

# STRUCTURE AND SEDIMENTOLOGY OF THE UPPER CARBONIFEROUS OF THE UPPER PISUERGA VALLEYS, CANTABRIAN MOUNTAINS, SPAIN

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## ABSTRACT

The results of an investigation of the structure and sedimentology of Upper Westphalian and Lower Stephanian strata in the eastern end of the Cantabrian palaeozoic core (NW Spain), are presented.

The sediments, shales, sandstones, limestones and coal seams occur in three main associations: the orthoquartzite-carbonate, the turbidite and paralic associations. Two facies are distinguished: a western, without turbidites, with relatively many coal seams and an eastern, with turbidites and a few coal seams.

Some evidence for a zone of less subsidence is present. This zone separates the two facies. The western and eastern facies are represented by the rocks in the Sierra Corisa and Redondo synclines respectively. Between the two synclines occurs a zone of long stretched narrow folds, often upthrust to the west. Fold axes generally plunge SSE. Some of the structural features are explained by disharmonic folding and extrusion tectonics.

In the eastern facies a formation occurs, which consists of graded sandstones alternating with mudstones.

Thickness measurements of the individual sandstone and mudstone beds are analysed with non-parametric statistical methods. Several regularities in the succession of lithological types or thicknesses are revealed. Correlations between thickness or position of variates (i.e. sandstone, mudstone, sideritic concretion) are tentatively explained in the light of the turbidity current hypothesis. Especially the successive sandstone thicknesses show an interdependence expressed in "fluctuations". Sandstone-mudstone thickness-correlation leads to the assumption of a very high mud content of the turbidity current in these cases, and considerable erosion by successive currents.

Sedimentary structures, especially those of the turbidite association, are described in detail. A short annotated bibliography on sole markings is given.

The palaeocurrent directions measured from sole markings and cross-bedding are discussed. The sequence of sole-marking-directions on successive turbidite layers indicates interdependence of these directions, which could also mean the interdependence of the depositing currents.

A litho-stratigraphic map, three structural sections and twelve stratigraphic sections are given.

## CHAPTER I

### INTRODUCTION

#### 1.1. *General*

The area which is described in this paper forms the eastern part of "Pernía", the mountainous northern part of the province of Palencia. It lies on the southern slope of the Cantabrian Mountains and covers part of the drainage area of the Rio Pisuerga. The highest point lies at 2222 m, the lowest part of the area is the Pisuerga valley near the artificial lake of Vañes at about 1100 m. Owing to a fairly dry climate the rocks nearly everywhere outcrop, while alluvial and other covers are rather scarce, except in the south. Hard rocks form ridges by selective erosion. The thick limestone and quartzitic sandstone beds can thus easily be traced in the terrain, and are therefore an important aid to geological mapping.

The area forms part of the coal basin of the Rio Pisuerga and consists of Upper Westphalian and Lower Stephanian sediments, bordered in the west by Devonian outcrops, and unconformably overlain by Triassic sandstones and conglomerates in the east. The latter form a crest attaining heights of over 2000 m, which is indicated as the "Cordillera Ibérica" on some topographic maps. To the north and south the area is bounded by the Castillería valley and by the watershed at Piedras Luengas respectively.

The aim of the study embodied in this paper has been the geological mapping of the area on a lithological basis and interpretation of the results on the basis of the palaeontological data obtained by Wagner with the fossil flora, and Van Ginkel with fusulinid zones.

The fairly large area in which Upper Westphalian and Stephanian A sediments are preserved enables a sedimentological study of these time-rock units to be made. This study has, for practical reasons, been concentrated on special topics like graded bedding, sedimentary structures and palaeocurrent directions. The good outcrops favourably influenced the number of observations and advantage was taken of this by using mathematical-statistical methods for analysis of the sedimentological data.

The facies changes in the area could not be represented in simple lithofacies maps because of the lack of detailed time-stratigraphic correlation and because of the intense folding. Therefore the sediment-associations have been indicated on the litho-stratigraphic map by special colours. In this way facies changes in a broad sense can be traced. On the second enclosure (stratigraphic sections) the inset map shows the location of the stratigraphic profiles. Here also time-rock unit boundaries are indicated, which in combination with the lithologic map can be used to provide a rough idea about the age relations. These boundaries have not been indicated directly on the litho-stratigraphic map because the correlations are partly of a preliminary character, and minor changes of the stratigraphic scheme may be expected if more palaeontological data become available in the years to come.

The topographical basis for the litho-stratigraphic map is the en-



largement of the 1:50,000 topographic map of the "Instituto Topográfico y Catastral", Madrid. Parts of the sheets 82 (Tudanca) and 107 (Barruelo de Santullán) have been used.

## 1.2. *Previous authors*

Only very few papers deal with eastern Pernía or adjacent areas. Among the publications mentioned below those dealing with geological aspects which are not, or only briefly dealt with in the present study are given especial attention.

The first geological map of northern Palencia has been made by Casiano de Prado (1856). For this map we refer to Kanis (1955, p. 386, fig. 4).

Oriol (1876) paid some attention to the intrusive rocks and mineralizations which occur in the area between San Salvador and Estalaya and along faults in the eastern flank of the Redondo syncline. The mineralizations in the Pisuerga valley which Oriol described are still mined for arsenic and copper (Mina Carracedo). The mines of "Pando", near the Sal de la Fuente produced a small amount of zinc and lead ore but were abandoned in 1876.

In 1926 Cueto y Rui-Díaz drew attention to the similar position of the strata in the Rubagón valley between Brañosera and Barruelo and the strata east of Santa María de Redondo. They concluded that the latter are overturned and that two orogenic phases have acted in this area.

After the map published by Dupuy de Lôme & de Novo (1924) followed a geological map dealing with the Mesozoic rocks by Karrenberg (1934) and a fairly detailed geological map by Quiring (1939). Except for the boundaries between Devonian, Carboniferous and Triassic, already established by Casiano de Prado, these maps have proved to be unreliable in detail. The present structural interpretation differs greatly from that of Quiring (1939) because more palaeontological data are available now.

One of the more recent geological descriptions is that of Alvarado & Sampelayo (1945). Since then several contributions to the Cantabric-Asturian geology have been made by Wagner & Wagner-Gentis (1952), Wagner (1955, 1958, 1959), Kanis (1955) and Wagner & Breimer (1958). The evidence for an important orogenic phase in the Lower Westphalian assembled by Wagner and Kanis, has played an important part in giving better understanding of the sedimentary history of our area.

A few publications on the coal mining in the area have been mentioned in a paper on the coal mining possibilities of the Pisuerga basin by Nederlof & De Sitter (1957).

The reader is referred to the paper of Nossin (1959) for the description of the geomorphology, the terrace gravels and glacial deposits.

Van Ginkel (1959) published a study about fusulinid zones which has been used as the basis for the correlation of the several limestones in the area.

For a more general picture of the geology of this part of the Cantabric Mountains, the reader is referred to a recent paper by De Sitter (1957).

In the list of references the papers dealing with the Cantabric-Asturian Mountains have been marked with an asterisk.

## CHAPTER II

### STRATIGRAPHY

#### 2.1. *Introduction*

The stratigraphy of the upper Pisuerga valleys presents many problems which can only be solved by painstaking palaeontological investigations. The major part of the sediments in this area are of Upper Westphalian and Stephanian A age. The thickness of the strata belonging to these sub-epochs exceeds three thousand meters. A very refined palaeontological correlation of the rock-units thus is needed as a basis for the discussion of facies changes and structure.

Only part of the fossils found in this area have been identified. The most important fossils from the point of view of time stratigraphy are:

Flora	found in San Felices, Santa Maria and S. Cristóbal.
Foraminifera	In nearly all limestones.
Corals	In many limestones and calcareous shales.
Brachiopoda	Especially in clayey limestones and calcareous shales.
Goniatites	In limestone of Peña Tremaya, and in a nodule from the marine level on top of the Redondo III coal seam.
Pelecypods	In limnic fauna of Reboyal coal-member in the Redondo syncline. In several marine fauna's together with brachiopods, gastropods and trilobites.

The fossil flora studied by R. H. Wagner (1952, 1955, 1958, 1959a, b) and the foraminifera studied by A. C. van Ginkel (1957, 1959) made some detailed correlation within the Westphalian and Stephanian A possible. Van Ginkel (1959) presents a comprehensive correlation chart in which all available palaeontological and stratigraphic data have been assembled.

Only a brief summary of the time-rock units in this area will be given here. More attention will be paid to the description of the sediments, which, after description of the stratigraphic sections leads logically to the distinction of several "consanguineous associations" of sediments in the sense of Pettijohn (1957, p. 611).

#### 2.2. *Summary of time-stratigraphic units in the upper Pisuerga valleys and adjacent areas*

Table 2.1. Major stratigraphic subdivisions

Quaternary	Alluvial; large blocks of Triassic conglomerate, old screes, moraines. Terraces near San Felices (1150—1300 m).
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ALPINE phases	Mesozoic in the south folded. Permo-Triassic in broad folds.
Triassic	Cordillera Ibérica conglomerate formation. Thick massive conglomerates and coarse, cross-bedded orthoquartzites. (Min. 300 m).
SAALIC ? phase	Strong angular unconformity.
Stephanian B-C	Pena Cildá formation, not present in our area, but in the southeast between Parapertú and Mercedes. (Wagner, 1955).
ASTURIAN phase	Strong angular unconformity. (Wagner & Wagner-Gentis, 1952, Wagner, 1955, 1959).
Stephanian A	Barruelo formation. Includes the coal seams of the Casavegas and Redondo synclines, the seams of S. Salvador, S. Felices and S. Cristóbal.
TWO MOVEMENTS expressed in the southern flank of the Sierra Corisa syncline as:	Angular unconformity of San Cristóbal. (De Sitter, 1955, p. 121.) Diasthem of Cabra Mocha. (De Sitter.)
Westphalian D	Sierra Corisa Limestone formation. San Cebrián coalbearing formation.
Westphalian C	No palaeontological proof for its existence in this area but possibly present below the San Cabrián formation and as the Peña Agujas Limestone.
Upper Westphalian B	Curavacas conglomerate formation. Fossil flora. (Kanis, 1956, Wagner, 1959a.) Not present in the area, but a few km to the W, near Resoba.
CURAVACAS phase	Strong angular unconformity.
Lower Carboniferous	Not outcropping in eastern Pernía, but in surrounding areas.

### 2.2.2. *Unconformities*

Some interesting facts about the stratigraphic succession may be mentioned here.

The sediments in the investigated area were deposited during a renewed subsidence of this part of the Cantabro-Asturic region after the Curavacas phase. (pre-Upper Westphalian B, Wagner, 1959). Marine and continental conditions alternated in a fairly irregular manner, while before the Asturian phase the area was tectonically disturbed by uplift and folding, of at least local importance.

In the Sierra Corisa Series a diasthem has been observed. It is described

in some detail in chapter V. It has only been traced for a few hundred meters in the southern flank of the Sierra Corisa syncline. (Cabra Mocha hill). The locality is not indicated on the lithologic map, but lies about two km south of San Felices.

As far as could be ascertained by fieldwork this diasthem is not connected with the angular unconformity of the San Cristóbal hill (de Sitter, 1955, p. 121), which was studied by Wagner & Breimer (1958). This latter unconformity is the result of tectonic movement of considerable intensity and subsequent erosion at the end of the Westphalian D or in early Stephanian A times. The eroded surface shows irregularities of about 10 cm depth. A reconstruction shows that at the locality the Westphalian strata dipped 65° ENE during the erosion and before burial under the unconformable sandstone formation. The beds directly above the unconformity have been traced along the syncline flank up to Herrerueta by Wagner & Breimer (1958).

### 2.2.3. *Dating of the coal seams*

Wagner has dated the coal seams of San Cebrián as lowermost Westphalian D. (Wagner, 1955). Probably the same medium-volatile seams, though much less developed occur near Celada (mina Perniana). Fossils were very scarce and no definite proof of the contemporaneity has been given yet. A comparison of the stratigraphic position of both coal-bearing formations shows that such a correlation is not unreasonable however.

The seam occurring a few tenth of meters above the San Cristóbal unconformity has been dated by Wagner (Wagner & Breimer, 1958) as lowermost Stephanian A. The seams occurring at San Felices (mina la Florida) and those east of Santa Maria de Redondo (mina Joaquín. El Olvido) have also been dated as Stephanian A. (Wagner, 1955, 1959b, Wagner & Wagner-Gentis, 1952).

### 2.2.4. *Fusulinid zones*

The limestones occurring at intervals throughout the stratigraphic column yielded many foraminifera. Van Ginkel (1959) has attempted to recognize several fusulinid zones in the Upper Carboniferous of northern Palencia. As a base section to which other sections have been compared, served a combined section through the Casavegas syncline. (Area to the northwest of the region described in the present paper.)

Although the comparison of fossil assemblages from different limestone outcrops (encl. 2) gives probable equivalencies of certain limestone levels, precise correlation of the fusulinid zones with time-stratigraphic units based on floral evidence (Westphalian D and Stephanian A) is still problematic.

Because of the hybrid nature of the palaeontological data available it has not been attempted to draw a geological map with time-rock units as subdivisions. Instead mappable rock-units have been used, which show more detail of the structure.

Stratigraphic sections in different parts of the area are compared in enclosure 2. Several outcrops of limestones not included in a section are indicated by local names on the level of probably equivalent limestones of a stratigraphic section (according fusulinid determinations by Van Ginkel, pers. comm.).

### 2.3. *Short description of the sections*

#### 2.3.1. *Sierra Corisa and Herreruela*

The southern flank of the Sierra Corisa syncline is well exposed on the slopes of the hills San Cristóbal, Cabra Mocha and Sierra Corisa.

Preliminary studies have been made by Quiring (1935, 1939), and Alvarado & Sampelayo (1945). The first detailed mapping of that area was started by Mrs. Wagner-Gentis (unpubl. report, 1955, Wagner & Wagner-Gentis, 1952, Wagner, 1955) and extended by Boschma (unpublished report) and Breimer (Wagner & Breimer, 1958). The area, from which stratigraphic sections 1 and 2 have been constructed, is not presented on the litho-stratigraphic map. The reader is referred to the geological map of the Pisuerga coal basin published by de Sitter and collaborators in 1957, (De Sitter, 1957), and to the inset map on enclosure 2.

The sections 1, 2 and 3 have the San Cebrián coal seams at the base. A few limestones occur below, between and above these seams. The upper limestone develops into the Cotarraso limestone in the valley north of Herreruela. (Wagner, 1955).

Between this Cotarraso limestone and the thick Sierra Corisa limestone lies a succession of sandstones shales and thin conglomerates. Above the Sierra Corisa limestone follow the San Cristóbal coal seams. The succession between these seams and the San Felices coal seams consists of about 1000 m of shales, sandy shales, proto- and orthoquartzites, very few limestones and some conglomerate. A fairly persistent limestone in this succession has been termed Estalaya-bed (De Sitter, 1957, p. 274). This bed consists of dark-grey, poorly bedded, crumply organoclastic, clayey limestone with abundant gastropods, some brachiopods, solitary corals, crinoid columnals and other fossils. It is a conspicuous limestone, about 4 m thick, exposed along the road between the Cantina de Vañes and Estalaya, and at several other localities in the Sierra Corisa syncline.

The San Felices coal seams lie approximately in the center of the syncline. They contain medium-volatile bituminous coal.

#### 2.3.2. *Celada*

Section 5 is an apparently continuous succession of Upper Westphalian and Stephanian A strata. Possibly the lowest part of this column belongs to the Westphalian C, but no palaeontological proof is at hand to substantiate this assumption. The lower 600 m consist of a monotonous sequence of shales, sandy shales and sandstones. Then a more interesting succession follows, which may be seen along the path leading from the old mine "La Perniana" to the village of Celada. This section is presented in table 2.2.

The limestones in this succession may be correlated with the Cotarraso limestone in the SE and with the Peña Tremaya lst. in the NW. In this section the calcareous mudstones of Celada contain many solitary corals and brachiopods. The equivalents of the Sosa and Verdegosa limestones are poorly developed in the section but thicken again to the east.

The important sandstone level above the limestone resembles the sandstone described by Wagner (1955). In the predominantly elastic succession which follows occur a few thin limestone knolls (Ermita limestone), impure

thin limestone beds and a 50 meter of sandstone-shale alternation which is similar to the Graded formation of the Redondo syncline.

TABLE 2.2

Detailed stratigraphic section of the sediments along the earth-road from Celada to the Mina Perniana and along the Arroyo de Castillería

Description	Thickness in meters
1. Marine sandstone, yellow, well medium bedded, cross-bedded, finegrained and slightly clayey.	15
2. Biostromal limestone, bluish-grey, massive to thick bedded, coralligene, colonial corals in situ.	20
3. Sandstone, grey, medium grained.	5
4. Sandy and silty shale, black to dark-grey, micaceous, often with plant remains.	3
5. Shale, black to dark-grey.	30
6. Shale with thin coalseams. Shale with small rootlets at the base.	1
7. Biostromal limestone, dark-grey to black, well medium to thick-bedded, coralligene.	15
8. Calcareous siltstone. Yellow, massive.	1
9. Sandstone, brownish-yellow, finegrained, massive.	1
10. Shale, dark-grey.	2
11. Sandstone, buff, poorly thick bedded, fine to medium grained.	10
12. Limestone, bluish-grey, partly coralligene, partly aphanitic.	30
13. Shale, dark-grey. With some sandy and silty intere.	25
14. Coal seam, semi-anthracitic, Mina la Perniana and other abandoned mines. At the base abt. 60 cm of grey, massive, micaceous, sandy mudstone with carbonized rootlets.	0.20—3

### 2.3.3. Redondo syncline

The Redondo sections contain at the base the Peña de las Agujas Limestone formation, developed as massive limestone knolls along the Permo-Triassic cuesta of the Cordillera Ibérica. According to Van Ginkel (1959) it is equivalent to the Camasobres limestone of the Casavegas syncline. Laterally, between the massive parts, it is developed as a thick-bedded partly recrystallized, or shaly thin-bedded or nodular limestone. Many corals can be found in the massive parts; forams are also abundant. In a general way the thickness of this limestone varies from abt. 100 m in the west to 600 m at Peña de las Agujas in the east. It is suggested that the irregular nature of this limestone and sudden thickness-changes are due to a patchy, biohermal development.

On top of the Agujas limestone formation lies an extremely regular alternation of calcareous finegrained clayey sandstones and dark grey mudstones. The formation which attains a thickness of about 300 m is poorly exposed. At Peña de las Agujas it immediately succeeds the limestone, whereas in the north both formations are separated by a 100 m of shales and sandstones without any regular alternation. The similarities of this formation and the Graded formation higher in this section suggests the possibility that it has been deposited by the same mechanism, discussed at length in Chapter IV. A lack of good outcrops made detailed thickness measurements impossible, however.

Succeeding the sand-shale alternation described above, a shale formation occurs, which contains a few brachiopods and crinoid columnals. Like most of the marine shales in this area, it is hard, dark-grey to black, slightly

micaceous and in places calcareous. In the southern part of the Redondo syncline a few important intercalations of sandy shales and orthoquartzites are found in this formation. In the upper part, especially in the E-flank of the Redondo Syncline, intercalations of black, nodular, clayey, organo-detrital limestone up to 10 m thick occur. They are very poorly sorted and resemble the very coarse limestone breccias of Pozo del Diablo in the Pisuergra valley (Camino del Pando) in many aspects.

The Abismo limestone formation overlies the lower part of the shale formation in the N, but is equivalent with the top part of the shale formation in the E. The Abismo limestone varies considerably in thickness (0—300 m) and wedges out in both flanks of the syncline. The upper part of this limestone formation shows interfingering of shales and impure limestones thickening to the east. The Abismo limestone is followed by shales and sandy shales in the northern area of the syncline (200 m).

In the east, however, it is succeeded almost immediately by the Graded sandstone formation. The more sandy Caldero formation follows upon the Graded formation. It extends slightly further westwards than the latter. Both formations wedge out towards the axis of the Los Llazos anticline and thin appreciably towards the southeast, in the opposite flank of the Redondo syncline. They are described in more detail in Chapter IV.

The Caldero formation contains a darkgrey to black, coarse organo-detrital limestone, called "Corros limestone member", which is important because it yielded relatively young fusulinids (Van Ginkel, 1957).

After these marine deposits a few continental layers occur which alternate with marine shales, sandstones and a thin limestone near San Juan de Redondo.

Coal-bearing members are from bottom to top the "Lomba", "Redondo", and "Reboyal". The sediments between these paludal and fluvial deposits are predominantly shales. The detailed section between the Redondo and Reboyal coal seams is given in table 2.3.

TABLE 2.3

Detailed stratigraphic section of the sediments above the Redondo coal seams, near Mina San Joaquín. Measured between Santa María and the mine, along the "Camino del Pando".

Description	Thickness in meters
1. Black silty shale with muscovite flakes and carbonaceous flakes.	50
2. Lightbrown, flaggy, fine-grained, cross-bedded protoquartzite with some muscovite on bedding planes.	10
3. Black shale with abundant sideritic concretions containing pyrite crystals of abt. 1 mm size.	8.50
4. Grey, nodular, calcareous mudstone with large brachiopod valves ( <i>Productus</i> ?) within the nodules.	0.25
5. Black, silty shale with two concretion levels of abt. 5 cm thick near the top.	2.50
6. Dark-grey, flaggy, to shaly, fine-grained protoquartzite with abundant muscovite on bedding planes.	1.50
7. Grey, shaly, finegrained, muddy protoquartzite, with some small muscovite flakes.	17
8. Black fissile shale.	14
9. Grey to brown, shaly, muddy, medium-grained protoquartzite.	15
10. White, brown weathering, flaggy, coarse-grained orthoquartzite with abundant carbonaceous flakes and "seeds", (see fig. 1a). Also a profusion of 3 to 5 cm long casts of asymmetric pelecypods.	0.25

Table 2.3. Continued.

11. Black to light-grey silty shales.	16
12. Flaggy, grey, concentric weathering, medium-grained protoquartzite, with abundant muscovite flakes.	10
13. Irregular sequence of black shales and grey, medium grained protoquartzites. Some sandstone beds are load casted at the base. Abundant carbonaceous flakes and muscovite in the protoquartzites.	60
14. Ripple-marked and current-bedded, yellow-brown, medium-grained orthoquartzite. Carbonaceous and muscovite flakes. In the very top a few cm with thick-shelled pelecypods, undet. fragments.	3
15. Black silty shale.	4.50
16. Grey to brown, shaly, medium-grained protoquartzite.	1.50
17. Grey to black shales.	4
18. Grey, shaly, fine to very fine-grained, muddy protoquartzite.	2
19. Black silty shale.	10
20. Yellow, cross-bedded, flaggy, to massive, finegrained orthoquartzite; very resistant to erosion.	6
21. Black, silty shale with some thin proto- and orthoquartzites.	14
22. Yellow-brown, flaggy, medium-grained orthoquartzite.	4.50
23. Black, silty shales with muscovite flakes and thin muddy protoquartzites.	35
24. Black, silty, calcareous mudstone, with concretions of siderite and calcite, and a profusion of pyritized marine fossils. Pelecypods, brachiopods, crinoid-stems, a nautilus and in a concretion a goniatite. (see fig. 1b).	0.30
25. Semi-anthracitic coal seam, Redondo III.	0.80
26. Greyish black, massive, silty mudstone, with abundant minute muscovite flakes and many sub-vertical carbonized rootlets.	0.50

#### 2.3.4. *The Rubagón valley*

It was suggested by Mr R. H. Wagner to study also the Rubagón valley-section through sediments of Stephanian A age, which seemed the continuation of sediments of the same age in the Redondo syncline. Indeed a similar lithofacies sequence was found here.

In the Rubagón valley between Brañosera and Barruelo several outcrops of graded bedding occur. The thicknesses of the very persistent sandstone beds are about the same as in the Redondo area and the composition is also a clayey, calcareous quartzose sandstone, to protoquartzite. The entire "Graded Rubagón formation" (belonging to the Brañosera group), which can be divided into a mudstone-rich lower part and a sandier upper part, is rich in sole markings of a great variety (cf. Chapter V).

The stratigraphic position of these beds included in the "paquete de Brañosera" has been discussed by Wagner (1955), Wagner & Breimer (1958, p. 11—13) and Van Ginkel (1959). It is likely that part of this succession of graded beds is synchronous with part of the Graded- and Caldero formations of the Redondo syncline.

#### 2.3.5. *The Casavegas section*

The sections through the Casavegas syncline, studied by Van Ginkel and Breimer (unpublished reports), display a great thickness of Upper Westphalian and Stephanian A sediments. Limestones sometimes biohermal, alternate with orthoquartzites, sandy shales and shales. Coal seams occur in the middle and upper part of the section. Graded bedding is lacking in the entire sequence, but large-scale cross-bedded sandstones are common. Like in the East-Pernía area marine conditions prevailed throughout and the coal seams



with adjacent continental deposits only formed an occasional episode, differing in so far from the sequence of Redondo and San Felices that the coal seams are much better developed in the Casavegas syncline.

#### 2.3.6. *The Triassic*<sup>1)</sup>

It consists of an alternation of thick beds of coarse quartz and quartzite-pebble conglomerate and coarse white to red, cross-bedded, quartzose sandstones. This sequence which is considered as Buntsandstein by Karrenberg (1934) retains its general character all along the "Cardillera Ibérica" on the Valdecebollas and Cueto and east of Herrerueta. Section 12 on the stratigraphic scheme was measured on the cliffs east of the Peña de las Agujas on the slope of Los Cervunales. The total thickness of the Triassic preserved there is 450 m.

### 2.4. *Description of the sediments*

#### 2.4.1. *Conglomerates*

The Triassic<sup>1)</sup> conglomerates which occur all along the eastern limit of the area consist of vein-quartz and quartzite pebbles. The matrix is coarse, fairly well rounded quartz sand. The sorting is generally good. Often streaks and lenses of coarse white quartz sand occur within thick massive conglomerate banks, which alternate with thick units of white coarse grained micaceous, flaggy, cross-bedded orthoquartzites. It probably is a marine, transgressive conglomerate.

Near and in the village of Herrerueta occur a few medium to thick Carboniferous conglomerate beds. They are rather persistent in thickness and composition and lie between black silty shales, sometimes with delicately striated load casts on the sole. The pebbles measure up to 3 cm in a 50 cm thick band and up to 5 cm in a layer of 2 m thickness. The latter follows abruptly on the black to dark grey shale, without any sign of scour and fill or other erosional phenomena. The components are almost entirely well rounded and siliceous sandstones pebbles. (Both the Lower Carboniferous and Devonian, contain quartzite sandstones: therefore, it is difficult to establish the provenance of these components). In addition to these hard components a minor proportion occurs of small rounded limestone pebbles and angular shale flakes. Towards the top the conglomerate grades into laminated coarse and medium grained slightly micaceous sand with some shell debris.

In the description of the sections through the Redondo syncline, the muddy limestone cobble and pebble conglomerates have been mentioned shortly. At Pozo del Diablo the coarsest example can be studied. Here a few blocks of several meters diameter are embedded in the calcareous shale, with occasional and widely spaced irregularly sized and shaped components. Many contorted and dismembered slabs of clayey sandstone occur at random in the shaly matrix.

The limestone components seldom are well rounded (rounded cobbles can be observed in the conglomerate lens of "Entre Monte"). The small pebble-size components often are subangular to angular and contain many fragments of corals. But the major part of the limestone cobbles are devoid of internal structures.

<sup>1)</sup> No palaeontological evidence presented, however.

The muddy character of the conglomerates of Herrerueta and of the Graded formation in the Redondo syncline cannot be explained by deposition by normal sea-currents. If the components would touch each other, one might explain the mud as introduced after deposition of the frame work. But the components do not build a stable frame work. Much attention to conglomerates of this type has been paid by Crowell (1957) and Grzybek & Halicki (1958). Large slide blocks are reported by McCallien & Tokay (1948) and many examples are reported from the "Wild-flysch" of the Alps. Submarine sliding also has been proposed as mode of formation of muddy breccias studied by Snyder & Odell (1958).

In the light of these recent advances in the study of "pebbly sandstones" it is proposed that the muddy conglomerates of the lower part of the Redondo Section and of the Corisa syncline are the result of submarine sliding of masses of conglomerate which were deposited by normal currents on an unstable clay bottom.

The conglomerate beds within the village of Herrerueta cannot be accounted for in this way, because they are not muddy and have persistent thickness.

A coal-cobble conglomerate of 50 m thick is present in the formation, containing the San Cristóbal coal seam (Stephanian A, Wagner & Breimer 1958). The components are slabs (oblate cobbles) of thick well rounded hard vitrain coal. Jointing within the cobbles is perpendicular to the flat surface, regardless of their position with respect to the bedding plane of the conglomerate. The sizes vary from granule to small boulders, but most common are cobble sizes (e.g. 30 by 6; 15 by 3; 15 by 2; 7 by 7 cm).

The matrix is a medium to coarse grained, grey, gritty sandstone, like the sandstones below and above the conglomerate-bed. The components often are separated by the matrix, suggesting contemporaneous, rapid deposition of coal-cobbles and sand. The lateral relationships could not be observed. From the outcrop however it seems justified to assume that the coal already was consolidated and hard when erosion set in during the early Stephanian.

It is very likely that this conglomerate and those of Herrerueta are connected with the erosion due to uplifts in late Westphalian D times, causing the unconformities in the southern flank of the Sierra Corisa syncline. Of course long transport is excluded because the jointing of the coal already was present in the components during transport.

Many coal-conglomerates have been described in the literature. A review has been given by Stutzer & Noe (1940), and Teichmüller (1951) described Westphalian coal granules in the sandy Lower Cretaceous of Germany. The large size of the coal slabs in our case seems to be rather exceptional.

#### 2.4.2. *The sandstones*

Orthoquartzitic sandstones (quartzose sandstones) (Pettijohn 1957, p. 295). Many of the sandstones which occur in the upper Westphalian and Stephanian A are almost entirely made up by more or less rounded quartz grains. In many cases secondary growth has transformed the rock into a real "quartzite", in which the original grains cannot be distinguished by the unaided eye. These white to yellow sandstones which are apparently devoid

of rock particles, mica and feldspar, may contain some shell-debris and brachiopod-molds. They are generally well sorted and are very hard by siliceous cementing. They form conspicuous features of the landscape because of their resistance to erosion. Cross-bedding on a scale of a meter is common, but also massive or poorly thick bedded types occur. They form relatively wide spread (up to 5 km) persistent beds up to 20 m thick, which grade below and above into either less mature, micaceous, clayey sandstones, or into foraminiferal limestone.

They tend to occur in limestone successions (e.g. the limestones in the Celada syncline, Verdegosa limestones), however several examples could be mentioned where they occur also in the coal-bearing sequences. An example is the orthoquartzite above the coal seams of Verdeña.

Protoquartzites and subgraywackes. The bulk of the sandstones of the coal-bearing sequences is to be described as protoquartzite (Pettijohn 1957, p. 316). These sandstones nearly always are greyish green, or light to dark grey. The grains are moderately to poorly sorted, seldom rounded and consist of quartz, mica and minor proportions of rock fragments (slate) and only a trace of feldspar. An abundant clayey matrix is common. Cementing is siliceous and calcareous. On the bedding planes much muscovite and coal-flakes are concentrated. The bedding is thin to medium and always well developed, whilst cross-bedding of various shapes at a scale of half a meter occurs rather often. These sandstones are stratigraphically connected with the coal seams and stigmara beds. Probably a large part of the shales, silty shales and protoquartzites are fluvatile. The irregular extension of the sandstone bodies and the many washouts may indicate this.

Subgraywacke as defined by Pettijohn (1957, p. 316) with more than 25 % unstable components only occasionally has been observed, where the micaceous components and shaly fragments have been concentrated locally.

Arkoses have not been found in the Upper Carboniferous of La Pernía.

Muddy sandstones. Typical regular sandstone-shale alternations occur in the upper Westphalian on top of the Agujas limestones (Redondo syncline) and in the Stephanian A, in the Graded and Caldero sandstone formations, in the sandstone-shale alternations in the Sierra Corisa syncline (Herreruela village and in the valley of the Arroyo Palas, N of San Felices). The sandstones are on the basis of maturity almost orthoquartzites but mostly protoquartzies. However they show a large amount of detrital matrix and shell-debris. A more detailed description of the sandstone of the Graded formation can be found in Chapter IV.

#### 2.4.3. *Shales and Mudstones*

All the transitions between clayshale and sandy mudstone on one hand and calcareous mudstone on the other occur in the area. It is impossible to give estimates about the relative importance of each type because of the rapid lateral facies changes and the difficulty of identification of such types in the field. Only the extreme end-members can be recognized readily. The main tendency observed is the association of pure black to brown clayshales with massive, thick limestones. Sandy and calcareous mudstones occur mostly near coal seams.

#### 2.4.4. Limestones

The limestones can be divided into the following groups:

1. Aphanitic, bluish-grey to brown-grey, dense non fossiliferous limestones which are very pure, about 96—99 % soluble in cold, dilute HCl. They are common in the Sosa limestone, the Abismo and in the Celada syncline.

2. Organo-detrital limestone (skeletal limestone), grey, coarse grained, partly recrystallized, dense limestones with a large variety of organic remains

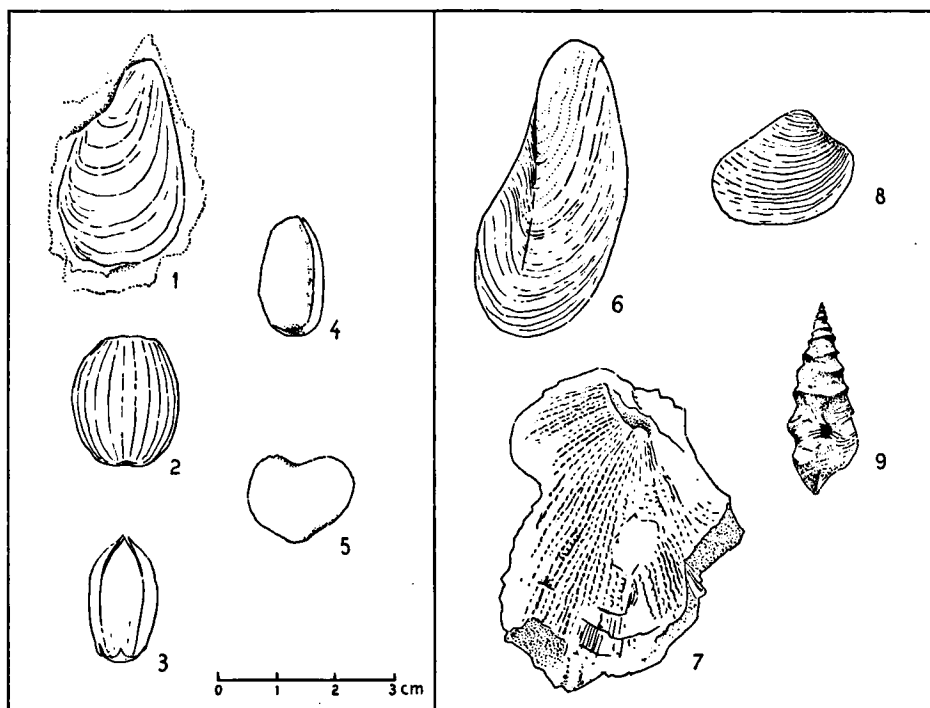


Figure 1. Fossils in sandstone, Stephanian A, Redondo syncline.  
 1a (left): 1, mold of pelecypod, 2—5, molds of seeds, 3, *Hexagonocarpus*, 4, *Trigonocarpus*, 5, *Cardiocarpus* (Det. Mr R. H. Wagner).  
 1b (right): Fossils in marine pyritiferous mudstone overlying Redondo coal seam III  
 Pelecypods (6 and 8), Fenestella-like bryozoa (7), and Gastropod (9).

of which the largest are broken. They are crinoid stems, echinid ossicles, oolites, coral fragments, calcareous algae, parts of bryozoa and brachiopod and pelecypod-shells. In several limestone formations.

3. Coralligene limestone, with large colonial and tabulate corals or with solitary corals. In biohermal development in the Peña Tremaya and Peña del Moro, in biostromal form in the limestones near Celada. The latter are brownish grey to dark grey and contain a fair amount of clay.

4. Muddy limestone with solitary corals, a lateral equivalent of the biostromes. In the village of Celada de Roblecedo.

5. Dolomitization has occurred in some of the aphanitic limestones: Sosa and Agujas limestone in the nose of Redondo syncline.

#### 2.4.5. Coal

The coal is semianthracitic except for the seams of Celada ("Por si Acaso"- and "Perniana"-seams) and San Felices, which are medium volatile bituminous coals. Analyses have been published in Quiring (1939) and Nederlof & De Sitter (1957). All coal seams have underclays which consist of dark grey, slightly micaceous, silty mudstone with many carbonized rootlets.

### 2.5. Conclusions

#### 2.5.1. Sediment associations

The Carboniferous sediments of eastern Pernía have been divided into three lithofacies associations, which are easily distinguishable in the field. The distinction of these associations is mainly based on the properties of the sandstones, i. e. mineralogical composition, persistence, sedimentary structures etc. Also the presence of coal in certain parts of the stratigraphic column and thick limestones in others suggested this distinction. The following associations are distinguished:

1. The *orthoquartzite-carbonate association*, consisting of pure massive and bedded limestones in units from a few tenth of meters to 600 m thick, a considerable amount of clay shale and beds of a few m thick of orthoquartzite. The latter are very pure, white or pink, siliceous, quartzose sandstones which often are intercalated in the thicker limestone units. The most common environment of deposition connected with this association is the shallow marine or neritic environment.

Examples are the Ajugas Limestone formation, the Sierra Corisa limestone formation, the Verdegosa and Sosa limestones. Of course lateral transitions from this entirely marine association to a paralic association are observed (for instance the Peña Tremaya limestone into limestones near Celada), and a more or less arbitrary boundary has to be drawn between both associations.

2. The *paralic association* consists of shales, sandy shales, sandstones (orthoquartzite or protoquartzite) and coal seams. Occasionally biostromal limestones have been included in this association (Celada, near the Mina Perniana). A great variety of sandstones accompany the coal seams. Common colours are light-grey, brown, red and green. The light grey, flaggy, very fine grained clayey, micaceous sandstones are the most common.

Cross-bedding generally attains a size of about half a meter and is of frequent occurrence. The beds are not very persistent in thickness except some of the siliceous orthoquartzitic beds which can be followed several km along the strike. These are very conspicuous but constitute but a minor proportion of the sandstone in this association. The shales play an important part and are marine for a large part (calcareous fossilifer. shales). Most of the coal seams are overlain by a black calcareous silty mudstone containing a wealth of marine fossils. (Redondo coal seams, Mina San Pedro, Mina Vasco Cantabria etc.). The environments of deposition range from epineritic to terrestrial.

3. The *turbidite association* consists of graded sandstones alternating fairly regularly with shales or without shale between the individual persistent sandstone beds. The characteristics will be dealt with in Chapter IV. Limestone-breccias or conglomerates with abundant clay matrix are included

in this association, which is thought to be the result of slumping and re-sedimentation.

The environments of deposition of this association range from infraritic to bathyal.

All associations contain a large amount of shale. The proportions of gross lithologies is indicated in table 2.4.

The associations are restricted to certain time intervals and areas. Their significance is thought to be mainly tectonic, assuming that rate of subsidence and sediment supply was largely defining the environment of deposition in this area.

TABLE 2.4  
Proportions of gross-lithologies in the associations

Sediment associations, time of deposition and locality	Volume of lithologies in percent.			
	congl.	sandst.	shale	limest.
Triassic, Cordillera Ibérica.	30	70	—	—
Orthoquartzite-carbonate association.				
Westphalian D, Sierra Corisa.	—	30	30	40
"    , Sosa.	—	5	75	20
Paralic association.				
Stephanian A, Redondo.	—	35	65	—
"    , Verdeña.	—	30	70	—
"    , Celada.	trace	40	55	5
"    , S. Felices.	trace	25	75	—
Westphalian D, Celada.	—	20	40	40
"    , Herrerueta.	trace	40	55	5
Average.	trace	35	60	5
Turbidite association.				
Average.	< 5	20	75	—

### 2.5.2. Facies

The lithologic aspect of the Upper Carboniferous in a western area, involving the Casavegas syncline and Sierra Corisa syncline s.l., differs from that in the eastern area, constituted by the Redondo syncline and the Rubagón valley (See encl. 2). The differences are the following:

1. The Ajugas Graded Sandstone formation, considered to be a turbidite, is present only in the Redondo syncline but not in the Casavegas syncline. In the latter syncline the equivalent of the Agujas limestone is succeeded by a marine shale formation.

2. Westphalian D coal seams only occur in the Sierra Corisa syncline.

3. In the Redondo syncline and in the Rubagón area early Stephanian sedimentation is largely represented by marine deposits and especially by the turbidite association. No such deposits have been found in the western area, though a few subordinate sandstone-shale alternation in this area may also be turbidites (see encl. 1 and 2).

The similarity between the two areas is the general change from marine to continental environment during Upper Westphalian and Lower Stephanian times. Camasobres-Agujas limestone and Sierra Corisa-Abismo limestone formations are present almost throughout the area.

The arrangement of facies indicates that the area of most rapid subsidence was situated somewhere in the east or northeast. This is in agreement with the observations made in the region SW of our area, where limestones are almost completely lacking in the coal bearing Lower Stephanian whilst in the western facies of our area still a notable amount of marine limestones is present.

### 2.5.3. *Differential subsidence*

The wedging out of a great thickness of sediments, both competent and incompetent, in the western flank of the Redondo syncline induces one to think of some irregularity of the sedimentation basin, situated near the axis of the Los Llazos anticline.

The evidence in favour of a zone of relatively small subsidence along the axis of the Los Llazos and Celada anticlines is the following.

#### a. From the east:

1. In the Redondo syncline the Agujas limestone, Agujas Graded formation, Abismo limestone, Graded sandstone and Caldero sandstone formations wedge out or thin appreciably towards the Los Llazos anticline. The Stephanian A paralic association does not seem to thin in this direction in the Redondo syncline.

2. The Verdiana-Frechila limestone most suddenly peters out to the west around the nose of the San Juan syncline.

3. The Sosa limestone at Campolanillo (E of Celada) is quite thick compared to the thin limestone beds in the predominantly sandy series, just south of Celada.

#### b. From the west:

1. The Peña Tremaya seems to be a thick development of the thin biostromal limestones near Celada.

2. The lowermost Sosa limestone in the Sosa syncline wedges out towards the east in the Celada anticline.

3. Also the upper Sosa limestone, though it extends further to the east, is much thinner and splits up into thin beds interfingering with the sandstone-shale series south of Celada.

Although accurate thicknesses of individual formations could not be measured, the differences definitely suggest that at certain intervals the zone of the Los Llazos anticline-Celada anticline subsided less than the areas east and west of it and subsequently received less sediment than adjacent areas.

This "ridge" could have separated the eastern and western lithofacies-belts at certain times during sedimentation.

### 2.5.4. *Tectonic framework of sedimentation*

The occurrence in time of the sediment associations indicates orogenic movements or periods of relative stability of the depositional basin and the source areas.

The simplest examples of the relation of the orogenic movements and sedimentation can be found in the tremendous thickness of Curavacas conglomerates and sandstones deposited in the Upper Westphalian B representing debris from the young mountainous areas of the Curavacas phase, and the Peña Cildá conglomerate formation of the Rubagón area deposited immediately after the Asturian phase (Wagner 1955).

The paralic association in one area may indicate the transition from the coarse deposits succeeding the Curavacas phase, to finer grained sedimentation when denudation in the source area proceeded. (Lower Westphalian D paralic association). In other cases it may be the result of a minor uplift, for instance the sudden change from orthoquartzite-carbonate to paralic association in the south, after the Cabra Mocha and San Cristóbal movements.

The turbidite association is very difficult to account for from the tectonic point of view. The only conditions for its deposition seem to be a long and considerable slope and a large supply of elastic materials. It indicates at least moderately deep water and would occur if the basin subsided at a greater rate. The appearance of the turbidite association after the limestone deposition in the Redondo syncline would favour such explanation.

The orthoquartzite-carbonate association would indicate a period of relative rest. (cf. Pettijohn 1957, p. 611).

The possible relations between the orogenic movements and the occurrence of sediment associations in Pernía can be inferred from table 2.5.

Table 2.5. Sedimentation in relation to orogenic movements in the Upper carboniferous of the Upper Pisuergra Valleys. For references on time-stratigraphy and folding phases see table 2.1.

Orogenic movement or uplift.	Time units.	Sedimentary associations.	
		west	east
Saalic?  Asturian  (San Cristóbal) (Cabra Mocha)      Curavacas	Triassic	Conglomerate-sandstone series (terrestrial)	
	Stephanian BC	Peña Cildá conglomerate formation (terrestrial)	
	Stephanian A	paralic .....	paralic ....
		paralic	turbidite
	Upper Westphalian D	Orthoq. limestone	.....
	Westphalian C?	paralic	turbidite
		orthoq. limestone	.....
	Upper Westphalian B	Curavacas conglomerate (terrestrial)	



## CHAPTER III

### TECTONICS

#### 3.1. *Introduction*

The structures of the Upper Pisuerga valleys are easily recognizable on aerial photographs. The fold axis run generally NNW—SSE and plunge southwards. Thrustfolds are steep and trend into the same direction. A general asymmetry of the folds is present, overturning some of the flanks to the WSW.

The area can be more or less naturally subdivided into three structural units, which have their own tectonic character. These are:

1. The wide Sierra Corisa syncline in the south.
2. The north flank of the Sierra Corisa syncline in the central part of the area, with smaller folds.
3. The wide Redondo syncline in the northeast.

From the strong angular unconformity, due to the Asturian phase, in the neighbourhood of our area, it follows that this phase has been responsible for a large part of the deformation. The Stephanian B is not present in the area, thus the influence of the post-Asturian—pre-Triassic phase can only be inferred from other regions, like part of the Barruelo area (Wagner & Wagner-Gentis, 1952) or other Stephanian B-C basins in León and Asturias. The conclusion is that this phase (Saalic?) probably also has been active in our area. The folding of the mesozoic cover also has affected the Carboniferous below. This lately has been described by De Sitter (1957, p. 279, fig. 9). Wide synclinal features with an EW trend can be followed from the Triassic in the east through the Sierra Corisa syncline up to the Westphalian Curavacas conglomerate in the west. This would explain the EW trend of the major axis of the Sierra Corisa syncline.

It is remarkable that the rocks are still quite fresh after all this folding. None of the shales show well developed cleavage. Only advanced siliceous cementing of sandstones and jointing are a common feature. Metamorphism is absent, except for a few cm around the small intrusives (granitic stocks and a few sills). Probably the overburden never has attained a great thickness. This is certainly true for the Asturian folding of the upper part of the 4000—5000 meters of Upper Westphalian and Stephanian A strata.

The study of the tectonics is difficult because of the irregular stratigraphy. The several limestone levels are not distinguishable in the field and hardly by fusulinid-zônes. Especially if thickly developed, competent limestones act as rigid bodies, a strongly disharmonic folding is to be expected.

Some parts of the area, with the present knowledge of their stratigraphy, are beyond structural interpretation.

### 3.2. Description of the structural units

#### 3.2.1. The Sierra Corisa syncline

This structure comprises the area between the Pantano de Requejada (Vañes) in the west and Mina Portillo (valley of Herrerueta) in the east. The southern flank lies south of the Rio Castillería. San Felices lies approximately in the centre. The involved sediments range from lowermost Westphalian D at San Cebrián (S of our area) to Stephanian A at San Felices.

In the centre, just north of San Felices, the beds generally are sub-horizontal, but show several secondary folds of small amplitude. A major synclinal axis crosses the Arroyo Palas abt. 500 m. NE of San Felices, while another synclinal axis passes just S of the Rio Castillería (fig. 2).

The many small faults and other disturbances which can be seen in the hill slope at Mina Mercedes and Mina La Florida indicate the complexity of the core of this syncline.

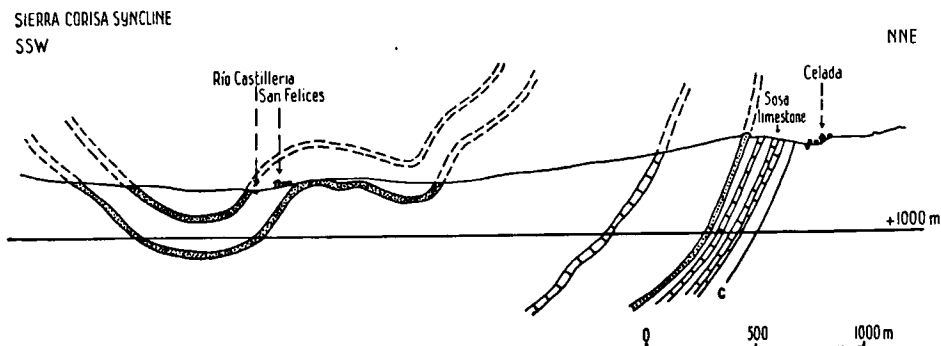


Figure 2. Section through northern flank of Sierra Corisa syncline along the Arroyo Palas, near San Felices.

A NE—SW section through the Palas valley is presented in fig. 2.

No trace of the unconformity of the southern flank has been found in the northern flank. None of the beds could be walked out around the syncline because the connections between the flanks are disturbed by many faults and intrusions in the west, and covered by scree in the northeast (Campolanillo).

The general characteristics of this syncline are: a simple southern flank dipping about  $45^\circ$  to the north; a curved axis running EW in the centre and SN near Herrerueta and Campolanillo and finally a very irregular and complicated northern flank, consisting of several minor synclines and anticlines, to be described below as the "central zone".

#### 3.2.2. The central zone

From west to east the following folds can be observed:

- a. Estalaya syncline.
- b. Verdeña anticline with the Peña Tremaya.
- c. Sosa syncline.
- d. Celada anticline.
- e. Celada syncline with Verdiana-Frechila syncline.
- f. Peña del Moro anticline.

The Estalaya syncline is a fairly narrow structure of limited extent. This syncline has been inferred from the dips and top and bottom features. The axis abuts against the anticlinal axis of Verdeña along which a few intrusives are arranged near Estalaya. The Estalaya syncline thus plunges to the NW, but, according to Cope (unpublished report, Leiden) a synclinal axis plunging SE can be inferred from outcrops in the woods on the right bank of the Pisuerga.

The Verdeña anticline is one of the most conspicuous features on the aerial photograph. It indicates a style of deformation in which the right hand blocks move relatively towards the northwest and are upthrust on the left hand blocks. The anticline has a steep western flank, cut off in the north by an important fault of unknown throw (San Salvador).

The axis, which plunges about  $35^{\circ}$  S, runs into a steep fault near the village of Verdeña. Along this fault the Sosa syncline moved towards the NW and partly upwards. A secondary fault, parallel to the larger one, separates a large limestone slice from the synclinal flank. The latter fault flexures out near summit 1361, but the larger transcurrent fault can be followed past the Verdegosa. Near the Verdegosa mineralization has occurred on the fault: calcite, malachite and barite have been found.

The Peña Tremaya limestone is older than the Sosa-Verdegosa limestones (Foraminiferal evidence) and occurs in the form of a very steeply plunging anticline. It is partly bordered by faults but it lies in a series concordant with the Sosa limestone. It seems to be a local, thick development of a limestone belonging to a succession of strata, which can be traced to Celada in the SE. The N-slope of the Peña Tremaya is very steep in the valley of the Pisuerga. The northeastern part seems to form a separate limestone body, imitating the structure of the main limestone-mass. A sandstone, an orthoquartzite of a few meters thick, separates the two as far as can be ascertained.

It is probable that more faults occur in the vicinity than are indicated on the map.

The simplest explanation for the "extraña estructura de la Peña Tremaya" (Alvarado & Sampelayo, 1945) is to assume that it is part of the core of the anticline of Verdeña, but partly disconnected from it by faults and subsequently folded in an aberrant way.

The structure of the Peña Tremaya and adjacent beds reminds one of the "style extrusif" (Viennot, 1927, 1928), which has been extensively described by Castany from Tunesia (Castany, 1955).

The Sosa syncline has vertical flanks for the level of the Sosa limestone, but at the level of the quartzitic sandstone of the Mina San Pedro, it has a steep W-flank, sometimes even overturned and a much less steep E-flank (abt.  $60^{\circ}$ ). The axis plunges vertical at the Sosa (1478 m) and flattens out rapidly to merge with the central depression of the Sierra Corisa syncline. The incompetent shales between the Sosa limestone and San Pedro sandstone have adjusted themselves to the geometry of the fold by forming many small-scale folds.

The syncline has been thrust towards the NW. An indication of a fault running approximately parallel to the western flank of the Sosa syn-

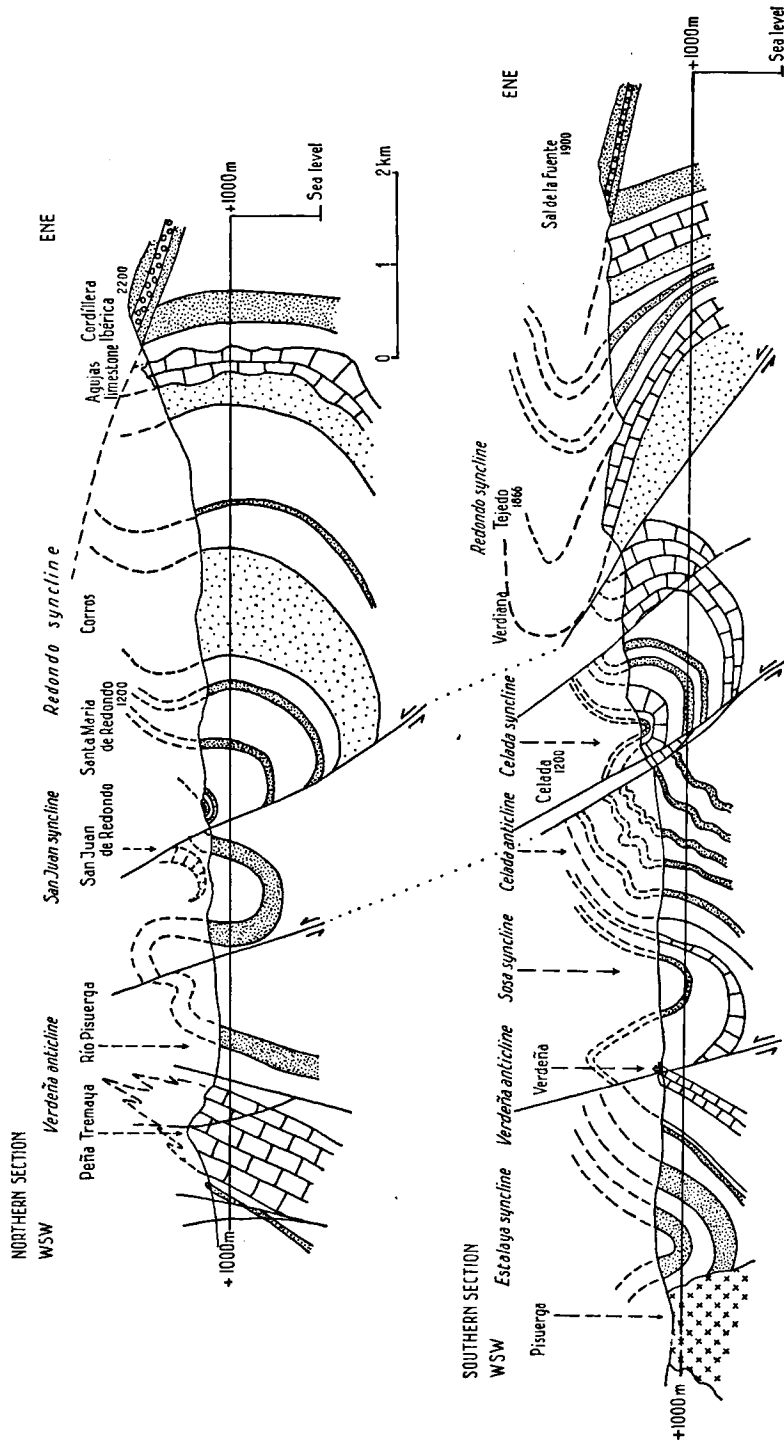


Figure 4. Sections through the Upper Pisuega valleys.

cline is found in the few aberrant dips, a km W of the Sosa. That a fault should be located there, seems to be evident from the whole structure. The most likely interpretation seems to be a steep thrust fault of limited throw, connected with the transeurrent fault of Verdeña in the W and flexuring out in the strike towards the E. This thrustfault, together with the fault of San Salvador, separates a stratigraphically lower and upper series which form one structural element in the Celada anticline, but two definitely different elements in the area of Peña Tremaya and Verdeña.

The anticline of Celada is narrow and asymmetric. The W-flank is overturned in that area where the Celada syncline has been upthrust on the eastern flank. In the north, at Sierra Luenga, the strike swings to the west. Following the flank of the anticline to the south and around the nose, we pass Celada and the Mina Perniana and arrive at a recent test gallery for coal, in which we can see how the coal seam of Mina Perniana abuts against the limestone of the Celada syncline. This locates the position of a transeurrent fault displacing the Celada syncline towards the NW.

The Celada syncline, with its nose at the Collada de la Verdiana (1698 m), and the Verdiana-Frechila limestone are believed to belong to one large narrow syncline. (A photograph of these structures can be found in Wagner, 1955, Lam. XXIX and XXX).

Foraminiferal evidence, especially from the assemblage of smaller foraminifera, points to a different age of Verdiana-Frechila (older) and Celada limestone (younger). Probably the same synclinal axis runs from a point at abt. 1 km N of San Juan de Redondo through both limestone bends, roughly in the direction of Campolanillo.

Thus interpreted, the structure, which might be called "San Juan Syncline", is very similar in style to the narrow Los Llazos anticline mapped in detail by Breimer (unpublished report). On the lithostratigraphic map this anticline would be located in the legend. In a hill-slope north of the Sierra Luenga covered by meadows and woods, a fault can be observed, separating the beds of the San Juan syncline from the sandstones in the core of the Celada anticline. This fault dips about  $45^\circ$  to the east, but it is not certain that it represents the main thrustfault-plane.

The connection of the San Juan syncline and the Sierra Corisa syncline must be sought in the synclinal axis near Campolanillo, east of Celada. Along the sinistral transeurrent faults, which partly are covered by scree, the Celada syncline was moved NW, relative to the Campolanillo syncline (north-eastern extension of the Sierra Corisa syncline). A view of these transeurrent faults as they appear on the right slope of the Castillería ravine is presented in fig. 3. The thrustfault near the Verdiana and south of it, also can be seen in the ravine of the Castillería. Probably that fault also dips steeply to the east and transects one by one the overturned limestone beds of the Verdiana, with nearly the same strike as the beds. (See Wagner, 1955, lam. XXXI).

Adjacent to the Frechila limestone, south of San Juan, a few isolated limestone bodies occur, which are taken together as Peña del Moro limestone. The large colonial corals occurring in this irregularly developed limestone

indicates the biohermal origin of these rocks. The top and bottom indications from corals and the sandstones nearby indicate that an anticlinal axis must be postulated between the Peña del Moro-outcrops and the Frechila limestone-disturbed zone is indicated as a fault on the lithostratigraphic map. It problematic. North and east of the Peña del Moro a fault zone is present, indicated by haphazard dip readings and small faults in many directions. This disturbed zone is indicated as a fault on the lithostratigraphic map. It probably represents a thrustfault along which the large Redondo syncline has been up-thrusted.



Figure 3. View to the north, on right slope of Arroyo de Castillería. Transcurrent faults through Celada syncline.

### 3.2.3. *The Redondo syncline*

The Redondo syncline is equal in area to the central zone. It is relatively simple in structure. The sediments in the western flank do not attain the thickness of those of the eastern flank. This circumstance affected the way of folding. It plunges to the south with an angle varying between 15 and 60 degrees.

The structure is symmetrical in the core, between San Juan and Santa María de Redondo, but the stratigraphically lower beds are strongly overturned in the SE. Quite unexpectedly the western flank is also overturned in places north and south of San Juan de Redondo, but the beds are still sub-vertical.

A zone of flexure extends from El Reboyal (Sta Maria de Redondo) towards a point between Lombatero and Alto Troncas in the NE. In this zone the NE-flank quite suddenly turns from the normal to the overturned position. Towards the south the overturning increases until the beds dip about 15° E in the Peña Tejado. At the basis of this limestone mass the Graded formation can be found dipping 45° E. The difference in dip between the two formations might be caused by disharmonic folding or by

a bedding-thrustfault displacing the overturned massive limestone towards the west.

The Peña Tejedo probably forms part of the overturned eastern flank of the Redondo syncline. This can be inferred from the knowledge that similar overturned limestones at about three levels, occur in this flank with dips and topographical position which allow extension into the Peña Tejedo. Other outcrops to the southeast of the Tejedo roughly can be correlated with it on lithological character. They dip below the Triassic cover.

About the two faults cutting the Agujas limestone and graded bedding in the eastern flank no more can be said than is indicated on the map. If they are steep, which is probable because they transect the contour-lines, they might be interpreted as transcurrent faults of dextral character, i. e. not in agreement with the general style of deformation.

### 3.3. *Small-scale structural features*

Zigzag folds of small size with steep axis plunging some 60° towards the E, can be seen in a hill north of San Juan de Redondo. They have a wave length in the order of 10 m and show sharp angular crests. Such folds testify to strong compression. Similar folds but not so angular occur in a sand-shale alternation one km NE of Celada, in that part of the Celada anticline which has been especially strongly compressed by the upthrusted Celada syncline.

Small size recumbent folds within the Graded formation occur occasionally. They show an almost plastic deformation and die out after a few meters along the axial plane. Their axes tend to dip parallel with the main dip of the synclinal flank.

The small scale folds and faults are concentrated in the zone of the Los Llazos anticline and San Juan syncline.

### 3.4. *Conclusions*

Summarizing we can say that the upper Westphalian and Stephanian A are preserved in a large synclinatorium between San Cebrián and Rabanal in the south and Caloca and Piedras Luengas in the north. The few thousand meters thick sediments are intricately folded and faulted with an asymmetry and thrusting towards the west and sinistral movements along transcurrent faults. Though it is probable that more than one folding phase attributed to the tectonic complication, only the tertiary phase, partly responsible for the Sierra Corisa syncline and other features arranged along an EW line, can be more or less separated from the NNW—SSE varistic trends. (De Sitter, 1957).

In adjacent areas in the NW and SE respectively lie the Casavegas syncline and the Rubagón overturned series. These may be structurally connected with the area figured on the geological map as follows.

The Casavegas syncline is a wide structure connected with the Redondo syncline by the narrow Los Llazos anticline. The connection with the structures of Peña Tremaya and San Salvador remains obscure. The Rubagón area presents sediments of Stephanian A age in structurally the same position as the eastern flank of the Redondo syncline (cf. Cueto y Rui-Díaz, 1926).

However, the Rubagón beds dip much steeper. A direct connection of the flanks is thus, in view of the tectonic complication of the area, a little hazardous. But the location and similarity in direction of the thrustfault of the Rubagón area and the zone of thrusting and narrow, long-stretched folds (San Juan syncline, Peña del Moro anticline, Las Llazos anticline) in our area, is striking<sup>1</sup>). It seems logical to consider these highly disturbed zones as one zone of weakness, probably already partly reflected in the sedimentary record (Los Llazos anticline—Celada zone).

<sup>1</sup>) Cf. Wagner (1955, p. 185—187).



## CHAPTER IV

### THE GRADED SANDSTONE FORMATION

#### 4.1. *Introduction*

##### 4.1.1. *Object of investigation*

Graded sandstones alternating with mudstones occur in the Redondo syncline as well as in several other places in the area studied. The general characteristics of this sand-mudstone sequence are constant within a long stratigraphic section, exposed in the Pisuergra valley. These conditions suggested the possibility of a detailed study of the stratonomy with statistical methods.

The main object of the study has been:

- a. To investigate the lithology of the beds in detail.
- b. To investigate whether regularities exist in the sequence of beds of different lithology, and in the sequence of beds of the same lithology.
- c. To interpret the results in the light of the turbidity-current hypothesis.

##### 4.1.2. *Geological setting*

In chapter II the stratigraphic position of the Stephanian-A graded sediments has been described. The study of these sediments in the field and in the laboratory has shown that the graded sandstone formation and at least the lower part of the Caldero formation must be regarded as "turbidites". The main facts that lead to this conclusion are:

- a. The conspicuous grading of most of the sandstone beds.
- b. The restriction of cross-bedding to one bed at a time.
- c. The occurrence of small-scale lenticular trough type of cross-bedding.
- d. The absence of fossils in situ.
- e. The association of the deposit with slumped lenticular bodies of muddy, biohermal talus breccia and conglomerate.
- f. The extremely persistent thickness of individual beds.
- g. The occurrence of a great variety of sole-markings, characteristic also of known "turbidite" sequences.

The lateral extension of the formation as deduced from the outcrops in the Redondo syncline only, would be a rectangular area of 8 by 2 km trending in a NW—SE direction from Alto Troncas to the Sal de la Fuente. If the correlations as proposed in chapter II are justified, the total extension would be even more, i. e. 20 by 10 km, from Alto Troncas in the NW, to a point near Barruelo in the SW. (See p. 614).

The thickness of the Graded formation varies from 0 to 1000 m. Towards the west it wedges out between shales and sandstones (of neritic character) of the axial region of the Redondo syncline, SW of the Peña Abismo. The

maximum thickness is reached in the section through summit 2222 m. This section is drawn perpendicular to the strike of the eastern flank of the Redondo syncline. Then further to the south the thickness decreases to about 600 m in the Pisuerga valley, and only 50 m is visible just beneath the Peña Tejedo. The thickness of the comparable formation of graded sandstones in the Sierra Corisa syncline is also in the order of 50 m, while in the Rubagón section, north of Barruelo de Santullán, about 250 m of graded beds are exposed.

Near Redondo the formation lies conformably on black shales, without a sharp transition. Further to the north this shale attains a thickness of about 200 m, and there it covers the Abismo limestone. The latter is not present in the eastern flank of the Redondo syncline.

The black shale, as well as the lower part of the Graded formation contains lenticular bodies, up to 10 m thick, of the muddy limestone breccia already described.

Upwards the Graded formation changes gradually into poorly sorted, calcareous, muddy finegrained sandstones and shales, in which the sandstones show neither cross-bedding nor conspicuous grading. These often homogeneous sandstones show very persistent thickness in outcrops showing 20 to 30 meters along the strike. They tend to occur in groups, without shale intercalations. About six or seven of these groups are present in the Caldero formation. They measure each about 20 meters in thickness and the sediment between these sandstone-groups is an alternation of shales with occasional sandstone beds.

The sandstone-soles of this formation show many flute and load-casts. The direction of sediment-transport is about the same as in the Graded formation and it seems possible that these sandstones also have been deposited by turbidity-currents.

The upper part of the Caldero sandstone formation must represent a rather rapid transition from the "turbidite environment" to the continental environment in which the thin Lomba coal seams were formed.

The depth of deposition of Graded formation and Caldero formation cannot be ascertained by palaeoecology, because of the lack of fossils, and the great geological age, but probably it was well below wave-base. The apparent absence of colonial and solitary corals, otherwise so common in the marine shales in this area, the presence of the muddy limestone breccia-slumps and the absence of all sedimentary structures indicative of deposition in shallow water, substantiate this conclusion.

## 4.2. *Lithological description*

### 4.2.1. *Habitus*

The Pisuerga valley cuts the graded beds almost perpendicular to the strike of the bedding. The white-brown sandstones stand out clearly against the intercalated black shales. In the outcrop the coarsest sandstones, which contain some calcium carbonate, are often leached out, they weather yellow, but are greyish-blue on a fresh surface. The sandstones measure from a few up to 50 cm, and, if thick enough, are heavily jointed perpendicular to the bedding plane. Often the upper part is laminated and splits easily along the laminae. The shale above is broken into angular, irregular fragments of

about 1 cm size. In many of these beds the term "mudstone" would be more appropriate, but for simplicity all these finegrained beds are called "shale" in the following discussion. The shale beds measure from 1 to 200 cm. (See fig. 5).

At irregular intervals small bands of concretions occur in the shale, throughout the section. These have a dark, deep brown-red colour, and are grey on the inside. Though they sometimes still show a lenticular form, the concretions mostly occur in continuous beds of about 5 mm to 10 cm thick.



Fig. 5. Outcrop of Graded Sandstone Formation in the Arroyo de la Varga

#### 4.2.2. *Mineralogy*

The sandstones consist of sub-angular quartz grains. Some beds contain considerable amounts of shell-debris. The carbonate contents of two samples of sandstones with shell debris were 11 and 14 %.

Carbonaceous matter, in which sometimes cell-structure is preserved, is common in the sandstones, and probably the black colour of the finer grained sediments is for a large part due to disseminated organic material.

From four crushed sandstone samples, two from the Redondo Graded formation and two from the Rubagón graded beds, the heavy minerals have been separated. Opaque grains constitute about 60 % of these samples. Zircon is abundant, while tourmaline, staurolite and garnet are present in minor amounts. The mineral associations show hardly any difference and in this way no proof of equivalence of the two formations could be obtained.

The black shales contain some mica-flakes and in their lower part a fair percentage of the same angular quartz grains and of the same size as the sandstones. In a few of the graded units the shale contains well-rounded siltstone pebbles, up to 5 mm in diameter, lying separately embedded in the shale.

The concretions, which occur in very persistent beds in outcrops 100 m long, are grey inside, but weather deep brown-red. Chemical analysis of two specimens has given the following result. (See table 4.1.).

The analysis shows that we may consider them as sideritic concretions,

"clay-ironstones", which are very common in coal-bearing sequences, especially on top of coal seams. The occurrence of sideritic concretions is also normal in marine sediments which accumulate in a slightly reducing environment. (Theodorovitch, 1949, Kimpe, 1956, van Voorthuysen, 1956, Pettijohn, 1957, Scheere, 1957). It does not give us any information about the depth of deposition.

TABLE 4.1  
Composition of concretions

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO
1	14.18	4.09	1.47	35.73	1.04	2.75	4.44 %
2	16.62	5.82	6.52	31.80	0.95	1.88	5.30 %
	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	CO <sub>2</sub>	C
1	0.55	0.60	2.39	0.49	0.52	31.—	0.87 %
2	0.68	0.76	2.73	0.48	0.53	25.—	0.82 %

#### 4.2.3. *Grainsize*

The maximum size of the quartz grains is roughly proportional to the thickness of the sandstone bed, a relation already noticed in graded and cross-bedded sandstones by Fiege (1937), Kurk (1941) and Schwarzscher (1953). In the Graded formation the size of the largest quartz grain never exceeds 1 mm. The shell-debris, occurring in the coarsest lower part of the sandstone beds, have a mean diameter of about the size of the largest quartz grain in the same level, and may measure up to 6 mm. It appears, therefore, that not size, but weight has been the most important factor in the sorting process. In the lower part of the sandstone bed the quartz grains touch each other, but not far from the base the clay-content is such that the grains generally lie separated in the matrix. Also at the base the average number of grain contacts per grain is appreciably lower than close packing would generate.

Nearly always the top part of the graded sandstone beds is laminated. This laminated part is generally thin with respect to the jointed part below, and forms the transition to the shale above. It is this rather rapid transition that enables us to distinguish a "sandstone part" and a "shale part" in the graded unit. Of course the very thin sandstone beds are in fact sandy siltstones or even laminae of siltstone. These will be called sandstones here, because it is not practical to make a distinction between the two in the present study, because complete transitions between finegrained sandstones and siltstones occur, and the process of deposition is probably the same for all.

In some of the beds the grading is obvious in a hand-specimen, but in many beds it is only clearly visible in thin-sections. To get an insight into the kind of grading involved, a set of thin-sections were made, perpendicular to the bedding plane, through a 6 cm thick graded sandstone bed. The specimen shows lamination in the upper two cm. The results of grain counts and size-analysis from microphotographs, without correction for the "thin-section effect", are shown in figure 6 and table 4.2. In this case it did not seem necessary to make use of one of the many methods proposed to calculate the

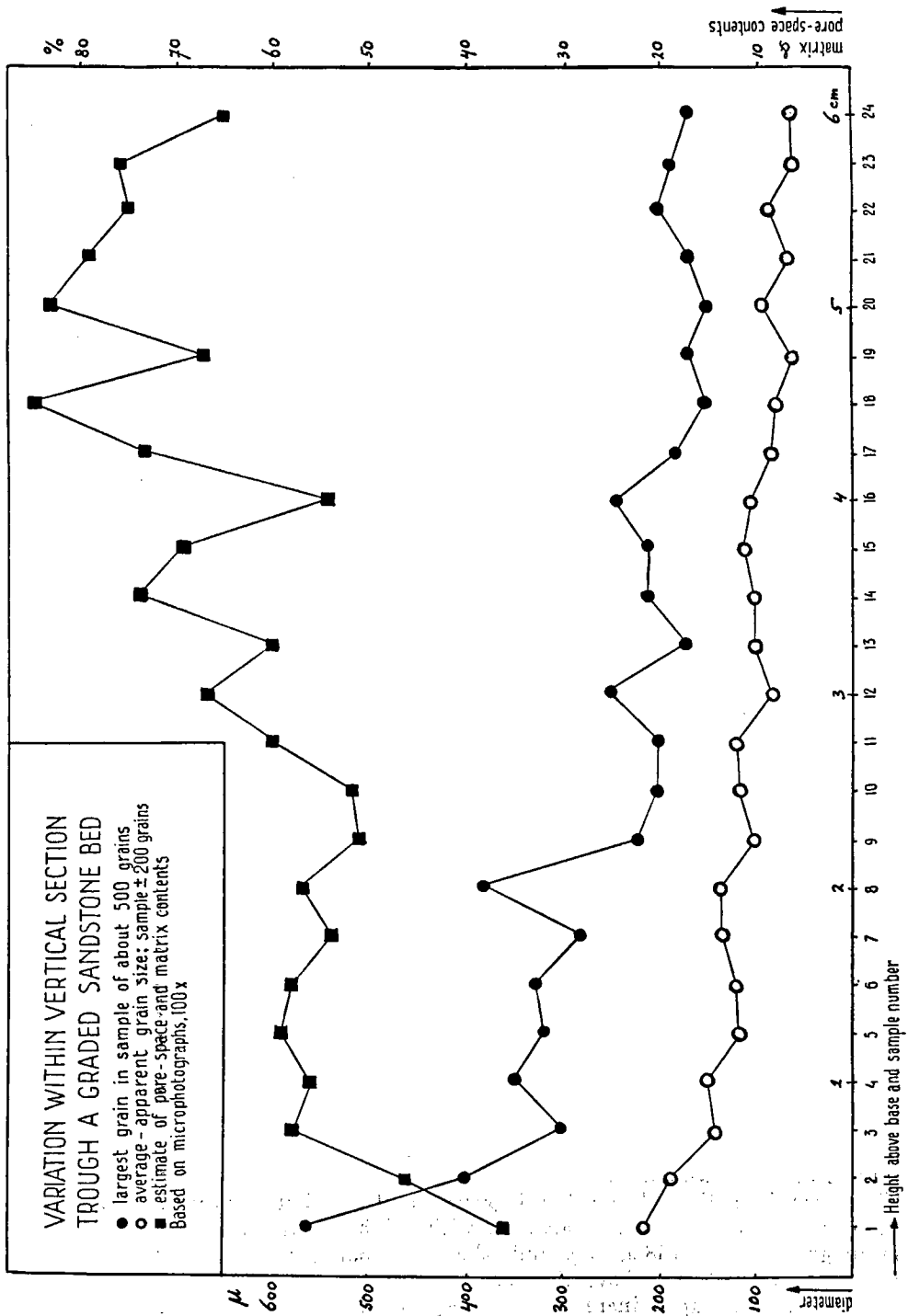


Figure 6.

grainsize distribution from the apparent grainsizes. (Krumbein, 1935, and several others).

For comparison with sieve data we should keep in mind that both maximum and average grainsize are too small, but they are useful for comparison within the thin-section through the graded bed. The estimate of matrix- and

TABLE 4.2

Variation in grainsize and matrix contents in a vertical section of a graded sandstone bed

1 Sample number	2 Height in mm above bottom- surface	3 Diameter of largest grain in sample, in microns	4 Average grainsize of quartz, in microns	5 Estimate of matrix and porespace in vol. percent.	6 Number of grains in sample
1	3.25	570	216	36	234
2	5.75	400	188	46	252
3	8.25	300	142	58	273
4	10.75	350	152	56	221
5	13.25	320	117	59	254
6	15.75	330	117	58	200
7	18.25	280	133	54	172
8	20.75	380	136	57	246
9	23.25	220	100	51	191
10	25.75	200	114	52	148
11	28.25	200	119	60	154
12	30.75	250	79	67	145
13	33.25	170	103	60	129
14	35.75	210	101	74	138
15	38.25	210	111	69	195
16	40.75	240	106	54	155
17	43.25	180	84	73	181
18	45.75	150	79	85	251
19	48.25	170	60	67	267
20	50.75	150	94	83	221
21	53.25	170	65	79	228
22	55.75	200	87	75	211
23	58.25	190	61	76	185
24	60.75	170	64	65	137

porespace-content is based on surface percentages. As the thin-section cuts at random through the quartz particles, which are dispersed at random in the clay, it is quite a reliable estimate of the volume not occupied by quartz grains. (Chayes, 1954).

Of course no distinction can be made between the porespace and the matrix, because on the 100-times magnifications used, particles smaller than  $10\ \mu$  hardly can be seen.

In a graded sandstone-bed, largest grainsize together with mean grain-size diminishes from the base upwards, as was shown by Radomski (1958). Radomski also observed that this decrease follows roughly an exponential law. The same is noticed here: the logarithms of maximum grainsizes show a negative, reasonably linear regression with height above base. In another bed mean grainsizes of  $138\ \mu$ ,  $55\ \mu$  and  $43\ \mu$  were found, respectively at the base, at 1 cm and at 2 cm above the base.

The rather rapid increase of porespace- and matrix-content cannot be

ascribed to the increase of porosity with decreasing grainsize because of the compaction. The greater part of it must be attributed to the increase of the clay-content towards the top of the sandstone bed.

The range of variation of the variables measured increases towards the top of the bed. It is the reflection of the lamination of the upper part.

#### 4.2.4. *Bedding types*

Though graded bedding is the most common type in this formation, other types do occur, sometimes alone, sometimes in combination with graded bedding. Of the bedding types described by Radomski (1958) from the Podhale Flysch, the following have been observed in the Graded formation, and are listed in order of their importance.

- a. Continuous graded bedding.
- b. Laminated beds.
- c. Cross-laminated beds.
- d. Homogeneous beds.

Among the combinations those of the continuous graded beds with laminated top parts are the most common.

The small-scale cross-lamination always is confined to the relatively thick sandstone beds ( $> 3.5$  cm). It mostly is of the irregular lenticular-trough type, which Van Houten (1954) described from the Ordovician Martinsburg slate and other "turbidites". In some instances the direction of transport can be deduced from the more regular cross-lamination.

In some of the sandstone beds the laminated part shows convolute lamination (Ten Haaf, 1956) in combination with irregular cross-lamination, but not with current-ripplemark.

#### 4.2.5. *"Turbidite shale" versus "normal shale"*

Bokman (1953) considers the shale between graded graywacke beds as representing "quiet-water marine sedimentation which was proceeding continually" ... "The periodic appearance of coarser material (the greywackes) represents, in a sense, foreign intrusions into this zone of sedimentation".

But earlier, Douglas, Milner & Maclean (1937) noticed the similarities in mineralogical and chemical composition between the siltstones and shales in the graded Halifax Series, Nova Scotia. This induced them to consider both lithological types as deposited by the same mechanism which sorted them into coarse and finegrained beds.

In the Carpathian flysch Ksiazkiewicz was able to find in an utterly homogeneous shale bed, the transition plane between a lower part with benthonic, resedimented foraminifera, and an upper part with a pelagic microfauna.

A similar result was obtained by Radomski (1958) who in the Podhale flysch could distinguish between "turbidite shale" with some angular quartz grains, and "normal shale", with rounded, sometimes frosted, aeolian sand grains.

These observations lead to the conclusion that not all the shale, but only some part of it belongs to the "normal" sedimentation, between the occurrence of turbidity currents. The evidence from deepsea-cores (Erickson, 1952) indicates that the finer grades can be deposited by the tails of turbidity-currents in relatively short time. In the North Atlantic layers of grey, calcareous clay,

often separated from the "normal", brown deepsea clay below by a film of silt, probably were deposited by turbidity currents which kept to the lowest parts of the irregular bottom.

In the Graded formation the shale attains sometimes considerable thickness. Therefore we should take into account the possibility that such an invisible transition occurs in some of the shale beds. That "normal" sedimentation can play a significant part is clear from the description of recent turbidites by Gorsline & Emery (1959).

### *4.3. Statistical methods applied to the thickness measurements*

#### *4.3.1. Introduction*

The measurement of three profiles, respectively with 364, 335 and 55 graded units, furnished the material for the statistical investigation. The two longest sections are situated in the Pisuerga valley, where the river cuts through the overturned eastern flank of the Redondo syncline.

The "second series" (364) refers to the stratigraphically lowest section, and the "first series" to the upper part of the Graded formation. Between the two sections occurs an estimated stratigraphic thickness of 450 m. The thicknesses of the second and first series are respectively 59 and 76 meter.

There are several ways of approach to the statistical analysis of the data, which here have the form of a time-series. A restriction in choice is caused by the probably random occurrence, in time, of the turbidity currents, because this excludes some methods applicable to equal time-interval sequences, as used in glacial varve analysis.

After the definition of the lithological units, (variates) which are supposed to belong to the same universe, it is necessary to get an insight into the size-frequency distribution of those units. In that case the time-series is regarded as an aggregate of values, drawn at random from a homogeneous universe. Often the frequency histograms can show anomalies if the aggregate was drawn from an inhomogeneous universe: e.g. polymodality or platykurtic shape of the normal distribution. Similar irregularities also arise, in other distributions, from the mixing of two populations, or from cyclic variation and trends.

Frequency distributions may also show if correction for gradual change can be carried out with the aid of moving averages of the original data, or whether first a transformation should be used to symmetrize the distribution.

The frequency distributions themselves present the problem of the origin of the thickness variation, which remains after the subtraction of the systematic variations with time, and which is rather subjectively called "random variation".

After investigation of the associations (non-parametric correlation) between the lithological units (variates), e.g. sandstone-thickness, remains the investigation of the regularities in the succession of variates of one sort.

The main theme in the serial correlation tests is comparison of the sequence of data with a hypothetical random sequence of data drawn from the same universe. It is then possible to keep or reject the hypothesis that the observed sequence can be considered as a random sequence. If we can prove that the series is not a random sequence, we should answer the question "what is the alternative"?. This is a far more difficult question. Several methods to solve this problem have been tried.



#### 4.3.2. *Measuring technique and the possible shortcomings of the material used in the statistical analysis*

The sections have been measured with tape to the nearest cm. The slope of the outcrop cuts almost perpendicular through the bedding planes, thus the stratigraphic thicknesses could directly be measured. It did not seem necessary to make a "compound section", by averaging the thicknesses of a bed measured in a few parallel sections, because important lateral variation of thickness has not been observed in the outcrop. Only the concretion beds pinch out and swell along the bedding planes. In that case an average thickness was estimated.

The transition from sandstone to shale in most cases is rapid enough to avoid bias in the sandstone- and shale thickness data.

Important is the fact that almost no beds have been found thinner than about 5 mm. This can be caused, in the case of the sandstones, by the positive association of grainsize with bed thickness. If the grains are too small, they mix with the underlying shale and make no sharp bottom contact. It then is easy to overlook such a lamina. The omission of a few sandstone beds would be very serious for a periodogram or harmonic analysis, especially if short waves are being looked for. In the present study it has no importance, provided that it does not occur frequently. The result of an omission of a few sandstone beds is a surplus of thick shale beds, and, consequently, a few too high shale percentages. The study did not show any alarming sign in this direction.

All relatively coarse beds in graded units, if they contain grains of silt or sand size are called for convenience "sandstones". The rest, even if it contains some siltstone in the lower part, or siltstone pebbles, is called "shale". Concretion thicknesses have been included in the shale thicknesses, for they represent the concentration of siderite in a special level in the mud. The average thickness of the concretion beds is very small compared to the average shale thickness. No trouble will arise through this method because the minor deviations in thickness generated in this way, only occur in the about 10 % of the units that contain clay-ironstones.

If a graded unit can be divided into a sandstone part and a shale part, a third interesting variate arises: the shale percentage in the unit. It is calculated as thickness of the shale-part times 100, divided by the total thickness of the unit. It plays the same role as a sand/shale ratio of the graded unit, but has some advantages. Its variation of course is of a complex nature; it is influenced by sandstone as well as shale thickness fluctuations, if these do not coincide. It is useful in comparing units with different total thickness.

The grouping of the thicknesses in the field into cm-classes, caused an irregular form of the shale-percentages histogram, but did not disturb the normal statistical methods.

In the statistical analysis the next four variates have been used

1. Sandstone-thickness.
2. Shale-thickness.
3. Shale-percentages.
4. Position of clay-ironstone bed in the graded unit.

### 4.3.3. Frequency distributions

Pettijohn (1949) showed that the frequency distribution of the thicknesses of graded units tended to follow the log-normal law, which can be expressed as:

$$y = \frac{1}{\sigma \sqrt{2\pi}} \cdot \frac{1}{x} \cdot e^{-\left[\frac{\ln x - m}{\sigma}\right]^2}$$

in which  $\sigma$  and  $m$  are standard deviation and mean calculated from the log values. (Edgeworth, 1903).

Since then it has been shown by many authors that all bed thickness-distributions are markedly skew. (Kolmogorov, 1949; Vistelius, 1950; Simonen & Kouvo, 1951; Bokman, 1953; Schwarzscher, 1953; Potter & Siever, 1955).

These investigators showed how special lithologies also have special thickness distributions. Sandstone and shale-thickness distributions often have the form of a symmetrical distribution, which has been truncated at the left side. The limestone distributions have a peculiar form. They start like an exponential distribution, but are truncated suddenly at some maximum thickness.

These investigations suggest the possibility to use bed-thickness statistics as comparable sedimentary properties.

Kelley, 1956, proposed a "stratification index", which is defined:

$$\text{Stratification index} = \frac{\text{Total thickness in feet}}{\text{Number of beds} \times 100}.$$

It is a reciprocal of the mean thickness of the beds in feet. Bokman (1957) proposed the  $\theta$ -scale, for thickness class-intervals. It is a scale like the Wentworth scale for grain-sizes.

$\theta$  is defined as:

$$\theta = {}^2\log \xi$$

in which  $\xi$  is the bed thickness in inches. Mean and standard deviation are then calculated and expressed in  $\theta$ -units. This method thus takes care of the skewness of the involved distributions.

Just as the  $\phi$ -scale in grain-sizes, it has some drawbacks if the actual distributions depart widely from the log-normal law.

A practical and theoretical difficulty for the study of bed-thickness distributions arises from the trends and cycles in the successive thicknesses, within one section. These seriously can disturb the original frequency distributions. Great difficulties arise when one tries to correct the data for such trends. Selection of similar parts of a section seems the appropriate method, but it involves the subjective separation of cyclic- or trend-variation from the "random" variation. In the case of the graded beds it even is impossible, because of the small-scale fluctuations of the thicknesses, which cover only up to 10 beds. (See 4.3.4.)

Deductive approach to the origin of thickness variation.

Kolmogorov (1949) tries to explain the typical form of some thickness distributions, by assuming a system of sedimentation, in which time-intervals of deposition alternate with intervals of sub-aquatic erosion. If the expectation of deposition thickness is greater than the expectation of the amount of erosion, some beds or parts of beds, are preserved. The thickness of beds thus formed, can be shown to follow a typical distribution, which is caused by the truncation of a theoretical, symmetrical distribution of differences

between deposited thicknesses and consecutive erosion-amounts. Kolmogorov assumed, just as an example, a De Moivre ("normal") distribution for the differences and calculated the resulting conditional distribution of bed thicknesses. The effect is shown in fig. 7.

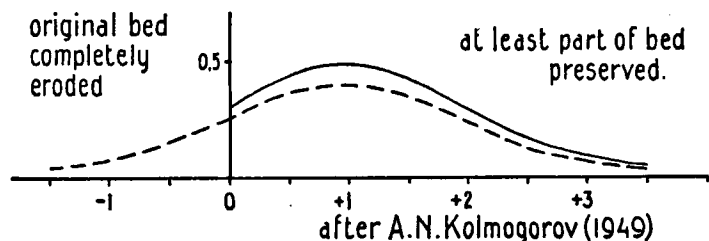


Figure 7. Skew thickness frequency distribution arising from penecontemporaneous erosion. Normal distribution used as an example.

The frequency distributions of sandstone and shale thicknesses of the Graded formation.

The thickness-frequencies of the sandstone and shale beds have been plotted on cumulative, log-normal probability paper (cf. Pettijohn, 1949). From these graphs (figs. 8 and 9) it can be seen that both sandstone and shale data fit the log-normal distribution rather well, but that a systematic deviation occurs for the thicker beds. The deviation is in this sense, that thick beds occur less frequently than could be expected if the distribution followed exactly the log-normal.

The straight lines drawn through the points on the graph, have not been calculated from the data, but in these cases serve the same purpose, i. e. the comparison of the cumulative curve with a straight line. In these graphs, partly by the choice of class-boundaries, no apparent difference between the sandstone and shale thickness distributions, other than average-difference, can be noticed. But if histograms are drawn, with arithmetic size classes, some characteristics of sandstone and shale distributions can be seen. In figs. 10 and 11 such histograms are shown. The first, second and third series refer to the Graded formation. The "Piedras Luengas" refers to a graded sandstone formation of probably Lower Carboniferous age, along the road Cervera-Potes, near the road junction north of the Piedras Luengas pass.

One of these features is that the sandstone-histograms, in all four cases, have their mode in the first class, while the shale beds, apart from a much larger variance, have their mode not in the first, but in the second or third class. Practically a sandstone bed thinner than the size of a sand grain is an impossibility, and the practical limit of sandstone thickness will lie near 0.5 mm. Then also the sandstone frequency distribution will show a zero-frequency below a minimum thickness, like the shale thicknesses do in these cases. A part of the apparent differences in type between the sandstone and shale distributions observed, can thus be ascribed to the lack of measurements in the 0—0.5 cm class and choice of class-boundaries. It is not probable though, that both distributions would match if reduced to the same scale.

The cause of this difference in distribution might result in part from the erosion between successive graded units, which, in the Graded formation

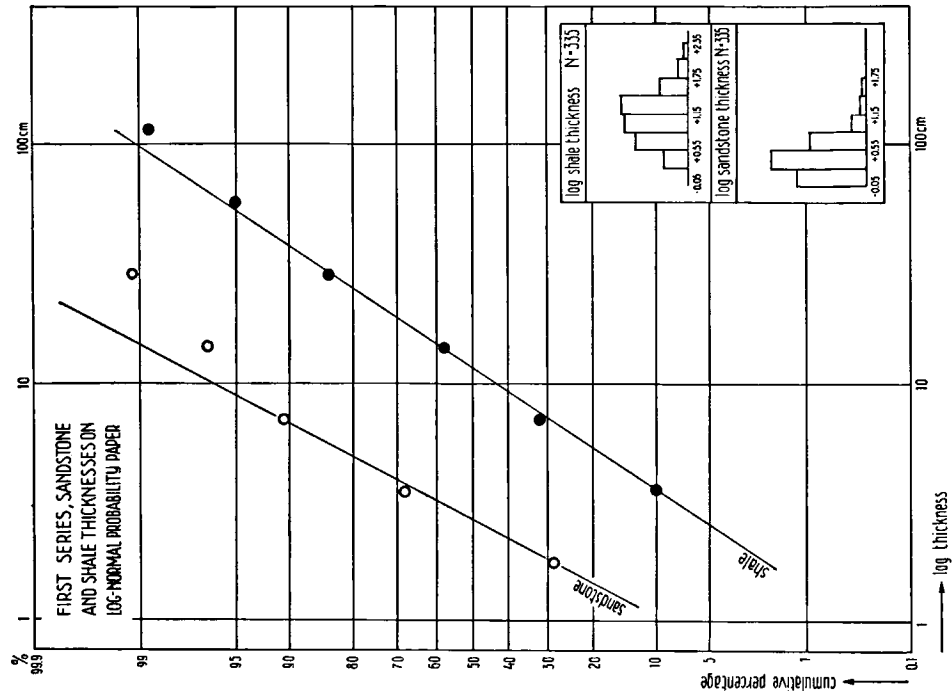


Figure 8.

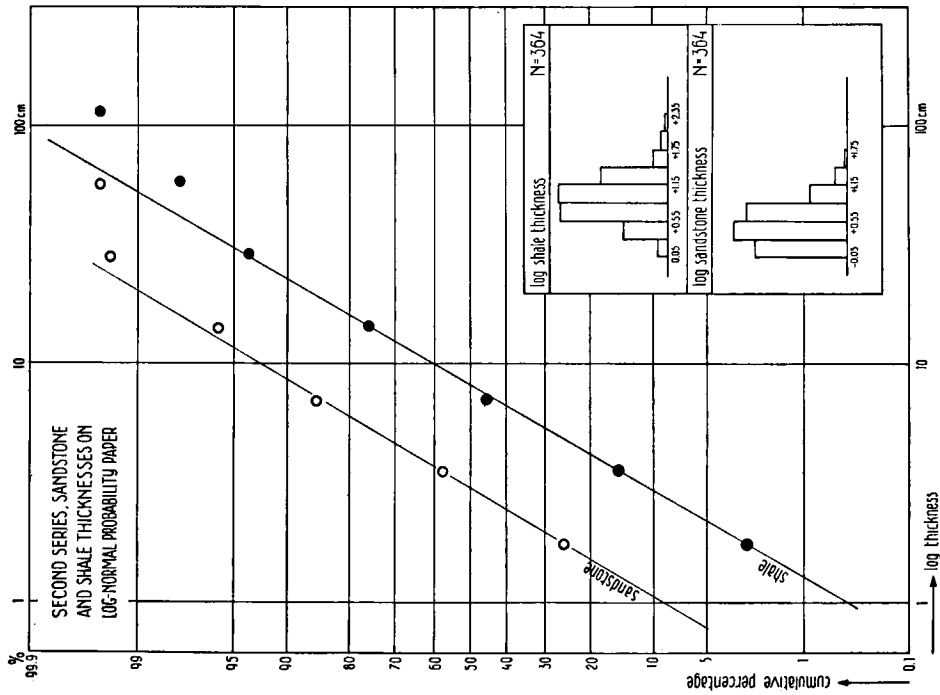


Figure 9.

only attacks the shale parts. In other graded sandstone formations the sandstones are eroded as well. Probably even then a difference would be noted because of completely lacking shale beds not taken into consideration or counted as zero thickness. Also the occurrence of a "normal part" of shale above a turbidite mudstone or shale contaminates the distribution of shale thicknesses if they are apparently the same and measured as one bed.

The complexity of the problem leads us to separate between sandstone and shale thickness if an attempt should be made to explain the thickness distributions of the graded units. The sandstone thicknesses are the best indicators of the size of the turbidity currents, but to a small extent only, because turbidity currents of the same size tend to deposit thicker sandstones near the source than far out in the basin.

#### Glacial varves versus slump-generated turbidite beds.

From the study of the histograms a practical result was obtained with respect to the following problem.

Pettijohn (1957, p. 178) mentions the difficulty of distinguishing thin bedded finegrained marine graded bedding from true glacial varves deposited yearly. If we compare the histograms of the "sandstone" thicknesses of true Pleistocene varves (Reeds, 1921, fig. 9 and 10), and of thin graded bedding which has no connection with glacial deposits, a striking difference is observed. In figure 12 two representative examples have been drawn. If total thicknesses had been used the difference between the thickness distributions would have been much less obvious.

Generally the glacial varve-thicknesses are better sorted (without log-transformation) the  $S_0$  lies near 0.6—0.7.  $S_0$  calculated as the square root of  $Q_3/Q_1$ .

Larger is the difference in skewness: ( $S_k = Q_1 Q_3 / M d^2$ ): the varves have  $S_k$  around unity (0.9—1.1), while the slump-generated sandstone thicknesses have  $S_k = 0.5$  to 0.6.

The difference in sorting might be explained by the smaller range of variability for the quantities of sediment available for the varves each year. The irregular occurring turbidity currents, supplied by subaqueous slumps have much less restriction in the choice of quantity, for they may involve the sedimentation of many years at the slope-area from which they originate.

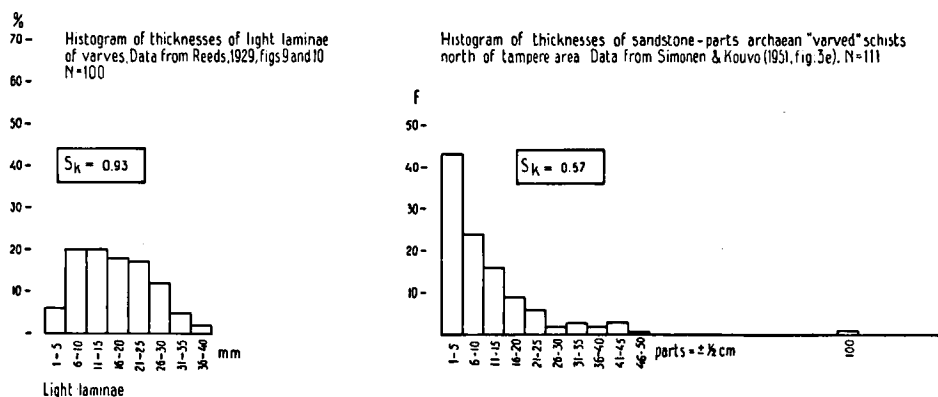


Figure 12. Comparison of sandstone-thickness histograms.

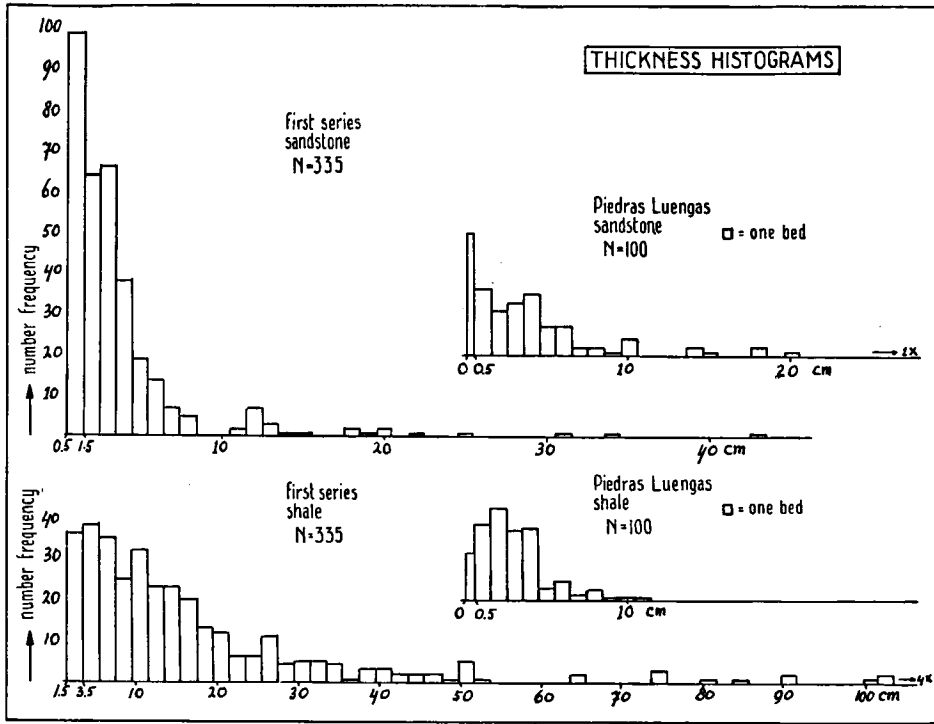


Figure 10.

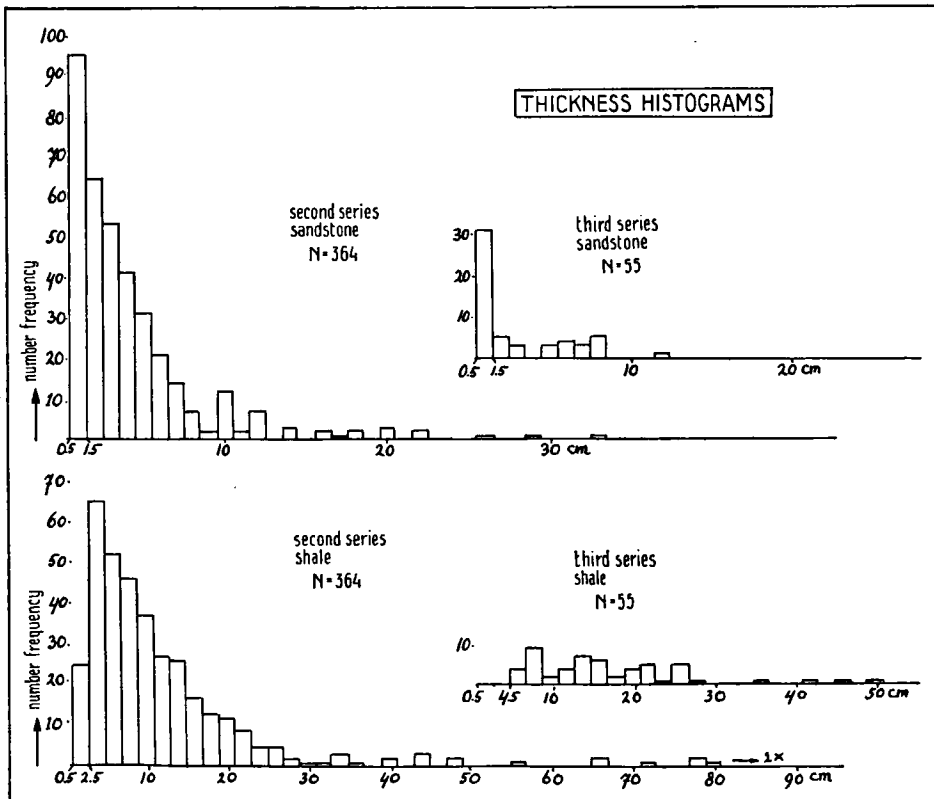


Figure 11.

The shale-percentage distributions show no polymodality other than ascribable to the grouping of the thicknesses into cm-classes in the field. The distribution is very roughly normal. The averages of the shale percentages are respectively 80.1 % and 70.44% for the first and second series. If the average shale percentages would have been higher, an angular transformation could have been necessary to obtain a better graph. (See enclosure 3 and 4.) In both the first and second series the shale-percentages show cyclic variation with small amplitude compared to the amplitude of the oscillations. Apart from such vague cycles with mean cycle-length of about 50 and 70 graded units, a certain trend occurs in the second series. A reasonable correction for result, can be obtained by the use of a moving average of the original percentage data.

The conclusions of the study of thickness frequency distributions are:

1. Generally, for all sediments in which bedding can be measured, it is useful to look at both the long-normal probability paper and the histogram on arithmetic base.
2. In the case of graded bedding the log-transformation normalizes the data sufficiently to apply several methods based on the normal distribution.
3. The histograms do not show polymodality.
4. The histograms are markedly skew, especially the sandstone thicknesses, and afford distinction between glacial varves and slump-generated turbidite beds.

#### 4.3.4. *Relationships between the measured variates*

Hypothetical system of sedimentation in the Graded formation. In figure 13 this system is indicated schematically. Five basic variates are involved, which for convenience will be denoted by the following symbols:

- a. Turbidity-current sandstone thickness.
- b. Turbidity-current shale thickness.
- c. Position of clay-ironstone bed within graded unit.
- d. Thickness of shale deposited by normal agents.
- e. Amount of erosion by the turbidity-current that deposited the next bed.

The actual measurements give the following variates:

- |   |   |
|---|---|
| (a)   | "Sandstone thickness".  |
| (b + d — e)                                 | "Shale thickness".  |
| $\frac{(b + d - e) 100}{(a) + (b + d - e)}$ | "Shale percentage".   |
| (c)   | "Position" expressed as percentage of shale thickness below the concretion level. |

The associations found between these measured variates can give information about relations existing between the basic variates. Here use is made of association tables to search for relationships, though in some cases also correlation coefficients have been used. The  $2 \times 2$  table involved much less labour though and gave as much information. The relationships among variates might also explain why and how the variates themselves change with time. Therefore it is useful to draw attention to the fact that the three measured variates sometimes show a definite trend, e.g. the shale percentages of the second series. (See 4.3.4.).

### Sandstone-shale thickness correlation.

The most prominent association exists between the sandstone and shale thicknesses, with association coefficients exceeding 0.9 in some instance. For example, if the sandstone beds of the first series are divided into thin and thick beds with the dividing point at 3.5 cm thickness, and the same with the shale at 9.5 cm thickness, the first 100 graded units give a coefficient of association  $Q = +0.929$ , with S.E. of  $Q = 0.053$ , hence  $P < 0.001$ . The association is so strong that it can be readily seen in parts of the graphs I and II, where the logs of sandstone and shale thicknesses have been plotted in opposite directions along a line, with bed number as abscis.

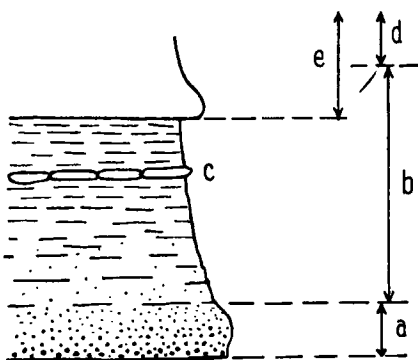


Figure 13. Hypothetical system of sedimentation.

A product-moment correlation coefficient has also been calculated from 200 units of the second series. The logs of thicknesses have been used here. The data have been corrected for the large trend by a moving average. The result was a correlation coefficient  $r = +0.44$  ( $P < 0.001$ ). In the first series the result was  $r = +0.55$  ( $P < 0.001$ ).

These results were not surprising, for already in the field an association was noted in parts of the sections.

For comparison a correlation coefficient between thicknesses of coarse and finegrained beds from the graded beds in the Tampere area, Finland (Simonen & Kouve, 1951), has been calculated. The result from 102 pairs of beds, coded in the logs of thicknesses gave  $r = +0.38$ . Another example can be found on Plate 22 of Pettijohns "Sedimentary rocks" (1957). Here almost perfect correlation is present between silt and slate thicknesses of the core.

What we have proved here is the association between the variates (a) and  $(b + d - e)$ . The interpretation can be given as follows. The most probable relation exists between the basic variates a and b. Kuenen showed in his experiments that a special composition of clay and sand is the most favourable for obtaining a relatively stable suspension. This suggests that only slumps with compositions varying between some boundary-compositions, could generate turbidity-currents, able to reach the site of deposition<sup>1</sup>).

<sup>1</sup>) The possibility is not excluded that part of the mud arrived in the form of mud-flakes, coprolites, etc. (cf. Dzulynski et al, 1959).



The association would then be caused by a restriction of possible compositions, while the independent  $d$  and  $e$  variates disturb the association but little.

If this interpretation is correct, we are in a position to say something more definite about the influence of  $d$  and  $e$ . For both will decrease the coefficient of association if their influence increases. The signs of  $d$  and  $e$  in  $(b + d - e)$  indicate in which way the shale thickness, and consequently the shale-percentages would be affected by them. Without influence of  $d$  and  $e$  the shale percentages would fluctuate around some special mean shale percentage, dictated by the composition of the turbidity currents, and distance from which they come. The influence of  $e$  is to decrease this percentage, while  $d$  would cause an increase.

The shale-percentage mean which is associated with the strongest association between sandstone and shale thicknesses is that which is nearest to the "composition-shale-percentage".

In table 4.3. use is made of the large trend in the shale percentages of the second series. Association tables for the sandstone and shale thicknesses have been set up for parts of the series, which are characterized by different average shale percentages. The result is also plotted in the graph of figure 14. In the Graded formation, in the second series outcrop, a shale percentage of 80 % seems to be normal, while in the larger part of this series the influence of  $e$  causes lower percentages. The influence of  $d$  is noted where the formation grades into shale without sandstone beds.

This percentage of 80 % shale has no special meaning for all turbidites; it only reflects the "composition of the turbidity current at the site of deposition", which is not the same as the initial composition at the slump-area. Experimental studies (Kuenen) have shown that the composition of the turbidity-current gradually changes during its course through deposition, and perhaps through erosion of the mud surface over which it flows.

The gradual change of the influence of  $e$  must be regarded as responsible for the large trend in the shale percentages. For if only a gradual change in the composition of turbidity-currents was responsible, no marked change in association coefficient between sandstone and shale thicknesses would be noticed.

The simultaneous occurrence of trends in the sandstone thicknesses and the shale percentages in the second series (see graph II) can be explained in the following way.

If the trend in the shale percentages is not caused by a gradual change in the composition of successive turbidity-currents, it is probable that the trend of the sandstone thicknesses neither can be explained by this mechanism. Then we should investigate the possibility that the trend in sandstone thickness is caused by a gradual change in magnitude of the successive turbidity currents, i. e. a trend in the initial thicknesses  $a + b$ . A thick initial turbidite bed would mean a big turbidity-current, and consequently, a high erosive power of the head of the current. This explanation seems to fit the observation reasonably well.

Another factor which could be of influence here is the gradual change in the rate of occurrence of turbidity-currents. The amount of erosion between units (cf. trend in shale percentages) could vary according to the mean length of time intervals between successive turbidity-currents. A long interval would give the clay surface time to consolidate in such a way that it could better

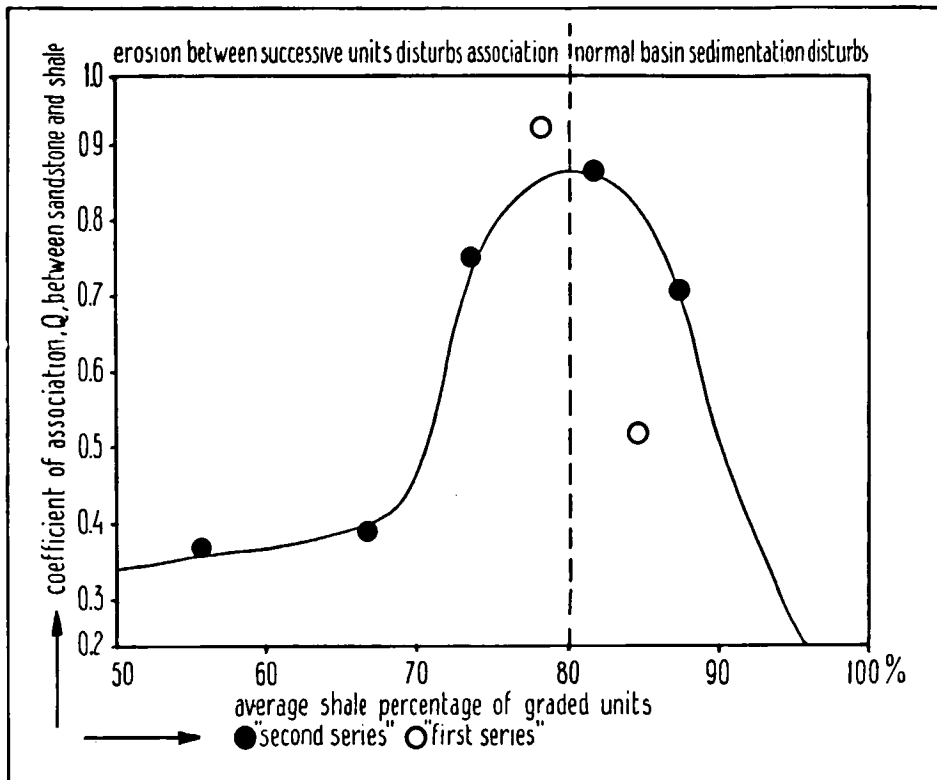


Figure 14. Relation between correlation-strength of sandstone and shale thicknesses of units and average shale-percentage.

TABLE 4.3

Association-strength between sandstone and shale thicknesses related to average shale percentages of the graded units

Part of series, unit numbers	Average shale percentage in unit	Coefficient of Association
<b>Second series</b>		
1—100	56	+ 0.376
51—150	67	+ 0.394
151—250	74	+ 0.759
265—364	82	+ 0.875
315—364	87.5	+ 0.721
<b>First series</b>		
1—100	78.5	+ 0.929
236—335	85	+ 0.527
<b>Third series</b>		
1—55	87	+ 0.905

resist erosion. But in that case no coincidence of sandstone thicknesses and sandstone percentage trends would necessarily occur.

Oscillations of the composition.

A rather high negative association is found between the thickness of the sandstone and the shale percentages of the graded units. Or, what is the same, a high positive association between sandstone thickness and sandstone percentage. At first sight this seems obvious, but it is not. For if the sandstone is thick the shale also should be thick, which means a thick unit in which the percentages remain the same. For this reason the association between (a) and its percentage is strong where the association between (a) and (b + d — e) is weak, while the reverse is also true. This relation is indicated by tables 4.4. and 4.5., in which respectively a part of the first series with strong sand/shale association, and a part of the second series with weak sand/shale association have been analysed. Similar results can of course be obtained from the shale thicknesses as compared to the shale percentages.

TABLE 4.4

Association between sandstone-thickness and shale percentage in first 100 units of second series. Percentages corrected for trend by 21-item moving average.

	Thick sandstone > 4.5 cm	Thin sandstone < 4.5 cm	$\Sigma$
Shale percentage in unit above mean.	13	42	55
Shale percentage in unit below mean.	32	13	45
$\Sigma$	45	55	100

$\chi^2 = 21.0$ ,  $P < 0.001$ . Yule's Coefficient of Association  $Q = -0.776$ .

TABLE 4.5

Association between sandstone thickness and shale percentage in 200 units of first series. Percentages not corrected for trend, for no visible large trend occurs, but cycles with amplitude relatively small compared to the variation.

	Thick sandstone > 3.5 cm	Thin sandstone < 3.5 cm	$\Sigma$
Shale percentage in unit above mean.	23	84	107
Shale percentage in unit below mean.	34	59	93
$\Sigma$	57	143	200

$\chi^2 = 5.6$ ,  $P < 0.05$ . Yule's Coefficient of Association  $Q = -0.355$ .

This "spurious" correlation between the sandstone-thickness and its percentage in the unit is just natural if the composition of the turbidite beds (before erosion) varied from bed to bed. But the total thickness of the turbidite beds (a + b) also could vary from bed to bed, and the question

arises if we could find a way to separate these variations of total thickness on the one hand and of composition on the other.

An important argument in favour of composition variation is found in the correlation mentioned. This may be summarized as follows.

If only variation in total thickness was present, and composition constant, negative correlation would arise by the influence of  $e$  (provided that  $\epsilon(d - e) < 0$ ). This can be shown thus:

Let the sandstone thickness be  $a$ ; the shale thickness is then  $k.a$ . The sandstone percentage is then, after erosion-amount  $z$ :

$$\frac{a \cdot 100}{a + k.a - z} = \frac{100}{1 + k - z/a}$$

If  $a$  increases with a positive thickness  $r$ , the sandstone percentage, on the basis of the same composition of the unit, decreases to

$$\frac{100}{1 + k - z/(a + r)} < \frac{100}{1 + k - z/a}$$

in which  $z$  is taken the same because of its independence of  $a$ .

That no negative association between sandstone thickness and its percentage is found in parts of the sequence in which the erosion played an important part, thus indicates that a fair amount of composition variation is present. More than this rough conclusion may not be gained by this method.

#### Clay-ironstone beds

The clay-ironstone beds are randomly distributed over the sections. The second series has 29 concretion beds, the first series has 59. They tend to occur in the upper parts of the shale beds, as can be seen on table 4.6., in which the data from the three series are combined. The favourite position of the concretions in the upper part point to a preference for finegrained sediments, or to a position near the sedimentwater interface, or both.

The fact that in 32 units the topmost bed is clay-ironstone suggests that some peculiarity of the unit is involved in such cases. The association found in table 4.7. is the confirmation of the idea that such units suffered generally more erosion than the other units in which concretion-levels occur. That the low shale percentage in these cases are erosion-generated may be indicated by the fact that no association has been found between the position of the clay-ironstone in the unit and the thickness of the sandstone.

That erosion in these 32 cases stopped at the surface of the concretion bed can be explained by assuming that the diagenetic processes had hardened the concretions already, whereas the clay below and above was still weak. The head of the turbidity current which deposited the next sandstone bed washed the tough concretion bed clean before depositing its load.

#### 4.3.5. Serial correlation

The graphs of the sandstone and shale thicknesses and the shale percentages show an irregular variation. In a few cases a trend is readily observed too. It is useful for both practical and theoretical reasons to divide

TABLE 4.6

Position of clay-ironstone within unite, expressed as percentage of shale thickness below the clay-ironstone band. First, second and third series combined.

0—10 %	5	50— 60 %	8
10—20 %	1	60— 70 %	11
20—30 %	6	70— 80 %	5
30—40 %	8	80— 90 %	16
40—50 %	8	90—100 %	33

A chi-square test of this distribution, compared to a rectangular distribution gives:

Total number of clay-ironstone beds 101.

$\chi^2 = 71.5$ , with 9 d.f.  $P < 0.001$ .

TABLE 4.7

Association of shale percentage in graded unit and top or within-position of the clay-ironstone in the unit. First, second and third series combined.

	Clay-ironstone within shale	Clay-ironstone on top of the shale	$\Sigma$
Shale percentage in unit above series- mean.	56	18	74
Shale percentage in unit below series- mean.	9	14	23
$\Sigma$	65	32	97

$\chi^2 = 9.02$ , 1 d.f.,  $P < 0.01$ . Coefficient of Association  $Q = +0.657$ .

In a few cases more than one clay-ironstone occurred in a graded unit. This did not occur in units with a concretion bed on top. From two, or three within-positions of a clay-ironstone in one graded unit, only one has been considered.

the observed variation into three types, between which transitions can of course occur.

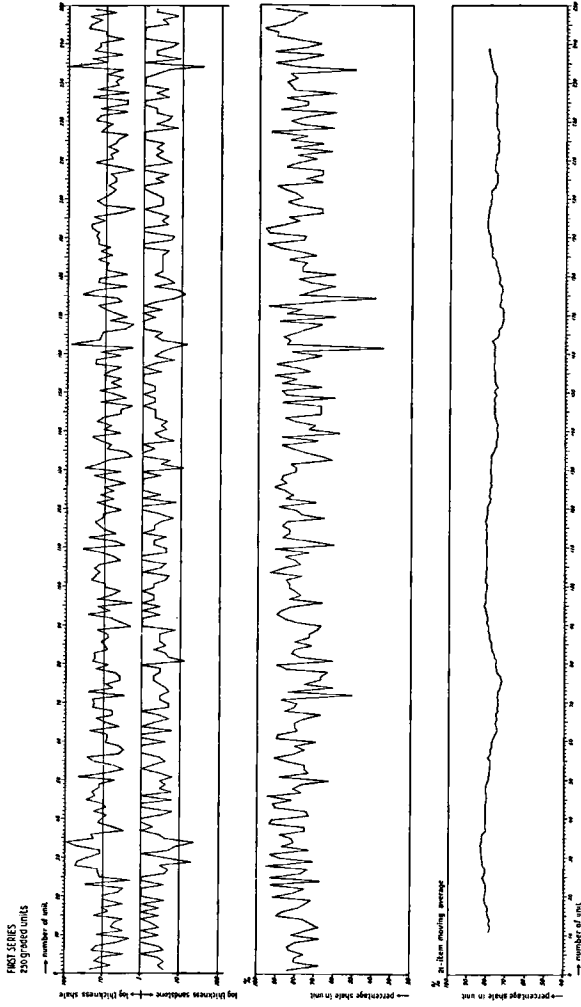
1. "Oscillations" are the variations on a small scale, from bed to bed and which are comparable with the variation in a random sequence of values.

2. "Fluctuations", the variations from 2 to, say, 15 units, which are too small to be recognized as "trends", but are not comparable with the variations of a random sequence, and indicative of interdependence between two or more graded units.

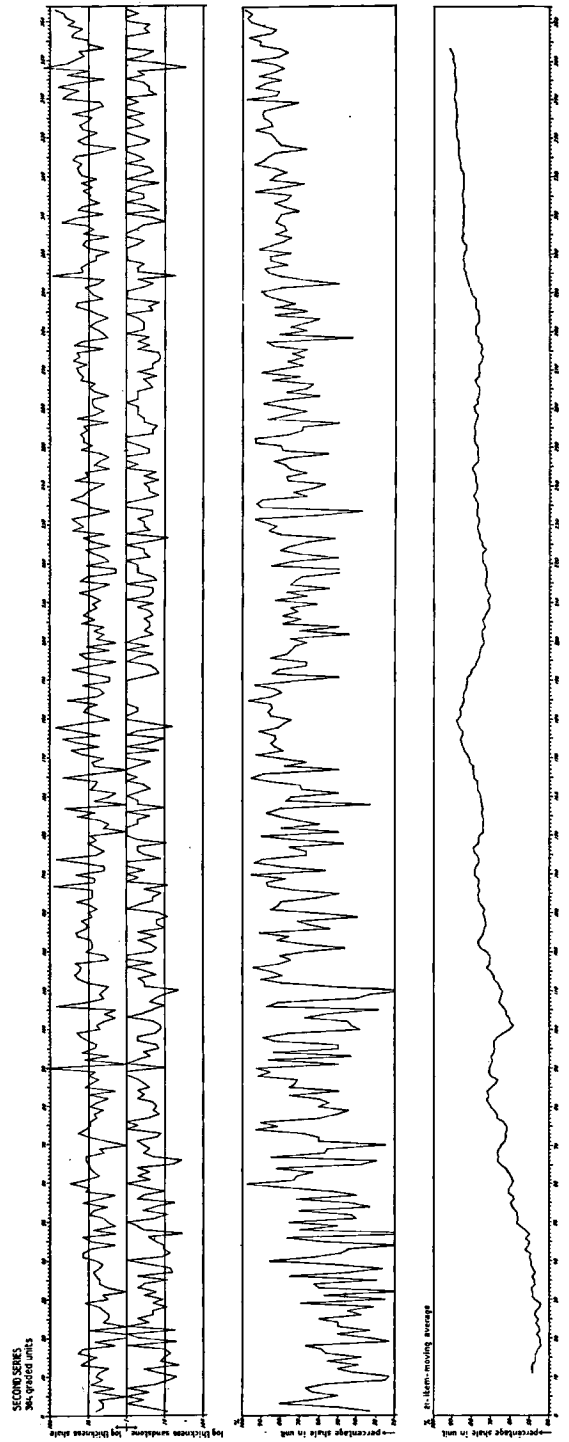
3. "Trend", irregular, continuous or cyclic gradual change of the mean level of oscillation. If not readily visible in the graphs, it can be detected by statistical methods, as is the case with the fluctuations.

The main object of the investigation was to ascertain the existence of trends and fluctuations in the series from the Graded formation, and in some series of thicknesses from graded beds quoted in literature. Also an attempt was made to find out something about the form of fluctuations.

The interpretation of the peculiarities of the sequence has been given



Graph 1



Graph 2

for the greater part in the preceding sections. The interpretation of the fluctuations in the sandstone-thicknesses sequence remains to be treated here.

The first attempt to investigate the alternation of graded beds systematically seems to be the statistical approach of Douglas, Milner & Maclean (1937). They analysed 684 bed thicknesses measurements from the graded Halifax formation in Nova Scotia, Canada. Unfortunately they had interpreted the silt-shale alternation as varves, and based their method of analysis on the hypothesis of equal time-intervals between the depositional episodes. Periodogram analysis for periods with wavelengths from 1 to 12 beds did not give any significant result.

In 1938 Sujkowski analysed some sequences from the Carpathian flysch, also without significant results.

The question arises now if it is possible that periodic processes could influence bed thicknesses of graded units in such a way that the periods would be preserved as periods in the bed-thickness graph.

Supposed that some periodic process, e.g. climatological conditions, influences the bed thicknesses of graded units, the random occurrence of the beds would disturb greatly the effect of it on the thickness sequence. This may be visualised in the following way.

Each maximum (or minimum) of the periodic variable is "sampled" by a set of graded beds, the number of beds in each set being a stochastic variable. If some periodic process has a wave-length, small as compared to the rate of occurrence of the turbidity currents, the irregularity of the "sampling" destroys the period. Only when the rate of occurrence is high as compared to the wave-length, the periods are preserved with sufficient accuracy to allow periodogram-analysis.

The first to use methods which are not disturbed by the random occurrence of the depositional episodes, is Vistelius (1949). The principal method used by Vistelius is that of the auto-correlation coefficient. It consists of the calculation of these coefficients up to the 12th order, from successive thicknesses (normalized by some suitable transformation). Vistelius was able to prove that in many lithologies significant positive, and sometimes negative auto-correlation existed. The coefficients of successive orders are arranged in a correlogram to show the type of correlation function. This characterizes a certain lithofacies and can be "translated" into geologic information.

Vistelius (1949) has also shown that some lithological alternations can be compared with Markov-chains. The lithological types are considered as the possible phases of a system that, with a special "transition probability" goes from one phase into the other. By counting all the transitions from one lithology to that of the next bed the Markov-matrix of transition probabilities can be obtained.

For both methods a fairly high number of observations is necessary and other methods have been used in our analysis.

### The methods

To investigate the series for trend on a large scale the chi-square test has been used. First a distinction was made between thick and thin beds at 9.5 cm. From the 360 sandstone thicknesses of the second series only 37 are thicker than 9.5 cm. These are denoted by  $m_0 = 37$ . The entire series

( $m=360$ ) is divided into  $l=6$  successive samples of length  $n_j=60$ . In each sample the number of thick beds is counted:  $n_{oj}$ . The  $n_{oj}$  and the  $m/l - n_{oj}$  are plotted in a table. (See table 4.8.)

TABLE 4.8

j	1	2	3	4	5	6	Total	
$n_{oj}$	23	4	7	1	1	2	37	$m_o$
$m/l - n_{oj}$	37	56	53	59	59	58	323	$m - m_o$
$n_j$	60	60	60	60	60	60	360	$m$

TABLE 4.9

j	1	2	3	4	5	6	7	8	9	Total	
$n_{oj}$	11	10	14	21	26	13	18	21	19	153	$m_o$
$m/l - n_{oj}$	29	30	26	19	14	27	22	19	21	207	$m - m_o$
$n_j$	40	40	40	40	40	40	40	40	40	360	$m$

To test the null-hypothesis that the thick beds ( $> 9.5$  cm) are distributed at random over the series the chi-square is calculated from the table as:

$$\chi^2 = \frac{m^2}{m_o(m - m_o)} \sum_{j=1}^l \frac{(n_{oj} - \frac{m_o}{m} n_j)^2}{n_j}$$

$= 65.1$  with  $l - 1 = 5$  degrees of freedom.

This value of  $\chi^2$  is highly significant ( $P < 0.001$ ).

Because of the rather arbitrarily chosen limit at 9.5 cm, we may for security, repeat the analysis for thin beds  $< 2.5$  cm, with the same series. The table which results is given in table 4.9. In that case  $\chi^2 = 23.3$  with 8 d.f. and  $P < 0.01$ .

The length of the samples has been taken fairly long to avoid contamination due to fluctuations in the thickness sequence.

The trends, especially that of the sandstone thicknesses, already have been observed by Fiege (1937), Simonen & Kouvo and Wood & Smith (1958b, p. 177). Fiege and Wood & Smith have explained these gradual changes as due to tectonic influences, like uplift of a source land.

Two significance tests for trends, but also for fluctuations are given by Robberts & Wallis (1957, chapter 18). The first test is a test for clustering of similar values in the series. The data are subdivided into a few classes according size; in our case in the classes High, Medium and Low, or only High and Low. Then the number of items in each class is counted, and the original data are coded into the symbols H, M and L. In the coded series the number of runs is counted; a run is defined as a set of consecutive symbols that are the same. The run may consist of one symbol only, between



two different ones. The sampling distribution of the number of runs  $r$ , counted in a random sequence, can be shown to be approximately normal. We therefore can test the result of an analysis by calculating the "standard normal variable"

$$K = \frac{\sum n_i^2 - n(n - r + \frac{1}{2})}{\sqrt{\frac{\sum n_i^2 [\sum n_i^2 + n(n + 1)] - 2n \sum n_i^3 - n^3}{n - 1}}}$$

where  $n$  is the total number of observations and  $n_i$  the number of observations belonging to class  $i$ . This test is developed by Mood (1940, p. 385, corollary I). A simpler formula, if only H and L are used is also mentioned by Robberts & Wallis (1957). In that test the correction for continuity is applied also by increasing  $r$  to  $r + \frac{1}{2}$ . It is shown by Swed & Eisenhart (1943) that if  $n_H = n_L = 20$ , the formula with continuity correction gives an adequate approximation of the probabilities. Up to these values for  $n_H$  and  $n_L$  the exact probabilities are given in their paper. The formula for the case of only H and L was found by Wald & Wolfowitz (1940), while the formula used to calculate the exact probabilities as given in the table of Swed & Eisenhart was found by Stevens (1939). Once  $K$  has been calculated, the probability of  $K$  exceeding the observed values by chance can be read from a table of the normal distribution. The rejection of the null-hypothesis that the sequence observed can be compared with a random sequence means that similar values tend to cluster. This of course if  $K$  is negative. If  $K$  was significantly positive there would be too much alternation of high and low values.

The second test is the difference-sign test for movements up and down in the series, here shortly referred to as "up and down-test". Instead of coding the values into High and Low as in the first test, the original data are coded into plus- or minus-signs, respectively if they are higher or lower than the preceding term. In the resulting series of  $n - 1$  plus and minus signs, runs are counted as in the first method.

The mathematical expectation of the number of runs,  $P$ , is now somewhat higher than in the case of the HL-test with equal  $n_H$  and  $n_L$ . The probability of the occurrence of a plus sign after another plus sign is generally affected adversely by the first plus sign, for the first plus sign means that the preceding term was already relatively high; the probability to get an even higher next term could be read from the frequency distribution of the values, and will be on the average less than one half. Again it can be shown that the sampling distribution of  $R$  is also asymptotically normal. The standard normal variate is here:

$$K = \frac{3R - 2n + 2.5}{\sqrt{\frac{16n - 29}{10}}}$$

Like in the first test, one-tail probability may be read from a table of the normal distribution integral. The rejection of the null-hypothesis that the series may be compared with a random sequence means here that more values

TABLE 4.10

Sequence tests applied to graded bedding measurements

Lithology	H-M-L-test	Up and down test:	Number of observations
Shale, First Series	$K = -3.67, P < 0.001$ $L < 7.5 < M < 16.5 < H \text{ cm}$	$K \approx 0$ N.S.	335
Shale, Second Series	$K = -3.32, P < 0.001$ $L < 5.5 < M < 12.5 < H \text{ cm}$	$K = -0.6$ N.S.	364
Shale Piedras Luengas, a	$K \approx 0$ N.S.	$K \approx 0$ N.S.	100
Shale, Tampere, Finland	$L < 3.5 < M < 6.5 < H \text{ d.}$ $K = -1.17$ N.S.	$K = -1.85$ $P < 0.05$	111
Sandstone, First Series	$K = -1.11$ N.S. $L < 2.5 < M < 5.5 < H \text{ cm}$	$K = -0.33$ N.S.	335
Sandstone, First Series, no trend	$K = -1.89, P < 0.05$ $L < 1.5 < H \text{ cm}$		250
Sandstone, Second Series	$K = -0.99$ N.S. $L < 3.5 < M < 9.5 < H \text{ cm}$	$K = -1.66$ $P < 0.05$	364
Sandstone, Second Series, corrected for trend	$K = -2.47, P < 0.01$ $L < 0.43 < H \log (a)$		360
Sandstone, Piedras Luengas, a	$K \approx 0$ N.S.	$K \approx 0$ N.S.	100
Sandstone, Tampere, Finland	$K = -3.40, P < 0.001$ $L < 8.5 < H \text{ d.}$	$K < 0$ N.S.	111
Shale percentages, First Series	Trend obvious	$K = -0.585$ N.S.	335
Shale percentages, Second Series, corrected for trend	Trend obvious, but corrected	$K = -2.97$ $P < 0.01$	364
Total thicknesses, graded beds of the Halifax formation	Trend obvious	$K = -3.90$ $P < 0.001$	668
Piedras Luengas, b Total thicknesses	$K = -0.71$ N.S. $L < 3.5 < H \text{ cm}$	$K = -0.5$ N.S.	78

Tampere data from figure, Simonen and Kouvo, 1951.

Halifax Formation from graph, Douglas, Milner and MacLean, 1937.

Piedras Luengas a and b, two sections in graded beds of unknown, probably Lower Carboniferous age, near the roadjunction north of the Piedras Luengas pass.

First and Second series from the Graded sandstone formation.

are involved in the formation of maxima than could be expected in a random sequence.

The result of the analysis carried out for different lithologies from several sections is summarized in table 4.10. In some cases the existence of trends is indicated, but in the case of the sandstone thicknesses of the first and second series, it is suggested that the results point to the presence of real fluctuations as we have defined them at the beginning of this paragraph.

That positive serial correlation is present in most of the series of table 4.10, is indicated by the often negative values of  $K$ , even if it does not pass the significance level.

Visser (1947) has very clearly shown how the expected number of runs of certain length can be calculated. The formula for the mathematical expectation  $K_m$  of the number of runs of length  $m$ , of symbols of one sort only, is given by:

$$K_m = \frac{(n - m - 1)! n_i! (n - n_i + 1)!}{n! (n_i - m)! (n - n_i - 1)!}$$

where  $n$  is the number of observations,  $m$  the length of the run and  $n_i$  the number of observations of class  $i$ . The formula can be found in Mood (1949, p. 372, 3—6).

Visser developed a significance test in order to test whether the observed number of runs of a special length differs importantly from the expected. As we have tested the series already with the HL-test we only compare the number of runs with the expected. This gives an impression of the magnitude of the fluctuations involved. It appears that the length is far from constant but lies roughly between 1 and 10 graded units. (cf. tables 4.11 and 4.12).

TABLE 4.11

## Sandstone second series

Sandstone thicknesses, corrected for trend by 28-item moving average of log values.

<i>HL-test.</i> $H > 0.43 > L$ . $r = 157, s(r) \approx 181$ . $K = -2.47$ , $P < 0.01$					
<i>Visser-test for length of runs:</i> $n_H = 185$ , $n_L = 175$ , $n = 360$ .					
High values			Low values		
Length of run	Expected number of runs	Observed number	Length of run	Expected number of runs	Observed number
1	44.1	31	1	46.5	32
2	22.7	21	2	22.5	22
3	11.6	12	3	10.9	10
4	5.94	5	4	5.24	8
5	3.03	7	5	2.52	1
6	1.54	1	6	1.20	3
7	0.78	1	7	0.58	2
8	0.39	1			

TABLE 4.12

## Sandstone first series

Sandstone thicknesses not corrected with moving averages, for no visible trends occur within the part of the series used.

<i>HL-test.</i> $H > 1.5 > L$ . $r = 98.8$ ( $r$ ) $\approx 111$ . $K = -1.89$ , $P < 0.05$ .					
<i>Visser-test for length of runs:</i> $n_H = 168$ , $n_L = 82$ , $n = 250$ .					
High values			Low values		
Length of run	Expected number of runs	Observed number	Length of run	Expected number of runs	Observed number
1	18.37	16	1	37.40	27
2	12.37	9	2	12.22	13
3	8.31	6	3	3.96	7
4	5.57	5	4	1.27	2
5	3.73	4			
6	2.49	4			
9	0.734	3			
11	0.322	1			
14	0.092	1			

Some indication about the shape of the fluctuations can perhaps be found in a "recurrence diagram", as used by Chree (cited in Chapman, 1951, p. 111). To construct such a diagram, maxima are chosen from the curve and averaged by placing the maximum values  $k$  in one column and the adjoining terms  $k-1$ ,  $k-2$ ,  $k-3$ ,  $k+1$ ,  $k+2$ , etc. in the adjoining columns of a table. If the column-averages are drawn in a graph, the form of the maxima that is not due to the random influences, stands out better. This procedure has been followed for the sandstones of the first and second series (see fig. 15). In both cases a slight skewness of the maxima is noted: the average of  $k+1$  terms is larger than the average of the  $k-1$  terms.

If we test the difference between the  $k-1$  and the  $k+1$  terms with the Wilcoxon test no significant result is obtained. However, if we compare the number of cases where the  $k+1$  value is higher than the corresponding  $k-1$  value, the result is as follows:

1.  $(k+1) < (k-1)$  10
  2.  $(k+1) > (k-1)$  21
  3.  $(k+1) = (k-1)$  4
- Second series, 35 maxima.

We divide the third group equally over the two groups (1 and 2). The probability to get such an asymmetrical result is then

$$2 \sum_{i=23}^{35} \binom{35}{i} \left(\frac{1}{2}\right)^i \left(\frac{1}{2}\right)^{35-i} \sim 0.098.^1)$$

If the results of the first and second series are combined we obtain

$$2 \sum_{i=36}^{57} \binom{57}{i} \left(\frac{1}{2}\right)^i \left(\frac{1}{2}\right)^{57-i} \sim 0.064.$$

<sup>1)</sup> If we discard the tied observations of group 3, the result is 0.072. With  $p = \frac{1}{2}$  and  $N > 25$  the normal approximation may be used.

This leads to the conclusion that the maxima seem to tend to be asymmetric in the sense indicated on fig. 15.

This asymmetry tended to occur in other graded bedding sequences as well. For this reason a set of sections were studied from literature, together with the section measured by the author. In the series of sandstone thicknesses the number of plus signs (up- and down-test) were counted and the number of sections counted in which the plus signs were in the minority. This happened to be the case in 12 out of 14. The probability to get such a result on the basis of our null-hypothesis that the number of plus and minus signs in a set is determined by the laws of chance can be calculated as

$$2 \sum_{l=12}^{14} \binom{14}{l} \left(\frac{1}{2}\right)^l \left(\frac{1}{2}\right)^{14-l} \sim 0.013.$$

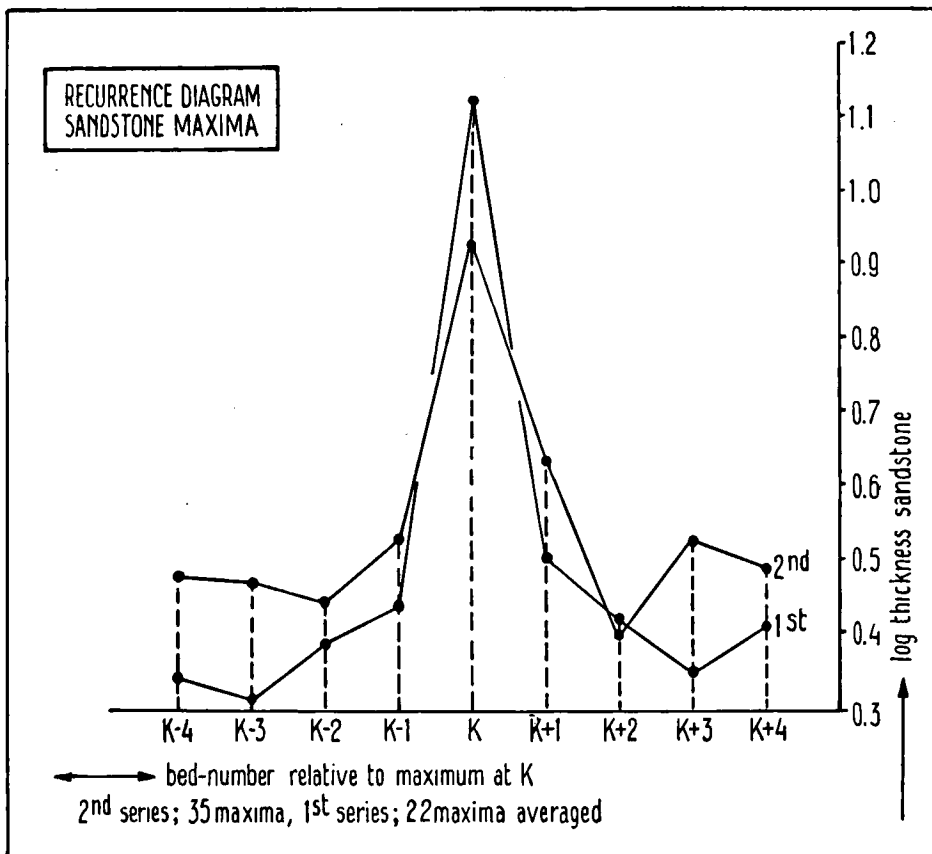


Figure 15.

This result indicates that at least some of the sections have real deficiency of plus signs, and hence a certain asymmetry in the thickness sequence.

This does not exclude the possibility of "real" asymmetry, inversed to the one just found, but if that exists it is of minor importance. The oscillations and fluctuations in the analysed series all have a great amplitude with respect

to the main trend, if there is a trend at all. Therefore we tend to ascribe the asymmetry to the fluctuations.

The fluctuations in sandstone thickness graphs originated probably by the arrival of a few turbidity-currents within a relatively short time interval from a common source area. In that case the distance to the site of deposition and the composition of the slumps would be similar favouring the equality of the sandstone thicknesses.

If this interpretation is right we cannot explain the form of the fluctuations from different original compositions of the turbidity currents, as will be accepted for the bulk of the oscillations, but rather from the difference in the sizes of the subsequent slumps that generated the turbidity currents. It is possible that the fluctuations grade into "multiple beds", both possibly caused by the repeated slipping from a slip-scar, because of the unstable edge left behind after the first slump. A special sequence of sizes is then imaginable (Wood & Smith, 1958, p. 189).

The studies suggest that it is worthwhile to study the thickness sequence of graded beds with statistical methods. However, the methods, even if they give highly significant results, do not prove by any means the conclusions we draw from them. But the statistical methods of analysis supply us with information which cannot be obtained by simply looking at an outcrop. The many interesting features that can be detected in the, at first sight, random sequence of thicknesses, may, after careful interpretation, lead to a better understanding of the mechanism of sedimentation.

## CHAPTER V

### SEDIMENTARY STRUCTURES

#### 5.1. *Introduction*

In the geological literature much attention has been paid to sedimentary structures. It is a pity that many interesting descriptions of sedimentary structures are scattered over regional studies. As these structures sometimes are diagnostic of special sedimentary environments and sometimes indicators of palaeocurrent directions, their study should be extended as much as possible, with full description of the lithofacies in which they occur.

The classification of sedimentary structures is very difficult because of the enormous variety of possible forms. The first distinction which can be made, is that between features which can be studied only, or easiest, in section and those which are more or less restricted to the bedding planes. Of course no structures exist which are restricted to two dimensions, but many structures are confined to the immediate vicinity of the bedding plane.

As the major part of the observed features can be attributed with reasonable certainty to some known mechanical or organic cause, a further classification on preponderantly genetic criteria is advisable. Nearly all sole-markings have been classified in this way.

Nearly all the structures found in the sediments of the Pisuerga basin have been described before from other sediments. Some types, though, occur in interesting forms, deserving description in the present chapter. Others are described for their environmental significance. In the case of the sole-markings, an attempt has been made to give a short annotated bibliography on the subject.

#### 5.2. *Intra- and interstratal structures*

##### 5.2.1. *Filled-in crevices in limestone*

In the narrow valley, crossing the southern flank of the Sierra Corisa syncline, between Rabanal and San Felices, a well exposed section in the Sierra Corisa limestones is observed. The succession consists of conglomerates, marine corallogene limestones, sandstones and black to grey shales. Between two beds of the sequence a hiatus in the sedimentary record must be present. The sedimentary succession in the vicinity of this diasthem is as follows:

9. 40 m bedded greyish blue limestones.
8. 3 m massive grey limestone.
7. 4 m bedded grey limestone.
6. 3 m bedded, cross-bedded, white to brown, moderately sorted, medium grained sandstone.
- ..... diasthem .....

5. 9 m massive grey limestone, on top some limestone-pebbles in dense, sandy limestone matrix; crevices filled with sandstone of number 6.
4. 15 m sandstone and shales.
3. 5 m bedded limestone.
2. 15 m thick bedded, green, medium grained sandstone.
1. 2 m massive corallogene limestone.

The top surface of the limestone (5) is irregular and shows a karst of up to 1.50 m. In some places patches up to a meter thick of poorly sorted conglomerate with components of 1—20 cm in diameter, lie in hollows or fill the crevices. Nearly all components are of the same type as the other limestones in the section. Only a few components are quartz or other lithologies. Matrix is sandy limestone. The crevices are narrow, perpendicular to the bedding plane and wedge- or funnel shaped. Some reach 5 m down into the limestone (no. 5). The sides are quite smooth.

The filling consists of the same sandstone as number 6, but a few limestone pebbles occur here and there. An example is shown in fig. 16. Crevices like this occur at intervals of about a hundred m along the strike.

The limestone in which this feature is observed apparently is not cut off by the sandstone, within the exposed few hundred meters.

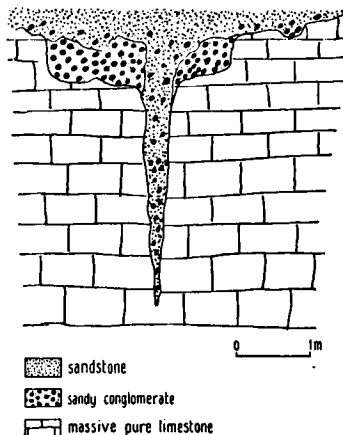


Figure 16. Filled-in crevices in limestone, Cabra Mocha diasthem.

The conclusions which can be drawn from these observations are the following:

1. The sedimentation was predominantly marine before the diasthem, but also afterwards.
2. A rise of the bottom is responsible for bringing the limestone bed in an environment where rather fierce erosion could act on the surface of it.
3. The limestone must have been lithified entirely before the erosion started, otherwise such delicate and deep crevices would not be preserved. The irregular form of the top surface indicates the same.
4. The crevices show some similarity to those in limestone beds at a beach, where solution of limestone in seawater and erosional forces are active,



especially if the top of the limestone is just about the mean water level. A relative rise of the sea level made possible the deposition of sand and conglomerate on the eroded limestone surface and in the crevices.

Crevices like those described, are mentioned by Shrock (1948, p. 222)

### 5.2.2. *Cross-bedding*

Many sandstones from the Carboniferous and the Triassic show cross-bedding. Cross-bedding on the largest scale occurs in the coarse white sandstones of the Triassic, which is excellently exposed on top of the Cordillera Ibérica. Here, sometimes, the thin top set beds are stripped off from the tabular current bedded units to show a set of arcs on the stripped surface (which is essentially parallel to the bedding plane). The arcs lie a few cm apart, roughly parallel to each other and convex in the down-current direction, arranged in rows. This feature has been described as "Schrägschichtungsbogen" by Gürich (1933). It shows the way in which the cross-bedded layer was built up by the simultaneous parallel advance of miniature deltas, the top arcs indicating periods of slackening current velocity. The arcs generally measure more than a quadrant. This means that also the dip directions of the fore-sets have considerable variance. This is reflected in the wide range of variation in direction of cross-bedding within one sandstone bed.

Recently Wurster (1958) and Niehoff (1958, p. 274, fig. 13) have studied the geometry of cross-bedding in three dimensions. According to Niehoff the distribution of current-directions, determined in one outcrop-plane often is far from "normal". In some instances it definitely tends to a U-form. Even a combination of data from randomly oriented outcrop planes may give a distribution of directions diverging widely from the "normal" distribution. We should thus be careful to estimate the standard deviation of a set of directions by subtracting 16 % from each tail of a histogram and dividing the remaining interval by two, as proposed by Raup & Miesch (1957).

Most of the protoquartzites and sandy shales, connected with the coal seams, show cross-bedding involving several layers. The variety of size and shape of the cross-bedded units is great and tabular and lenticular forms most often occur. Many have been measured to study the palaeocurrent-directions and a few of the sandstone beds with tabular cross-bedded units showed the smallest spread in direction. Those with lenticular units were the most inconsistent in direction.

In the paralic association, the size of the cross-bedded units, i. e. their thickness, is of the order of 0.5—5 m.

Much smaller in size is the cross-lamination observed in the Graded formation. Some of the relatively thick sandstone beds (about 5—30) show an irregular type of cross-lamination. The thickness of the cross-laminated units or zones never exceeds 5 cm. The frequency of occurrence of this feature in the graded beds is about the same as reported from the Podhale flysch by Radomski (1958).

The most conspicuous type is a wavy development of cross-laminated units. Probably this wavy appearance is caused by pene-contemporaneous deformation, because it is hardly possible to visualize a sedimentation process which generates such irregular cross-lamination with dips of the fore-sets exceeding 40 degrees.

Often this wavy cross-lamination is overlain by a few centimeters of silt

with convolute lamination. It seems possible that similar processes caused the wavy appearance of the cross-laminated and the convolute zones in the graded beds. A few examples are shown in fig. 17 and 18. These forms and those studied in the field closely resemble the lenticular through type of current-bedding described by Van Houten (1954).

### 5.2.3. *Convolute lamination*

Ten Haaf (1956, 1959) describes "convolute lamination" as folds of the laminae within a bed, with typically sharp anticlines and wide, rounded throughs.

The laminary part of graded beds in the Redondo syncline and in the Rubagón section near Barruelo, often shows this feature. Convolute lamination has been reported from many turbidites.

Van Houten (1954) calls attention to the preference of convolutions to occur in a special zone within a graded bed, above a zone with cross-lamination, often of the "lenticular trough type" and below a thin undisturbed zone of silt. The same was noted in many examples from the Graded formation. Fig. 18 shows such convolutions in a calcareous graded bed. Above the rather regular convolute "folds" the muddy black material has risen like turbulent, dense smoke clouds into the fine, silty sand above.

Convolutions with the typical broad, rounded throughs and sharp crests are shown in fig. 19. The base of the bed is load-casted. There is no relation between the situation and size of the load casts and the convolute folds.

The combination of current ripple mark with convolute lamination has not been observed in eastern Pernía, though convolute lamination has been observed in about fifteen beds.

The attractive explanation of convolute lamination by accentuation of current ripple mark (Ten Haaf, 1956) does not seem appropriate for these cases. Probably convolute lamination can develop in laminated beds as well as in ripple marked beds. In the latter case the ripple crests can be accentuated to form the sharp pointed crests of the convolutions.

Ten Haaf (1959) has noticed that some of the "Sub-aquatiscche-Rutschungen" described by Kühn-Velten cover about all the characteristics of convolutions. Kühn-Velten observed that the average wave-length of the convolutions are positively correlated with the thickness of the convoluted part of the bed (the wave-length attained a maximum of abt. 25 cm). It should be investigated if such a relation also exists between wave-length of ripple-marks and thickness of the sandstones in which they occur.

The convolutions most often occur in the calcareous beds. Kühn-Velten observed that the original lime-content of a bed influenced the lability of the sediments positively.

### 5.2.4. *Load casts*

Load casts are caused by the sagging of water-saturated coarse sediment into the hydroplastic, finergrained material. Most often it is described from turbidites, but also in other environments than in which graded beds are deposited, load cast processes may take place. In this paragraph examples of the latter case are described.

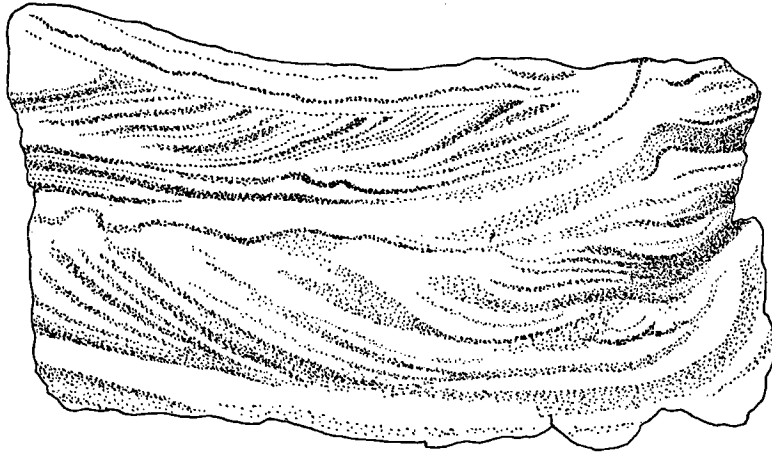


Figure 17

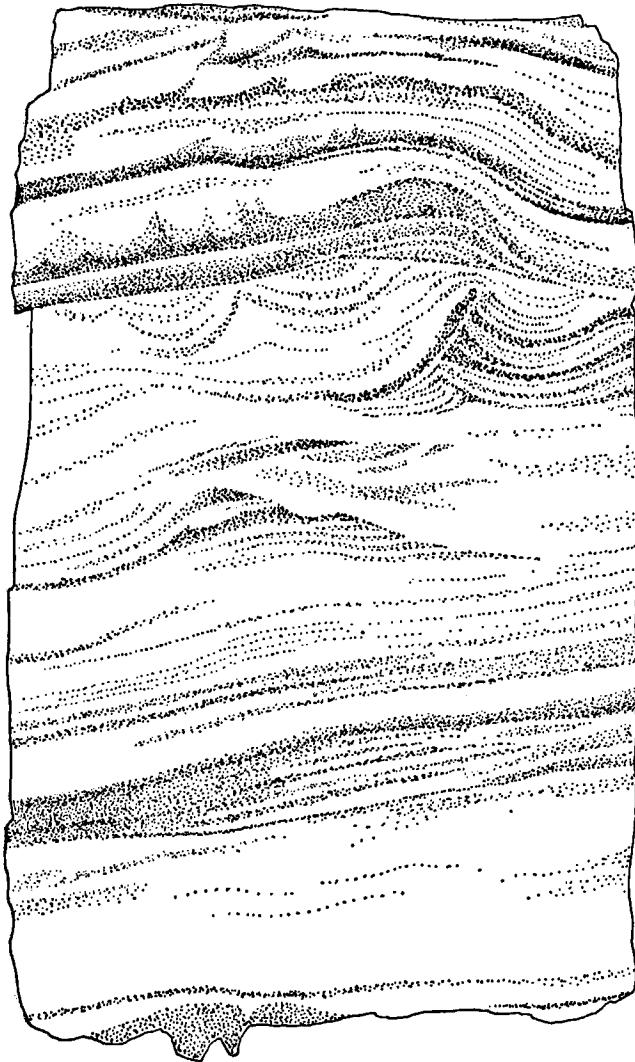


Figure 18

Figures 17 and 18. Wavy-lamination and convolute lamination in silty fine-grained, laminated calcareous sandstone. White: sandstone; black: fine grained material. Drawn after sawcut through specimen, appr. natural size.

An example of large scale load casting is the "Wilder Stein" described by Kukuk (1920, p. 805; 1936, p. 2027) from coal seams of Westphalia, Germany. Irregular rounded bodies of sandstone protude from the overlying sandstone. Sometimes they reach more than a meter downward in the seam. Weber (Kukuk, 1920) studied recent examples of such load casts in a moor which was covered by sand.

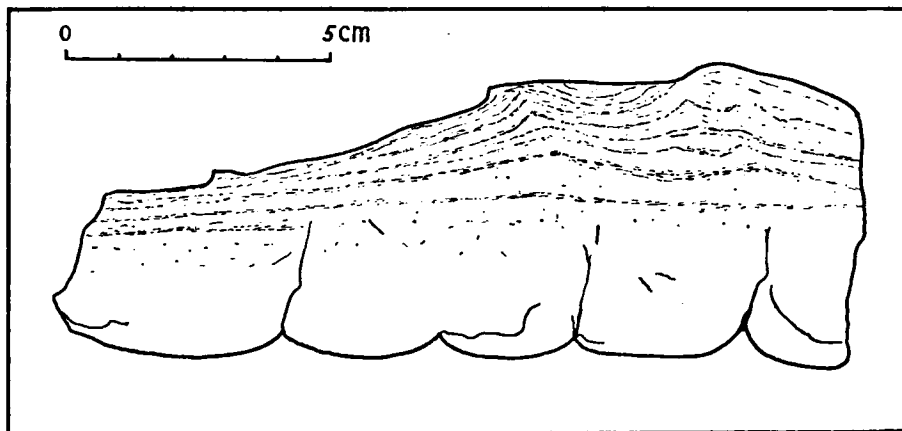


Figure 19. Convolute lamination and flame structures in load casted sand-layer. From Rubagón graded beds. Specimen collected by Mr R. H. Wagner.

In the Devonian of Belgium, Macar (1948) and Macar & Antun (1950) studied "pseudo-nodules", which are rounded bodies of sand or silt, often with fine lamination, concordant with the outer form of the body. These pseudo-nodules still are connected to the sand- or siltstone above, or they are completely detached, lying separately in the underlying shale.

Certainly a process of load casting, sometimes in combination with flowing of the soft sediment downslope is responsible for this phenomenon.

Pelhat (1957, fig. 2 and 3) describes large size load casts from a probably lacustrine environment. (Westphalian of Bretagne, France). Here coarse arkosic sandstone has been loaded on clay with occasional pebbles. Most of these load casts have been torn off their native sandstone bed. The rounded form of the pseudo-nodules has been caused by bending of the sandstone and turning about in the shale, after the disconnection from the sandstone bed. This bending is indicated by the fact that many of the pseudo-nodules have considerably larger grain size in the margin than in the center. Hatai & Funayama (1957) also described large load casts from tuffaceous sediments. The maximum size was about 1.30 by 1.50 m.

In Pernía, a few hundred meters east of the Cantina de Vañes, in a cutting on the left side of the road from Vañes to San Felices, examples of very large load casts can be studied. They occur where brown-grey sandstone beds up to half a meter thickness are interbedded with thinner black shales. This alternation attains a total thickness of at least 5 m and overlies the following beds:

- 2 m shale.
- 1 m massively bedded grey medium grained quartzose sandstone.
- 0.90 m black shale.
- 4.30 m of impure dark-grey coarse organo-clastic limestone, which almost entirely consists of the broken parts of marine fossils of many kinds. (Estalaya beds, Chapter II).

The load casted sediment lies in a flat synclinal structure, dipping ten degrees to the north, and is exposed in vertical section about 150 m along the road. Some small faults have been noticed.

The sandstones are grey to grey-brown, medium to fine grained, quartz-cemented, with some current bedding on a small scale (about 3 cm).

When not disturbed by the load casting process, they often are laminated, including dark bands with carbonaceous material. In the vicinity of and within load casts, the sandstone may contain up to 50 % subangular shale fragments, up to one cm in size. This suggests that the shale was enough consolidated to be broken into subangular fragments, but some of it was still soft enough to be partly assimilated by the water-saturated sand at the time of formation.

In a few instances the shale between the sandstone beds is replaced by a contorted bed. Such beds up to 30 cm thick can be traced about 5 m along the strike. The sandstone rests on these contorted beds with small load casts of irregular shape and size, while they do not show to much irregularity if lying on the pure black shales.

The contorted beds contain balls and more irregular bodies of the same material of which the large load casts consist. The large load casts can attain depths of one meter below the bottom of the sandstone bed from which they originated (fig. 20, 21 and 22). Thin sandstone beds and shales are bent down under their weight, but more often the load casts cut them off at their subvertical margins.

As far as could be ascertained, they are sub-circular in horizontal cross-section and rounded at the bottom. Fig. 20 shows how an apparently small load cast of about 15 cm depth has acted on the underlying beds. It is possible though, that we see but a small part of the load cast which induced the peculiar bending of the underlying beds. On fig. 21 load casts still are attached to their parent sandstone bed, but on fig. 22 they are completely separate bodies. The environment of sedimentation is probably marine.

The general characteristics of these structures are such that load casting is the most obvious explanation. But the fact that some of the load casts cut right through the underlying shales and sandstones indicates that the quicksand forming the casts was able to assimilate the underlying material completely. Therefore lateral supply of sand was not necessary and the sandstone bed from which they protude was not disrupted like a "quake-sheet" or contorted bed (Kuenen 1958b).

### 5.2.5. *Slumping*

Slumping may be defined as the deformation of unconsolidated rocks due to sliding on an inclined plane.

In most cases this sliding involves an upper bed of the sediments, after

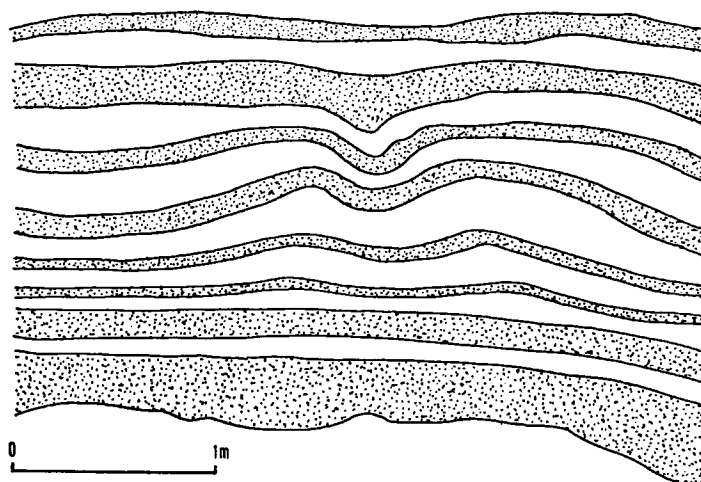


Figure 20.

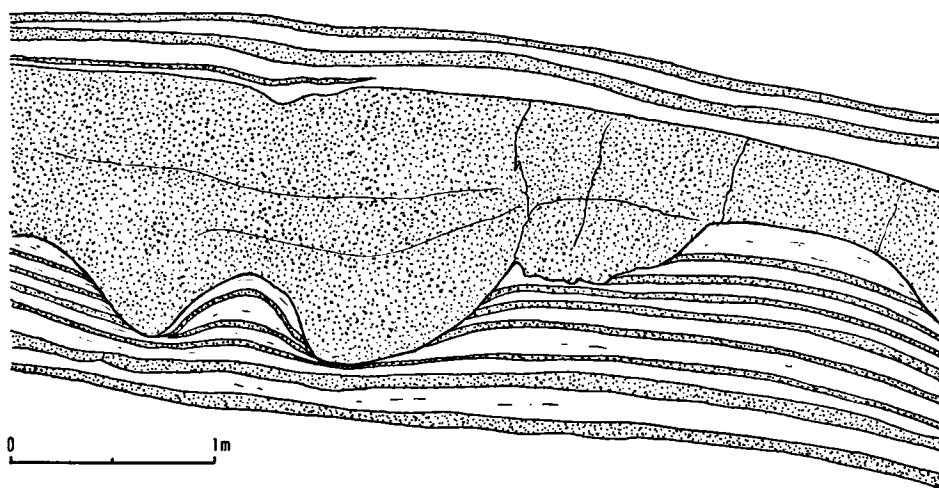


Figure 21.

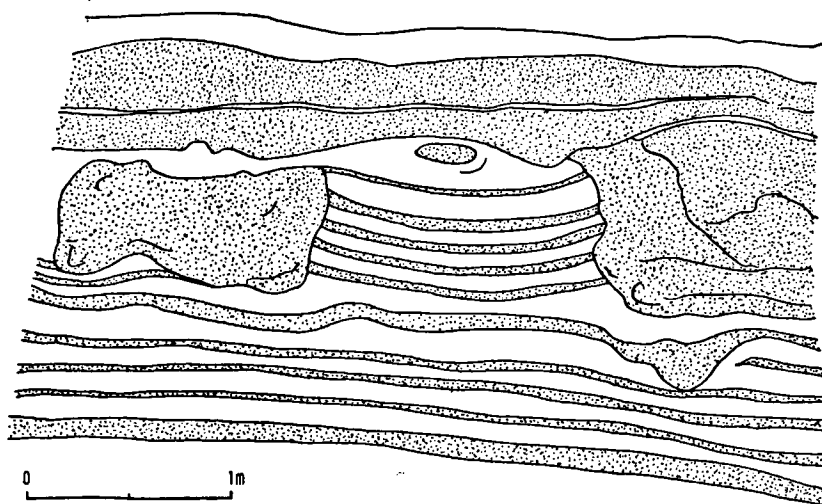


Figure 22. Load casts in sandstone-shale alternation near Estalaya based on field sketches.  
White: shale or mudstone.

which erosion bevels the irregular surface of that bed. The slumping process may start on very gentle slopes and is observed in sediments of all kinds from many environments. Generally it is associated with rapid deposition in a deltaic environment or at the margin of the shelf.

Slumping of various sizes is noted in the Pisuega basin. Most common is the occurrence of contorted beds. In a shale matrix disrupted bodies of sandstone of all sizes lie between undisturbed sandstone layers. Erosion of the top of the contorted layer is a rule. The best examples are found in the village of Herrerueta. Here shales, sandstones and contorted layers lie stratigraphically between impure organo-clastic limestones and muddy conglomerates.

The example of fig. 23 is from the protoquartzite beds a hundred meter

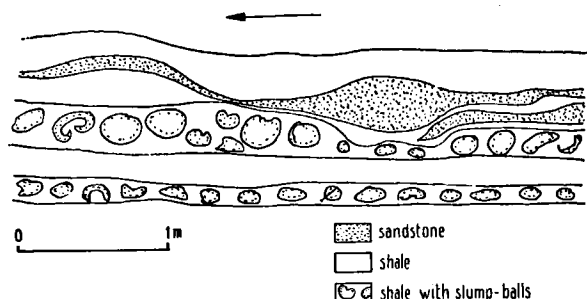


Figure 23. Slumping near Santa María de Redondo.

above the Redondo coal group, near the road from Santa Maria de Redondo to the Mina Joaquín. The arrow indicates the current direction, obtained from current ripple mark observations in undisturbed beds about a hundred meters to the right in the same level. Slabs and balls of the similar sandstone as the overlying beds, are embedded in the shale beds.

Kuenen (1958b) has pointed out that some "contorted beds" might have been formed by a load cast process and that lateral movement is not indispensable for its formation. In the cases described here, always some supplementary indication or real slumping is present.

Some of the muddy limestone breccias and conglomerates occurring in the Graded formation, are ascribed to the slumping of bioherm-talus material into the adjoining basin.

### 5.3. Structures on bedding planes

#### (A. On top of beds.)

##### 5.3.1. Current ripple mark

Only one type of current ripple mark has been observed, both in the paralic association and in the turbidite association. The troughs are not deeper than 5 mm and the wave length is around 5 cm. They are strongly asymmetric in cross-section.

*(B. On the underside of beds.)*

## Sole markings.

Kuenen proposed the term "sole marking" for the sedimentary structures on the underside of sedimentary layers (Kuenen 1957). Most often they occur on the bottom of graded beds, resting on mudstone or shale beds. That is one of the reasons why most often they are described from turbidites, but sometimes they occur in similar forms in other sedimentary associations, like red-beds and lacustrine environments. In the last century they have been referred to as "hieroglyphs" and a lot of morphologically inspired terms have been used to distinguish several classes of sole markings. Now so many papers have been published about the mode of formation of the sole markings, often explaining them convincingly, that accepted nomenclature and classification generally is based on genetic criteria. Further classification is then made by morphological characteristics, if necessary. Probably the first to mention a type of sole markings is James Hall (1843). This famous geologist also noted the similarity in direction of groove cast in outcrops many miles apart, in the Devonian of New York. In 1859 Hauer reported the "Hieroglyphen" from flaggy sandstones in the NE of Hungary.

In Austria Zugmayer (1875) used the sole markings as top and bottom criteria, and Paul & Tietze (1879) used sole markings to define stratigraphic entities in the Carpathen as "Obere Hieroglyphen-schiefer".

Also Hilber (1884, 1885) noted that the hieroglyphs invariably occurred on the bottom of sandstones in the Carpathian flysch.

A more descriptive and experimental study was presented by Fuchs (1895), principally treating load casts. Fugger (1899) described sole markings of the flute cast type. Since then, more information on this subject has been published, of which most is scattered in stratigraphical and sedimentological literature.

Probably my search has still missed quite a few items and certainly has not been exhaustive, but nevertheless it seems worth while to present the main results together with the description of the sole markings from the turbidite association of the upper Pisuerga valleys and the Rubagón area.

The most important and instructive papers on sole markings are the following:

1. Birkenmayer .....	1958	6. Kuenen .....	1957
2. Crowell .....	1955	7. Rücklin .....	1938
3. Dzulinski, Ksiazkiewicz & Kuenen	1959	8. Seilacher .....	1954
4. Ten Haaf .....	1959	9. Shrock .....	1948
5. Kelling & Walton .....	1957	10. Walton .....	1956

This selection covers about all the different types of sole markings, both organic and inorganic.

Birkenmayer (1958) also describes some forms from the top of beds which are genetically related to the sole markings.

5.3.2. *Flute casts*

The term flute cast has been introduced by Crowell (1955, p. 1359). These markings involve the erosion of the mud, silt or sand surface in a peculiar way. The surface of the mud is scoured by the current and depressions



are formed, with their deepest part on the upstream end. This involves the transection of the laminae of the underlying sediment. The infilling may show cross-lamination and often the sandgrains are coarser than those of the sandstone above. The flute casts most often are arranged in diagonal patterns, but also may occur separately.

*Bibliography. Flute casts and related markings*

Fugger (1899, p. 299) described "Kegelwülste from Bergheim, Austria. The description of these marks indicates, almost without doubt, that Fugger found examples of well-developed flute casts. The sizes are: length 20—25 cm, width 6—8 cm, depth 2—4 cm.

Lugeon (1915, 1921) describes hard rock-erosion by "striage du lit fluvial" (in Escher, 1948, p. 154 and fig. 197, 198). Very similar in size and form to some types of flute casts (Cf. Maxson et al.)

Smith (1916, p. 154) is probably the first to attribute some of the irregularities on sandstone-soles to current scour and subsequent infilling, though he does not distinguish between this mode of formation and a load cast process for his "ball and pillow structures".

Clarke (1918, p. 203, 204, Plate 13 and 14); "Lobate rill marks" which are bulbous flute casts with sometimes spiral terminations.

Gürich (1933, p. 655, fig. 5); "Flieszwülste", probably flute casts with a depth of 2—3 mm.

Freudenberg (1934, p. 59); "Wülste", flute casts from the Bunt-sandstein of Heidelberg, Germany. This is an occurrence of flute casts from another sediment association than flysch.

Häntzschel (1935, fig. 6); "zapfenförmige Flieszwülste", recent examples of partly destructed current ripple crests on a tidal-flat surface bear striking resemblance to the flute casts described by Gürich. Flute casts should then be interpreted as positive surface features on the upper side of the bed, instead of negative casts on the sole. This hypothesis cannot be held in the light of the information about flute casts now available.

Maxson & Campbell (1935) describe the "Fluting" of hardrock bed of a stream, or boulders, by a fast, sand-transporting current. The forms of fig. 5—9 resemble closely the flute marks which must have been cut in soft sediment by turbidity currents.

Rücklin (1938); "Flachzapfen, einfache Zapfenwülste, Korkzieherzapfen". Rücklin's hypothesis about the formation of flute casts by current scour and subsequent infilling of the flute marks, is sustained by experiments with a shallow, sheet-current, flowing over an unconsolidated sand surface or mud. The locations of the flutings on the mud surface seem to be determined by relatively tough spots, which stand out on the surface after superficial washing away of the mud. These relatively high places act like objects on a beach causing rill markings on their down-current side. Rücklin claims to have produced spiral terminations in flute marks as well. Rücklin gives a hydrodynamical explanation for these forms. The hard-rock examples of Rücklin come from the Grenzletten, the transition from Buntsandstein to Muschelkalk, Niedtal, Germany. The Grenzletten do not belong to the turbidite association. The sizes are: length 3—5 cm, depth down to a few cm.

Peabody (1947); "Current crescents", resemble flute casts, but are formed on a mud flat by off-running water around objects, like the rill marks of the third type of Shrock (1948, p. 130, fig. 90-C). Sizes are: length 5—20 cm, depth a few mm.

Shrock (1948, p. 130—132, fig. 92) redescribes the "lobate rill marks" of Clarke and mentions other non-turbidite occurrences of these flute casts.

Rich (1950, fig. 4 and 8; 1951); "flow markings, flutings", sizes: length up to 30 cm, depth to 3,5 cm.

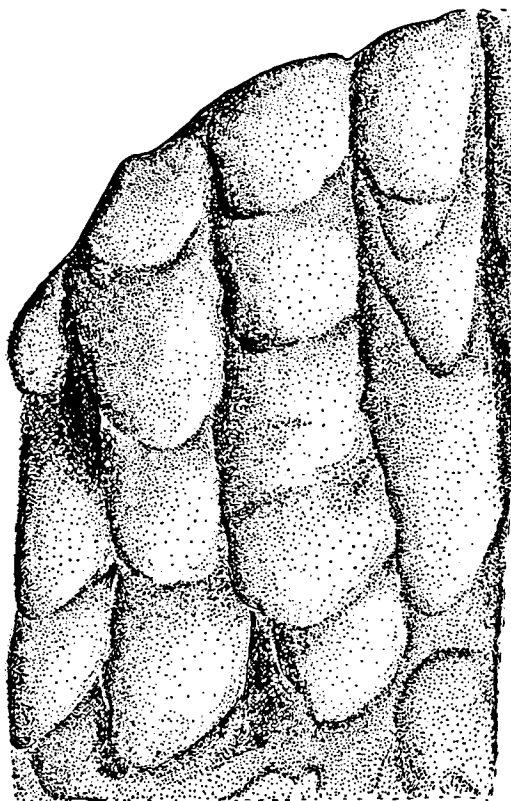
Bokman (1953, plate Ic); "tongues or fingers, scour-fingers", are flute casts with the following sizes: length several inches, width several inches, depth a quarter to one inch.

- Kuenen (1953) "flow markings".
- Hills & Thomas (1953, p. 125, plate I-1 and 2), "flow cast", length up to 10 cm.
- Mc Kee (1954) "current crescents", the same markings described by Peabody. (1947)  
Size: width 3—5 cm.
- Kopstein (1954) "flow markings".
- Van Houten (1954) flute casts with length of 3,5 cm and depth of 1,2 cm.
- Crowell (1955, p. 1959, plate I-1, 3 and 4) introduces the terms "flute cast" and "torose load cast". The latter may also have some genetic connection with the flute casts.
- Wellman (1955, p. 116) "tongues" of about 2,5 cm long.
- Prentice (1956, fig. 1) "flute casts", size: length up to 10 cm, width 3—4 cm, depth 1 cm.
- Cummins (1957).
- Kuenen (1957); extensive treatment of flute casts, several drawings and photographs.
- Kuenen & Prentice (1957) discussion of the nomenclature.
- Pettijohn (1957, p. 174, Plate 3) "flow cast".
- Sujkowski (1957) reports flute casts among other markings from the Carpathian flysch.
- Birkenmayer (1958, Plate XXIII) "flute cast", size: length 5 cm, width 2,5 cm, depth 5 mm, especially about the directions of turbidity currents as reconstructed from flute- and groove casts and the, often aberrant, direction of slope indicated by oriented load casts and "flowage casts".
- Cummins (1958, Plate 2, fig. 1) "flute casts", sizes: length 5 cm width 2 cm, depth 0,5—1 cm. The facies of the Keuper Sandstones in which these casts occur, is not indicative of deep-water environment. According to Cummins, flute casts are reported also from probable shallow, freshwater sediments, the Allegheny sandstones of Indiana (Pennsylvanian), and in the Devonian Old Sandstone facies, presumably also fresh water, in the Gaspé Peninsula, Canada and in Scotland, Westoll (1957).
- Glaessner (1958, Plate I—D) "flute casts", several types, sizes: length up to 10 cm, width 0,5—4 cm, depth  $\pm$  1 cm.
- Kingma (1958, p. 12, fig. 12 and 13) "scour casts", length 5 cm, width 2 cm, depth 1 cm.
- Radomski (1958) fig. 10, 11; Plate 39; fig. 1 and 2) "flat flute cast", "typical flute cast", "hoof-like flute casts", "composite flute casts" and "crescent casts". Size: length up to 5 cm, depth 5 cm.
- Wood & Smith (1958, p. 168).
- Cope (1959, p. 227, Plate XVIII; fig. 2, 3, 6 and 7).
- Ten Haaf (1959, p. 27—29, fig. 12, 13 and 14) proposes to distinguish "fan-shaped, linguiform, bulbous and voluted forms".
- Sutton (1959) Flute casts from turbidites for correlation.

### *Description of flute casts from Pernia.*

The largest flute casts are those occurring separately- on the sole of thick sandstone beds in the sandy series above the Rubagón graded formation. They are well developed, show rounded, bulbous ends and have a length up to 10 cm, a width of 7 cm and 3 cm relif. The most common type, nearly entirely restricted to the Caldero formation and the Rubagón graded beds

is linguiform. This type always occurs in groups, arranged in diagonal patterns. On the same sole they vary only a little in size. Fig. 24 shows a part of a sole with small, but well developed fan-shaped flute casts from the Caldero formation. In a section of the same specimen the current direction indicated by the flute casts is confirmed by cross-lamination. On Plate I-b flute casts are shown, which have been accentuated by subsequent load casting. In that specimen the length of the flute casts ranges from 2—4 cm and the relief from 0,7 cm to 1,5 cm. In the linguiform flute casts the relief seldom exceeds 5 mm.



2:1

Figure 24. Flute casts, Caldero sandstone formation, Pisuerga valley. ( $\times 2$ ).

The smallest flute casts covering entire soles as far as visible, recall the load cast striations as described from the Apennines by Ten Haaf (1959, p. 46, fig. 31). They invariably are of the linguiform type and have the following sizes: length 2—3 cm, width 3—7 mm, relief 1—2 mm. A type of flute cast of intermediate size is shown in Plate I-a.

On these soles all transitions from real flute casts to structures resembling load cast striation may be observed, which indicates a possible explanation for the latter structure, described by Ten Haaf. On the same soles, impact-

casts occur. The flute casts point towards these impact structures and probably the latter have been formed earlier and concentrated the current in their neighbourhood before they were filled in.

In no instance squamiform load casts (Ten Haaf 1959, p. 46) have been found, but it is possible that in the review of literature about flute casts, especially if described brief, squamiform load casts have been taken for flute casts. Ten Haaf noticed that the sense of the current direction in the case of squamiform load casts is found, by considering the culminating point. This is on the down current side, while flute casts culminate on the up-current side.

### 5.3.3. *Groove casts*

Groove casts are rectilinear ridges on sandstone soles. The cross-section may be rectangular, semicircular or triangular, symmetric or not.

Groove casts often contain coarser grains at the bottom than the sandstones on which they occur. The infilling generally lacks visible structure. Often sets of nearly parallel groove casts occur on a sole. Also discontinuous forms may be found. They are formed by the dragging of hard objects over the soft mud bottom by a swift, probably turbulent stream. About the nature of these objects very little is known. Ice-blocks, pieces of wood, animals, stones, concretions and angular pieces of indurated mud have been proposed. Only the last type of object has ever been found at the end of a groove cast or "slide mark". (Dzulinski & Radomski 1955).

#### *Bibliography. Groove casts and related markings.*

Hall (1843a, p. 234—237; 1843b, p. 422—432; 1843c, p. 148—149); "casts of mud-furrows", groove casts from the devonian Portage sandstone, which are possibly deposited by turbidity currents (cf. Shrock, 1948).

Lyell (1845, p. 162 and fig. 17) described groove casts on sandstone soles near Halifax, Nova Scotia, and proposed that they were cut in a shallow bottom by ice blocks, drifting in a tidal current.

Dawson (1855; 1868), cf. Shrock, 1948.

Clarke (1918; p. 204—206) was inclined to accept the hypothesis put forward by Woodworth, that ice-blocks, drifting in shallow water, caused the grooves.

Shrock (1948, p. 162—166, fig. 121 and 122).

Rich (1950; 1951).

Ksiazkiewicz (1952); "groove casts", dragmark type. Ksiazkiewicz proposes that they have been formed by the dragging of objects along the bottom by a slow current. Because the examples described from the Carpathian flysch are linked to the soles of turbidite beds, this explanation is not very probable.

Bokman (1953, Plate I, fig. 3).

Van Houten (1954).

Crowell (1955, p. 1358, Plate I-2 and Plate II-1b and 3).

Dzulinski & Radomski (1955) "groove casts", but many of the examples they present, belong to the "slide mark" type (Kuenen & Sanders, 1956).

Link (1956, fig. 3 and Plate I-3) "Schachtelhalm"-impressions, not real groove casts, but genetically related with these,

Cummins (1957).

Dunbar & Rodgers (1957, p. 194 and fig. 100) describe groove casts, and also "chevron markings" which resemble the "herringbone pattern" of Kuenen (1927, Plate 2-be).

Kuenen (1957, p. 243—246, fig. 11, 12, 13a, 15; Plate I-c).

Pettijohn (1957, p. 174, Plate 3).

Sujkowski (1957).

Vaidyanadhan (1957) Groove casts in a deltaic (f) environment.  
Birkenmayer (1958).

Cummins (1958, Plate 2, fig. 4) "Ctenoid casts" (compare Linck, 1956) and groove casts. The latter are like flute casts, not restricted to turbidites, but may occur in shallow water and even continental environments.

Glaessner (1958, p. 4) large groove casts attaining a length of up to 7 meters, width of 12 to 25 cm and depth of 5 cm.

Radomski (1958, Plate 38-1) "groove casts" and introduction of the term "impact cast".

Wood & Smith (1958, p. 168).

Cope (1959), p. 228).

Ten Haaf (1959, p. 31—39, fig. 16—23) describes groove casts and slide casts from the Apennine flysch and discusses the mode of formation in detail.

Dzulinski, Ksiazkiewicz & Kuenen (1959, p. 1115—1117, figs. 10—12); "bounce-, prod- and skip-markings", which are different impact casts.

### *Description of groove casts of East Pernia*

The occurrence of groove casts is almost restricted to the Graded formation and the Rubagón graded beds. Occasionally they also occur associated with flute casts on the soles of the Caldero formation in the Rubagón valley. The best developed groove casts and related features can be studied in the overturned eastern flank of the Redondo syncline.

In the Graded formation sets of small groove casts, very near each other, occur on the bedding plane. Larger groove casts are beset with many minor ones, as if the cutting object had many sharp points. (See cross section on Plate Ic.)

Groove casts like rectilinear ridges most often occur with sizes between the following limits:

length	5—250 cm
width	0— 7 cm
relief	0— 3 cm

In a few instances, discontinuous groove casts are noticed. In one example the length of the parts of the groove casts and the intervals between were measured in a downcurrent direction as follows (the lengths of the groove casts are in italics):

40 — 65 — *65* — 40 — 35 — 50 — 25 — 30 — 30 — 60 — 70 cm

Total length at least 5 m, width 1 cm and depth 5 mm.

A very large straight groove cast has been observed in the Caldero formation. The length is at least one meter, the width 50 cm and the depth 10 cm. Two parallel groove casts of 1 cm depth and 3 to 4 cm width occur

on the bottom of it. No flute casts occur on the bottom of this groove cast, nor on the sole. The size of this structure reminds one of gouge channels (Kuenen, 1957, p. 242).

There seems to be a relation between the width and the depth of the groove casts, which can be generated by many causes and does not throw much light on the nature of the objects that did the cutting.

Perhaps a very detailed and painstaking study of the cross section of groove casts, where these have not been deformed by subsequent load casting, would reveal something about the form of the objects which served as cutting tools. The presence of many concretion beds (clay-iron stones), which probably were eroded away in some instances by the next turbidity current, could be a point in favour of the hypothesis, with much reservation presented by Ten Haaf (1959, p. 35), that nodules might be the dragged objects. At least we found evidence for the syngenetic nature of the clay-ironstone nodules and an indication that they formed tough or hard beds, which would break into angular fragments if erosion was strong enough.

There remains the difficulty that never any nodule has been found at the end of the groove casts.

The only objects ever found in a groove cast in Pernía are two goniatites of about 2,5 cm diameter very near each other at the bottom of a groove cast of considerable size. They were washed in before the deposition of the sand and certainly have not caused the grooving, because they are located at about the middle of the length of the groove cast.

Ten Haaf (1959 p. 36 and 37) postulates the following sequence of events: "precurvery grooving in an aberrant direction — further grooving and subsequent fluting in the principal direction — preservation of all these markings by deposition". Geological observations together with the statistical analysis of bed thickness sequence have shown that most erosion occurred where the sandstones are thick and the shale beds between, thin or absent. This explains why the groove casts were most often preserved in the Graded formation and the flute casts in the sandier Caldero formation.

In the latter case the groove casts may have existed for a very short time, but were eroded away with all the mud or the greater part of it. This strong erosion was able to form the fluting on the surface.

In chapter 6 it is pointed out that a deficiency of measurements probably causes the apparent grouping of groove cast — directions around two or three azimuths. However if more sets can be measured, this peculiarity is fading and the directions seem to be scattered about one mean azimuth.

This conclusion strongly favours the possibility mentioned by Ten Haaf (1959 p. 38) that the lobate fronts of turbidity flows caused the aberrant directions of groove casts.

#### 5.3.4. *Impact and related markings*

Radomski (1958) described "impact casts" as the casts of markings made by objects, flung against the mud bottom. The "bounce casts" mentioned by Wood & Smith (1958 p. 168) probably are of the same nature.

Birkenmayer (1958 Plate XXII, fig. 1) illustrated an "angular fragments groove cast" which closely resembles some of the casts of the turbidites of Pernía.

The frequent occurrence of these markings with groove casts and the inter-

mediate forms between impact casts and groove casts shows the intimate genetic relationship between the two types. Several different types can be distinguished as indicated by Dzulinski, Ksiaskiewicz & Kuenen (1959 "prod-, skip- and bounce casts").

Impact casts have been found in the Graded formation, Caldero formation and Rubagón Graded Sandstone formation.

They range from about 1–15 cm in length and from 0–3 cm in width and depth.

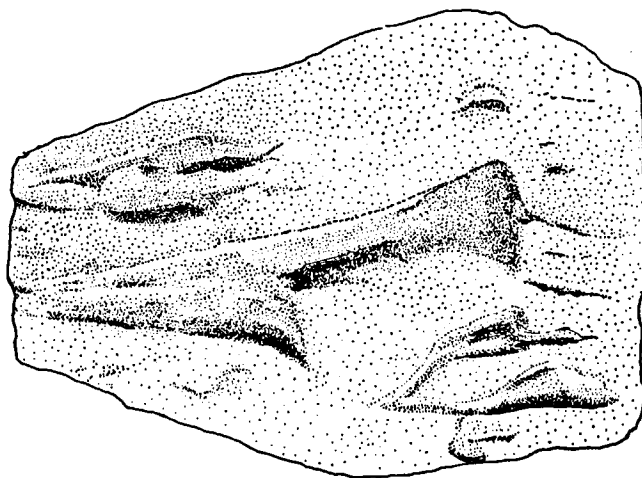


Figure 25. Impact cast, Rubagón graded beds, Rubagón valley.

Some have the form of a triangle with the base on the sole of the bed and two gently curved sides in a plane which can be inclined at every possible angle to the bedding plane. The base of the triangle lies parallel to the other markings on the sole. This form could be explained by assuming that a rod-like object touched the soft mud bottom with one end, which at that moment also was the downstream end. This end sagged a few mm into the mud and was retarded in its movement. The upper end, dragging behind, now would rotate by the couple formed by the current-force on the upper part and the resistance of the mud on the buried part. The hinge point would be situated somewhat below the mud-water interface and probably at the lower end of the rod, because there the mud would be most resistive. This process could act both when the object rotated in a vertical plane and when it turned about in an inclined plane. After the cutting, the current caused the object to slip out of the marking.

An example of such an impact cast is shown in fig. 25. These triangular forms (skip markings?) occur in all the turbidites.

Other forms, probably "prod casts", which are straight ridges ending abruptly down current, are fairly common on the soles with miniature flute casts. In such cases the prod casts and the triangular forms are antedated by the flutings, because the latter point toward these markings in the vicinity.

The use of impact casts as paleocurrent direction-indicators is restricted to the cases where many occur on the same sole, because a minor number of

dubious or inverted forms may be present. The range of direction-variation of these markings seems to be less than that of the groove casts. This might indicate a greater velocity of the current.

### 5.3.5. *Problematic features*

A problematic sole marking from the Rubagón graded beds schematically is shown in fig. 26, which is drawn after a specimen. The black lines are ridges, about 1 mm deep and 1—2 mm wide, which are sub parallel, join each other, split and do not show any pattern at large scale, as rill marks should do. They invariably occur on thin laminated beds and cover the sole as far as can be ascertained. Some irregularities are situated on the ridges. These probably were holes in the mud surface before the current action formed the grooves (black spots on fig. 26). Because the ridges sometimes split in the direction

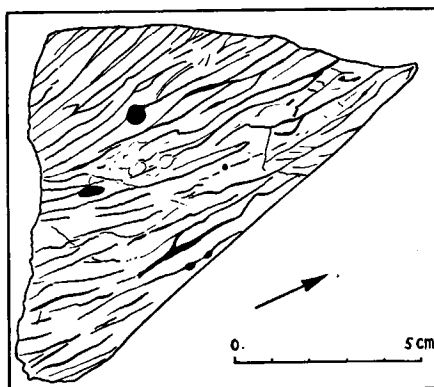


Figure 26. Problematic current markings, Rubagón graded beds.

of the current it is not probable that dragged objects caused this phenomenon; they seem to be due to the scouring of the mud surface by a sand laden current, which was not fast enough to erode the bottom by fluting. Also the underlying mud surface itself may have been in a special state, to allow this kind of erosion, rather than fluting.

### 5.3.6. *Load casts and flow casts*

About the mode of formation of these markings much has been said and written. The vast bibliography, not only is due to the fact that load casts and related markings occur so often, but also to the controversy between those who consider load casting (vertical movement) and those who consider flow casting (lateral movement) the most important factor.

The key to a better understanding of the processes involved lies essentially in the difference in relation between the grains and the pore-water in a sand and in a clay. The sandstone having a considerably greater permeability can easily get rid of its pore water, whereas this process takes considerable time in the clay. The loading of the clay or mud with the sand bed increases the water-pressure but not the grain-pressure in the clay. As a consequence the clay particles first touching each other become floating again and solid lumps



of sand sink into the fluid clay. This is the "quick sand principle" of soil mechanics, also described by De Sitter (1956, p. 41). It explains the close relation between "flame structures" and load casts.

According to Kuenen & Prentice (1957) it not always is possible to distinguish load casts and flow casts. While the process of load cast formation clearly is envisaged as the sagging of relatively heavy coarse material into the lighter finer grained hydroplastic sediment, the definition of flow cast still is somewhat obscure.

Kuenen & Prentice (1957, p. 173) mention the following process:

"The horizontal movement of the base of a bed of sand during or after its emplacement on a mobile substratum combined with sinking and ploughing up of the latter. This might be called flow and the resulting structures flow casts".

The lateral force which causes this flow is the component of gravity along the slope or the drag of the depositing current.

However, not only flowing may produce asymmetric structures. Asymmetry in a preferred direction also may be of primary origin (Ten Haaf 1959, p. 45). Load casts can be exaggerations of asymmetric flute casts.

From these considerations it is clear that no precise terminology is possible. A few examples from eastern Pernía, though, will be described, using the usual terminology.

#### *Description of load casts and related markings in the turbidite association*

The Graded formation does not often show load casts or deformation of groove casts by load casting. The Caldero formation and the Rubagón graded beds however show a variety of markings belonging to this class.

Small size load cast, i. e. load cast on the bedding planes will be considered here. They may be found on the soles of sandstones in the paralic association, but are more common in the turbidite association.

Loadcasting of earlier markings, like flute- and groove casts, is of frequent occurrence. An example of loadcasted flute casts is shown on Plate I-b. The fanshaped and linguiform flute casts of 2,5 cm length and 1 cm width have exaggerated depths of up to 7 mm. Besides, these flute casts have vertical to overhanging sides where they merge with the bedding plane.

Irregular load casts of lumpy polygonal form, if seen from below, have been found in the Rubagón graded beds. The diameter is about 3 cm. There is no indication that these load casts are deformations of some earlier marking. They have no asymmetry in a preferred direction and the most interesting fact is that the structures on one bed all show the same relief (1 cm). Ten Haaf (1959, p. 43) explains this feature by assuming that load casts only could sag into a level, below which the sediment was settled enough to resist the pressure of the loading. In some cases load casts, sagged to a common level, may spread out and even join laterally. An example is shown on Plate I-d. The depth is 1,2 cm, average size of the casts is 4 cm.

A bed which creeps downslope may cause asymmetry in the load casts and flame structures at its base. The direction of movement indicated by the asymmetric, irregular load casts of plate I-f does not coincide, however with the main current directions measured in outcrops in the vicinity (Rubagón graded beds).

Flow casting requires a very mobile state of the sand and clay, which

is reflected in the character of the resulting structures. The few examples which have been found are from the Rubagón graded beds. The example of Plate I-e probably is of the "multi-directional flowage cast" type described by Birkenmayer (1958).

Flame structures nearly always are associated with load casts (see fig. 19). If the load casts show asymmetry in a certain direction the flame structures also do. The flame structures are more or less circular in cross section in the small area bordered by three load casts.

In one example the load casts are not visible and perhaps never existed. The flames however, rise up to over the middle of the thickness of the sandstone bed (fig. 27).

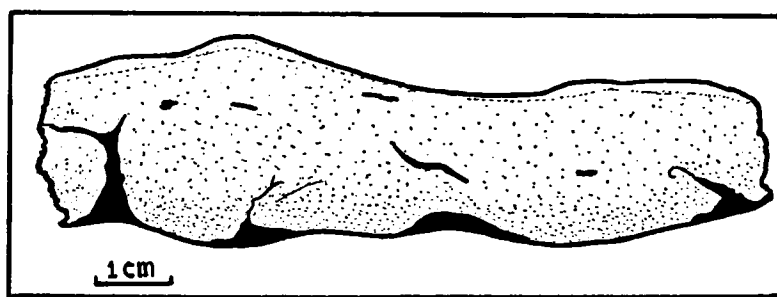


Figure 27. Flame structures in graded sandstone bed.  
Rubagón graded beds. Black: clayey material.

In this case asymmetry in both directions occurs.

Small penecontemporaneous faults may be localized by load casts. In one example the laminated top part of a sandstone bed could not deform by flow and was transected by a miniature gravity fault at one side, a few cm above the margin of a load cast. As the penecontemporaneous character of the fault is proven by the undisturbed laminae covering the faulted part of the bed, also the time of formation of the load cast is fixed as before the end of the deposition of the whole composite bed.

Penecontemporaneous faults of much larger size and in very different sediments have been described by Fairbridge (1947, fig. 5 and 6b); Shrock (1948, p. 259, fig. 227) Hatai et al. (1956, fig. 5 and 8a, b).

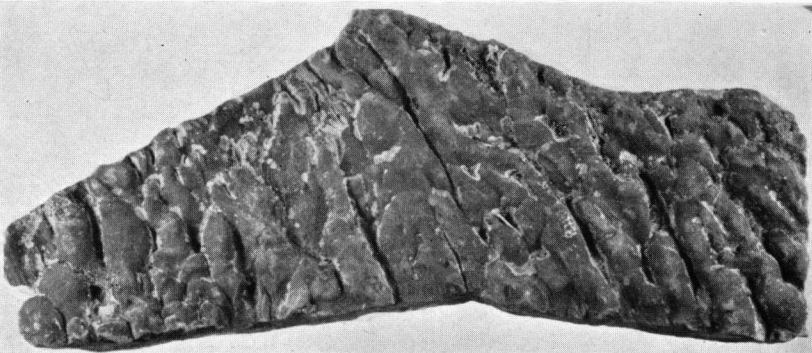
#### DESCRIPTION OF PLATE I

- a. Linguiform flute casts, Caldero formation, Redondo syncline. Current direction towards upper right corner of photograph.
- b. Load casted, bulbous flute casts, Caldero formation, Redondo syncline. Current direction indicated by arrow. Length of specimen about 30 cm, relief of the casts up to 7 mm.
- c. Groove casts ("drag marks"), Graded formation, Redondo syncline. Width of specimen 15 cm, relief of casts up to 7 cm.
- d. Slightly asymmetric load casts, with almost flat bottoms. Length of specimen about 28 cm, relief of the casts 1.2 cm.
- e. Flow casts ("multi-directional flowage casts"), Rubagón Graded beds, north of Barruelo.
- f. Asymmetric load casts, Rubagón Graded beds, north of Barruelo.
- g. Variety of organic markings, Graded formation, Redondo syncline, third series. Wormtrails probably post-depositional. Natural size, relief a few mm.

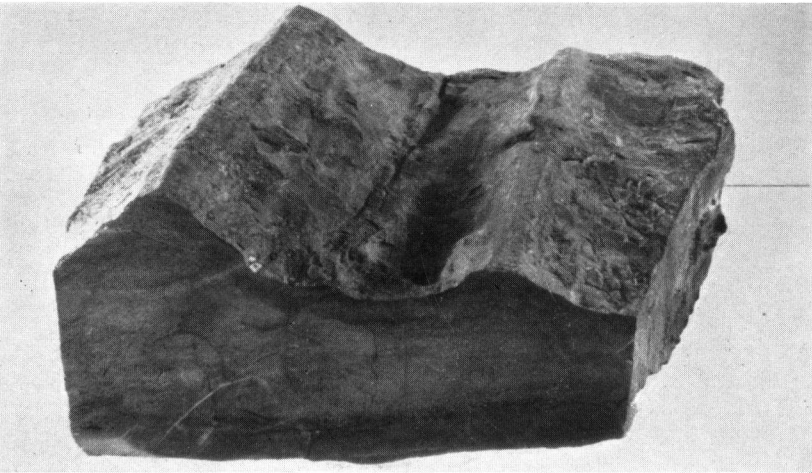
a



b



c



d



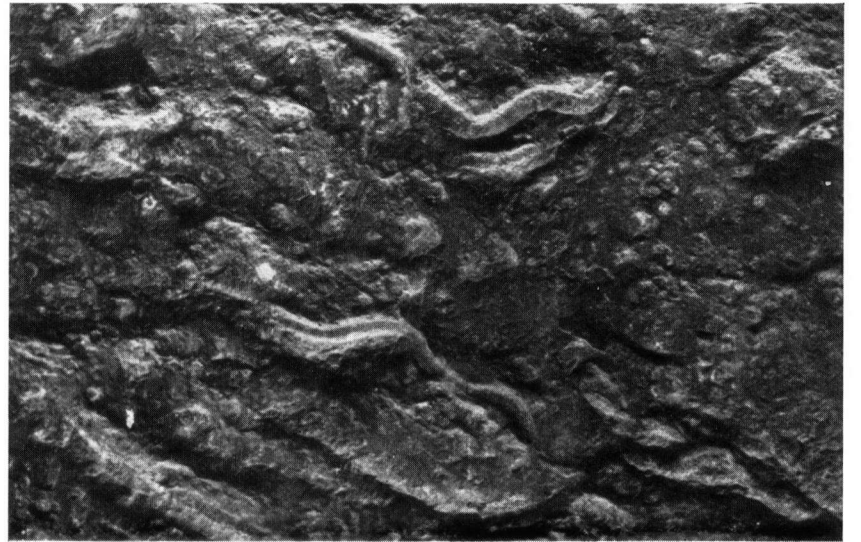
e



f



g



*Bibliography on load casts and related markings*

- Hall (1843, p. 233 and fig. 101).
- Hauer (1859, p. 420). The structures described are probably load casts of small size.
- Zugmayer (1875, p. 292—294).
- Fuchs (1895, p. 370, plate I-4 and I-6). Irregular and rippleform load casts are described. Flowing rather than loading is proposed as mode of origin. Compare "flow casts" of later investigators.
- Smith (1916, p. 154, fig. 8) mentions the possibility of a load cast process for his "pillow structures".
- Kukuk (1920, p. 805) "Wülste", load casts in the top of a coal seam.
- Hadding (1931, p. 380).
- Kraus (1932, p. 30, 59, 69, and fig. 13) "Wülste", load casts with 5—15 cm diameter and about the same depth.
- Rettger (1935) has shown in experiments how soft sediment can be deformed. Instructive for better understanding of the deformations, especially the bending and rupture of unconsolidated strata under load.
- Kukuk (1936, p. 1026—27), "Wilder Stein", large load casts in the top of coal seams.
- Lamont (1938, p. 14) "antidunes", structures later described as flame structures, and probably intimately related to load casts.
- Brueren (1941, p. 59) describes an example of slumping in turbidites, in which probably also load-casting took place.
- Hills (1941, p. 183, fig. 12a) "basal sandstone deformations", descriptions of load casts and flame structures.
- Lamont (1941, p. 150) "Antidunes", equivalent to flame structures?
- Cooper (1943, p. 193—201) describes "flow structures" from Lower Mississippian sediments. Current bedded sandstone was deposited by a river on fine grained sediments. Cooper thinks sliding on a slope as the most important factor in the process of formation.
- Hills & Thomas (1945, p. 57, fig. 5). The spacing and location of "basal sandstone deformations" may be determined by markings on the top of the former sandstone bed, provided the intervening shale is thin enough.
- Niggli (1948, p. 153).
- Shrock (1948, p. 156—162, figs. 116—120) introduces the term "flow cast", proposed by Whitehead; the term has now a more restricted meaning.
- McCallien & Tokay (1948, p. 161—162, figs. 4, 5 and 6). "Pockets and antidunes", i. e. load casts and flame structures.
- Macar (1948) "Pseudo-nodules" are in fact a special sort of load casts. Compare the experiments of Kuenen (1958b).
- Emery (1950, p. 111—115) described Pleistocene load casts on marshland clay.
- Macar & Antun (1950, figs. 2—10, plate I and II) consider both loading and flowing responsible for the formation of the pseudo-nodules.
- Ksiazkiewicz (1952) mentions "flow casts"; mode of formation discussed in the light of Fuchs' hypothesis.
- Kuenen & Menard (1952, p. 89—91, figs. 4, 5 and 6) description of load casts and flames in experimental turbidites.
- Carozzi 1952.

Bokman (1953).

Kuenen (1953, p. 1058, figs. 12 and 13). Definition and introduction of the term "load cast".

Van Houten (1954).

Kaye & Power (1954, p. 309) describe "load casts" of about 15 to 20 cm diameter and sandstone balls, torn loose from a sandstone bed. The features are less than ten years old and occur in a deposit of a river in an artificial lake.

McKee (1954, p. 63, plate 9a and c); "flow marks", but very probably load casts; the environment is probably a mudflat.

Kopstein (1954), load casts on graded sandstone soles.

Pepper, de Witt & Demarest (1954, p. 88, 89, figs. 52—55) propose the term "flow rolls" for very large load cast-like structures. (cf. Cooper, 1943). The rounded bodies measure up to 4 meter in diameter and are explained by these authors as the results of unequal loading and unloading of plastic sediment.

Chvorova (1955, tag. VIII, fig. 27) describes several structures among which a "multi-directional flowage cast" in the sense of Birkenmayer (1958).

Crowell (1955, p. 1358—1359, plate 1—4). Load cast-lineation, "torose load casts", etc.

Dzulynski & Radomski (1955, p. 57, fig. 6) describe deformation of groove cast by compaction of the underlying mud; a reminder of the fact that not only load casting can deform a marking, but that also other mechanisms may play a part.

Kühn-Velten (1955) "Wülste", probably load casts.

Sutton & Watson (1955, p. 116, fig. 5) "flame structures".

Greensmith (1956) describes "flow casts, load casts and parallel load casts or rills" from sediments which have probably nothing in common with turbidites except the load casts.

Hatay & Funayama (1956, p. 141). Siltstone blocks sagged into arkosic sand. A combination of slumping and load casting.

Prentice (1956) propose the reintroduction of the term "flow cast" for load cast. Discussion of the load cast and flow cast processes.

De Sitter (1956, n. 301 and 302, figs. 228—230).

Walton (1955, plate 1-a, 1956, figs. 1-c, 4 and 5-a) "load casts and flame structures".

Dunbar & Rodgers (1957, p. 192, fig. 99) "flow rolls".

Hatay & Funayama (1957, p. 12). Large detached load casts of up to 1.5 m size, embedded in underlying bed or lying with flattened bottom on a still lower bed. The surface of the latter is sometimes bent under the load. Occurs in tuffaceous sediments.

Hull (1957, fig. 13 and 14); "flow cast", asymmetric load casts and flame structures. Explanation of asymmetry by flow of the sediment during deposition.

Kelling & Walton (1957) stress the fact that a load cast-process may deform previous markings or irregularities of the mud-sand interface beyond recognition. But in many instances nomenclature of load casts is possible on the basis of their derivation from pre-existing structures.

Kuenen (1957, p. 246—253, figs. 15—18). Several examples of load casts and discussion about the origin.

Kuenen & Prentice (1957). Discussion of the meaning of the terms "load cast" and "flow cast", with the conclusion that precise terminology is not possible.

Lamont (1957, figs. 1 and 2). "Antidunes" which are the same as, or related to flame structures. Lamont proposes the possibility of turbulent scouring and centrifugal force exerted by eddies during the emplacement of the sandstone bed as a cause.

Pelhate (1957) describes large load casts of more than a m from a lacustrine environment.

Vaidyanadhan (1957). Flow casts; "flow out" proposed as a new term for flow cast.

Kuenen and Crowell (1958) discuss sole markings.

Kuenen (1958b, p. 17—21, figs. 9—10, plate I, II and III) describes experiments relative to load casts. Influence of thixotropy; "contorted beds" and "quake sheets" in connection with the pseudo-nodules of Macar.

Glaesner (1958, plate I-a and I-b).

Birkenmayer (1958). Apart from a statistical study of direction measurements to show the discrepancy between slope-direction and turbidity-current direction, introduction of a few new terms, covering several types of load- and flow casts. In addition a description of some markings on the tops of turbidite sandstone beds.

Wood & Smith (1958, p. 168).

Cope (1959, p. 229, Plate XVLLL-6 and 7).

Ten Haaf (1959, p. 43—49, figs. 27—33). Description and terminology of several new forms, as "squamiform" and "syndromous load casts".

## CHAPTER VI

### PALAEOCURRENT DIRECTIONS

#### 6.1. *Introduction*

The importance of palaeocurrent studies has been fully recognized in the last quarter century. Many systematic studies of primary current structures of all kinds have been published. Pettijohn (1957, p. 578) emphasizes this importance as follows: "Geological fieldwork involving the coarser elastic sediments can now be considered acceptable only if it includes mapping of the primary sedimentary structures of these rocks. Stratigraphic field studies omitting such features, are as incomplete and unsatisfactory as geological maps of complex structures without observations of strike and dip of bedding, cleavage, lineation and so forth."

Though our area is very well exposed, relatively few measurements could be made. A thorough search has been made in all sandstones for primary current structures, but the possibilities for a direction-study in this area are very small. In total about a hundred cross-bedding measurements, a few current ripples and a hundred and sixty sole marking-directions furnished the material for this study. These measurements of palaeocurrent directions were made in the Upper Westphalian and Stephanian A of the Pisuerga basin.

Because of the complicated folding of the beds, corrections have been made for axial dip of the folds. The magnitude and size of these corrections were derived from the graph published by Ten Haaf (1959, p. 74—75, fig. 55). The axial dip was estimated by considering the dip in the vicinity of the axial plane. The form of the structures is far from cylindrical (e.g. Redondo syncline) and causes a great inaccuracy in the obtained directions.

The palaeocurrent directions, indicated by red arrows on the map, should be considered with much reserve, especially where they are situated in overturned flanks of folds. For example, the directions obtained from sole markings in the overturned east-flank of the Redondo syncline, have been corrected with 30—60 degrees, based on an estimated axial dip of about 20 degrees to the SE. If 30 degrees axial dip had been more appropriate, the average direction in this flank would roughly be 20 degrees more to the south, while, with 10 degrees axial dip, the directions on the map would shift about 15 degrees to the north. This indicates that, because of the uncertainty in the estimation of axial dip, we should measure about 30 degrees on either side of the vectors to obtain a reasonable confidence interval around the observed directions, before drawing palaeogeographic conclusions from them.

The cross-laminations have been measured by taking strike and dip of foreset-laminae and strike and dip of the truncating beds. In principle it should be better to use the average strike and dip of the whole sandstone body at the outcrop, but the range of variation in strike and dip is often

too wide to allow such procedure. Of course there is no guarantee that the truncating surface originally was horizontal, but it is the best available reference plane. Probably a part of the variance in the directions is due to the use of this truncation-plane instead of the bedding plane. Nevertheless, from nearly all current bedded sandstone outcrops measured, significant direction vectors have been obtained.

The reconstruction of the direction from the two strike and dip readings has been made by use of a meridional stereographic grid (Fisher, 1938). At the same time the inclination of the cross-laminae at the time of deposition has been measured graphically.

The inclinations of 83 laminae from several outcrops vary between 0 and 36 degrees (fig. 28).

The average inclination is 18 degrees. This is in excellent agreement with the results obtained by measurement of cross-bedding in unfolded or slightly folded rocks (Pettijohn 1957, p. 168). It seems to justify the applied measuring technique.

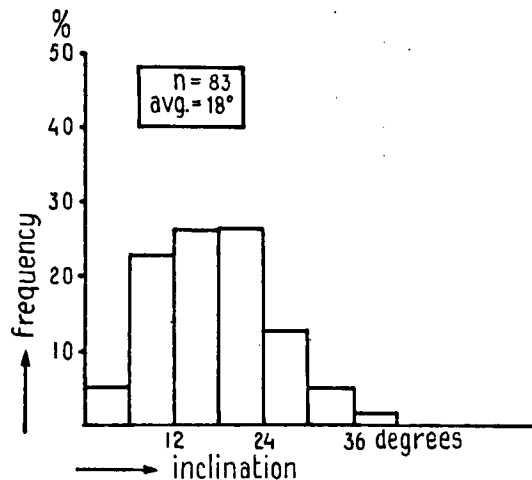


Figure 28. Histogram of cross-bedding inclinations.

A difficulty with regard to the interpretation of the result arises from the shortening due to the folding of the beds. To interpret the directions, a palinspastic reconstruction of the sedimentation area must be made (Kay 1945). We can only roughly estimate the amount of shortening. In the case of the east flank of the Redondo syncline we may estimate the displacement towards the southwest to be about  $\frac{2}{3}$  of the involved length.

Relatively to San Juan de Redondo, the Graded formation outcrops represent the sedimentation in a site, about three kilometers NE of the Cordillera Ibérica.

The area of the Pisuerga basin covered by the Westphalian D and Stephanian A sediments now measures 20 by 12 km, with the long side in a NNW—SSE line. After "palinspastic reconstruction" it would be more like a 20 by 20 km square. It is necessary to keep these considerations in mind while evaluating the palaeographic significance of the data.



The tectonics greatly have limited the possibilities of palaeocurrent studies in this area, but still some interesting conclusions may be drawn from the results.

## 6.2. *Turbidite association*

### 6.2.1. *General*

Palaeocurrent studies, involving several classes of sole markings, have been made by many authors during the last five years. In the following list turbidite studies involving palaeocurrent measurements, are assembled:

1.	Kopstein	1954
2.	Guazzone	1954
3.	Cromwell	1955
4.	Dzulinski and Radomski	1955
5.	Kuenen and Sanders	1956
6.	Prentice	1956
8.	Cummins	1957
8.	Lamont	1957
9.	Birkenmayer	1958
10.	Radomski	1958
11.	Cope	1958
12.	Ten Haaf	1959
13.	Bouma	1959

The most important studies about the theoretical difficulties in interpretation of the results, have been made by Birkenmayer 1958, Kuenen 1958, and Ten Haaf 1959.

The primary current structures in the turbidite association of the Pisuerga and Rubagón basins are:

1. cross-lamination
2. flute cast
3. convolute lamination
4. groove cast
5. impact cast
6. charcoal lineation
7. striation cast.

### 6.2.2. *Agujas graded sandstone formation*

From the turbidite formation, directly overlying the Aguja limestones, only two or three inconsistent groove cast measurements have been obtained. All outcrops with overturned strata, in this formation, lie at the foot of the Cordillera Ibérica, where the topography only occasionally allows erosion to clean a sole of the adjoining shale.

### 6.2.3. *Graded sandstone formation and Caldero sandstone formation*

The outcrops of the Graded formation and the Caldero formations are situated more favourably. Here many dip-slopes are showing large surfaces of undersides of graded beds.

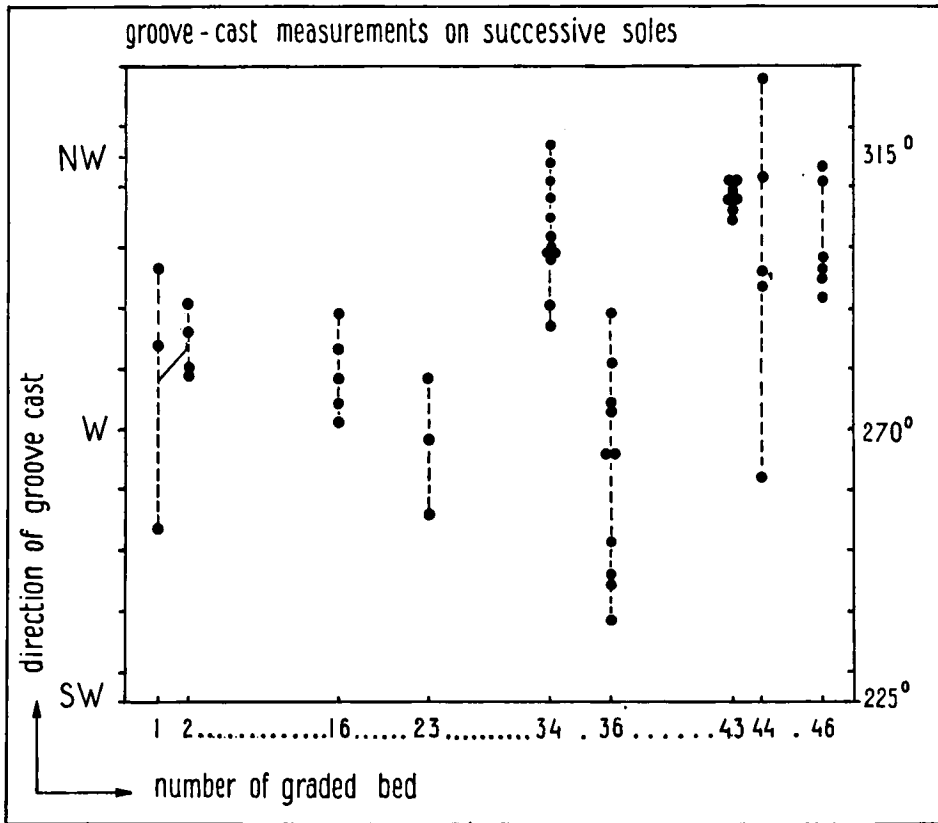


Figure 29.

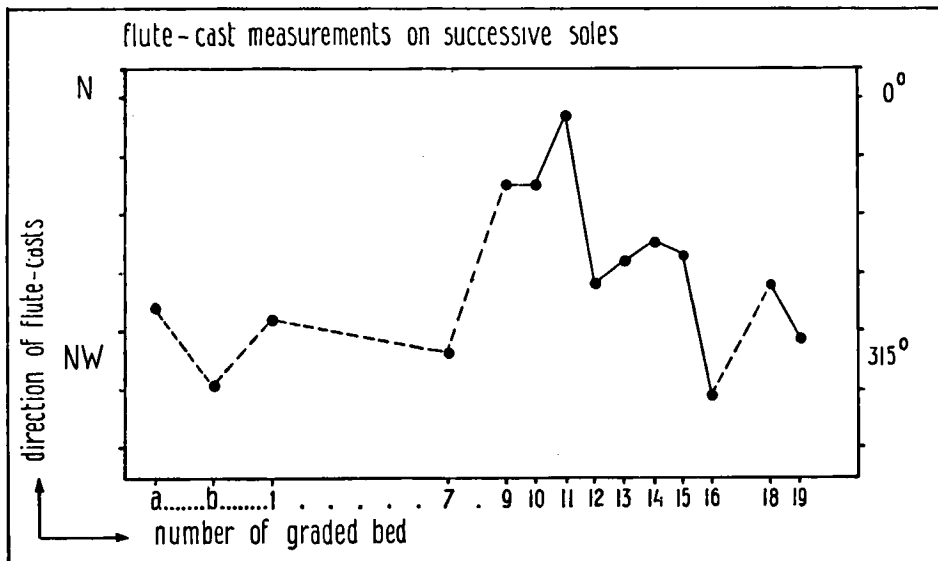


Figure 30.

In the Graded formation the directions have been derived from groove cast measurements. The sense of the directions was obtained from impact casts and small scale current bedding. In one excellent outcrop in the upper part of the Graded formation, many soles with groove casts were exposed. Some of the soles showed a profusion of organic markings. The total surface of exposed sole, distributed unequally over nine beds, exceeded a thousand square meters. This unique opportunity was used to study the variability of directions of groove casts.

A choice was made from the groove casts on the bedding soles to avoid measuring apparently mutually dependent groove casts as separate directions. To this aim intermittent groove casts and sets of exactly parallel groove casts near each other, were counted as one measurement. This approach is subjective and the conclusions must be made with much caution. The result is shown in fig. 29.

It must be emphasized that the absolute "value" of the directions as pointed out above is very uncertain. The graph only is useful to indicate the range of variation on and between successive or nearly successive soles. Part of the variation, probably up to 5 degrees, results from the slight variations of strike and dip of the bedding planes in the outcrop. In 4 beds cross-lamination was observed, always dipping into the NW quadrant.

In some cases there apparently is significant difference in average direction between bedding planes. The obtained results seems to indicate that in this section two different directions of stream prevailed, intersecting each other with an angle of 20 degrees (fig. 29, beds 1, 2, 16, 23 and 36 against 34, 43, 44 and 46).

Important is the rather large spread in the directions of groove casts on the same bedding plane. The range of variation varies from bed to bed and is naturally dependent of the number of measurements in these small samples. On two bedding planes it nearly reaches 60 degrees. This divergence is about twice as large as the maximum reported by Ten Haaf (1959, p. 32). This is due to the fact that we have measured groove casts tenth of meters from each other on the same bedding plane.

The observation by Ten Haaf that "groove casts, intersecting at large angles on a single sole, are not scattered about a mean azimuth, but run parallel to either of two (very rarely three) dominant directions making a constant angle", seems to need extension in the case of the Graded formation. Indeed sets of parallel groove casts intersecting each other occur, but the number of sets is not restricted to two or three. If larger surfaces of sole can be observed, consequently a larger number of groove casts (or sets of parallel groove casts) is noticed, and the direction of the sets show to be scattered around a mean azimuth.

#### 6.2.4. *Consistency of directions*

From the sandier Caldero formation a short section with flute-casted soles has been measured in detail. The directions on the subsequent soles are indicated in the graph of fig. 30.

The directions vary within a range of about 50 degrees, which is near the average spread in the directions of the groove casts of fig. 29. Like on fig. 29 there seems to be some grouping of similar directions in adjacent beds. The number of subsequent soles is rather small, but a simple test may

be used to obtain an indication of the probability that such grouping, as observed here, may arise by chance.

If we divide the directions into two groups on either side of some chosen reference direction ( $340^\circ$ ) and code the sequence of directions of fig. 30 like this:

N N N W W W W W      (two runs,  $u=2$ )

where N signifies a direction north of the reference direction and W a direction west of it, we may test the grouping in this sequence by using the tables prepared by Swed & Eisenhart (1943, p. 70–87). It follows then that this “clustering” of similar directions results only once in 28 times if they are shuffled and laid out in a row. The total number of possible different arrangements (permutations) is  $8!/5!3!=56$ .

If we also involve the other directions, from not directly adjacent soles, we observe, using the same reference direction:

a — 19: W W W W N N N W W W W W W W       $u=3$

The probability to get this result, or still less runs is  $P(u \leq 3) = 0.038$ . The probably significant result might have arisen from the favourable choice of the reference direction. Therefore we repeat the analysis with reference direction at  $330^\circ$ . The sequence becomes:

a — 19: W W W W N N N W N N N W W W       $u=5$

The probability is then 0.086. Not quite so significant, but still an indication of clustering.

The same has been done with the average directions of the groove casts on the 9 soles of fig. 2. The reference direction is chosen at  $290^\circ$ . The sequence is:

1 — 46: W W W W N W N N N       $u=4$

The probability is 0.262. The clustering may easily have arisen by chance.

As a third example the sequence measured by Ten Haaf (1959, p. 66, fig. 50) in the Apennine flysch, is analysed here. The reference direction here is chosen at the average indicated on Ten Haaf's figure. The sequence of the fifteen directions on successive soles is then:

1 — 15: E E S S S S S S S S E E E E S       $u=4$

The probability is 0.015, i.e. nearly at the 1% level of significance.

The conclusion seems to be warranted that similar directions tend to occur in sets of successive soles. This regularity in the succession of directions might be explained by assuming that sets of turbidity currents arrive one after the other from sources near each other. Spreading out on the sea bottom, the currents arrive at the observation point from the same direction, while slumps at other places cause turbidity currents from other directions at the same observation point.

Another possible explanation might be the constancy of the direction of maximum slope of the sea floor during a certain time interval. Downwarping of the basin might change this direction, causing the turbidity currents to flow in other directions.

The first explanation appears the simplest to the author, and more attractive because it fits the character of the thickness sequence with its sandstone-thickness fluctuations, which have been attributed to the same cause.

The general coincidence of groove and flute cast directions, indicates the usefulness of the groove casts as current direction indicators. An illustrating example is shown on fig. 31.

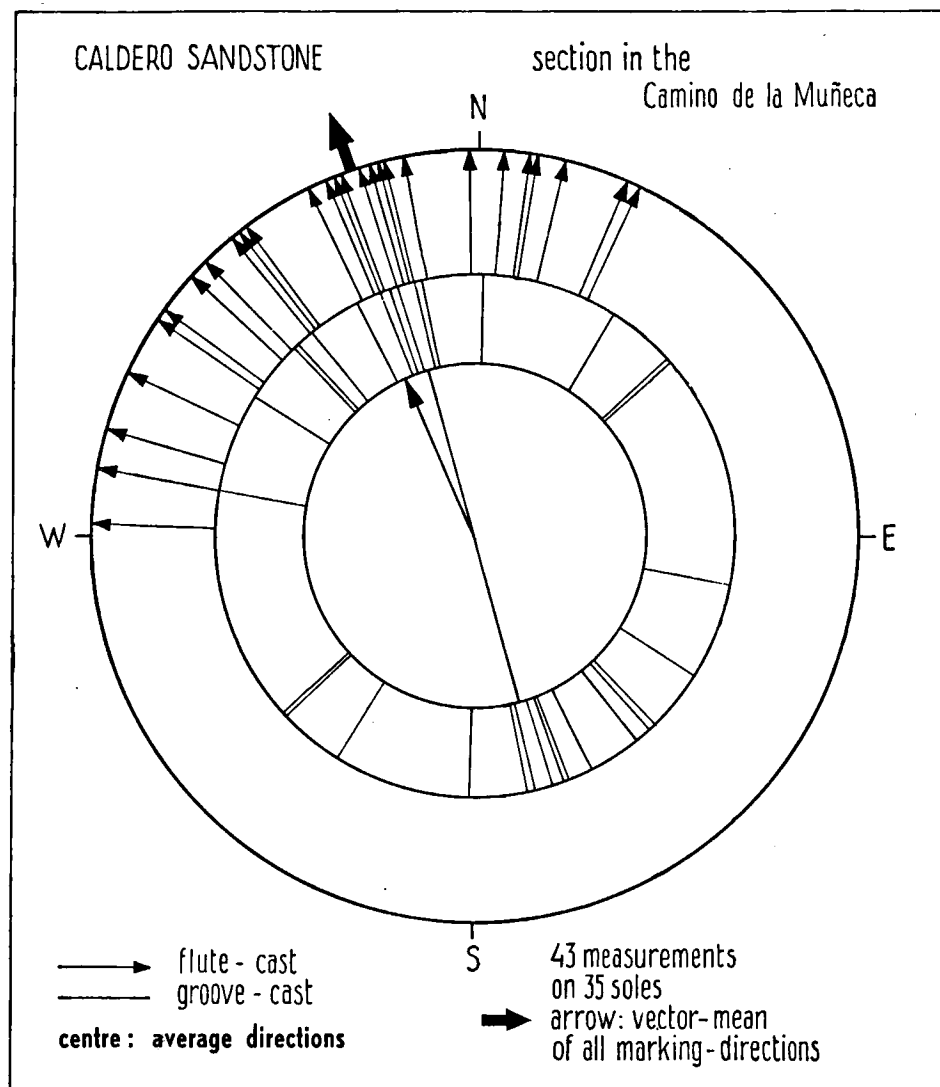


Figure 31. Coincidence of groove cast and flute cast measurements.

#### 6.2.5. Direction pattern

The pattern of directions in the Graded- and the Caldero formations is quite consistent. In about ten places, covering the whole thickness and the outcrops in the Redondo syncline north of the Rio Pisuerga, the directions indicate a supply from the SE quadrant.

A short investigation made in the Rubagón graded beds near Barruelo,

which approximately are of the same age, gives SSW directions, i. e. a supply from the NNE.

The latter measurements were made in overturned strata, dipping some 70 degrees to the NE. It is not clear how the main structure, to which this flank belongs, dips. Thus we should not try to explain this enormous difference in current direction, as compared to the Redondo syncline, by suppositions of palaeographic kind.

In the Redondo syncline the most important fact is that the currents did not simply go into the most obvious direction, i. e. from SW to NE, as inferred from the stratigraphical successions in the whole region.

The queer directions in the younger deposits of the Redondo syncline, which indicate sediment supply from the NE, point to a limitation of the basin in the NE. If we assume a certain ridge between the Redondo region and the Rubagón during Stephanian A times, the center of the basin in which the graded sediments accumulated, had a probable supply region, bordering it in the NE, S and SW. Probably it had a longest dimension in a SE—NW direction. These considerations lead to the hypothesis that the basin was principally filled by turbidity currents flowing in an oblong direction, while it was bordered at the SW side by an area of shelf sedimentation! Probably the basin was connected with a still larger through in the north.

This hypothesis agrees with the observations involving basins many times larger than this one, by Ten Haaf (1959), Książkiewicz (1957), Kuenen (1958) and others.

The observed palaeocurrent directions in the Graded formation and the Caldero formation indicate that the centre of the basin was situated somewhere in the north.

### 6.3. *Current-bedding measurements in the paralic association*

Pettijohn (1957) mentioned many palaeocurrent studies based on current bedding measurements.

The paralic association includes many sandstones of terrestrial deposition. If we assume them to have been deposited by meandering rivers, the directions will not be consistent. This also will be true in an estuarine environment. It is logical therefore that the directions obtained by measuring cross-bedding, slumping and current-ripple marks in the paralic association in the Westphalian D and Stephanian A show a very irregular pattern. Only if a vast number of measurements is available a certain trend may be observed.

The palaeocurrent directions obtained by current-ripple mark and cross lamination, have been indicated with special symbols on the geological map.

A few directions not indicated on the map, are the following: (the number of measurements averaged is indicated in parenthesis after the direction quadrant)

#### A. Southern flank Sierra Corisa syncline.

1. Sierra Corisa series, Westphalian D, about 2 km ESE of Vañes. Thick brown, lenticular current-bedded protoquartzite, cut off by the angular unconformity of San Cristóbal. Direction: to the W (33). Size (thickness) of current-bedded units about 0.5 m.

2. Same locality, above the angular unconformity, massive bedded greenish-grey protoquartzite and shales. Stephanian A. Direction: to the S (7). Size of current-bedded units about 30 cm.

B. Casavegas syncline.

1. Road junction Cervera-Potes, Cervera-Casavegas, about one and a half km west of Camasobres. Current-bedded, pink weathering, protoquartzite, about 10 m above the coal seam of Casavegas. Stephanian A. Size of the lenticular current-bedded units 25 cm. Direction: to the E (25).

2. 500 m SW of Camasobres at the turn of the road Cervera-Potes. Sandstone below and above the Camasobres coalseams, Stephanian A. Size of the tabular current-bedded units 50 cm. Direction: to the NE (2).

3. One km NW of Casavegas, sandstone 15 m above the Camasobres coalseams. Size of the current-bedded units 50 cm. Direction: inconsistent: (5) NE and (5) W.

The lack of sufficiently exposed rock and the lack of current-bedding in general, have caused a deficiency of measurements. The only area where the directions do not diverge widely, is the centre of the Redondo syncline. The directions in about 500 m sediment-thickness, (Stephanian A) overlying the Caldero formation, suggest a general supply from the NE (total of 25 measurements). The importance of this current-trend has been pointed out already in the discussion of the turbidite-current directions. The intricacy of the palaeocurrent pattern, through Westphalian D and Stephanian A times, reflects the unstable character of this part of the sedimentation basin, which also is reflected in the complex stratigraphy.

## SUMARIO

### *Capítulo 2. Estratigrafía*

Las rocas en los valles del tramo superior del Río Pisuerga son de edad Westfaliense Superior y Estefaniense A.

Las pizarras predominan, aunque también hay bastante cantidad de arenisca y caliza. Las capas de carbón, que se encuentran en varios niveles de la columna estratigráfica, contienen antracita, semi-antracita y hulla.

En el sur-oeste se encuentran rocas intrusivas (graníticas) que atraviesan los estratos del Carbonífero.

Según la composición mineralógica y las propiedades sedimentarias se pueden dividir los sedimentos Carboníferos de la región en tres asociaciones lito-estratigráficas, que están indicadas en el mapa. Son las siguientes:

1. *Asociación ortocuarcítica-carbonatita* con pizarras gris-morenas, calizas macizas puras (biohermas) y algunos estratos de arenisca cuarzosa muy pura.

2. *Asociación turbidita*, una alternación de areniscas calcáreas-arcillosas con estratificación graduada<sup>1)</sup>, que muestra una multitud de estructuras sedimentarias ("sole markings") y fangolitas oscuras. Esta asociación también contiene conglomerados y brechas con clastos de caliza juntamente con estructuras que indican "slumping" (subsoli-fluxión).

3. *Asociación parálisis*, relativamente arenosa, con predominancia de proto-cuarcitas sobre ortocuarcitas, bastante estratificación diagonal y entrecruzada de tamaño apreciable. Esta asociación incluye todas las capas de carbón y algunas calizas delgadas de origen biostroma.

La significación de la subdivisión mencionada parece esencialmente tectónica.

Dos facies se pueden distinguir: en el oeste la sucesión contiene más sedimentos continentales que la sucesión oriental. Sin embargo, varias formaciones marinas, sobre todo las calizas, se extienden en toda la región. Las dos facies están separadas por una zona donde algunas formaciones marinas son más delgadas y hasta desvanecen. Esta zona se encuentra a lo largo de los ejes de los anticlinales de Los Llazos y de Celada.

El aparecer de sedimentos clásticos en la columna estratigráfica fué relacionado con los movimientos orogénicos en el esquema 2.5.

### *Capítulo 3. Tectónica*

Las fases orogénicas que afectaron la región estudiada son la fase Curavacas, pre-Westfaliense B sup.; dos fases locales siendo la Cabra Mocha y la San Cristóbal en el Westfaliense D y entre Westfaliense D y Estefaniense A respectivamente, que ambas desvanecen hacia el centro de la cuenca: la fase Astúrica entre Estefaniense A y B, y una o varias fases post-astúricas-pre-Triásicas.

La región puede dividirse en tres unidades estructurales:

1. El amplio *sinclinal de Sierra Corisa* en el sur.

<sup>1)</sup> "Graded bedding".



2. La *zona Central*, que constituye el flanco norte del sinclinal de Sierra Corisa y contiene de WSW—ENE: el sinclinal de Estalaya, el anticlinal de Verdeña (junto con la Peña Tremaya), el sinclinal de Sosa, el anticlinal de Celada, el sinclinal de Celada (con las calizas de la Verdiana y Frechna: el sinclinal de San Juan) y al fin el anticlinal de la Peña del Moro.

3. El amplio *sinclinal asimétrico de Redondo* con el flanco oriental volcado.

Con la ayuda de zonas de fusulinidas estudiadas por Van Ginkel y las floras fósiles identificadas por Wagner se formó una interpretación de algunas estructuras problemáticas. La Peña Tremaya se explica como parte del anticlinal quebrado de Verdeña. El sinclinal de San Juan se podría explicar como parte del sinclinal de Celada. La Peña Tejado constituye parte del flanco oriental invertido del sinclinal de Redondo.

#### *Capítulo 4. Formación de arenisca con estratificación graduada.*

Muestras de esta formación fueron investigadas en el laboratorio. Mediciones de espesor en la alternación de arenisca y fangolito fueron investigadas con métodos matemático-estadísticos. Argumentos geológicos conducen a la hipótesis de sedimentación por corrientes de turbidez. Por consiguiente las conclusiones del análisis estadístico son interpretadas a base de esta hipótesis.

Las areniscas son calcáreas, finas hasta medianas, angulosas y poco seleccionadas, con gran proporción de matriz arcillosa. No son grauvacas en el sentido mineralógico de Pettijohn. Hacia arriba la arena cambia gradualmente en limo y fango. Esta transición de arenisca a fangolita es bastante repentina y permite la medición de una parte "arenisca" y una parte de fangolita o "pizarra". De vez en cuando se encuentran niveles de concreciones dentro de la alternación siempre igual. La posición de éstos, juntamente con los espesores de las areniscas y pizarras fueron analizados con el objeto de establecer regularidades en su sucesión.

La distribución de las frecuencias de los espesores medidos en tres secciones de 364, 335 y 55 unidades graduadas, son del tipo asimétrico corriente. Se normalizan bastante por transformación logarítmica para determinados objetos. Sin embargo, la mayoría de los métodos estadísticos empleados no dependen de la distribución (no-paramétricas), evitando así dificultades que resultaran de las insuficiencias de transformación.

La diferencia fundamental entre varvas (marinas o lacustres) glaciales y estratificación graduada por re-sedimentación con intervalos irregulares, resalta más claramente en los histogramas de espesor de las partes arenosas.

La más importante relación que existe entre los variables es la correlación positiva entre los espesores de arenisca y fangolita. Se explica esta relación con la hipótesis de sedimentación de las dos litologías por una corriente de turbidez con, más o menos, la misma composición en todos los casos.

La intensidad de esta correlación varía con el porcentaje medio de fangolita en las unidades graduadas. Esto indica erosión de la primera unidad por la corriente que depositaba la segunda, en unos casos, pero en otros, una deposición adicional de arcilla o fango que se produjo en condiciones "ordinarias".

Correlación positiva entre espesor de arenisca y su porcentaje indica la importancia de variaciones en composición de las corrientes en el punto de observación (dependiente entre otras cosas de la composición original y de la distancia del origen).

El aumento del espesor medio de las areniscas se explica por corrientes de turbidez más importantes, lo que puede significar un acercamiento del origen o levantamiento del mismo.

Las concreciones de siderita-arcillita se encuentran casi siempre en la parte superior de las pizarras. En muchos casos la superficie fué lavada por la corriente de turbidez que luego depositó un estrato de arena. Sólo puede resultar esto, si las concreciones estaban duras o resistentes durante el paso de la corriente de turbidez. Las unidades que tienen concreciones como último estrato están generalmente faltas de pizarra, lo que indica el lavamiento del nivel de concreciones antes de una deposición nueva.

El análisis estadístico del orden en que los estratos de arenisca de diferentes espesores se encuentran, revela en primer lugar un "trend", pero también fluctuaciones que comprenden hasta diez unidades graduadas, generalmente de forma asimétrica. Las fluctuaciones tienden a empezar con un estrato grueso y después con estratos de espesor cada vez menor. Pueden ser independientes y también traslapan unas a otras. Se notan estas fluctuaciones por la tendencia de que aparecen espesores semejantes en sucesión. Las fluctuaciones podrían producirse cuando varias corrientes de turbidez naciesen, en sucesión, de la misma pendiente subacuática, por causa de la inestabilidad del primer hundimiento. La investigación de otros ejemplos de la literatura dió los mismos resultados.

#### *Capítulo 5. Estructuras sedimentarias*

Las estructuras sedimentarias se dividen en dos grupos.

Primero: las que se estudian con más ventaja en perfiles. En segundo lugar: las estructuras que se estudian sobre el plano de estratificación.

Al grupo primero pertenecen las grietas rellenas en la caliza del diastema de Cabra Mocha, la estratificación entrecruzada y diagonal, laminado diagonal, "convolute lamination", "load cast" de gran tamaño y "slumping".

Como segundo grupo se describen varias "sole markings". La bibliografía es una tentativa de establecer una relación entre las "sole markings" de las descripciones anteriores y la terminología moderna.

#### *Capítulo 6. Direcciones de paleo-corrientes*

Las direcciones fueron medidas en la asociación parálica y turbidita. En la primera asociación, la estratificación diagonal y el "slumping" indicaban la dirección. Las direcciones son poco consistentes y las posibilidades de medición estaban limitadas. Sin embargo, en el centro del sinclinal de Redondo existe una dirección desde NE hacia SW.

En la asociación turbidita en el sinclinal de Redondo la dirección va desde SE hacia NW según indicación de las "sole markings".

La sucesión de direcciones sobre planos sucesivos de estratificación fué analizada y se ha hecho una tentativa de establecer una relación entre las series de direcciones similares y las fluctuaciones.

La variabilidad de direcciones de los "groove casts" (surcos) en grandes superficies del plano de estratificación fué medida en condiciones muy favorables. El resultado sostiene la hipótesis de Ten Haaf acerca de las direcciones de "groove casts".

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# LEIDSE GEOLOGISCHE MEDEDELINGEN.

Deel 24, Aflevering 2, p. 603—703.

STRUCTURE AND SEDIMENTOLOGY OF THE UPPER CARBONIFEROUS OF  
THE UPPER PISUERGA VALLEYS, CANTABRIAN MOUNTAINS, SPAIN.

## ERRATA

Page	paragraph	line	
607	1.2.	15	"They concluded that ..." should be: He concluded that ...
628	3.2.2.	4	Line 4 should be: ridge. The extension of this structure towards the <i>S</i> is pro-
640	4.3.3.	3	In formula the exponent of <i>e</i> should be: $-\frac{1}{2} \left[ \frac{\ln x - m}{\sigma} \right]^2$
640	4.3.3.	5	"(Edgeworth, 1903)" should be: (Edgeworth-Kapteyn formula, Kapteyn, J. C. 1903. Skew frequency curves, Groningen.)
640	4.3.3.	17	"Stratification index = ..." should be: Stratification index =

$$= \frac{\text{Number of beds} \times 100}{\text{Total thickness in feet}}$$

640	4.3.3.	9 —	"(See 4.3.4.)" should be:
		— from below	(See 4.3.5).
686	6.2.1.	11	Cromwell 1055 should be: Crowell 1955.

In the bibliography on sole markings no mention has been made of the interesting letters by J. E. Prentice, E. S. Hills and G. Kelling & E. K. Walton, which appeared in 1958 in the *Geol. Mag.*, vol. XCV, no. 2, p. 169—172.

In the legend of the Lithostratigraphic map, under the heading "Paralic Association" occurs: "Orthoquartzite within molasse association". This should be: Orthoquartzite within paralic association.

Geological maps, based on fieldwork around 1950—1953, and partly overlapping the area will be published in due time by Mr. R. H. Wagner (area in the S and SE, overlapping up to San Felices-Celada-Peña Tejedo) and by Mr. H. van Hoeflaken (the area W of the Pisuerga between Vañes and Aneños, but overlapping to Estalaya and Verdeña approximately).