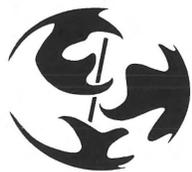


## THREE PROFILES THROUGH THE CENTRAL PYRENEES<sup>1</sup>



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### ABSTRACT

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The Palaeozoic stratigraphic sequence of the Pyrenees, folded in Late Carboniferous time during the Variscan orogeny, consists of Cambro-Ordovician phyllites and quartzophyllites, Silurian carbonaceous shales, Devonian limestones, calcslates and slates with local sandstones, and Early Carboniferous shales. Igneous rocks consist of a pre-Variscan granite and late- to posttectonic granodiorites. Several generations of folds were formed during the Variscan orogenic period, of which the first two are responsible for most of the major structures. A large part of the folds shown on the profiles date from the second fold generation, usually called the main phase. These structures are accompanied by an axial-plane cleavage in low-grade rocks. In these rocks in the axial zone the cleavage forms half of a fan, which was formed by a late phase of tilting.

In the high-grade infrastructure axial planes of folds and foliations are usually gently dipping. These structures were formed later and at the expense of earlier steep structures. Yet later fold generations have in general only resulted in small-scale structures.

### INTRODUCTION

At first sight the Pyrenees look like an intercontinental mountain chain, bordered on its northern side by the Aquitanian Basin and on the southern side by the Ebro Basin. However, the situation is more complicated, due to the fact that the Pyrenees were built in at least two orogenic periods, the Variscan and the Alpine orogeny. At present the main body of the Pyrenees, the central zone, usually called axial zone, consists almost entirely of rocks folded, metamorphosed and intruded during the Variscan orogeny in Carboniferous times, whereas both to the north and to the south, narrow strips of Mesozoic rocks have been folded during at least two phases of the Alpine orogeny. In recent years it has become evident that the axial zone has also been influenced by the Alpine orogeny.

Rocks similar to those in the axial zone are to be found north of the Pyrenees in the Mouthoumet, the Montagne Noire, and in boreholes in the Aquitanian Basin, and to the south along the Mediterranean and elsewhere in Spain. These rocks are, however, mostly covered with epi-conti-

mental sediments of Mesozoic and Tertiary age. Consequently the Variscan Pyrenees as they stand out at present are nothing but a large uplifted block with two subsiding regions to the north and south. The uplift took place in the Tertiary. For the Alpine Pyrenees the situation is different insofar that folding is restricted to those regions in and close to the axial zone. However, one could hardly consider the Pyrenees as belonging to the Alpine chain proper, although it has a number of characteristics of an orogenic belt.

The backbone of the Pyrenees consists of Palaeozoic rocks and was mainly formed during the Variscan orogeny. To the north the axial zone is cut off by a large fault, the North-Pyrenean fault, to the north of which Palaeozoic rocks are exposed in the so-called North-Pyrenean massifs, surrounded by folded Mesozoic rocks. Although strike-slip movements on this fault may have occurred, it certainly has a large vertical component of movement, locally amounting to five or more kilometres. For this reason some of the deepest exposed rocks occur in the North-Pyrenean massifs.

The structure on the southern side is even more complex. Although the axial zone there is unconformably covered by Stephanian, Permian or Triassic, faultblocks of Palaeozoic and younger rocks occur immediately to the south in the so-called Nogueras zone (Encl. I).

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## STRATIGRAPHY

The existence in the Pyrenees of a reasonably well-dated stratigraphic sequence comprising Upper Ordovician, Silurian, Devonian and Lower Carboniferous is known already for a long time. Work of the Leiden group has especially tried to unravel the lithostratigraphy of the upper part of the Ordovician (HARTEVELT, 1970), the Devonian and the Carboniferous (MEY, 1968). More recently the biostratigraphy of the Devonian has been studied with the aid of conodonts by BOERSMA (1973), whereas more recent work is being done by other groups.

The dated Upper Ordovician is underlain by a thick sequence of slates, phyllites, quartzophyllites, quartzites and some marbles which has yielded no fossils. Based on comparisons with the Montagne Noire, CAVET (1957) has suggested the Cambrian to be present in this sequence. We have used the term Cambro-Ordovician for this unit, supposing that Cambrian is present. The absence of fossils is in part due to the increase in grade of metamorphism. In many areas the Cambro-Ordovician phyllites grade into micaschists and then into migmatites, or they are underlain with a sharp contact by felsic augen- or orthogneisses like in the Canigou and Aston massifs. As metamorphic isograds cut across the stratigraphy, there is no doubt that Cambro-Ordovician rocks are present as migmatites in amphibolite facies, for example in the Trois Seigneurs and Aston massifs. In other areas the phyllites are not deeply enough exposed to see a substratum. This is the case in the Orri dome near Seo de Urgel, in the Garonne dome in the Valle de Arán, and other exposures of Cambro-Ordovician in the central and western Pyrenees.

*Precambrian*

A Precambrian basement on which the Cambro-Ordovician sequence presumably was laid down, is exposed in a number of North-Pyrenean massifs, like Agly, St. Barthélemy, Arize and Castillon, where high-grade paragneisses in granulite facies occur. They are shown on profile 2 (Encl. III) as garnet-bearing granitic gneiss. The original unconformity is no longer recognizable due to a strong metamorphic overprint of Variscan age. Leucocratic orthogneisses in the Canigou massif in the eastern Pyrenees are by French geologists also considered as a Precambrian (Cadomian) basement. However, this interpretation is less certain.

*Cambro-Ordovician*

As has been indicated in the previous section, a large part of the Cambro-Ordovician is unfossiliferous, and the oldest palaeontologically dated rocks are of Caradocian age.

For the eastern Pyrenees the Cambro-Ordovician has been described by CAVET (1957), for the Central Pyrenees a comprehensive review is given by HARTEVELT (1970), whereas in the western Pyrenees only very little Cambro-Ordovician is exposed.

In the Central Pyrenees the Cambro-Ordovician shows many similarities to the development in the eastern Pyrenees and consists of a monotonous sequence of phyllites and quartz-phyllites with occasional quartzite and limestone intercalations, called the Seo Formation.

Locally a mappable stratigraphy in the Upper Ordovician occurs. It has been worked out by HARTEVELT (1970), and that author has also compiled the data outside his own map area (Encl. II).

An important limestone unit occurs in the upper part of the Seo Formation on sheets 4 and 5. In the French literature this limestone is called the 'calcaire métallifère' because of the frequent lead-zinc deposits in this limestone.

The upper boundary of the Seo Formation is defined by the presence of a conglomerate horizon occurring in many areas in the Pyrenees. This horizon is called the Rabassa conglomerate by Hartevelt. It consists of pebbles of quartz, quartzite, slate and occasionally black schists or gneisses in a matrix of slate or sandy slate. The size of the pebbles varies from a maximum of 50 cm to the size of large sand grains. It is absent in the northern part of the axial zone. Its thickness and pebble size increase towards the south, namely to more than 100 m.

The Rabassa conglomerate is overlain by the Cava Formation which is only developed south of Andorra. This formation consists from bottom to top of greywackes, red and green slates, siltstones and a purple quartzite. Fossils (brachiopods, tentaculites, cystoids and Bryozoa) have been found and indicate a late Caradocian age.

*Silurian*

The Silurian in the Pyrenees is characterized by a very uniform development of black, carbonaceous shales, which in the field are easy to recognize. It thus divides the Palaeozoic into a lower Cambro-Ordovician and an Upper Devonian-Carboniferous part. Although the Silurian is usually very thin, it has, due to its softness and incompetent behaviour in deformation, a profound influence on the topography and on the tectonic style of the folds, where it may cause decollement and diapiric structures. When fresh, the Silurian consists of black, staining and often strongly contorted slates. On weathering the rocks become rusty brown, yellow and white due to the oxidation of pyrite and the occurrence of sulphur or alum. Small streams are often iron-stained. Near the top a black, fossiliferous, sometimes nodular limestone has been found frequently. Fossils have been found at many localities. In the black slates the fauna consists almost exclusively of various species of *Monograptus*. In the limestones *Orthoceras* sp. and *Cardiola interrupta* are recorded from different places. In Andorra a *Scyphocrinus* sp. was discovered, indicating a very late Silurian age. The graptolites have given Llandoveryan, Ludlovian and Wenlockian ages, and seen over a large area the whole of the Silurian seems to be present. However, due to strong tectonization nowhere a complete

and uninterrupted sequence of the Silurian has been recorded.

### *Devonian*

In contrast to the Ordovician and Silurian, the Devonian is very variable throughout the Pyrenees. Thickness and facies changes, both along and across the strike of the Pyrenees, are common. Although a great deal of stratigraphical and palaeontological work has been done during the last two decades, we are still far from a complete synthesis. Major contributions have been made by MIROUSE (1966) and MEY (1967, 1968). The latter author proposed four facies areas for the Devonian and Carboniferous, a southern, a central, a northern and a western facies area. For further details, reference can be made to ZWART (1979).

In general the Devonian consists of limestones, slates and calcslates, with a thickness varying from a few hundred metres near the Maladeta granodiorite to 1500 metres in the northern part of the axial zone. The uppermost part of the Devonian usually consists of a nodular limestone of Frasnian-Famennian age (Encl. II). An important limestone, the Basibé Formation of Siegenian-early Emsian age occurs in the southern part of the axial zone. The central part of the axial zone, like the Valle de Arán is characterized by a sequence of graded sandstones of Frasnian to Famennian age, the Las Bordas sandstones (Encl. II). These have also been recognized further west as the Sia Formation.

### *Carboniferous*

The Carboniferous in the Pyrenees can be subdivided in two groups, viz. those deposits taking part in the major Variscan orogeny, and those deposits occurring unconformably on top of the folded Palaeozoic. The Dinantian, Namurian and lower Westphalian participated in the major orogenic movements and are referred to as pre-Variscan Carboniferous, whereas the upper Westphalian and Stephanian are post-Variscan, although not wholly unaffected by some tectonic movements. Like the Devonian, the pre-Variscan Carboniferous occurs in certain facies areas which follows those of the Devonian.

In the northern facies area, sediments of Carboniferous age are mainly restricted to the Dinantian and lower Namurian. The sequence begins sometimes with nodular limestones, much like in the Upper Devonian, but more often the lower part of the Carboniferous is characterized by a black chert layer of a few metres to some tens of metres thickness. Interlayering of chert and nodular limestone is also reported. This chert horizon carries occasionally Radiolaria, and more often phosphate nodules and manganiferous layers (Encl. II).

According to new palaeontological data (BOUQUET & STOPPEL, 1975) the often described hiatus in the Tournaisian seems to be non-existent as one is dealing with a condensed sequence. In this case the lowermost Tournaisian consists of

nodular limestones whereas the cherts were deposited during the remainder of the Tournaisian. The cherts are followed by a rather monotonous sequence of shales and siltstones which has been dated as Visean at several localities. To the east of the map area, conglomerates, carrying pebbles of gneisses, have been found.

In the central facies area the Carboniferous of Plan des Étangs in the upper Esera and Artigua de Lin valleys north of the Maladeta granodiorite, the Devonian basal limestone is directly overlain by a sequence of thick-bedded micaceous, coarse-grained greywackes, grading into fine- to coarse-grained conglomerates. Fine-grained greywackes and slates are in the minority. Most of these sediments are dark coloured and contain abundant but badly preserved plant fragments indicating a Namurian to early Westphalian age.

East of the Maladeta granite appears another syncline with Carboniferous in the core: the Llavorsi syncline. Despite the apparent continuity, there is little reason to assume a connection between the two synclines, as the lithologic differences are rather large.

The Carboniferous of the southern facies area, consisting of a sequence of dark grey to black, micaceous, often chloritoid-bearing slates occurs in the western part of the Llavorsi syncline. Towards the east the sequence becomes more sandy, but still contains clastic micas and new chloritoid. There is some palaeontological evidence that at least the base of this sequence is of Devonian age.

In the southeastern part of the map area, west of the Palaresa valley, in the Segre valley, and from there further east, the Carboniferous is quite similar to the northern facies area. The Carboniferous begins with a chert horizon, followed often by a thin limestone layer and then a sequence of black and brown shales with sandstone layers and lenses of conglomerates. The pebbles in the conglomerate consist of quartz, quartzite, chert, gneiss, porphyrite, granite and limestone. Fossils indicate a Tournaisian, Visean and possibly Namurian age.

The post-Variscan Carboniferous deposits in the area of study are strictly non-marine and largely fluvial. Volcanic deposits (Erill Castell volcanics) occur on top of strata dated as Westphalian D (Aguiró Formation) and below strata having a Stephanian age (Malpas Formation). Only a few levels have yielded fossils, mainly in the form of plant imprints. The Aguiró Formation is composed of mainly coarse conglomerates with locally, at the base, a horizon of breccia and some coal stringers. It rests unconformably on folded and cleaved Lower Carboniferous and older rocks.

The volcanic Erill Castell Formation is composed of mainly light-coloured tuffs containing bombs of up to 1 m, which in the Erill Castell-Peranera area are overlain by a dark-green, massive basaltic-andesite sheet. The Malpas Formation comprises a series of dark-grey and brownish fluvial sediments with intercalations of coal seams of up to 2 m thickness, and some carbonate beds.

## *Orthogneiss*

In the Aston-Hospitalet massif large bodies of a felsic orthogneiss are found. In the Aston massif this gneiss occurs as a thick sheet, as it is underlain by migmatites and quartzdiorites formed from Cambro-Ordovician pelitic rocks. In the Hospitalet massif the orthogneiss forms the core of a large antiformal structure and its base is not exposed. In both massifs the gneisses are overlain by micaschists of Cambro-Ordovician sedimentary age (Encl. I). In the last-named massif the gneiss occurs as a linear augengneiss with predominant low-dipping schistosity but following the antiformal shape, and E-W lineations. These structures are formed during the Variscan orogeny. Consequently the original material predates this major event. The derivation of these gneisses from original granites follows from their very homogeneous character and their granitic chemistry. The contacts with the metasedimentary rocks are always sharp. The mineralogical composition in quartz, albite/oligoclase, potassium feldspar, biotite and muscovite. Both feldspars contribute to the eyed character of the rocks, whereas quartz and micas form a foliated fabric between these augen.

In the Aston massif, augengneisses occur also, but in this region the gneisses have been migmatized and granitized, resulting in flaser-gneisses, granitic gneisses and granites. The mineralogical composition is similar to the rocks of the Hospitalet massif. The migmatization is accompanied by mobilization, which results in irregular folding and disorientation of gneiss remnants in a granitic matrix. Some controversy about the age of the original granite exists. According to JÄGER & ZWART (1968) the granites were emplaced 475 Ma ago, based on a Rb-Sr isochron.

In the Canigou massif where similar orthogneisses are exposed, GUITARD (1970) believes that they belong to a Precambrian basement upon which the Cambro-Ordovician was deposited unconformably. Geochronological measurements have given dates of 535 Ma, that is Early Cambrian. If Guillard's interpretation is correct, the granites were formed during the Cadomian orogeny. Although conclusive evidence cannot be given, the present author thinks it to be more likely that these rocks belong to the ubiquitously occurring suite of granites within the Variscan belt, and intruded mainly during Ordovician times.

## *Granodiorites*

Bodies and batholiths of granodiorite occur commonly in the Pyrenees. They are intrusive in Cambro-Ordovician, Silurian, Devonian and Carboniferous rocks, and in most cases in a low-grade environment. Granodiorites in high-grade micaschists or migmatites are rare; the only example in our map area is the small stock on the southern side of the Trois Seigneurs massif. The bodies are generally elongate in the direction of the general trend of the Variscan structures, like the Bassiès-Auzat and the Maladeta massifs, but they are

discordant with regard to the country rock, and clearly post-date the  $S_1$  cleavage.

The granodiorites in the various bodies are quite similar. They are unoriented rocks of medium grain size and quite homogeneous throughout. The mineralogical composition is quartz, oligoclase/andesine, potassium feldspar and biotite. Hornblende-bearing varieties do occur occasionally. The granodiorites have a well-defined aureole of contact metamorphic rocks, consisting of hornfelses and spotted slates. Common contact-metamorphic minerals are biotite, muscovite, andalusite and cordierite. Staurolite has not been observed as a contact-metamorphic mineral, despite its frequent occurrence in regional metamorphic rocks.

## *Muscovite-granite*

Muscovite-granites occur as small bodies, stocks and patches within the regional metamorphic terrains of the Pyrenees, like in the North-Pyrenean massifs, Aston massif, Lys-Cail-laouas massif, and Bosost area. The country rock is always of amphibolite-facies grade, either as aluminium-silicate-bearing micaschists or as migmatites. Sometimes they occur as well-defined, sharply bounded bodies, as in the Trois Seigneurs massif and in the Bosost area, but elsewhere as small patches, sills, dykes and irregular masses in the augengneisses of the Aston massif. The first group must be considered as intrusive, but rather parautochthonous than allochthonous, as they probably were produced not far from the place where they occur. The second group is thought to be produced in place by melting of the felsic orthogneisses. The muscovite-granites are always accompanied by pegmatite sills and dykes. The mineralogical composition is quartz, albite/oligoclase, microcline, muscovite and biotite. Occurring in high-grade rocks, they have no contact aureole. Chemically they resemble the pre-Variscan granites, and it is suggested here that they are the product of melting of these rocks, a process which occurred undoubtedly in the Aston massif.

## STRUCTURE

### *General remarks*

Except for the Precambrian rocks in the North-Pyrenean massifs, all rocks involved in the Variscan folding are of Cambro-Ordovician to Carboniferous age. The whole sequence of Ordovician, Silurian, Devonian and Carboniferous is conformable, and despite the presence of conglomerates in the Upper Ordovician, there is no Caledonian folding phase.

The age of the main folding can be established in the area shown on Encl. I. The youngest rocks involved in major folds with development of cleavage are of Westphalian A age, whereas near Aguiró, Westphalian D is already unconformable. Elsewhere, the Stephanian volcanics and sediments are not involved in major folding and rest unconformably on

older rocks. The main folding in the Pyrenees took therefore place in the Westphalian. Weak late Variscan folding is witnessed by the unconformity between Triassic and Permian rocks. However, folds in the Stephanian and Permian generally are devoid of well-developed cleavages, and the folding was not very intense. Alpine folding has, however, influenced these folds. The large structural units are represented on Encl. I. These are metamorphic massifs as Aston-Hospitalet, Garonne dome and Lys-Caillaouas, a number of syn- and anticlinoria in the Palaeozoic sequence, the North-Pyrenean massifs, the Nogueras zone, and a number of granite to granodiorite massifs.

The large-scale structures can best be seen on the Profiles 1, 2 and 3 (Encl. III). From these profiles it is evident that two structurally different domains occur in the Pyrenees, viz. regions with high-grade rocks like the Aston-Hospitalet massif, the Garonne dome with the Bosost area and some of the North-Pyrenean massifs, and regions with low-grade rocks, where metamorphism does not reach beyond the upper greenschist facies. In the first domain, structures are mainly characterized by recumbent folds and flat-lying schistosity, in the second by steep folds and cleavages, although in the southern part of the axial zone, cleavages have quite a low dip as well. This is, however, attributed to a late effect of tilting.

In the metamorphic regions, usually within the biotite isograd, the layering of the rocks and the schistosity are gently undulating as shown on profile 3. It could be shown that the undulation is due to one or two late folding phases and that the original position of the schistosity must have been close to horizontal. Large-scale structures have not been found in these metamorphic regions.

In the Hospitalet-Aston massif the attitude of the schistosity forms a major antiform. The Garonne region has a large flat dome structure. In earlier publications, I have called these regions with flat-lying schistosity 'the infrastructure'. However, its position is not directly related to depth of burial, but more to a higher temperature, as from east to west in the Pyrenees the infrastructure is gradually lying higher in the stratigraphic sequence. In the low-grade, suprastructural Palaeozoic rocks a number of roughly E-W trending major structures can be distinguished. They are anti- and synclinoria involving Cambro-Ordovician, Silurian, Devonian and Carboniferous sediments.

The Silurian has played a particular role due to its special nature, causing it to be a very incompetent layer between the Cambro-Ordovician and the Devonian. In general it acted as a decollement surface, and the structures above and below the Silurian are strongly disharmonic. This behaviour is also very outspoken in the Llavorsi syncline where elongate diapiric structures of Silurian slates (with graptolites) occur within the Carboniferous (HARTEVELT, 1970).

In the axial zone two large anticlinorial structures in Cambro-Ordovician rocks can be distinguished: the Pallaresa anticlinorium and the Orri-Payasso dome. The Pallaresa an-

ticlinorium grades towards the east in an infrastructure with the high-grade rocks of the Aston-Hospitalet massif. To the west the anticlinorium becomes very narrow and is known as the Central anticline, which further west includes the Lys-Caillaouas granite body.

The Orri dome with low-dipping cleavage described by HARTEVELT (1970) plunges westwards underneath the Devonian, but reappears again in the small Payasso dome. Due to the lack of marker beds in the Cambro-Ordovician, the detailed structure of these anticlinoria cannot be worked out, and on the profile sheet the structure is depicted in a schematic manner. It is clear that many small-scale structures occur in the Cambro-Ordovician, but they cannot be continued beyond the scale of one outcrop. The fact that large-scale structures do occur in these Cambro-Ordovician regions, is shown by the Siluro-Devonian Tor syncline in the southern part of the Pallaresa anticlinorium.

These two large structures and the metamorphic massifs are separated by synclinoria with Silurian, Devonian and Carboniferous rocks. Due to the fact that there is a well mappable lithology in these systems, also large-scale structures in these synclinoria can be deciphered. Along the northern side of the axial zone and north of the Pallaresa and Garonne unit lies the northern synclinorium, of which profile 1 gives a good view of the structure.

Similar structures as in the northern synclinorium can be found in the Valle de Arán synclinorium, between the Garonne dome and the Pallaresa anticlinorium (Profile 1). The northern and Valle de Arán synclinoria are, at least in part, overlying the Garonne dome.

Between the Pallaresa anticlinorium and the Orri dome appears one of the largest structures of the map area, the Llavorsi syncline, which can be followed along strike from Andorra to the Maladeta granodiorite. It is a tight to almost isoclinal structure, which must reach to a depth of several kilometres. Its axial plane dips 30-50° to the north. Many small folds accompany this large structure. To the east it branches into several synclines which abut against the Andorra-Mont Louis granodiorite. In westerly direction the Llavorsi syncline is cut off by the Maladeta granodiorite, and it does not reappear west of this batholith.

The southern synclinorium occurs south of the Orri dome and the Maladeta granodiorite. In its eastern part it has horizontal to gently north dipping folds (Profile 2), but to the west the structure becomes complicated as can be seen from profile 1. At least part of the stratigraphic sequence there is inverted.

From the profiles it is evident that the axial planes of the folds, and the accompanying cleavage in the suprastructure in the northern part of the axial zone are steep to vertical, and that towards the south the attitude of these planes is gradually less inclined to the north, so that finally recumbent structures are found. Looking from this point of view a major structure is present in the axial zone, namely half a fan which is independent of the described syn- and anticlinoria.

Crosscutting through all these structures occur a number of large granodiorite bodies, which show, however, the same general trend as the major E-W structures.

### *Fold generations*

Although on the small-scale geological map (Encl. I) the major structure seems to be quite simple, many detailed investigations have shown that several fold generations occur in most Palaeozoic rocks. It could be shown that folding took place already before the development of the E-W cleavage folds, whereas several other fold generations postdate it. In our previous work it was assumed that the major folds in the suprastructure all belong to one folding phase usually called the main phase, as it is for a large part responsible for the map pattern.

Folds predating the E-W cleavage folds and called  $F_0$  folds occur at many places in the Pyrenees, especially near the southern and northern border of the axial zone. They were first discovered by BOSCHMA (1963) in a dome-shaped structure in the Ribagorzana River. They have also been described from the region near Estours (DE SITTER & ZWART, 1962) and they have been extensively treated by MEY (1967, 1968). These are an early generation with N-S to NE-SW trending folds with steep axial planes, and a later generation with an E-W to NW-SE direction and N to NE dipping axial planes. The second set is accompanied by a well-developed cleavage, and is correlated with the main phase elsewhere in the Pyrenees. In the field it is clear that the N-S to NE-SW striking limbs of the first-generation folds are cut by an E-W cleavage and small-scale folds. The cleavage cuts undisturbed through the limbs and the noses of the early folds. The cleavage-bedding intersections show a great circle distribution in stereograms.

As has been said already, the main phase is responsible for most major folds in the Palaeozoic of the Pyrenees, and hence also largely for the map pattern. Furthermore a distinction has to be made for the low-grade suprastructure and the high-grade infrastructure with respectively steep- and low-dipping folds and cleavages.

*Suprastructure* – The major structures and structural units, the map pattern and the three profiles through the Central Pyrenees have already been briefly discussed. From these profiles it appears that in the Devonian-Carboniferous sequence the folds are usually very tight to almost isoclinal. In well-bedded Devonian rocks chevron folds are common. Minor folds show the same style. As has been remarked before, the attitude of these folds varies. They are vertical in the northern part of the axial zone and in some of the North-Pyrenean massifs, inclined to the north in the more southerly part of the axial zone, for example in the Llavorsi syncline, and further south they may be recumbent.

In the Cambro-Ordovician there is also a large variation in size of the folds, and in these rocks there is an axial-plane

cleavage as well. It is, however, much more difficult to trace out major folds, as marker beds do not exist in the monotonous quartzophyllites.

In the Pallaresa antiform, small-scale folds are tight to isoclinal. In the south, for example in the Orri dome, folds in the Cambro-Ordovician slates are less appressed, usually no longer isoclinal but close to tight. In the profiles this is only schematically portrayed.

As has been mentioned before, the  $F_1$  folds are all accompanied by an axial-plane cleavage in pelitic, in psammitic and in calcareous rocks. The nature of the cleavage depends largely on the rock composition. In pelitic rocks, up to Carboniferous age, north of the southern limb of the Llavorsi syncline,  $S_1$  is a slaty cleavage determined by a parallel arrangement of phyllosilicates. However, in some rare cases it can be seen that the cleavage is a very fine crenulation cleavage, which probably developed on a fine-grained sedimentary fabric. In many cases, however, the  $S_1$  cleavage has been folded by one or two later crenulation cleavages.

In pelitic rocks of Cambro-Ordovician age south of the Llavorsi syncline, the foliation is usually a crenulation cleavage, according to the author's opinion developed on a sedimentary fabric. In quartz-rich rocks a fracture cleavage or a differentiated layering is often present, whereas in calcareous rocks the cleavage is usually accompanied by a differentiated layering.

The change of the slaty cleavage in the north to the crenulation cleavage in the south is rather abrupt, but coincides with a fault along the southern limb of the Llavorsi syncline. This fault, the Llavorsi fault, probably of Alpine age, apparently has cut out a fairly thick rock sequence.

*Infrastructure* – Structures within the metamorphic realm are characterized by their flatlying to horizontal attitude. This is clearly the case in the Aston-Hospitalet massif and in the Garonne dome, and outside our map area in the Caginou-Carança massif in the eastern Pyrenees. Later folding phases often have changed these low-dipping structures to a steep orientation. In our map area it has not been possible to locate large-scale structures in these rocks, in contrast to the opinion of GUITARD (1964), who has described large-scale Penninic type nappes in the Canigou massif. Although it is not absolutely excluded that a large nappe or a recumbent fold occurs in the Aston massif, there is very little direct proof for it. In the Hospitalet massif and the Garonne dome certainly no nappes are exposed now.

The most obvious microstructure is a schistosity or slaty cleavage. In the augengneisses of the Hospitalet massif, which is a deformed homogeneous granite, a schistosity is defined by flat feldspar eyes surrounded by a quartz-mica fabric curving around the feldspars. In addition an E-W lineation due to elongate feldspar and mica crystals is present. As the original granite had no layering, folds related to this schistosity are absent. Later folds, folding the schistosity, are common in the Aston massif. In the micaschists, covering the

augengneisses of both massifs, the same fabric elements, a schistosity and a lineation due to the shape of quartz and mica grains are found. In most cases this schistosity is parallel to a layering, which is certainly of sedimentary origin in some outcrops. Minor isoclinal folds of this layering with an axial-plane foliation occur at many localities. They are often asymmetric, but the presence of a constant sense of asymmetry could not be established.

In the Garonne dome, consisting of Cambro-Ordovician rocks, only the area around Bosost and Bagnères de Luchon is metamorphosed to amphibolite-facies grade; in the remainder of this large structure the grade is very near the biotite isograd. In the whole of the Garonne dome the schistosity was originally flat-lying, but has been steepened by later folds (BOSCHMA, 1963). Isoclinal recumbent folds also occur in these rocks, but they are quite rare.

In previous publications the present author (ZWART, 1979) has always defended the opinion that the folds and accompanying foliations in the supra- and infrastructure have been formed simultaneously, but in different positions. However, a mechanical interpretation of this feature could not be given.

New work in the western part of the Aston massif with a group of second-year students from the University of Utrecht in 1980 revealed that the situation in the low-dipping schists of the infrastructure is more complex than in the steep infrastructure. In the latter domain the steep slaty cleavage with tight to isoclinal folds of bedding proved to be the earliest structure. In the higher-grade schists below, the gently dipping schistosity belongs to at least a second and perhaps already a third generation of structures, and postdates the steep slaty cleavage, on which they are overprinted. In this original steep cleavage a number of pegmatite dykes and sills were emplaced. Both, cleavage and pegmatites were folded by a second generation of folds with gently dipping axial planes. In the pegmatites and quartzitic layers these folds are still present, but in pelitic layers a new schistosity was produced, wiping out almost entirely the previous steep cleavage. On the basis of these observations it appears that the low-dipping infrastructure is produced after the formation of the steep suprastructure. Obviously there is a direct relation with the grade of metamorphism as the transition between the two domains always is situated somewhere in the middle of the greenschist facies. Therefore mechanical properties of the rocks changed as they became hotter. Also from other evidence, as the growth of porphyroblasts it had already become clear that the rocks of the infrastructure have been subject to a rise in temperature during their orogenic development.

From the present situation it has the appearance that the formation of the low-dipping foliation is due to a kind of gravitational collapse, perhaps accompanied by some shear in the underground. The structural succession is therefore mainly due to a rise of the thermal front.

The antiformal or dome shape of the Aston-Hospitalet

massif is most probably the result of a later warping or up-doming of the horizontal  $S_2$  planes, and is perhaps also a thermal effect whereby a beginning diapiric uprise is the cause of these large scale structures. Further work has to confirm a similar structural succession in the Garonne dome and Bosost area. The common occurrence of rotated porphyroblasts in the latter area with a horizontal sense of shear is probably indicative of such a similarity.

#### *Later fold generations*

In the Palaeozoic of the Central Pyrenees several deformation phases have been active after the foliation forming  $F_1$  and  $F_2$  structures. The size of these later folds is, with few exceptions, small, and they have not changed the pattern of the geological map. Usually it concerns folds on a millimetre scale up to a size of several metres or tens of metres. Only in the northern border of the Lys-Caillaouas granite, major folds belonging to a late phase have been found. In addition the large structure, forming half a fan of the main phase cleavage, is a late feature.

*F<sub>3</sub> folds* – In the Aston-Hospitalet massif and the eastern part of the Pallaresa anticlinorium  $F_3$  folds occur abundantly. They have been described by LAPRÉ (1965), OELE (1966) and ZWART (1979). According to these authors there are two sets of  $F_3$  folds which together form a conjugate system. One set ( $F_{3a}$ ) has NW-SE striking, steep to vertical axial planes, the other ( $F_{3b}$ ) NE-SW striking, steep to vertical axial planes. The first set predominates over the second. These structures fold the compositional layering and  $S_1$ ; in case there is an  $S_2$  schistosity or there are  $F_2$  folds, there is a clear overprinting relationship, indicating the younger age of  $F_3$  folds. Interference between the two sets ( $F_{3a}$  and  $F_{3b}$ ) has been found, but no clear succession could be established. Therefore it is not certain that it concerns a conjugate system, as this hypothesis was solely based on the symmetric relationship of the two sets with the overall large-scale structure.

As the  $F_3$  folds occur both in the infrastructure and suprastructure, without change of the attitude of the axial plane, it is certain that the formation of these two domains predates  $F_3$ . The fold axes vary within the axial plane from horizontal to vertical, depending on their occurrence in the infrastructure, in the suprastructure or in the transition zone. Also the shape of the folds depends on their locality. In the flat-lying rocks of the Aston-Hospitalet massif, they are open to closed and symmetric; in the steep slates they are tight to isoclinal and strongly asymmetric, the NW-SE set with an S-shape, and the NE-SW set with a Z-shape. The size of the folds varies from microfolds in crenulated schists and slates to mesoscopic folds with amplitudes of a few metres, and occasionally some tens of metres. In the steep phyllitic rocks  $F_3$  folds are always accompanied by a well-developed crenulation cleavage. They are especially abundant in the transition zone between the infra- and suprastructure, that is in the

western plunge of the Aston and Hospitalet massifs (OELE, 1966).

*F<sub>4</sub> folds* – Folds with E-W striking steep to vertical axial planes occur frequently in the Aston-Hospitalet massif and in the Pallaresa anticlinorium. They are less closely associated with higher-grade rocks than the F<sub>2</sub> and F<sub>3</sub> folds, and occur at many places in the Cambro-Ordovician phyllites of the Pallaresa anticlinorium. The first description dates from DE SITTER (1954) who described some minor folds and cleavages from the Cardos valley, without recognizing, however, that these folds are due to a late folding phase. In this outcrop good overprinting relationships occur between F<sub>1</sub> and F<sub>4</sub> folds.

Overprinting criteria with F<sub>3</sub> folds are not rare in the Aston massif where they have been described by LAPRÉ (1965) and OELE (1966). In the flat-lying metamorphic rocks the F<sub>4</sub> folds are mostly symmetrical, have limbs of a size up to a few tens of metres, and not uncommonly they are chevron folds. Their degree of closure varies from close to tight. In the steep low-grade rocks the folds are usually asymmetric and have an S-asymmetry looking west. This is related to the attitude of the S<sub>4</sub> plane which dips steeper to the north than S<sub>1</sub>. The S<sub>4</sub> folds are usually accompanied by a crenulation cleavage in the slaty layers of the rocks; it does not penetrate the quartzite layers. Due to their size F<sub>4</sub> folds have no effect on the large-scale structure, except in the Caillaouas massif.

#### *The cleavage-fan in the axial zone*

In the suprastructure of the axial zone one more major structure can be discerned. When only the attitude of the main phase cleavage is considered, irrespective of lithology or stratigraphy, it appears that S<sub>1</sub> is arranged in a fan-like structure.

In the northern part of the axial zone the cleavage has a steep dip to the south; then a zone with vertical cleavage occurs, whereas further to the south the cleavage gradually gets a more gentle dip to the north, until it finally is close to horizontal (Profiles 1, 2 and 3). Thus the main phase cleavage forms half of a large fan structure. The origin of this fan has been a controversial issue. ZANDVLIET (1960) has done some detailed work on it. He has shown that in fact the cleavage does not change its dip gradually, but there are compartments with the same dip, separated from other compartments with a somewhat different dip. According to Zandvliet there occur faults between the different compartments. In his interpretation the formation of the fan is a late Variscan structure due to uparching of the northern part of the axial zone, resulting in a gravity-induced tilting of the cleavage. This feature probably predates the intrusion of the Maladeta granodiorite, as it is in contact with low-dipping slates. Zandvliet also suggests that the formation of kinkbands is related to the fan formation. This interpretation was accepted by the present author (ZWART, 1963).

MEY (1967) did not agree with this conclusion. He assumes that in the southern part of the axial zone the cleavage was originally formed with a gentle dip. He puts forward some arguments for this hypothesis (MEY, 1968), one of his main arguments being his inability to find the faults along which cleavage should have been tilted. The same fan structure continues to the west, where it has been described by MULLER & ROGER (1977). They interpret it also as a feature postdating the formation of an originally steep cleavage. According to these authors it is partly of late Variscan, partly of Alpine age. The present author is of the opinion that it concerns a late Variscan feature, formed in the way Zandvliet envisaged. Due either to N-S tension, or to vertical uplift in the northern part of the axial zone, the cleavage became rotated to a less inclined position. This could take place along many normal faults parallel to the cleavage with a downthrown northern block. These faults stand out as a zone of stronger weathering and thus can be identified in the field.

As can be deduced from the attitude of the unconformable Permo-Triassic it is quite probable that the southern part of the fan structure has been influenced by an Alpine movement, producing an additional tilting. In addition kinkbands are especially frequent near these faults and indicate the same stress field with a vertically directed maximum principal stress and a North-South directed horizontal tension.

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