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THE STRUCTURAL HISTORY OF THE VALL FERRERA AREA, THE TRANSITION ZONE BETWEEN THE ASTON MASSIF AND THE SALAT-PALLARESA ANTICLINORIUM (CENTRAL PYRENEES, FRANCE, SPAIN)

BY

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ABSTRACT

Cambro-Ordovician clastic sediments varying in composition from microconglomerates to slates occur. A more precise stratigraphic assignment is impossible, because of the lack of fossils and traceable stratigraphic horizons.

The Cambro-Ordovician rocks have undergone four Hercynian deformation phases. Each phase was accompanied by the formation of cleavages (slaty, fracture or crenulation cleavage). In the Vall Ferrera area these four deformation phases are well developed. Their relative age relationships were known from other parts of the Central Pyrenees and could be established in many outcrops. The first deformation, accompanied by a regional synkinematic metamorphism and caused by a N-S compression, divided the orogene into (1) the infrastructure (e.g., the Aston massif) with medium to high grade metamorphism and a flat cleavage plane, and into (2) the suprastructure (e.g., the Salat Pallaresa anticlinorium), with low grade metamorphism and a steep cleavage plane. The second phase produced N-S trending folds and was caused by an E-W compression. The third phase made a conjugate fold system in a NW-SE and a NE-SW direction; the asymmetry proves that an E-W compression caused these folds. The fourth phase was produced by a renewed N-S compression and a vertical E-W cleavage was formed. Finally blockfaulting occurred by which the Mérens fault, which seperates the Aston massif from the Hospitalet massif, was formed.

A literature study, concerned with the different types of deformation, shows that the direction of the extension can be parallel or perpendicular to the fold axis with transitions in between. Such a "deformation pattern" is found in the Vall Ferrera area. The relationship between this pattern and the metamorphism is given.

CONTENTS

INTRODUCTION

This thesis forms an independent contribution to the detailed geological survey of a part of the Central Pyrenees, carried out by the Department of Structural Geology of the Geological Institute of Leiden University. This survey is directed by Prof. Dr. L. U. de Sitter and Dr. H. J. Zwart.

LOCATION OF THE PRESENT AREA

The investigated area is situated between the Cardos valley in the west and the Mounicou valley in the east. The northern boundary is formed by the Bassiès granodiorite; the southern boundary by the line running E-W through the village of Areo, situated in the Ferrera valley.

The Spanish part covers a portion of the sheets Noarre (150) and Tirvia (182) of the "Mapa Militar de España", published by the "Instituto Geografico y Catastral". The French part covers a portion of the sheet Aulus les Bains no. 7 and 8 and of the sheet l'Hospitalet près l'Andorre no. 1 of the French 1 : 20.000 maps published by the "Institut Géographique National".

The investigated area will be referred to as "the Vall Ferrera area".

GEOMORPHOLOGY

The interesting geomorphology of the area has been described by Zandvliet (1960, p. 9—31). The area is divided in two parts by a high, partly inaccessable crest running NW-SE. This crest forms the frontier between France and Spain and has an altitude varying from 2500 m (Port de Boet, Port Vell) to 3141 m (Pica d'Estats). Pica d'Estats is the highest mountain of Cataluña. The French part of the region consists of the steep western slope of the Mounicou valley, a typical glacially eroded valley. The Spanish part, consisting of the valleys of the Ferrera and Cardos rivers and their tributaries, has also been strongly eroded by the glaciers. As a whole the region exhibits typical "Alpine" mountain forms. The remnants of the pre-alpine denudation surfaces, found in many parts of the Central Pyrenees, are only found in the western part of the area, where they form the flat summit of the Montareño (Zandvliet, 1960, p. 12).

GEOLOGICAL SETTING

Up to 1966 six geological maps of the Central Pyrenees have been published by the Department of Structural Geology on a 1 : 50.000 scale. In this thesis no new geological map is published, because the major aim of this work was the establishment of the position and the nature of the transition zone between the Aston massif and the Salat-Pallaresa anticlinorium. This transition zone is situated between the low grade metamorphic rocks (in general quartz-phyllites of Cambro-Ordovician age) of the Salat-Pallaresa anticlinorium and the higher grade metamorphic rocks (in general gneisses, migmatites and micaschists) of the Aston massif. The rocks of the Aston massif are at least partly the stratigraphic equivalent of the Cambro-

DEFORMATION PHASE	FOLD-AXIS	S-PLANE	SYMMETRY	TECTONIC AXES	STRESS-FIELD	SECTION PERPENDICULAR TO THE B-AXIS
1	B1 E-W	Suprastructure: vertical E-W	Orthorhombic	a Vertical b E-W c N-S	ó3. Vertical	
		Infrastructure: flat	Monoclinic	a N-S flat b E-W c Steep	ó2 E-W ó1 N-E	
2	B2 N-S	Flat	Monoclinic	a E-W flat b N-S c Steep	ó3 Vertical ó2 N-S ó1 E-W	
3	B3 Vertical to NW-SE and NE-SW	Vertical NW-SE	Monoclinic (Orthorhombic)	a NW-SE b Vertical c NE-SW	ó3 N-S	
		Vertical NE-SW	Monoclinic (Orthorhombic)	a NE-SW b Vertical c NW-SE	ó2 Vertical ó1 E-W	
4	B4 E-W	Vertical E-W	Orthorhombic	a Vertical b E-W c N-S	ó3 Vertical ó2 E-W ó1 N-S	

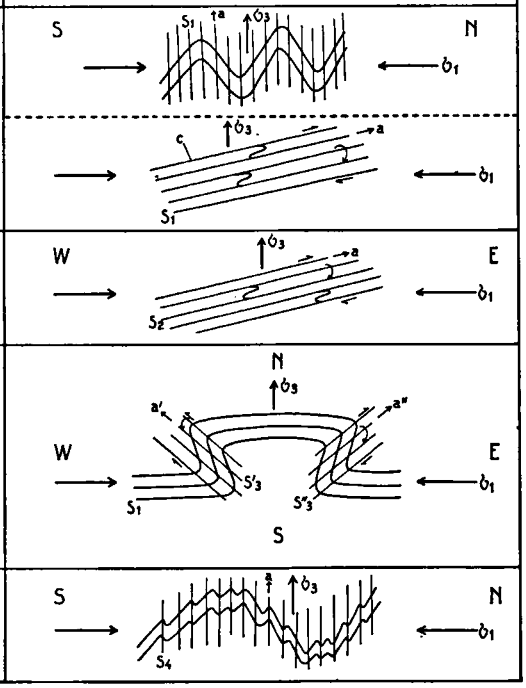


Fig. 1. Tectonic scheme of the deformation phases of the Central Pyrenees, σ_1 is larged compressive stress, σ_2 intermediate stress, σ_3 smallest compressive stress (after Zwart, 1963).

Ordovician sediments of the Pallaresa anticlinorium. The geological map of the investigated region is published on the eastern part of sheet 5 (Zandvliet, 1960) and on the western part of sheet 6 (Zwart, 1965). The work of the staff and students of the Geology Department of Leiden University has provided us with a detailed history of the deformative and metamorphic events that took place in the Pyrenees during the Hercynian orogeny. This large volume of information serves as a firm foundation for further studies in this mountain chain. A deformation scheme is one of the results of this work. On this scheme (fig. 1) we see that the main deformation acted in a different way in the various parts of the orogene. The orogene can be divided in two parts: here called the infrastructure and the suprastructure. The infrastructure forms the deeper parts of the orogene where rocks like gneisses, migmatites and micaschists are found. The suprastructure, situated on a higher orogenic level than the infrastructure, consists of lower grade metamorphic rocks.

The tectonic styles of the two subdivisions are different. In the infrastructure a sub-horizontal schistosity is present. The recognizable structures are small (maximum: some tens of metres) and a distinct mineral orientation, trending E-W, is found on the schistosity planes of the micaschists. Asymmetrical isoclinal main phase folds are present; their axes trend also E-W. In the suprastructure on the other hand, a sub-vertical cleavage plane is found. Recognizable folds have dimensions ranging from a few millimetres up to some kilometres. The axes of the main phase folds trend again E-W. These folds are in general tight. The folds of the Devonian of the Valle d'Aran form a good example of the suprastructure style of folding (fig. 2).

It is clear that a detailed study of the transition zone between the infrastructure and the suprastructure might possibly reveal interesting facts about the differences in tectonic styles under, in and above the transition zone. It was with great interest that Kleinschmiede and other geologists from Leiden studied this zone in the Valle d'Aran (Kleinschmiede, 1960) (fig. 2). This transition zone in the Valle d'Aran is situated in the black slates of the Silurian. The relatively incompetent Silurian strata acted as a detachment zone separating the infrastructure from the suprastructure. This disharmony is shown on fig. 2.

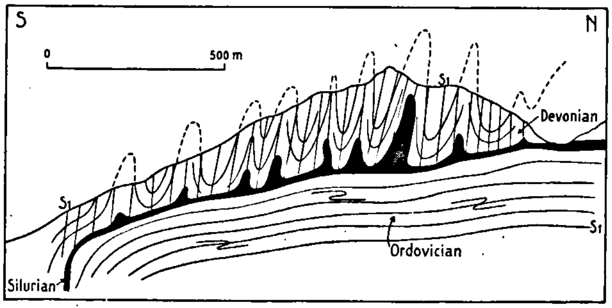


Fig 2. Section in Bosost area, showing the transition between infra- and suprastructure (after Kleinschmiede, 1960).

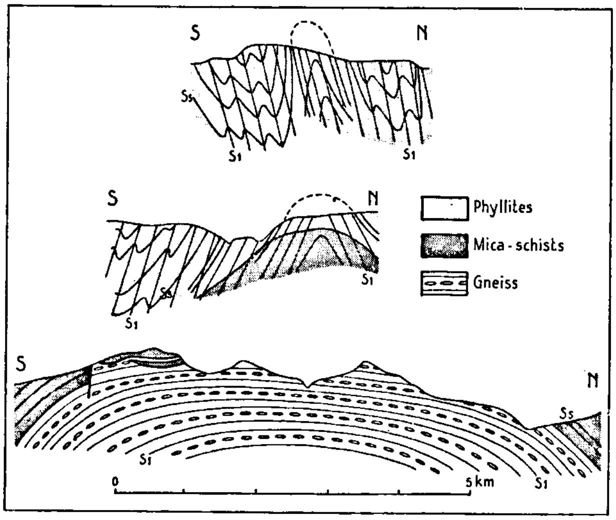


Fig. 3. Three sections through western part of Hospitalet Massif and anticline. Sections are 12 km. apart (after Zwart, 1963).

A somewhat different transition zone was described by Zwart (1963) in the western part of the Hospitalet massif. On fig. 3 three N-S sections through this transition zone are given. As the distance between the sections is about 12 km, the change in attitude of the cleavage is gradual.

In the western part of the Aston massif a décollement was not found. This is to be expected because the transition is situated in the rather uniform Cambro-Ordovician sequence in which the formation of any detachment plane would be unlikely.

The time relation between the deformation in the infrastructure and the deformation in the suprastructure is difficult to establish in the Valle d'Aran. In spite of the parallelism of the fold axes below, in and above the detachment zone, it could be assumed that the deformation in the suprastructure postdates that in the infrastructure. It is known, however, from other places in the Pyrenees that no important unconformities exist between the Cambrian and the Dinantian. The deformation of this sequence took place during the Hercynian orogeny. Evidence for the existence of a pre-Hercynian deformation is lacking. For this reason it is clear that all structures involving the infrastructure and the suprastructure were formed in the same orogenic period. Furthermore it is certain that the cleavage plane of the first Hercynian deformation is the first cleavage plane that was developed in the Central Pyrenees. Finally, nowhere in the suprastructure, indications for the occurrence of folds and cleavage planes of an infrastructural type, or suprastructural folds in the infrastructure, have been found. Therefore it is quite certain that the flat cleavage planes of the infrastructure and the steep cleavage planes of the suprastructure are formed contemporaneously.

The present author was instructed to investigate a transitional zone between the infrastructure and the suprastructure, and to make a connection with the four deformation phases known from other parts of the Central Pyrenees.

GENERAL REMARKS

Terms used

ss	sedimentary stratification
s_1	cleavage or schistosity plane of the first deformation.
s_2	cleavage or schistosity plane of the second deformation.
s_3	cleavage or schistosity plane of the third deformation.
s_4	cleavage or schistosity plane of the fourth deformation.
l_1 or δ	intersection of ss/s_1
l_2	intersection of s_1/s_2 or ss/s_2
l_3	intersection of s_1/s_3
l_4	intersection of s_1/s_4
B_1	fold axis of first deformation
B_2	fold axis of second deformation
B_3	fold axis of third deformation
B_4	fold axis of fourth deformation

The classification of cleavages

In this paper a morphological classification of cleavages, like the one proposed by Knill (1960) is used. The terms used, have no genetic implications. A short discussion of the different types of cleavage is given below.

a. Slaty cleavage (flow cleavage, schistosity) occurs in rocks in which a parallel arrangement of the micaceous minerals is present, such as chlorite, biotite and muscovite. The distance between the cleavage planes is determined by the basal cleavages of these minerals.

b. Fracture cleavage occurs in rocks in which only part of the micaceous minerals are oriented parallel to the cleavage plane. This kind of cleavage occurs in competent, equidimensionally grained rocks like quartzites in which the formation of cleavage is difficult, due to the small percentage of micaceous minerals. Transitions exist between slaty and fracture cleavage. This can best be seen in banded sequences.

c. Crenulation cleavage. This kind of cleavage is found in rocks that possess a pronounced planar structure, which is older than the crenulation cleavage. This planar structure (usually slaty cleavage) is micro folded (fig. 4).

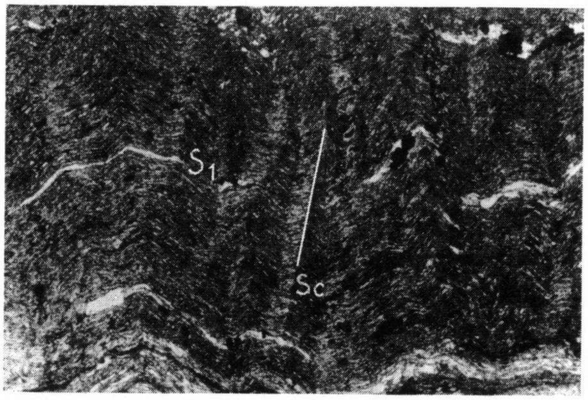


Fig. 4. Crenulation cleavage. The folded surface is the s_1 cleavage plane.

Different opinions exist concerning the origin of slaty cleavage. According to Sorby (1853), and many others, the slaty cleavage plane is a plane of flattening and/or a plane of recrystallization perpendicular to the direction of the greatest stress (pure shear).

Becker (1896), Schmidt (1932) and Sander (1948) considered the cleavage plane to be a shear plane which is oblique to the direction of the greatest stress (simple shear).

Because the investigations that led to these two popular theories were made in different mountain chains and in areas with different geological settings, one might expect that slaty cleavage can form in more than one way. In some cases the first theory has proved to be acceptable; in other cases the second theory appears reasonable.

Lineations

In this paper the term lineation is used for two different kinds of linear structures.

In the first place the term lineation is used in the sense of an intersection; for example between bedding and the cleavage. The occurrence of four successive deformations in the Vall Ferrera area makes it necessary to distinguish four generations of intersection lineations, l_1, l_2, l_3, l_4.

Secondly the term lineation is used for linear structures formed by a parallel orientation of minerals or elongated rock fragments.

Deformation ellipsoid and tectonic axes.

Some attention is drawn to the form and orientation of the deformation ellipsoid connected with the first deformation. The method used by Flinn (1962) and others, designating the principal axes as $Z>Y>X$, will be used in this paper. These axes are merely descriptive and have no genetic implication; the correlation with Sander's tri-axial system has to be studied in each case.

Fold axes are designated as B-axes. The direction within the cleavage plane, perpendicular to the fold axis is called the a-axis and the direction perpendicular to the cleavage plane is the c-axis.

In order to compare the structures found in the Central Pyrenees with structures found in other orogenes, a literature study concerning the different types of deformation was made. In table I the results of this literature review are given. The measurement of deformed objects, whose shape before deformation is known, has proven to be a profitable approach to the study of deformation. One notices that in many examples deformed conglomerates have been used to determine the amount and kind of deformation, although only in rare cases precise data have been obtained (e.g. Flinn, 1956). In spite of this restriction the author believes that the discussed examples give a good indication of the kinds of deformation that occur in different cases. In our opinion a cleavage plane is a plane of flattening. During this flattening

TABLE I

Types of deformation

Type 1: The main direction of elongation is perpendicular to the fold axis

author	locality	deformed object	grade of metamorphism	attitude of the cleavage plane
Brace, W. F. (1955)	Central Vermont; U.S.A.	conglomerate	low grade	moderate to 60°
Cloos, E. (1947)	Maryland; U.S.A.	oolite	low grade	moderate to flat
Davis, G. R. (1954)	Zambia; Africa	conglomerate	low grade	steep
Heim, A. (1878)	Switzerland	fossils (crinoids)	low grade	steep
Lapré, J. F. (1965)	Central Pyrenees; (Aston), France	conglomerate	low grade	steep
Oele, J. A. (1966)	Central Pyrenees; Spain	conglomerate	low grade	steep
Poll, J. J. K. (1966)	Sulcis; Sardinia	conglomerate, oolites	low grade	steep
Zwart, H. J. (1964)	Devon; England	fossils	low grade	steep
Zwart, H. J. & Oele, J. A. (1966)	Rocroi; Beglium	pressure shadows of magnetite crystals	low grade	moderate to steep

flat: 0°—30° moderate: 30°—60° steep: 60°—90°

Type 2: The main direction of elongation is parallel to the fold axis

author	locality	deformed object	grade of metamorphism	attitude of the cleavage plane
Badoux, H. (1963)	Leytron, Switzerland	fossils: crinoids	low grade	flat
Balk, R. (1952)	New England, U.S.A.	quartzites	medium grade	moderate to steep 40°—80°
Breddin, H. (1964)	St Gallen, Switzerland	fossils	low grade	steep to vertical
Burckhart, C. E. (1942)	Val Bedretto, Switzerland*	conglomerates	medium grade	steep (originally flat?)
Elwell, R. W. D. (1956)	Mayo, Eire	conglomerates	medium grade	variable 35°—70°
Fairbairn, H. W. (1936)	N.W. Ontario, U.S.A.	conglomerates	low grade	vertical
Flinn, D. (1956)	Fetlar, Shetland, Gr. Br.	conglomerates	medium grade	25°—45°
Koark, H. J. (1961)	Trondheim, Norway*	conglomerates	low grade	moderate
Kvale, A. (1945)	Bergsdalen, W. Norway*	quartzites	low grade	flat
Mehnert, K. R. (1939)	Sachsen, D.D.R.	conglomerates	medium grade	moderate to steep 50°—70°
Oftedahl, C. (1948)	Central-Norway	conglomerates	low grade	low angle
Strand, T. (1944)	Valdres, S-Norway*	conglomerates	low grade	variable
Tavener-Smith, R. (1962)	Zambia, Africa	conglomerates	medium grade	variable
Walton, M. et al (1964)	Kalatar; Ontario; U.S.A.	conglomerates	medium grade	low to moderate 20°—40°
Wennekers, J. H. N. (1964)	Vallée de Lys, Pyr., France	conglomerates	medium grade	moderate to flat
Zwart, H. J. (1964)	Devon, England	volcanic bombs	low grade	flat
	Verrucano, Switzerland*	conglomerates	low grade	flat

flat: 0°—30° moderate: 30°—60° steep: 60°—90°

process different directions of elongation (extension) can develop.

Two different types of deformation are distinguished: (fig. 5 and TABLE I)

1. The main direction of elongation lies in the cleavage plane and is perpendicular to the fold axis. This direction is often named "the direction of tectonic transport", a term that gives a misleading impression, as other directions of tectonic transport exist also. In this case the elongation is in the direction of the a-axis, and occurs in many orogenes all over the world. It can be seen, however, in table I, that this type of deformation appears to be restricted to the higher levels of orogenes where the metamorphism is of low grade. The cleavage, developed in these cases, is steeply dipping (fig. 5, a).

2. The main direction of elongation lies in the cleavage plane and is parallel to the fold axis (fig. 5, b). This type of deformation causes B-lineations, due to mineral orientation and/or elongation of rock frag-

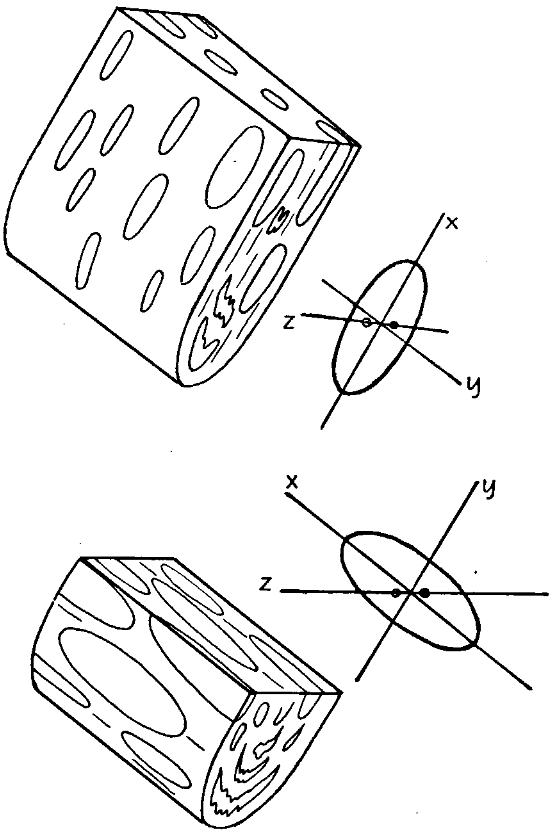


Fig. 5a. scheme of a deformation in which the main direction of elongation is perpendicular to the fold axis. b. scheme of a deformation in which the main direction of elongation is parallel to the fold axis.

ments. This deformation type is common and appears to occur in general in the medium and high grade metamorphic, rather deep seated, parts of orogenes. In some of these examples evidence for the shear character of cleavage is found. The second list of examples of table I can be subdivided in two parts, if we compare the direction of the folds in a certain mountain chain with its trend. In the first case the fold axes and the orogenic trend are parallel. This is the type that occurs in the Pyrenees. In the second case, the fold axes are perpendicular to the orogenic trend. This is the type found in the Penninic zone of the Alps. In some rocks which have been thrusted over large distances, fold axes are found that are parallel to the direction of thrusting. A lineation, (due to mineral orientation or elongated rock fragments), indicating the main direction of elongation, is parallel to the fold axes and to the direction of thrusting, but perpendicular to the trend of the Alps. These examples are marked with an asterisk.

This special kind of deformation is not separated from the second group, because one is not sure of the nature of the deformation of the examples cited. They might belong to "normal" B-tectonics or to the B$\perp$B' tectonics.

From the dynamic viewpoint a fundamental difference exists between the two deformations of the second type. In the first case the axis of elongation is perpendicular to what is presumed to be the direction of the largest principal stress (the fabric found in the metamorphites of the Pyrenees). In the second case the axis of elongation is parallel to the direction of largest principal stress (the fabric found in the Pennides of the Alps).

The determination of the initial attitude of the s_1 planes and the relationships between the different deformations

The first aim of the field work was to detect the initial attitudes of the s_1 planes. As the second, third and fourth deformations have disturbed these initial attitudes, some geometrical techniques were required to subtract the effects of these later deformations.

By measuring the intersection (l_3) of the first cleavage with the third cleavage, one can determine the apparent dip of the s_1 plane in the direction of the intersection (fig. 6). By collecting the l_3 measurements and putting them into regional diagrams, one can obtain an idea about the initial attitude of the s_1 planes (map no. 2), as far as these structures are not deformed by s_4 folds.

The age relationships between the different deformations, can be determined on a mesoscopic scale and on a microscopic scale.

As far as mesoscopic structures are concerned, the normal geometrical techniques were used. Some examples of the use of these techniques are found on page 153 where some interference patterns are discussed.

Due to the differences in degree of recrystallization one can usually solve the problem about the age relationships. Two examples can be distinguished and will now be discussed.

Figure 7 is a photograph of a thin section of a banded quartz phyllite. In the micaceous bands a cleavage is developed at a large angle to the banding. A detailed examination of the orientation of the micaceous minerals shows us that only in the thin zones, indicating the cleavage, the micaceous minerals are oriented parallel to this cleavage. This structure was formed as follows: Alternating sandy and clayey layers were laid down. These layers were folded during the first deformation and perpendicular to the sedimentary banding

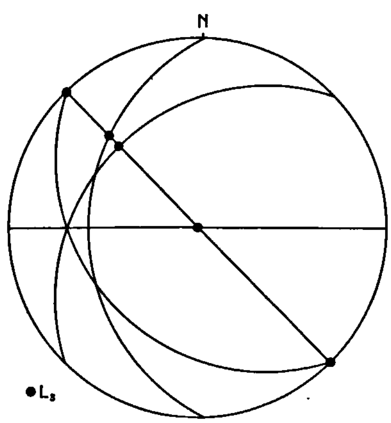


Fig. 6. Intersection of s_1 and s_3 (l_3) for different attitudes of s_1.

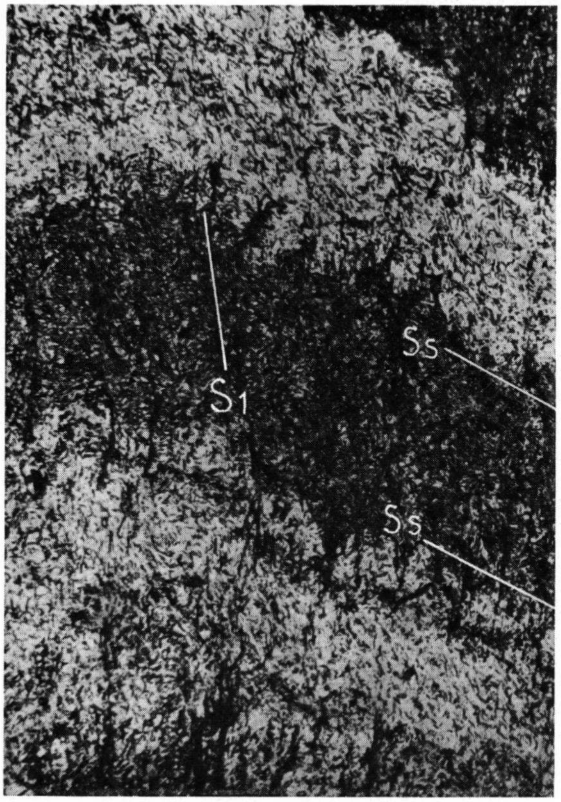


Fig. 7. Development of first cleavage in a layered sequence. The cleavage is of the fracture cleavage type.

Fig. 8. Development of a crenulation cleavage (sc) in a layered sequence. The folded surface is the s_1/ss surface.

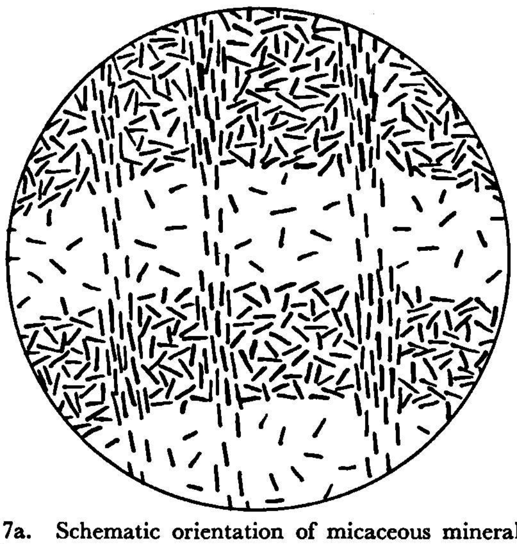


Fig. 7a. Schematic orientation of micaceous minerals in fig. 7.

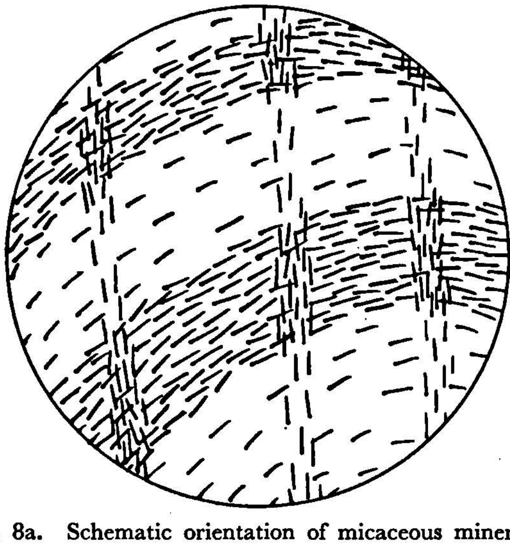


Fig. 8a. Schematic orientation of micaceous minerals in fig. 8.

the s_1 cleavage developed. The s_1 cleavage in this case is of the fracture cleavage type.

Figure 8 also shows a thin section of a banded quartz-phyllite. The orientation of most micaceous minerals is parallel to the banding. This banding is folded and parallel to the axial plane of the fold a cleavage is developed. The author proposes the following events to explain the structures in this thin section. Alternating sandy and clayey layers were laid down. Isoclinal folding of these rocks during the main phase deformation caused the micaceous minerals to be oriented parallel to the s_1 cleavage. Because of the isoclinal character of the s_1 folding, the s_1 cleavage is in most cases parallel to the sedimentary banding. Following the s_1 deformation another folding occurred during which the visible fold was produced, and a new cleavage developed, which is oblique to the original cleavage.

STRATIGRAPHY

The Vall Ferrera area is situated in the eastern part of the Salat-Pallaresa antiform where only rocks of Cambro-Ordovician age occur.
The Cambro-Ordovician strata consist of slates, sandstones, quartzites and microconglomerates.
In the eastern part of the investigated region a few isolated limestone outcrops have been found (Zwart, 1965, sheet 6). These limestones may be stratigraphically equivalent to the Ransol formation (Zwart, 1965, p. 199).
The discussed region is divided in two parts by the Mérens fault. The northern part forms the cover of the Aston massif and the southern part the cover of the Hospitalet massif. As discussed by Zwart (1965), a different stratigraphic sequence is found in these two areas.

ASTON MASSIF

In the northern part of the area, in the upper Brohate valley, a rock sequence with many microconglomerate intercalations has been found. These rocks form the continuation of the series in the Artique valley described by Caralp (1888), Destombes (1954), Allaart (1954), Lapré (1960, 1965), Raguin (1964) and Zwart (1965). Destombes (1950) suggested that these conglomerates represent the boundary of the Cambrian with the Ordovician, but as was stated by Zwart (1965, p. 197) this suggestion seems improbable.
In a recent publication, Raguin (1964) discussed some of the stratigraphic problems in the surroundings of the Pic de Montcalm. The present author cannot agree with the structure pictured on page 74 of this publication. The presence of the "séries gréseuses de l'Ordovicien" on the top of the Pic de Montcalm was not established by the present author. In addition the correlation of these series with the gneiss de Peyregrand seems rather hazardous. The stratigraphic position of these series remains, in spite of the investigations made by many French and Dutch geologists, a problem.

HOSPITALET MASSIF

Along the southern border of the region black slates are found. According to Zwart (1965) they represent the continuation of the Ransol formation found farther to the east in Andorra. Zandvliet (1960) mapped these rocks as belonging to the Lleret-Bayau formation, thus representing the core of the big Pallaresa-Salat anticlinorium; consequently this formation was considered to consist of the oldest rocks found in this part of the Central Pyrenees.
The work of Zwart (1965), Verspyck (1965) and Lapré (1965), however, revealed that this sequence belongs to the Ransol formation and has a much higher stratigraphic position. This implies that a correlation of this succession with the Canaveilles formation (Cavet, 1951, 1958) cannot be made.
Concluding we might say: In the discussed region clastic sediments of Cambro-Ordovician age are deposited. These sediments vary in composition from slates to microconglomerates with pebbles up to 2 cm. Both in vertical as in lateral direction these sediments pass into each other and form a quite variable sequence.
The absence of marker horizons and the complexity of the fold systems make it impossible to construct the present attitude of the bedding planes in the Vall Ferrera area. However regional investigations of Zandvliet (1960) and Zwart (1965) allow us to make some reasonable speculations (page 144).

TECTONICS

INTRODUCTION

In the Central Pyrenees several phases of deformation accompanied by or alternating with the rising of metamorphic fronts have been found. The geometrical properties of the deformations are rather constant over several hundred kilometres in the direction of the mountain chain. This gave Zwart and his associates the opportunity to make a deformation scheme that is valid for most of the Central Pyrenees (fig. 1).
The first deformation phase, usually called the "main phase" or s_1 deformation, was presumably caused by a strong N-S compression. The different structures produced by this compression shall be discussed in detail on the following pages.
After, and perhaps partly during, the s_1 deformation, a second set of folds developed. This deformation formed folds with N-S axes and a sub-horizontal cleavage plane. This deformation was apparently caused by an E-W compression and occurs only locally in the Pyrenees.
Following this second event there was another deformation that produced two sets of vertical s-planes which strike NW-SE and NE-SW. This is the third deformation. The first set mentioned, is more strongly developed than the second one. The relative movements, along these shear planes, indicate that this deformation was also caused by an E-W compression.
The last deformation phase of the Hercynian orogeny, that produced folding, is called the E-W refolding or the s_4 deformation. This deformation formed vertical E-W striking cleavage planes and was caused by a renewed N-S compression.
This short synopsis is given here because in the discussion of the attitudes of the s_1 planes on the following pages, all these deformations are mentioned. A more detailed description of the s_2, s_3 and s_4 deformations is given further on.

THE FIRST DEFORMATION

Symbols:

cleavage plane of first or main phase deformation	s_1
intersection of ss and s_1	l_1
fold axis of first deformation	B_1

Fig. 9. s_1 fold, subarea 15, 250 m. S of Mérens fault.

Description of some s_1 folds

Folds belonging to the main phase deformation are rarely found. This is due to the isoclinal character of the s_1 folds and to the recrystallization during this folding which in some cases has obliterated bedding structures.

During the survey of the Vall Ferrera area some dozens of these folds were found. The best examples are discussed below.

The first example is found in the suprastructure of the Hospitalet massif (fig. 9, fig. 10) in subarea 15, in the highest part of the Sellente valley. This fold shows the strong deformation, characteristic of the main phase. The cleavage in these quartzitic rocks is of the fracture cleavage type. Fig. 10 shows us a detail of this fold in which the thickening in the hinge zone and the fanning of the cleavage is evident. These folds are presumably developed as parasitic folds on larger s_1 folds. The amplitudes of the larger folds are unknown in the Vall Ferrera area, but in other places in the Central Pyrenees (fig. 2), they amount to several hundreds of metres.

More of these parasitic folds are found in subarea 7; an example of a part of such a fold is shown in fig. 11. This fold is also developed in a quartzitic rock. The cleavage is of the fracture cleavage type. By studying this example under the microscope, a form orientation of the quartz grains was detected; the longest axes of the grains are perpendicular to the fold axis and lie in the cleavage plane.

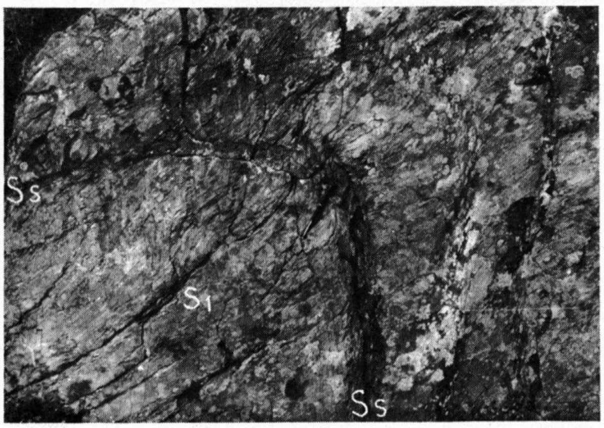


Fig. 10. Detail of fig. 9.

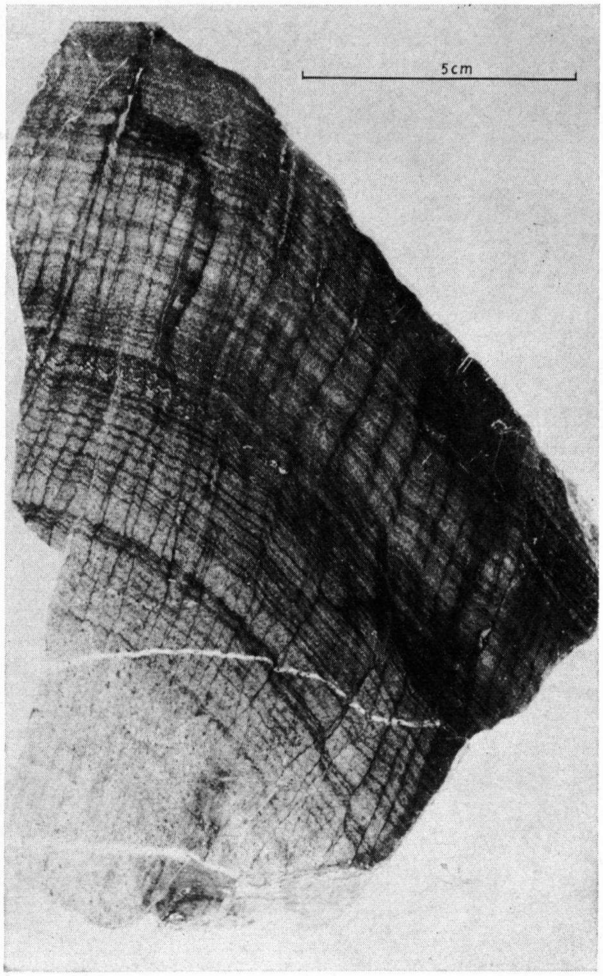


Fig. 11. A part of the hinge of a s_1 fold in a layered quartzitic sequence; cleavage is of the fracture cleavage type.

Fig. 12 shows a s_1 fold in subarea 16 on the southern flank of the transition zone. In this case the fold is developed in pelitic sediments. As a result of recrystallization, the bedding is almost obliterated and the fold is only visible in the left portion on the figure. Due to the pelitic composition of the rocks the s_1 cleavage plane has a constant attitude in the fold. These three examples (fig. 9, fig. 11, fig. 12) are found in the western part of the transition zone.

In the eastern part of this zone, near the micaschist boundary, well exposed s_1 folds are found. In these rocks with their western dipping s_1 planes, many quartzitic layers occur in which s_1 folds are evident. Fig. 13 shows us a fold, seen perpendicular to the fold axis that plunges 25° to the west. These folds have a rather irregular form. These irregularities are more pronounced in fig. 14 in which one of the few limestone outcrops in the area is shown. This limestone occurs in subarea 23, 500 m N of the Port Vell on the French

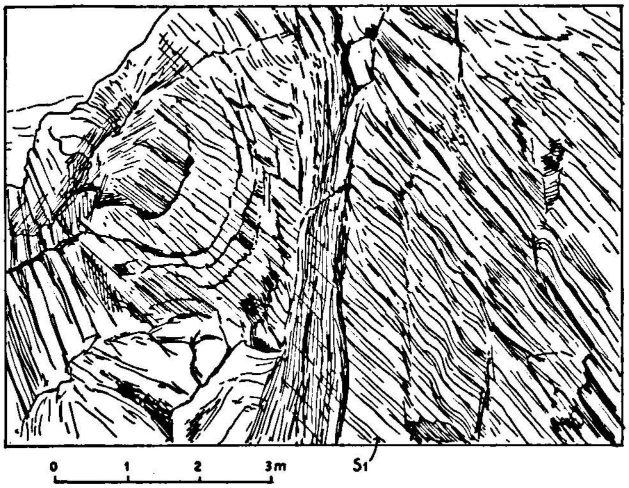


Fig. 12. s_1 fold in southern flank of s_1 structure, subarea 16, Sellente valley.

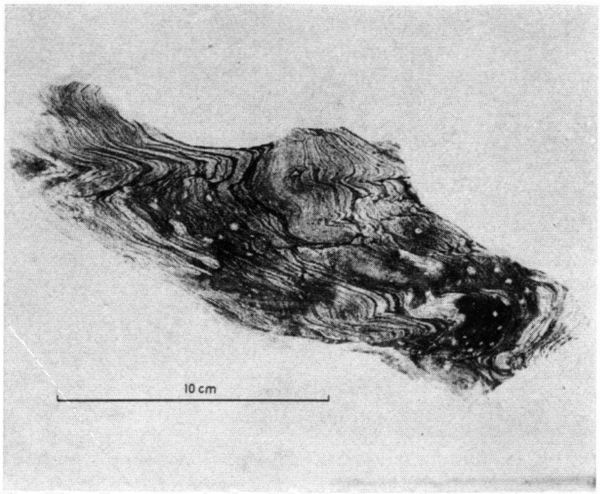


Fig. 15. Asymmetrical s_1 folds in layered quartzites, Etang de la Gardelle, subarea 18.

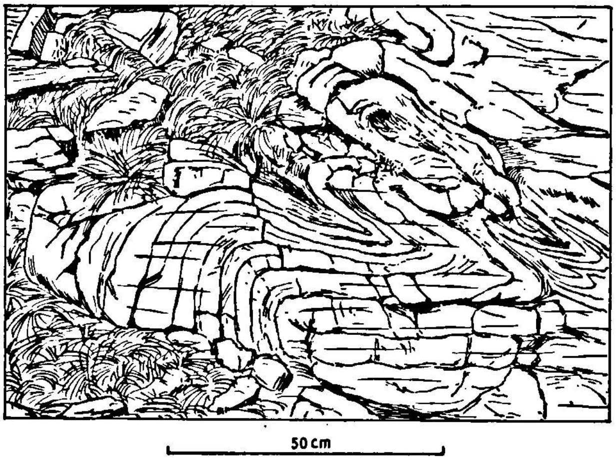


Fig. 13. s_1 folds, seen on a sub-vertical, N-S striking, plane, *subarea* 13.

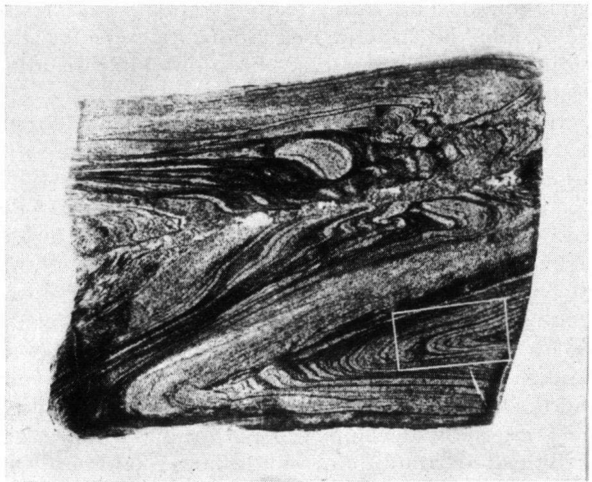


Fig. 16. s_1 folds in layered quartzites, subarea 13.

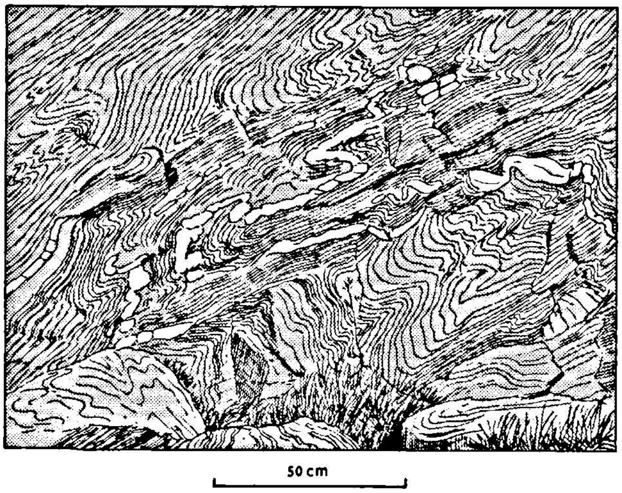


Fig. 14. Irregular s_1 folding in limestone, 500 m N of Port Vell, subarea 23.

Fig. 17. Detail of fig. 16, showing orientation of micaceous minerals, parallel to axial plane of s_1 fold.

side of the frontier. This irregular kind of folding is due to the plastic behaviour of the limestone in between the quartz-phyllites.
Fig. 15 shows an asymmetrical s_1 fold in the layered quartzites of subarea 18. The asymmetry is found in many of the s_1 folds indicating a movement from S to N. The problems involving these asymmetries and movements are discussed on page 159.
The final example (fig. 16) shows us a very good picture of the style of the s_1 folds. It is a s_1 fold in a layered quartz-phyllite. An interesting phenomenon is shown on fig. 17 in which a detail of one of the isoclinal folds of fig. 16 is seen; an orientation of the micaceous minerals parallel to the axial plane of the fold is present.

Description of the attitude of the main phase cleavage planes
A kilometre-grid corresponding to the grid on the French 1 : 20.000 maps was put on the map. The region was subdivided into 24 subareas and in each of these subareas at least one hundred measurements of the main phase cleavage plane were made. From these measurements 22 diagrams were constructed and these diagrams were collected on map no. 2 to show the attitude of the s_1 planes in each subarea. We shall discuss the main phase structure of the region as follows: 1) the steep s_1 cleavages in the west, 2) the subhorizontal s_1 cleavages in the east and 3) the transition zone in between.

1. *The western region.* — In subarea 1, located in the northwest part of the region, a steep s_1 cleavage, dipping 80° to the north, is present. Diagram no. 1 shows a high maximum (27 %) common for the regions with a steep cleavage. However, a spread towards the NE and E is found; this spread is due to the occurrence of third folds with vertical fold axes, which have deviated the main phase cleavage planes from an E-W strike to a NW-SE strike. An example of one of these folds is found on page 150. (fig. 37).
In subarea 2, located E of subarea 1, a steep N dipping cleavage is also present. The maxima represent about the same attitude of the s_1 planes as in diagram no. 1, but a larger spread both to the NE as well as to the NW is found. This spread is related to the s_3 folds which rotated the s_1 planes to a NE strike, and to the position of this subarea on the northern flank of the transition zone. The strike of the main phase cleavage plane is not strictly E-W in this subarea, but about WNW-ESE. This change of the attitude of the s_1 plane is more evident in subarea 3 (diagram no. 3). The maximum has turned to a NW position. It is important to mention that although the cleavage plane remains steep in this subarea, its attitude is different from the normal picture, because of the presence of the transition zone.
Going futher to the east, across the frontier into France, we come to the area mapped by Lapré (1965). The strike of the s_1 planes remains NE-SW, but near Etang Sourd (44—523) it changes to an E-W direction, parallel to the border of the Aston massif.

In subarea 4 (diagram no. 4) the main phase cleavage planes have a different attitude. Although the maximum remains the same as in the subareas 1 and 2, many planes with NE-SW strikes and SE dips, occur. Most of this variation is due to the refoldings, especially the third deformation, which gave rise to folds with amplitudes up to some tens of meters. These folds are well exposed in the outcrops around the Bohavy flat. They are among the largest third folds found in this part of the Central Pyrenees (page 150).

2. *The eastern region.* — In the Mounicou valley, located east of the presently described region, flat lying s_1 planes occur. This is the area mapped by Lapré (1965) and for the details of the structures we refer to this publication. To the north, near the border of the Aston massif the s_1 plane steepens. Along the border it is vertical.
Going up the western slope of the Mounicou valley, we observe a gradual change from a subhorizontal (about 10° dipping to the north) attitude to a western dipping (30°—40°)attitude.
Subareas 13, 18 and 23 are located in this region and should give a good picture of these western dipping structures, but in these subareas the original attitude has also been changed by the s_3 and s_4 deformation.
Subarea 18. Although in subarea 18 many structures of the fourth deformation are found, diagram no. 18 gives us a good picture of the original attitude of the s_1 plane. The maximum represents a plane that dips 35° to the WNW. The spread of the s_1 planes is due to the above mentioned fourth deformation folds. The folds have amplitudes of some tens of metres and can be followed over a distance of some hundred metres (fig. 49). These folds turned the western dipping s_1 planes to attitudes with NW or SW dips, depending on which limb of the fold it occurs.
Subarea 23. This subarea shows a big spread; two maxima of 9 % occur. One maximum represents a plane dipping 10° to the NW and the other one represents a plane dipping 50° to the NNE. The large spread is due to the existence of many third and fourth folds, which are strongly developed in this subarea. The folds of the E-W refolding have an asymmetrical form, the southern limbs being shorter than the northern ones, because northern dipping s_1 planes form the maxima on the diagram.
The discussion of the s_1 structure in these subareas provides us with the following interesting fact: the s_1 structures in the valley of Lago Aresti form the concordant continuation of the s_1 structures in the micaschists of the Mounicou valley.

3. *The transition zone.* — In the region lying between the discussed subareas, the transition from the steep s_1 cleavage to the flat s_1 cleavage takes place. This zone extends from 7 km in E-W direction to 5 km in N-S direction. This is not the original area covered by the transition, zone, as it is cut off in the south by the Mérens fault.
We shall now discuss the attitudes of the s_1 planes in

the transition zone starting in the west at the steep borders of it.

Subarea 5. The s_1 plane is steep, gradually changing from an E-W strike to a NE-SW strike. In this subarea some second phase folds are found, which are probably connected with the transition zone (page 149). The s_1 planes are rotated about N-S axes and they become partly overturned. This is indicated by the s_1 planes with eastern dips. The spread of the s_1 planes along the border of the diagram is caused by steep to vertical s_3 and s_4 folds with steep axes.

Subarea 6. This subarea has a complicated structure. All four deformation phases occur here. In spite of the disturbance of the original attitude of the s_1 planes some information about its attitude can be obtained. The change of the attitude of the s_1 plane, already mentioned in the discussion of subarea 5, is more pronounced here. The maximum of 13 % corresponds to a plane dipping 50° to the WNW. We approach here the centre of the transition zone, hence western dipping s_1 planes are found.

Eastwards in France, the NW and W dipping structures, discussed by Lapré (1965), occur. Their steep attitudes are due to rotation of the s_1 planes around the N-S axes of the second deformation.

Subareas 7, 8 and 9 are situated at the centre of the transition zone. In these subareas the crest of the s_1 antiform is found and, due to this position, the diagrams 7, 8 and 9 give an interesting picture.

Diagram no. 7 represents the measurements in a subarea where refoldings are almost absent, as is evident from the lack of l_2, l_3, l_4 lineations. Therefore the diagram shows the original attitude of the s_1 planes. The spread in this diagram is not due to rotation of the s_1 planes about refolding axes, but is due to the antiformal attitude of the s_1 plane in the centre of the transition zone. This means that in the same overall stress field, variations in the orientation of the cleavage planes can be found. These variations are considerable over a small distance. The possible reasons for these variations are discussed on page 159.

The spread mentioned in subarea 7 is even better seen in subarea 8 (diagram 8) where a complete girdle of the s_1 planes is developed. This girdle indicates the gradual change of the attitude of the s_1 plane. The maximum, representing the southward dipping s_1 planes, is higher than the maximum representing the s_1 planes with a northward dip. This is caused by the asymmetry of the s_1 structure (fig. 18).

In subarea 9 most s_1 planes dip to the west. The maximum of diagram 9 (10 %) represents a plane that dips 45°—50° to the west. A variation from W over NW to N dipping planes is present. This is due to both: the main phase deformation itself and to the refoldings. The same variation of the initial attitude of the s_1 planes over short distances as discussed above, occurs in this subarea. Refolding is strongly developed here, especially the second folding phase.

On the flat summit of the Pic de Montcalm westward dipping s_1 planes are found; in some outcrops the dip is 70° to 80°. These steep dips are caused by s_2 folds. Fig. 25 shows us such a fold from this subarea. These folds have rotated the original westward dipping (35°—45°) s_1 planes to steep and vertical attitudes.

Proceeding to the east the same original attitudes of the s_1 planes are found. According to the structural map of Lapré (1965, p. 266), the structures of the phyllites are parallel to the structures in the micaschists.

The structures in subareas 10, 11, 12 and 13 give us a good picture of the attitudes of the s_1 planes on the southern flank of the transition zone.

In subarea 10 (diagram 10) we are able to make a diagram representing the original attitude of the s_1 plane because of the absence of the refolding phases in this subarea. The maximum of diagram 10 represents a plane that dips about 45° to the south.

Continuing to the east in subarea 11 (diagram 11) we observe the change of the attitudes of the s_1 planes from a southward dip in subarea 10 to a southwestward dip in subarea 11. Although the maximum of diagram 11 represents a steeper plane than the maximum of diagram 10, the overall attitude of the s_1 planes becomes flatter. The larger spread of the s_1 planes in diagram 11 is caused by the occurrence, especially north of Lago Baborte, of the NE-SW set of the third deformation.

The disturbing effect on the initial attitude of the s_1 planes caused by the refolding phases is manifested in subarea 12. This subarea is located in a part of the transition zone with originally moderately dipping s_1 planes. In contradiction to its place in the transition zone, diagram 12 shows us many planes with steep dips. This is caused by the refoldings. Consequently a large spread of the attitudes of the s_1 planes is found. A proof of the initial moderate dip of the s_1 plane is found by examining the attitude of the l_3 lineations. The plunge of these lineations varies from 10°—40° in this subarea. These low to moderate plunges are restricted to areas with initially low and moderately dipping s_1 planes (map no. 1). One should expect to find in subarea 12 and 13, southward dipping s_1 planes in accordance with the structure in subarea 10 and 11, because these areas are located on the southern flank of the main phase structure.

In the Mounicou valley, however, the attitude of the s_1 planes in the micaschists give an asymmetric picture on a N-S profile (fig. 18). The same asymmetry is found in the Aresti and Sotllo valleys. In these areas no originally south dipping s_1 planes are found. The whole structure is dipping to the north. This same asymmetry is found in subarea 12-13, and is due to the presence of the Mérens fault.

Subarea 16 is located around Lago de Baborte, one of the glacial lakes of the region. In this subarea, as in the neighbouring subarea 10, the refolding phases are hardly developed; the initial attitudes of the s_1 planes are still present. The gradual change from s_1 planes with southern dips to southwestern and to western dips becomes clear by studying diagram 16, which has a maximum that corresponds to a plane

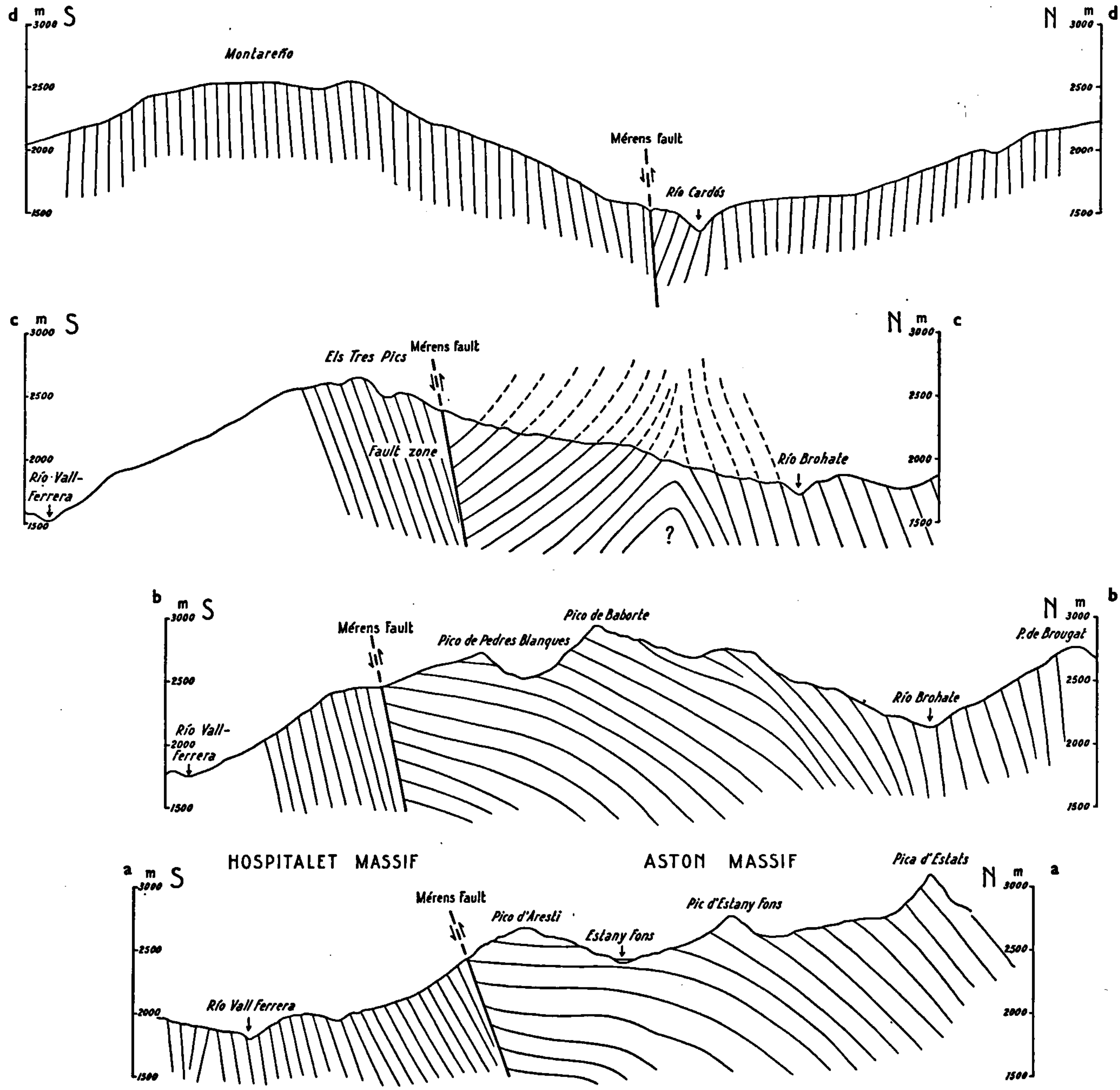


Fig. 18. Four N-S sections through the Vall Ferrera area showing the presumed attitude of the s_1 planes, before the refolding took place. For locations see fig. 58. Scale 1:50.000.

that dips about 60° to the southwest. In the diagram a variation from steep southward dipping s_1 planes to horizontal and westward dipping s_1 planes is found; these latter occur in the western slope of the Pico de Llats.

Subarea 17 is situated east of the Pico the Llats ridge (diagram 17). This subarea reveals structures that are typical of the lower parts of the Sotllo and Aresti valleys. As one notices on diagram 17 the main phase planes have a large variation both in strike and dip, but, as is to be expected, gently dipping planes form the maxima. The initial attitudes of the s_1 planes were difficult to unravel in this subarea due to the intense deformation by the refoldings. We suppose that the initial dip direction of the s_1 planes was between north and west; the amount of dip between 30° to 40° (map no. 2).

This is seen to better advantage in subarea 18 (diagram 18) where a maximum of 15 % is found, representing a plane that dips about 35° to the west. The border of the micaschists lies within this subarea.

The effect of the second deformation phase is manifested by the presence of a girdle along the E-W direction and the effect of the third deformation phase by the variation about the NW-SE direction

Subarea 21. This subarea, just north of the Mérens

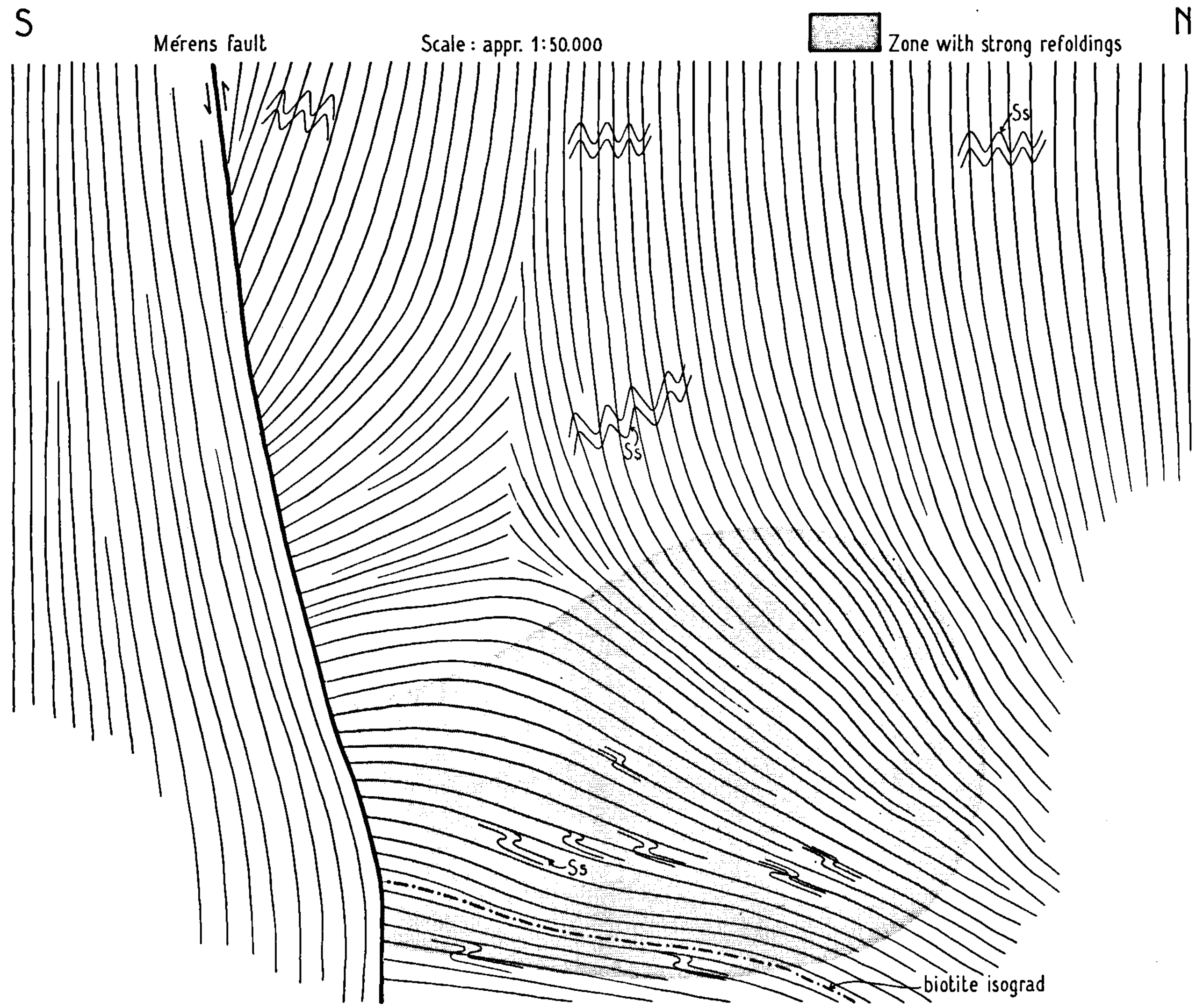


Fig. 18a. Schematic section trough the transitionzone.

fault, is located in the Sotllo valley in the moderately dipping structures of the transition zone. Diagram 21 has three maxima, each of 11 % and representing s_1 planes with dips of about 40°.

In subarea 23, situated in the Aresti valley, a similar diagram has been constructed. In these two subareas the initial picture is strongly disturbed by the later refoldings, but the maxima indicate the flat attitude of the s_1 plane.

4. *The area south of the Mérens fault.* — These subareas are situated in the low grade metamorphic cover of the Hospitalet massif and form a part of the suprastructure of this massif. The s_1 planes are subvertical and have dips of 50°—60° N along the Mérens fault.

In subarea 14 (diagram 14) we notice a strong maximum indicating the regular attitude of the s_1 planes. A deviation from the general E-W striking structure is found; the maximum represents a plane that dips 80° to the NNW. This is presumably due to a change in the attitude of the Mérens fault. In the eastern part of the region the fault runs parallel to the general trend of the mountain chain, but from the Port Vell (37—524) to the western border of the region it turns to the NW. The s_1 planes, south of the fault, are parallel to it over a distance of some hundreds of meters.

Subarea 19 (diagram 19) gives about the same picture as subarea 14, but the deviation from the E-W strike is smaller. In the rocks just south of the fault, s_1 planes occur with dips of 50°—70° to the north. Due to the movements along the Mérens fault the vertical structures were rotated to these northward dips. This rotation is better seen in subarea 22 (diagram 22) where on the crest of the Pico d'Aresti the main phase cleavage dips 20° to 30° to the north over a small area along the Mérens fault. The normal picture is, that in this subarea the Mérens fault dips about 60° to the north, and over a distance of about 500 m to the south of the fault, the s_1 planes have

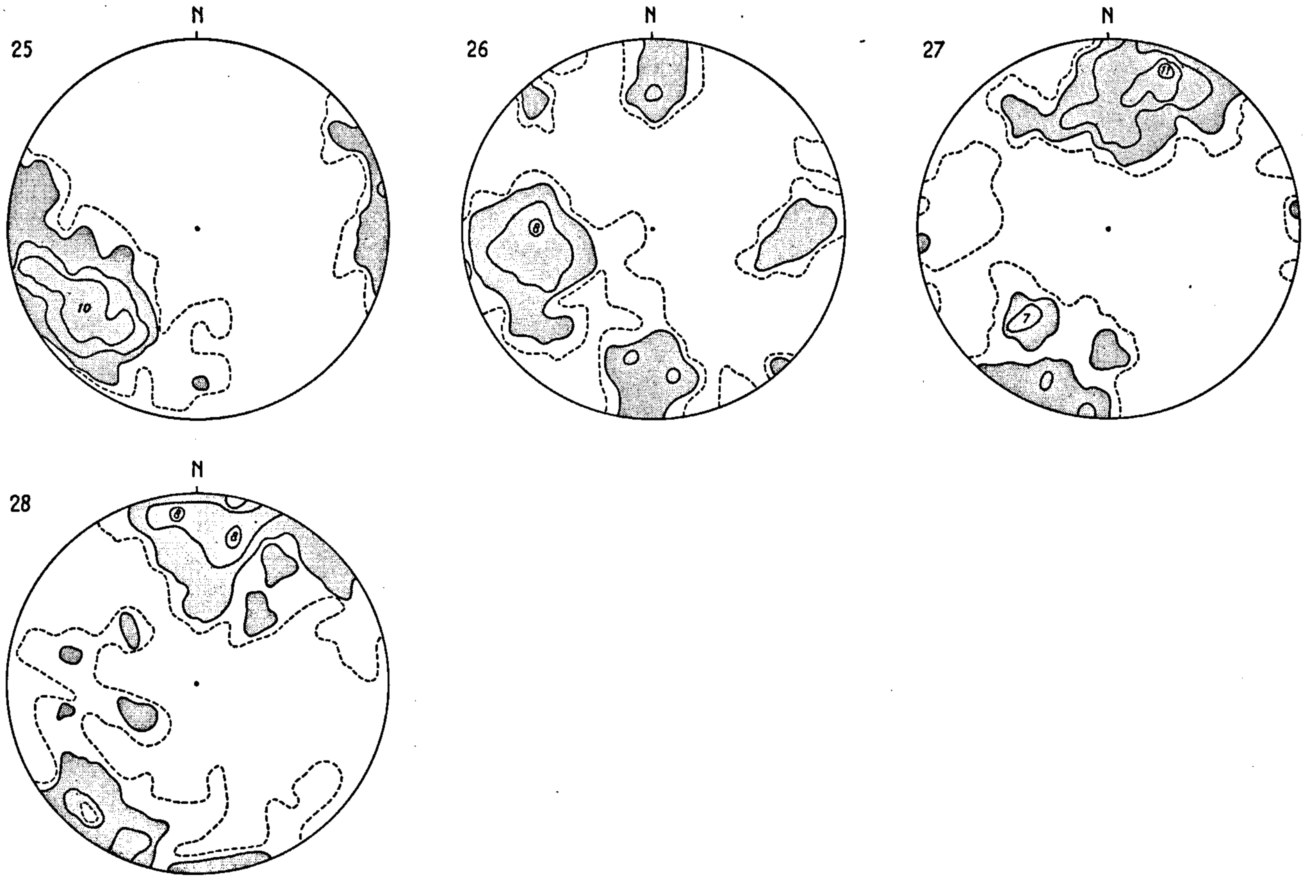


Fig. 19. Diagrams showing attitude of l_1 and l_2 lineations, discussion in the text.
no. 25 — subareas: 4, 7, 10.
no. 26 — subareas: 5, 8, 11, 16.
no. 27 — subareas: 9, 12, 17, 21.
no. 28 — subareas: 13, 18, 23.

about the same northward dip. Further to the south the s_1 planes are vertical as is seen on the structural map no. 2.
Approximately the same attitude of the s_1 planes is found in subarea 24. The high maximum of 26 % indicates the regular northward dipping attitude of the s_1 planes in this subarea. The attitude of the Mérens fault turns to vertical as is seen in the Port Vell (on the French maps indicated as the Port de Roumazet); the pass is structurally determined by the presence of the fault.
On the slope, west of the Rio Aresti (subarea 22 and 24), peculiar structures in the steep phyllites of the Hospitalet massif are found. These structures do not agree with the deformation scheme worked out for the Central Pyrenees. No indication for the correlation of these folds with the "normal" refolding phases has been found. The author suggests that these "anomalous" structures were caused by the movements along the Mérens fault. These movements might have produced smaller faults and folds near the main fault.

Orientation of the B_1 foldaxes, the l_1 and the l_2 lineations
The parallelism of the s_1 and the s_2 planes (apart from the hinges of second folds) and the strong recrystallization during these two deformations makes it difficult to establish the difference between the l_1 and l_2 lineations, except for their difference in direction.
For these reasons the diagrams no. 25, 26, 27 and 28 on fig. 19 have been made of measurements of lineations caused by the intersection of bedding and cleavage (δ lineations). Regional investigation by Zandvliet (1960) and Zwart (1965) has shown that the l_1 and B_1 in general have an E-W orientation.
Diagram no. 25: This diagram is made of measurements in subareas 4, 7 and 10. Due to its position on the western border of the transition zone (on the suprastructural side) this diagram shows about the same pattern as discussed by Zandvliet (1960, p. 90—93), although a difference exists. This difference is found in the fact that the maximum of 10 % occurs on the southwestern side of the diagram and not on the western side. To the author's opinion this variation is due to some local changes in the attitude of the bedding plane before the s_1 deformation. A few south trending lineations indicate the presence of the s_2 folding.
Diagram no. 26: On diagram no. 26, made of measurements in subareas 5, 8, 11 and 16, several maxima occur. One of 8 %, representing a line that dips 40° to the west (fig. 20) and three maxima of 5 %, lying

Fig. 20. Intersection of bedding and first cleavage (δ lineation) seen in the s_1 plane, Sellente valley, subarea 7.

on a N-S girdle. This diagram makes it clear that two girdles can be separated: the first one lying in an E-W plane, indicating the l_1 lineation and the second one lying in a N-S plane, indicating the l_2 lineation. In these subareas the s_2 deformation is strongly developed.

Diagram no. 27: On diagram no. 27, made of measurements in subareas 9, 12, 17 and 21, we see that almost no E-W oriented lineations are found. The maximum is formed by a line that dips 10° to the NNE. In these subareas many s_2 folds are found. The absence of E-W (l_1) lineation causes a great problem. It is not probably, since in all adjacent areas E-W trending l_1 lineations are found, that these should have a different orientation in these subareas. Therefore we presume that, due to the strong development of the second deformation, most E-W running lineations have been obliterated (as we noticed also by Zwart in the micaschists of the Valle d'Aran, Zwart, 1963).

Diagram no. 28: In this diagram, made of measurements in subareas 13, 18 and 23, the maximum of 8 % also represents a l_2 lineation. In these subareas the amount E-W trending l_1 lineations is also small, but the outcrops around Etang de la Gardelle show very clearly that both deformations are present and microstructural work has shown the age relationship between the two deformations.

Summarizing we might say, that in the Vall Ferrera area the intersection of ss and s_1 and the intersection of s_1 and s_2 (or ss and s_2) give the same type of intersecting lineation (normally called the δ lineation). Due to this similarity, those lineations have been recorded together in the diagrams. In general, two maxima can be distinguished: one representing the l_1 in an E-W direction and one representing the l_2 in a N-S to NNE-SSW direction.

The diagrams can give us no answer to the question whether on a regional scale the bedding is parallel to the s_1 planes or cuts through these s_1 planes. This question is of great importance for the macrostructure of the whole Aston massif. In a recent paper Zwart (1965) paid attention to this problem. There can be less doubt that the oldest rocks of the Aston massif are found in the centre of it. Going from this centre to the border of the massif, younger rocks occur of a lower metamorphic grade. A certain parallelism between the metamorphic isograds and the structure is present, but as we know of Zwart's data (Zwart, 1965, p. 197) examples of the oblique relationship between the bedding and the epizonal and mesozonal boundary occur.

The present author proposes the following connection between bedding and the s_1 planes: In the transition zone of the Vall Ferrera the isograds of the metamorphism, that is contemporaneous with the s_1 deformation, have a steeper attitude towards the west than the s_1 planes. The place of the transition zone is determined by the differences in metamorphism and by the stress conditions in the various parts of the orogene. This place is not determined by an earlier deformation.

The form and orientation of the deformation ellipsoid

In this discussion no attention can or will be paid to the absolute ratios between the different axes of the deformation ellipsoid. It is the changes in the ratios

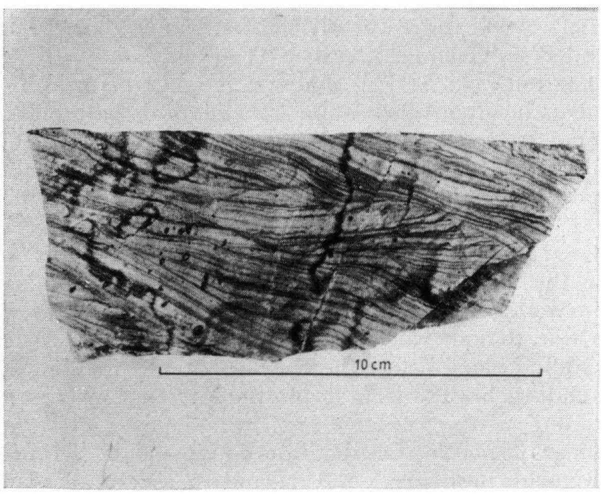


Fig. 21. Cross bedding, seen on the s_1 plane, bedding is perpendicular to the s_1 plane.

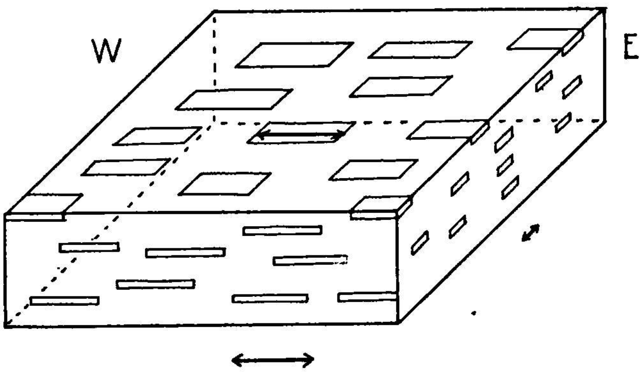


Fig. 22. Fabric of a micaschist in the Mounicou valley eastern part of the region.

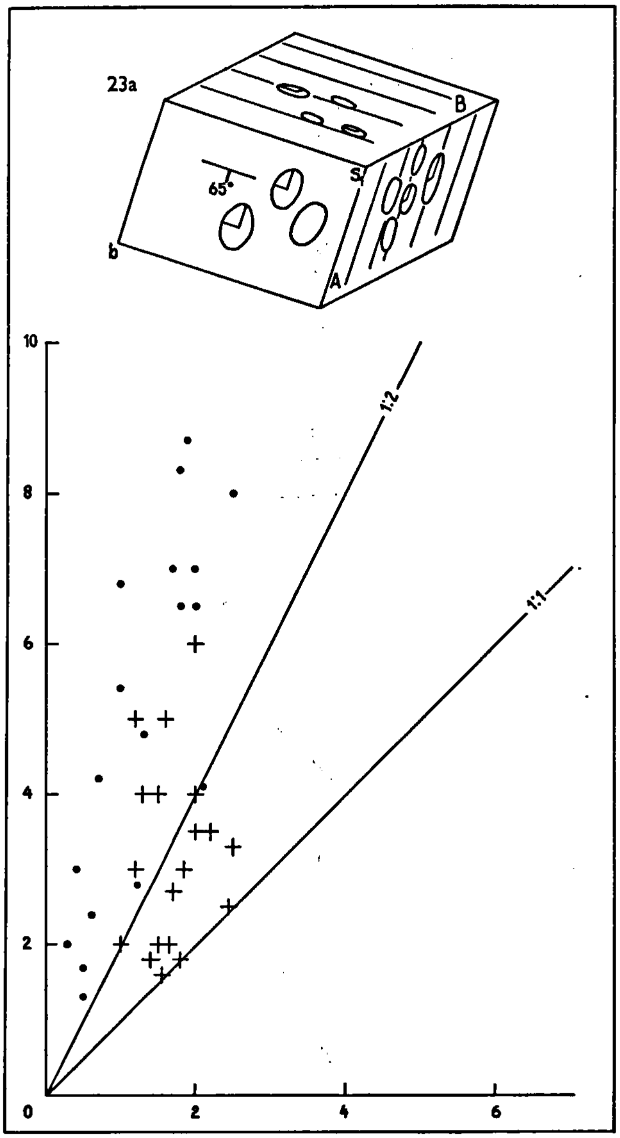


Fig. 23. a. Orientation of s_1 fabric in a microconglomerate on the northern flank of the transition; s_1 plane dips 65° to the north.

b. Measurements of deformed pebbles in the conglomerate of fig. 23a. The dots indicate the ratio between shortest and longest axes (measured on plane A of fig. 23a). The crosses indicate the ratio between shortest and intermediate axes (measured on plane B of fig. 23a). Each scale unit represents one mm.

between the different axes that we are interested in. Some information is available in the Vall Ferrera area for determining the form and orientation of the deformation ellipsoid connected with the main phase deformation.

The fabric of the micaschists in the Mounicou valley gives us important information (fig. 22). On fig. 22 we notice the form orientation of flaky minerals. This orientation was produced during the first deformation; and we presume that the longest, intermediate and shortest axes of the flakes of the minerals give an idea about the orientation of and the ratio between the different axes of the deformation ellipsoid of the first deformation. The fabric indicates that the main elongation is in an E-W direction, consequently the longest axis is oriented in the E-W direction. The intermediate axis has a N-S direction and is lying, like the longest axis, in the s_1 plane. The shortest axis is perpendicular to the s_1 plane and is vertical. Detecting the form and orientation of the deformation ellipsoid in the steep phyllites is a more difficult task as the fabric of these rocks gives little information. This is due to the fact that the recrystallization, during the s_1 deformation, caused only very small crystals to form. But as discussed on page 136 microconglomerates occur in the western part of the transition zone and the deformation of these conglomerates gives us the key for detecting the form and orientation of the deformation ellipsoid.

In fig. 23 the results of the measurements of the deformed pebbles are given. This information was obtained by measuring the pebbles on a vertical E-W trending plane and on the plane vertical to the longest axes of the pebbles (fig. 23). The dots indicate the ratio between the longest and shortest axes and the crosses indicate the ratio between the intermediate and shortest axes. In this sample from the Sellente valley the s_1 plane dips about 65° to the north. The longest axis of the pebbles is directed down the dip of the s_1 surface; the intermediate axis is about horizontal and the shortest axis is perpendicular to the s_1 surface.

These observations, combined with those concerning the attitude of the s_1 planes in the transition zone, bring us to the following hypothesis: The orientation and form of the deformation ellipsoid change, going from the infrastructure to the suprastructure. In the infrastructure the longest axis is about horizontal and has an E-W direction; this attitude changes gradually in the transition zone to a vertical position. The intermediate axis changes from a horizontal N-S attitude to a horizontal E-W attitude and the shortest axis changes from a vertical attitude to a horizontal N-S attitude. These changes are shown in fig. 24.

Discussion

In a recent paper, Flinn (1965) described the occurrence of different kinds of tectonites. It is interesting to compare these tectonites with those described by the present author from the Vall Ferrera area. As one possible fabric system, Flinn proposes the L-S fabric system in which the L-tectonite represents a lineated, non-schistose rock and the S-tectonite a schistose, non-lineated rock.

In the Vall Ferrera area, the s_1 deformation produced also different kinds of tectonites as we have discussed on page 145, but the fabric system differs from the L-S fabric system described by Flinn. In the Vall Ferrera area the whole fabric system is characterized by a schistose rock and the differences in this fabric system are found in the different orientation of the main direction of extension on the cleavage or schistosity plane. In the infrastructure the main direction of extension lies in the cleavage plane parallel to the fold

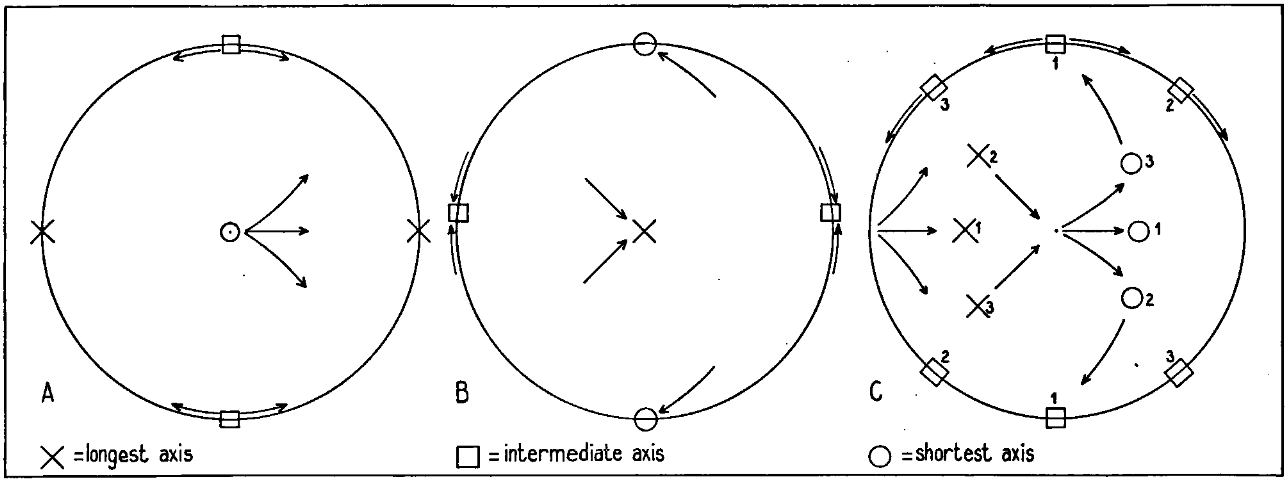


Fig. 24. Orientation of longest, intermediate and shortest axes of deformation ellipsoid in infrastructure (A), transition zone (C) and suprastructure (B) shown on the lower hemisphere of the Lambert projection. On fig. 24 C. The orientation of the deformation ellipsoid is given for three attitudes of the s_1 plane in the transition zone. The arrows indicate the gradual change in orientation of the deformation ellipsoid going from infrastructure to suprastructure.

axis (i.e. E-W); in the suprastructure the main direction of extension lies in the cleavage plane perpendicular to the fold axis (i.e. vertical). Between these two kinds of deformation a pattern in the sense of Flinn (1965, p. 38) exists. The intermediate fabric of this pattern in which elongation parallel to and perpendicular to the fold axis are equal (no direction of preferred orientation on the cleavage plane) coincides with the S-tectonite of Flinn's L-S system.

L-tectonites in the sense of Flinn have not been recorded from the Pyrenees. The occurrence of these L-tectonites seems to be restricted to zones of orogenes in which a very great amount of deformation and movement occurred and may be this kind of fabric is related to the B⊥B′ tectonites discussed on page 134. Consequently the occurrence of Flinn's L-S system might be restricted to these zones with a great amount of deformation and movement.

In the Tor valley, one of the valleys of the Vall Ferrera, south of the present area, deformed Cambro-Ordovician rocks occur, in which the elongation in B and a are equal. This could be measured on deformed pebbles. These pebbles are rotation ellipsoids and the kind of deformation represents the intermediate form of the fabric system, found in the Vall Ferrera area. Schroeder (1966) described structures from an area in Ostthüringen (D.D.R.), which are more or less comparable with those of the Vall Ferrera area. Schroeder (1966, p. 80) makes a connection with the occurrence of low dip cleavages ($< 30°$) and zones of negative gravity anomalies. These latter are connected with the occurrence of granites on lower levels. This indicates that in this case also the differences in degree of metamorphism may have caused the differences in attitude of the cleavage planes.

THE SECOND DEFORMATION

Symbols:

cleavage or schistosity plane	s_2
intersection of s_1 and s_2	l_2
fold axis	B_2

Introduction

Folds with N-S trending axes and sub-horizontal cleavages have been found in several parts of the infrastructure of the Central Pyrenees (Zwart, 1960 and 1963). These folds can be seen to deform the main phase folds and hence are younger. The s_2 cleavage usually makes only a small angle with the s_1 cleavage, except in the hinges of s_2 folds.

In the Bosost area this second deformation produced a new schistosity or reactivated the existing s_1 plane. Zwart has proved the shear character of this deformation in the Bosost area (Zwart, 1962) and since in the Aston massif a deformation with the same geometrical properties is found, it seems probable that this second deformation has the same character in the latter massif. This second deformation also occurred in the St. Barthélemy, Castillon and Agly satellite massifs. In the gneisses of these areas strong N-S lineations and folds with N-S axes occur, which may be attributed to this second folding phase.

Description of some second folds

The occurrence of this phase of deformation will be discussed in some detail, because up till now little was known about the presence and distribution of these structures in the western part of the Aston massif. Second folds have amplitudes which vary from some millimetres to some metres. The folds are generally asymmetric, the shape varies from open to isoclinal and they are usually similar; axial plane cleavage is well developed.

Fig. 25 shows an outcrop at 3000 m altitude in the small valley between the Montcalm and Estats summits (subarea 9). Many of such open folds with amplitudes of one or more metres occur in this area, particularly on the steep southern slope of the Montcalm. The folded plane is the s_1 plane. Axial plane cleavage is almost absent as is seen in fig. 26, except for the right side of this figure where a s_2 cleavage is developed. The s_1 cleavage plane dips 80° to the west.

The originally low dipping s_1 planes were rotated to steep attitudes by the second deformation.
In the Sotllo valley many second structures have been recognized. Fig. 27 shows a s_2 fold from an outcrop in subarea 17. A distinct cleavage is developed; the s_2 plane is horizontal and the fold axis trends N 15° E.
In subarea 12 many minor second structures are found. Figure 28 shows an E-W section of a fold with a N-S trending axis. In the thin section it can be established that these folds belong to the second deformation as the s_1 fabric is folded.
In the Aresti valley asymmetrical s_2 folds have been found. In subarea 23, just east of the Lago Aresti, these asymmetrical folds can be studied and it is

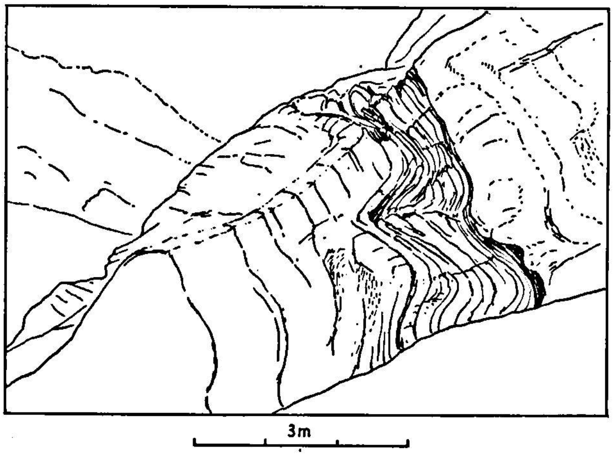


Fig. 25. Second folds, north of Pica d'Estats, subarea 9.

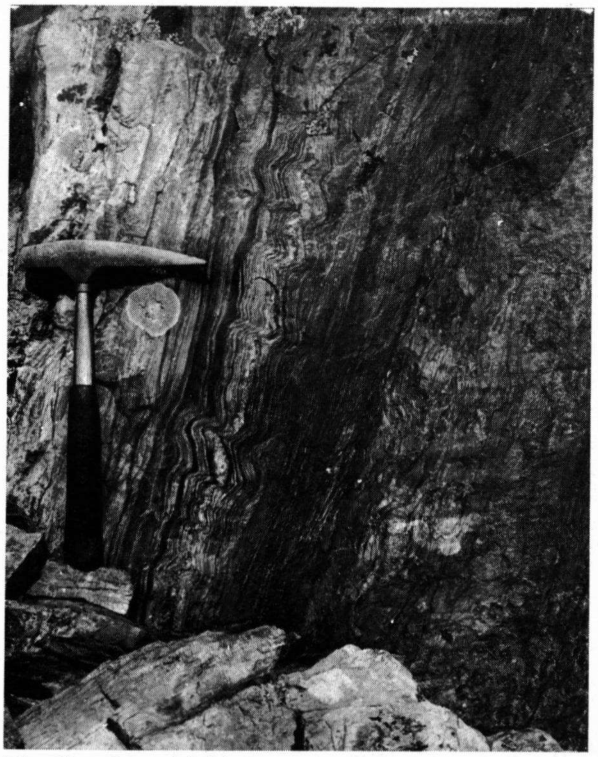


Fig. 26. Second folds, Lago de Barz, subarea 9.

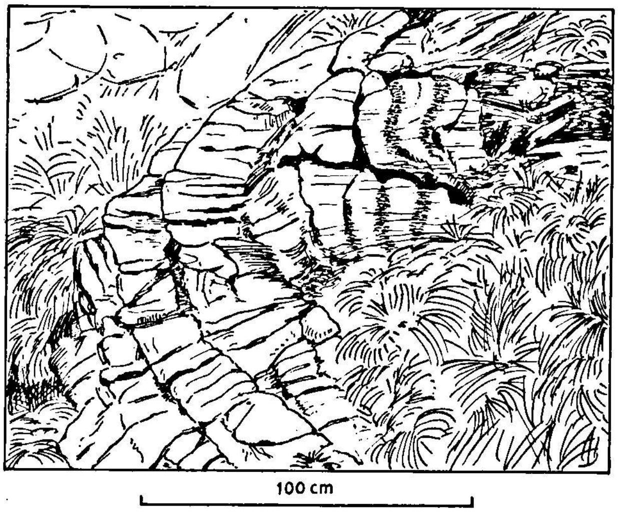


Fig. 27. Second folds with strong recrystallization // to s_2 plane, Sotllo valley, subarea 17.

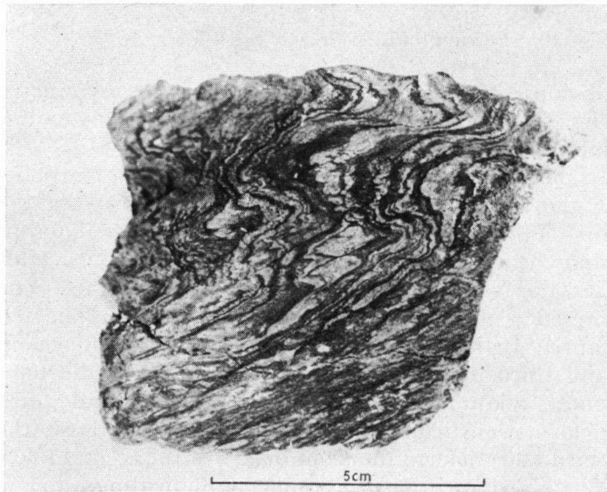


Fig. 28. Second folds in irregularly layered quartzites, Lago Estats, subarea 12.

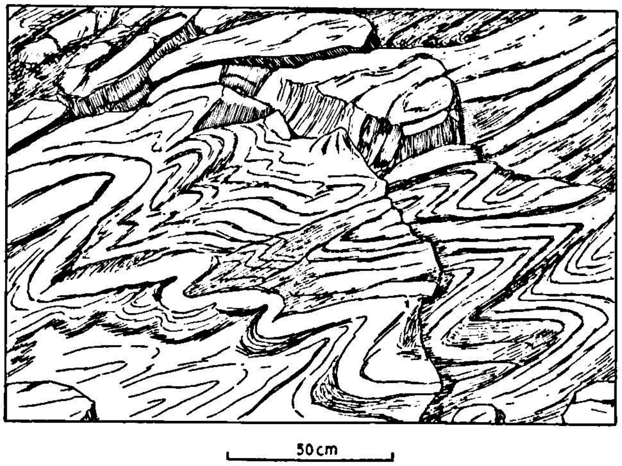


Fig. 29. Asymmetrical second folds, Lago Aresti, subarea 23.

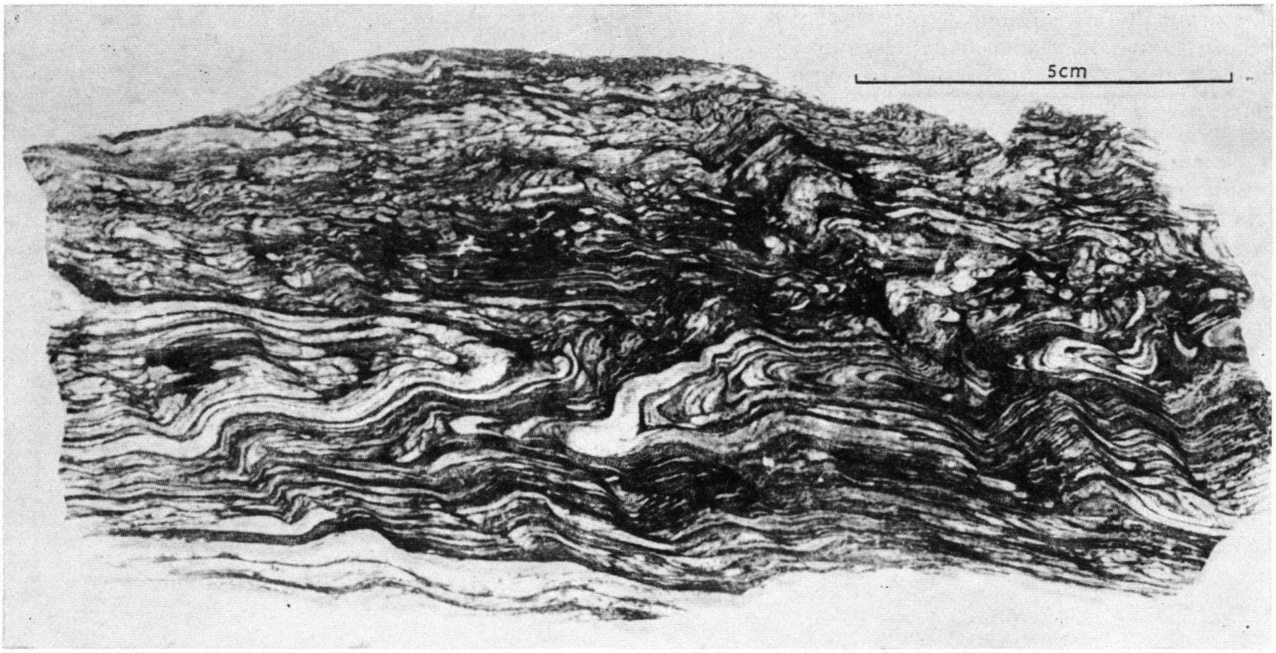


Fig. 30. Second folds, folded by third folds.

obvious that all the folds have the same asymmetry (fig. 29). A relative movement from west to east is indicated.
In the Mounicou valley around Etang de la Gardelle, in the west dipping micaschists of subareas 18 and 23, first and second folds are found. It is in these outcrops that the age relationship, between the E-W first folds and the N-S second phase folds, was established. The presence of third folds gives the rocks a complicated fabric. In fig. 30 the interference pattern of second and third deformation folds is illustrated. The temporal relationship between the second and third deformations can be established here because the third folds deform the axial planes of the second folds. The above mentioned asymmetry, indicating a movement from west to east, is found in most outcrops where s_2 structures occur. In some cases, however, an opposite sence of movement is found. Figure 31 shows an example of such folds from the Mounicou valley in subarea 18.

Fig. 31. Asymmetrical second folds, subarea 18.

Orientation of the B_2 fold axes

The parallel to subparallel orientation and the similar nature of the s_1 and s_2 cleavages makes it difficult to differentiate these S-planes. Both l_1 and l_2 are formed by intersection of bedding and cleavage. The only criterion left are the differences in direction of these two lineations. To show the N-S orientation of the second folds diagram no. 29 was made (fig. 32). A maximum of 12 % is found representing a line that plunges 18° to the north.

Distribution of the second deformation

The detailed survey of the Vall Ferrera revealed that the second deformation is restricted to an area bound-

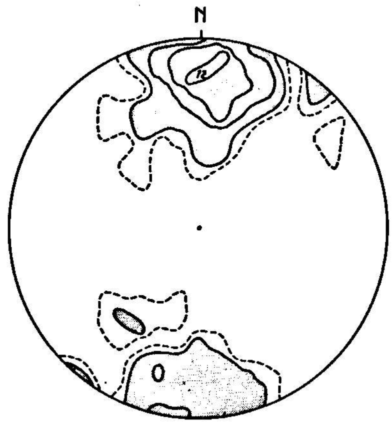


Fig. 32. Diagram, showing orientation of B_2 foldaxes. Contours 1 %, 2 %, 5 %, 8 %, 11 % per 1 % area.

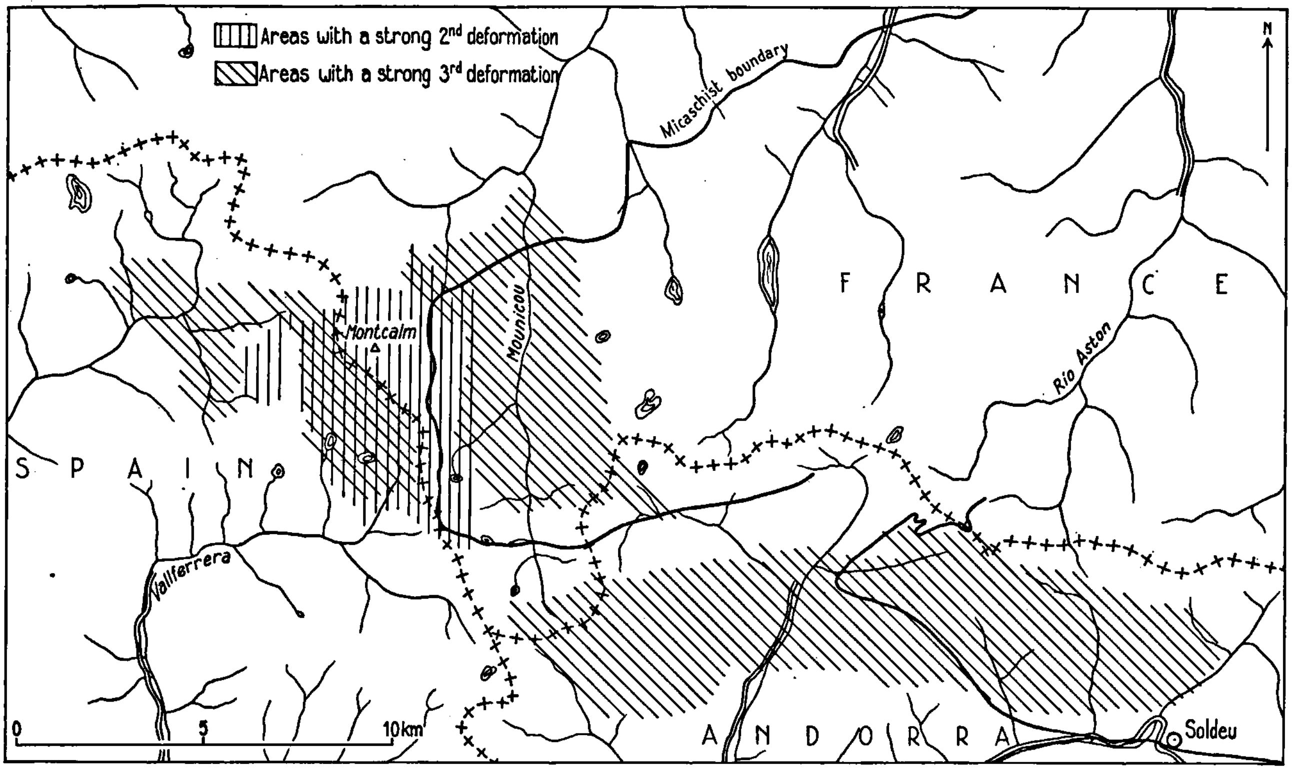


Fig. 33. Distribution of second and third deformation in western part of the Aston and Hospitalet massif.

ed by the Mounicou valley on the east and the Sotllo valley on the west. This N-S trending line more or less parallels the boundary of the micaschists (fig. 33). This distribution of the second deformation along the micaschist boundary, in the transition zone, suggests that there might be a genetic relationship between the second deformation and its occurrence in the transition zone. This presumption is corroborated by the fact that almost all second folds show an asymmetry that indicates a movement from west to east. The line of reasoning is as follows: In the infrastructure the main direction of elongation is parallel to the fold axes (i.e. in an E-W direction). In the suprastructure the direction of elongation is perpendicular to the fold axes and is vertical. Consequently the deformation in the infrastructure produced movement in an E-W direction; in the suprastructure no movement in an E-W direction occurred. This might have caused an "underthrusting" of the infrastructure in a western direction. By this process the folds with N-S axes and the named asymmetry could be formed.

THE THIRD DEFORMATION

Symbols:

cleavage plane of the third deformation	s_3
intersection of s_1 with s_3	l_3
fold axis	B_3

Introduction

The existence of this deformation was first established by J. F. Lapré (1960 and 1965) in the micaschists of the Aston massif in the Mounicou valley, which forms the eastern border of the investigated region. Structures, resulting from this deformation, are also found in other parts of the Pyrenees, e.g. in the micaschist cover of the Aston and Hospitalet massif in the Valle d'Aran (both in the infrastructure as well as in the suprastructure). Furthermore the deformation is reported from the eastern Pyrenees and from some of the north-Pyrenean satellite massifs.

It was made clear by Zwart (1960 and 1963), that this deformation is manifested by a conjugate system of folds, one in the NW-SE direction and one in the NE-SW direction. Therefore the folds of this deformation are shear folds and the cleavage planes of this deformation are shear planes.

It is difficult, perhaps impossible, to establish the shear nature of this deformation in the Vall Ferrera area. However, as stated on page 136, it is probable that this deformation has the same character over some distance in the Central Pyrenees, especially since the micaschist area, where the shear character was established, is the Aston-Hospitalet massif.

The plunge of the intersection of the s_1 plane and the s_3 plane is dependent on the attitude of both planes. Because the attitude of the s_3 planes is rather constant (fig. 34), the variation in plunge and direction of the intersection is dependent on the attitude of the s_1 planes. In the Vall Ferrera region, with its varying attitudes of the s_1 planes, varying plunges and directions of l_3 and B_3 can be expected (map no. 2).

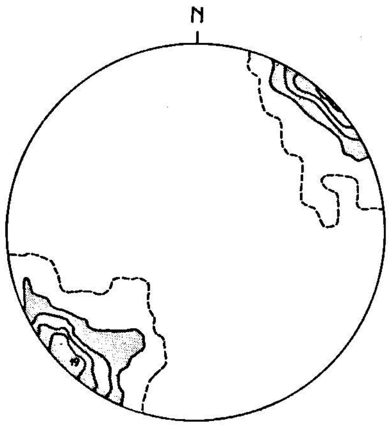


Fig. 34. Diagram, showing orientation of s_3 cleavage, NW-SE set. Contours 1 %, 5 %, 9 %, 13 %, 17 % per 1 % area.

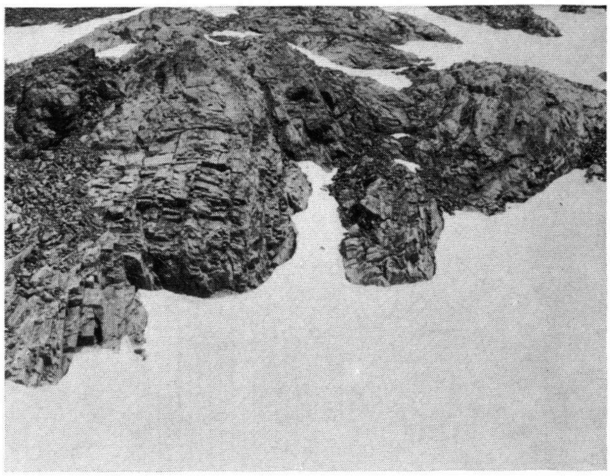


Fig. 36. Third folds and cleavages on the western slope of the Pico de Sotllo; subarea 9.

Description of some third folds

Folds belonging to the third deformation occur in many outcrops in the investigated area. In the western part of the transition zone this deformation occurs more frequently than in the eastern part.

The form of the third folds varies from open to tight. The hinges are in general round. The amplitudes of the folds vary from some millimetres up to several tens of metres, though mesoscopic structures prevail. In some third folds no axial plane is found. On the other hand in other folds a strong axial plane cleavage is developed.

Fig. 35 shows an outcrop in the Circlo de Sotllo (subarea 12) in the centre of the transition zone. The original attitude of the s_1 plane varies from moderate (20°—40°) westward to northward dips (see map 1; the l_3 lineation). The folded surface on this picture is

Fig. 35. Third folds in the Circlo de Sotllo; subarea 12.

the s_1 surface, the s_3 plane is vertical. The fold axis plunges about 20° to the NW.

Fig. 36. These outcrops form a part of the western slope of the Pico de Sotllo (subarea 9) at a height of 2800—2900 m. These rocks originally had a moderate to steep NW dipping attitude; consequently the fold axis is steeper than in figure 35 and plunges 35° to the NW towards the observer. The s_1 plane is easily recognizable; so are the steep s_3 planes and the l_3 lineations.

Fig. 37 shows a third phase structure in the part of the region with steep s_1 planes; consequently the fold axes are steep to vertical. In these quartz-phyllites of the lower Brohate valley the s_3 cleavage is poorly developed as is seen on this figure; the folded surface is the s_1 plane.

In the highest parts of the Brohate valley a distinct s_3 cleavage is found, as can be seen in fig. 38. The folded quartz lenses indicate the form of the s_1 plane, the s_3 plane is the plane parallel to the symmetry plane of the small open folds.

The NE-SW set of the third deformation is usually

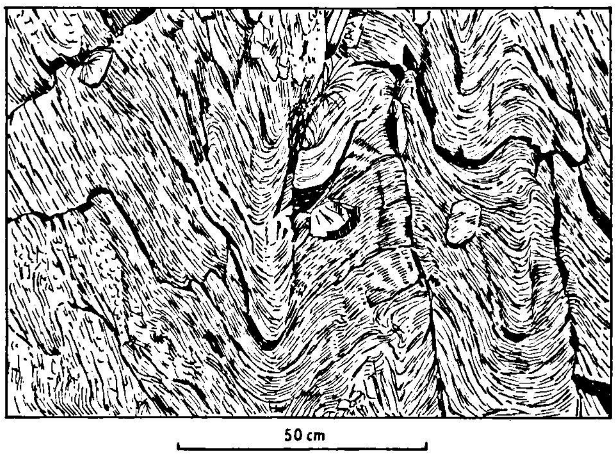


Fig. 37. Third folds with vertical fold axes, Lower Brohate valley; subarea 5.

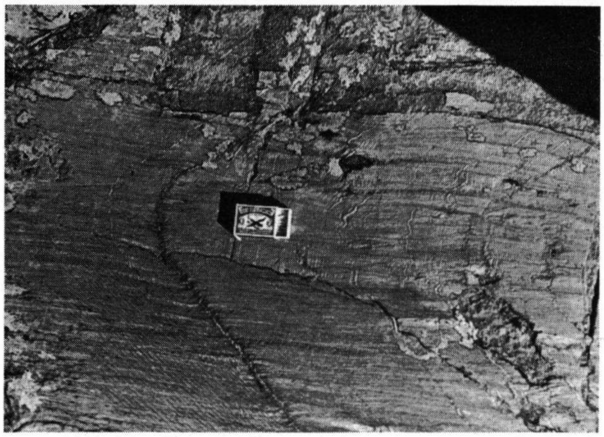


Fig. 38. Third folds with a well developed axial plane cleavage; the lineation on the lower left part of the figure belongs to the fourth deformation; subarea 6.

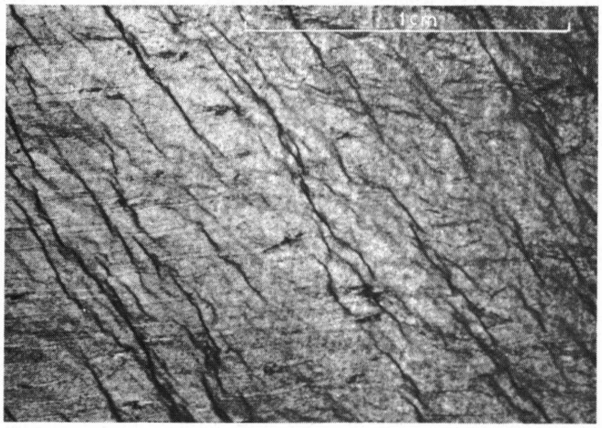


Fig. 41. Development of third cleavage.

Fig. 39. Third folds; NE-SW set of the third deformation; fold axes are vertical; subarea 4.

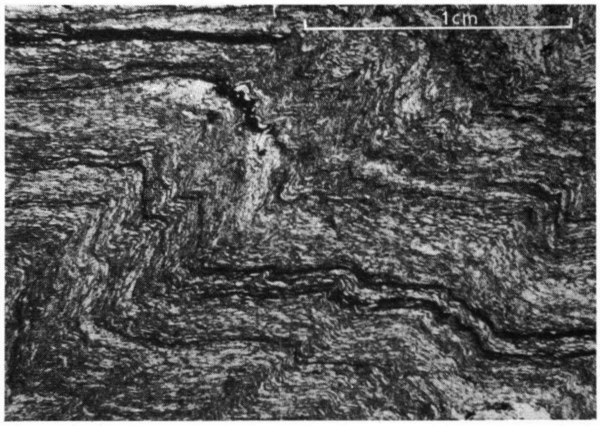


Fig. 42. Third microfolds, producing a crenulation cleavage.

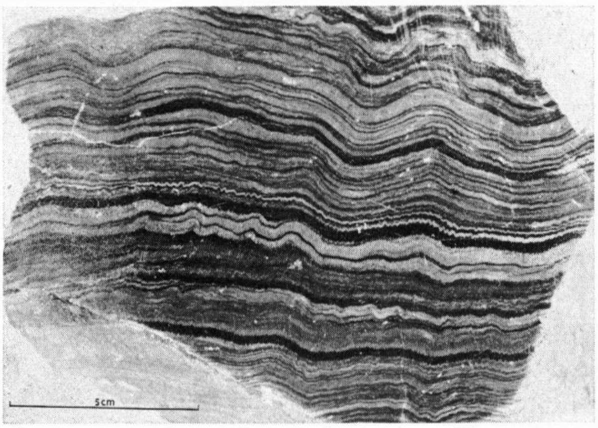


Fig. 40. Small open third folds in a banded quartz-phyllite; Lago Estats; subarea 12.

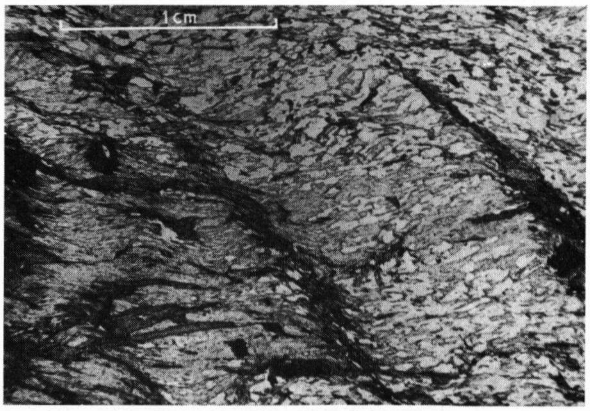
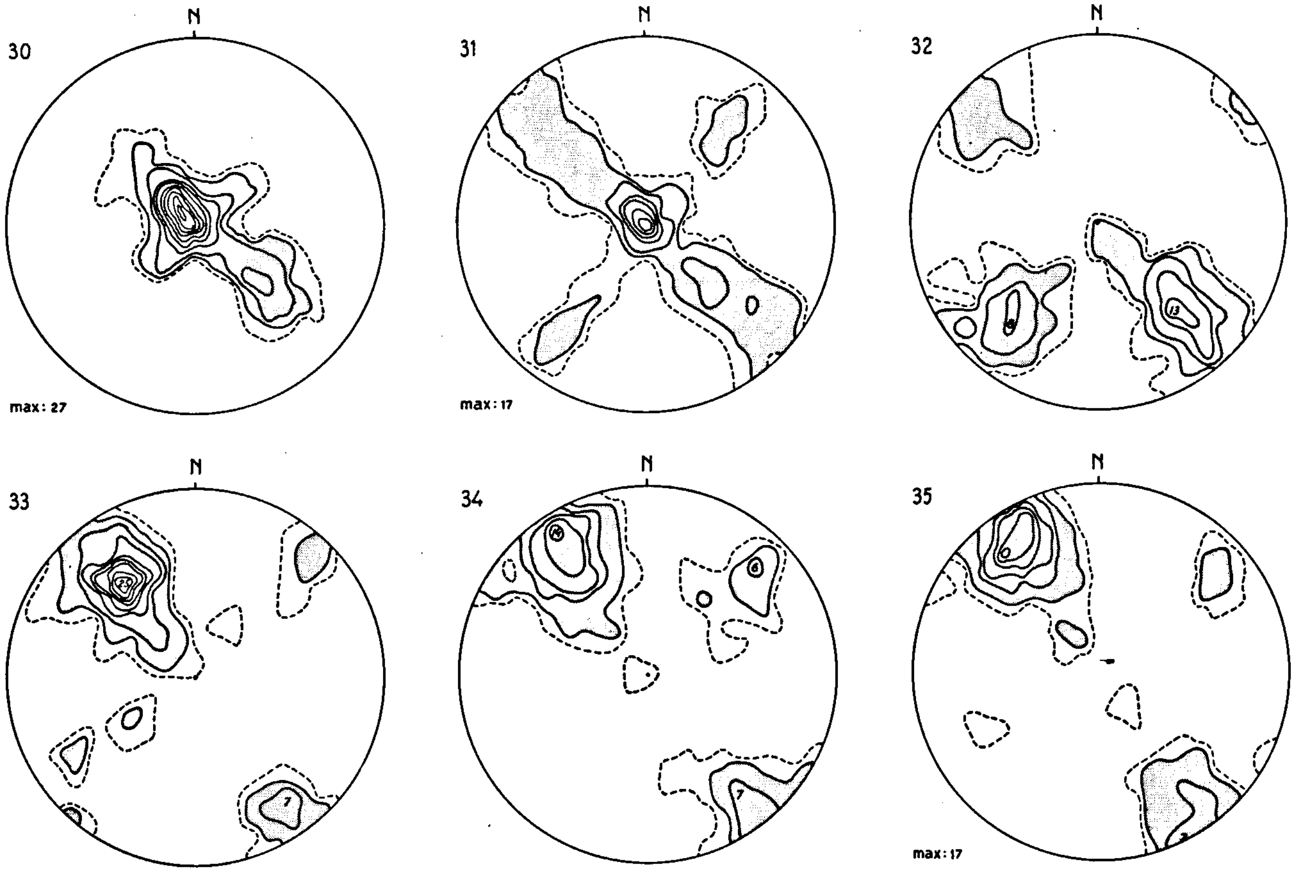


Fig. 43. Development of a tectonic banding in a mica-schist, due to recrystallization of biotite on the third cleavage plane; Etang de la Gardelle; subarea 18.

less frequently found than the NW-SE set. In some parts of the region however, many folds belonging to this set, do occur. In fig. 39 such a fold is represented. These folds are found near the Bohavi flat (subarea 4). The s_1 plane is vertical and so is the fold axis. The folds are seen on a horizontal plane.
Fig. 40 represents a s_3 structure in more detail than the preceeding figures. This is a photograph of a banded quartz-phyllite from the upper Sotllo valley. The open s_3 folds crumpled the s s // s_1 banding into microfolds. Axial plane cleavage is only developed in the micaceous bands.
Fig. 41 shows the development of the s_3 cleavage in the thin section. The s_1 cleavage is unfolded or only slightly folded. The s_3 axial plane traces consist of very small pelitic minerals that crystallised in the cleavage planes of the s_3 deformation.
In fig. 42 the typical microscopic third folds are represented. The s_3 cleavage is a crenulation cleavage; the folded surface is the s_1 surface. The recrystallization along the s_3 planes is not visible on this scale.
This recrystallization is better seen in a third fold in a micaschist (subarea 18) fig. 43. The s_3 plane is indicated by the dark zones in which flaky (micaceous) minerals are crystallized. This process by which a new banding parallel to the s_3 plane can originate, is the same as the one mentioned by de Sitter (1964, p. 313—314).



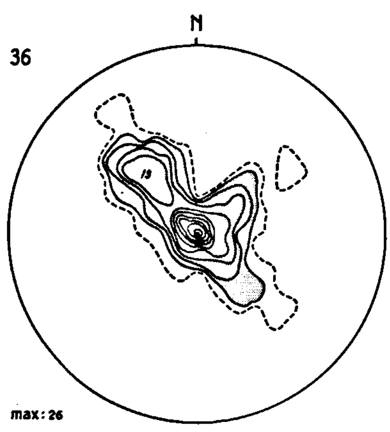


Fig. 44. Diagrams, showing orientation of l_3 lineations. Contours 1 %, 2 %, 5 %, etc. per 1 % area.
no. 30 — subareas 1, 2, 3, 4.
no. 31 — subareas 5, 7, 8.
no. 32 — subareas 10, 11, 16.
no. 33 — subareas 9, 12, 13.
no. 34 — subareas 17, 21.
no. 35 — subareas 18, 23.
no. 36 — subareas 14, 15, 19, 20, 22, 24.

Orientation of l_3 *lineations and* B_3 *fold axes*

To obtain a picture of the attitude of the l_3 lineations and B_3 foldaxes, some hundreds of measurements of l_3 and B_3 were taken. A portion of these measurements is pictured on map no. 1. On map no 2, seven diagrams (each of 100 measurements) are represented in order to give the attitude of these lineations and fold axes in the different parts of the area. On fig. 44 these diagrams are given in more detail. Diagram 30 is made of the measurements of l_3 and B_3 in the subareas around the lower Brohate and Sellente rivers. The s_3 plane has a steep attitude; consequently these lineations and fold axes are steep to vertical. A maximum of 27 % represents a lineation that dips 80° to the NW. A s_3 fold, typical for these subareas, is reproduced in fig. 37.

Diagram 31 represents the attitude of l_3 and B_3 in the centre of the transition zone in the Sellente valley. The original attitude of the s_1 plane varies from northward dipping to southward and southwestward dips. Therefore a whole girdle is found in the NW-SE direction; a partial girdle occurs in the NE-SW direction.

The attitude of the l_3 and B_3 in the southern part of the transition zone is represented in diagram no. 32. Due to the southern dips of the s_1 planes the maxima are found on the southern part of the diagram. It is interesting to notice that on this flank of the s_1 antiform the NE-SW set becomes more frequent.

The three diagrams, no. 33, 34, 35, are made from lineations and fold axes occurring in the more horizontal part of the transition zone, as we can conclude from the attitudes of the l_3 and B_3. These diagrams give approximately the same picture. Their maxima represent lines that plunge to the NW, at 35°, 12° and 20° respectively; these northwestward plunges indicate that in these subareas s_1 planes occur with moderate to low dips, varying from west to north (c.f. the diagrams no. 13, 17, 18 on map no. 2).

Diagram no. 36 represents the attitude of l_3 and B_3 south of the Mérens fault. In this suprastructural part of the Hospitalet massif the s_3 and s_4 structures are less frequently found than in the transition zone. The vertical s_3 plane forms a steep intersection with the s_1 planes, the same picture as in diagram 30.

Interference of first, second and third folds

The relative age relationship between the different deformations can be studied with good result in outcrops showing interference patterns. Fig. 46 shows us the interference of first and third folds (Bohavi flat — subarea 4). The axial plane of the first fold (fig. 46b) is deformed by the third fold (fig. 46c).

On fig. 47 (subarea 12) the interference between the second and third deformation is shown on a subhorizontal plane. The B_2 fold axis plunges 25° to the north. The angle between the s_2 plane and the outcrop surface is about 30°. The third deformation

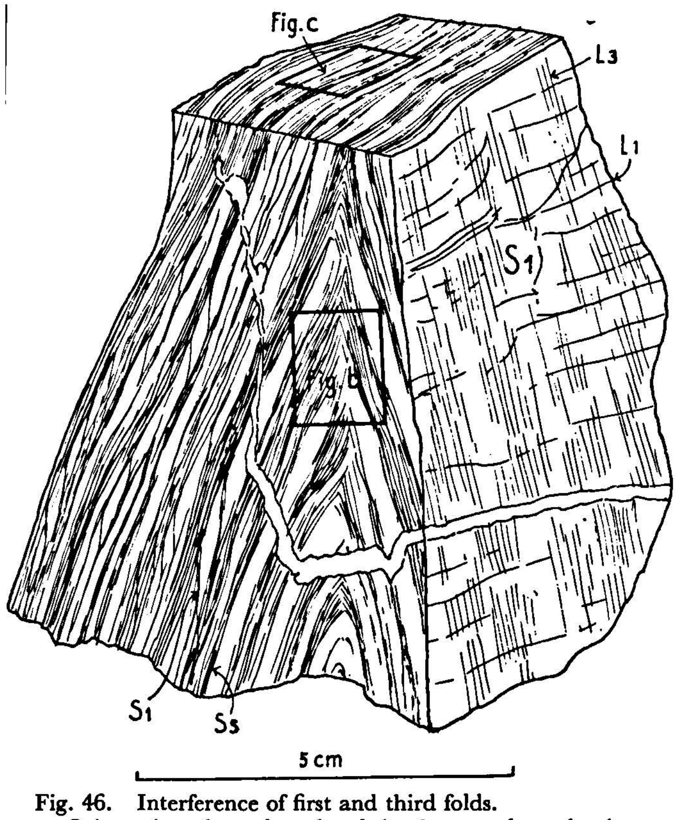


Fig. 46. Interference of first and third folds.
a. Orientation of ss, s_1 l_1 and s_3, l_3 in the sample and orientation of fig. 46 b, c.

b. Detail of the hinge of the s_1 fold. In the core the bedding (ss) is almost obliterated.

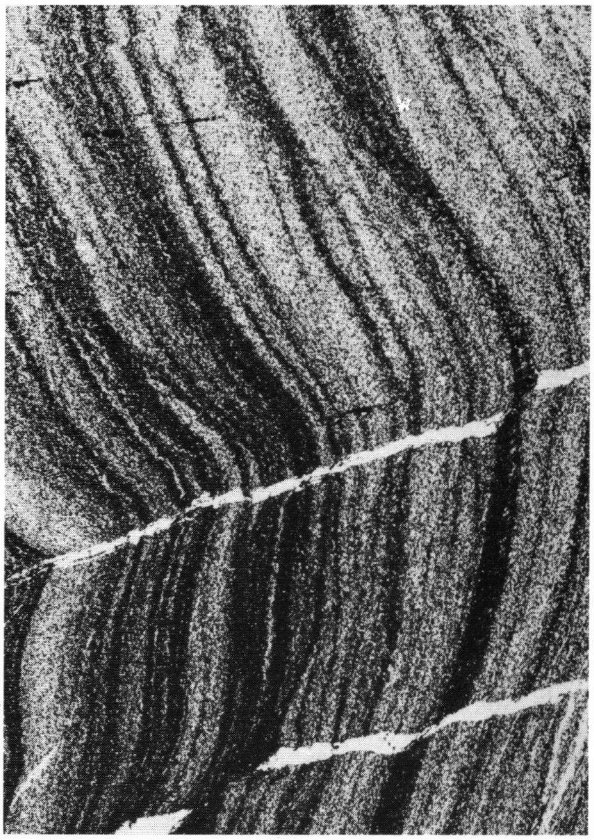
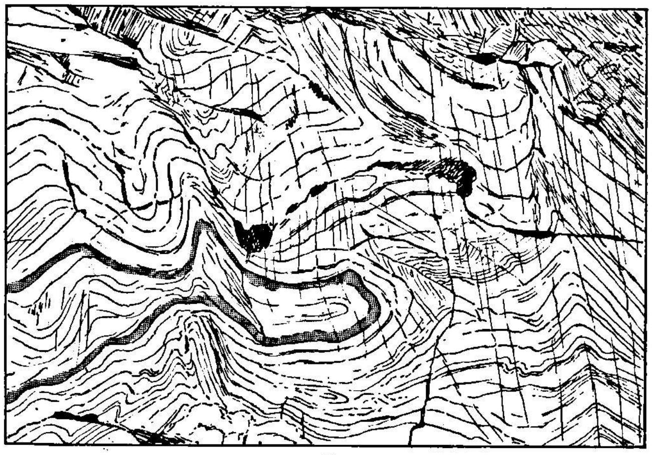


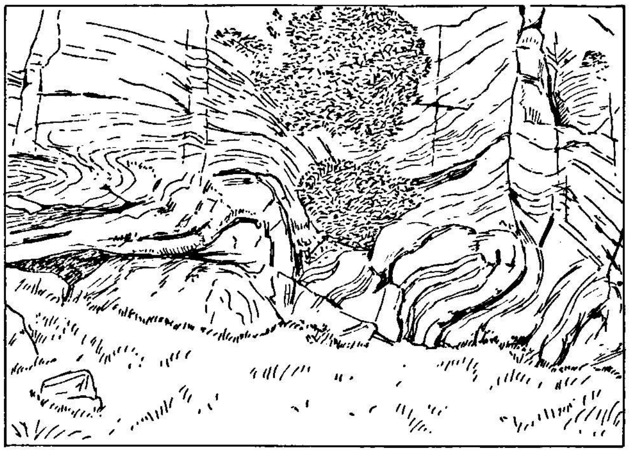
Fig. 46c. Detail of the small, open folds produced by the third deformation.



50 cm

Fig. 47. Interference of second and third folds seen on a sub-horizontal surface; subarea 12.

produced a vertical cleavage plane; consequently the third folds deform the second folds. On fig. 48 the same interference is found (Pla de Socalma — subarea 17), but now seen on a vertical plane looking in a southern direction. The B_2 fold axis makes an angle of 45° with the outcrop surface. The B_3 fold axis is perpendicular to the outcrop surface.



1 m

Fig. 48. Interference of second and third folds, seen on a vertical plane, looking in a southeastern direction; subarea 17.

Distribution of the third deformation

In fig. 33 the distribution of the third deformation is given. The detailed survey of the area revealed the fact that the s_2, s_3 and s_4 deformations occur in certain zones of the region; this distribution is different for each deformation.

To construct a map of the distribution of the third deformation is a difficult task. On map no. 1 this deformation seems to occur all over the discussed area. However, certain zones can be recognised in which the s_3 deformation is strongly developed; in some cases the older structures have almost been obliterated (for example a zone east of the Pico de Llats). It is these zones that are represented on the distribution map.

As has been noticed the variation in plunge of the fold axes and lineations is caused by the variation of the attitudes of the s_1 planes in the transition zone. As postulated by Zwart (1963), this deformation was caused by an E-W compression. It is peculiar to note that in spite of the fact that the NW-SE set occurs more frequently than the NE-SW set, the general picture is still rather symmetrical with regard to the E-W axis of the mountain chain. In the present author's opinion it is impossible to detect the whole effect of the third deformation on the preexisting structures.

It is possible that as in the case of the second deformation phase, the third is connected with the presence of local stress fields caused by differences in the style of deformation between the infrastructure and the suprastructure.

THE FOURTH DEFORMATION

Symbols:

cleavage plane of the fourth deformation	s_4
intersection of the s_1 plane with the s_4 plane	l_4

Introduction

This deformation is the last of the refolding phases found in the Central Pyrenees and is also called the E-W refolding phase, indicating the E-W strike of the cleavage plane belonging to this deformation. As is seen on the deformation scheme the cleavage planes of these folds strike E-W and has a vertical attitude. The amount of plunge of the fold axis and the l_4 lineation is dependent on the angle between the s_1 and the s_4 plane. As the strikes of both deformations in general are E-W, the fold axes in most outcrops are almost horizontal.

In the Cardos valley, near the village of Arahos, outcrops with microfolds of the Cambro-Ordovician, forming a part of the Pallaresa-Salat antiform, occur. It was in these outcrops that for the first time in the Pyrenees the fourth deformation was recognized (de Sitter, 1954; Zwart, 1963).

The geometrical properties of this deformation are constant over a large part of the Central Pyrenees, and due to this fact, the time relationship of this deformation with other deformations, established in the higher metamorphic parts of the Aston and Hospitalet massif, is valid in the Vall Ferrera area. Zwart established the time relations of the different refoldings in the higher metamorphic areas, where deformational and metamorphic events can be used as time markers. Zwart (1963 and 1965), Verspyck (1965) and Lapré (1965) described this deformation in the Aston and Hospitalet massif.

Furthermore this deformation has been found in the region of the Lys-Caillaouas granodiorite (Wennekers, 1964); in the north Pyrenean massifs and the Canigou massif.

In the southern Pyrenees (Roberti, internal report, 1965) a refolding is found with E-W axes, but with a moderately dipping cleavage plane (50°) to the north. A correlation of the fourth deformation in the Central Pyrenees with these structures is difficult, since in the southern Pyrenees this refolding is restricted to some zones and no continuous distribution is found. It is possible, however, that these refolded structures, found in these southern parts of the Pyrenees, belong to the same deformation as the fourth structures in the Central Pyrenees.

In the western part of the Aston massif, this deformation is found in many outcrops, both in the micaschists as well as in the phyllites.

In the Pallaresa-Salat antiform the fourth deformation occurs in a few small areas: one of these forming the outcrops of Arahos (see above). The reason for this distribution may be found in the fact that in areas with a steep s_1 plane this deformation did probably not produce folds, but used the s_1 planes for further flattening.

In the micaschists and the transition zone with their flat and westward dipping s_1 planes, the s_4 deformation produced many folds. A description of a few examples, as they are found in the region, is given. Fourth folds have amplitudes which vary from some millimetres to some tens of metres; the general foldsize varies from some centimeters to some decimetres. Most fourth folds are accordion folds with sharp hinges and straight flanks, although aberrant fold forms are found. Axial plane cleavage is in some cases absent, but mostly well developed.

Description of some fourth folds

The best examples of the fourth deformation are unboubtedly found in the higher part of the Aresti valley (524; 40) (subareas 13, 18). In the outcrops forming the ridge between Spain and France, folds with amplitudes varying from some tens of metres to folds on microscopic scale, are found. The axes of these folds plunge about 40° to the west (map no. 1), being down- dip the s_1 planes (fig. 49). The effect of these folds on the original structure is seen in diagram 18 and map no. 1. The original westward dipping s_1 planes are turned to southwest and northwest positions. The s_4 cleavage plane is well developed. This cleavage is, as will be clear, of the crenulation cleavage type (fig. 4).

In France, just north of the Port Vell, the outcrop represented in fig. 50 is found at a height of 2100 m. The accordion folds (de Sitter, 1956, p. 312) typical of this deformation, are well developed in this outcrop. The folds are seen on vertical N-S striking surface; the fold axes plunge 25° to the west.

In the upper part of the Brohate valley (subarea 6) interesting fourth folds are found. In some of the outcrops folds with amplitudes up to several tens of metres and a distinct axial plane cleavage occur (fig. 51). The attitudes of the fold axes and cleavage planes clearly indicate that these folds belong to the fourth deformation, a conclusion that is fortified by the study of thin sections of these folds. The s_4 cleavage is well developed; the older structures are difficult to recognize.

In the lower part of the Brohate valley steep s_1 planes occur, which deviate in strike from the E-W direction; consequently the fold axes of the refoldings are steep too. Fig. 52 shows us an outcrops with fourth phase

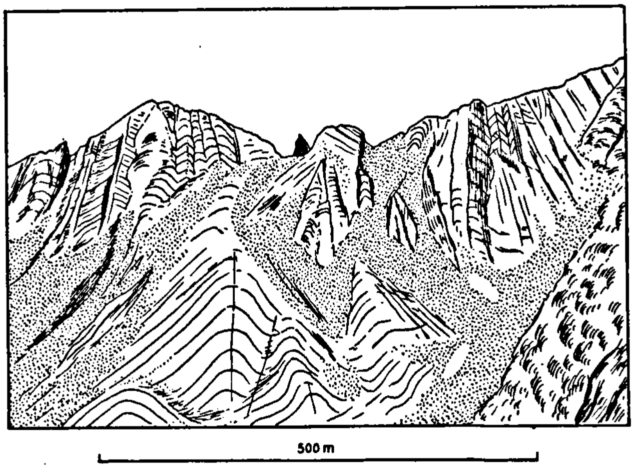


Fig. 49. Fourth folds on the eastern slope of the Aresti valley, subarea 13, 18.

folds with vertical fold axes. The exposed surface is about horizontal. A cleavage (the s_4 cleavage) is developed in the axial plane although its traces are not well visible.

In fig. 53 and 54 remarkable s_4 folds are shown. Fig. 53 represents a specimen found on the ridge between the Pico de Canalbona and the Pica d'Estats (subarea 9). The folded surface is the s_1 cleavage. We notice that in the axial planes of the accordion folds no cleavage is developed. Such folds are typical of the s_4 deformation. Fig. 54 is taken from a specimen located in subarea 23. In this example a distinct s_4 cleavage is developed in the pelitic parts. We notice that in the s_4 folds the tightness varies from open to isoclinal. In the upper right portion of the figure the s_4 cleavage has obliterated the older s_1 cleavage planes. The s_4 cleavage is a crenulation cleavage.

Fig. 50. Fourth folds, north of Port Vell; subarea 23.

Orientation of l_4 lineations and B_4 fold axes

In order to get an idea of the attitude of the s_4 plane, the l_4 lineations and the fold axes, some diagrams of measurements of these structural elements were made.

First we wish to discuss diagram 44 (fig. 55), made from a hundred measurements of s_4 planes, collected

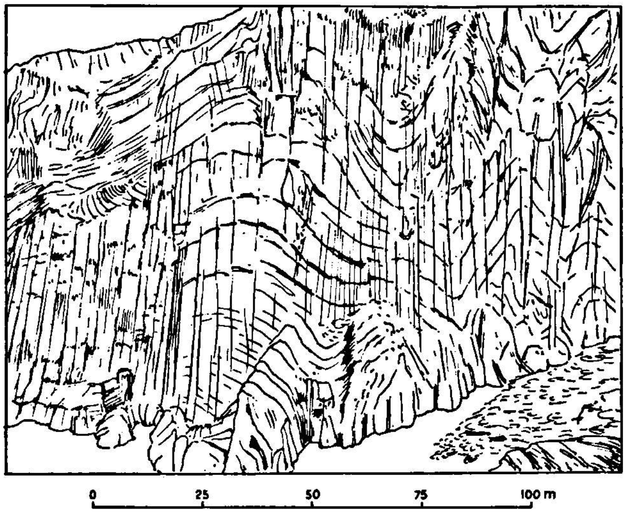


Fig. 51. Fourth folds with strongly developed axial plane cleavage. Rio Brohate; subarea 6.

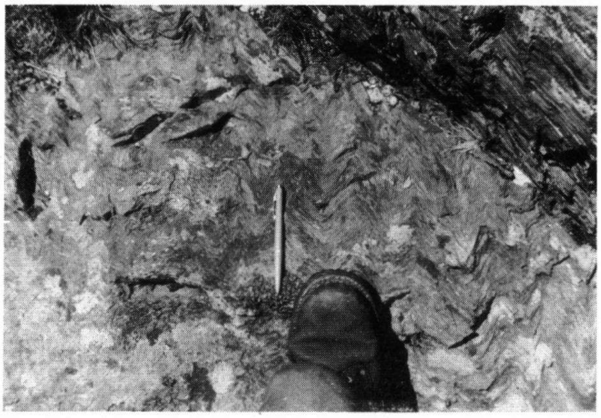


Fig. 52. Fourth folds with vertical axes, Rio Brohate; subarea 5.

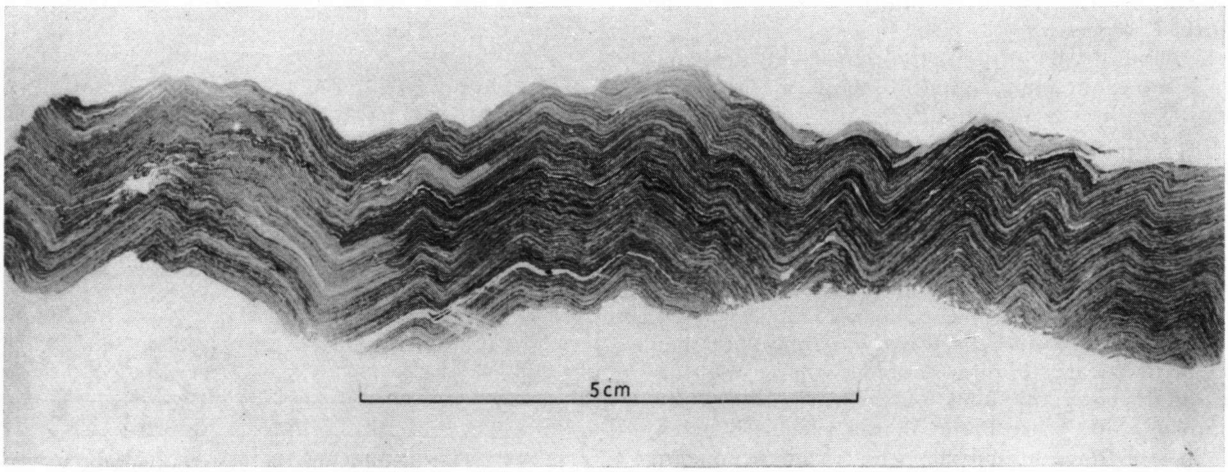


Fig. 53. Fourth, accordion type, folds; subarea 9.

Fig. 54. Fourth folds in banded phyllite; in the upper right part of the figure the ss and s_1 are almost oblitared and the s_4 is developed.

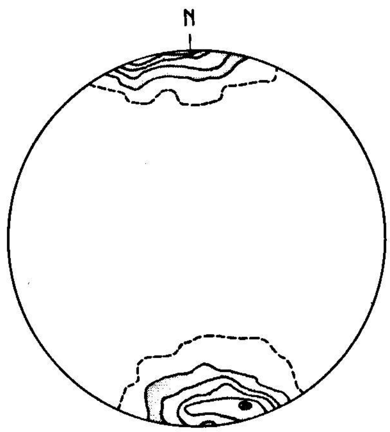


Fig. 55. Diagram showing the orientation of the s_4 cleavage planes in the Vall Ferrera area. Contours 1 %, 2 %, 5 %, 8 %, 11 %, etc. per 1 % area.

all over the region. This diagram shows us the steep attitude of the s_4 planes; the maximum of 25 % represents a plane that dips 80° to the north. A small variation about the E-W strike is present, but as a whole the attitude of the s_4 plane does not vary much over the area. This is what one should expect of the attitude of the cleavage plane of the latest Hercynian deformation occurring in the Central Pyrenees.

Furthermore three diagrams were made of the attitude of the B_4 fold axes and the l_4 lineations (fig. 56):

Diagram 40 is constructed out of measurements collected in subareas 5, 6, 7, 10, 11. In these subareas the western border of the transition zone is found. In this diagram almost a whole girdle, indicating the different plunges of the l_4 lineations is present, but as these subareas are located in the western dipping s_1 structures, the maximum of 18 % represents a line that plunges 35° to the west.

Approximately the same distribution is found in diagrams 41 and 42. Diagram 41 is constructed of measurements out of subareas 9, 12, 17 and 22. These subareas are located in the middle of the transition zone and because in these subareas many s_3 structures are folded by s_4 structures, a whole girdle in the s_4 plane is present. This is caused by the fact that a part of the measurements were made on the hinges of s_3 folds. Depending on the place on the fold, the l_4 lineations plunge to the west or to the east.

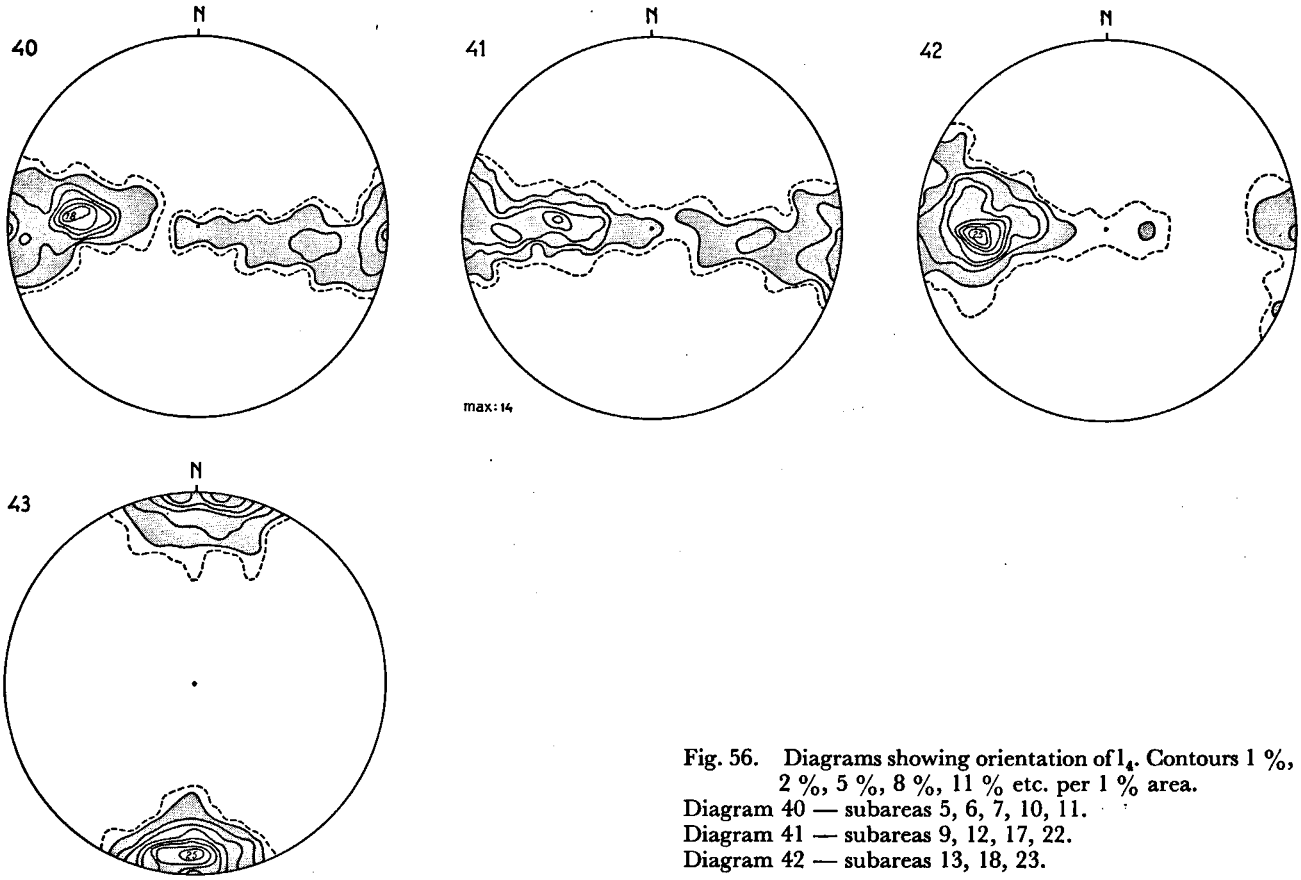


Fig. 56. Diagrams showing orientation of l_4. Contours 1 %, 2 %, 5 %, 8 %, 11 % etc. per 1 % area.
Diagram 40 — subareas 5, 6, 7, 10, 11.
Diagram 41 — subareas 9, 12, 17, 22.
Diagram 42 — subareas 13, 18, 23.

In diagram 42 a maximum of 25 % is found, representing a line that plunges 30° to the west. Most of these measurements were made in the outcrops mentioned in fig. 49, and as one notices in this diagram, only a few eastward plunging l_4 lineations are found. Interference structures like the ones mentioned in subarea 17 (diagram 41) are rarely found.

The similar character of the s_4 folds can be detected by studying the interference pattern of the s_3 and s_4 folds. This pattern can be studied in the field by measuring in detail the exposures in which both deformations interfere. The same result is obtained by collecting all data of the two deformations and by putting them into the same diagram.

To explain the above reasoning, fig. 57 was made. It shows us the theoretical possibilities on the diagram of the interference pattern (Ramsay, 1963).

As case d of fig. 57 agrees with the pattern found in the field data, the fourth folds have a similar character.

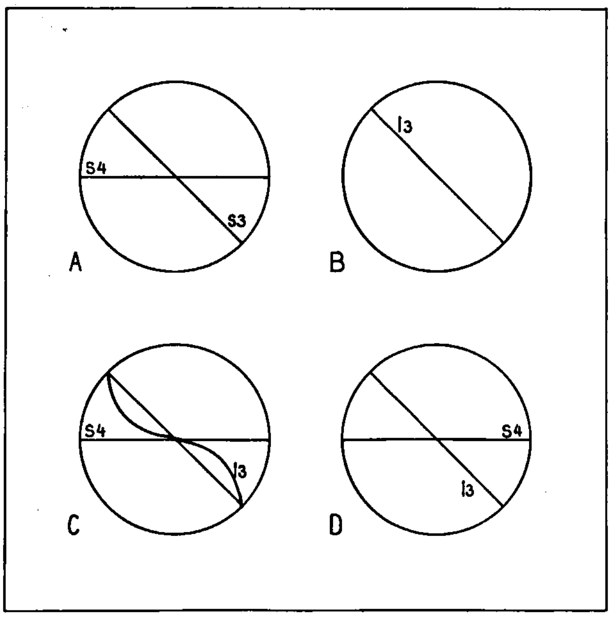


Fig. 57. a. Diagram showing orientation of s_3 and s_4
b. Diagram showing orientation of the locus of l_3
c. Diagram showing orientation of the locus of l_3 folded by flexural s_4 folds.
d. Diagram showing orientation of the locus of l_3 folded by similar s_4 folds.

CONCLUSIONS

The survey of the Vall Ferrera area learned us that in this part of the Central Pyrenees a transition is found between low grade rocks with a vertical cleavage plane (suprastructure) and medium to high grade metamorphic rocks with a subhorizontal cleavage plane (infrastructure).
The first thing to establish was the relative age-relationship between the structures in the infrastructure and the suprastructure. There has been found evidence that these structures have developed simultaneously and were formed by a stress field with its direction of maximum principal stress N-S. This being established we have tried to detect the differences and similarities in deformation between the suprastructure and the infrastructure (table II). Some comments may be added to this table. Let us first consider the differences in deformation.
In the first place there is a difference between the mechanical significance of the cleavage planes in the suprastructure and the infrastructure. The observations of Zwart (1963, 1965) in the metamorphites of the Aston and Hospitalet massifs and in the Bosost area indicate that the cleavage plane in these rocks (metamorphites) is not merely a plane of flattening, but also a plane of movement, thus a monoclinic fabric was produced.
On the other hand the observations in the lower grade rocks of the Central Pyrenees indicate that the cleavage plane is a plane of flattening and that little or no movement occurred along these planes during the first deformation; these structures have an orthorhombic symmetry.
Possible explanations for the disharmonic configuration, produced by the first deformation, must be sought in the changing metamorphic conditions and the differences in confining pressure going from the suprastructure to the infrastructure.
In the western part of the Aston massif the boundary between structures with monoclinic and orthorhombic symmetries is situated along the biotite isograd. Hoeppener (1962, 1964) discussed the occurrence of fabrics with different symmetries and his remarks from a physical-tectonic point of view agree with our observations: the occurrence of monoclinic fabrics in the deeper and warmer part of the earth's crust is caused by the greater influence of frictional forces (Hoeppener, 1962, p. 225). Under the higher temperatures and consequently the lower friction below the biotite isograd, a shearing could develop in the infrastructure.
The differences in confining pressure were discussed by Zwart (1963, p. 203). He suggested that in the flat lying metamorphic rocks, extension in a vertical direction is not probable, due to the horizontal attitude of the s_1 planes. This in spite of the fact that the recumbent s_1 folds are stacked on top of each other, thus indicating a thickening in vertical direction, but this must have been partly compensated by a flattening of the rocks with an extension in E-W direction. The disharmonic configuration is determined both by changing metamorphic conditions (temperature) and by the presence of the suprastructure on top of the infrastructure.
The occurrence of the refoldings in the Vall Ferrera area.
The strong development in the transition zone of the second and third deformation indicates, that a genetic relationship between this zone and the stress fields, that produced the second and third deformation, may exist. As was discussed on page 149, the distribution of the second deformation in the discussed area seems to be restricted to a zone adjacent and parallel to the micaschist boundary (fig. 33). The distribution may have resulted from the difference in extension in the E-W direction during the first deformation in the transition zone.
As the third deformation is also caused by a stress field with an E-W directed maximum principal stress and as this deformation is also strongly developed in the transition zone, the same relationship might occur.
The idea that all Hercynian deformations of the Central Pyrenees were caused by or derived from the main N-S stress-field (Zwart, 1963, p. 202) is fortified by our observations.
It is interesting to note that the first deformation in the infrastructure and the second deformation have the same character; we might call them "metamorphic" deformations. Both produced asymmetrical folds, and a mineral orientation parallel to the fold axis, and both deformations are manifested by shear planes. This indicates that during the first and second deformation the temperature conditions did not change much. During the third and fourth deformation the metamorphism decreases in this part of the Pyrenees: the fourth deformation has the same character both in the infrastructure and in the suprastructure.

TABLE II

Characteristic differences between infrasructure and suprastructure during the first deformation (Aston Massif, Central Pyrenees)

	Infrastructure	Suprastructure
zone of metamorphism	mesozonal-katazonal	epizonal
attitude of cleavage	sub-horizontal	vertical
attitude of fold axis	horizontal E-W	horizontal E-W
direction of main elongation	horizontal E-W	vertical
nature of cleavage plane	flattening + shearing	flattening
symmetry of deformation	monoclinic	orthorhombic

EXCURSION No. I

Start and finish on the Bohavi flat; *duration* 8 h. *Requirements*: Topographic map of France Aulus no. 7 and Aulus no. 8 1 : 20 000 and the map no. 1 and 2 of this paper.

This excursion should only be made under good weather conditions. This excursion takes us along the northern part of the transition zone. In this part many second, third and fourth phase folds occur.

Leave the car at the end of the road on the Bohavi flat and walk to no. 1 near the provisional bridge over the river.

No. 1 the vertical s_1 cleavage is folded by the third deformation; intersection of s_1 and s_3 is vertical. s_3 folds with amplitudes varying from some decimetres to some millimetres.

Cross the river and walk up the path in the forest. At 1700 m we come to a little meadow; here we cross the Sellente river and go up the southern slope of the Brohate valley. The path is indicated by painted stones. Before entering the bush, be sure to follow the path. On this path, that follows the southern slope of the valley, nice outcrops of the s_3 and s_4 deformation are found; all folds have vertical folding axes (*no.* 2).

At 2100 m the valley sides become flatter and no longer a path is found.

At 2150 m we turn to the south and ascend the south-

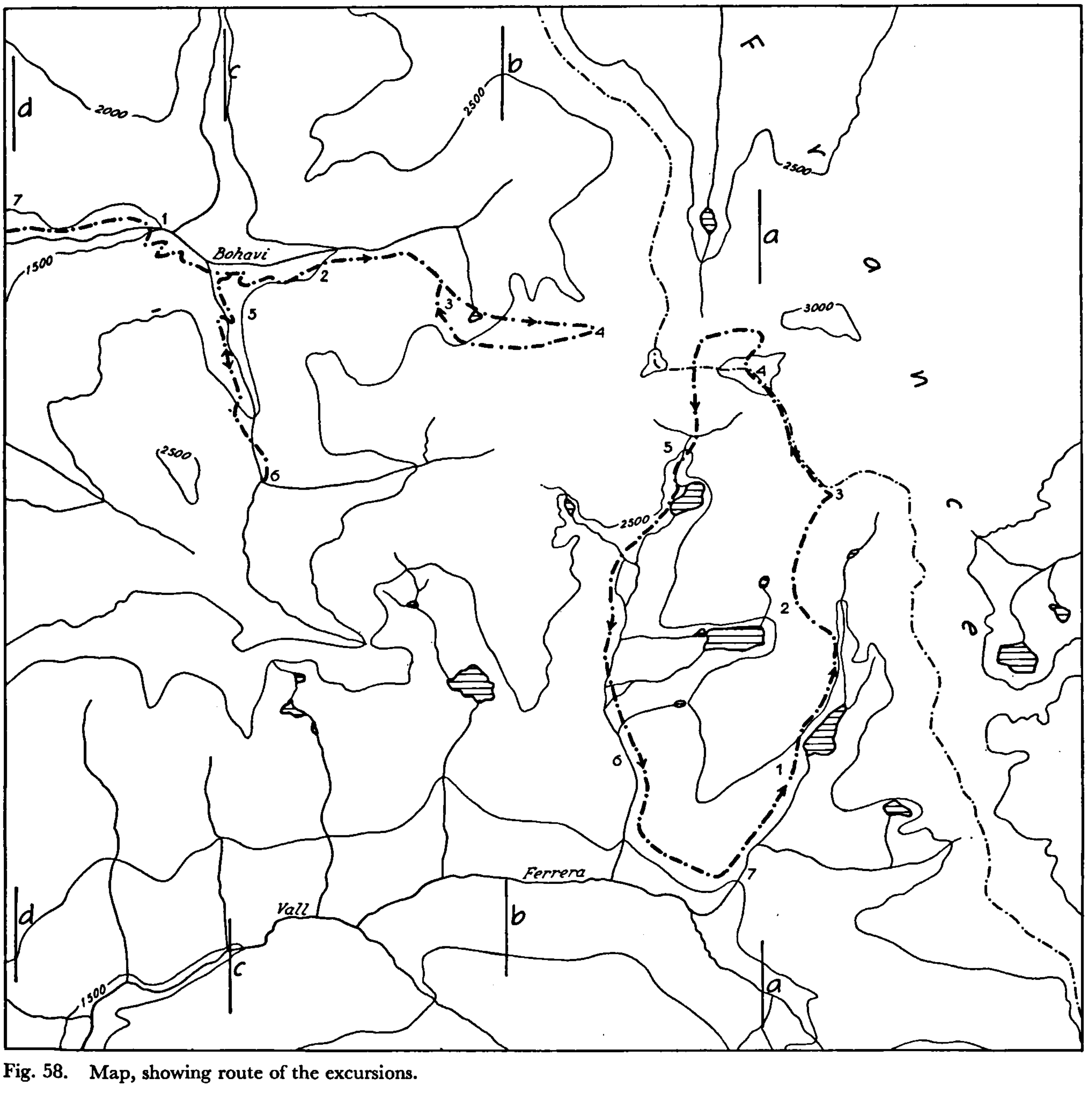


Fig. 58. Map, showing route of the excursions.

ern valley until the little lake (no. 3). Going up this hill side we see many s_3 folds with vertical axes and good developed s_3 cleavage planes.

We pass this lake along the northern side and go up the valley in the direction of the Pico de Sotllo. This route offers us the gradual change in attitude of the s_1 planes and consequently in the change of plunges of the l_3 and l_4 lineations.

No. 4 At 2700 m in a small pass on the ridge to the frontier ridge we have a good view on the western dipping s_1 planes, west of the *Pico de Sotllo.* The l_3 lineations dip about 30° to the NW.

On our way back we follow the southern side of this valley and in some outcrops folds with N-S axes and sub-horizontal axial planes are found (second deformation).

Near the little lake (no. 3) we pick up the track and walk back to the meadow near the Sellente river at 1700 m. If there is enough time left we can make a walk along the track following the Sellente river.

No. 5 These outcrops are located in the steep north part of the transition zone. Going from no. 5 to no. 6 we notice a gradual change in the attitude of the s_1 planes as we talk through the centre of the transition zone (map no. 2).

No. 6 These outcrops are located on the southern flank of the transition zone: southern dipping s_1 planes occur.

EXCURSION No. 2

Start and finish: 3 km N of Areo in the Vall Ferrera; at the end of the road. *Duration*: a day and a half; the night can be spend in the "Refugi lliure de Vall Ferrera". *Requirements*: Topographic map of Ramón de Semir de Arquer; scale 1 : 37 500 edited together with the guidebook "Vall Ferrera" at the "Editorial Alpina"-"Granollers" (segunda edicion, 1953) and the maps no. 1 and 2 of this paper.

This excursion takes us along the eastern portion of the transition zone and along the area south of the Mérens fault.

Leave the car 150 m N of the first bridge N of Areo and walk along the track (marked with red painted sign posts) to the "refugi" located at the northern side of the valley at 1940 m (duration 2 h.).

At five or six in the morning (watch carefully weather conditions) we leave the "refugi" and walk up the Aresti valley (keep clear of the Aresti river and follow the meadows on the western slope).

No. 1 Mérens fault. On our way we notice the steep attitude of the s_1 planes (Hospitalet massif). Approaching the fault many folds with different fold axes and axial planes are found. This zone is most probably connected with the movements along the Mérens fault. The precise location of the fault is difficult to establish. Going to the north we come into the transition zone. The sub-horizontal attitude of the s_1 planes, though masked by many fourth folds can be seen on the glacially eroded outcrops south of the Aresti lake.

We pass this lake along the western side and walk up the valley until the little pass to the Sottlo valley is west of us and go up the grass slope to the pass (2690 m).

No. 2 Looking to the east we see on the frontier ridge many fourth folds with amplitudes of some tens of metres and the fold axes dipping 30° to the west. We follow our way to the Pico de Canalbona (2959 m).

No. 3 Pico de Canalbona. From this point we have a good view into the Rio Fret with its westward dipping s_1 planes. On the lower part of the Rio Fret micaschists and pegmatites can be seen. From this Pico we follow the crest to the Pica d'Estats or take a track along the southwestern slope. Along this route, examples of the four deformations, occurring in this part of the Central Pyrenees, are found.

No. 4 Pica d'Estats on the sharp summit a strong s_3 cleavage is developed. We walk back along the "classic" track indicated in the guidebook. We go down into France until the little pass between "Pica d'Estats" and "Pico de Montcalm" turn to the west and descend to the little lake (Lago de Barz) and turn to the south and go up the "Puerto de Sotllo" (2890 m), and go down to the "Lago de Estats".

No. 5 Lago d'Estats. In the outcrops around this lake many outcrops with second and third folds are found. The moderate plunge of the third folds indicate the initial moderate dips of the s_1 planes. Along the track down to the main valley many second, third and fourth folds can be seen, especially just north of the Mérens fault.

No. 6 Pla de la Socalma. On the western slope the presence of the Mérens fault is indicated by a straight gully on the ridge of the Pico de Llats. On the eastern slope the fault can also be followed. Near the ridge the fault flattens over a small distance. We follow the track on the east side of the river at 2100 m and come at the red iron sign post above the "refugi" and descend along the path to the road above Areo.

RÉSUMÉ

Dans la région explorée, il se trouve la transition entre deux types de roches, l'une avec une métamorphisme hercynienne, épizonale (qui forme la suprastructure), l'autre avec une métamorphisme hercynienne, mésozonale (formant l'infrastructure). La première déformation, contemporaine avec la métamorphisme, a formé un clivage schisteux sub-horizontal dans les zones mésozonale. On trouve des indications que ce clivage est un plan de mouvement et d'aplatissement. A l'opposé de ceci, cette déformation a formé dans les zones épizonales un clivage schisteux et sub-vertical (ce clivage est un plan d'aplatissement). Dans la "Vall Ferrera" la transition entre les deux attitudes de clivage a une caractère graduelle. La transition occupe une région de 7 à 5 km. L'orientation et la forme de l'éllipsoide déformationelle des fabriques de la première déformation montre que dans les régions avec un clivage sub-horizontal, l'axe plus longue est orienté dans le sens E-W, situé parallèlement aux axes des plis (B-tectonites); tandis que dans les régions

avec un clivage sub-vertical, l'axe plus longue est orienté verticalement et perpendiculairement aux axes des plis (a-tectonites). Dans la "Vall Ferrera" on trouve une transition graduelle du B-tectonites aux a-tectonites. La première déformation s'est formée par une force orientée dans le sens N-S.
La première déformation est suivi par une deuxième avec des plis orientés dans le sens N-S et un clivage sub-horizontal. Cette déformation est formée par une force en sens E-W. La troisième déformation se manifeste par deux clivages schisteux de caractère cisaillante; le clivage le plus échéant est vertical avec une direction NW-SE, tandis que l'autre, situé verticalement comme le premier, a une direction NE-SW, L'assymmétrie des plis indique que cette déformation est produit par une force qui est orienté dans le sens E-W. L'intersection des premiers clivages avec les troisièmes varie dans la zone transitionelle. En mésurant l'intersection on peut calculer l'attitude originale des premiers clivages. La quatrième déformation se manifeste par un clivage vertical avec une direction E-W. Les plongements des quatrièmes axes de plissement sont variables par le système complex de plissage.
La région est divisée en deux parties par la faille de Mérens (formée dans une phase tardive hercynienne). Dans la partie septentrionale, appartenant au Massif de l'Aston, la transition se trouve entre l'infrastructure et la suprastructure.
Là partie méridionale appartient à la suprastructure du Massif de l'Hospitalet.

RESUMEN

Se encuentra en la región explorada la transition entre dos tipos de rocas, uno con un metamorfismo herciniano, epizonal (que forma la supra-estructura), el otro con un metamorfismo herciniano, mesozonal (formando la infra-estructura). La primera deformación, contemporanea con el metamorfismo, ha formado un clivaje esquitoso y sub-horizontal en las zonas mesozonales. Se encuentran indicaciones de que este clivaje es un plano de movimiento y de aplanamiento. Al contrario del ultimo, esta deformación ha formado en las zonas epizonalas un clivaje esquitoso y subvertical (este clivaje es un plano de aplanamiento). En el "Vall Ferrera" la transicion entre los dos actitudes de clivaje tiene un caracter gradual. La transicion ocupa una región de 7 a 5 kms. La orientacion y la forma del elipsoide de deformación de las fabricas originadas por la primera deformación demuestra que en las regiones con un clivaje subhorizontal, el eje mas largo es orientado en el sentido E-W, situado paralelamente a los ejes de los plieques (B-tectonitas); mientras que en las regiones con un clivaje sub-vertical, el eje mas largo esta orientado verticalmente y perpendicularemente a los ejes de los plieques (a-tectonitas). En el "Vall Ferrera" se encuentra una transicion gradual de las B-tectonitas. a las a-tectonitas. La primera deformación se ha formado por una fuerza orientada en el sentido N-S. Una segunda deformación con plieques orientados en el sentido N-S y un clivaje sub-horizontal siguie a la primera. Aquella deformación esta formada por una fuerza en el sentido E-W. Se manifesta la tercera deformación por dos clivajes esquitosos de caracter cizallante, el clivaje mas developado esta vertical con una dirección NW-SE, mientras que el otro situado verticalmente como el primero, tiene una dirección NE-SW. La asimetria de los plieques que esta deformación se ha producido por una fuerza que esta orientada en el sentido E-W. La intersección de los primeros clivajes con los terceros varia en la zona transicional. Mediendo la intersección se puede calcular la attitud original de los primeros clivajes. La cuarta deformación se manifiesta por un clivaje vertical con una dirección E-W. Los buzamientos de los ejes cuartos de plegamiento son variables por el sistema complejo de plegamiento.
La región esta dividada en dos partes por la falla de Mérens (formada en una fase hercinana tardia). En la parte septentrional, que forma parte del macizo de l'Aston, la transición se encuentra entre la infraestructura y la supra-estructura.
La zona meridional forma parte de la supra-estructura del macizo del Hospitalet.

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