SUCCESSIVE HERCYNIAN STRUCTURES IN SOME AREAS OF THE CENTRAL PYRENEES

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CONTENTS

ABSTRACT

In the central part of the axial zone of the Pyrenees five distinct phases of folding have been distinguished from the study of minor structures. Traces of a very early phase have been found only in the northern and southern part of the region, which appear on the map as oblique fold structures, and are most prominent from the divergency of lineations and fold axes in these parts of the region. The present aspect of the mountain chain is primarily due to the effects of the main phase in which strong compression produced tight but non isoclinal folds with axial plane slaty cleavage. In the Garonne Dome the slaty cleavage was initially flatlying, in general parallel to the bedding, but occasional folds with crosscutting cleavage have been found. Steep slaty cleavage folds of the Devonian overlying the flatlying slaty cleavage folds of the Cambro-Ordovician of this dome form a beautiful example of disharmonic folding. The main phase slaty cleavage has been found to be folded in the greater part of the area investigated, generally by small minor accordion folds. In several areas two phases of refolding have been distinguished, one with a trend diagonal to the orogene, one parallel, E—W. The intensity of the refolding is strongest in the oldest strata of the sequence. The succession of phases is evident from the folding of the planes of reference and twisting of the lineations. The patterns of the stereographic plots of data do not always show clear evidence of the succession. Knick zones accompanied the end of the Hercynian history of the mountain chain which mainly consisted of arching of the orogene, together with faulting and blockwise tilt. This period of deformation shows several characteristics of tensional stress.

INTRODUCTION

The mapping of the central Pyrenees is carried on by geology students of the Leiden University under the direction of Prof. Dr. L. U. de Sitter. In this paper some small scale structures of several parts of this mountain chain will be discussed, thus allowing a more detailed analysis of the structural history than could be done from the 50,000 mapping. In the region north of the Maladeta granite massif, geological mapping of the Valle de Arán has been carried out by Kleinsmiede (1959) and several others (unpublished reports). In 1960 and 1961 mapping south of the granite was still in progress by D. J. Burkens, J. A. J. Smit and P. H. W. Mey, all from Leiden University. Their results will be published in due course. In the Rio Tor area a group of undergratuate students did some provisional mapping in the summer of 1955.

Dr. H. J. Zwart has investigated the metamorphic parts of the central and northern Pyrenees for many years, partly with the cooperation of students, surveys which have resulted in the establishment of a succession of deformation phases. (Zwart, 1960). The desirability arose to investigate the effects, if any, of these phases in low grade and non-metamorphic strata. The major aim of the present investigation was the establishment of the succession of the various phases of folding. Although the study was concerned with minor and micro-structures, these are most probably parallel to and contemporaneous with major structures, so that the conclusions are valid for the whole folded mountain structure.

The field work has been carried out under the supervision of Prof. Dr. L. U. de Sitter and Dr. H. J. Zwart. To Dr. H. J. Zwart I am indebted for guiding my first steps in the interesting field of micro-tectonics. He also gave valuable advice during the preparation of the manuscript. Critical remarks on the manuscript and important help in correcting the text have been received from Mr. J. F. Savage, M. Sc. Special thanks are due to Mr. J. A. J. Smit who kindly placed field data at my disposal and to Mr. B. H. G. Sleumer, who translated the German summary. I am grateful for the assistance of Miss T. W. Terpstra in typing the manuscript. For technical help I am indebted to Miss C. P. J. Roest, who expertly produced the drawings, while Mr. J. Hogendoorn carefully prepared the photographs. The thin sections have been made by Mr. C. J. v. Leeuwen and Mr. M. Deyn.

CHAPTER I

GENERAL REMARKS

From the published geological map and sections it appears that the Palaeozoic of the Central Pyrenees is strongly compressed and folded. The most important phase of folding which was active in the whole orogene is called the main phase. During this phase tight folds roughly with E—W strike developed with the associated development of slaty cleavage. The trend of these structures coincides with the present mountain trend. This phase was preceded by a phase of concentric folding, locally with oblique trend and not developed everywhere. The main phase itself was succeeded by several phases during which its slaty cleavage was folded. Thus the prominent structures are folded beds with associated slaty cleavage called cleavage folding, and subsequent folded slaty cleavage or folded cleavage.

Due to this sequence of repeated folding a succession of cleavages has been developed. Generally these cleavages are parallel to the axial planes of the associated folds.

Knill (1960) has proposed a classification of cleavages, based on their morphological characteristics:

Slaty cleavage
Fracture cleavage
Crenulation cleavage

Slaty cleavage, synonyms flow cleavage and schistosity. Although the mechanical origin of slaty cleavage may vary, the parallel fabric of minerals throughout the rock is characteristic. The cleavage may be dull, as in slates, or it may glitter as in phyllites. When folded, the typical shining surface was very useful for recognizing these planes in the field.

Fracture cleavage is distinguished from slaty cleavage by the presence of microlithons (de Sitter 1954). It is developed in incompetent as well as in competent rocks. In the incompetent slates of Viella (Valle de Arán), for instance, the development of slaty cleavage is not complete. The rock is divided into narrow zones, alternating ones showing slaty cleavage, whereas in the others the minerals show no preferred orientation (fig. 1). In this case the fracture cleavage represents an initial stage in the development of the slaty cleavage and the process of cleavage development stopped before the rocks recrystallized completely. In competent rocks like sandstones, most micas are found on the cleavage planes (fig. 2). Due to the abundance of quartz grains the cleavage development does not usually proceed beyond this stage.

Crenulation cleavage. The term is suggested by Knill (1960) to replace strain slip cleavage. Crenulation cleavage generally means micro-folded slaty cleavage. A typical example of the development of crenulation cleavage is shown in fig. 3. Although this is not expressed in the Sitter's definition (1954) the term microlithon is useful in the case of crenulation cleavage as well as in that of fracture cleavage.

Two opinions exist about the mechanical origin of slaty cleavage. According

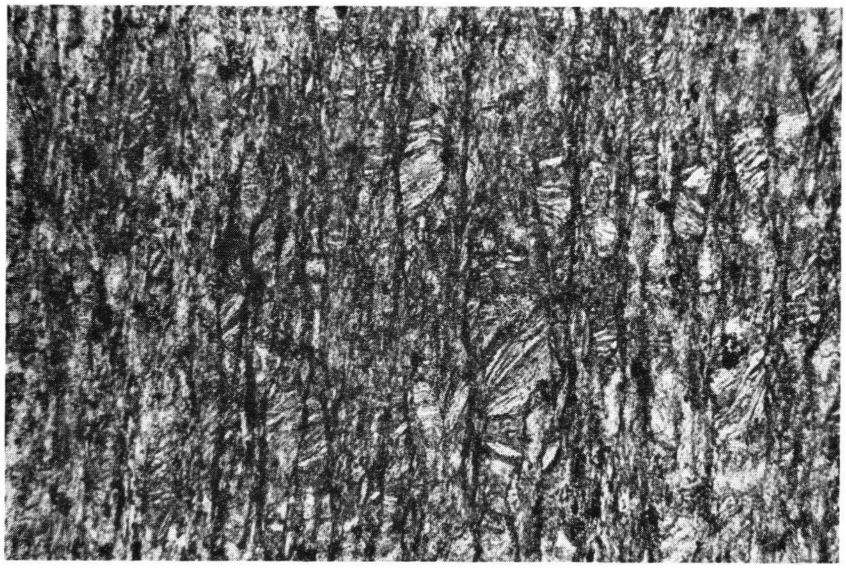


Fig. 1. Incomplete slaty cleavage development with unoriented minerals between cleavage planes. (60 ×)

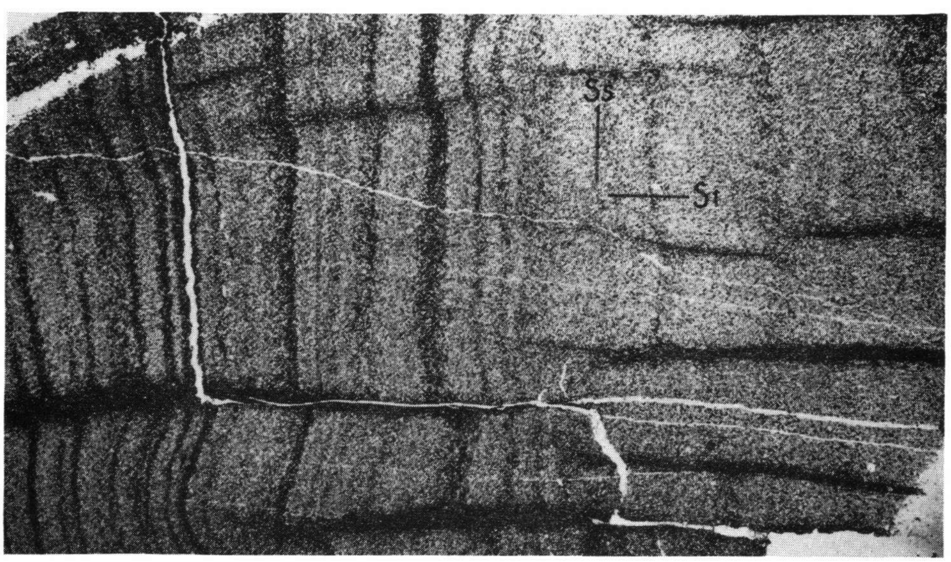


Fig. 2. Sandstone with mica development on the fracture cleavage planes. (3 ×)

to Sorby (1853), Sharpe (1847, 1849), Leith (1905), Goguel (1945), Hoeppener (1956) and de Sitter (1956) the slaty cleavage plane is mainly a plane of flattening and not necessarily a shear plane. Crystallization occurs perpendicular to the greatest stress (Born, 1929) and the cleavage is brought about by recrystallization in a stressfield. The other opinion holds that the cleavage plane essentially is a shear plane under a certain angle to the principle stress direction (simple shear), Becker (1893), Schmidt (1932), Sander (1948). The movement along the plane together with active recrystallization is regarded as the main origin of the parallel mineral orientation.

For the Pyrenees it is logical to suppose, that the direction of maximum stress during the main phase with the development of axial plane slaty cleavage was horizontal and directed N—S. Thus the axial planes of folds developed as sub-vertical planes. Later movement appears to have brought some of these

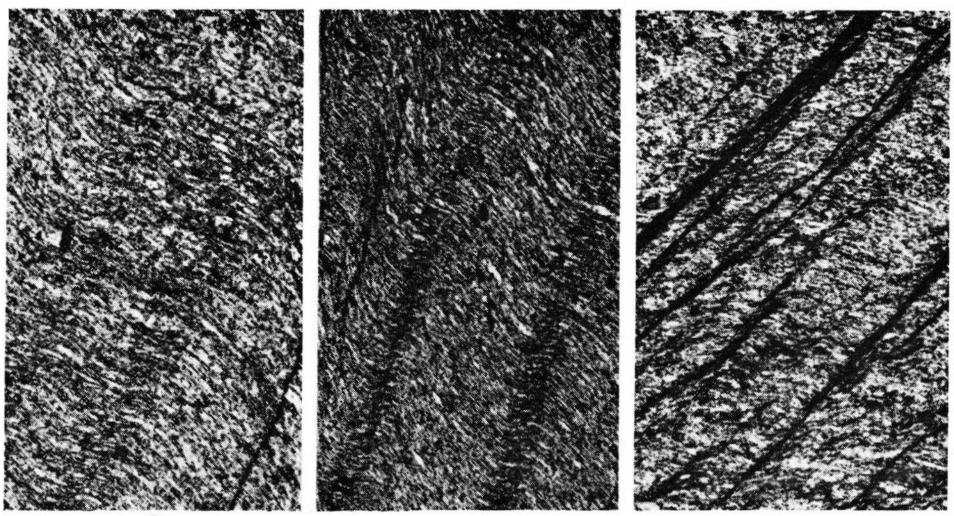


Fig. 3. Development of crenulation cleavage. (25 ×)

planes into their present inclined position. In the Garonne Dome in the central Pyrenees, however, two different cleavage structures are to be found, one originally flatlying, the other originally steep. It is considered that the steep cleavage developed according to the first hypothesis perpendicular to the greatest stress. The origin of the flatlying cleavage is less certain, but it might have been the result of shearing movements as postulated in the second hypothesis.

The term minor structure will be used in the sense of small structures larger than the size of microscopic observation, but too small to be visible on a general geological map. In the present investigation much attention has been paid to minor and micro-structures.

Foliation is used as a descriptive term to denote parallel surfaces without implying their mode of origin (Weiss, 1959).

Parasitic folds (de Sitter, 1958) are small folds of competent layers within larger cleavage folds. The term replaces the two older ones — crestal folds and drag folds. In the area investigated the folded phyllites and slates contain numerous minor folds which are parallel to larger folds. It seems reasonable to extend the definition of parasitic folds in general to small folds which have been contemporaneously developed within larger ones.

Shear zones. The foliation has been sheared along zones which in fact are secondary fracture cleavage planes for which the term shear cleavage might be used. Crenulation cleavage is the most common secondary cleavage in the Pyrenees; the micro-folds formed demonstrate a shortening in a direction parallel to the slaty cleavage planes. However, the shear zones clearly show a lengthening of a direction parallel to the slaty cleavage. This difference seems to originate in the different attitude of these secondary cleavage planes to the previous slaty cleavage, which caused an opposing sense of movement. The development of this kind of secondary fracture cleavage seems very much like the development of the secondary cleavage as described by Hoeppener (1956). In most areas the shear zones appear either irregular, or in a simple parallel set, but in one case as a conjugate set. No folds are developed associated with the shear zones.

Knick zones. These are fault-like zones, along which the slaty cleavage is knicked. This means a shortening in the plane of the cleavage. In general the knick zones seem to have been formed rather later than most structures.

Refolding of existing structures can be proved, when the axial planes of the first set of folds are seen to be distorted by the second set, whose axial planes are themselves undeformed. Since the slaty cleavage in this region is parallel to the axial planes of folds, folding of such surface is then obviously due to a later phase of deformation. For this reason the slaty cleavage and not the sedimentary bedding is in most cases the plane of reference, although in certain parts of the region the bedding is well enough preserved to be used for demonstrating successive folding.

When the slaty cleavage is folded twice, and two secondary cleavages are developed, the succession of these last two phases is much more difficult to determine, although the principle of deformation of the earlier axial planes by the later folds remains valid. Hence it is necessary to find an outcrop, or a thin section in which both later phases interfere in order to solve the problem.

The presence of successive folding can also be deduced from stereograms. Folding of a bedding plane about one axis produces a girdle of poles to that plane in the diagram. The fold axis is normal to the girdle (β-axis). The fold axes, measured in the field or constructed from adjacent bedding plane measurements coincide with the β-axis.

When an axial plane cleavage is developed, the poles to the cleavage plane produce a point maximum, sometimes partly spread about the β-axis, due to fanning of the cleavage in the folds. The lineations, which result from intersection of cleavage and bedding again produce a point maximum, which coincides with the β-axis.

Folding of such structures about an oblique axis will produce a spread of the bedding plane girdle and the fold axes are spread into a girdle. Perpendicular to the plane through this girdle we find the new axis b^1. According to Ramsay (1960) the girdle follows either a great circle — in the case of similar folding; or a small circle — in the case of concentric folding.

Thus the spread of fold axes indicates successive folding. Cleavage-bedding lineations which are parallel to fold axes are obviously also spread into a similar girdle. The cleavage belonging to the first set is spread into a girdle about the second fold axis, but the second cleavage, being parallel to the axial planes of the secondary folds, produces a point maximum of poles. The intersections of first and second cleavages also produce a point maximum. The lineations of the secondary cleavage in the bedding plane are spread, as these lineations result from the superimposition of structures on the already folded planes.

The spread of lineations and axes accordingly is due either to superimposition on a curved surface, or to folding of original parallel lineations. The choice between these two possibilities follows from the recognition of the associated cleavage planes. The last developed cleavage plane is still a planar surface.

Folding of the slaty cleavage plane is found in the Pyrenees on various scales. Some structures are several hundreds of metres wide, although they are hard to detect in poorly exposed areas, and they only appear on the map. Smaller folds, up to several tens of metres wide are easier to find. Finally there are the micro-folds, which cause a crumpling of the slaty cleavage plane and have been studied in thin sections of specimens from many places.

Usually the slaty cleavage planes in the Pyrenees have been folded at least twice. One of the objects of the present work is the establishment of the succession of these phases.

Previous studies of successive folding phases in the Pyrenees have been made by Zwart, Guitard and Lapré, while Zandvliet and Kleinsmiede drew the attention to some of the minor structures.

Zwart worked mainly in the metamorphics of the Aston-Hospitalet massif, in the northern satellite massifs (1959, 1960) and in the Bosost area of the Garonne dome (1958, 1962). He was the first to define the various folding phases in the Hercynian Pyrenees, the associated metamorphism and granitization, and to establish their succession.

Guitard (1960) studied a part of the eastern Pyrenees, where basically he distinguishes a main phase and a later phase. During the latter the main phase schistosity was folded into minor and micro-folds. As in the work of Zwart, much attention has been paid to metamorphism and granitization and their relation to the folding phases.

The work of Lapré (1957—1960) has not yet been published, but it is filed as a report in the Geological Institute of the Leiden University. Lapré studied the successive phases with the associated micro- and minor structures and metamorphism in the Aston massif and its western margin. The intricate structures which result from repeated folding of a surface in different directions was given special attention in the exposure and sample, as well as in thin sections. Lapré was the first to recognize and study the diagonal refolding in the W part of the Aston massif.

Zandvliet (1960) first described the knick zones found in the southern part of the Central Pyrenees. Kleinsmiede (1960) mentioned both knick zones and folded cleavage in the Valle de Arán. His map and sections have been of much help in the present study of the more detailed structures of the Valle de Arán.

CHAPTER II

THE GARONNE DOME

INTRODUCTION

The area along the Garonne river on both sides of the French-Spanish border consists of Cambro-Ordovician phyllites and sandstones with a few exposures of Silurian slates. To the south the rocks gradually change into the metamorphic schists around Bosost. Due to this gradual change no sharp southern boundary of the non-metamorphic area can be defined. To the south the present investigation has been extended about two kilometres south of Bausén. The metamorphic Bosost area has been described by Zwart (1962).

Major structures

The most remarkable feature in this region is the fact, shown by the field work, that the structure of the Devonian-Carboniferous is greatly different from that in the Cambro-Ordovician. In the Devonian-Carboniferous we find steep tight folds with near vertical axial plane cleavage, while in the Cambro-Ordovician the slaty cleavage generally is flatlying, parallel to a banding. The banding in many cases may be of tectonic origin, but in several places it is obviously the bedding. The cleavage appears to have been formed in this flatlying attitude, except near the northern and southern borders of this area. Thus the Cambro-Ordovician forms a dome-like structure, which has been called the Central Anticline by Kleinsmiede (1960), and Garonne Dome by de Sitter and Zwart (1962).

The shape of the Garonne Dome is also well expressed towards the east, where the limestone on the Mail de Bulard forms a flat, nearly unfolded layer (de Sitter & Zwart, 1962).

The very plastic Silurian slates have adapted themselves to the horizontal structure at their contact with the Cambro-Ordovician, and to the steep structures at their contact with the Devonian. This is an exceptionally well developed case of disharmonic folding on a large scale. The special nature of the two styles of folding will be dealt with later on.

The section of fig. 6 runs parallel to the Spanish part of the Garonne and then over the Mt. de Sijol in France. The geological data have been obtained from the area around this line. The section shows the gentle major folding of the Cambro-Ordovician. Here the folding is to be seen in the bedding planes and the often parallel slaty cleavage or cleavage banding. Only a general impression is sketched of the associated minor folds.

In the Devonian and Carboniferous on the section, the folded lines represent the bedding planes.

Minor and micro-structures

Cleavage is developed throughout the greater part of the region except in the Carboniferous rocks, where such structures are poorly developed or even

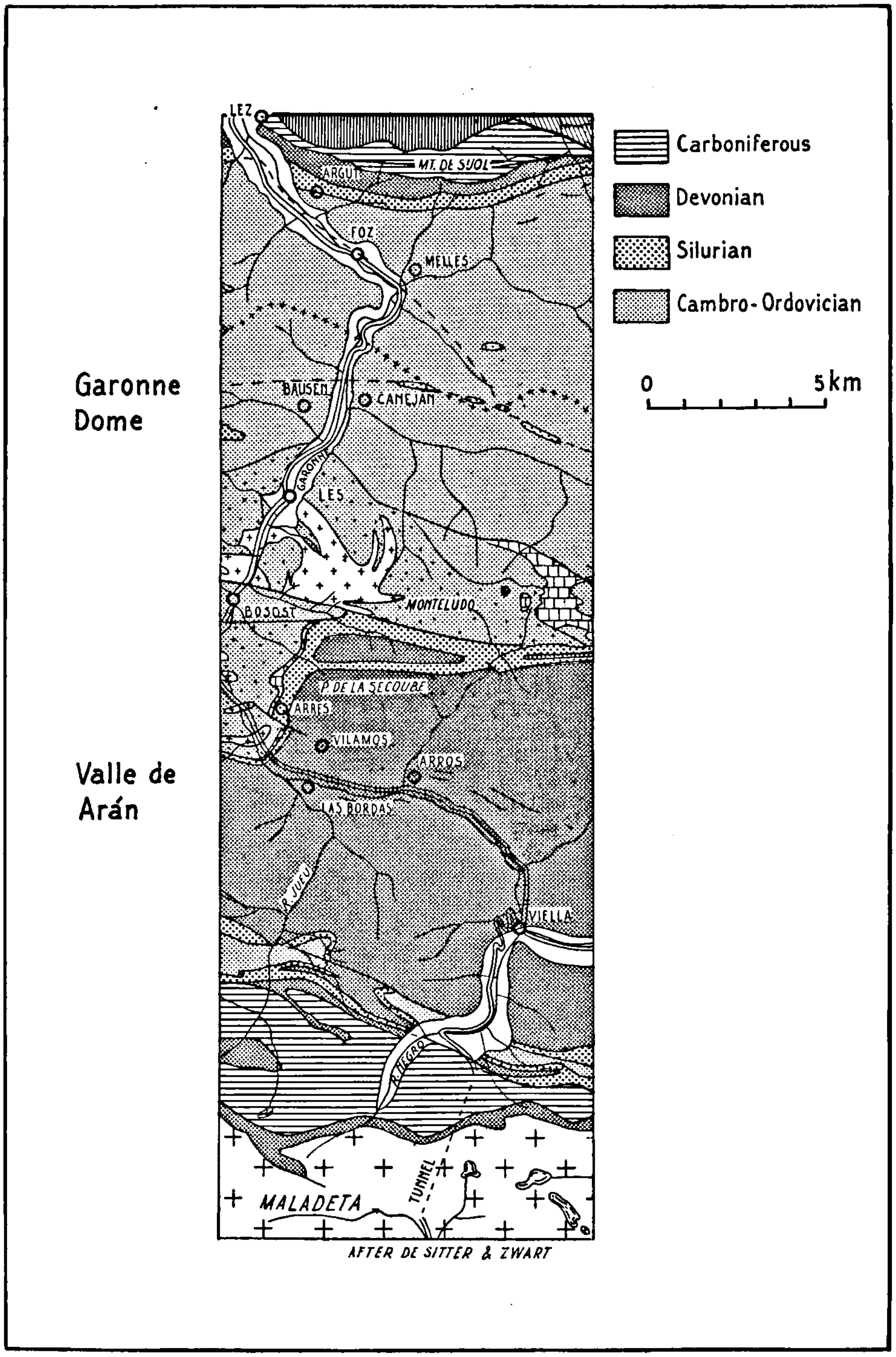


Fig. 4. Geological map of the Garonne Dome and Valle de Arán areas.

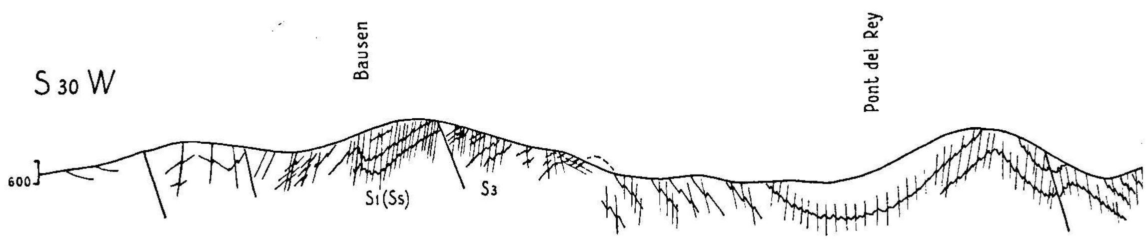


Fig. 6. Garonne Dome section with

absent. Two types of cleavage are generally found in the more pelitic rocks of the area: slaty cleavage and crenulation cleavage. No crenulation cleavage has been found in rocks without slaty cleavage as for example parts of the Carboniferous. Further, typical fracture cleavage has been observed in more sandy and quartzitic layers.

Lineations caused by micro-folding of the slaty cleavage and intersections of that surface with crenulation cleavage are common throughout the area.

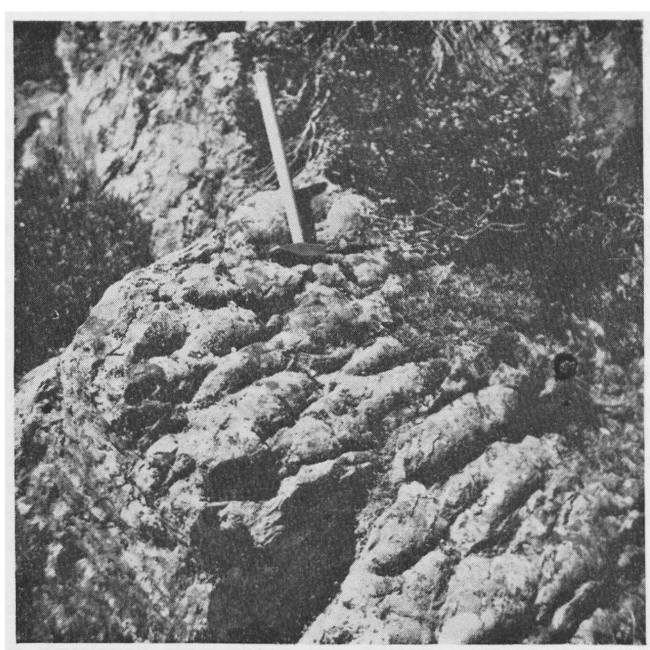
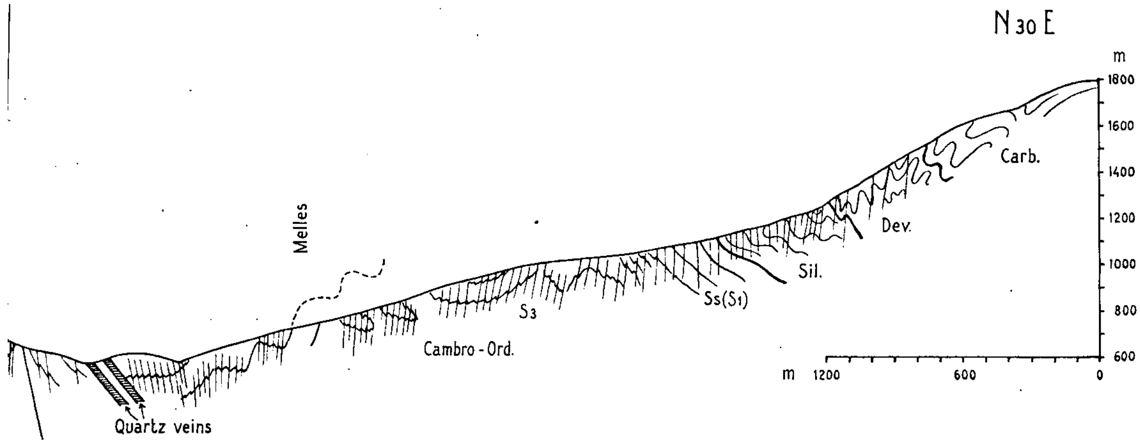


Fig. 5. Parasitic folding on the surface of a Carboniferous sandstone bed near Mt. de Sijol.



bedding planes and first and second cleavage.

THE STRATIGRAPHICAL LEVELS

The Carboniferous

The Carboniferous of the Mt. de Sijol area consists of sandy shales, sandstones, quartzites and conglomerates, all with poorly developed cleavage. The bedding surfaces separating layers with different competencies generally show good lineations, caused by minor folding (fig. 5). The thin sections of the shales with poorly developed cleavage show some sericite parallel to the cleavage planes, but also many randomly oriented sericite flakes between the planes. The cleavage is more or less parallel to the axial planes of minor folds. Only one cleavage is developed.

The Devonian

The Devonian south of the Mt. de Sijol and between Argut and Lez consists of limestones and slates with a typical nodular limestone, the "griotte" at its top. The cleavage is mostly well developed as a roughly vertical axial plane slaty cleavage. The griottes are perfectly cleaved within the slaty part of the rocks although thin sections still show much random sericite in the slates. The limestone nodules have been flattened and arranged parallel to the axial planes of minor folds, which are parasitic folds on the strongly compressed major folds. They are a few metres in width but not so tightly compressed as the major folds.

South of the Mt. de Sijol only one cleavage is found in the Devonian, but in the Argut-Lez area the axial plane slaty cleavage is intersected by a steep NW—SE striking crenulation cleavage and by another steep E—W striking crenulation cleavage. In several exposures these cleavages are parallel to the axial planes of small minor folds, but generally only intersection lineation of the crenulation cleavage on the slaty cleavage is found.

The section (fig. 6) gives an impression of the folded bedding plane in the Devonian and Carboniferous. The gradual change in dip of the axial planes towards the south is evident. The axial plane cleavage and the folding of those planes is not drawn in the section.

The Silurian

The Silurian in the area forms a boundary between the structures of the Devonian-Carboniferous and those of the Cambro-Ordovician, and has been intensely crumpled. Moreover exposures are easily disturbed by creep.

The bedding is difficult to distinguish. Crenulation cleavage is irregularly developed in several directions. Accordingly the Silurian, unlike the Devonian and Cambro-Ordovician, shows a very irregular structural pattern.

The Cambro-Ordovician

The Cambro-Ordovician consists of an often flatlying alternation of slates or phyllites, sandstones and quartzites. At the top this bedding is thinly laminated, but farther down the individual layers become thicker.

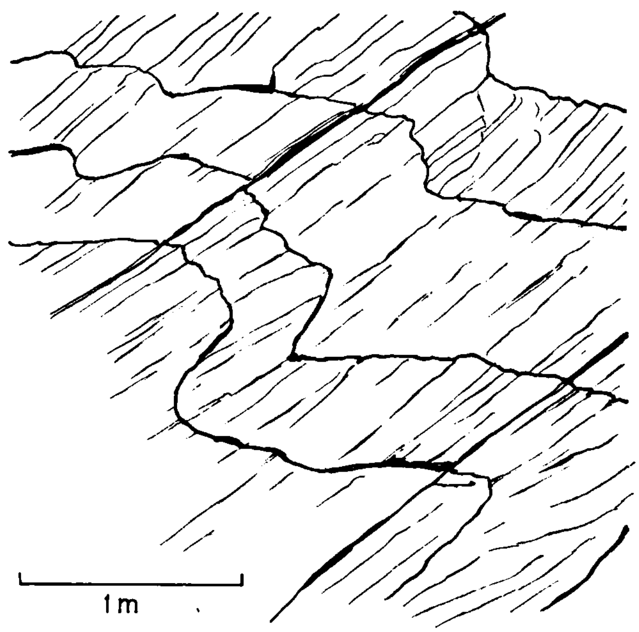


Fig. 7. One of the few folds with crosscutting slaty cleavage in the Cambro-Ordovician near Bausén (after photo).

In most exposures a slaty cleavage is developed, which shows a parallel arrangement of sericite, some chlorite and locally biotite. Generally this cleavage plane is found parallel or nearly parallel to a layered structure, strongly resembling bedding but in many cases certainly due to tectonic banding. A few flexures show crosscutting cleavage (fig. 7).

Although the frequent parallelism between slaty cleavage and bedding would suggest a mimetic crystallization of sericite in the bedding, the occurrence of a few recumbent folds with transverse cleavage indicates that at least some deformation of the Cambro-Ordovician occurred during this process. The same conclusion has been reached for the Bosost area, where main phase lineations in the mica schists indicate recrystallization under kinematic circumstances and not simply a static phenomenon (Zwart 1962).

Fig. 8. Minor accordion folds of the E—W refolding phase in the Cambro-Ordovician between Bausén and Caneján (after photo).

No structural difference can be found between the phyllites of the present area and the schists of the Bosost area; only a gradual increase of metamorphic state.

At the junction of the main road from Les to the French border with the road to Bausén, an exposure is found showing beautiful minor accordion folds. Owing to new road constructions, which are still in progress, this exposure and its vicinity give good examples of the minor structures in the Cambro-Ordovician (fig. 8).

The folds in this exposure show an alternation of long and short limbs, the shorter ones consistently dipping to the north; not far away, but across the strike, the opposite is to be seen. The axial planes of the accordion folds dip steeply to the north; most fold axes plunge gently to the east, a few to the west. Several quartz veins have been found which run oblique to the foliation and which are folded together with it.

The accordion folds show a distinct asymmetry when developed on not too steeply dipping foliation, but on horizontal foliation the accordion folds are symmetric. Between outcrops with steep foliation and those with flat foliation the transition seems gradual as all gradations between extreme asymmetric and symmetric accordion folds have been developed. When the foliation becomes steeper than about 60°, no accordion folds are found.

The size of the accordion folds depends on the thickness of the competent layers, however, no fixed rule concerning this matter has been established. Generally the structures are very regular, parallel and uniform, but occasionally irregularities can be observed without any obvious reason.

The limbs of the folds are generally rather straight, although in bigger folds they become more and more curved. The same is true for the hinges, rounded in the larger folds, but sharp in the small accordion folds. Thickening of the strata in the crest, and thinning of the limbs besides the high parallelism of the structures all indicate the similar character of the folds. Crenulation cleavage is developed in the micaceous layers in the crests of the accordion folds, and generally also in the limbs.

The small structures are parallel to the larger ones and again to the major ones. They constitute a uniform system, the smaller parasitic to the larger ones. In other outcrops, like those more to the north along the French side of the border, the structures are more rounded. Generally the appearance of the folds is a question of scale as folds of equal size have been developed with rounded hinge in thickly foliated or with sharp hinge in thinly foliated rock. Here also minor folds are found parasitic to larger ones.

Shear zones are mainly found in two small areas. One halfway between Foz and Argut shows the shear planes dipping steeply to the SW, the sense of movement is dextral (fig. 10).

South of Bausén another system is found, consisting of a conjugate set. One component dips to the north, the other to the south. The trend of both is about E—W (fig. 11). Fig. 9 shows the interference of this system with the E—W minor folds in a thin section. The conjugate system of Bausén has never been found intersecting with the steep diagonal zones. Occasionally in other exposures one of the shear zones is found, but never the two directions together.

The width of the zones varies from less than one mm to several cms as often observed in the thin sections. Along these zones the rock is sheared. This shearing demonstrates the directions of movement. As the shearing means a lengthening of the slaty cleavage, no folds are found associated with the shear zones. The movement indicates a N—S compression; perpendicular to the trend of the Palaeozoic.

Because they distort the E—W minor folds, the shear zones are later than these structures and seem to represent the last stage of compression in the orogene.

The shear zones cannot be contemporaneous with knick zones, as these represent a stage of release. A comparison moreover is difficult to make as the best knick zones are found in the Ribagorzana and Tor area, and the shear zones in the Garonne Dome. Unlike in the Southern Pyrenees where the development of knick zones is the most conspicuous feature in some exposures, in the northern Garonne Dome they are scarce and irregularly spread. In the whole sequence only a few are found, dipping west, knicking down in the opposite direction.

Fig. 9. Minor accordion folds of the E—W refolding phase ruptured by a conjugate set of shear zones (1.5 ×).

DIAGRAMS

The region between Les and Lez is not structurally homogeneous. For the presentation of the structural data the region is divided into four subareas, which can be considered to be homogeneous.

— The area between Mt. de Sijol and the village of Melles, consisting of Cambro-Ordovician, Silurian, Devonian and Carboniferous.

— The area between the villages of Argut and Lez, with Devonian and the top of the Silurian.

— The area between Argut and Foz with Cambro-Ordovician and Silurian.

— The area around Canejån and Bausén with Cambro-Ordovician and lower Silurian.

The poles to the bedding planes, the various cleavage planes and some lineations have been plotted on equal-area (Schmidt) stereographic nets. These diagrams, even without any explanation or contouring, give a clear impression of the tectonic framework of the areas better than a map. The number of points bears no relation to the intensity of the feature encountered. Usually one point per exposure has been plotted, although for bigger exposures more have occasionally been taken.

The diagrams are made with the object of presenting the features as seen and measured in the field. It has not been the intention to derive conclusions from the diagrams, which could not be derived from the field evidence.

The directions of the structures of the Devonian and Carboniferous of the Mt. de Sijol are displayed on fig. 12. The poles to the bedding planes are irregularly spread, and the poles to the slaty cleavage form a partial girdle. This appears in the field as a gradual flattening of the cleavage plane towards the north. Both the bedding planes and cleavage show little concentration and accordingly the variation of directions of fold axes also is considerable. Crenulation cleavage is not found in this area.

The structures of the Devonian between Argut and Lez appear in the diagrams of figs. 13 and 14. In fig. 13, slaty cleavage, bedding and fold axes are shown. The cleavage measurements indicate the predominance of near vertical cleavage planes. The poles to the bedding plane show a partial girdle about an axis, which coincides with the cluster of fold axes. The poles to the crenulation cleavage planes and to the axial planes of minor accordion folds are shown in fig. 14. Two maxima are apparent, one in E—W, the other in NW—SE direction. Only a few knick zones are present.

The diagrams in this paper are lower hemisphere equal-area projections.

Fig. 10. Cambro-Ordovician between Foz and Argut.
Poles to first, second and third cleavage planes, to shear cleavage planes and to the planes of knick zones.

Fig. 11. Cambro-Ordovician between Caneján and Bausén.
Poles to first, second, third and shear cleavage planes.

Fig. 12. Devonian and Carboniferous between Mt. de Sijol and Melles.
Poles to the bedding planes and to the first cleavage planes and axes of folded bedding.

Fig. 13. Devonian between Argut and Lez.
Poles to first cleavage and bedding planes and axes of folded bedding.

Fig. 14. Devonian between Argut and Lez.
Poles to second and third cleavage planes and to the planes of knick zones.

Fig. 15. Devonian between Argut and Lez.
Lineations of refolding on first cleavage.

Fig. 16. Silurian and Cambro-Ordovician between Mt .de Sijol and Melles.
Poles to first, second and third cleavage planes.

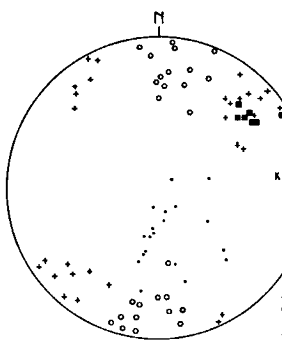
Fig. 17. Cambro-Ordovician between Argut, Bausén and Caneján.
Lineations of refolding on first cleavage.

Fig. 18. Cambro-Ordovician along the Garonne Dome section.
Poles to the first cleavage planes.

The traces of the crenulation cleavage on the slaty cleavage are shown in fig. 15. Here we see a cluster of these lineations plunging gently to the east and a more widely spread group of steeper lineations in the centre of the diagram. The gently plunging lineations represent the intersection of the E—W crenulation cleavage with the slaty cleavage; the steep lineations are the result of the intersection of the NW—SE trending crenulation cleavage with the slaty cleavage.

The figs. 10, 11 and 16 cover the Cambro-Ordovician in the region. The poles to the slaty cleavage of the subareas are assembled in one diagram (fig. 18). This diagram shows a girdle about an E—W horizontal axis. At many places the slaty cleavage has a gentle dip.

The presence of two distinct directions of crenulation cleavage planes and axial planes of minor accordion folds is obvious; as in the Devonian, one E—W and the other NW—SE. The poles to these planes either show a fair concentration



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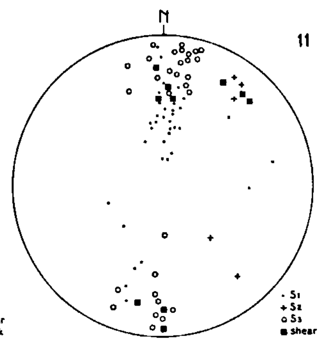

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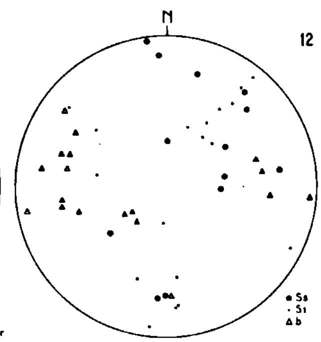

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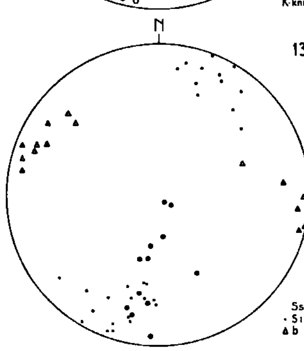

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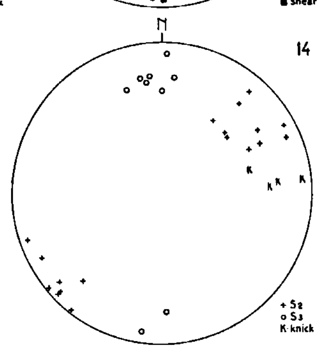

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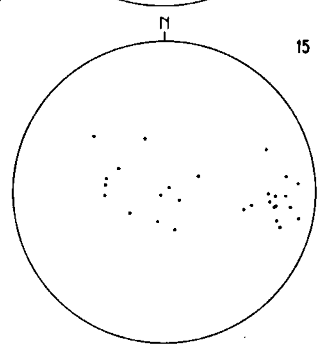

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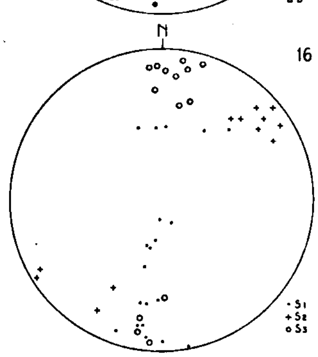

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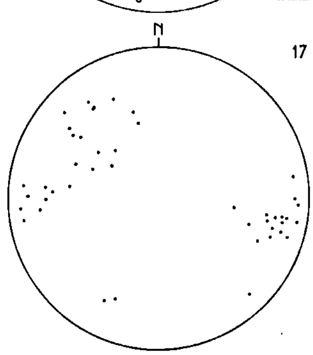

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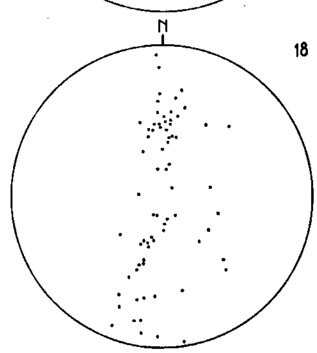

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(fig. 16) or they show some spread, but still within a distinct culmination as in fig. 10. A regular spread, in the form of a partial girdle is only observed in the lower part of fig. 11. This feature has been observed in the field as a gradual change of the dip of these planes. The planes with different dip do not intersect, but form fans. Fig. 10 shows a third cleavage direction to the NE, which is less well developed. Knick zones and shear zones are also shown in this diagram. The single direction of shear zones of fig. 10 is also present in fig. 11. In fig. 11 the conjugate set of shear zones near Bausén is represented by a few components with northerly and a few with southerly dip.

The traces of the crenulation cleavage on the slaty cleavage in the Cambro-Ordovician are shown in fig 17. As has been shown above the directions of crenulation cleavage in these rocks are similar to those in the Devonian (fig. 15). In the Cambro-Ordovician, however, no steep lineations belonging to the NW set have been found, as the slaty cleavage often is a gentle dipping plane (fig. 10). In the Bausén-Canején subarea (fig. 11) the slaty cleavage has a steeper attitude. But on those steep planes no lineations belonging to the NW set have been found. The NW lineations which appear in the diagram are from the exposures, in which the attitude of the slaty cleavage plane still is rather flat.

The association of the E—W lineations as represented on fig. 17, with the folding of the slaty cleavage plane is shown by fig. 18. The pole to the plane through the girdle of fig. 18 coincides with the maximum of E—W lineations in fig. 17.

CONTEMPORANEITY OF SLATY CLEAVAGE DEVELOPMENT

Both the flatlying cleavage in the Cambro-Ordovician and the vertical cleavage in the Devonian are intersected by crenulation cleavages. The planes of these crenulation cleavages are parallel to the axial planes of minor accordion folds. As has been shown, two systems of minor folds are developed, one with steep axial planes striking E—W, and one, also with steep axial planes, striking NW—SE. A few others with NE—SW strike have been found.

These systems of crenulation cleavage and associated minor folds are strikingly parallel in the Devonian as well as in the Cambro-Ordovician. Accordingly the slaty cleavage plane in both levels must be older than the crenulation cleavages.

A good argument for the contemporaneity of slaty cleavage structures is the parallelism of fold axes in both levels. Although in the present area only few folds syngenetic with the slaty cleavage have been found in the Cambro-Ordovician, they have the same E—W trend as those in the Devonian. The parallelism of lineations in supra- and infra-structure is more prominent in the area of the Aston-Hospitalet massif in the east of the Central Pyrenees. There the parallel structures in both flatlying metamorphics and the steep slates also suggest contemporaneity (Zwart 1960). Hence, although there is little direct evidence in the present area, the slaty cleavage itself is supposed to have developed contemporaneously in both the Devonian and Cambro-Ordovician rocks.

REFOLDING

Since a slaty cleavage plane is produced during a certain phase of deformation, folding of this planar fabric must be due to a later phase, as has been recognized in many regions.

In the present area folding of the slaty cleavage plane is only occasionally found in the Devonian, whereas in the Cambro-Ordovician it is the most conspicuous feature in nearly all exposures, samples and thin sections. Accordingly the crenulation cleavage plane and axial planes of minor accordion folds of figs. 10, 11 and 16 belong to such refolding phases.

The slaty cleavage plane has been folded in minor folds with axial planes parallel to the crenulation. Due to this folding the poles to the slaty cleavage plane show a girdle in the stereogram, instead of a point maximum. The girdle has an E—W axis (fig. 18) and obviously the E—W system is well developed in the area.

The minor folds with E—W axis are larger than those with diagonal trend. The latter folds are microscopically small and do not disturb the general strike and dip of the slaty cleavage, but only produce a rippling. This accounts for the fact, that no girdle of poles to the slaty cleavage planes around a NW axis is produced.

Nevertheless the occurrence of two separate sets of crenulation cleavage indicates that at least two phases of refolding have been active in the area. The poorly developed set (fig. 10) in NE direction even suggests a possible third phase.

THE SUCCESSION OF FOLDING PHASES

The structures in the Carboniferous of the Mt. de Sijol show a divergency of fold axes, which is expressed on the map of this area (de Sitter & Zwart, 1962) by oblique trending pebble beds, and in the diagram of fig. 12 by the great spread of the poles to the bedding planes. The most probable explanation of this feature is that two successive phases of folding are involved, since a strong divergency of bedding planes and fold axes should occur, when a set of folds is refolded with an oblique trend, as explained in the introduction. Since the slaty cleavage dating from the main phase is not deformed, a folding phase preceding the cleavage folding seems clearly established in this part of the area. The same conclusion has been reached about the Devonian of the Estours region farther east (de Sitter and Zwart, 1962) and also about the Ribagorzana and Tor region (p. 143). However, in the Devonian, Silurian and Cambro-Ordovician of the Garonne Dome no evidence of earlier folds has been found.

Folding of the slaty cleavage plane is a general feature in the area of the Garonne Dome. The major part of the folding in the Cambro-Ordovician here was associated with the development of a crenulation cleavage, which succeeded the main phase. The trend of this refolding is E—W, the attitude of the axial planes and crenulation cleavage is generally steep. The minor folds in exposures and samples show a lineation on the folded surface, parallel to the E—W fold axis, but often also a second lineation, oblique to this axis, on the flanks of E—W folds. These oblique lineations seldom appear on the hinges, because of the intensity of E—W crenulation cleavage there. The lineations generally are due to crenulation of the surface but occasionally associated small folds are found. As the flanks of the E—W accordion folds are generally planar surfaces, the oblique lineations appear as straight lines. In a few cases these lines are sheared by the intersecting E—W crenulation cleavage (fig. 19).

Thus the E—W crenulation cleavage was preceded by a diagonal crenulation cleavage. The majority of the diagonal crenulation cleavage planes dip steeply to NE or SW, with a few dipping to the SE. These various types of diagonal cleavage seldom intersect and when they do, the intersections give no consistent solution to the succession. It is supposed that the two directions form a contemporaneous conjugate set. From the small amount of evidence found, this

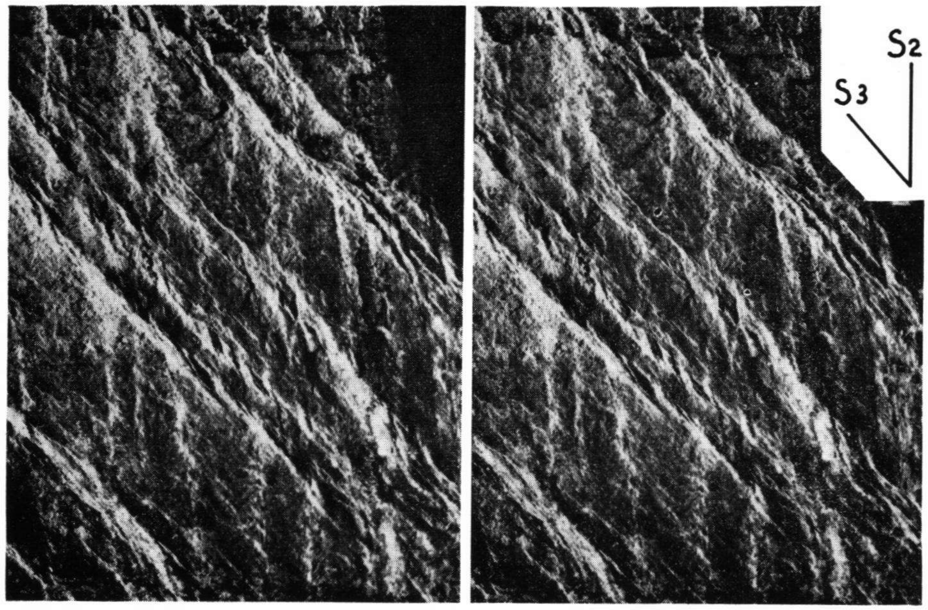


Fig. 19. Shearing of older lineations by later crenulation cleavage. (Hand specimen, 6 ×).

could not be established adequately, although the contemporaneity of the two directions has already been suggested by Zwart (1960).

In thin sections the folding of the slaty cleavage by diagonal and E—W crenulations is obvious. The diagonal crenulation cleavage is occasionally seen to be disturbed by the E—W crenulations confirming the field evidence as to their succession (fig. 20).

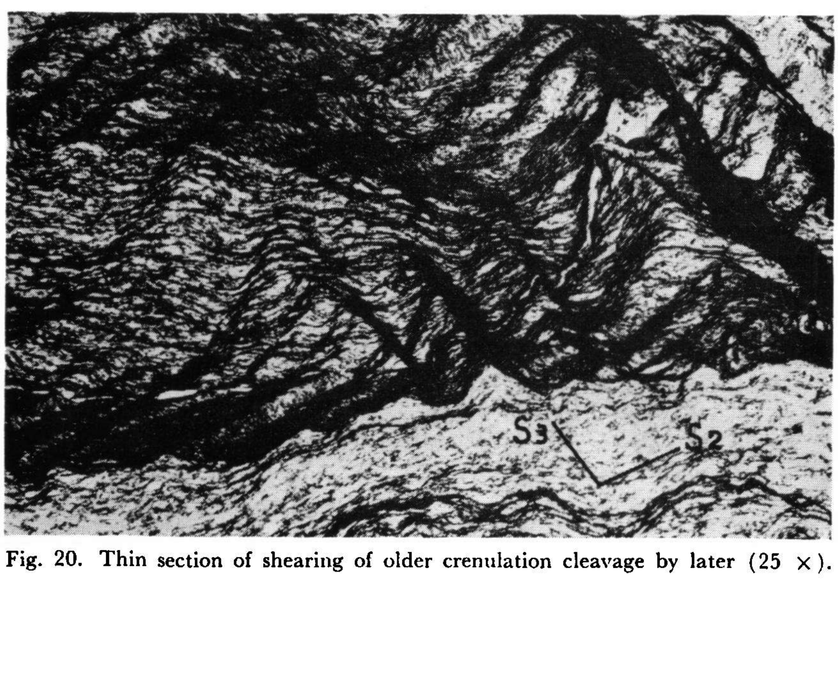


Fig. 20. Thin section of shearing of older crenulation cleavage by later (25 ×).

The E—W crenulation cleavage planes are mostly seen in the field to be undisturbed planar surfaces. The diagonal cleavage planes generally fade away, due to the strong E—W cleavage, but when it is found it curves with the folds of the E—W phase.

Another impression of the successive phases is found in the diagrams of the traces of crenulation cleavage and axial planes on the slaty cleavage. These traces generally are prominent in the field, even when the associated crenulation cleavage plane has been destroyed by the successive cleavage developments.

In fig. 17 those traces are shown, as collected in the Cambro-Ordovician, mainly between Argut and Foz, and in the vicinity of Bausén and Caneján, where the slaty cleavage plane occasionally dips rather steeply (fig. 11). On the steep slaty cleavage of Bausén few diagonal traces are found, probably due to the intensity of the E—W refolding. The steepening of the foliation is contemporaneous with the E—W crenulation cleavage and due to minor accordion folds. The diagonal refolding produced gently dipping lineations on the sub-horizontal slaty cleavage plane.

Quite the opposite is shown in fig. 15 of the Devonian between Argut and Lez. Here the diagonal refolding is represented by steep lineations, due to intersecting with the steep slaty cleavage plane.

Little deformation of one phase by the succeeding is expressed by the diagram, presumably because the diagonal structures are not consistently parallel amongst themselves, but also because in the Devonian both phases produced mainly small minor folds or only crenulation cleavage. The diagonal phase neither produced large structures, in the Cambro-Ordovician, whereas the E—W phase produced minor and major folds.

The shear zones distort the E—W accordion folds and accordingly are of later date (fig. 9). The deformation shows compression perpendicular to the regional trend, which is also true for the E—W refolding structures. Accordingly the shear zones are supposed to represent the final stage of the E—W refolding phase, rather than a separate phase.

Only a few knick zones are found. As they disrupt the crenulation cleavage, they are obviously of later date.

A comparison with the results derived by Zwart (1960) gives the same succession of phases of deformation.

- Concentric folding (pre-cleavage).
- Main phase folding about E—W axes with development of slaty cleavage and schistosity.
- (Folding about N—S axes, not observed in the present area).
- Crossfolding. Diagonal refolding axial planes and crenulation cleavage developed in two pronounced directions.
- Refolding about E—W axes, with crenulation cleavage, in the present area succeeded by shear zone development.
- Knick zones.

CONCLUSIONS

In the Devonian the main phase minor folds show axial-plane slaty cleavage with E—W trend. This plane is regarded as the plane of flattening. Accordingly the original dip of the cleavage plane is supposed to have been about vertical, perpendicular to the postulated stress direction.

In the Argut-Lez area this cleavage plane shows intersections with steep

E—W striking secondary cleavage planes. This secondary system can be traced southward all over the area between Lez and Les. As it is present everywhere and shows such a consistent strike and dip, it must be a contemporaneous system for the whole area.

Accordingly the steep structures in the Ordovician, which shows this secondary cleavage as axial plane cleavage must be younger than the steep Devonian main phase structures north of Argut. The same reasoning holds for the secondary cleavage and the folds developed by the diagonal refolding. The presence of this intermediate system in both excludes the possibility that the E—W slaty cleavage in the Devonian would be contemporaneous with the E—W crenulation cleavage in the Ordovician.

Thus we come to the conclusion that the main phase produced steep structures in the Devonian and Carboniferous and flat structures in the Ordovician, the zone of transition between the two being formed by the Silurian black slates.

The diagonal refolding produced a conjugate set of distinct accordion folds and crenulation cleavage. This, however, must have been only a very small scale affair. No big folds have been found associated with this phase. No distortion of the first cleavage plane in the Cambro-Ordovician by the diagonal is seen in the diagrams.

The axial planes and the crenulation cleavage planes of the diagonal refolding structures do not form a parallel set, as the deformation by the succeeding E—W refolding phase did not scatter the poles to the diagonal planes into a partial girdle, but rather into an irregular concentration on the diagrams.

The E—W refolding produced a distinct girdle of the poles to the Cambro-Ordovician slaty cleavage plane as seen on the diagrams of figs. 10, 11, 16 and 18.

The E—W refolding phase produced crenulation cleavage, micro-, minor and major accordion folds, the smaller ones parasitic to the larger. It is possible that some initial undulation of the main phase foliation of the Garonne Dome was produced before the development of the E—W crenulation cleavage.

CHAPTER III

THE VALLE DE ARAN (fig. 4)

INTRODUCTION

In this chapter the occurrence of at least two folding phases in a part of the area will be described. A recent map of the Valle de Arán on 1 : 50,000 scale and published by the Leiden Geological Department, has been prepared for a great part by Kleinsmiede (1960). In his work we find the description of many structures with numerous sections.

Mullions in graded sandstones are mentioned by Kleinsmiede, but he does not discuss their origin. Here they are considered to have been caused by parasitic folding and cleavage, belonging to the main phase of the Hercynian orogeny.

In the Bosost area the Cambro-Ordovician consists of mica schists, grading northward into phyllites (Zwart, 1962). The Devonian south of this formation shows an alternation of shales and limestones, altered into crystalline marble near the metamorphic Bosost area. The limestone content decreases upward and sandbearing slates and sandstones appear. In the upper part of the Devonian there is a sequence containing graded sandstones (Kleinsmiede, 1960). The Devonian between the villages of Arrés and Arrós (Entecada formation) consists of slates and limestones (Kleinsmiede, 1960), passing up into the graded sandstones. The top of the Devonian in the Valle de Arán consists of fine-grained slates and sandstones.

STRUCTURES

The Arrés-Arrós area

The major structures in the Cambro-Ordovician are strikingly different from those in the Devonian; the disharmonic folding of the two with the Silurian as a plastic horizon in between is exceptionally well developed south of the Montludo (cf. Kleinsmiede, 1960, p. 202, fig. 24). The role of the Silurian as a dividing level between two different styles of folding has been described above (p. 112).

The Devonian, with which we are mainly concerned here, shows strongly compressed folds with a subvertical, axial plane slaty cleavage. The fold axes in this part of the Valle de Arán plunge E to ESE at about 10° to 20°. This folding phase is the first one to be distinguished in the area.

The area between Arrés and Arrós is chiefly characterized by ESE plunging lineations and fold axes, as has been demonstrated by Kleinsmiede (1960, figs. 26, 47), who measured a large number of lineations and fold axes in the Valle de Arán. Although the normal trend of the Hercynian structures is E—W, the same diversion of trend into an ESE—WNW direction is found in the Bosost area.

On the Pico de Secoube the axial plane cleavage in the Devonian is a vertical plane. No secondary cleavage is found here. Going south about halfway to the village of Vilamós a secondary cleavage in the form of crenulation cleavage starts to develop. Between Vilamós and Arrés the slaty cleavage is folded into flexurelike folds. The folds are up to a few metres in width. Like many of the accordion folds of the Garonne Dome they are asymmetric, the short limbs mostly dipping south. The larger folds are wide and round, with rounded limbs and without a definite sharp hinge. The smaller folds are sharp accordion folds.

The attitude of the axial planes of these new folds is rather irregular. Mostly they dip at more than 45° in northerly direction. The strike is consistently ESE—WNW. These structures are found everywhere between Vilamós and Arrés; they are also common between Vilamós and Arrós. (Vilamós is situated halfway between Arrós and Arrés).

Fig. 21. Folded main phase cleavage near Arrés.

Fig. 21 shows the axial plane cleavage in a metamorphic limestone-slate alternation. Obviously the cleavage plane has been bent in a later phase. In the area between Arrés and Vilamós several of these structures are found. The plunge of the folds which deform the slaty cleavage is to the ESE and generally is parallel to the main phase lineations.

In the Silurian slates of Arrés only crenulation cleavage and small minor folds are developed, but in the Devonian limestones some folds are a few metres wide. In the graded sandstone series a crenulation of the slaty cleavage plane in the slates is the only refolding feature observed.

Around Arrés such folded slaty cleavage can be traced from the Cambro-Ordovician into the Devonian with inclined slaty cleavage planes. The steep axial plane cleavage in the Cambro-Ordovician belongs to the same phase of refolding as the steep axial plane crenulation cleavage in the Devonian. Where in the Devonian the slaty cleavage planes are vertical, as it is not far to the north, no folding of this planar structure has been observed.

Where the axial plane cleavage of the main phase structures is folded, the succession is clear. In the Devonian limestones, however, several structures have been found, which show bending and folding of the bedding plane without development of associated cleavage. Moreover, because of the nearness of the metamorphic Bosost area (Zwart, 1962), the structures in the limestones tend to be irregular. In those cases of repeatedly twisted planes the succession of phases could not be solved (fig. 22). Generally, however, owing to cleavage development, refolding of the main phase structures could be proved.

Fig. 22. Repeatedly twisted bedding plane in the Valle de Arán.

The fold axes and lineations in the Valle de Arán, as shown by Kleinsmiede (1960), partly represent structures which can be attributed to the main phase, as for example the mullions and most of the axes of large folds. In the area around Vilamós, however, folded slaty cleavage occurs in several exposures, which was not recognized by Kleinsmiede.

Besides the minor and micro-folds of the slaty cleavage in E—W direction similar kinds of small scale structures occur in other directions, although accompanying crenulation cleavage is often difficult to observe. It seems probable that those folds can be correlated with the NW phase described from the Garonne Dome section, which preceeds the late E—W phase.

From the Cambro-Ordovician of the metamorphic Bosost area Zwart (1962) describes several folding phases, of which the last two have a NW—SE and an E—W direction. Undoubtedly they are the same phases which are recognized in the Devonian.

The fine-grained slates around Viella

The fine-grained green or grey-green slates and sandstones around Viella show

Fig. 23. Parasitic folding in the slates near Viella.

Fig. 24. Diagonal refolding of the slaty cleavage near Viella.

a well developed cleavage. Due to the grain size and the pelitic composition this cleavage is rather intense. In thin section, however, the cleavage appears to be imperfectly developed and contains microlithons with unoriented relicts between the cleavage planes.

In many exposures the bedding plane is difficult to detect, but in some cases a more sandy layer can be seen parasitically folded (fig. 23). Sometimes minor parasitic folds are even seen in the cleaved slate.

In the fine-grained slates no E—W refolding has been found, which may be due to the fact that the secondary steep axial planes would be parallel to the first slaty cleavage in these exposures. On the other hand the lack of secondary crenulation cleavage might presumably be due to the imperfect fabric of the main phase slaty cleavage.

Some refolding with NW—SE striking axial planes has been found in a few outcrops. Immediately south of Viella a few minor folds are exposed along the road to the Maladeta tunnel. The exposure is near the base of the fine grained formation and consists of limy slate with perfect cleavage, which is folded with the axial planes dipping to the NW (fig. 24). Only a few knick zones and joints indicate later movement.

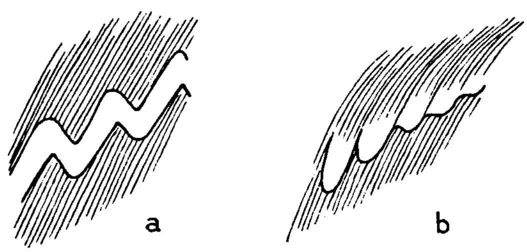


Fig. 25. Sketch of development of parasitic folds (a) and mullions (b).

Lineations in the sandstones between Viella and Las Bordas

Parasitic folding is present in particular in the Las Bordas formation of the Valle de Arán, where various rock types such as slates and graded sandstones are exposed. Where thin competent (sandstone) beds are folded in a thick incompetent environment (slates), the concentric folds of the sandstone often show maximum bending, i. e., the convex surface is folded to a radius equal to the thickness of the layer. The outer arc is broad and round, the inner arc is sharp (fig. 25a). The diagram shows that the sharp arcs face the relatively competent bed.

Several parasitic folds have been found, where deformation of the competent rocks went even beyond this stage and flattening and stretching by plastic deformation occurred. The basic form of rounded and sharp arcs of these parasitic folds has been maintained, independent of the degree of compression during continued deformation.

In graded beds in the Las Bordas formation the plane of sharp contact between sandstone and slate, the sole of the graded bed, shows this same kind of surface with round synclinal bends and sharp anticlines. With further deformation the cleavage planes become planes of movement and the folded layer is separated into mullions (fig. 25b).

Through the sharp arcs the cleavage planes of the slates intrude into the competent sandstone, but at the round outer arcs the cleavage stops at the contact. Here the bedding plane shows some shearing.

Often the mullions are shifted one over the other. In the Las Bordas area it seems that the shift is always an upthrust, although this may not be a general rule, as in this area mullions have only been studied on the lower surface of fairly steep dipping graded beds. The result is a lineation of the bedding plane, often resembling sedimentary ripple marks. Because bed after bed shows the same strictly parallel ripples there can be no doubt that this coarse lineation is of tectonic origin.

The extension of the folds in the direction of the lineation shows a large variation. Some lineations seem without end and they can be traced all along

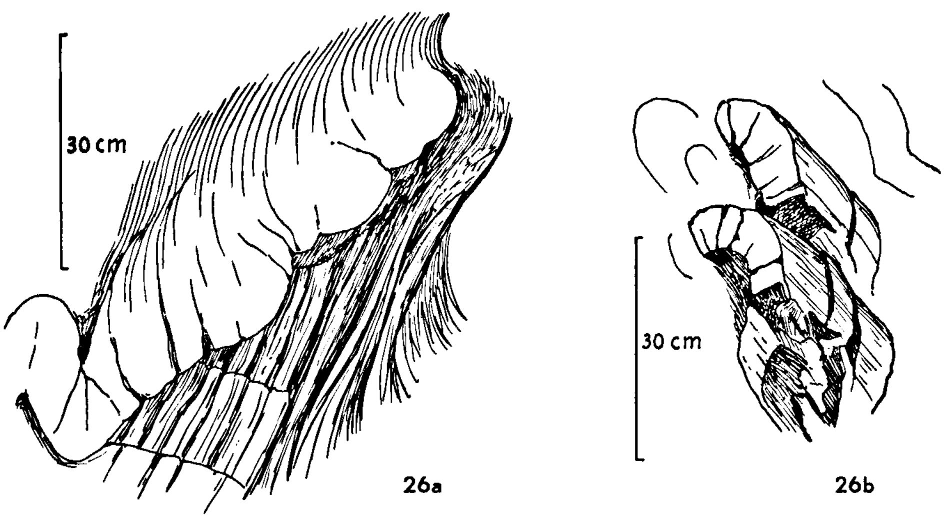


Fig. 26a. Mullions in graded beds near Las Bordas (after photo).
Fig. 26b. Fold mullions in non-graded beds near Las Bordas (after photo).

the exposure. The ripples on the bedding surface are strictly parallel without broadening or narrowing of the separate parasitic folds. In other cases the folds are short, and only two to twenty times longer than broad. They end quickly, but are clearly recognizable as folds. Both structures are dependent upon the difference in competency of sedimentary layers.

Slaty cleavage is developed in the incompetent slates. In the parasitically-folded sandstones fracture cleavage is observed. In the graded series the fracture cleavage at the bottom grades into the slaty cleavage at the top by gradual increase of cleavage intensity (fig. 26).

Most graded beds show sigmoidal cleavage and both mullions and sigmoidal cleavage are best developed in graded beds. The sigmoidal cleavage, however, is not the origin of development of mullions although their shapes may be influenced by it. Both are the result of deformation during folding of the same sedimentary texture.

The difference between mullions and boudins is clear. The Las Bordas mullions are a further development of parasitic folds of the bottom surface of graded beds, and they are the result of shortening, whilst boudinage is the result of stretching of the beds. Boudins are also found in the same lithologic formation, but never together with mullions or parasitic folds in one exposure. Boudinage occurs in beds where the cleavage runs almost parallel to the bedding. Whether boudins or mullions develop depends on the attitude of the layers in the stressfield as is demonstrated by the diagram of de Sitter (1958, p. 281), which illustrates the relation between parasitic folds and boudins and is also valid for the Las Bordas mullions, since these are a special kind of parasitic folds.

According to the role of the cleavage the mullions of Las Bordas are cleavage mullions, but their initial stage of parasitic folding makes the term fold mullions preferable (Wilson 1953, de Sitter 1956).

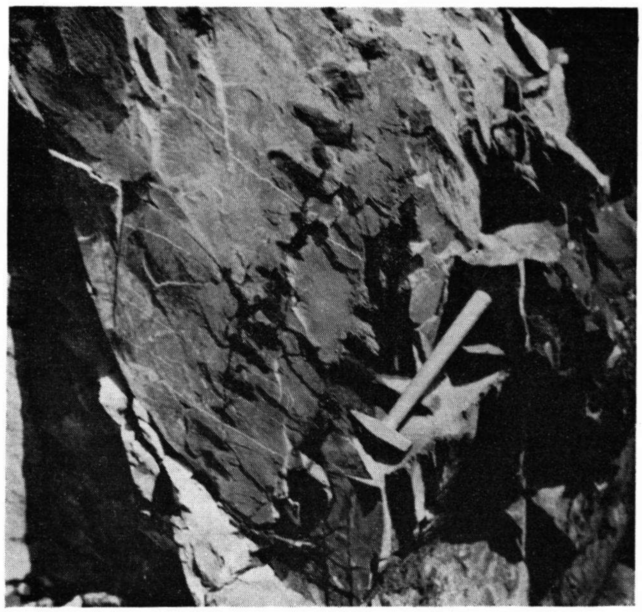


Fig. 27. Section through cleavage mullions near Arros.

Pure cleavage mullions are found in the Valle de Arán when the differences in competency are not very great and little or no parasitic folding occurs (fig. 27).

Wunderlich (1959) assumes separation to occur previous to the rounding, unlike the development of the Las Bordas mullions. His fig. 4 seems to represent a special case, and evidence in this region seems to demonstrate that it does not account for mullions in general.

Schmincke (1961) extended the definition of mullions given by Pilger and Schmidt (1957) to include structures appearing on steep and overturned limbs as well as on flat beds, on both sides of the bedding plane. His observations seem to fit the Pyrenean examples better.

The Las Bordas mullions show the presence of only one folding phase and no evidence was found here of a second cleavage, which was considered necessary for mullion development in the region described by Pilger and Schmidt (1957).

CHAPTER IV

THE RIBAGORZANA AND TOR VALLEYS

INTRODUCTION

South of the Maladeta granite the rivers Ribagorzana and Tor pass through Cambro-Ordovician, Silurian, Devonian and Carboniferous strata, and finally enter the Mesozoic.

The stratigraphy of this region still is a subject of investigation by several students. At the present moment it seems established that at least two different longitudinal facies zones of the Devonian occur. In the rocks contained in the thermal metamorphic zone of the Maladeta granite it is assumed that besides Silurian and Cambro-Ordovician, Devonian and Carboniferous are again present. The subdivision into lower, middle and upper Devonian which is used has no chronological meaning, but only indicates the succession.

The deepest exposed rocks of the Cambro-Ordovician are a series of well cleaved slates and a series of finely alternating slates and thin quartzitic bands, well bedded and with a cleavage almost parallel to the bedding, because of near-isoclinal folding. In the Silurian well cleaved limestone beds are sometimes found. The horizon of Silurian black slates is very incompetent and mostly shows intense and irregular folding. The lower Devonian limestones again are thinly bedded, and the slates show a well developed slaty cleavage. In the middle Devonian the quartzites and dolomites occur as thick beds with coarse fracture cleavage — intermediate slates show slaty cleavage. Accordingly the sequence can be divided into a lower part with mostly high fissility and a less fissile upper part. Due to this difference in character both parts show a difference in tectonic style.

On structural grounds the region of the Ribagorzana and the Tor has been divided into three areas.

1. The southern area with Devonian and Carboniferous along Ribagorzana and Tor.
2. The northern part of the Tor, with Cambro-Ordovician, Silurian and Lower Devonian rocks.
3. The northern part of the Ribagorzana, with Silurian and lower and middle Devonian.

Besides the separate discussion of the three areas a fourth section will be dedicated to the knick zones, which are very conspicuous in the southern Tor area and in most of the Ribagorzana area.

THE SOUTHERN AREA

Introduction

The area comprises Devonian and Carboniferous on the east and the west slopes of the valleys. To the south this area is bordered by the Triassic, which unconformably overlies the Carboniferous shales and sandstones. The northern boundary is not very sharp and is formed by a line which runs more or less along the Llausel rivulet and south of the village of Barruera.

The stratigraphy of the Devonian has been studied by several students and will be published by P. H. W. Mey. For the present paper it is of importance to note that the Devonian is generally well bedded, consisting, from bottom to top, of limestone, slate, quartzite and dolomite, and again slate and limestone. The competent beds in this sequence sometimes are quite massive. A special rock type of the upper Devonian is the "Griotte", a nodular limestone. According to Dufrénoy (1833) the nodules of the griotte in the French part of the Pyrenees consist mainly of fossiliferous material. This has not been confirmed for the present areas. Moreover, because of intense deformation and cleavage development, most of our griottes are linear, and their possible nodular sedimentary origin is not evident.

The Carboniferous in this area consists of slates or micacious shales with many bands of limestone and sandstone. The well bedded Devonian-Carboniferous sequence is folded tightly, although the folds are never completely isoclinal. A prominent feature of these folds is the axial plane slaty cleavage. This cleavage is present in all Devonian slates, and in several limestones. The quartzites show little or no cleavage in hand specimens, but the thin section often reveals parallel mica flakes. In the Carboniferous the cleavage generally still is in the stage of fracture cleavage.

The development of slaty cleavage varies in intensity in the Devonian slates. In the initial stage where the slaty cleavage is developing from a fracture cleavage, we still see microlithons with random sericite. The intensity of slaty cleavage depends not only on the degree of deformation and metamorphism, but also obviously on the mica content of the rock.

In quartzites with fracture cleavage the microlithons contain quartz grains, while the cleavage planes have been coated with sericite. A parallel arrangement of flattened quartz grains is seldom found. Probably this texture develops only under much stronger deformation.

In most minor folds the cleavage is parallel to the axial planes. Some divergency occurs due to fanning out of the cleavage, or curving of the cleavage plane when passing through rocks with varying competencies. Apart from such variations the slaty cleavage is parallel over fairly large areas.

A gradual change in strike is found from east to west. From north to south the dip decreases gradually.

Pronounced linear structures have been developed, either as intersections of the bedding and cleavage planes, or due to folding of one of these surfaces. The characteristic features of those linear structures can be studied on each of the following three planes.

a. On the bedding plane.
b. On the cleavage plane.
c. On a section perpendicular to both these planes.

a. The bedding plane shows small folds which are the result of the differences in competency between beds. These folds of competent layers are caused by compression whereby the incompetent slate yielded by flattening, the sandstone or limestone by concentric folding (de Sitter 1958). Similar parasitic folds have been described from the Valle de Arán. The parasitic folds often become separated by cleavage going through the hinges. These folds can be quite continuous in axial direction and are in fact mullions when seen in their long direction.

Not only are thin competent beds in an incompetent environment parasitically folded, but also the thick competent beds show the same feature. Here the rippling effect is mostly just superficial, only the cleavage goes straight through the competent rock.

b. The trace of the bedding on the cleavage plane is a very common lineation in the area. Due to intersecting with bedding planes with various competencies the cleavage plane is curved. The curving of the cleavage causes a lineation on that plane, which is parallel to the axes of the minor folds.

c. The parasitic folds, their stretching and separation and the further

Fig. 28. Intersection of cleavage and bedding in upper Devonian griotte in the Rio Tor valley.

rounding and flattening are best studied in a section perpendicular to the fold axis.

As the limestone reacted differently to the deformation than the less competent surrounding rock, the variations in competency are clearly shown. The limestones have been cut into mullions, which in some cases became wholly separated (fig. 28). The boundaries are either sharp or a transition zone is present (figs. 29, 30). The separated mullions have been flattened.

Sometimes the mullions are more soluble than the surrounding rock because they are made of purer limestone, so that we find rows of little holes, indicating the bedding. In other cases the competent lenses are more resistant, so they stick out of the weathered surface.

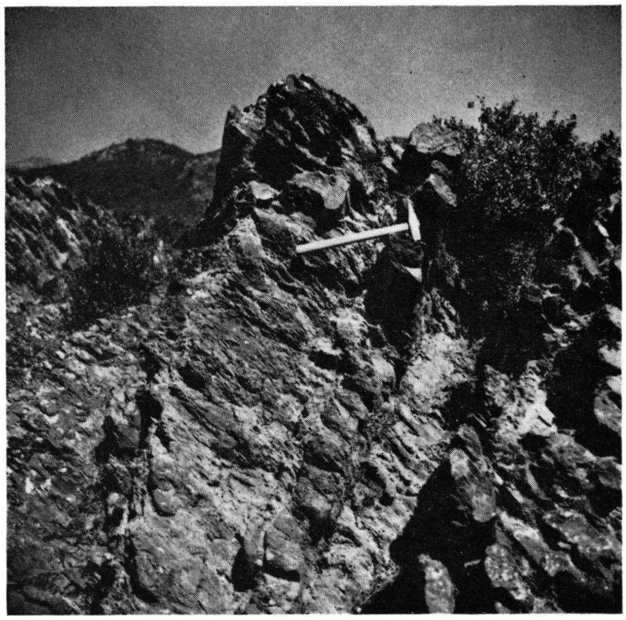


Fig. 29. Intersection of cleavage and bedding in upper Devonian slates and limestones in the Rio Tor valley.

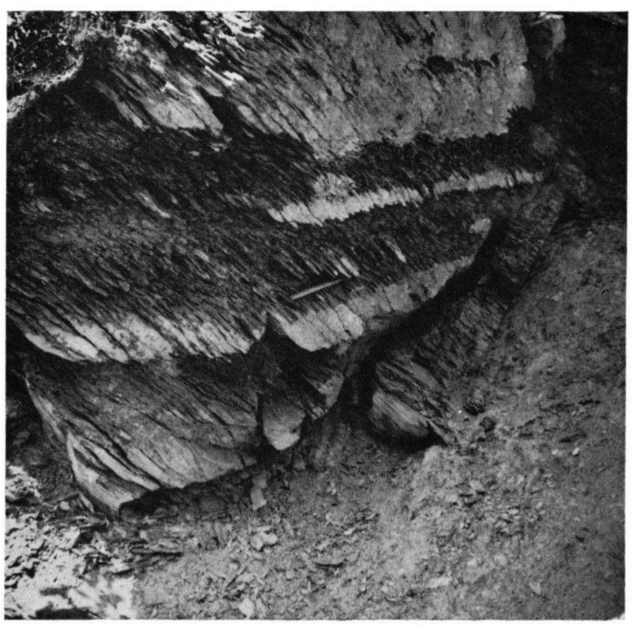


Fig. 30. Intersection of cleavage and bedding in upper Devonian slaty limestone in the Rio Tor valley.

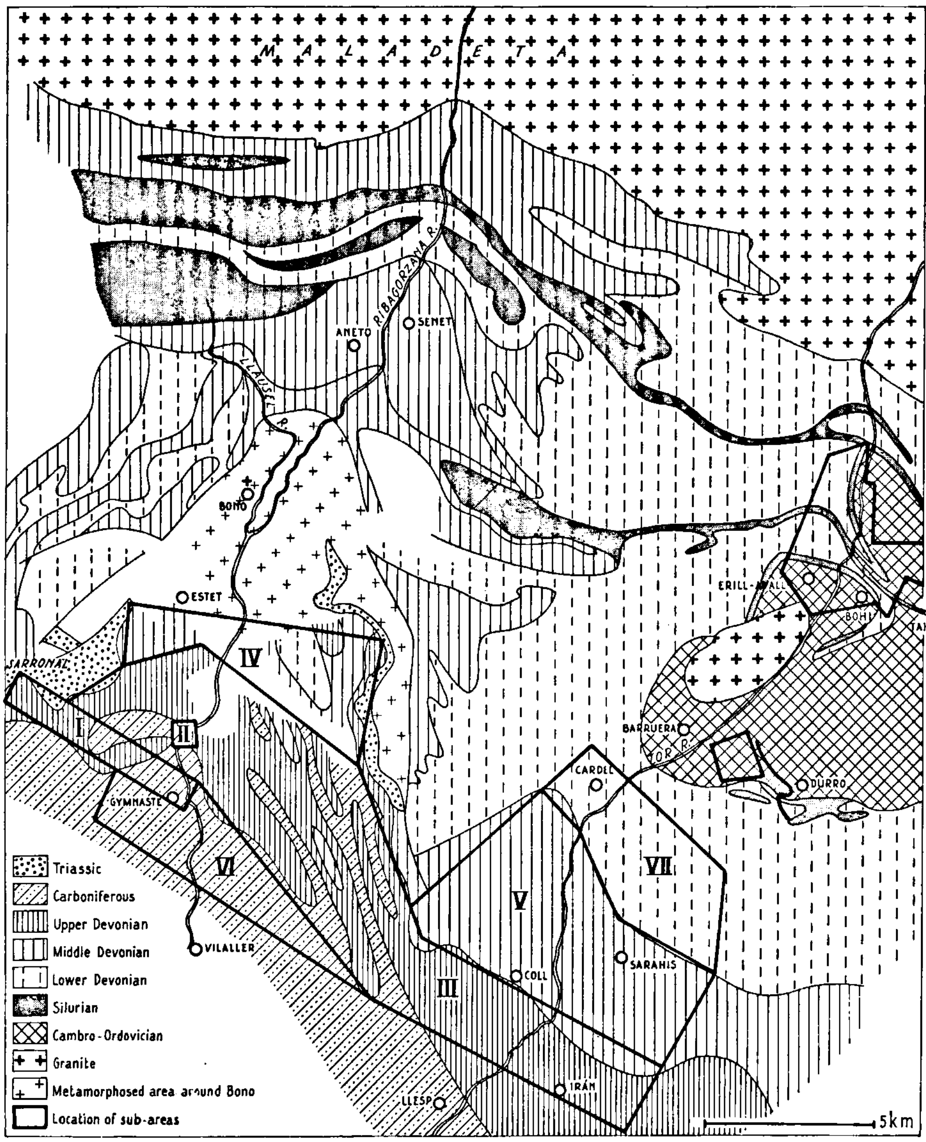


Fig. 31. Geological sketch map of the Ribagorzana and Tor valleys.

The subareas

The southern part of the Rio Ribagorzana and the Rio Tor has been divided into subareas (fig. 31).

The first area I between the village of Gymnaste and the Mt. Sarronal consists of an overturned series of lower Carboniferous and upper Devonian rocks. The second area forms a small dome structure in the upper Devonian limestone, right in the middle of the Ribagorzana valley II. The third area III covers the upper Devonian limestone in both the Ribagorzana and the Tor. The middle Devonian of the Ribagorzana and Tor is covered by subareas IV and V. Subarea VI deals with the borderzone of Devonian and Carboniferous along the Rio Ribagorzana. Only the upper part of the lower Devonian in the Rio Tor is included in subarea VII. The structures in the lower strata in both Ribagorzana and Tor will be discussed later on.

In the subareas the following features have been measured:

Strike and dip of the bedding planes.
Strike and dip of the cleavage planes.
Cleavage-bedding lineations.

The lineations and the poles to the planes are plotted on stereograms. Fold axes have been constructed by measuring the intersections of adjacent bedding planes on a stereographic net and are likewise plotted. Accordingly they represent axes of minor folds.

Subarea I. The upper Devonian and lower Carboniferous between Gymnaste and the Mt. Sarronal. The poles to the bedding planes in fig. 33 show a large variation, and it should be noted that they do not lie in a distinct girdle. The concentration of poles to the cleavage planes as shown in fig. 32 indicates strong preferred orientation of these surfaces. A mean cleavage plane has been constructed and drawn in the several diagrams. The cleavage-bedding lineations are plotted in fig. 32. They lie on a partial girdle which coincides with the mean cleavage plane. The axes of the folded bedding planes on fig. 34 show an obvious spread. Most axes plunge to the north, parallel to the cleavage, but several diverging axes are found, not parallel to the cleavage. The lack of fold axes with plunge to the east or west is most remarkable since this direction is to be expected in an orogene with an E—W trend.

The concentration of poles to the cleavage planes indicates that these planes are undeformed and apparently no folding took place after the development of these planes. Micro-folding of the cleavage planes also is absent.

When the diagrams 32 and 34 are compared, it is evident that the history of this area is more complicated than would be expected from only one phase of folding. The spread of the bedding planes, the presence of a girdle of cleavage-bedding intersections, defining fold axes associated with cleavage development, and the divergence of the fold axes constructed from adjacent bedding planes with regard to cleavage bedding lineations, leaves no doubt that two folding phases with different directions must be involved, according to the principles outlined in the introduction of this paper.

Since the cleavage itself is undeformed, a phase of folding must have preceded the cleavage folding, and since only one cleavage occurs, the first folding must have been of the concentric type. The direction of the cleavage folding is ENE—WSW, as shown by the strike of the cleavage. The direction of the first folding is difficult to determine from the diagrams.

In addition, the intersecting lines of cleavage measurements are constructed in diagram 35. The spread of the intersections results from the fanning out of the cleavage in the folds and hence does not represent folding of the cleavage plane. The intersecting lines of cleavage and bedding and the fanning of the cleavage are parallel and spread in the same girdle. The parallelism of these two cleavage features is expressed in the diagrams 35 and 32, and consequently the fanning of the cleavage is symmetric with the curving of the bedding plane, and perpendicular to the axis of the fold, rather than to the median axis of the stressfield.

Subarea II. The Dome structure. Immediately south of the hydroelectric plant "Central de Bono" the road crosses a bridge over the River Ribagorzana, and then cuts through a structure in upper Devonian nodular limestone. Standing in this roadcut one finds oneself in the centre of a dome (fig. 36).

The diagrams of the dome structure shows a good concentration of the poles to the cleavage planes (fig. 37). Thus after their development little or no disturbance of these planes occurred. In the field some deviation of cleavage planes is to be seen, like fanning out in the folds, and curving due to passing through beds with different competencies.

The poles to the bedding planes as plotted on fig. 38 show a concentration on a small circle and more or less indicate the shape of the dome. Most bedding planes are rather flat, some dip steeply between NW and ENE, and a few to WSW and SW. The diagram of the lineations of cleavage and bedding intersections shows a distribution of points in a girdle which coincides with the mean cleavage strike and dip (fig. 37).

The same reasoning as in the Gymnaste structure can be applied here, which implies that the dome must be the result of two successive folding phases of which the last one was accompanied by the development of slaty cleavage, whereas the first structure was a concentric fold. The direction of

Devonian-Carboniferous between Mt. Sarronal and Gymnaste.

Fig. 32. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 33. Poles to the bedding planes.

Fig. 34. Axes of folded bedding.

Fig. 35. Intersecting lines of cleavage planes.

The Dome structure.

Fig. 37. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 38. Poles to the bedding planes.

Upper Devonian Ribagorzana. Upper part of western slope.

Fig. 39. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 40. Axes of folded bedding.

Upper Devonian Ribagorzana. Lower part of western slope.

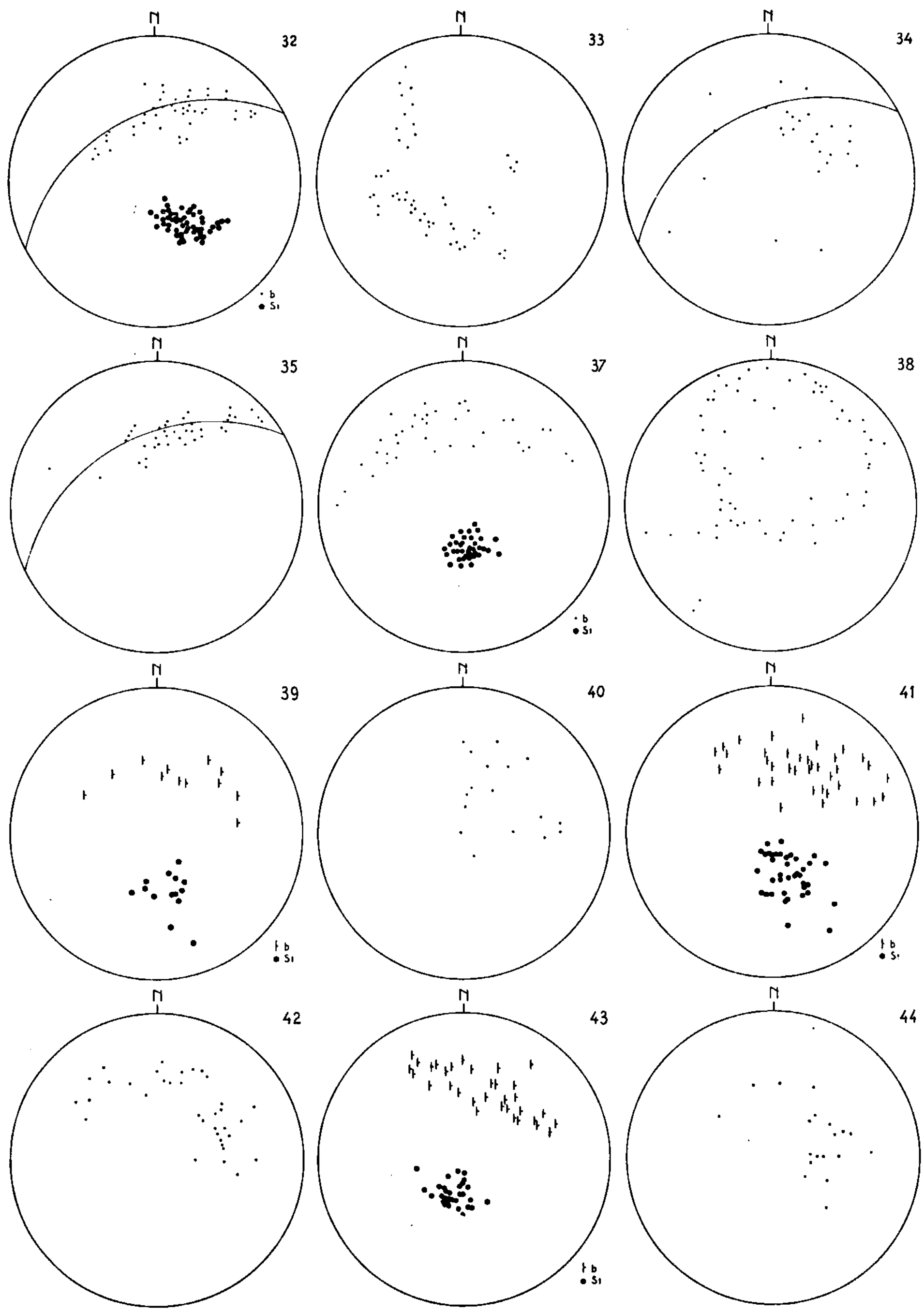
Fig. 41. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 42. Axes of folded bedding.

Upper Devonian Ribagorzana. Lower part of eastern slope.

Fig. 43. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 44. Axes of folded bedding.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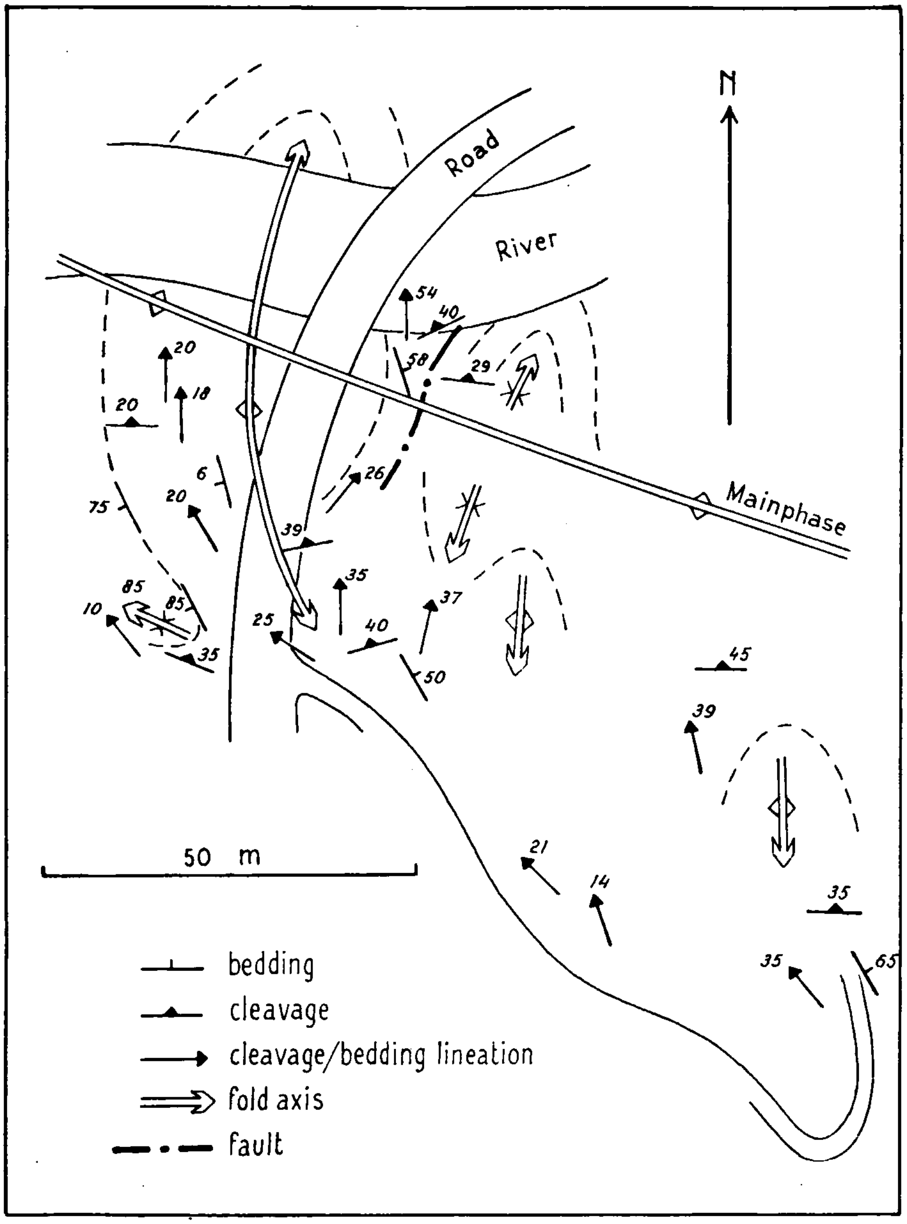


Fig. 36. Structural sketch map of the Dome structure.

the cleavage is clearly E—W, parallel to the strike of most of the Palaeozoic of the Pyrenees. The first folds seem to have had a N—S direction.

Subareas III, IV, V and VI covering the middle and upper Devonian and the lower Carboniferous in the southern Ribagorzana and Tor area. In addition to the investigation of the small subareas I and II data have been collected in the middle and upper Devonian along the Ribagorzana and the Rio Tor between the Mt. Sarronal and the village of Iran. The diagrams constructed from this survey confirm the conclusions from the subareas I and II.

The data of area III (Ribagorzana part), IV and VI have for a great part been collected by J. A. J. Smit during his work on a Master's thesis. Area III covers the upper Devonian limestone and nodular limestone. Areas IV and V cover the middle Devonian and area VI the transition zone between Devonian and Carboniferous. The diagrams 39—58, of subareas III, IV, V and VI, show the poles to the slaty cleavage forming a highly concentrated cluster, demonstrating that there has been no deformation of the cleavage here. This undeformed nature of the slaty cleavage is comparable to that found in the Gymnaste and Dome structures. One exception has to be made for the numerous knick zones, but they do not affect the general attitude of the cleavage measured. For the present discussion, exposures too much influenced by knick zones have been purposedly left out, so that they do not effect the stereograms. The knick zones will be treated further on (p. 166).

The poles to the first cleavage plane and the cleavage-bedding lineations of subarea III are shown on figs. 39, 41, 43, 45 and 47. A gradual shift of the attitude of the cleavage can be observed. The cleavage-bedding lineations lie on a partial girdle. The poles to the bedding planes as presented on fig. 48 show a spread still indicating more than one folding phase. The fold axes of figs. 40, 42, 44, 46 and 49 show a great divergency. Several fold axes lie in the same girdle as the lineations but divergent fold axes occur as well. This leads to the same conclusion as for the Gymnaste and Dome structures, that a phase of concentric folding was followed by a phase of cleavage folding with different trend.

Equal structures are to be found in areas IV, V and VI. The diagrams of area IV show north-plunging lineations and fold axes (figs. 50, 51) and a considerable spread of fold axes in the eastern part of the subarea (fig. 53). The diagrams of subarea V (figs. 54, 55, 56) and those of subarea VI (figs. 57, 58) show the same features. In all subareas I—VI the direction of the cleavage folding is roughly E—W, parallel to the general trend of the Palaeozoic.

Minor folds of two phases. In conclusion it can be stated that in the middle and upper Devonian and in the Carboniferous of the Ribagorzana and Tor valleys the occurrence of two phases of folding is clearly demonstrated. The two phases are: a pre-cleavage (pre-main-folding) phase of concentric folding with a N—S to NE—SW axial direction and a phase of cleavage folding which can be correlated with the main folding of the Hercynian orogeny, with E—W to ESE—WNW direction.

An analogous succession has been found in the Carboniferous along the northern boundary of the axial zone on Mt. de Sijol (p. 123) and near Estours (de Sitter and Zwart, 1962). The continuation of the present structures to the West has been mapped by P. H. W. Mey, who comes to the same conclusions (pers. comm.).

In the Devonian and Lower Carboniferous of the Ribagorzana and the Tor valleys, all cleavage-bedding lineations lie on a girdle coinciding with the mean cleavage plane, as shown in the stereograms. The intersecting lines of cleavage and bedding run parallel to the axes of minor folds. Some of these folds are only a few metres in width. The cleavage plane is parallel to the axial planes of the folds.

Several minor folds are found, which are transected obliquely by the slaty cleavage. Some major folds appear on the map, running obliquely to the E—W trend of the Palaeozoic, and also intersected by main-phase cleavage development and folding. (Map to be published by de Sitter and Mey).

In the upper Devonian the stratigraphic boundaries run NW—SE notwithstanding the numerous minor folds with axial plunge between NW and NE (or even SE). These minor folds all share the axial plane cleavage. The first folding seems to have been merely a gentle buckling of the bedding plane. In the middle Devonian the stratigraphic boundaries run oblique to the cleavage trend, the first folding was more intense, and smaller major folds were produced.

Since the main phase happened to be a period of intense folding with the development of cleavage and lineations, the minor folds of the main phase are more easily detected than the older structures. Where exposures run about E—W, however, several of the older folds can be seen. For example, the steep but well exposed limestone mass above the "Central de Bono" on the western bank of the Ribagorzana shows minor folds of both phases.

Upper Devonian Ribagorzana. Upper part of eastern slope.

Fig. 45. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 46. Axes of folded bedding.

Upper Devonian Rio Tor.

Fig. 47. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 48. Poles to the bedding planes.

Fig. 49. Axes of folded bedding.

Middle Devonian Ribagorzana. Western slope.

Fig. 50. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 51. Axes of folded bedding.

Middle Devonian Ribagorzana. Eastern slope.

Fig. 52. Poles to the first cleavage planes and cleavage-bedding lineations.

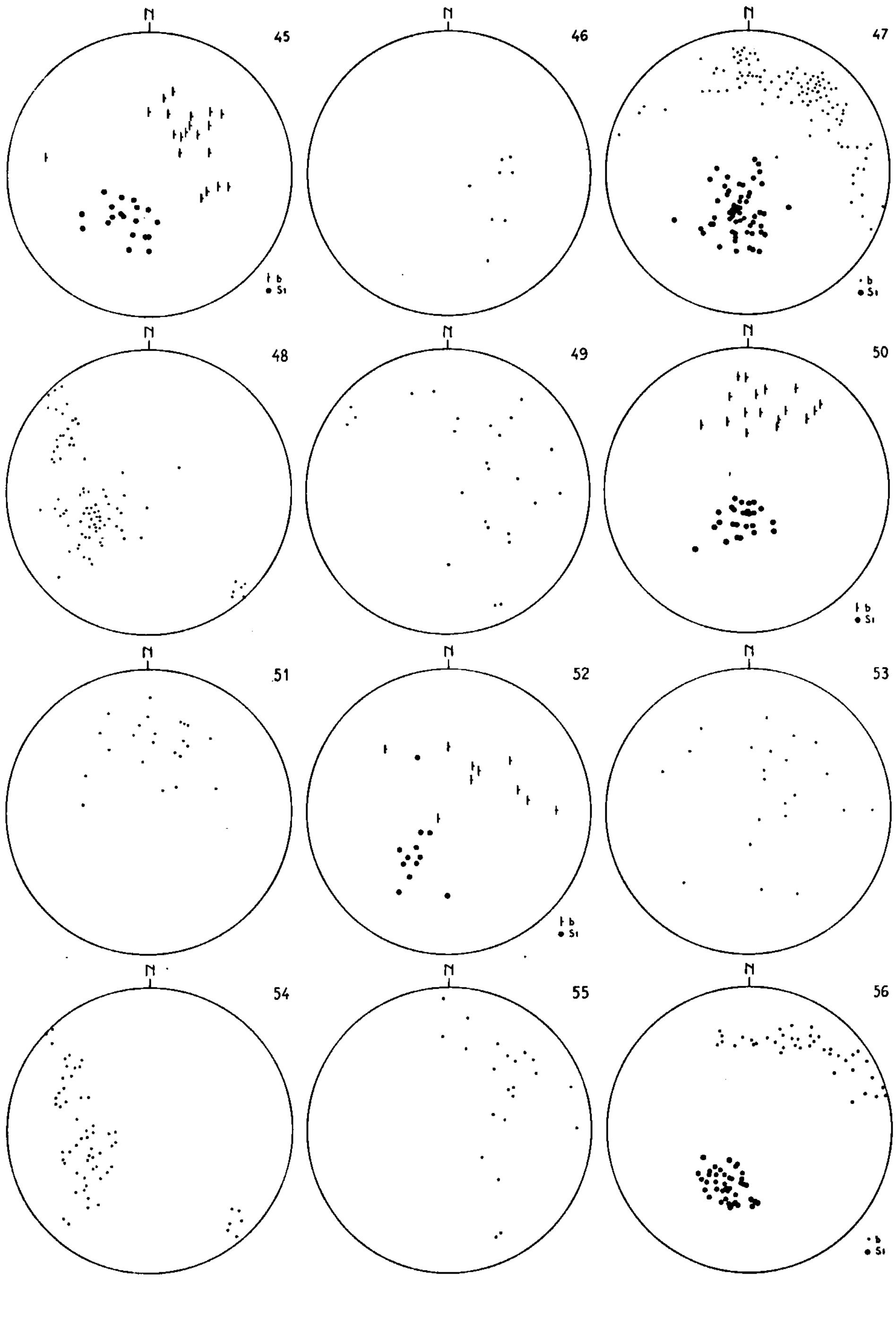
Fig. 53. Axes of folded bedding.

Middle Devonian Rio Tor.

Fig. 54. Poles to the bedding planes.

Fig. 55. Axes of folded bedding.

Fig. 56. Poles to the first cleavage planes and cleavage-bedding lineations.



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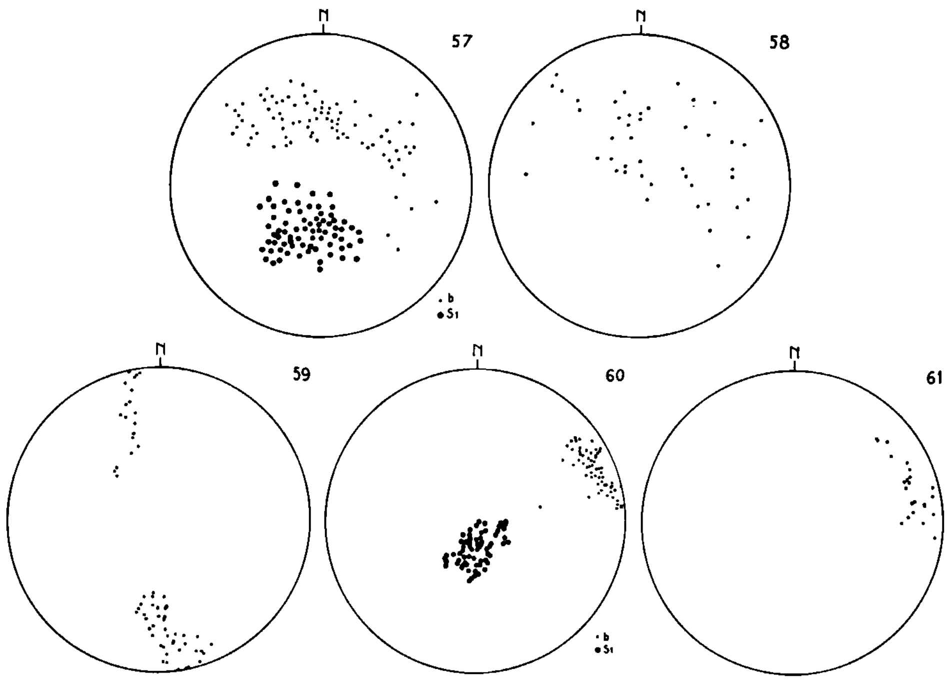


Devonian-Carboniferous Ribagorzana.

Fig. 57. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 58. Axes of folded bedding.

Lower Devonian Rio Tor.

Fig. 59. Poles to the bedding planes.

Fig. 60. Poles to the first cleavage planes and cleavage-bedding lineations.

Fig. 61. Axes of folded bedding.

Subarea VII. The lower Devonian around Cardel. A different structural history is shown by the lower Devonian represented by figs. 59, 60, 61. The subarea is situated along both slopes of the Rio Tor around the village of Cardél.

The poles to the bedding planes show a girdle (fig. 59) the axis of which nearly coincides with the cluster of cleavage-bedding lineations (fig. 60) and that of the fold axes (fig. 61). Unlike in the previous subareas, the lineations are not spread in a girdle. This together with the concentration of the poles to the cleavage planes, indicate that no folding succeeded the formation of the cleavage, while oblique pre-cleavage folding also is absent in this area. Consequently, the present subarea has been affected by only one folding phase.

Further north, going down in the stratigraphical sequence, the slaty cleavage plane itself is often folded into minor accordion folds. The diagrams constructed for these areas show different patterns of orientation. Here, in the lower part of the lower Devonian around Barruera and Durro not only the fold axes, but also the cleavage planes show a strike which is at variance with the regional trend. South of Durro the cleavage dips to the southeast, to change gradually to a more normal position near Bohi. In this whole zone, however, so much folded slaty cleavage is present that the role of the first folding phases is difficult to establish.

THE LOWER PALAEOZOIC IN THE RIO TOR AREA

Introduction

The area includes the Cambro-Ordovician and the lowermost Devonian of the Rio Tor valley. The Cambro-Ordovician mostly consist of finely laminated alternations of slates and thin quartzites with a few thicker quartzite beds. The Silurian black slates are intensely cleaved and very crumpled; the limestones generally thinly laminated. The lower Devonian limestones and slates also form a finely laminated series.

Thus the whole of the lower Palaeozoic consists of fine sedimentary alternations, but an even greater fissility has resulted from the intense development of axial plane slaty cleavage. This cleavage can be traced down from Devonian folds through the Silurian into the Cambro-Ordovician. This crosscutting axial plane orientation of the slaty cleavage in the Cambro-Ordovician in the present area differs from that in the Garonne Dome, where the slaty cleavage in the Cambro-Ordovician is often parallel to the bedding plane. Lineations, due to intersection of cleavage and bedding are well developed. Where minor cleavage folds could be studied, the cleavage was always found to be parallel to the axial planes and cleavage-bedding lineations parallel to the fold axes. The most important feature of the axial plane cleavage in the lower Palaeozoic of the Rio Tor area is its high parallelism, making it a good form surface for the detection of subsequent folding. Its high fissilty also allowed small folds to be easily produced.

The slaty cleavage plane and the axial planes of the associated folds in general dip at approximately 50° N, although in detail many variations in the degree and the directions of the dip occur. The folds generally are tightly compressed and in a few cases may even be isoclinal. In such cases a parallel foliation of cleavage and bedding as in fig. 62 is developed.

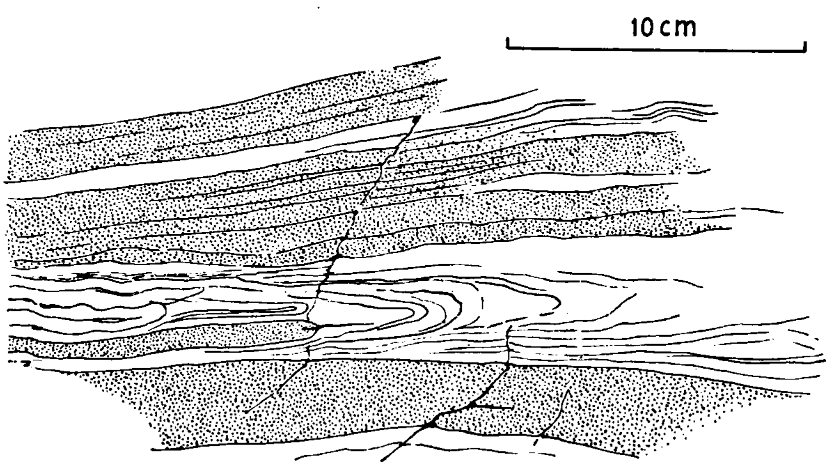


Fig. 62. Tight main phase fold between Erill Avall and Bohi (after photo).

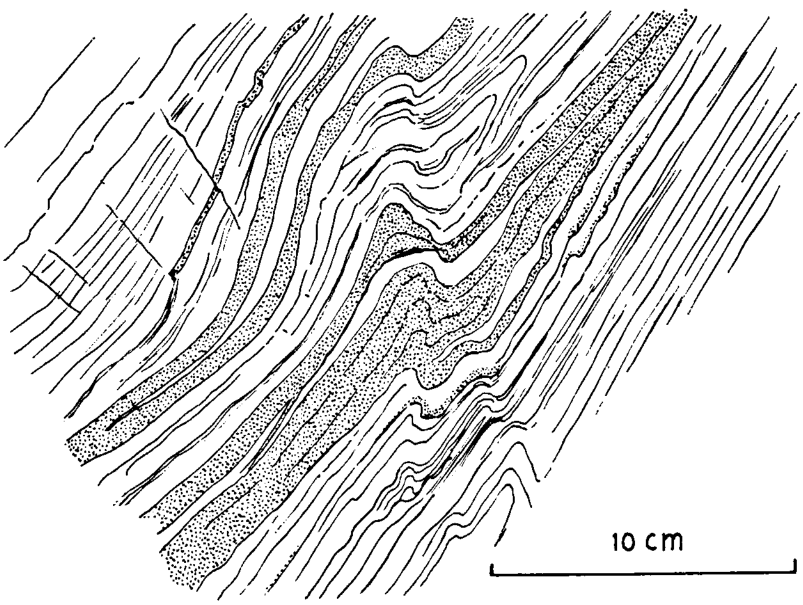


Fig. 63. Folding of main phase banding near Erill Avall (after photo).

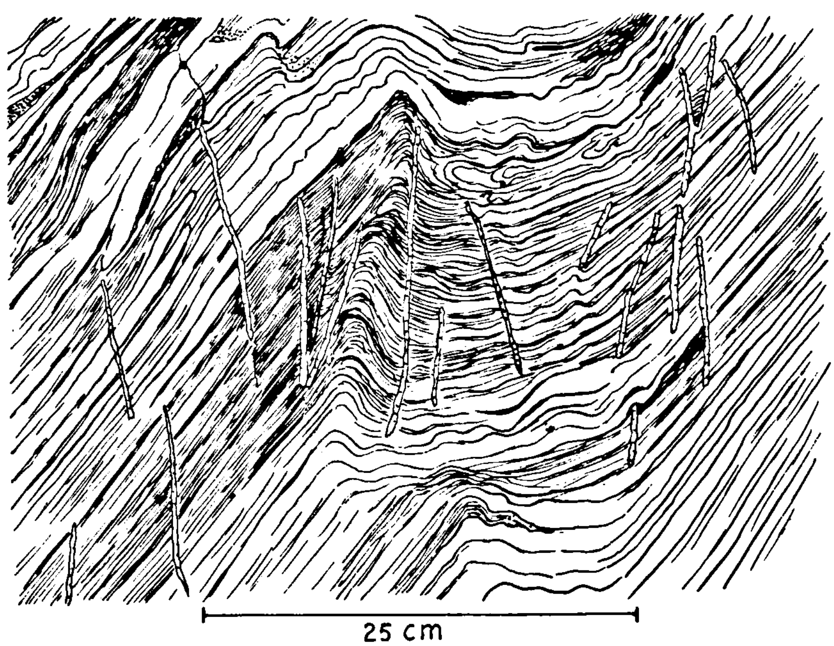


Fig. 64. Folding of main phase banding near Erill Avall (after photo).

The folding of the slaty cleavage is clear in several exposures. The most conspicuous folds are small accordion folds as in the northern Garonne Dome. At several places the main phase folds can be seen to have been refolded as in figs. 63 and 64. Such later folds show a high parallelism of axial planes and crenulation cleavage. Axial plane crenulation cleavage has been developed in the hinges of most accordion folds, and sometimes even in their limbs. The folds are usually not very tight but in some outcrops they are extremely compressed, becoming nearly isoclinal. Then a new fissility is produced of near parallel limbs and crenulation cleavage. Although the folds appear to be inhomogeneous in several exposures, the axial planes are parallel in uniform rock (see fig. 65). The irregular structures of figs. 66 and 67 are due to the heterogeneity of layers and bands, each of which has been flexured to the maximum possible extent. The size of the minor folds depends largely on the thickness of the layers. The limy slates near Bohi show banding with microlithons of a few mm thick. In this banding the accordion folds vary in size of one to a

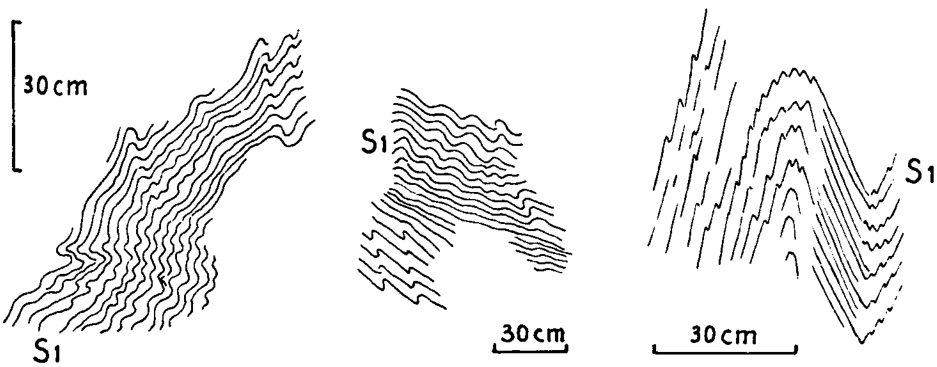


Fig. 65. Irregular folding of homogeneous slates near Bohi (after photos).

few cm. The same size of folds is found in the fissile quartzitic Cambro-Ordovician, with a foliation of also a few mm thick. Well bedded limestones and sandstones, in which the first cleavage is poorly developed, show accordion folds of the size of several tens of cm. The angle between the axial plane of the folds with the slaty cleavage determines the symmetry of the folds. Some show equal limb lengths when the angle is large. A few show an alternation of long and short limbs when the angle is small. In some outcrops only a few accordion folds are found, in others the entire rock has been folded into these minor folds. Such structures have been developed in parallel sets, some of which intersect. Fig. 68 shows how these features appear in the exposures. The most pronounced plane in this exposure is that of the secondary crenulation cleavage, which has been folded during a later folding phase. The main phase slaty cleavage is still visible in places. In fig. 69 the same relationships are present. Here the main phase cleavage plane is only visible to the naked eye in the competent bed, although it can be distinguished under the microscope in the incompetent bed. Fig. 70 has been drawn from a hand specimen. The bedding plane is clearly shown to be folded in two perpendicular directions. Both folds have axial plane cleavages which intersect with the bedding and the main phase slaty cleavage

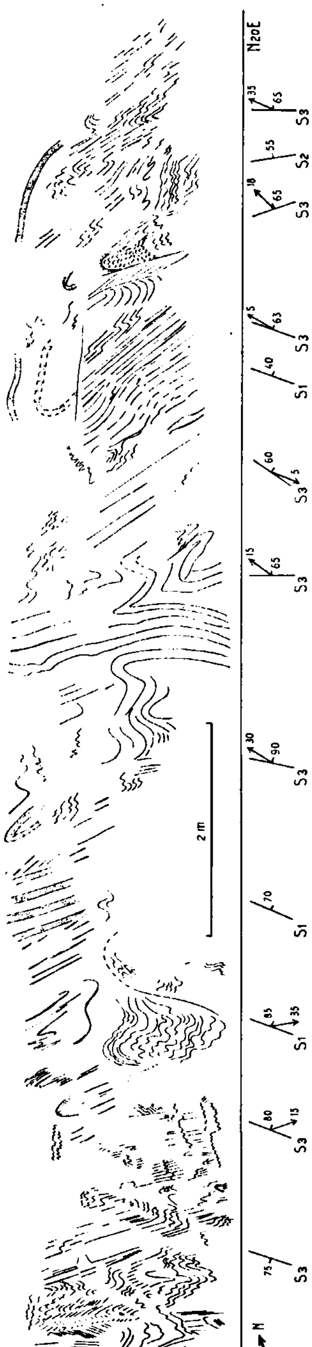


Fig. 66. Sketch of an exposure north of Erill Avall.

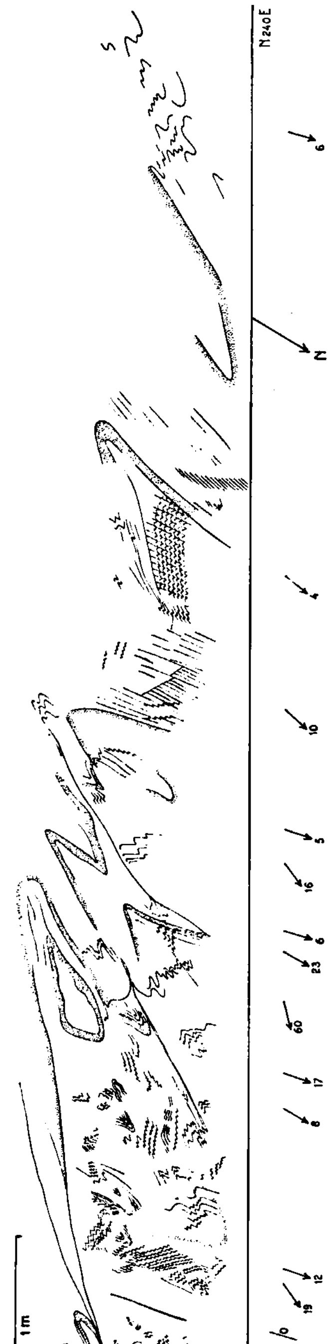
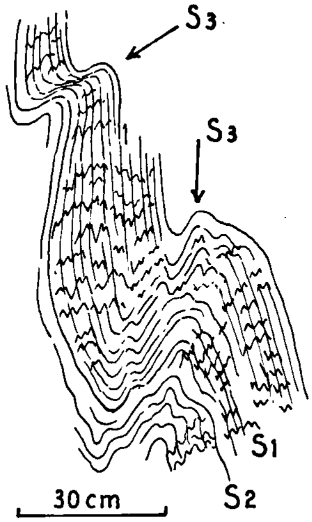


Fig. 67. Sketch of an exposure near Bohi with axes of folded cleavage.



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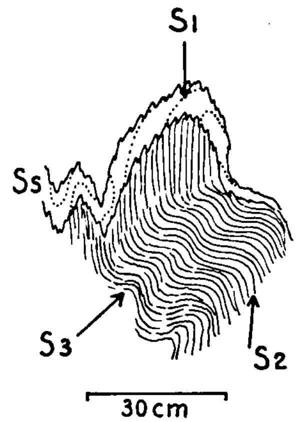

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Fig. 68. Refolding of minor accordion folds near Bohi, with three planes of reference (after photo).
Fig. 69. Intersection of four planes of reference, near Bohi (after photo).

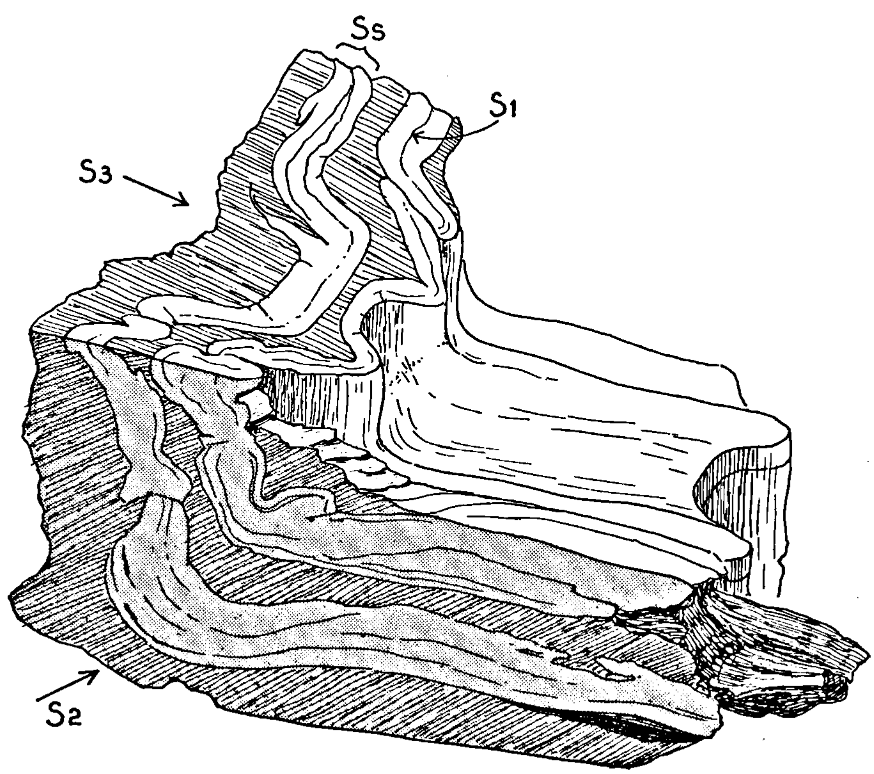


Fig. 70. Sample from an exposure north of Bohi, showing evidence of successive phases of folding (natural size).

plane. The slaty cleavage makes a small angle with the bedding plane. The later crenulation cleavage is the most pronounced in the sample as well as in the exposure, and has partially destroyed the earlier one. Consequently a chronological succession of two crenulation cleavages seems clearly established in the area.

When the succession of differently oriented minor accordion folds has been sufficiently well determined for one exposure, it is assumed to be a general rule, which can be used in the outcrops in the immediate vicinity, where a succession could not be established, or where only one direction is present. Thus the poles plotted on the diagrams either represent the axial planes of folds of which the succession is established in the field, or axial planes parallel to those in the vicinity. As a general rule it can be stated that the main phase cleavage has been folded first diagonally with minor accordion folds of which the axial planes usually trend NW—SE, seldom NE—SW, and secondly with folds of the same appearance, but with their axial planes trending roughly E—W.

Knick zones are distinguished from the accordion folds by their irregular axial planes; the lack of parallelism which allows them to converge; the lack of associated crenulation cleavage; the frequent brittleness of the rock in the knicked zone in comparison with its surroundings. An important feature of the knick zones is the fact, demonstrated by the way they cut other structures, that they, together with the shear zones, are later than the accordion folds.

On the stereograms the following data have been plotted:

The poles to the slaty cleavage planes.

The poles to the crenulation cleavage planes.

Some axes of minor folds.

In the stereograms a distinction has been made between two sets of crenulation cleavage. Although the structures themselves do not show any remarkable differences, they often intersect in such a way that two sets are obviously present, as has just been described above.

The Subareas

The lower Palaeozoic rocks of the area around Bohi are very well exposed in some road cuts, while the slopes of the mountain are also moderately well exposed. New roads have recently been built and works were still in progress when the area was investigated. Other good exposures exist along a concrete hydro-electrical canal on the slope between Barruera and Durro, which cuts through upper Ordovician, Silurian and the lowermost Devonian. Besides these artificial exposures, natural ones are found in the brooks and rivulets and along bare steep slopes.

A common feature of all exposures in the lower Palaeozoic of the Rio Tor area is the folding of the main phase axial plane slaty cleavage. Small accordion folds and wrinkless are abundant everywhere. In several exposures they appear to be the only structures present.

To give a better review of the tectonic pattern, the area has been subdivided into six subareas, for which separate stereograms have been constructed. The map (fig. 71) shows the strike and dip of the slaty cleavage planes, the axial planes, crenulation cleavage planes, fold axes of folded slaty cleavage and the planes of knick zones and shear zones.

The area north of Erill Avall. This area consists of Cambro-Ordovician,

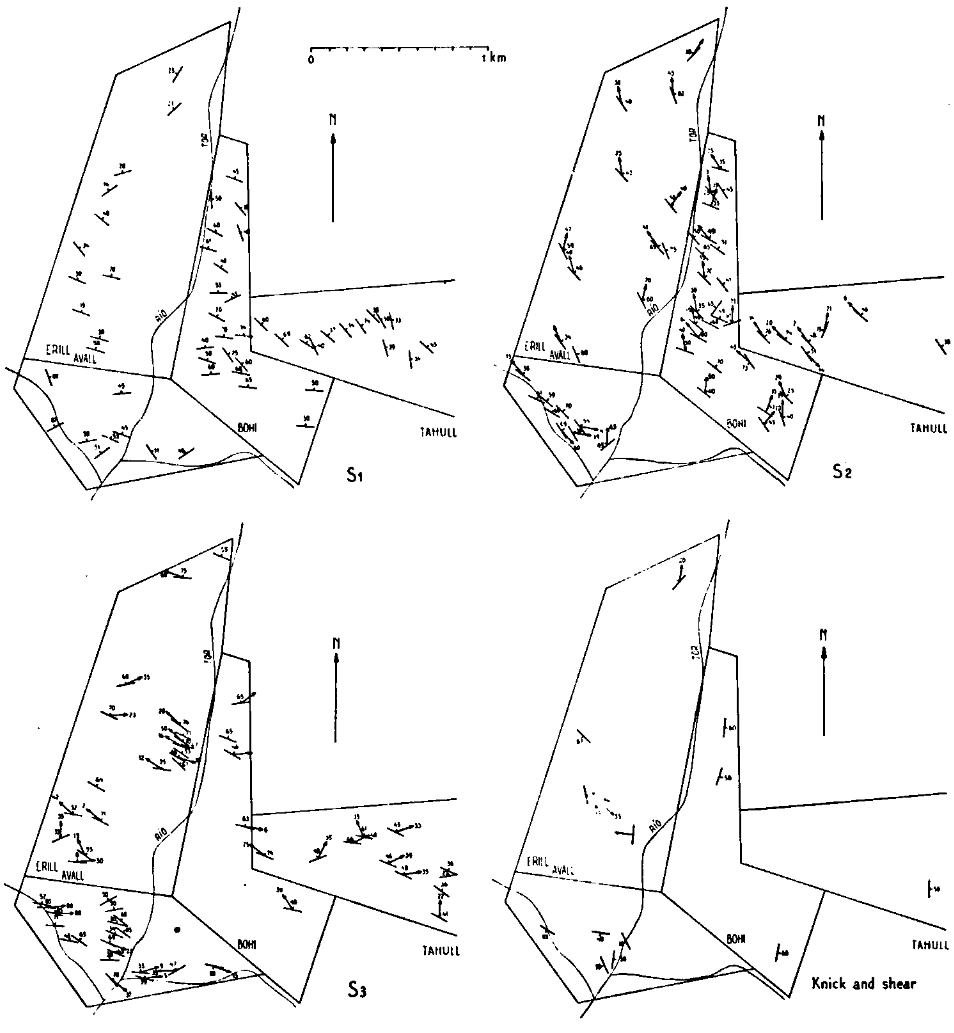


Fig. 71. Sketch map of the upper Rio Tor area.

Silurian and lower Devonian, all well cleaved and thinly laminated rocks. No tectonic differences have been found between adjacent parts of the formations; therefore none of the subareas coincides with a stratigraphic unit. Major and large minor folds are to be seen with slaty cleavage developed parallel to their axial planes. Some folds are very tight, but real isoclinal folds are rare. A good exposure, created during the reconstruction (1959—'60) of the main road between the side roads to Erill Avall and Bohi, shows well developed accordion folds. Here lower Devonian slates show well developed slaty cleavage, which has been folded into minor accordion folds about steeply plunging axes. These accordion folds have been folded again by minor folds of equal size. The folding of the axial planes of the first folds as well as the twisting of the fold axes are very clear.

Other exposures in the vicinity show similar features. A few knick zones are present, but show rather random orientations.

The data collected in the area are presented on the diagrams of figs. 72 to 75. As the size of the minor accordion folds is rather small, they have little influence on the spread of the measurements of the slaty cleavage planes. When the axial planes of the minor folds make a small angle with the slaty cleavage, the long flanks of the minor folds were measured. When the angle is wide the crestal plane over these small folds and wrinkles has been measured as a mean slaty cleavage plane. The spread shown on fig. 72 is accordingly not due to these minor accordion folds.

The poles to the axial planes of the accordion folds are shown in figs. 73 and 74. The relationship between the groups as presented on the diagrams is not evident from the patterns they form although their maxima are very distinct. Yet the exposures show the succession from twisting of lineations and folding of the crenulation cleavage as described above (p. 149). The traces of secondary cleavage on the slaty cleavage plane and the axes of folded slaty cleavage are presented on fig. 75.

Obvious is the northerly plunge of the axes associated with the crenulation cleavage of fig. 73. We can find a significantly different pattern when we compare the structures of the Garonne Dome with those of the Erill Avall area. In the Garonne Dome the steep slaty cleavage of the Devonian shows lineations and fold axes with gentle to steep plunges to the east (fig. 15), whereas the Cambro-Ordovician of that area, having a flatlying cleavage, can only show gently plunging structures (fig. 17). Most of these are oriented E—W, but some have NW plunges, which approach the northerly directions shown by the group of axes of the Erill Avall area (fig. 75).

Area north of Erill Avall.

Fig. 72. Poles to the first cleavage planes.

Fig. 73. Poles to the second cleavage planes.

Fig. 74. Poles to the third cleavage planes.

Fig. 75. Axes and lineations of second and third cleavages on first cleavage.

Area north of Bohi.

Fig. 76. Poles to the first cleavage planes.

Fig. 77. Poles to the second cleavage planes.

Fig. 78. Poles to the third cleavage planes.

Fig. 79. Axes and lineations of second cleavage on first cleavage.

Area between Erill Avall and Bohi.

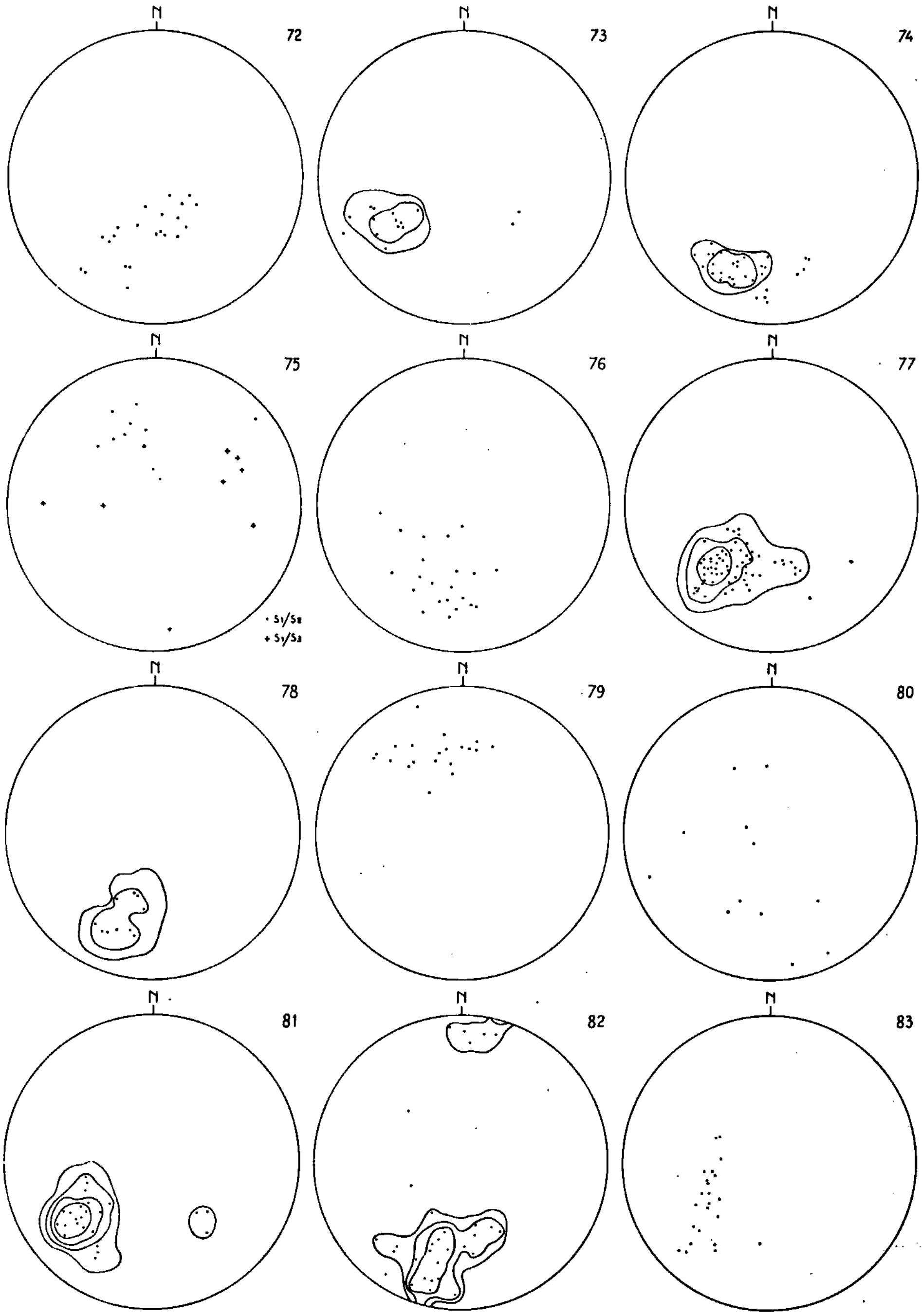
Fig. 80. Poles to the first cleavage planes.

Fig. 81. Poles to the second cleavage planes.

Fig. 82. Poles to the third cleavage planes.

Area northwest of Tahull.

Fig. 83. Poles to the first cleavage planes.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The area north of Bohi. This area covers the outcrops along the river and the road and on the slope of the mountain between the village of Bohi and the road to St. Nicholas. Here Cambro-Ordovician rocks are exposed with narrow strips of lower Devonian and Silurian in between, partly folded, partly faulted and all with well developed slaty cleavage. Good exposures are easily accessible along the main road from Bohi to the north.

The slaty cleavage dips in northerly directions between NNW and NE (fig. 76) and is intensely folded into small accordion folds, several only of a few mm width. In some exposures this secondary folding is nearly isoclinal, and first and second cleavage are parallel. Generally only one phase of folding of the slaty cleavage is present. The axial planes of these minor folds usually have a NW—SE trend, with a few trending SW—NE (fig. 77). Intersection of these two directions is difficult to find and no decision could be reached about a possible succession. In a few exposures the axial planes of these folds are very irregularly oriented, making a fan with all intermediate trends between ENE and SW. In such a case it seems possible that the folds with variable axial planes have been contemporaneously developed.

In several outcrops minor accordion folds have been found with steep axial planes and E—W trend. These succeed the structures with NW—SE trend as shown on fig. 70. They also succeed the few structures with SW—NE trend. The distribution of the poles to the axial planes of the successive folds does not show much concentration in the diagrams, but although the group of points overlap, the maxima are clearly separated (figs. 77 and 78). A very pronounced feature in most exposures in the Bohi area is the northerly plunge of minor fold axes of the first phase of refolding (fig. 79).

Knick zones and shear zones are of little importance in this area as everywhere else in the lower Palaeozoic of the Rio Tor. Several of them have been found, mostly steeply dipping, but they have irregular trends as well as uneven occurrence through the area.

The area between Erill Avall and Bohi. Between Erill Avall and Bohi only Cambro-Ordovician slates and quartzites are found. This thinly cleaved sequence is intensely folded. In several outcrops tight main phase folds with axial plane slaty cleavage occur. This cleavage is intensely folded by minor folds of various sizes, the scale of which depends on the fissility of the rock. They range from a few mm to some tens of cm in width, the smaller ones often parasitic to the larger.

The axial planes of accordion folds with NW—SE trend show remarkable concentration (fig. 81). The axial planes of the E—W phase have a wider spread (fig. 82). The spread shown in the stereograms by the poles to the E—W phase axial planes seems to be due to the operation of two phases of refolding with parallel trends. Some of the folds with steeper axial planes and crenulation cleavage of this group deform others with less steep attitude, and accordingly the former represent a subsequent phase of deformation of the main phase cleavage plane. Presumably they were formed in a later stage of the same phase than the more gently dipping ones. The present area is the only one, where two generations of the phase with E—W trend seem to be present.

As in the areas described above the best exposures are easily accessible along the main road, and also along the river. Interfering folds of successive phases are to be found in the outcrops between the road and the Tor river. Here folds with axial planes dipping to the NE are found deformed by later folds with steeper axial planes, dipping to the north or NNE. Also shear zones have been found, deforming all previous structures. In some outcrops isoclinal main phase folds are well exposed, which have been deformed by later accordion folds.

The area NW of Tahull. Here again the upper part of the Cambro-Ordovician is exposed, as thinly cleaved slates and thin quartzites with a few more massive quartzites. The slaty cleavage dips in directions varying between ESE and NE and in a few cases even north (fig. 83). The dips also vary from near vertical to about 30°, but the changes in directions are gradual without breaks. Both diagonal and E—W refolding phases have been found, but seldom in the same exposure. Where both directions occur together, one is usually only developed on microscopic scale, whereas the other develops small minor folds (figs. 84 and 85). Only a few knick zones and shear zones have been found.

The canal between Durro and Barruera. The section along this hydro-electric canal is illustrated by the diagrams 86, 87, 88 and 89 and fig. 90. A distinct slaty cleavage is developed here in all the lower Paleozoic rocks. The main phase minor cleavage folds are several metres in width. Superimposed on these folds we find small accordion folds, generally of a few cms wide. These small structures only affect the incompetent beds. The girdle of the poles to the bedding planes in fig. 87 shows no influence of the later phases as only the competent beds have been measured, since they clearly represent the sedimentary bedding.

The main phase structures are the usual tight folds with axial plane cleavage development. As the cleavage is parallel to the axial planes, the variations of the cleavage, like fanning out in the folds and curving due to changing rock competencies, take place about axes parallel to the fold axes. The strike of these structures, however, is abnormal. Most fold axes plunge to the south, a few to the north, the cleavage dips in directions between NE and SE, thus oblique to the trend of the Hercynian structures.

The folding of the main phase cleavage is not as intense as in the areas around Bohi and Erill Avall; only isolated accordion folds have been found. In several instances two successive phases have been found intersecting and in such cases the later one has a fairly steep axial plane with a roughly E—W trend. Such axial planes are represented in the diagram of fig. 89. The axial planes of other accordion folds show a more random distribution as represented by the poles to these planes in fig. 88. The order of succession of some of these divergent minor folds has not been adequately solved.

A few knick zones have been found in the area, very irregularly directed and distributed. When they intersect accordion folds, they are always obviously of later date.

The area between Barruera and Durro. In this area only Cambro-Ordovician rocks are present, although only partially exposed, due to vegetation and agriculture, as well as scree cover.

In the outcrops the main phase slaty cleavage is generally to be seen, but associated folds are seldom found. The few minor folds encountered have the slaty cleavage parallel to their axial planes. In the diagram of fig. 91 the poles to the slaty cleavage plane are spread in a scattered girdle.

This slaty cleavage plane has been folded into minor accordion folds of which the majority do not exceed the size of several centimetres, as in the previously described area. These folds can be seen to intersect so that the presence of at least two generations is established. The second generation is represented on the diagram of fig. 93. The poles to the axial planes of the first accordion folds are shown in the diagram of fig. 92. These show more spread, and are divided into two groups, a large one in the SW corner of the diagram, a smaller group in the SE corner. Accordingly the associated axial planes trend NW and NE.

Finally knick zones are developed, often clearly disturbing all previous structures.

As in the previous areas, the succession of the folding phases could only be established in the outcrops, since again the structures are too small to affect the slaty cleavage on a scale that would be clearly expressed by the spread of the poles of this surface in the stereograms. The spread presented is too irregular to derive conclusions of successive folding phases. On the diagram the axes of accordion folds and related traces on the slaty cleavage plane show a great variety due to the spread of the slaty cleavage plane and of the axial planes of the folds (fig. 94).

Some influence of later phases on earlier ones

From the description of the subareas it follows that a number of successive planar elements can be distinguished. In several instances the succession is clear, beginning with axial plane slaty cleavage and followed by the folding of this plane and finally shear zones and knick zones. Once the succession is established, the question arises, how much of the total deformation is due to each of the distinct phases.

Area northwest of Tahull.

Fig. 84. Poles to the second cleavage planes.

Fig. 85. Poles to the third cleavage planes.

The hydro-electric canal section.

Fig. 86. Poles to the first cleavage planes.

Fig. 87. Poles to the bedding planes and axes of folded bedding.

Fig. 88. Poles to the second cleavage planes.

Fig. 89. Poles to the third cleavage planes.

Area between Barruera and Durro.

Fig. 91. Poles to the first cleavage planes.

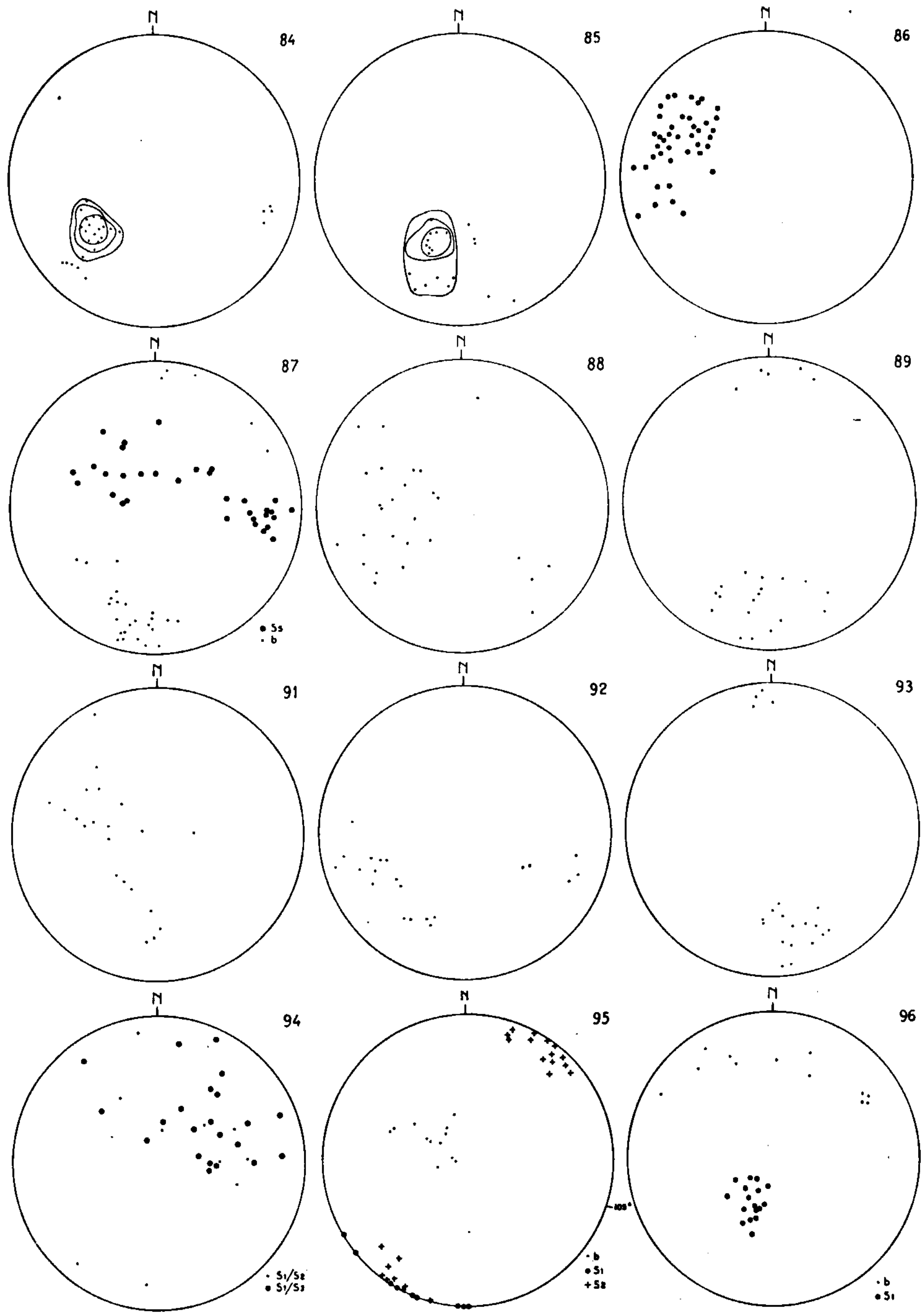
Fig. 92. Poles to the second cleavage planes.

Fig. 93. Poles to the third cleavage planes.

Fig. 94. Lineations and axes of second and third cleavages on first cleavage.

Fig. 95. Rotation of a group of structures near Bohi into steep attitude.

Fig. 96. Poles to the first cleavage planes and axes of folded bedding of Devonian slates and limestones west of Aneto.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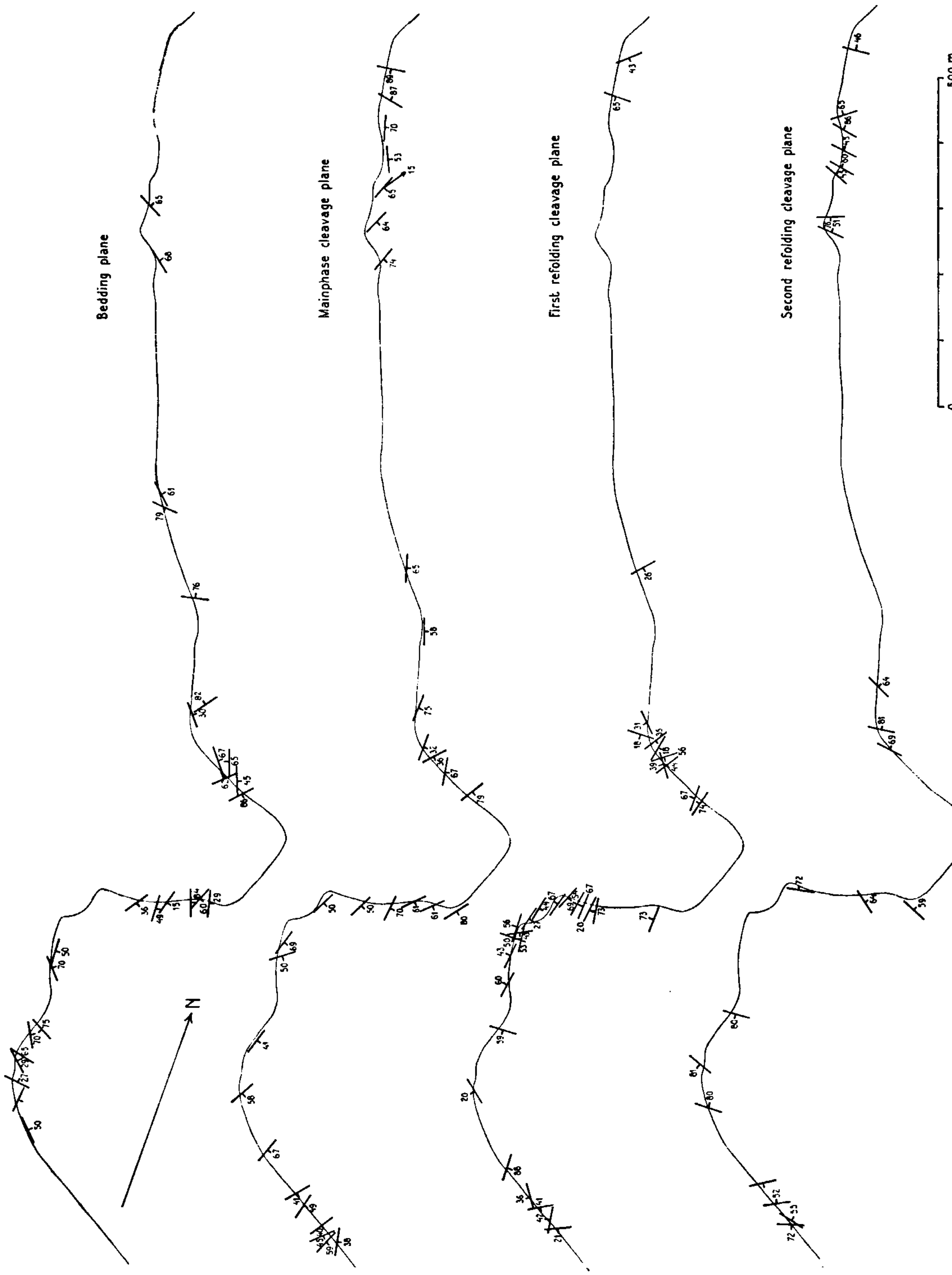

Fig. 90. Sketch of the hydro-electric canal section.

The presence of the main folding is obvious, overall folding of the Palaeozoic rock, sometimes with isoclinal folds and everywhere with the development of axial plane slaty cleavage. The role of the successive phases of folding is manifest in as far as minor folds are concerned. However, following the orientation of the slaty cleavage plane from one subarea into another, we see a gradual change of directions:

Erill Avall area:	between	NE	and	NW	(fig. 72).
Bohi:	„	N	„	E	(fig. 76).
Tahull:	„	SE	„	NE	(fig. 83).

South of Bohi the mean dip is to the north, changing to northeast and east towards Durro; and to between ENE and SE along the Durro hydro-electric canal (fig. 86).

In the area north of Erill Avall the poles to the slaty cleavage tend to lie on a partial girdle (fig. 72). The same is the case in the area NE of Tahull (fig. 83). The girdles, however, are quite different. Their difference in attitude means a different attitude of the mean slaty cleavage plane. This does not represent a deviation of axes within the slaty cleavage plane, but it is a major flexure of the main phase structure itself, and therefore it is supposed to be a deformation of later origin.

In the areas around Erill Avall, Bohi and Tahull, the attitude of the refolding phases does not seem to have been disturbed in the same sense as the main phase cleavage. The gradual change mentioned above is not evident in these structures. They are superimposed on the major flexure of the slaty cleavage. It may be that some minor accordion folds are parasitic on that major flexure.

The constant attitude of the axial planes of the E—W refolding phase indicates that after their development little or no deformation of the structures occurred. As they are moreover oblique to the major flexure of the slaty cleavage, they are of later data. The influence of the E—W refolding phase on the minor diagonal folds is evident in the exposures. If major folds did form during this E—W refolding phase, no evidence of them could be found in this investigation.

The northerly plunge of the axes in the folded slaty cleavage is a remarkable feature in the exposures around Bohi. In these areas the axes of the accordion folds plunge to the north and the axial plane cleavage of the main phase dips to the north. Comparing this structure with the Valle de Arán, where the axial planes and cleavage of the main phase are steep, the only difference to be seen is the inclination.

Zandvliet (1960) has previously noted that in the Pallaresa region the cleavage becomes flatter towards the boundaries of the axial zone. This flattening takes place in distinct stages rather than in a gradual sequence. In the present area of Ribagorzana and Tor the flattening seems more gradual, and is even accompanied with zones which are again steeper. In fact it seems that the flatter attitude of the slaty cleavage has been brought about by later tilting even after the diagonal refolding. This is shown by the relation of the slaty cleavage to the axial planes of the diagonal folds and it does not seem possible that the slaty cleavage could have developed in its present inclined attitude. When we rotate the whole picture on the stereogram until the main phase cleavage resumes the vertical position, we have:

Vertical main phase axial planes and cleavage.
Steep or even vertical refolding minor fold axes.
Steep axial planes of those folds.

This is a common attitude for the axial planes and fold axes of the diagonal refolding in the centre of the axial zone. It is also similar to the attitude found in the Argut-Foz area (fig. 14). The present attitude of the axial planes and crenulation cleavage of the E—W refolding phase does not suggest much flattening of the dip of the slaty cleavage after that phase. An overall flattening of the dip of cleavage planes is supposed to have happened between the two phases of folding of the slaty cleavage. When, as between Erill Avall and Bohi more than one phase of E—W folds are found (p. 156), those with steeper axial planes are the last, which indicates continued rotation of the older structures during E—W refolding.

Thus the following history can be established:

(I. Oblique, pre-main phase folding).
II. Main phase folding with vertical axial planes and cleavage development.
III. Diagonal refolding with steep axial planes presumably developed as a conjugate set.
IV. Warping of the cleavage so that it is now progressively flatter towards the south.
V. E—W refolding with steep axial planes.
VI. Continued inclination, with very little new E—W refolding and finally with shear zones and knick zones.

It is unfortunately impossible to determine from an independent source the orientation of the axis about which the warping took place. In the Ribagorzana and Tor area the strike of the slaty cleavage is about 105°, which has been chosen as the probable axis of rotation in fig. 95. Using this axis to rotate the slaty cleavage into the vertical attitude, it is found that several groups of diagonal fold axes now coincide with the steep attitude seen in the centre of the axial zone.

THE NORTHERN PART OF THE RIBAGORZANA AREA

The massive limestone in the Ribagorzana area north of Bono represents a facies of the lower and middle Devonian different from that in the south (P. H. W. Mey, pers. comm.). North of this limestone formations are exposed with limestones and fairly black slates of Devonian and Silurian age. Typical black slates, which form the most conspicuous part of the Silurian elsewhere, are rarely found, so that they are of little help in the determination of the age by lithostratigraphic correlation.

The Devonian limestone shows the contact metamorphic influence of the intrusive granite near Bono. The slates are baked and the brittle slate is broken into little flakes, which appear to be swimming in the surrounding limestone.

To the north the metamorphism due to the Bono granite decreases and the limestone here often shows a well developed cleavage. It is an axial plane cleavage associated with many minor folds. The cleavage planes dip between north and northeast. The axes of the minor folds have a variation of plunge direction within the cleavage plane between NW and ENE (fig. 96).

A secondary crenulation cleavage is developed in the slaty part of the formation. Knick zones also are usually found in the slates.

The limestone is often nodular and in it as well as in other competent beds, a coarse fracture cleavage is to be found. The rock is cut into microlithons of about 2—3 cm width. The cleavage planes are mainly open fissures, often filled with calcite (fig. 97). The planes dip very consistently some 15—20° NNE;

much flatter than the bedding which dips about 35°. No fold associated with this cleavage has been found. Further south this cleavage can be traced into the dolomites of the middle Devonian of the southern facies. This flat cleavage it not developed in the slates so it seems to be restricted to the more competent limestones only. No comparable cleavage has been found in the metamorphosed areas.

Along the Rio Llausel middle Devonian slates occur stratigraphically below the Devonian limestone and north of these, Silurian slates are found. Owing to intense cleavage development only faint indications of bedding can be seen in these slates. Some thin beds and calcite veins show very tight folding, indicating intense flattening of the rocks.

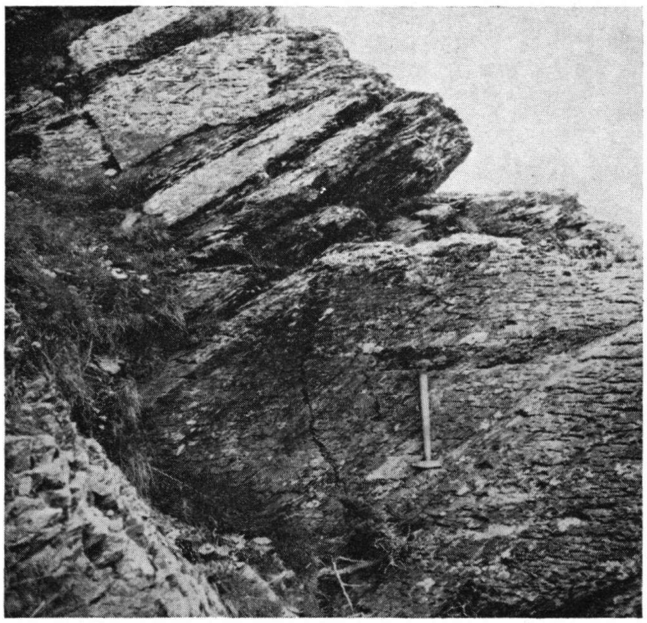

Fig. 97. Flat open-fissure cleavage southwest of Aneto.

The slaty cleavage dips to the north, secondary crenulation cleavage and a few secondary folds have been found with E—W axial planes and fold axes. An occasional exposure shows secondary cleavage which dips to NE, in the same direction as the diagonal refolding around Bohi-Tahull (Rio Tor).

In some exposures, as around the village of Aneto and in their continuation to the west, knick zones occur in several sizes. Most knick zones dip steeply to the south and only a few flatlying ones have been found.

The Silurian slates contain two fault systems. One dips steeper to the north than the cleavage and has a normal movement (fig. 98). The other dips very gently to the north and shows reverse movement. All faults, slaty cleavage and knick zones are parallel to the E—W trend of the Hercynian orogene.

The northern zone of the slate formation consists of Silurian sandy slates with thinly laminated quartzite-slate alternations. North of these slates a for-

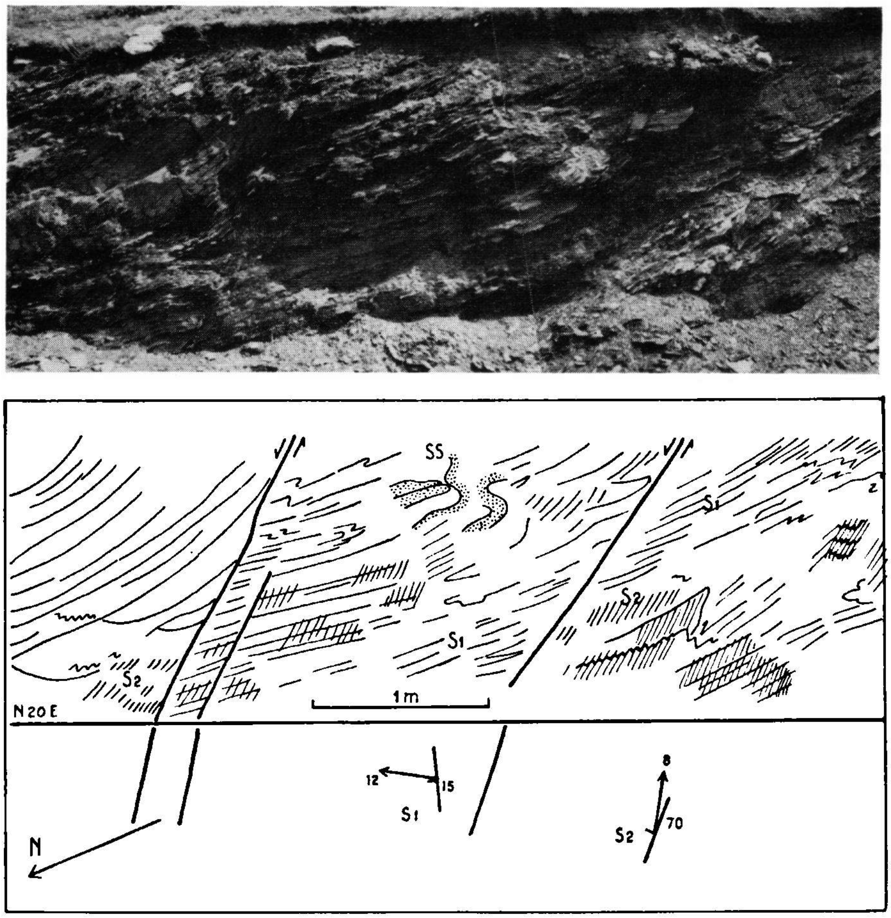

Fig. 98. Normal faulting parallel to the secondary cleavage in middle Devonian slates. along the Llaussel.

mation of slates and limestones occurs. The proximity of the Maladeta massif is evident from the metamorphic state of the sediments, which are of lower Devonian and Silurian age.

The limestones show tight folding with axial plane cleavage developed in the slaty parts. This cleavage does not appear to have been folded. Some north plunging fold axes suggest the presence of a folding phase previous to cleavage development. The Silurian shows several minor folds. Nearing the Maladeta granite folded cleavage is to be seen. Often only the traces of secondary cleavage have been found. From the little evidence gathered it seems, that the intrusion of the Maladeta took place between the diagonal and the E—W refolding phases (Dr. H. J. Zwart, pers. comm.). In the area of moderate or high contact metamorphism very few refolding structures have been found. This metamorphism has also altered many of the distinctive lithological characteristics, so that the stratigraphy has not yet been satisfactorily established.

The succession of the structures. The steep normal faults are often parallel to the E—W crenulation cleavage plane, but the faults represent a movement later than this refolding, and have made use of this secondary cleavage (fig. 98). Both faults and knick zones in the present area formed later than the E—W crenulation cleavages. Only a few knick zones are known in the neighbourhood of the faults but they do not cross them.

A flat overthrust fault brings Devonian on top of the Triassic at the Mt. Sarronal. Many small faults with the same attitude and the same direction of movement have been found in the Ribagorzana area. These small upthrust faults are supposed to be contemporaneous and are obviously post-Triassic.

The origin of the flat open fissure cleavage is still unsolved as it is not found to cut structures other than the slaty cleavage. Probably it was a horizontal plane from the beginning. In that case it would have been later than the warping and so perhaps even post-Triassic.

CHAPTER V

KNICK ZONES

Knick zones have been found in most investigated areas in the Pyrenees. They are prominent in the Ribagorzana and southern Tor area, and are also present in the Valle de Arán but only a few occur in the French-Spanish border zone.

The knick zones probably form conjugate sets, although a complete set, that is zones having opposite senses of movement and different dips, seldom appears in a single exposure. Even in these rare exposures it is still unusual to see the intersection of these opposing knick zones. In the Ribagorzana and the Tor areas the dip of the most common knick zones is towards the south, opposite to that of the cleavage. The movement in the zones is downward to the south. The angle between the cleavage and the knick zones is rather constant, somewhat less than 90°. Where the cleavage is flat, the knick zones tend to be vertical or even dip steeply north. This seems to indicate a continued rotation of the cleavage after knick zone development. The other component of the conjugate set are usually flatlying planes, dipping gently north or south, having an opposite sense of movement.

The trace of the knick zone on the main phase cleavage is not straight. Since the knick zones vary in dip, they cross each other as can sometimes be seen in exposed cross sections. When two knick zones with the same sense of movement converge, they generally coalesce and hence give no indication of different phases of formation. Intersections of the conjugate set are rare, but if found they form a box fold (fig. 99).

The sharpness of the hinge is determined by the thickness of the foliation. In thinly cleaved slates the knick zones are very sharp, in less well cleaved rock the hinges are much rounder. This, however, is a matter of scale. Under the microscope the hinge of the knick zone even in the finest slate shows bending of the cleavage plane on the hinge. Despite the complete curvature the hinge is frequently broken along the axial plane.

In rocks showing equal intensity of cleavage the size and width of the knick zones may vary. In the same outcrop very narrow zones are often found next to wider ones. In other exposures, however, all knick zones are equal in dimensions.

In many fissile slates, several knick zones can be seen to start as a small rounded flexure fold, passing into a sharp knick zone, which in turn ends in a fault. Sometimes several are seen overlapping each other in such a way that in the same group of cleavage planes, flexure folds as well as knick zones and faults have been developed. Here the lithology can have been of no influence, but in the same rock the amount of deformation took place in different ways. Where the knicking is sharp, all deformation seems to have been concentrated in the zone itself, but still even in thin section, slip along the cleavage plane is difficult to prove.

Several structures have been found which consist of a set of wider and smaller knick zones as shown in fig. 100, where ordinary knick zones have been superimposed on a big knick zone like flexure. The knick zones are genetically associated with the flexure. These irregular flexure structures are common in the upper Devonian and the lower Carboniferous of the Rio Ribagorzana and Rio Tor area. Their trend is parallel to those of the knick zones, about E—W.

Knick zones in the Valle de Arán have been noted by Kleinsmiede (1960) and Zandvliet (1960) has described them from the Pallaresa area. Zandvliet characterizes the knick zones as secondary coarse cleavage which occurs in pairs. The pairs enclose a narrow zone in which the slaty cleavage is knicked or flexured and the mechanism of the knicking is compared with that of twin gliding in calcite (1960, p. 87). The dilation in a horizontal sense suggests horizontal tensional stress.

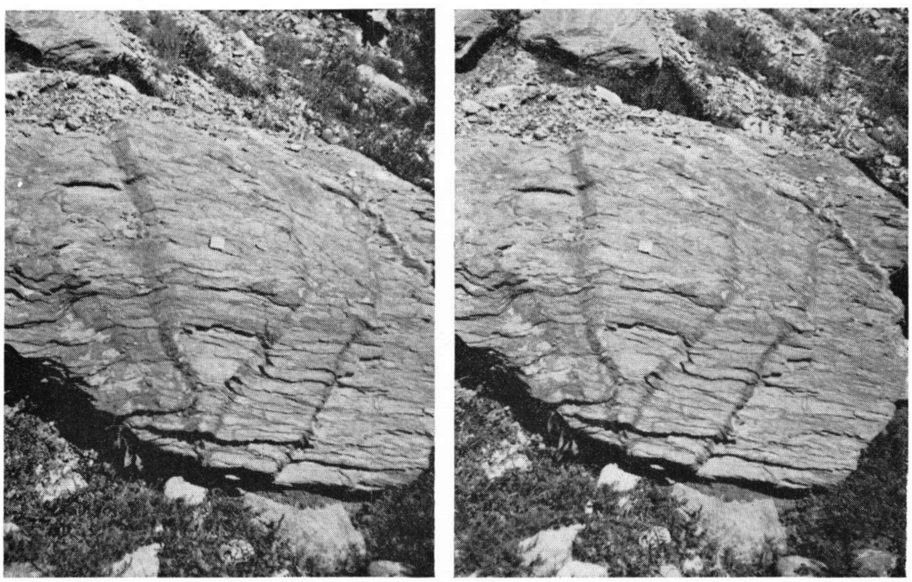

Fig. 99. Boxfold of conjugate knick zones in upper Devonian griotte of the Ribagorzana.

Knick zones are known from the Palaeozoic of the Rheinische Schiefergebirge, from the British Palaeozoic and from many more regions. Engels (1959) considers the knick zones to be a special feature of "Schubklüftung", a coarse fracture cleavage. When his fracture cleavage planes occur isolated in pairs, Engels uses the term "Knitterung". His analyses and descriptions are so similar to those of Zandvliet in particular, that it is clear that his structures are knick zones in the sense used here.

An important feature, which distinguishes the knick zones from asymmetric folds of similar size and shape, is the development of axial plane cleavage. The minor accordion folds show folding of the slaty cleavage plane accompanied by crenulation cleavage parallel to the axial planes and the occurrence of abundant parasitic folds. The traces of the accordion folds on the slaty cleavage plane generally are straight and parallel. Crystallization of quartz or calcite seldom occurs along the axial planes. The knick zones show folding of the slaty cleavage

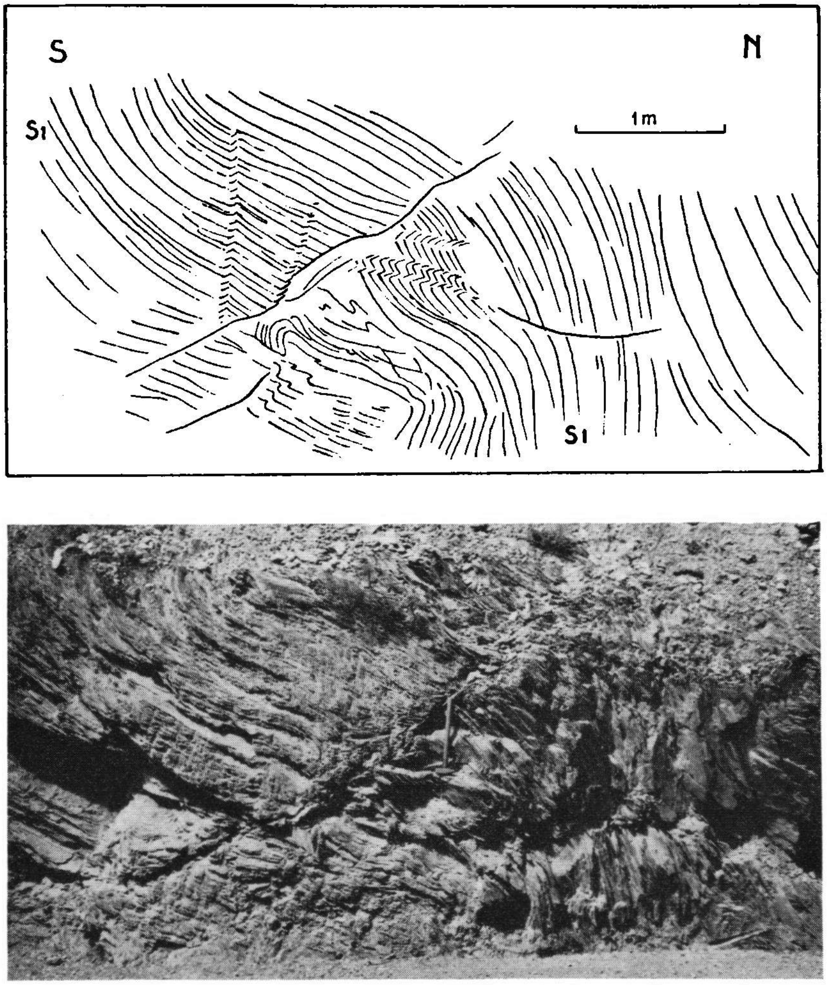

Fig. 100. Knick zones superimposed on flexure (Rio Tor valley).

plane without the development of crenulation cleavage. Sometimes a broad knick zone is divided into several narrower knick zones. The traces of knick zones on the slaty cleavage plane are irregular and frequently cross each other. The knick zones often form a zone of preferred crystallisation of quartz or calcite. Unlike the preceding refolding structures, the movement of the typical knick zone is restricted to the knicked part only. This is not due to the composition or the fissility of the present rock, as in the same rock real folds are to be seen, often nearly parallel to the knick zones, indicating that the formation of the knick zones was controlled by the stress field instead of rock properties. The earlier refolding structures show axial plane cleavage, are strongly compressed and accordingly have been produced under compressive stress.

It is assumed that the knick zones have been formed as the result of release. The total movement due to the knick zones is directed downward, towards the border of the mountain chain. The stress field necessary for these structures has its greatest component directed downward, opposite to the horizontal stress field necessary for all the other structures.

According to Hoeppener (1955) the development of the knick zones is related to the warping of the cleavage. The slaty cleavage in the Pyrenees seems to have been affected by a similar type of deformation. It occurred after the diagonal refolding phase, as described above in the discussion of the Rio Tor area (p. 161). Zandvliet (1960) also favours warping of the cleavage after the main phase. If the knick zones were related to the warping, they must be older than the Triassic, because this is deposited on Devonian with inclined cleavage. In the Ribagorzona and the Tor areas it has been found that, although the knick zones are seen to be later than these structures, some warping preceded the E—W refolding. Accordingly the knick zones were produced during the last stage of the warping. Regular knick zones seldom occur together with E—W refolding and when they do so, the knick zones are the later structures. Both types of folds occur separately, one almost to the exclusion of the other. Only in overlapping zones the succession is now and again revealed.

Evidence from the Tor area shows that tilting continued throughout the period of the E—W refolding. Within this still operating compressive phase we have a tilting and it seems most likely that this tilting formed part of the deformation under compressive stress. Consequently there have been two warping processes, one accompanying the E—W refolding, under compressional stress, and the other accompanying the knick zones under tensional stress.

Zandvliet assumes an arching of the centre of the orogene, warping the vertical cleavage. Hoeppener (1955) shows the knick zones to be related to normal faults parallel to the slaty cleavage: "Schieferungs parallele Abschiebungen". These faults are described by Zandvliet, together with the blockwise tilt, but he did not recognize their identity or function. In the Pallaresa area these faults have been proved to coincide with belts having an unusual abundance of knick zones (Mr. J. A. Oele, pers.comm.). The abundance of knick zones near to faults and their antithetic nature is typical of Hoeppener's normal faults.

It is striking that notwithstanding the arching no obvious change of stratigraphical level is apparent. This is easily explained by faults of the type described above, along which the blocks settled back downwards into their original level but now in tilted attitude.

The joint drags described by Knill (1961) are similar to the knick zones described by the German authors and those found in the Pyrenees. Knill suggests that they were formed as a series of slip structures contemporary to a tear-fault system. The term joint-drag has been coined by Flinn (1952) who described these structures from Shetland. Like the knick zones in the Pyrenees the "joint-drags" tend to occur in belts up to 100 metres in width. The joint-drags themselves vary in size. Crinkling of the cleavage plane of 0.2 mm up to warping of the foliation, 20 metres in wavelength, described by Knill, resemble some Pyrenean knick zone structures. The occasional continued thrusting mentioned by Knill is not known in the Pyrenees.

Alpine knick zones

Occasional knick zones have been found in the Triassic beds. Often these are real knick zones, developed in very well bedded sediments with a poorly developed cleavage parallel to the bedding. Van der Lingen (1960) mentions fracture cleavage in varve-like sediments of the Permo-Triassic. This is also to be found in the Triassic of the Ribagorzana area, where the structures resemble small knick zones. The first cleavage is not very well developed and the minerals still show little recrystallization.

The occurrence of knick zones in the Triassic do not compel us to consider all knick zones as Alpine structures. However, it emphasizes the idea that the knick zones are not restricted to a single deformation phase.

CHAPTER VI

CONCLUSIONS

The structural history of the area investigated can be divided into several phases. Fig. 101.

1. Pre-folding phase
2. Main folding phase
3. Diagonal refolding phase
   Initiation of tilt
4. E—W refolding phase
   Continued tilt with warping
5. Knick zones with warping

1. The first phase is distinguished by the development of fold structures with a trend strikingly oblique to the present trend of the orogene. These features are exposed in the southern region of the Ribagorzana and the Tor rivers, but occasional fold axes with diverging plunge in other areas suggest that this phase was active over a much greater part of the orogene. In the north traces of this phase have been found in the Carboniferous of Mt. de Sijol. The folds which resulted from this phase are concentric without the development of slaty cleavage. Their wavelength ranges from several kilometres to less than a metre.

2. The main phase dominates the present aspect of the orogene, as most major folds have been developed during it. The trend of the main phase is parallel to the present mountain trend. Two regions can be distinguished in the area investigated which are basically different in structure. The flatlying main phase structures of the Garonne Dome represent a different style of folding to the steep main phase structures in the rest of the area. This difference has also influenced the attitude of the succeeding structures. The metamorphism of the Garonne Dome started in the main phase (Zwart 1962).

3. The diagonal refolding was active in the Garonne Dome and in the Cambro-Ordovician of the Rio Tor area. Structures found in the Valle de Arán are attributed to this phase. In the Garonne Dome this phase was accompanied by renewed metamorphism (Zwart 1962). The intensity of the diagonal refolding increases with the intensity of the metamorphism. In the flat Garonne Dome the lineations plunge gently, whereas elsewhere steeply dipping cleavages occur, on which steeply plunging lineations have been found. The refolding phases are recognized by the folding of the main phase cleavage. Minor accordion folds are the most common features of these refolding phases.

Tilting of the main phase slaty cleavage started after the diagonal refolding, as is demonstrated by the relationships found in the Rio Tor area.

4. The E—W refolding has been found in the greater part of the area with increasing intensity and size of folds towards the lowest level of the sequence. In the upper Devonian and Carboniferous this phase is generally absent, neither

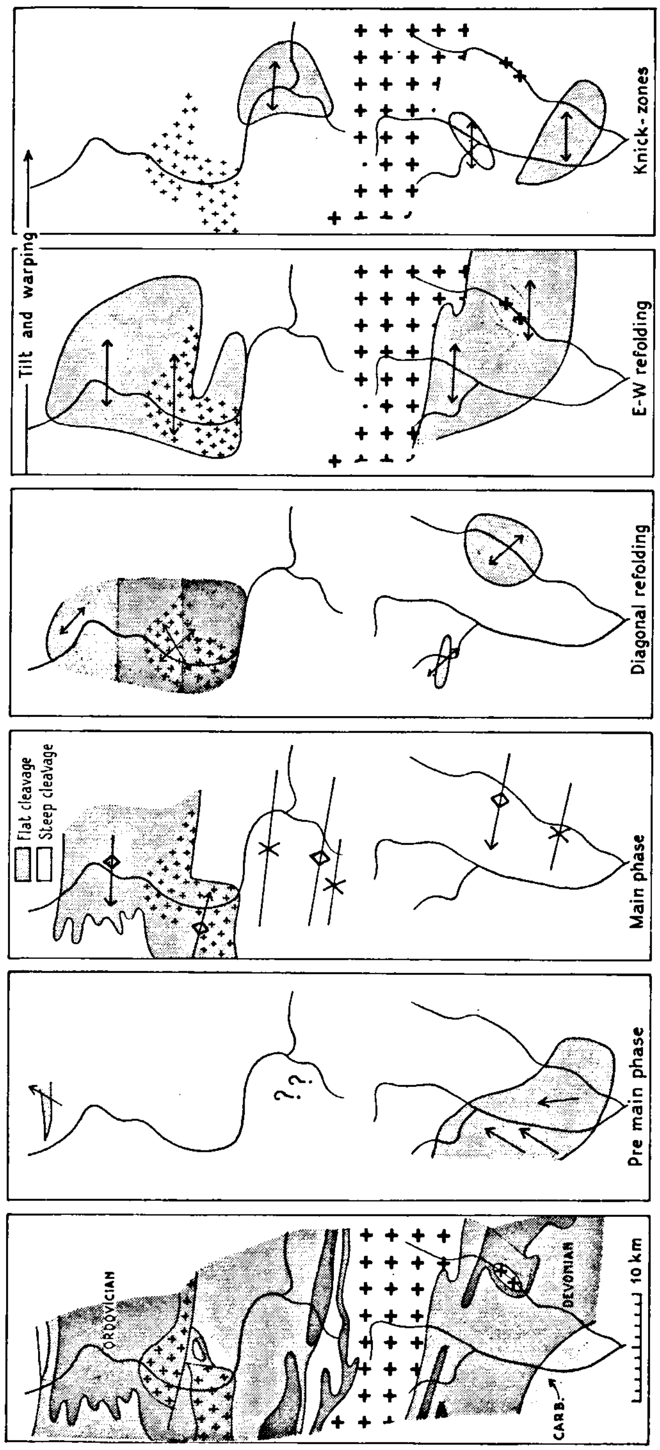

Fig. 101. Distribution of the successive phases over the area.

has it been found in the steep slaty cleavage of the Valle de Arán. The folds show the same morphological features as those of the preceding phase, so that their identification depends on the recognition of the sequence of deformations.

The tilt of the slaty cleavage continued as has been concluded for the area between Erill Avall and Bohi, where two successive E—W refolding stages seem to have occurred. The conjugate set of shear zones near Bausén also represents a late stage of the E—W refolding.

The intrusion of the Maladeta massif seems to have happened before the E—W refolding. Renewed metamorphism occurred in the Garonne Dome.

5. Continued warping of the slaty cleavage preceded the development of the knick zones. These structures indicate tensional stress, while the preceding structures indicate compression. The warping is assumed to be the result of arching of the axial zone, accompanied by faulting.

		GARONNE DOME	VALLE DE ARÁN	RÍO TOR	RÍO RIBAGORZANA
Pre main phase		Carboniferous	?	Carboniferous Devonian	Carboniferous Devonian
Main phase	flat	Cambro-Ord.	Cambro-Ord.	—	—
	steep	Devonian	Devonian	Carboniferous Devonian Cambro-Ord.	Carboniferous Devonian Cambro-Ord.
Diagonal refolding		(Devonian) Cambro-Ord.	(Devonian) Cambro-Ord.	(Devonian) Cambro-Ord.	(Devonian) Cambro-Ord.
E-W refolding		Devonian Cambro-Ord.	Devonian Cambro-Ord.	Devonian Cambro-Ord.	Devonian Cambro-Ord.
Knick zones		(Devonian) (Cambro-Ord.)	Devonian	Devonian (Cambro-Ord.)	Devonian (Cambro-Ord.)

Distribution of the successive phases in stratigraphic levels.

Thus the structural history of the axial zone has been divided into distinct phases, although no conclusion as to the complete continuity of deformation could be reached. This follows from the nature of the present work, restricted to the study of minor structures. Zwart (1960) has proved the discontinuity of deformations by the study of synkinematic and postkinematic mineral growth.

The tectonic activity started after the deposition of the lower Carboniferous, in which traces of the first phase of folding have been found. In the unconformable Stephanian deposits near Malpas (southern Pyrenees) pebbles have been found with slaty cleavage and crenulation cleavage in them. It is not clear whether this crenulation cleavage represents the E—W refolding or only the diagonal refolding.

ZUSAMMENFASSUNG

Kleintektonik wurde in einigen Gebieten der zentralen Pyrenäen untersucht. Auf die verschiedenen Arten von Schieferung wurde speziell geachtet. Druckschieferung entwickelte sich im ganzen Paläozoikum während der Hauptfaltungsphase. Diese Schieferungsentwicklung wird begleitet von einem Metamorphismus mit paralleler Rekristallisation der Glimmermineralien im Gestein. Dieses parallele Gefüge ist leicht im Aufschluss zu erkennen. Während der Faltungsphasen die der Hauptfaltungsphase folgten, wurde die Schieferung gefaltet in kleine und grosse Falten. Die Aufeinanderfolge der verschiedenen Phasen ist deutlich zu erkennen aus der Interferenz der kleinen Strukturen. Die Lage der planaren und linearen strukturelen Elemente ist auf Lagenkugelprojektionen abgebildet.

Im "Garonne Dome" gibt es zwei Gebiete mit verschiedenen Schieferungsstrukturen. In dem einen Gebiet ist die Schieferung in flacher Lage entwickelt, in dem andern steil, und gibt uns so ein besonders gut entwickeltes Beispiel disharmonischer Faltung. Das Gefüge dieser Schieferungen ist dasselbe und es ist sehr wahrscheinlich dass beide zur gleichen Zeit entstanden sind. Die darauffolgende Entwicklung der zweiten und dritten Schieferungen ist parallel in beiden Gebieten, sodass die Disharmonie nur während der Hauptfaltungsphase bestanden scheint zu haben. Kleinfaltung mit zweiter und dritter Schieferung von zwei aufeinanderfolgenden Phasen konnte unterschieden werden. Es zeigte sich, dass das Gefüge der zweiten und dritten Schieferungen in den Falten verschieden ist von der ersten Schieferung.

Im Valle de Arán wurde die ursprünglich steile Schieferung örtlich gekippt und aufs Neue in verschiedene Richtungen gefaltet. Von diesen Umfaltungsphasen ist die letzte immer parallel zum Streichen der Strukturen der Hauptfaltungsphase. Die Entwicklung der "mullions" wurde in diesem Gebiet untersucht. Sie sind deutliche "fold mullions" und sie entstanden während der Hauptphase.

Im Devon des Ribagorzana und Tor Gebietes wurde bewiesen, dass an der Entwicklung der Schieferung der Hauptphase eine Faltungsphase vorausging, schiefwinklich zu den heutigen Streichen des Paläozoikums. Dies ergibt sich aus verschieden Strukturen die auf der Karte erscheinen, aber geht auch hervor aus den Lagenkugelprojektionen, welche die Verteilung der Faltungsachsen und Linearen in einem Gürtel in dem nicht deformierten Schieferungsflach zeigen.

Die erste Schieferung des Unterdevons und Cambro-Ordoviciums von dem Rio Tor wurde stark gefaltet. Zwei Phasen mit Kleinfaltenbildung wurden unterschieden. Kippung der Schieferung fing an vor der letzten Faltungsphase und setzte sich danach fort. Lagenkugelprojektionen zeigen die Lage der Strukturelemente; die Aufeinanderfolge der Strukturen wurde jedoch im Gelände ermittelt.

Im nördlichen Teil des Ribagorzanas wurden die gleichen Erscheinungen gefunden wie im übrigen Gebiet, aber weniger gut entwickelt und teilweise durch Kontaktmetamorphose verwischt.

Die letzte Deformationsphase wird vertreten durch die Entwicklung von Knickzonen, Brüche und blockgeweises Kippen der Druckschieferung. Diese Erscheinungen beweisen Dehnung, während die vorhergehenden Strukturen durch Einengung verursacht wurden. Die erste Faltungsphase begann nach der Ablagerung des Unterkarbons. Das diskordante Stefan wurde abgelagert nach der erneuten Faltung der Schieferung. Der Trias überlagert alle diese strukturen diskordant.

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