *The infrastructure*

The Aston and Hospitalet massifs formed originally one large unit which has been dissected by the important Mérens fault. Both structures have an exposed length of about 45 km and a width of 20 km. They have an anticlinal shape in the sense that in the centre of the massifs the oldest rocks are exposed and on the north- and south-side younger rocks crop out. Originally we referred to these structures as gneissdomes, but as the mantled gneissdomes described from Finland by Eskola are of a different kind, it seemed advisable to abandon this name and we now use the term anticline or massif.

As can be seen from the sections adjoining the map, the Aston massif shows a gently generally north dipping foliation which near the northern border quite suddenly becomes steeper to a vertical position. At the same place the grade of metamorphism drops to epizonal. In the south the Aston massif is cut off by the Mérens fault. The Hospitalet massif has a more sharply defined anticlinal structure and plunges to the west and to the east (outside the map), but southward it is also cut off by a fault. It is probable that here also the flat schistosity steepens rapidly, as in the epizonal phyllites south of the fault the cleavage has a steep dip.

As has been described in the chapter on stratigraphy, the deepest exposed rocks in the Aston massif consist of migmatized micaschists which are overlain by a sheet of leucocratic gneisses with a thickness of at least 3000 m. The same gneiss, although less recrystallized, forms the deepest exposed level in the Hospitalet massif. In both massifs, these gneisses are overlain by micaschists which on their turn are overlain by epizonal phyllites, as can be seen in the plunging noses.

Closer investigation of the metamorphic rocks revealed that more deformation is involved in these major structures than only the warping of a sequence of rocks. This is mainly apparent from minor and microstructures as schistosity, lineations and folds,

Whether the large scale layering has to be interpreted as original bedding depends largely on the interpretation of the leucocratic gneisses, but it is quite certain that this layering was present at the beginning of the Hercynian folding, although at that time the rocks were not in a metamorphic state.

The structural history of the metamorphics in both massifs is quite complex, involving several phases of deformation, metamorphism and granitization. This latter process has made large parts of the Aston massif unsuitable for a tectonic analysis, and for instance all migmatites, quartzdiorites and most of the leucocratic gneisses have lost their original structures. Fortunately enough, though, a large part of the Hospitalet massif has been spared from migmatization and granitization and therefore this massif proved to be a key area in unraveling many structures.

The gneisses of the latter massif are structurally quite homogeneous; they contain one schistosity plane and one lineation. The schistosity is dipping gently or has a horizontal attitude, it is parallel to the micaschist boundary and follows the anticlinal shape of the massif (see sections). The schistosity is determined by the orientation of minerals, micas, quartz and feldspars, and the lineation is due to the fabric habit of these minerals. The latter structure trends E-W to N 70° E, and plunges gently to the east in the eastern part and to the west in the western part of the massif. Folds have not been found in these gneisses; this is probably due to the extreme homogeneity of the rocks. In the original material no banding or layering will have been present otherwise some folds would have been observed. From these structures little information can be gained concerning the mode of deformation.

In the micaschists overlying these gneisses more information could be gathered. These rocks also are schistose and linear, both structures have the same orientation as in the gneisses and are determined by the same fabric elements, but in addition folds of bedding occur in the schists. The axes of these folds are parallel to the lineation and trend E-W. The folds are usually very small, up to a size of a few dm and further they are recumbent, isoclinal and strongly asymmetric. Except for the fold hinges the schistosity parallels bedding. The number of such folds is rather limited and only a few can usually be found in a days work. Most of these folds occur when quartzite beds are involved, and in that case the strong deformation is apparent from the shape of the folds (fig. 14). Only in the eastern plunge of the massif they seem to be somewhat more common. As far as could be ascertained the sense of asymmetry of all folds is similar and suggests movement from south to north. As the axial plane of these folds is parallel to the schistosity, the folding and the formation of schistosity and lineation must have been a synchronous process, and consequently also the formation of these structures in the gneisses must date from the same period.

In the micaschists of the Aston massif folds and lineations occur which bear a strong resemblance to those in the Hospitalet massif and also the sense of asymmetry of the folds seems to be the same.

As the formation of this schistosity and the folds belonging to it is one of the most important deformation phases of the Hercynian orogeny and is accompanied by major folds it is called the main phase. The name first phase is also used since it is the first deformation phase connected with fabrics like schistosity and lineation. This main phase has left its traces everywhere in the Paleozoic of the Pyrenees and is in the non-metamorphic or low grade regions accompanied by the formation of cleavage folds in E-W direction. There is a little evidence, however, that some metamorphism is earlier than this phase or possibly dates from an early stage in this phase, as will be discussed in the last part of this chapter. There are good reasons to assume that some large scale concentric folding preceded this main phase. This is evident for instance, in the Ransol syncline south of the Hospitalet massif (see section 4). This large gentle syncline lies with its northern part in mesozonal schists and with its southern part in epizonal phyllites. The schistosity cuts obliquely through the large structure and only minor structures superposed on the large one have a schistosity parallel to their axial plane. Therefore it seems probable that the large fold already existed at the time that the schistosity started to develop. Mutatis mutandis this should also apply to the large Hospitalet anticline and the Aston massif. More arguments for this pre-schistosity folding have been mentioned by the author (Zwart, 1963).

It is quite remarkable that between the major anticlinal structure of the Aston-Hospitalet massif and the minor folds no other dimension of structure seems to exist; at least no one has been found. This might indicate that the internal deformation accompanying the schistosity was in general rather homogeneous throughout the pile of metamorphic rocks.

As far as the origin of the schistosity is concerned, it is likely that it is a plane of movement, and it is assumed that laminar flow has taken place during the main phase of deformation. The monoclinic symmetry of the fabric is evident from the asymmetry of the folds. In the gneisses the symmetry of the fabric seems orthorhombic, and the proof of its monoclinic character awaits further petrofabric investigation.

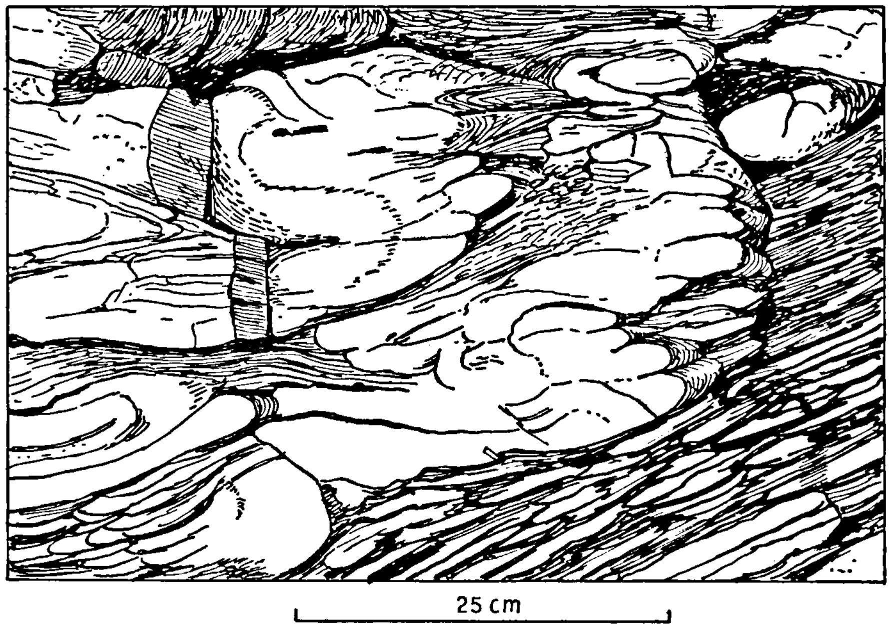

Fig. 14. Folded quartzite in biotite-schists; first phase.

4.1.2 *The supra-structure*

The epizonal Cambro-Ordovician, Devonian and Carboniferous shows a completely different pattern of folding. In general these rocks are deformed in tight folds with a steep to vertical axial plane which everywhere on sheet 6 is accompanied by an axial plane slaty cleavage. Bedding is usually crosscutting with regard to the cleavage. The largest structures are the Devonian synclines north of the Aston massif, the Tor and Llavorsi synclines and the Massana anticline south of the Hospitalet massif. These folds have an exposed width of about 2—3 km. Superimposed on these large folds are smaller ones of a size of some hundreds of metres, which are still represented on the map, for instance near St. Joan de Caselles in Andorra, where the contact Silurian-Devonian is thrown into several folds (see sections). Folds visible in outcrops with a size of several metres are quite frequent and the smallest visible folds have centimetre to decimetre dimensions. All these folds belong to the same generation, as axial planes and foldaxes are parallel throughout these various structures. The foldaxes have in general a gentle plunge to east or west or they are horizontal. The axial planes are steep to vertical and strike E-W.

North of the Aston massif two large Devonian synclines occur with Silurian in between. The northernmost syncline is cut off by the North-Pyrenean fault. These structures have been described by Allaart (1953).

In Andorra south and west of the Hospitalet massif the following structures are recognized: the Hospitalet anticline which is the continuation of the Hospitalet gneiss anticline, the Ransol syncline, which curves around the large mass of Silurian near Llorts, and the Valpeguera anticline. The latter anticline occurs only on the western part of the sheet, as it is cut off by the Soldeu-Lanous fault in the east. All these structures are tightly appressed folds with an axial plane cleavage in rocks of Cambro-Ordovician age. South of the Valpeguera anticline a large Devonian syncline occurs, the Tor syncline which due to its axial depression is almost wholly represented on sheet 6. The Cambro-Ordovician Massana anticline plunges to the east under the Silurian, but reappears again farhter east. The southernmost major structure is the rather complicated Llavorsi syncline in which the only Carboniferous rocks of this sheet occur except for some outcrops in the St. Barthélemy massif. Due to axial plunge the structure disappears to the east. Near Coll de la Devesa it splits in two synclines; the north branch can be followed to near Pas de la Casa, the south branch follows the contact with the Andorra granite.

Two aberrant structures occur on sheet 6. One is the Ransol syncline and has been described on p. 220. The other is the large mass of Silurian in the valley of the Valira del Norte near Llorts. This mass partly covers the Cambro-Ordovician discordantly and must have been thrust over the Ransol syncline. As the cleavage cuts undisturbed across the fault plane (section 2, 3) the accumulation of the black slates and its thrusting will have taken place before or early in the main phase.

Of particular interest is the transition of the flat metamorphic structures to the steep cleavage folds. This transition can be studied in the western plunge of the Hospitalet and Aston massifs. From the available data it appears that there occurs a transition zone where the one type of structure grades into the other. In the Aston massif this zone is still under investigation. In the Hospitalet massif the change can be seen in the section 1—6.

4.2 SECOND PHASE N-S STRUCTURES

In the Aston as well in the Hospitalet massif many small folds occur which postdate the main phase structures as they deform the cleavage or schistosity planes of these structures. These later structures have been described from various parts of the Pyrenees (Zwart, 1959, 1963, Boschma 1961, Guitard 1960). They were the special subject of a study of J. F. Lapré who mapped the Mounicou valley in the western part of the Aston massif.

Four sets of such small structures have been found; they can be determined with the aid of the trend of foldaxes and the attitude of their axial planes. In chronological order these are folds with N-S axes and recumbent axial planes, a conjugate system of two sets with steep axial planes striking NW and NE, and a set of folds with E-W axes and steep E-W trending axial planes. The succession has been established in different parts of the Pyrenees, for example in the Bosost area, the Tor valley and also in the Aston-Hospitalet massif.

Structures belonging to the second phase with N-S fold-axes are rather scarse in the mapped area, although its influence may be greater than apparent from outcrops or handspecimen. N-S folds occur mainly in the western part of the Aston massif on the ridge east of the Mounicou valley near the micaschist-phyllite boundary and from here also father west in the phyllites. The folds have a size not exceeding a few decimetres. Like the main phase folds they have rather flat lying axial planes, usually dipping gently to the west. The surface which is folded is the main phase schistosity plane, but an almost complete new schistosity has been formed parallel to the axial planes of the folds. This is also apparent in thin sections. In a number of cases the first schistosity is indicated by a parallel sericite fabric whereas the second schistosity is determined by a parallel arrangement of more coarse grained biotite. Interference patterns of folds of the first and second phase have been found (fig. 15).

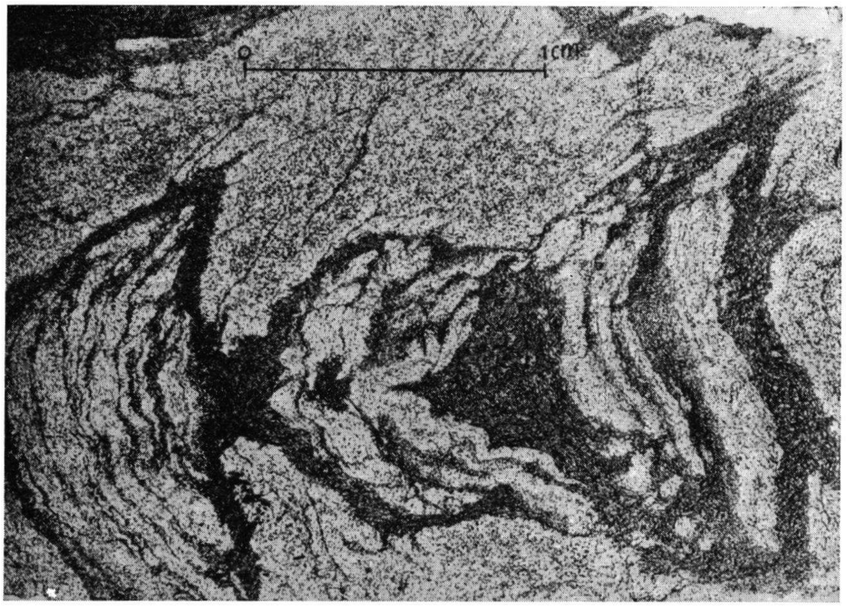

Fig. 15. Mushroom fold; interference of first and second folds.

They show the characteristic mushroom shape as described by Reynolds & Holmes (1954) and Ramsay (1962). Folds of this second phase have thus far been found exclusively in the infrastructure with flat lying schistosities. It is quite possible that this phase has been much more important than can be concluded from field evidence. At many places, also in the Hospitalet massif, porphyroblasts of aluminium silicates occur, which are rotated about N-S trending axes. Like in the Bosost area this is probably due to the second phase, but since rotations of crystals also took place during the first and third phases, it is not always easy to be certain about the phase to which the rotation belongs, without further detailed investigation.

Furthermore it is possible that more vestiges of the second phase are to be found in the granitic muscovite-biotite gneisses (or gneiss de Peyregrand). In these gneisses layers of finegrained granitic gneisses occur with quartz-sillimanite lenses which are interpreted by Raguin as metaconglomerates. The lenses are flat and elongated in a NNE direction so that these rocks have a distinct lineation. Folds have not been found in these gneisses and therefore the attribution of these peculiar rocks with quartz lenses to deformation of the second phase rests uncertain, but there are good reasons to assume that they recrystallized later than the first phase, as gneisses deformed by this phase have E-W lineations, and that they are earlier than the third phase which made irregular folds of the s-planes in the gneisses.

4.3 THIRD PHASE: NW-SE AND NE-SW FOLDS

Folds and other structures belonging to the third phase of deformation are very common throughout the Hospitalet and Aston massifs. We consider the two sets of folds with NW-SE and NE-SW striking axial planes as belonging to one conjugate system (Zwart 1963). The set with NW-SE direction is by far the most common. Especially abundant are folds of this set near El Serrat and Soldeu in Andorra, and near

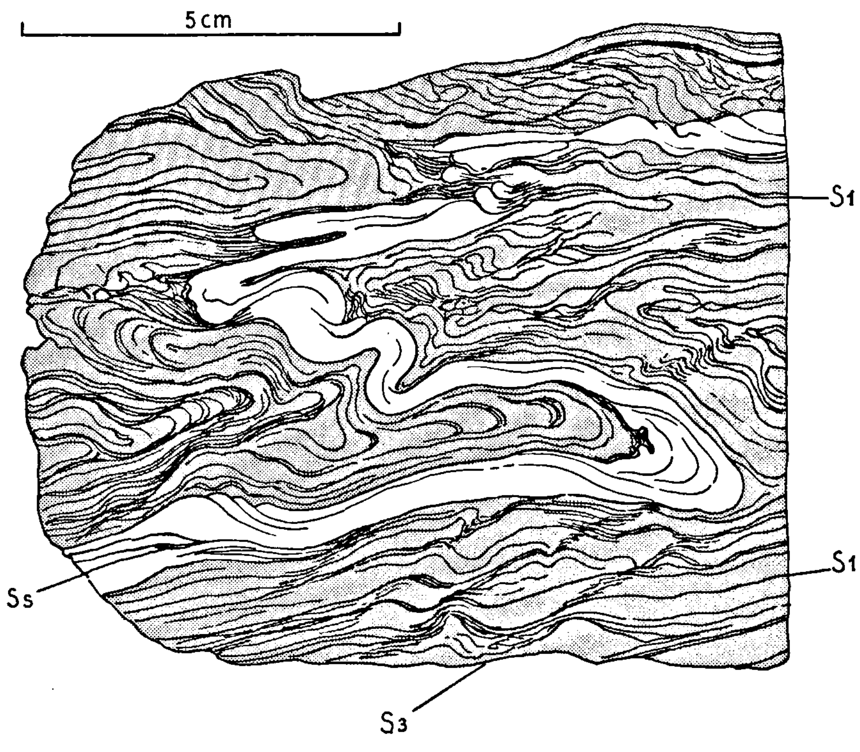

Fig. 16. Interference pattern of first and third folds.

Etang Fourcat, the Mounicou and Subra valleys in the Aston massif, but at many other localities as well, folds belonging to either of the sets are common. In phyllites, micaschists and to a lesser extent also in the migmatites the folds are rather regular as far as the attitude of the axial plane is concerned, but in the leucocratic gneisses of the Aston massif they are much less regular, with axial planes and foldaxes in various directions.

The folds belonging to this system are usually of minor dimension and seldom exceed a size of one metre, but they may be very intense so that large masses of rock are strongly contorted by these folds (fig. 16). Unlike folds of the second phase, those of the third are widespread in the steep phyllites of the suprastructure. In this case the intersection of the steep s_1 plane with the steep s_3 planes has a steep to vertical plunge and consequently the foldaxes plunge in the same direction. In the phyllites these folds are always accompanied by a crenulation cleavage. These steeply plunging folds have everywhere a strong asymmetry and for both sets the asymmetry has always the same sense. For the NW set a sinistral rotation and for the NE set a dextral rotation is found.

Fig. 17. Third folds with axial plane cleavage.

In the gentle dipping metamorphics the axial planes of folds of both sets have the same orientation as in the steep phyllites, but due to the different position of the s_1 plane the intersection has a gentle plunge to NW or NE. In the transitional area between infra- and suprastructure intermediate plunges occur. Where the s_1 surface was originally horizontal the folds are usually very open and show no asymmetry, but where this surface has a moderate dip, like in the Serrat area, the asymmetry becomes immediately apparent. Typical crenulation cleavages are mostly absent in the metamorphics due to the larger grainsize, but a coarse axial plane cleavage due to parallel biotite flakes may be present (fig. 17).

Particular structures belonging to this phase are to be found north of Soldeu in the micaschist cover of the Hospitalet massif. Here large andalusite and cordierite crystals of a size up to 10 cm often show a preferred orientation in NW-SE direction. Small wrinkles of the schistosity plane in the same direction occur frequently. After closer inspection it can be seen that these crystals contain an internal fabric, apparently due to small inclusions, which often makes an angle with the external lineation. This seems to be the result of rotation of these crystals with axes perpendicular to the schistosity plane. In all cases the rotation is sinistral, proving that the NW direction is a shear direction (Zwart 1963). This is in agreement with the sense of asymmetry of the folds. Consequently it is very probably that the NE set is the complementary shear direction and that both sets form a conjugate and contemporaneous fold system.

4.4 FOURTH PHASE; E-W FOLDS

A fourth set of folds has E-W trending foldaxes within a vertical E-W striking axial plane. Folds belonging to this set occur mainly in the metamorphics but also locally in the steep phyllites. They are widespread in the western part of the Aston massif for instance in the Mounicou and Subra valleys. They are scarce in the Hospitalet massif, except in its eastern plunge outside the map, but they are present in the Cambro-Ordovician of Andorra, usually as a crenulation cleavage. The folds of this phase generally are of the same size as those of the third phase (fig. 18, 19), but locally for example on the high ridge south of the Pic de Montcalm, they reach a size of several tens of metres. In general these folds have a gentle plunge but in the western part of the Aston massif where the original s_1 plane had a steeper dip, plunges from 30—40° are common. In the steep phyllites south of the Auzat granodiorite where the strike of the slaty cleavage s_1 is not E-W but ENE, the folds have also rather steep plunges. In the micaschists and phyllites the folds are not very tight, often rather open and always of similar shape. Their asymmetry, if present, depends on the attitude of the original s_1 plane. A crenulation cleavage, in large outcrops visible as a conspicuous joint system occurs parallel to the axial planes of the fourth folds. In the micaschists and migmatites such typical crenulation cleavage is usually absent, but a kind of fracture cleavage always occurs.

In the gneisses of the Aston massif many folds occur which certainly are to be correlated with the third and fourth phase. The plane that is folded is the schistosity plane of the augen- and flasergneisses and therefore these folds post-date the main phase. The folds are of minor size and are characterized by irregular shapes, and more or less randomly oriented foldaxes and axial planes (fig. 11). They obviously are produced by irregular flow and the rocks will have been in a very plastic state during this folding. This is also apparent from the metamorphism which accompanied this folding. All these gneisses are very strongly recrystallized and show in thin section almost granitic textures partly with obliteration of the original s-plane. Moreover completely unoriented patches and masses of granitic rocks occur in these gneisses. These features can easily be interpreted if one assumes that the rocks were in a partial state of melting or anatexis, making them very mobile and thus easy to deform. It has to be added that in the Hospitalet massif, where the same gneisses are not so strongly recrystallized, no such unoriented flow folding took place. Since in the western part of the Aston massif the highest metamorphism was reached around the third phase, as will be shown later on, it is very probable that this peak of metamorphism is reflected in the gneisses as their granitization and mobilization.

The same applies more or less to the migmatites in the southern part of the Aston massif, but here the orientation of foldaxes in NW- and E-W direction shows more directly the relations between metamorphism and folding.

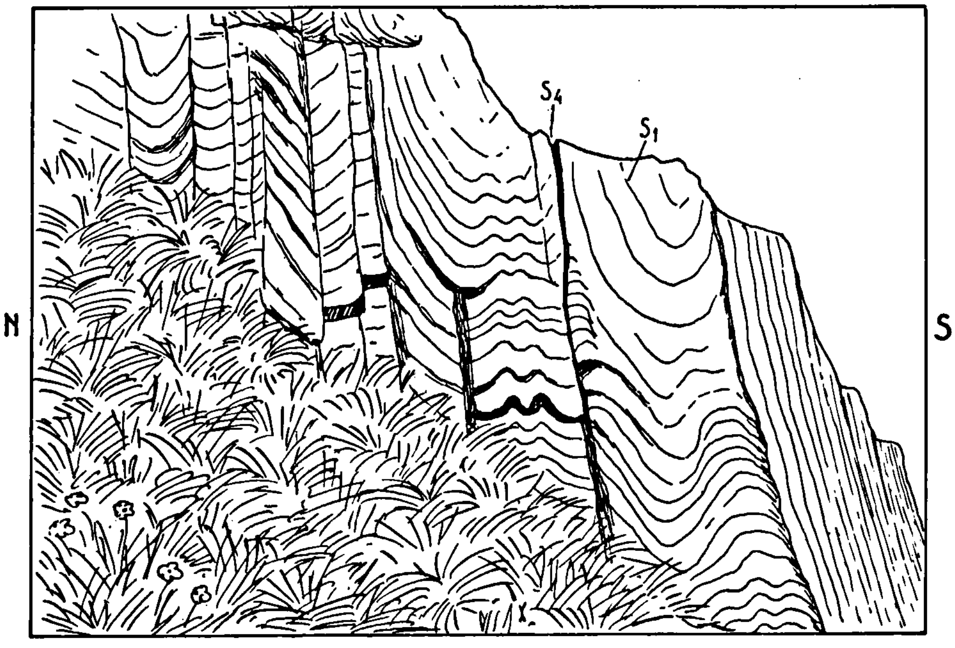

Fig. 18. First cleavage folded by fourth folds.

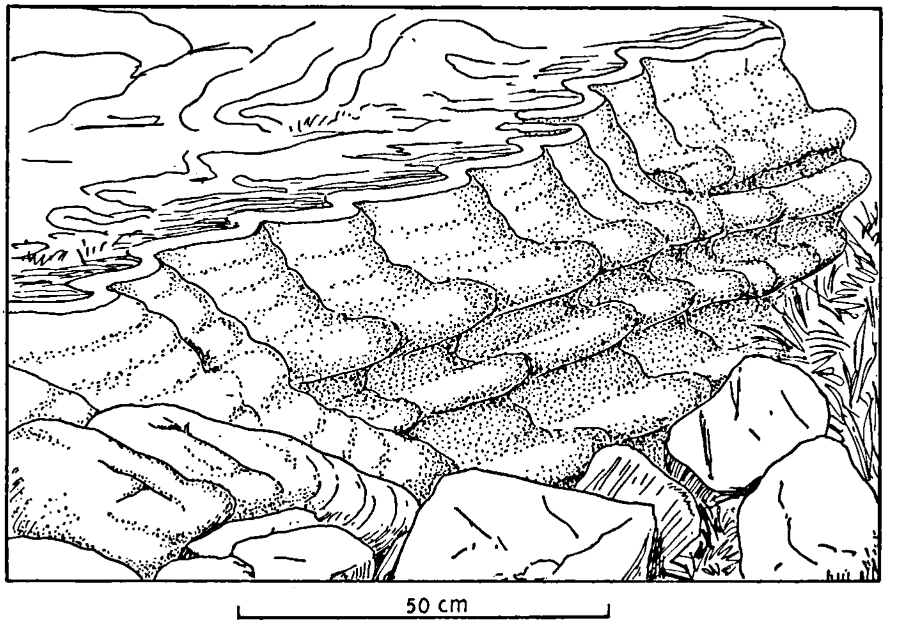

Fig. 19. Interference pattern of third and fourth folds; folded surface is first phase schistosity.

4.5 KNICKZONES

Folds of a special kind are the so-called knickzones (or kinkbands) which occur especially in the Ordovician and Devonian south of the Hospitalet massif. They are formed by somewhat irregular pairs of planes, between which the cleavage is kinked, so that it indicates a southward movement. Their direction is mostly E-W, but locally other directions prevail. It is a rather weak kind of deformation, much less intense than any of the previous phases of folding, and its total effect will be almost negligent. These knickzones have been formed in a tensional stress field at the end or after the cessation of the orogeny, either as an elastic rebound feature, or connected with a southward tilting of the vertical cleavage planes.

4.6 RELATIONS BETWEEN METAMORPHIC AND DEFORMATION PHASES

For the geologist who is interested in time relations between metamorphism and deformation the rocks of sheet 6 offer a wonderful opportunity for such a study. Especially in the micaschists of the Aston-Hospitalet massif various metamorphic minerals and structures occur, the relations of which can be investigated with satisfactory results.

The most persistent phase, though not the highest grade of metamorphic recrystallization occurred during the main phase of folding, during which all paleozoic rocks of sheet 6, except the later intrusives were metamorphosed. The Devonian, Silurian and the Cambro-Ordovician outside the Aston-Hospitalet massif were subject to a strong dynamo-metamorphism resulting in lowgrade (epizonal) slates and calcslates. As has been mentioned before, the slaty cleavage, a mineral orientation, occurs usually in a steep position parallel to the axial planes of folds. In the Aston and Hospitalet massifs a higher grade regional metamorphism operated at the same time, and resulted in schists and gneisses with low angle schistosity. The phyllites are bordered by a zone of biotite-muscovite-schists, and closer to the gneisses the schists were staurolite-andalusite-cordierite bearing. In the leucocratic gneisses occur biotite, muscovite and feldspar and no other index minerals. Therefore the grade of metamorphism of these rocks cannot be determined accurately. As they underlie the andalusite-schists, their grade will be the same or higher. Metamorphism of the staurolite-andalusite-cordierite-schists was in the cooler part of the amphibolite facies.

Higher grades of metamorphism are reached after the first folding phase (fig. 20). Migmatites and schists may contain sillimanite and no longer staurolite and andalusite. The leucocratic gneisses also become higher grade, whereas epizonal phyllites may be recrystallized in the staurolite-andalusite zone. During the first phase then, there was a simple arrangement of the metamorphic zones around the gneiss cores of the Aston-Hospitalet massif. After this phase the simplicity disappeared as a result of the rise of local heat fronts, although the general concentricity of the metamorphic zones is still there.

There are signs that the degree of metamorphism or the isograds started already to rise at certain localities during the second phase of deformation. In N-S folds belonging to this phase and occuring in the western part of the Aston massif near the epi-mesozonal boundary, it has been observed in several thin sections that the folded surface (s_1) consists mainly of sericite, whereas in the axial planes of the s_2 folds biotite is developed. This biotite obviously belongs to the second phase and hence indicates a rise of temperature during this phase. This is also apparent from interference structures of first and second phase, with sericite in the axial planes of the first, and biotite in those of the second generation of folds. These observations indi-

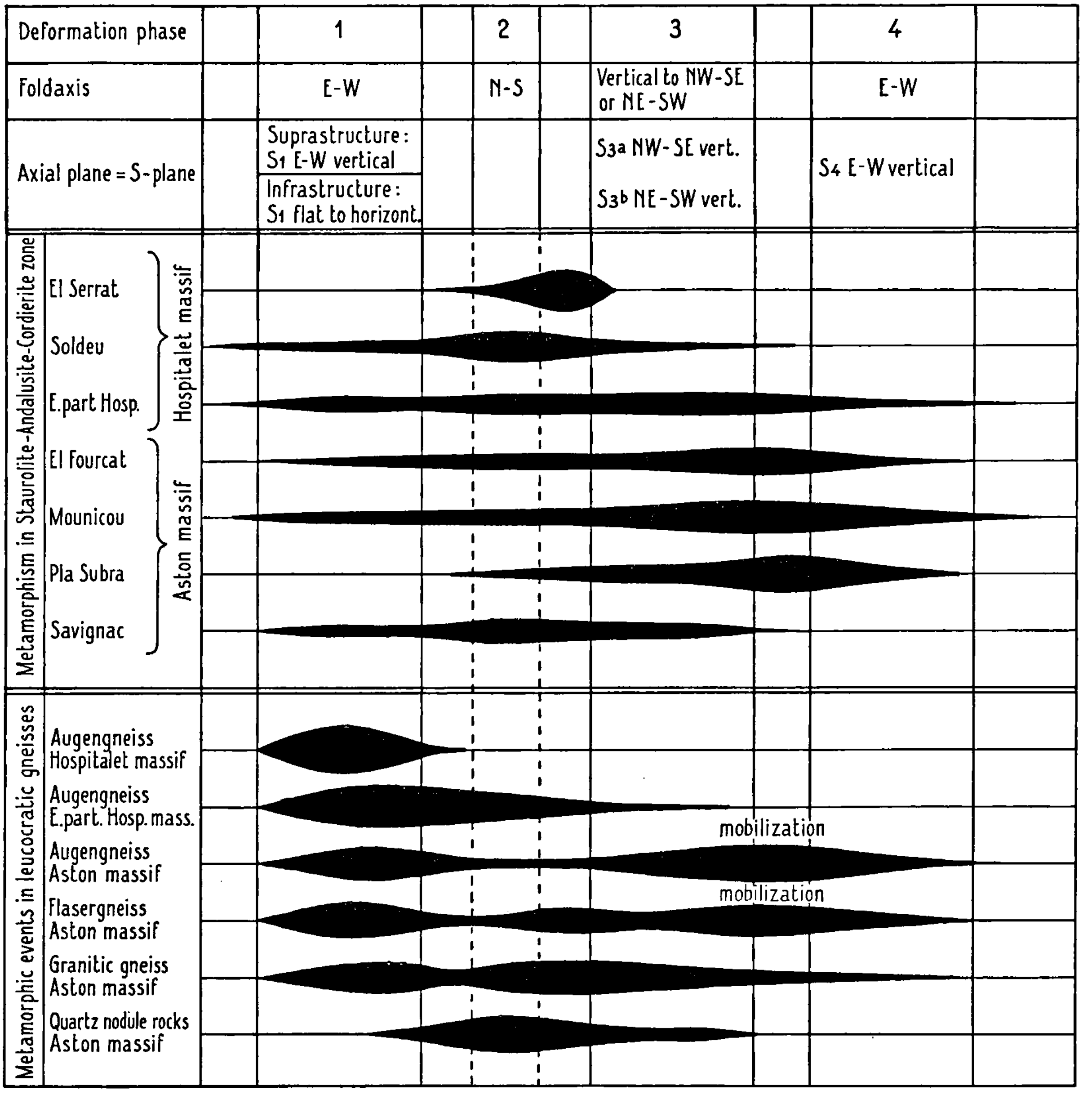

Fig. 20. Table showing relations between deformation phases and metamorphic events.

cate that during the second phase the biotite isograd was rising in the western part of the Aston massif.

In the Hospitalet massif the relations between crystallization and folding are rather complicated, especially in the central and eastern part. However, in the western part near El Serrat these relations are rather simple, as the growth of porphyroblasts lasted short in this region and can easily be dated with regard to the folding phases. Therefore first the Serrat area will be treated, then the eastern and central part of the Hospitalet massif.

The best place to study these rocks is in the valley of the Rio de Rialp, upstreams from El Serrat. From the examination of thin sections it appeared that the matrix of the schists consists of muscovite and quartz with a parallel orientation, although usually strongly folded. This fabric apparently dates from the main phase, which is corroborated by the occurrence of E-W folds with s_1 as axial plane. The grade of metamorphism was epizonal. No record of the second phase has been found in this area, but there is abundant deformation of the third phase, consisting of folds with NW-SE trending axial planes. Most of these folds are of minor size. In these rocks abundant and large-sized crystals of staurolite, andalusite and cordierite occur. In the field it can be seen, that these crystals contain folds. In other cases andalusites or staurolites are rotated in the limbs of folds. In thin sections it appeared that the matrix of the schists is strongly microfolded. Porphyroblasts of staurolite, andalusite and cordierite contain an internal fabric determined by rows of inclusions mainly of small quartz grains. Biotite forms small porphyroblasts often also with a si, and roughly oriented parallel to the axial planes of the microfolds (fig. 17). From the internal fabric in biotite is it clear that the crystals did not grow in this direction, but were rotated into it by the folding process. Deformed crystals are therefore quite common. The staurolite crystals show, almost without any exception, a planar si in a strongly folded matrix. This clearly indicates that these crystals grew before the third folding phase which was responsible for the formation of the microfolds. On the other hand the crystals postdate the main phase which produced the schistosity inherited by the crystals. As the shape of the staurolite is usually short prismatic and this mineral apparently rather competent with regard to the schistmatrix, deformation of the staurolite is very rare (fig. 21, 22).

Similar relations between internal fabric and folds of the schists exist in andalusite and cordierite. In these crystals also the schistosity is inherited as a planar fabric, but due to the third phase folds, the crystals may be rather strongly deformed (fig. 23). Especially andalusite seems to be folded quite easy, and without exception the folds of the crystal and the rotational extinction keep the same pace, so that after unrolling the fold the inclusions are planar.

Summarizing the results from the El Serrat area, it can be stated that during the main phase metamorphism was epizonal and produced muscovite-schists. After this phase temperature rose so as to form biotite, staurolite, andalusite, cordierite and some garnet. After cessation of the growth of these minerals the rocks were strongly folded by the third phase with NW-SE striking axial planes.

Going eastward from El Serrat the relations change gradually. In the first place the schists contain biotite which shows an E-W lineation by its fabric habit. This lineation apparently formed during the main phase and indicates that here metamorphism was in the mesozone at that time. On these rocks again a staurolite-andalusite-cordierite metamorphism is superposed much like in the El Serrat area. In the Ransol and Incles valleys the time of crystallization of aluminium silicates lasted even longer. In these schists clearly two lineations are present. The first one in E-W direction is determined by the fabric habit of the micas and is parallel to minor isoclinal

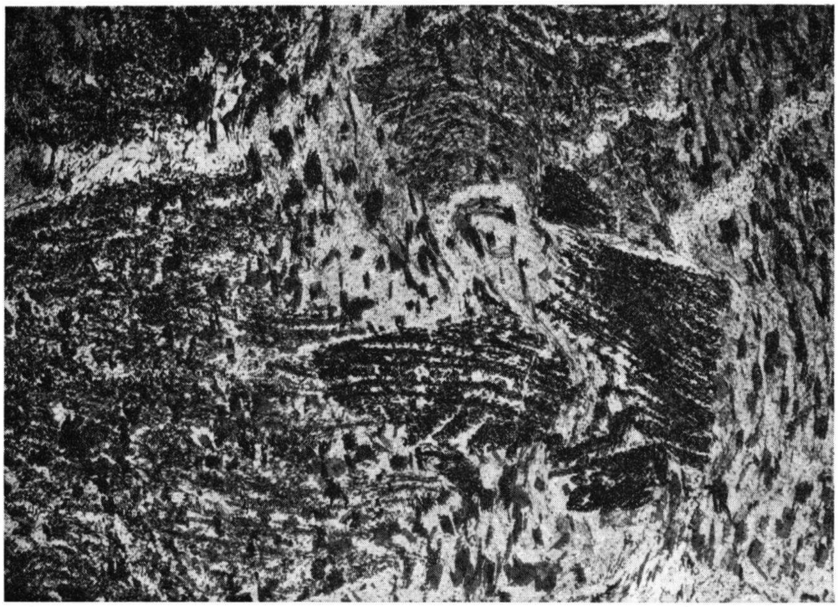

Fig. 21. Staurolite with planar si in matrix folded by third folds; (El Serrat).

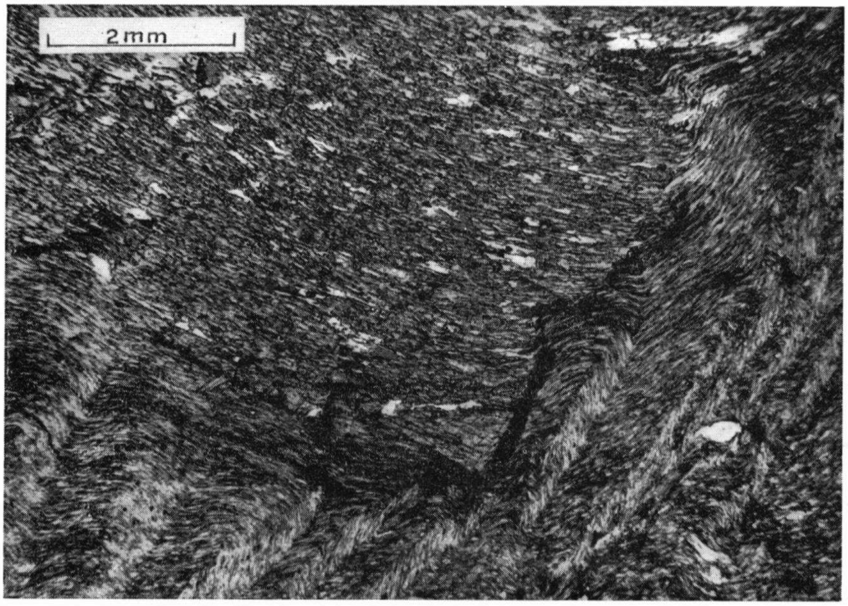

Fig. 22. Andalusite with planar si in matrix folded by third folds; (El Serrat).

folds. The other lineation has a NW-SE direction and is indicated by the preferred orientation of long andalusite and cordierite crystals. Closer inspection of these schists reveals that the E-W lineation can be followed in the porphyroblasts as included lineations, much the same as a schistosity can be inherited by rows of inclusions. In most porphyroblasts aligned in NW-SE direction it can be seen that the included lineations make an angle with the outside lineation and not uncommon are crystals with s-shaped trends of inclusions. In any case where the outside lineation can be seen entering the crystals the direction is the same, suggesting a sinistral sense of movement.

It appeared that staurolite, andalusite and cordierite were already present during the main phase as several of these crystals are rotated about E-W axes. In these cases the matrix is strongly flattened with regard to the crystals, indicating that penetrative movements have taken place after the growth of these crystals. Furthermore some andalusites with spiral shaped si, rotated about E-W axes have been found. They crystallized during the main phase.

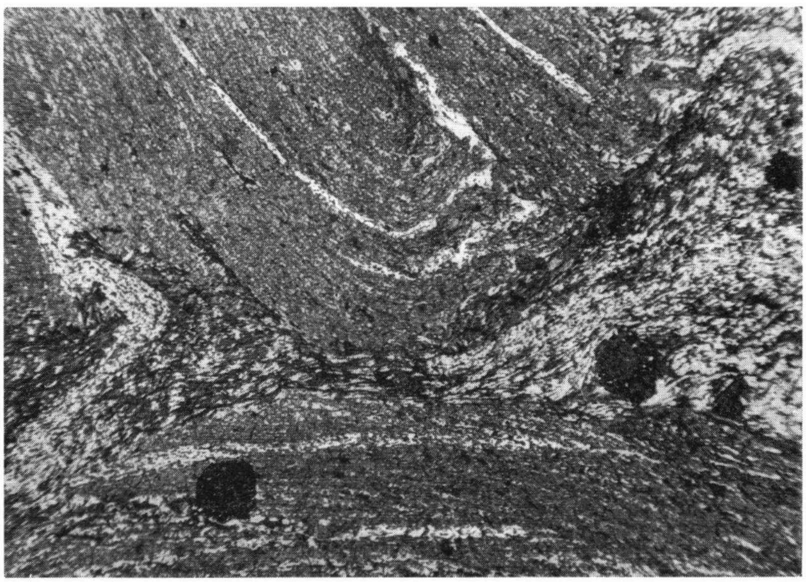

Fig. 23. Andalusite folded by third folds; (El Serrat).

Other observations which are more difficult to interpret, concern porphyroblasts of staurolite and andalusite containing a folded si. The matrix around these crystals, however, shows only a planar se, without folds. Moreover the crystals are rotated with E-W axes and the matrix curves strongly around the porphyroblasts. It is possible that the helicitic folds are incipient main phase folds. All the different patterns of crystals with no inclusions, with helicitic folds, with planar inclusions, but rotated about E-W axes and with a strong curvature of the schistosity around the crystal point into the same direction, crystallization of these minerals early in and during the first phase of deformation.

Helicitic folds of the third phase have been found in staurolite, cordierite and biotite, indicating that crystallization went on after this phase (fig. 24). In the eastern part of the Hospitalet massif helicitic folds of the fourth (E-W) phase have been observed in andalusite so that locally metamorphism outlasted this phase. There is no doubt, however, that the main period of crystallization lies between the first and third phase, like in the Serrat area.

Summarizing the results from the Hospitalet massif it can be stated that porphyroblastesis started early in or may be even before the first (main) phase of deformation in the schists bordering the gneisses. This process went on after this phase, reached its maximum before the third phase but continued locally until after the fourth phase. Farther away from the gneisses, in the Serrat area, the porphyroblasts grew in an epizonal phyllite. Here these minerals formed during a relatively short period, between first and third phase, contemporaneous with the optimal growth farther east (see fig. 20).

At several localities in the Aston massif micaschists with abundant aluminium silicates occur, for instance in the surroundings of Etang Fourcat near the border

Fig. 24. Helicitic folds, third phase in andalusite; Inclès valley.

between France and Andorra, in the Mounicou and Subra valleys in the western part of the massif, in the Arties valley and along the northern border of the massif.

Near the Etang Fourcat large andalusite and cordierite crystals are very common. The schists here contain a s_1 due to the main phase, which is strongly folded in NW direction by the third phase. In several thin sections the porphyroblasts contain a planar si about which the matrix is strongly curved. In most sections evidence of rather late crystallization is present. Helicitic folds of the third phase occur in andalusite and cordierite and these minerals are later than this phase.

More or less the same relationships occur in the Mounicou valley outside the area where much granites are exposed. The earliest porphyroblasts occur in a matrix of muscovite and biotite which strongly curves around the crystals.

Porphyroblastesis was however more important during, before and after the third phase. Typically static, unoriented staurolite, andalusite, cordierite and biotite crystals with a planar si and not disturbing the schistosity are very common (fig. 25). Also crystals with helicitic folds of the third phase are abundant. Other crystals contain a planar si in a microfolded (third phase) matrix with a more or less well developed axial plane schistosity. This new s-surface curves around the crystals. Some porphyroblasts show helicitic folds of the third phase, but after the growth of the crystals deformation went on, the matix flattened and a new schistosity, s_3, was produced. In this case the crystals actually grew during the third phase (fig. 26).

Near the western edge of the micaschists the porphyroblasts are superposed on epizonal phyllites, much like in the El Serrat area. The time relationships are somewhat similar to those in the Mounicou valley, but growth of the porphyroblasts started later, generally not before the third phase. Their younger age than the main phase is also shown by the random orientation of the crystals. Most porphyroblasts

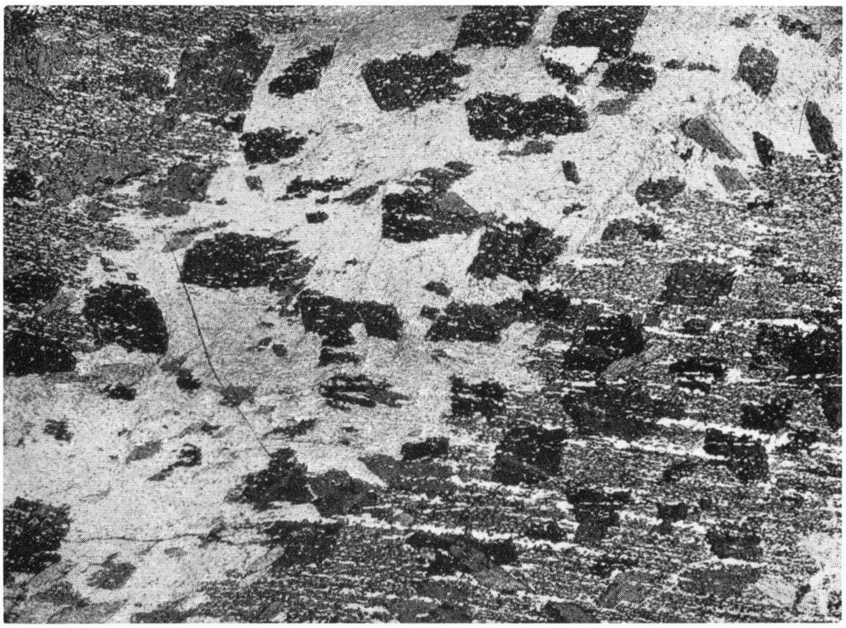

Fig. 25. Andalusite and biotite porphyroblasts with planar si in unfolded matrix (Mounicou).

grew during or after the third phase as shown by the rather frequent occurrence of helicitic folds. This process went on, although less active, during and after the fourth phase (fig. 20).

In the micaschists along the northern border of the Aston massif staurolite, andalusite and cordierite have also been encountered. Partly they formed early, probably during the first phase, as shown by rotated crystals.

Summarizing these results from the Aston and Hospitalet massif, it appears that the earliest, synkinematic (with regard to the first phase) porphyroblasts occur in schists close to the gneisses, and that farther away from the contact porphyroblastesis starts gradually later. In both massifs the culmination of the metamorphism occurred around the third phase, close to the gneisses as well as father away, so that during this time aluminium silicates grew in epizonal phyllites.

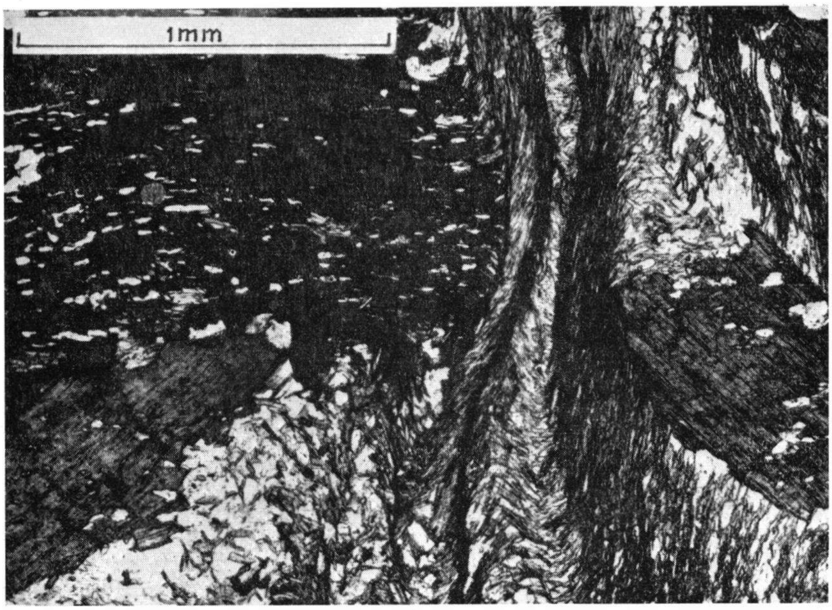

Fig. 26. Biotite porphyroblasts with s_3 curving around crystal (Mounicou).

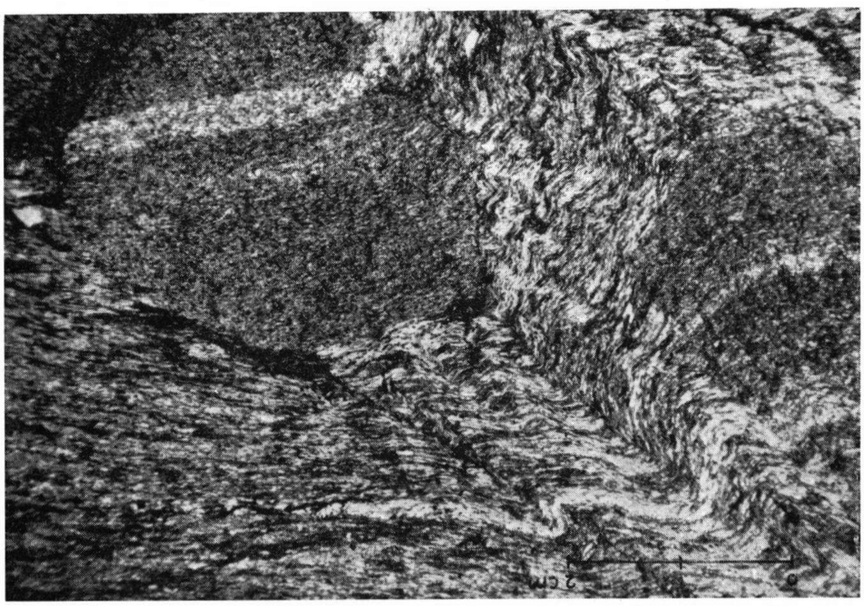

Fig. 27. Cordierite in hornfels; fourth folds later than crystal (aureole of Bassiès-Auzat granodiorite).

A similar technique as the one applied to the micaschists can be used for the contact metamorphic hornfelses of the Bassiès-Auzat and Andorra-Montlouis granodiorites. In the aureole of the Bassiès-Auzat batholith minor folds, cleavages and lineations of the fourth phase are common. In thin sections it can be seen that porphyroblasts of andalusite and cordierite (usually altered into sericite and chlorite) contain a planar si within a microfolded matrix (fig. 27). Further some crystals may be slightly rotated. Obviously these crystals predate the fourth phase. As no structures of the third phase have been found, dating with regard to it was not possible. It is likely, however, that the contact metamorphism and with it the intrusion of the granodiorite postdates the third, but predates the fourth phase of deformation. For the Andorra-Montlouis granodiorite it was found that in Andorra folds of the fourth phase are hornfelsized, but farther east, near the Bouillouse lake (outside our map), the same relations as in the aureole of the Auzat granodiorite have been found. Contact metamorphism started therefore before the fourth, but continued after this phase. The intrusion of the granodiorite must also have started before the fourth phase.

4.7 FAULTS AND MACROJOINTS

Many faults and large joints occur on sheet 6, but only a few of them are very important as far as the amount of displacement is concerned. These important ones are the North Pyrenean fault, the Mérens fault and the Soldeu-Lanous fault. Many smaller faults and macrojoints occur on sheet 6, especially in the gneisses of the Aston-Hospitalet massif.

The three large faults have in common that the fault plane is very steep to vertical and that the sense of movement is the same e.g. a downthrow of the southern block. The throw is largest for the North Pyrenean fault and is estimated at 4—5000 m in the area of sheet 6. Its properties have been described by de Sitter (1953) and de Sitter and Zwart (1959) and for more details I refer to these publications.

The Mérens fault is also very important and has a throw, which on the eastern part of sheet 6 has to be estimated at several thousands of metres. Its western part lies in Cambro-Ordovician phyllites, where it is difficult to locate and the amount of slip cannot be determined. More to the west the fault continues on sheet 5, where it gradually dies out in the Cambro-Ordovician. To the east the throw rapidly increases and it forms the separation between the Aston and Hospitalet massifs. Still farther east, outside our map, it can be continued all the way to the Mediterranean and consequently it has a length of at least 100 km. On sheet 6 the fault is a steep upthrust; the dip of the faultplane being 60—80°. Farther east it seems to flatten and there it has an overthrust character which also involves Mesozoic rocks indicating that at least some movement is of Mesozoic or Tertiary age. The displacement of the fault on the eastside of sheet 6 is in the order of magnitude of 2—3 km and may be even more. Between the Aston and Hospitalet massif the structure is somewhat more complicated by the fact that a second subsidiary fault accompanies the Mérens fault a few hundred metres to the south. This second fault, which has been called the Pinet fault (Zwart, 1958) is the northern boundary of the Hospitalet massif. Between the two faults occurs a sedimentary zone consisting of phyllites and limestones which is correlated with the Ransol formation (p. 199). These rocks are only weakly metamorphosed in contrast with the gneisses and migmatites of the Aston and Hospitalet massifs. It seems likely, especially in view of the continuation of this sedimentary zone to the east and the west, that it represents the original cover of the Hospitalet massif which is sheared off its basement by the movements along the Mérens fault. The gneisses of the Aston massif have undergone an intense mylonitization as a result of the fault movements. This mylonite zone occurs especially in the migmatites and gneisses, and is less conspicuous in the schists in the western part; it may be up to 500 m thick. Various degrees of mylonitization can be observed, from lightly cataclastic augengneisses, through strongly sheared gneisses to laminated finegrained mylonites in which almost nothing of the original gneiss can be recognized. The latter rocks occur often along the northern border of the mylonite zone and the farthest removed from the fault itself. Folds are frequent in the mylonites. Some folds have gently plunging axes, but most have steep axes plunging down the dip of the schistosity plane. Most of these folds are asymmetric with a dextral sense of movement. In a few samples two sets of folds occur, clearly indicating that movements in more than one direction have occurred. In view of the fact that steeply plunging folds are the most conspicuous, it seems probable that strike slip movements were the last movements to occur, although the vertical component is certainly much more important than the horizontal one.

The mylonites are often strongly banded, dark bands alternating with light coloured bands. The latter consist almost entirely of quartz with a strong preferred lattice orientation which is very conspicuous when using the gypsum plate. When these bands are folded it is evident that the quartz orientation has some relation with these folds as they cannot be unrolled. Therefore recrystallization of quartz apparently operated during the mylonitization.

The "gneiss granulé" described by Raguin (1963) from a locality near Mérens, east of the Ariège river, and interpreted as metavolcanics, lie in the mylonite zone of the Mérens fault. To our opinion these rocks are mylonitized migmatites and the small feldspar crystals are porphyroclasts, as evident from thin sections.

TABLE 6.

SiO_2	71.11	74.53	74.72
TiO_2	0.41	0.10	0.06
P_2O_5	0.22	0.20	0.18
Al_2O_3	14.20	14.57	14.14
Fe_2O_3	1.56	0.38	0.25
FeO	1.63	0.35	0.72
MgO	0.97	0.37	0.30
CaO	1.12	0.96	0.75
Na_2O	3.30	4.60	3.52
K_2O	4.40	3.35	4.68
H_2O	0.80	0.33	0.42
	99.72	99.74	99.74

Analyses by petrochemical laboratory, Department of Geology, Leiden. For locality of specimens see fig. 3.

The gneisses of the Hospitalet massif south of the fault are not mylonitized.

The age of the Mérens fault is difficult to ascertain. Probably movements took place at several times. It is likely that the first faulting movements occurred already during the Hercynian orogeny, but it is certain that Mesozoic or Tertiary displacement took place, as farther east Mesozoic rocks are involved in the fault movements.

Three chemical analyses of mylonites have been made (table 6). The samples originate from the ridge west of the Etang de Soulanet where the mylonite zone occurs in the micaschist-derived migmatites. The samples were, however, rather leucocratic with regard to the normal migmatites in the surroundings. From the analyses it is clear that they are almost identical with those of the leucocratic gneisses of the Aston and Hospitalet massif and therefore it seems likely that they are pieces of these rocks brought up along the Mérens fault. If this is true very little change has accompanied the mylonitization. It has to be added that the three samples are not as strongly mylonitized as many other rocks and they can be best described as sheared gneisses.

The Soldeu-Lanous fault is less important than the Mérens fault. It has no such intense mylonitization and not such a large displacement as the latter fault. It forms the southern boundary of the Hospitalet massif and can be continued farther east. To the west its character changes or perhaps it dies out and another fault lies in its continuation. Here a fault runs around the large mass of Silurian of Llorts in the Valira del Norte valley (see also p. 222).

Numerous faults occur in the gneisses of the Aston and Hospitalet massifs. As there are no marker beds it is difficult to ascertain whether there is any displacement, but as many of these faults are accompanied by mylonite zones of several metres thickness, there must have been some movement. Others probably have no or very little displacement and are macrojoints. They can be mapped with the aid of aerial photographs. A well developed mylonite zone occurs near the Riète dam. Here also steep folds occur in the laminated mylonites, comparable to those of the mylonite zone of the Mérens fault. In this case also a strong preferred orientation of quartz is present.

5. PETROGENESIS

For most of the rocks of sheet 6 the geologic history and their origin has been established satisfactorily with the exception, however of one large group of rocks, the muscovite-gneisses and granites of the Aston-Hospitalet massif. The origin and age of these rocks is more difficult to ascertain and for this reason they deserve to be treated separately.

At the beginning of our survey we had the impression that all these gneisses were orthogneisses; that is intrusive granites deformed to augengneisses during the Hercynian orogeny (Zwart 1954). Later we found reasons to doubt this interpretation and the possibility of a metasomatic or sedimentary origin was considered. The homogeneity of the gneisses without any certain sedimentary layer in it, their chemical composition and their sharp contacts with the micaschists have convinced us that these rocks can be interpreted best as orthogneisses, a view which was fully accepted during the Azopro excursion in 1963 and also by our french colleagues, who for a long time upheld their belief in a sedimentary or volcanic origin.

There can exist no doubt about the age of the gneissification of these rocks as their structures are homoaxial with the covering micaschists, a feature which is especially clear in the Hospitalet massif. The imprint of the schistosity and lineation must be of Hercynian age and consequently the age of the original granite must be greater. Thus far it is not possible to make a definite statement about this age, but three possibilities exist: 1) the granite belongs to the Hercynian orogeny and intruded in the Cambro-Ordovician sediments shortly before the first phase of deformation, 2) they do not belong to the Hercynian orogeny but intruded long before it, for example in late Ordovician time, and can in that case be considered as an indication of a Caledonian magmatism, 3) they belong to an older orogeny and the Cambro-Ordovician is the original unconformable cover of these gneisses which then have been deformed for the second time during the Hercynian orogeny. In the latter case the relationships are quite similar to those of the Pennine nappes of the Alpes.

It seems to us that the first alternative is the most likely one, mainly in view of the tectonic complexities arising from the third possibility which invokes the presence of large nappe structures in the Pyrenees, as the orthogneisses are again underlain by Cambro-Ordovician metasediments. Other arguments are the absence of any unconformity or a basal conglomerate in the schists covering the gneisses. It is true that an unconformity will have been largely obliterated by the Hercynian orogeny but locally the unconformity might have been spared. Further it is remarkable that everywhere in the Pyrenees where these gneisses occur, they are surrounded by at least mesozonal metamorphic rocks so that it seems probable that some connection between these gneisses and the regional metamorphism exists, which makes it improbable that the second hypothesis is the right one. A difficulty in our view is the origin of the granitic magma which in most orogenes is generated by regional metamorphism and anatexis, phenomena usually occurring rather late in the orogeny and not as early as has to be assumed in our case. For the nappe hypothesis any stratigraphic proof is completely lacking in the Pyrenees and therefore this hypothesis has to be considered as questionable. The solution of this problem has to await radiometric dating which will be executed in the near future. Whole rock analyses probably will tell us the age of the original granite.

For further petrogenetic considerations the age of the original granite is of no concern as during the first phase of the Hercynian orogeny all gneisses occurred as homogeneous augengneisses, the only local difference being the grainsize of the rocks which varies a little throughout both massifs. After the main phase several acts of deformation and metamorphism greatly changed these gneisses to different rock types (fig. 20). From the chemical analyses it appeared that these processes involved little or no change in composition. Also the mineralogical composition did not vary very much, and therefore there is no reason to accept fundamental differences in the rocks as has been done by Destombes and Raguin (1963).

In the western part of the Hospitalet massif the augengneisses occur in their original state and have not been subject to later recrystallization. In the eastern part of this massif, from the Ariège valley eastwards, these gneisses are strongly recrystallized after the imprint of the schistosity, resulting in less strongly oriented rocks, or even completely unoriented granitic rocks. No mobilization or folding accompanied this recrystallization in the Hospitalet massif.

More complicated are the relations in the Aston massif which has a greater variety of rocks. In the eastern and northern part augengneisses occur, grading into flasergneisses in the west. These flasergneisses grade on their turn into granitic gneisses and gneissose granites. Especially in the latter gneisses particular layers of gneissose granitic rocks with quartz-sillimanite nodules occur.

In the eastern part of the massif the original augengneisses have been changed by recrystallization, granitization and mobilization. In the field the augengneiss character is still evident but locally the rocks are invaded by smaller or larger masses of granite, the largest one being the Ax granite. These granites often cut discordantly the augengneiss structures and are consequently later than the gneiss. In thin sections it appears that the augengneisses are strongly recrystallized and have an almost granitic texture. Mobilization is evident from the strong contortion of the s-planes with irregular foldaxes. Furthermore rotated fragments of augengneiss occur in the granite, showing that the latter have been in a very plastic, or perhaps in a completely molten state (fig. 11). As has been discussed earlier, this mobilization and granitization took place during the third and fourth phase of deformation. Locally the granites intruded for a short distance in the gneisses as evident from some dykes, but even the large Ax granite did not intrude into the micaschists. The only exceptions are probably the granites and pegmatites in the Mounicou valley and a granite body north of the Pic de l'Estagnole, both occurring in micaschists. They probably originated as a magma in the gneisses and intruded in the micaschists, although there are indications that some in situ granitization occurred also.

To the south and west the Aston augengneisses grade into flasergneisses by gradual disappearance of the feldspar eyes. The schistosity of these gneisses is folded in a similar manner as in the augengneisses and also the same masses of granite occur here. Therefore it is obvious that both types of gneiss have undergone the same process of mobilization and granitization and the difference between both gneisstypes dates from an earlier time. The gradation of the two types and the occurrence of large bodies of augengneiss in the flasergneiss and their chemical analogy indicates that both rocktypes were originally the same kind of gneiss, which by recrystallization after the main phase lost their eyed character resulting in schistose gneisses. This process must have taken place between the first and third phase (see fig. 20).

Farther west the flasergneisses change again to a more regular, finer grained and more granitic gneiss. Feldspar eyes are rarely present. The schistosity is seldom folded and completely unoriented granites in small or large bodies are rare. These granitic gneisses (= Gneiss de Peyregrand of Raguin and Destombes) show in thin sections a granitic appearance with only a preferred orientation of the micas. They will have gone through a stage of static recrystallization after they were deformed to tectonites during the main phase. Presumably they also were augengneisses as testified by the scarce occurrence of feldspar eyes. Due to the recrystallization most feldspar eyes were replaced by a granoblastic intergrowth of quartz and feldspar. It is a striking that no mobilization has accompanied this process in this part of the Aston massif. The cause of the absence of mobilization is not evident; it may be due to lower temperatures so that the rocks were not as close to their melting point as those farther east. This could not be ascertained with mineral associations, but the hypothesis is supported by the absence of granites. Another possibility is that during the recrystallization less water was present and in this case no temperature difference would have existed to explain the absence of mobilization.

Fig. 28. Quartz-nodule gneiss with discordant vein.

Of special interest are layers of fine grained gneissose granites with the quartz nodules. They occur most frequent in the granitic gneisses of the western part of the massif, but they occur also in the flasergneisses and even in the augengneisses. They are absent in the Hospitalet augengneisses.

These rocks are interpreted as metaconglomerates by Raguin and Destombes (1960, 1963). Serious objections against this hypothesis exist. According to Raguin and Destombes these layers are the metasomatic equivalents of the conglomerates in the micaschists and phyllites in the Pradières and Mounicou valleys. In the sections published by Raguin and Destombes the change from phyllite or schist to granitic gneiss takes always place in the air. Nowhere is this change exposed as the boundary between schists and gneiss is everywhere sharp and not gradational. These relations between the metasediments and the granitic gneisses make such a correlation extremely doubtful. Moreover, if the quartz nodule rocks and the enclosing gneisses should represent metasediments, a very important metasomatic introduction of silicon and alcali's and a removal of aluminium, iron and magnesium would have taken place. Raguin and Destombes presume that such changes in chemistry occurred.

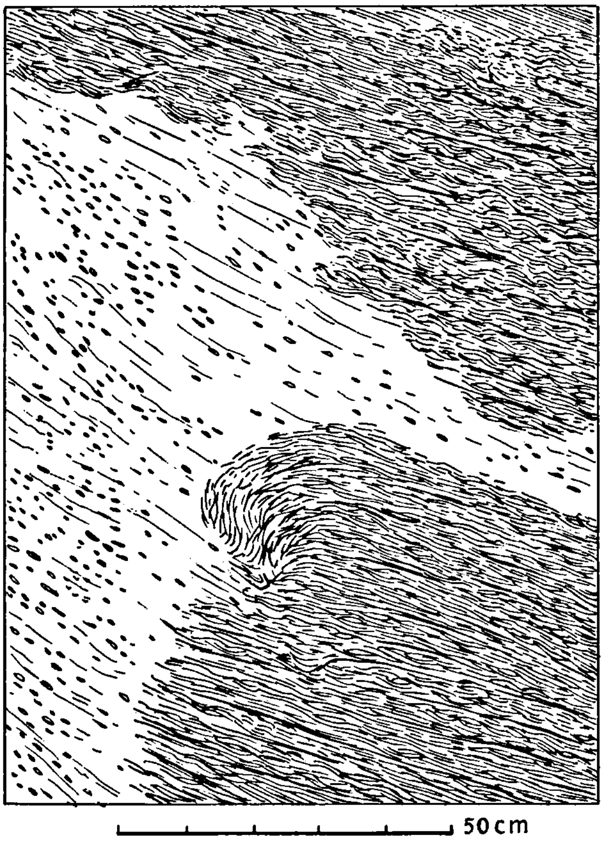

Fig. 29. Discordant contact between quartz-nodule gneiss and enclosing gneiss.

If, like I suppose, the whole leucocratic gneiss series is of ortho-origin, as strongly suggested by their homogeneity and composition, these quartz nodule rocks cannot be of sedimentary origin and moreover it is not necessary to assume such important chemical changes. Another argument against a correlation with the conglomerates in the Cambro-Ordovician is that the latter consist of closely packed quartz pebbles whereas the quartz nodules in the gneissose granite occur separately. According to Raguin and Destombes the smallest quartz pebbles did not survive the metamorphism and were digested so that only the largest pebbles are preserved. Further it is remarkable that the nodules always consist of quartz and sillimanite. It seems hard to understand why quartz pebbles should have such affinity to sillimanite.

One field observation made near Etang de Peyregrand, proved that the quartz nodule layers are not always concordant but may be cut off by the normal gneiss (fig. 28, 29). This is not a sedimentary feature. It is true, however, that many of these layers occur near the base of the leucocratic gneisses in the western part of the Aston massif. Many other occurrences, however, are spread throughout the gneisses and do not occupy special stratigraphic levels.

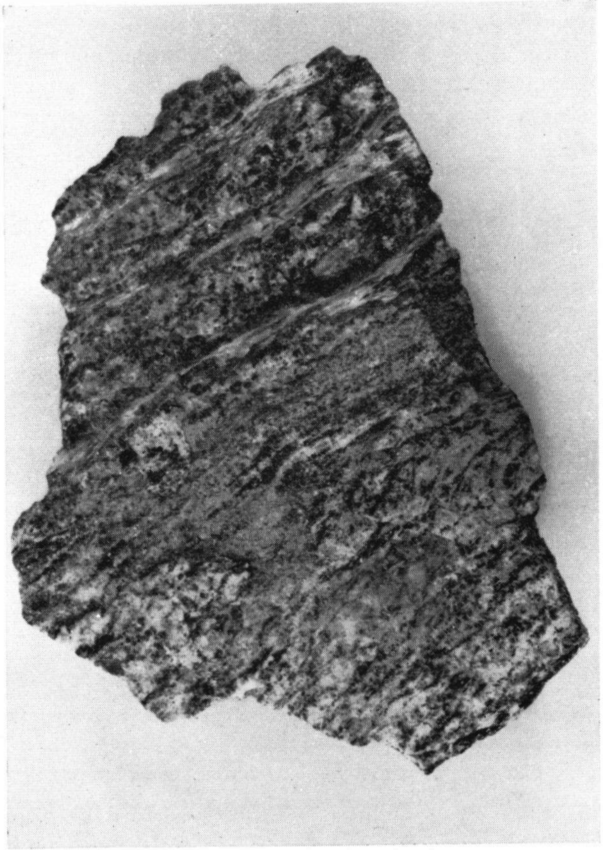

Fig. 30. Shearplanes with quartz and sillimanite in granitic gneiss.

In our explanation therefore the point of origin is not a sediment, but an orthogneiss. In trying to interprete these rocks the following data have to be kept in mind:

1. the rocks in which the quartz pebbles occur have a granitic tecture, indicating that recrystallization after the main phase was important,
2. the quartz-fibrolite nodules are elongated and flattend in NW to NNW direction, hence they are tectonites,
3. shearplanes occur in many of these rocks, and these planes are always lined with a thin veneer of quartz and sillimanite (fig. 30),
4. the shearplanes show lineations in the same direction as the quartz nodules,
5. small granite patches may cut across these shearplanes.

From these observations it can be concluded that shearing movements took place in the gneisses and in view of the direction of the lineations they took place during the second or third phase of deformation. On these shearplanes solution of alcalis occurred, leaving silicon and aluminium behind and resulting in the growth of quartz and sillimanite. By continued recrystallization the rocks became more granitic and the quartz-sillimanite layers concentrated in nodules (fig. 20). That recrystallization and granitization were active after the formation of these shearplanes is shown by the small granite patches which cross the shearplanes (fig. 31). The preferred occurrence of these quartz nodule layers near the base of the leucocratic gneisses can be explained by the fact that the boundary with the underlying schists or migmatites is often a movement zone. It should be added that in the mylonite zone of the Mérens fault Verspyck found similar quartz nodules.

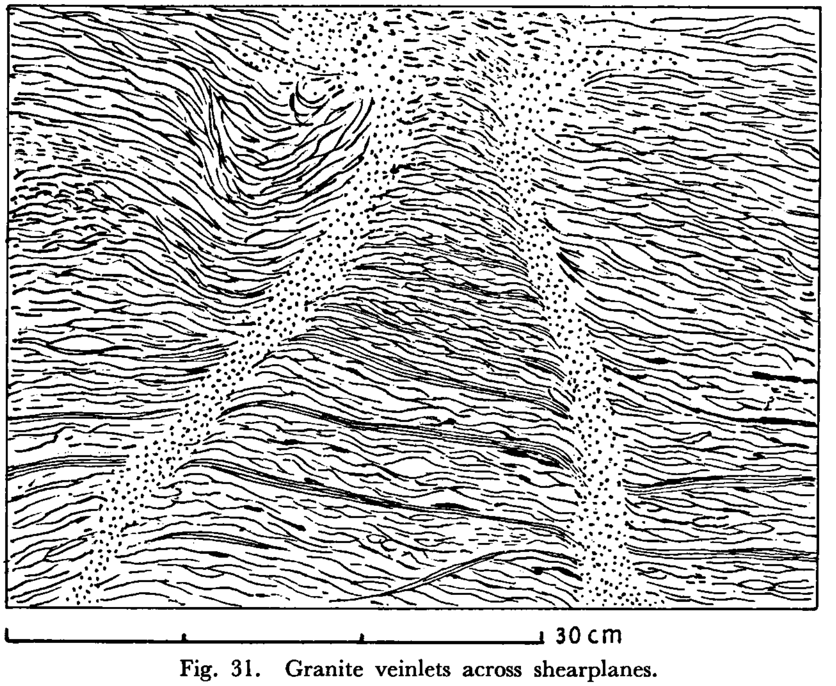

Fig. 31. Granite veinlets across shearplanes.

Similar quartz-sillimanite nodules have been described from various other regions, for instance Scotland, Norway and Bavaria. In neither of these cases the rocks are interpreted as metaconglomerates.

Summarizing the history of the orthogneisses of the Aston-Hospitalet massif, it can be stated that a leucocratic granite is transformed to an augengneiss during the main phase of the Hercynian orogeny. The chemical and mineralogical composition of these gneisses is quite uniform. In the eastern part of the Hospitalet massif some recrystallization took place after the main phase. All gneisses of the Aston massif are recrystallized, resulting in recrystallized augengneisses, grading into flasergneisses and granitic gneisses. Granitization and mobilization took place on a large scale in the augen- and flasergneisses. Intrusion of granites occurred on a limited scale in the micaschists of the western part of the massif. The quartz-sillimanite nodule rocks are tectonites probably formed during the second phase, and recrystallized afterwards (fig. 20.)

6. MORPHOLOGY

The morphology of sheet 6 shows several interesting features which certainly deserve a better study than the few remarks presented in this short description. As our attention was mainly paid to the structural and metamorphic geology, the morphological observations were only superficial.

Three different morphological phenomena can be distinguished, viz. the preglacial relief, the glacial modeling and the post-glacial erosion.

6.1 THE PRE-GLACIAL RELIEF

The Aston massif contains beautiful examples of the preglacial relief and in fact possesses the best preserved remnants of a Tertiary denudation surface in the Pyrenees. This surface has been described by Faucher and Sermet, as the "niveau supérieur de la plateforme de l'Aston" (Faucher, 1938) and the "plateform de l'Aston" (Sermet, 1950). This Aston plateau is especially well visible from the south slope of the St. Barthélemy massif as a gentle north dipping grass covered surface above which the high peaks of the central frontier ridge rise.

On the map the surface has been marked with a special ornament and is left blank as outcrops are usually absent on it. It appears that largest relicts of this aplanation surface occur on the gneisses of the Aston massif; on the schists to the west almost nothing of it is preserved. The gneisses of the Hospitalet massif also do not carry such large aplanation surfaces, although farther south near the Envalira pass a large one occurs.

The largest surface in the Aston massif, occurring east of the river of this name has a length of about 8 km and an area of 7.75 square km. The second largest surface east of the Luzenac valley has about the same length with an area of 5.45 square km. Another large one is to be found west of the Ariège river south of Ax les Thermes. This surface is by later erosion dissected in two parts, the north part is called the plateau de Bonascre. The total length of the two parts is 6 km. Smaller ones occur in the western part of the Aston massif, for instance south of the Ressec valley with an area of 2,8 sq. km. and west of the Planel de Brouchet with an area of 2,2 sq. km.

The highest parts of these surfaces are to be found near the high central divide between France and Andorra. Here remnants of this surface may reach up to 2300—2400 m. From there the surface slopes gently to the north where the lowest portions lie at an elevation of about 1600 m. The average dip of the surface is about 4—5° to the north, but as the slope near the central ridge is usually much higher, dips of 1—2° are common. Especially around the 1900—2000 m level the surface may almost be horizontal. The denudation surface is mostly covered with grass and used for cattle. Outcrops are usually absent (fig. 32).

As has been remarked already the largest remnants of the denudation surface are to be found on the gneisses of the Aston massif. In the schists west of these gneisses almost no remnants occur. This is undoubtedly due to the character of the rocks, schist instead of gneiss, which lents itself to a faster erosion, resulting in a complete dissection of the ancient surface.

South of the divide few remnants of the surface are preserved in the Hospitalet massif and south of it.

It is obvious that the high peaks of the central ridge reaching up to 3000 m altitude stand out above this surface and do not form a part of it. Whether they belong to another higher denudation level, a gipelflur or a "niveau des cretes" is not certain. It is a fact however, that one of the highest summits, the Pic de Montcalm has a rather flat surface that may belong to an older erosion cycle. The Pic de l'Estanyo (2912 m) is also rather flat topped.

The age of these planation surfaces is difficult to determine, but there is a genaral agreement that they date from late Tertiary times.

6.2 GLACIAL RELIEF FEATURES

The glacial features are due to quaternary glaciers which occupied most valleys of sheet 6 during the ice ages.

It is probable that after the uplift of the mountain chain the Tertiary denudation surface was dissected by streams and rivers. These preglacial valleys were occupied by glaciers during the glaciation resulting in the formation of typically glaciated

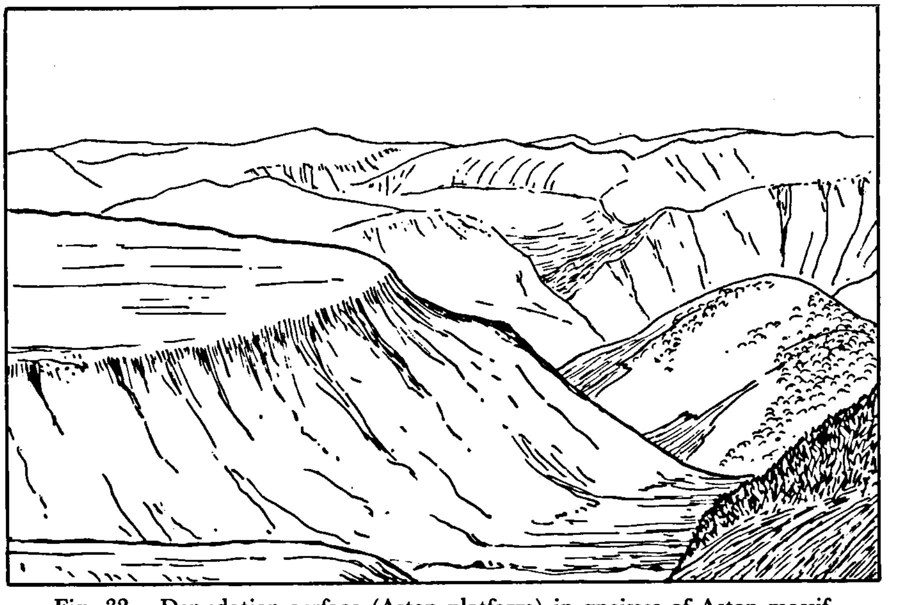

Fig. 32. Denudation surface (Aston platform) in gneisses of Aston massif.

U-shaped valleys. The glacial erosion has been strong enough to leave no traces of the shape of the original valleys. It is not well known whether all four quaternary glaciations have resulted in the development of large valley glaciers in the Pyrenees, but there is evidence, that at least the Risz and Würm glaciation were characterized by the occurrence of important glaciers (Goron, 1942).

The largest glacier of sheet 6 was the one in the Ariège valley, having its source near the France-Andorran frontier south of the Envalira pass. From here the valley runs north to Ax-les-Thermes and then WNW to Tarascon approximately parallel to the strike of the Pyrenees, and from this village north to Foix. The terminal moraine of the last glaciation lies between Tarascon and Foix outside the map. There is some evidence that earlier glaciers reached beyond Foix. The Ariège valley has many tributary valleys which issued glaciers into the main valley. The most important ones are the Mourgouillon, Nagéar, Luzenac rivers, then the large Aston valley, the Siguer river and finally the important Vicdessos valley which itself consists of many branches. Altogether these valleys form the drainage area of the whole of the Aston and most of the Hospitalet massif. South of the watershed glaciers occupied the valleys of the Valira del Norte and Valira de l'Oriente which join near the town of Andorra. This glacier was far shorter than the Ariège glacier and did not even reach the Sègre valley. The difference is certainly due to the climate, the northern slope being much more humid than the southern one. Glaciated tributaries of the Valira de l'Oriente are the Incles, Ransol and Riu valleys; those of the Valira del Norte the Arinsal valley. Most of these valleys are U-shaped and most glaciated forms are quite fresh, especially in the gneisses of the Aston and the Hospitalet massif. The valleys in the schists, like the Vicdessos valley have less typical U-shapes. Moreover these valleys are asymmetric with a very steep west slope and a much less steep east slope. Good examples of such asymmetric valleys are the Mounicou and Artiès valley.

One of the most pronounced features of the glaciated valleys are cirques and rock bars. A large numer of cirques occur on sheet 6, almost in every small valley, at an altitude of more then 2000 m. Many of these cirques are now occupied by small lakes which are especially abundant in the gneisses of the Aston and Hospitalet massif and in the Andorra granodiorite.

Stepped valleys are numerous on sheet 6. A good example is the Mounicou valley in which four large flat parts are separated by rock bars. These flat parts are called "pla" by the local people. Some of these flat valley bottoms are as long as 2 km and almost one km wide. They may have contained lakes. Several of them are partly filled with peat deposits. The rock bars separating the "Pla's" are usually not determined by more resistant rocks and consequently they are solely the result of glacial excavation. Another feature due to glacial erosion are the hanging tributary valleys which are rather numerous in the Aston massif. Other erosion features are the roches moutonnées, often with glacial striae. They occur frequently in gneisses and granite probably because they are the best preserved there.

Sedimentary deposits due to the glaciers consist mainly of moraine material in the valleys. Terminal moraines have not been observed in the mapped area. The most interesting deposits are certainly the rock glaciers which occur abundantly on sheet 6 and marked with a special signature. They occur usually rather high in the cirques of many valleys and consist of garlands and curved ridges of coarse debris. They probably formed during a late stage of the glaciation.

6.3 THE POSTGLACIAL RELIEF

Erosional features after the disappearance of the glaciers are mainly the incision of rivers and brooks in hanging valleys and rock bars of the stepped valleys. Long or deep gorges were, however, not formed on sheet 6. Depositional features are mainly the scree slopes, alluvial fans and the filling up of some lakes.

6.4 THE INFLUENCE OF THE HERCYNIAN STRUCTURES ON THE RELIEF

In general the influence of the Hercynian structures on the present relief is rather small in the mapped area. This is also apparent from a study of the aerial photographs which yield little information about the structures as seen in the topography. The only features which can be recognized on the aerial photos are faults and macrojoints. The Mérens fault has some influence on the relief as the sedimentary zone between the two gneiss massifs is less resistant, resulting in a number of cols on the N-S ridges. Some rivers follow faults, for instance the Aston upstreams from Riète is situated on a fault. Also some other valleys are located on fault lines. In general, however, the most important valleys of sheet 6 have a north-south direction perpendicular to the Hercynian structures.

One feature that has to be noted here, concerns the difference in erosion pattern in the gneisses of the Aston and Hospitalet massif. In the former area the gneisses always show more or less rounded erosion forms, whereas in the latter area the gneisses are much more angular. This is undoubtedly due to the fact that the Hospitalet gneisses are strongly schistose with regular s-planes, whereas the Aston gneisses are more granitic and less schistose.

7. ECONOMIC GEOLOGY

Since the closing down of the Puymorens mine a few years ago no mineral deposits are exploited in the area covered by sheet 6. Several deposits, mainly of metals, have been worked during the last century and earlier, but none of those proved to be of great importance.

7.1 IRON

Several iron mineralizations occur around the Aston-Hospitalet massif; in this respect there is some resemblance to the "ceinture ferrifère" around the Canigou massif farther east. Ancient mines existed between Gestiès and Sem northwest of the Aston massif. In earlier days the mines of Rancié were wellknown. Exploitation of iron ore started already in the 14th century and reached a peak during the 19th century. Mining activity ceased, however, a long time ago and almost no remains of this activity are to be found in the area.

Most of the iron ore between Sem and Gestiès occurs in Devonian limestone or Silurian slate. The ore consists of hematite and iron carbonates and occurs as masses and veins or finely disseminated in the limestones. Locally small masses of red crystalline metalliferous limestone is found in the blue-grey Devonian limestone. These deposits have been described in some detail by Mussy (1868—1869). According to him some of the ore bodies occur in Liassic limestones but to our opinion these limestones belong also to the Devonian, and all the ore is probably related to the Hercynian orogeny. The ore is probable of epigenetic origin and possibly related to the regional metamorphism in the Aston massif.

Altogether these iron deposits were apparently quite large, but they were exhausted by intensive mining.

Another small deposit occurs in the Devonian limestones near Lassur north of the Aston massif. It consists of veins of hematite. A larger deposit of hematite and magnetite is to be found west of the Puymorens pass in or near limestones of uncertain age in Cambro-Ordovician slates. This deposit has been worked until a few years ago. Details about this mine have not been published.

A small hematite mineralization occurs in the Ransol valley near Coll de la Mina, where some excavation has been done in the past. The ore is concentrated in the limestones and black slates of the Ransol formation.

7.2 COPPER

Copper has been reported from Ranet in the Vicdessos valley where it occurs in Cambro-Ordovician slates. It has been mined in the 19th century.

Another small copper deposit occurs in the gneisses of the Aston massif south of Vaychis. The mineralization here also comprises some lead and zinc.

Chalcopyrite has been found in micaschists of the Hospitalet massif NE of Ransol

7.3 THERMAL SOURCES

Of more economic importance are thermal waters used mainly for medical purposes. Well known are the hot springs of Ax-les-Thermes which in medieval times was already mentioned as a place where the sick could be cured with the aid of the water from the thermal sources. This small town has many hot sulfurous sources of which the temperatures range from 31—77°. According to Destombes (1962) who gave a description of these springs, they occur on N-S faults in the Ax granite. The following elements occur in the water: anions: K, Na, Ca, SO ; cations: Cl, S, S_2O_3, SiO_2.

Another thermal source occurs in the village of Mérens with a water temperature of 36—45°. It contains the same elements as the water of Ax-les-Thermes and the spring is probably also situated on a fault.

In Las Escaldes, Andorra, a thermal spring with a temperature of 38—66° occurs on a fault between the Andorra granodiotite and the Devonian limestone. It contains S and Na.

8. EXCURSIONS

A number of interesting excursions can be made in the region covered by sheet 6. Some fieldtrips have been described in an excursion report (de Sitter and Zwart 1961). A short description of some excursions is given here. For the excursions it is advisable to use the new 1 : 50.000 sheets Vicdessos and and Ax-les-Thermes of the "Institut Géographique National", and for Andorra also a 1 : 50.000 topographic map.

1. El Serrat, Andorra, ½ day

By car from Andorra-la-Vella (town of Andorra) to El Serrat through valley of Valira del Norte. A small numbers of stops can be made in Carboniferous, Devonian, Silurian and Cambro-Ordovician rocks as the Llavorsi and Tor syncline and the Massana anticline are crossed. In the neighbourhood of Llorts the metamorphic Silurian with large chiastolite porphyroblasts and microfolds of the third phase can be studied.

From El Serrat on foot along path upstrean the Rio de Rialp. After a walk of about one hour very good outcrops with large folded andalusite and cordierite crystals and smaller staurolites. Abundant folds of the third phase with NW trending axial planes. Also small tight folds of first phase can be found.

This excursion can be extended to a whole day by following the valley until it turns to the west. From this place a track leads eastwards to the port de Banyells where the Mérens fault and its mylonites can be studied. Also the black slates and limestones of the Ransol formation can be seen here. North of the Etang Soulanet, beyond the pass the migmatized micaschists with amphibolites and marbles of the Canaveilles formation can be studied.

2. Val d'Incles, $^3/_4$ day

From Andorra-la-Vella by car to Soldeu, crossing the Massana anticline and the Tor syncline. Stop between Encamp and Canillo to see Cambro-Ordovician and minor folds. Near bridge 1 km SW of Canillo interesting cleavage folds in Devonian, and knickzones in Cambro-Ordovician south of bridge. From Soldeu by foot on west slope of Incles valley along path. In small valleys coming from Cap d'Entort many specimens of schists with andalusite, cordierite and staurolite. In outcrops two lineations with E-W and NW-SE direction. Small folds in NW direction can be observed. Rotated crystals of andalusite and cordierite are abundant. In quartzites of Ransol formation many first phase folds. Farther north black schist and marble of Ransol formation. Continue to Etang de Quérol where contact between micaschist and gneiss is exposed. Augengneiss with strong schistosity and E-W lineation. From here to Port de Fontargent to study augengneiss and erosion remnants on top of gneiss. Back through valley to Soldeu.

3. Pla Subra and Mounicou, ½ or 1 day

By car from Vicdessos to Marc in Mounicou valley. South of Auzat the Bassiès-Auzat granodiorite is crossed. Contact aureole can also be studied along the road. Then continue through steep phyllites of Cambro-Ordovician. Stop on roche moutonnée between Marc and village of Mounitou. Here third phase folds with steep axes and NE trending axial plane. By car farther up the Mounicou valley to Pla de l'Isard. Rock bar upstreams consists of muscovite granite and pegmatite with schist inclusions . Between village of Mounicou and this Pla transition of steep cleavage in phyllites to flat lying schistosity in biotite-schists. Trip can be continued on track in valley; micaschists with third and fourth phase folds and porphyroblasts. For Pla Subra valley back by car to Marc and from there to the Montcalm refuge in the Artigue valley. From here by foot along good track in Subra valley. Here andalusite-cordierite-staurolite-schists with third and fourth phase folds. Good collecting localities for large porphyroblasts.

4. Aston valley, ½ or 1 day

By car from Les Cabannes on highway Tarascon-Foix to village of Aston and farther upstream in the Aston valley to end of road near dam of Riète. Several stops along the road can be made to study Cambro-Ordovician phyllites and micaschists, but main point of interest are granitized augengneisses with masses and veins of granite and pegmatite. From Riète on foot along track in Quioulès river. Near lake of Riète mylonite zone with steeply plunging folds. In Quioulès river outcrops of mobilized flasergneiss.

Excursion can be extended to whole day by continuing up the valley to the Seignac river and from there over pass in N-S ridge near Pic de l'Homme Mort. The pass lies in the Mérens faultzone and good outcrops of the mylonites with two generations of folds can be studied here. Back through the valley of Etang de Coume d'Ose and Quioulès river. Here also outcrops in quartzdiorites of migmatites underneath flasergneiss.

5. Etang de Peyregrand or Etang de Neych, 1 day

By car from Vicdessos direction Tarascon; turn right into Siguer valley. Continue to south of Centroux where car can be parked at station of cableway. On foot along good track in valley of Etang de Peyregrand (direction SE). In steep gorge good outcrops of migmatites and quartz-diorites. Beyond gorge in Pla de Brouquenat view on superposition of granitic gneiss on migmatite. Continue to Etang de Peyregrand in granitic gneiss with several outcrops of quartz nodule gneisses. From Etang de Peyregrand a climb of 150—200 m in westerly direction leads to outcrops with discordant quartz nodule rocks.

Alternative program is to turn sharp right in Brouquenat d'en bas along track in direction Etang de Neych. Good view on relations migmatite-gneiss and layers of quartz nodule rocks at the base of the gneiss. Other outcrops near the small lakes show elongated and linear quartz nodules.

REFERENCES

ALLAART, J. H., 1954. La couverture sédimentaire septentrionale du Massif Ax-Montcalm. Leidse Geol. Mededel. 18, 254—269.

—— 1959. The geology and petrology of the Trois Seigneurs massif, Pyrenees. Leidse Geol. Mededel. 22, 97—214.

BOISSEVAIN, H., 1934. Etude géologique et géomorphologique d'une partie de la vallée de la Haute Sègre, (Pyrénées Catalanes). Bull. Soc. Hist. Nat. Toulouse, 66, 32—170.

BOSCHMA, D., 1963. Successive Hercynian structures in some areas of the Central Pyrenees. Leidse Geol. Mededel. 28, 103—176.

CARALP, L., 1888. Etudes Géologiques sur les hauts massifs des Pyrénées Centrales (Haute Ariège, Haute Garonne, Vallée d'Aran). Thesis Toulouse, Durand, Fillons & Lagarde, 512 p.

CAVET, P., 1951. Découverte du Cambrien à Archaeocyathidés dans la zone axiale des Pyrénées-Orientales; interprétation stratigraphique de cette zone. Comptes Rendus Ac. Science, 232, 858—859.

—— 1958. Stratigraphie du Paléozoique de la zone axiale pyrénéenne à l'Est de l'Ariege. Bull. Soc. Géol. France, (6) 8, 853—867.

DESTOMBES, J. P., 1950. L'Ordovicien de la Haute-Ariège. C. R. somm. Soc. Géol. France, 5, 75—77.

—— 1962. Etude hydrogéologique de la région d'Ax-les-Thermes (Ariège). Bull. Rech. Géol. Min. 1, 29—43.

DESTOMBES, J. P. & E. RAGUIN, 1954. Le Pic de Montcalm et le massif de l'Aston dans les Pyrénées ariégeoises. C. R. somm. Soc. Géol. France, 51, 279—280.

—— 1955. Etude de la partie occidentale du massif de l'Aston. Bull. Soc. Géol. France, (6) 5, 101—113.

—— 1960. Sept coupes à travers le massif de gneiss de l'Aston (Pyrénées de l'Ariège). Bull. Soc. Géol. France, (7), 2, 28—37.

FAUCHER, D., 1938. Surfaces d'aplanissement dans les Pyrénées ariégeoises. Congres intern. Géogr. Amsterdam, Paris, 34—38.

GORON, L., 1942. Le rôle des glaciations quaternaires dans le modelé des vallées maitresses des Pré-Pyrénées ariégeoises et garonnaises. Thèse Toulouse, 460 p.

GUITARD, G., 1960. Linéation, schistosité et phases de plissement durant l'orogénèse hercynienne dans les terrains anciens des Pyrénées-Orientales; leurs relations avec le métamorphisme et la granitisation. Bull. Soc. Géol. France, (7), 2, 862—887.

—— 1963. Sur l'importance des orthogneiss dérivant du métamorphisme d'anciens granites parmi les gneiss du Canigou (Pyr.-Orientales). C. R. somm. Soc. Géol. France, 4, 130—131.

GUITARD, G. & M. FONTEILLES, 1964. L'effet de socle dans le métamorphisme hercynien de l'enveloppe paléozoique des gneiss des Pyrénées. C. R. Ac. Science Paris. 258, 4299—4302.

MUSSY, M., 1868. Description de la constitution géologique et des ressources minérales du Canton de Vicdessos et spécialement de la mine de Rancié. Ann. Mines, (6), 14, 57—112.

—— 1870. Carte géologique et minéralurgique de l'Ariège, Texte explicatif. Foix, Pomiès, 275 p.

RAGUIN, E., 1955. Texture originelle et migrations chimiques dans le gneissification d'un poudingue Pyrénéen. Colloque intern. Pétrogr. Nancy, 17—24.

—— 1964. Les problèmes du massif de l'Aston dans les Pyrénées de l'Ariège. Bull. Soc. Géol. France, (7) 6, 69—86.

RAGUIN, E. & J. P. DESTOMBES, 1953. Observations préliminaires sur le massif de gneiss Ax-Montcalm (Ariège). C. R. somm. Soc. Géol. France, 5, 73—74.

RAMSAY, J. G., 1962. Interference patterns by the superposition of folds of the similar type. Journ. Géol. 70, 466—481.

REYNOLDS, D. L. & A. HOLMES, 1954. The superposition of Caledonoid folds on an older fold system in the Dalradians of Mallin head, Co. Donegal. Geol. Mag. 91, 417—444.

SERMET, J., 1950. Réflexions sur la morphologie de la zone axiale des Pyrénées. Pirineos, 6, 17—18, 323—404.

SITTER, L. U. DE, 1954. La faille Nord-pyrénéenne dans l'Ariège et la Haute-Garonne. Leidse Geol. Mededel. 18, 287—291.

SITTER, L. U. DE & H. J. ZWART, 1959. Geological map of the Paleozoic of the Central Pyrenees, sheet 3, Ariege, France, Leidse Geol. Mededel. 22, 351—418.

—— 1961. Excursion to the Central Pyrenees, September 1959. Leidse Geol. Mededel. 26, 1—49.

ZANDVLIET, J., 1960. The geology of the Upper Salat and Pallaresa valleys, Central Pyrenees, France/Spain. Leidse Geol. Mededel. 25, 1—127.

ZWART, H. J., 1954. La géologie du massif du Saint-Barthélemy. Leidse Geol. Mededel. 18, 1—228.

—— 1958. La faille de Mérens dans les Pyrénées ariégeoises. Bull. Soc. Géol. France, (6) 8, 793—796.

—— 1959. Metamorphic history of the Central Pyrenees, part 1. Leidse Geol. Mededel. 22, 419—490.

—— 1960. Relations between folding and metamorphism in the Central Pyrenees, and their chronological succession. Geol. & Mijnbouw, 22, 163—180.

—— 1962. On the determination of polymetamorphic mineral associations, and its application to the Bosost area (Central Pyrenees). Geol. Rundschau, 52, 38—65.

—— 1963. The structural evolution of the Paleozoic of the Pyrenees. Geol. Rundschau, 53, 170—205.